Legacy of Bruno Pontecorvo and Research Perspectives at JINR

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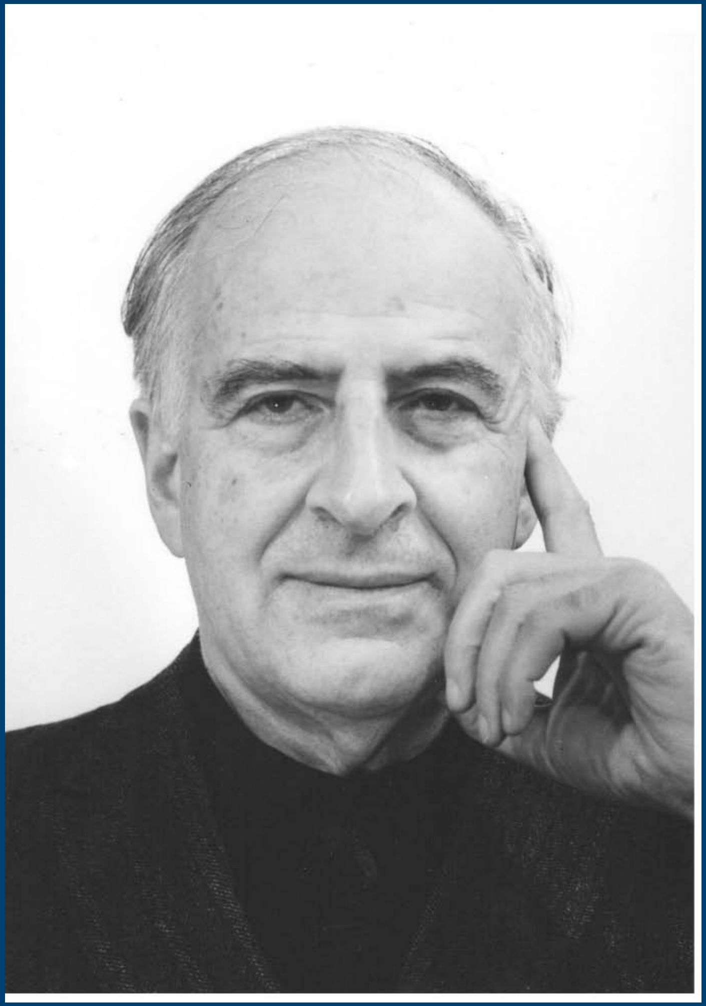
THE CENTENARY OF BRUNO PONTECORVO



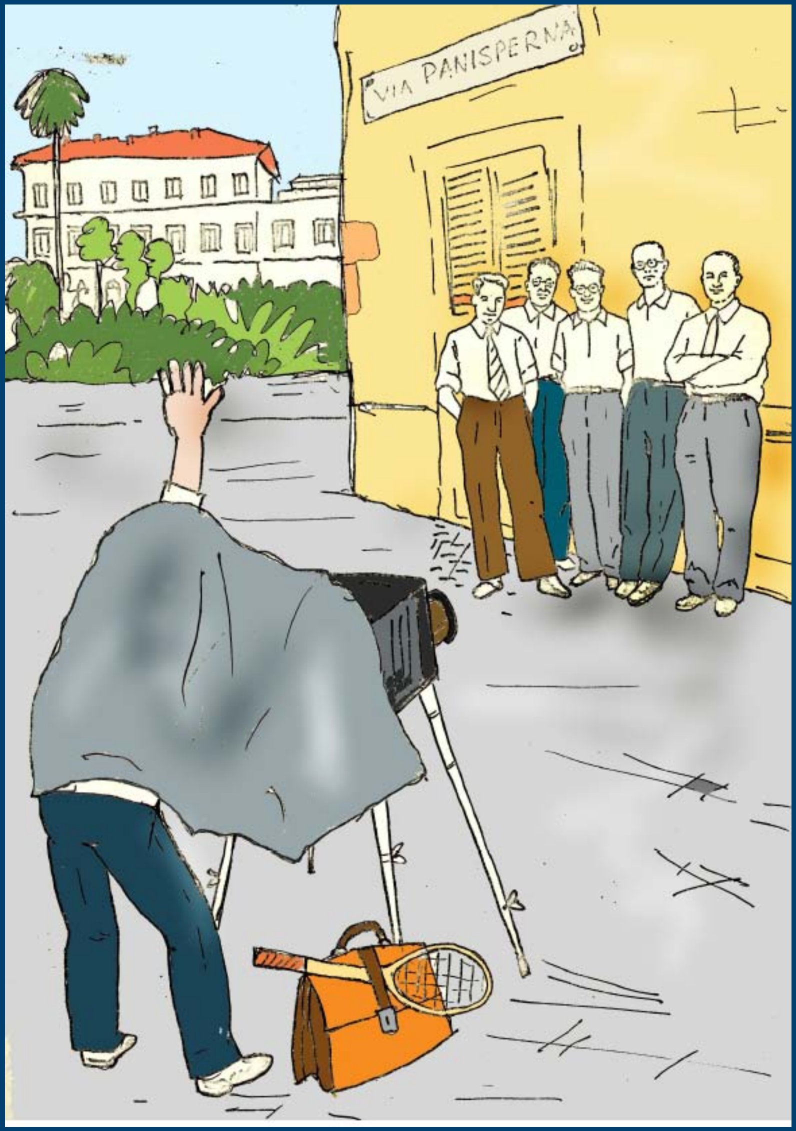
Born on 22 August 1913 in Pisa

Was already celebrated by series of events:

- ✓ V International Pontecorvo School on Neutrino Physics, 6-16 September, 2012, Alushta, Crimea.
- ✓ Ceremony of EPS Historic Site Opening in Dubna, 22 February, 2013.
- ✓ XVI Lomonosov Conference, 22-28 August 2013, Moscow.
- ✓ Scientific Session of RAS on Perspectives in Neutrino and Astroparticle Physics, 2-3 September, 2013, Dubna.
- ✓ The Legacy of Bruno Pontecorvo: the Man and the Scientist Conference, 11-12 September, 2013, Rome.
- ✓ Pontecorvo 100: Symposium on the centennial of the birth of Bruno Pontecorvo. 18-20 September, 2013, Pisa.

1931-1936 – B.Pontecorvo was a student and then a member of the widely known group of “Via Panisperna boys”.

Under the guidance of Enrico Fermi B.Pontecorvo studied the properties of slow neutrons and took part in the discovery of the phenomenon neutron moderation



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1936-1940 – B.Pontecorvo worked with F.Joliot-Curie at the Radium Institute in Paris.

1939

RECENT EXPERIMENTAL RESULTS IN NUCLEAR ISOMERISM*

The hypothesis that two atomic nuclei indistinguishable in respect of atomic and mass number could nevertheless have different radioactive properties (the hypothesis of nuclear isomerism) was put forward for the first time by Soddy [1] in 1917. In 1921 uranium Z was discovered by Hahn [2]; by studying the chemical and radioactive properties of this element, Hahn deduced that uranium Z and uranium X_2 are isomeric nuclei. The problem of uranium Z has been taken up recently by Feather and Bretscher (Proc. Roy. Soc., 1938, vol.165, p.542). It should be noted that, for many years, uranium Z and uranium X_2 were the only known example of an isomeric pair.

After the discovery of artificial radioactivity, the study of isomerism received considerable impetus on account of the experimental material assembled in the course of research on artificial radioelements. The first *certain* example of an isomeric pair to which it has been possible to attribute a mass number ($A = 80$) in the domain of the artificial radioelements was furnished [3] by the study of the radioactivity produced in bromine by neutrons (slow and fast) and by γ rays of great energy.

Then, as the experimental material on artificial radioelements has increased, the number of pairs of nuclei which are undoubtedly isomeric has grown to such an extent that it is not possible to quote here all the investigations which have been published on the question. More than thirty such pairs are known and there is no doubt that the number still unknown is much greater. We can say, now, *that nuclear isomerism is by no means an exceptional phenomenon.*

It is natural to think that the physical difference between two isomeric nuclei is connected with two states of different excitation of the same nucleus (let us say ground state and first excited state). But in this case, how could the upper state be metastable, that is, how could it live for any length of time (greater than one day, in some cases)? By what mechanism would it be preserved from destruction in a very short time by the emission of an electromagnetic radiation? Weiszäcker has answered this question [4].

According to Weiszäcker's *hypothesis*, nuclear isomerism may be explained by assuming that *the lowest excited state of the nucleus has an angular momentum differing by several units from that of the ground state*. Selection rules may then be invoked to weaken considerably the probability per unit of time of the transition from

*Nature, 1939, vol.144, p.212—213.

The research of nuclear isomerism led him to the discovery of a New phenomenon of nuclear phosphorescence (excitation of metastable states of a beta-stable isotopes with MeV gamma-quanta)

1940-1942 – a private company in the USA

B.Pontecorvo studied geophysical methods of oil wells' probing

He suggested and worked out a new effective method of oil exploration in 1941 – the neutron logging that tops the chronology of important applications of neutron

1941

**NEUTRON WELL LOGGING.
A NEW GEOLOGICAL METHOD
BASED ON NUCLEAR PHYSICS***

Since April 1940, when radioactivity well logging was offered to the trade by Well Surveys, Inc., the laboratories of the company have been engaged in continuing the search for new curves. The development of an additional parameter has fortunately become possible at time when the commercial experiences in the United States and in South America have shed considerable light on the usefulness of radioactivity well logging. A second curve should necessarily operate independently of casing and possess the detailed correlating power of the radioactivity log, and, above all, should add some new information. At the time of this writing, the initial field trials have been completed on a new process, neutron well logging, which appears to fulfill the foregoing requirements.

The well-logging instrument consists of a strong neutron source (radium plus beryllium).and an ionization chamber, so arranged that the ionization chamber is considerably shielded from the rays coming directly from the source (Fig.1). As a consequence of the interaction of the primary rays from the source with the surrounding formations, the indication furnished by the ionization chamber varies with the properties of the strata. What radiations do come through the shield directly from the source are a constant amount throughout the log. The present experimental subsurface instrument is a single cylindrical unit, similar to the one used for radioactivity logging. The maximum outside diameter of the present experimental instrument is 5.5 in. The total length of the subsurface instrument including the amplified and the power supply is 7 ft.

The curves shown in Fig.2 give good correlations, as can be seen. It is likely that the new curve will add enough new information to make possible the distinction of many types of strata which, hitherto, could not be recognized. Particularly, it is hoped that the new curve will:

1. Distinguish limestones from sandstones.
2. Distinguish more easily from shale the various rock types which consist of other materials mingled with shale.
3. Enable new and useful correlation horizons to be found in shales.
4. Enable some information to be gathered, by comparison, which will help in regard to the fluid content problem.

*Oil and Gas J., 1941, vol.40, p.32—33.

It seems at present that the neutron logs may be very valuable in areas where the producing formations are limestones and dolomites. In general, the neutron curves

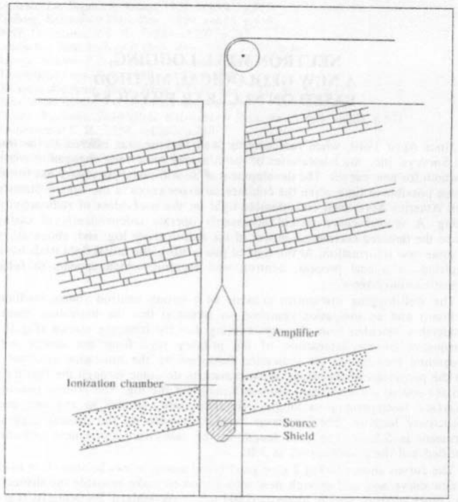
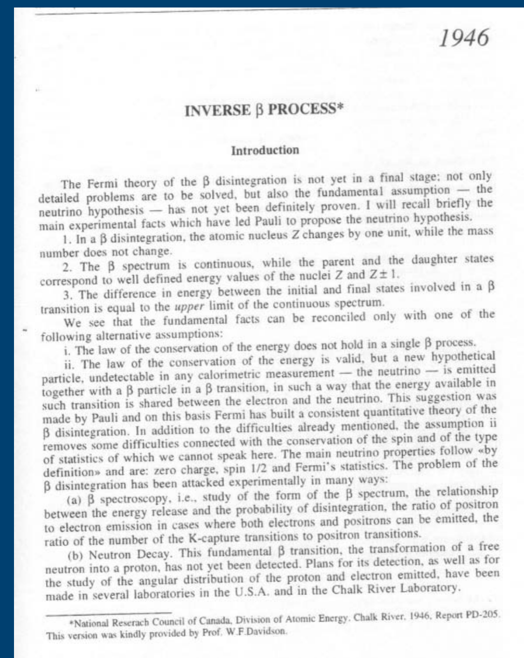


Fig.1. Diagram showing the arrangement of the various components of the subsurface equipment with respect to the neutron source

give geologists a new tool to work with, which may be applied equally well to old or new wells. It is certain that the neutron well-logging method is able to log in cased and uncased holes alike with comparable results, and that the logs are characterized by deep penetration. It is also certain that valuable logs can be made in areas of salt beds, such as West Texas and western Kansas, and in places where the various electrical-logging methods fail.

1934 - Bethe and Peierls evaluated the cross section of neutrino interaction with matter (which turned out to be less than 10^{-44} cm^2) it was thought that neutrino was impossible to be registered.

Bruno Pontecorvo was the first to doubt it.



1946

INVERSE β PROCESS*

Introduction

The Fermi theory of the β disintegration is not yet in a final stage; not only detailed problems are to be solved, but also the fundamental assumption — the neutrino hypothesis — has not yet been definitely proven. I will recall briefly the main experimental facts which have led Pauli to propose the neutrino hypothesis.

1. In a β disintegration, the atomic nucleus Z changes by one unit, while the mass number does not change.

2. The β spectrum is continuous, while the parent and the daughter states correspond to well defined energy values of the nuclei Z and Z ± 1.

3. The difference in energy between the initial and final states involved in a β transition is equal to the *upper* limit of the continuous spectrum.

We see that the fundamental facts can be reconciled only with one of the following alternative assumptions:

i. The law of the conservation of the energy does not hold in a single β process.

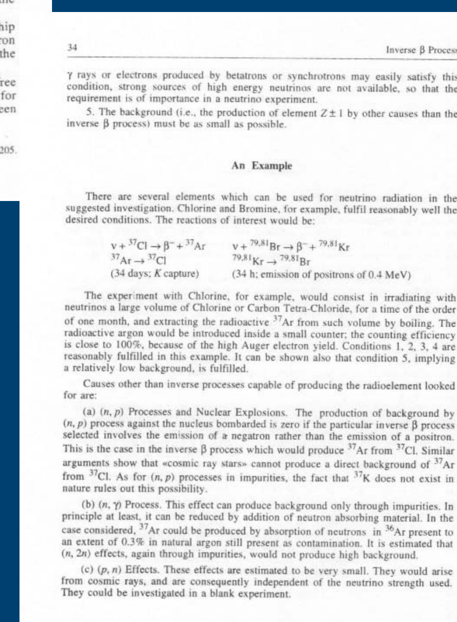
ii. The law of the conservation of the energy is valid, but a new hypothetical particle, undetectable in any calorimetric measurement — the neutrino — is emitted together with a β particle in a β transition, in such a way that the energy available in such transition is shared between the electron and the neutrino. This suggestion was made by Pauli and on this basis Fermi has built a consistent quantitative theory of the β disintegration. In addition to the difficulties already mentioned, the assumption ii removes some difficulties connected with the conservation of the spin and of the type of statistics of which we cannot speak here. The main neutrino properties follow «by definition» and are: zero charge, spin 1/2 and Fermi's statistics. The problem of the β disintegration has been attacked experimentally in many ways:

(a) β spectroscopy, i.e., study of the form of the β spectrum, the relationship between the energy release and the probability of disintegration, the ratio of positron to electron emission in cases where both electrons and positrons can be emitted, the ratio of the number of the K-capture transitions to positron transitions.

(b) Neutron Decay. This fundamental β transition, the transformation of a free neutron into a proton, has not yet been detected. Plans for its detection, as well as for the study of the angular distribution of the proton and electron emitted, have been made in several laboratories in the U.S.A. and in the Chalk River Laboratory.

*National Reserach Council of Canada, Division of Atomic Energy, Chalk River, 1946, Report PD-205. This version was kindly provided by Prof. W.F.Davidson.

He realized that it was the reactor that could be an intense neutrino source (today we know that it is antineutrino), and suggested in 1946 a method to register these neutrinos by the extraction of an argon isotope that was produced at the inverse beta decay



γ rays or electrons produced by betatrons or synchrotrons may easily satisfy this condition, strong sources of high energy neutrinos are not available, so that the requirement is of importance in a neutrino experiment.

5. The background (i.e., the production of element Z ± 1 by other causes than the inverse β process) must be as small as possible.

An Example

There are several elements which can be used for neutrino radiation in the suggested investigation. Chlorine and Bromine, for example, fulfil reasonably well the desired conditions. The reactions of interest would be:

$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$	$\nu + {}^{79,81}Br \rightarrow \beta^- + {}^{79,81}Kr$
${}^{37}Ar \rightarrow {}^{37}Cl$	${}^{79,81}Kr \rightarrow {}^{79,81}Br$
(34 days; *K* capture)	(34 h; emission of positrons of 0.4 MeV)

The experiment with Chlorine, for example, would consist in irradiating with neutrinos a large volume of Chlorine or Carbon Tetra-Chloride, for a time of the order of one month, and extracting the radioactive ${}^{37}Ar$ from such volume by boiling. The radioactive argon would be introduced inside a small counter; the counting efficiency is close to 100%, because of the high Auger electron yield. Conditions 1, 2, 3, 4 are reasonably fulfilled in this example. It can be shown also that condition 5, implying a relatively low background, is fulfilled.

Causes other than inverse processes capable of producing the radioelement looked for are:

(a) (*n*, *p*) Processes and Nuclear Explosions. The production of background by (*n*, *p*) process against the nucleus bombarded is zero if the particular inverse β process selected involves the emission of a negatron rather than the emission of a positron. This is the case in the inverse β process which would produce ${}^{37}Ar$ from ${}^{37}Cl$. Similar arguments show that «cosmic ray stars» cannot produce a direct background of ${}^{37}Ar$ from ${}^{37}Cl$. As for (*n*, *p*) processes in impurities, the fact that ${}^{37}K$ does not exist in nature rules out this possibility.

(b) (*n*, γ) Process. This effect can produce background only through impurities. In principle at least, it can be reduced by addition of neutron absorbing material. In the case considered, ${}^{37}Ar$ could be produced by absorption of neutrons in ${}^{36}Ar$ present to an extent of 0.3% in natural argon still present as contamination. It is estimated that (*n*, 2*n*) effects, again through impurities, would not produce high background.

(c) (*p*, *n*) Effects. These effects are estimated to be very small. They would arise from cosmic rays, and are consequently independent of the neutrino strength used. They could be investigated in a blank experiment.

(neutrino + ${}^{37}Cl \rightarrow {}^{37}Ar$ + electron).

Now the whole world knows this phenomenon as the radiochemical chlorine-argon method to detect neutrinos from the Sun.

In 1948 B.Pontecorvo designed a proportional counter of a small size with a big signal amplification. While applying it, he observed for the first time in 1949 the nuclear capture of L-electrons in argon and made the first measurement of the tritium beta spectrum from which the first restriction on mass of the electron neutrino of less than 500 eV was obtained.

1948

THE ABSORPTION OF CHARGED PARTICLES FROM THE 2.2-MICROSECOND MESON DECAY*

In collaboration with E.P.Hincks

The energy spectrum of the charged particles (commonly assumed to be electrons) emitted in the 2.2-μsec meson decay is still unknown. Conversi and Piccioni [1] in 1944 deduced from the relative numbers of decay electrons escaping from iron plates 0.6 cm and 5 cm thick that their mean range is about 2.5 cm of iron. According to the range-energy relationships of Bethe—Bloch—Heitler [2], this corresponds to an energy of about 50 MeV, which was consistent with the Yukawa β-process picture of a meson decaying into an electron and neutrino, each of about 50 MeV. Subsequently, Anderson and co-workers [3] observed two instances of meson decay in a cloud chamber, and were able to measure accurately the energy of the decay electron. This was found in both cases to be close to 25 MeV. To explain this low energy they postulated that the decay process might be

$$\text{charged meson} \rightarrow \text{electron} + \text{neutral meson}, \qquad (1)$$

with the kinetic energy of the electron having a unique value of about 25 MeV. Since the present experiment was initiated there have been reported a few results [4] obtained with cloud chambers that seem to indicate a considerable spread in the energies of the decay particles. A 3-particle decay process in which the electrons may be emitted with any energy up to about 50 MeV has been suggested recently [5].

Our experiment, carried out in the Chalk River Laboratory, is an attempt to derive some information about the energy of the decay electrons by measuring their penetration through a solid absorber. The method differs from that used by Conversi and Piccioni; in particular, a low atomic number absorbing material (carbon**) for the electrons was used in order to decrease the energy losses by radiation which complicate the interpretation of the experiment.

A section of the counter arrangement, together with a block diagram illustrating the function of the electronic circuits, is shown in Fig.1. A meson beam entering the apparatus is defined by a coincidence between counter trays A and B. The positive and negative mesons which are stopped in a graphite block 20 cm × 40 cm × 4.2 g/cm² thick are detected by the anticoincidence $(AB-C)$, which initiates a grating pulse

*Phys. Rev., 1948, vol.74, p.697—698.

**For one run a small thickness of iron was added on top of the graphite.

4.6 μsec in width and delayed by about 1 μsec. This pulse is then mixed separately with the outputs from A, B, and C, so that if the decay electron passes through A, B, or C between 1 and 5.6 μsec after an anticoincidence $(AB-C)$, a delayed coincidence is recorded which we designate by $(A)_{del}$, $(B)_{del}$, or $(C)_{del}$. In particular, a decay electron passing through both B and A gives an event $(AB)_{del}$.

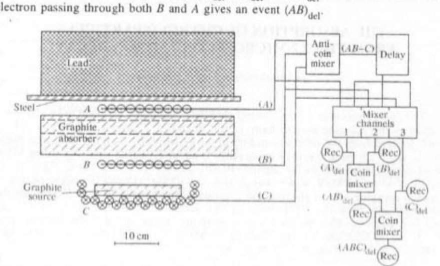


Fig.1. Experimental arrangement. The geometry in the plane perpendicular to the paper be inferred from the length of the counters, which is 35 cm

In order to measure the penetration of the decay electrons, the rate $(AB)_{del}$ is measured as a function of the thickness of a graphite absorber placed between A and B*. Some events $(AB)_{del}$ are also events $(ABC)_{del}$ and are caused essentially by a meson traversing the three trays by chance within the delayed interval. The events $(ABC)_{del}$ are also recorded and enable us to disregard most of the chance $(AB)_{del}$.

It will be noticed that A and B have two functions: (i) detecting the passage of the primary meson and (ii) detecting the passage of a decay electron. Because of the counter dead time, only those decay electrons will be detected which pass through a different counter from that traversed by the meson. This decrease in the effective sensitivity of tray B would be serious if the meson absorber (i.e., the «source» of decay electrons) were placed very close to B; a favorable position of the source (4.1 cm below B) was determined graphically.

The results are summarized in the Table.

*The absorber for the decay particles, when placed between A and B, produces a negligible change in the number of mesons stopped in the graphite below B, so that the strength of the «source» of decay electrons is sensibly constant as indicated by the rate $(B)_{del} + (C)_{del}$.

THE β SPECTRUM OF ^3H*

In collaboration with G.C.Hanna

The proportional counter technique previously described [1,2] has been used to study the β spectrum of ^3H, an investigation of which has recently been reported by Curran et al. [3].

The two counters I and II described in Ref.2 were used. The fillings are given in Table 1.

Table 1. Counter fillings used

Gases	Counter I	Counter II
Xenon	50 cm Hg	26 cm Hg
Argon	—	14 cm Hg
Methane	10 cm Hg	10 cm Hg
Hydrogen	~ 1 cm Hg	~ 0.2 cm Hg
^3H	~ 7,000 counts/min	~ 30,000 counts/min
^{37}Ar	—	~ 6,000 counts/min

Both counters were operated at gas multiplication factors of several thousand. The absolute energy scale was obtained by firing into the counter a beam of MoK_α–X-rays (17.4 keV) from a crystal spectrometer. In counter I this beam was parallel to the counter wire, in II perpendicular to it. The assumption that these energy calibrations were representative of the properties of the counter as a whole was checked directly for counter II by measuring the Mo $K_\alpha/^{37}Ar$ pulse size ratio**, and is inferred for counter I from the agreement between the end point energy determinations in the two counters.

The complete spectrum was investigated in counter I. Since counter linearity had to be maintained up to 20 keV, we were not able to use multiplication factors as high as those used in the investigation [4] of the Cl L_1 peak (280 eV). Consequently the amplifier noise was apparent at energies as high as about 600 eV.

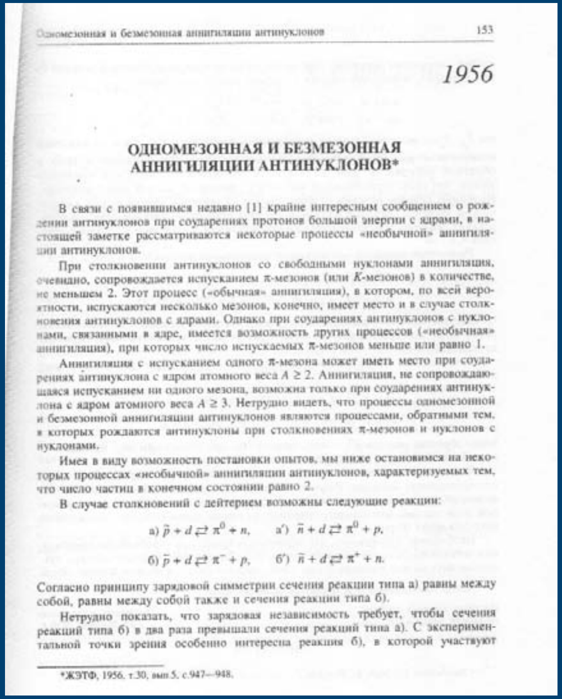
At the ends of the counter the multiplication falls off due to reduced field strength. Disintegration occuring in this region will produce pulses of spuriously low amplitude. Clearly the shape of the spectrum is most affected at low energy. Due to lack of data the correction to be applied is uncertain, a fact which precludes a quantitative comparison of our result with Fermi's theory in the region near the most

*Phys. Rev., 1949, vol.75, p.983—984.

**^{37}Ar gives a 2.8-keV calibration line which is truly representative, since, as for ^3H, the disintegrations occur uniformly throughout the counter volume.

August 1950 – B.Pontecorvo came to live in USSR

1953 - Bruno Pontecorvo expressed a hypothesis on simultaneous production of kaons and hyperons and together with L.B.Okun came to a conclusion that the quantum number “strangeness” can change by not more than 1 in weak processes.



Одномезонная и безмезонная аннигиляции антинуклонов 153

1956

ОДНОМЕЗОННАЯ И БЕЗМЕЗОННАЯ АННИГИЛЯЦИИ АНТИНУКЛОНОВ*

В связи с появившимся недавно [1] крайне интересным сообщением о рождении антинуклонов при соударениях протонов большой энергии с ядрами, в настоящей заметке рассматриваются некоторые процессы «необычной» аннигиляции антинуклонов.

При столкновении антинуклонов со свободными нуклонами аннигиляция, очевидно, сопровождается испусканием π-мезонов (или K-мезонов) в количестве, не меньшем 2. Этот процесс («обычная» аннигиляция), в котором, по всей вероятности, испускаются несколько мезонов, конечно, имеет место и в случае столкновения антинуклонов с ядрами. Однако при соударениях антинуклонов с нуклонами, связанными в ядре, имеется возможность других процессов («необычная» аннигиляция), при которых число испускаемых π-мезонов меньше или равно 1.

Аннигиляция с испусканием одного π-мезона может иметь место при соударениях антинуклона с ядром атомного веса $A \geq 2$. Аннигиляция, не сопровождающаяся испусканием ни одного мезона, возможна только при соударениях антинуклона с ядром атомного веса $A \geq 3$. Нетрудно видеть, что процессы одномезонной и безмезонной аннигиляции антинуклонов являются процессами, обратными тем, в которых рождаются антинуклоны при столкновениях π-мезонов и нуклонов с нуклонами.

Имея в виду возможность постановки опытов, мы ниже остановимся на некоторых процессах «необычной» аннигиляции антинуклонов, характеризуемых тем, что число частиц в конечном состоянии равно 2.

В случае столкновений с дейтерием возможны следующие реакции:

а) $\bar{p} + d \rightleftarrows \pi^0 + n$, а′) $\bar{n} + d \rightleftarrows \pi^0 + p$,

б) $\bar{p} + d \rightleftarrows \pi^- + p$, б′) $\bar{n} + d \rightleftarrows \pi^+ + n$.

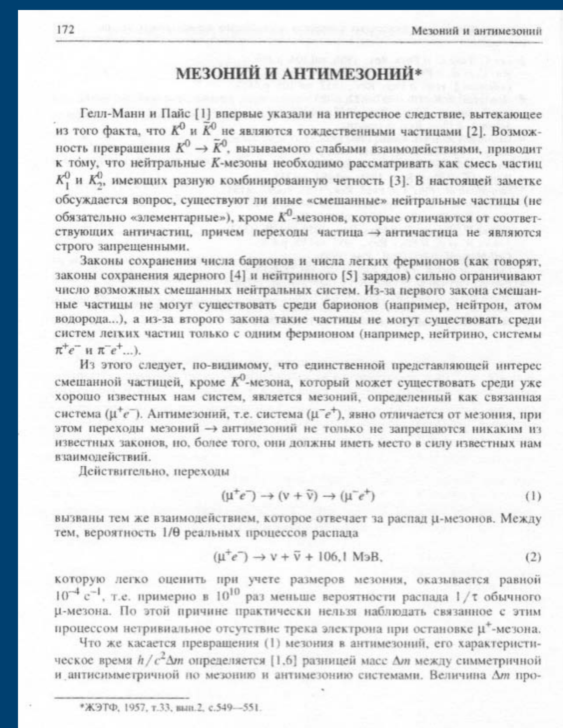
Согласно принципу зарядовой симметрии сечения реакции типа а) равны между собой, равны между собой также и сечения реакции типа б).

Нетрудно показать, что зарядовая независимость требует, чтобы сечения реакций типа б) в два раза превышали сечения реакций типа а). С экспериментальной точки зрения особенно интересна реакция б), в которой участвуют

*ЖЭТФ, 1956, т.30, вып.5, с.947—948.

1956 - B.Pontecorvo published a paper on a possibility of exotic annihilation reactions forbidden on one nucleon but allowed when the antiproton annihilates in the nucleus. This type of reaction is known today as “the Pontecorvo reaction”; it gives new opportunities for meson spectroscopy.

In 1957 B.Pontecorvo for the first time expressed the idea on possible existence of muonium transitions (μ+e-) into antimuonium (μ-e+). In this process the lepton numbers of particles change immediately by 2 and, consequently, this process is totally forbidden in the Standard Model. Discussing the muonium-antimuonium transitions, B.Pontecorvo presupposed that oscillations can occur not only in the case of bosons (neutral kaons and muonia), but also in the case of electrically neutral fermions. It was the birth of the neutrino oscillation hypothesis.



172 Мезоний и антимезоний

МЕЗОНИЙ И АНТИМЕЗОНИЙ*

Гелл-Манн и Пайс [1] впервые указали на интересное следствие, вытекающее из того факта, что K^0 и $\bar{K}^0$ не являются тождественными частицами [2]. Возможность превращения $K^0 \to \bar{K}^0$, вызываемого слабыми взаимодействиями, приводит к тому, что нейтральные K-мезоны необходимо рассматривать как смесь частиц K_1^0 и K_2^0, имеющих разную комбинированную четность [3]. В настоящей заметке обсуждается вопрос, существуют ли иные «смешанные» нейтральные частицы (не обязательно «элементарные»), кроме K^0-мезонов, которые отличаются от соответствующих античастиц, причем переходы частица → античастица не являются строго запрещенными.

Законы сохранения числа барионов и числа легких фермионов (как говорят, законы сохранения ядерного [4] и нейтринного [5] зарядов) сильно ограничивают число возможных смешанных нейтральных систем. Из-за первого закона смешанные частицы не могут существовать среди барионов (например, нейтрон, атом водорода...), а из-за второго закона такие частицы не могут существовать среди систем легких частиц только с одним фермионом (например, нейтрино, системы π^+e^- и π^-e^+...).

Из этого следует, по-видимому, что единственной представляющей интерес смешанной частицей, кроме K^0-мезона, который может существовать среди уже хорошо известных нам систем, является мезоний, определенный как связанная система (μ^+e^-). Антимезоний, т.е. система (μ^-e^+), явно отличается от мезония, при этом переходы мезоний → антимезоний не только не запрещаются никаким из известных законов, но, более того, они должны иметь место в силу известных нам взаимодействий.

Действительно, переходы

$$(\mu^+e^-) \to (\nu + \bar{\nu}) \to (\mu^-e^+) \tag{1}$$

вызваны тем же взаимодействием, которое отвечает за распад μ-мезонов. Между тем, вероятность 1/θ реальных процессов распада

$$(\mu^+e^-) \to \nu + \bar{\nu} + 106{,}1 \text{ МэВ}, \tag{2}$$

которую легко оценить при учете размеров мезония, оказывается равной 10^{-4} $с^{-1}$, т.е. примерно в 10^{10} раз меньше вероятности распада $1/\tau$ обычного μ-мезона. По этой причине практически нельзя наблюдать связанное с этим процессом нетривиальное отсутствие трека электрона при остановке μ^+-мезона.

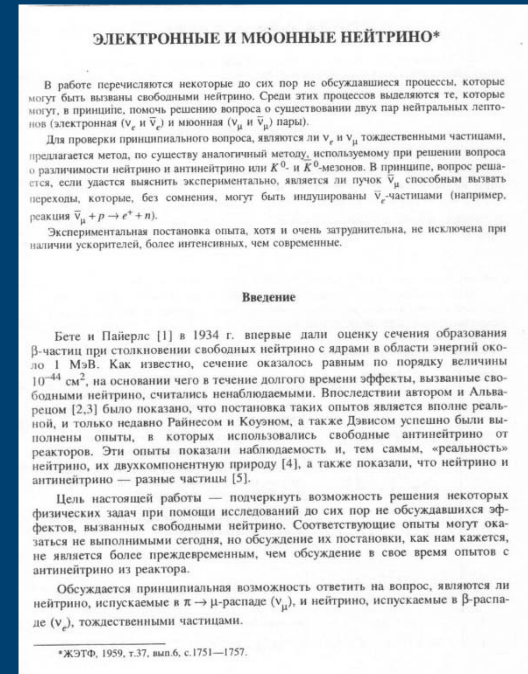
Что же касается превращения (1) мезония в антимезоний, его характеристическое время $h/c^2\Delta m$ определяется [1,6] разницей масс Δm между симметричной и антисимметричной по мезонию и антимезонию системами. Величина Δm про-

*ЖЭТФ, 1957, т.33, вып.2, с.549—551.

It was founded on the deep analogy of the weak interaction of leptons and hadrons that motivated Bruno Pontecorvo long before the occurrence of the quark-lepton symmetry in the modern Standard Model.

B.Pontecorvo regarded neutrino oscillations as a phenomenon analogous to neutral kaon oscillations possible only in the case when neutrinos possess small, different from zero, masses.

After 1957 the scientific interests of B.Pontecorvo turned again to physics of weak interactions, and especially, to neutrino physics. In the paper “Electron and Muon Neutrinos” (1959) he showed that neutrinos from the accelerator can be detected with big detectors and proposed an experiment that could give an answer to the question if electron and muon neutrinos differed from each other.



ЭЛЕКТРОННЫЕ И МЮОННЫЕ НЕЙТРИНО*

В работе перечисляются некоторые до сих пор не обсуждавшиеся процессы, которые могут быть вызваны свободными нейтрино. Среди этих процессов выделяются те, которые могут, в принципе, помочь решению вопроса о существовании двух пар нейтральных лептонов (электронная (ν_e и $\bar{\nu}_e$) и мюонная (ν_μ и $\bar{\nu}_\mu$) пары).

Для проверки принципиального вопроса, являются ли ν_e и ν_μ тождественными частицами, предлагается метод, по существу аналогичный методу, используемому при решении вопроса о различимости нейтрино и антинейтрино или K^0- и $\bar{K}^0$-мезонов. В принципе, вопрос решается, если удастся выяснить экспериментально, является ли пучок $\bar{\nu}_\mu$ способным вызвать переходы, которые, без сомнения, могут быть индуцированы $\bar{\nu}_e$-частицами (например, реакция $\bar{\nu}_\mu + p \to e^+ + n$).

Экспериментальная постановка опыта, хотя и очень затруднительна, не исключена при наличии ускорителей, более интенсивных, чем современные.

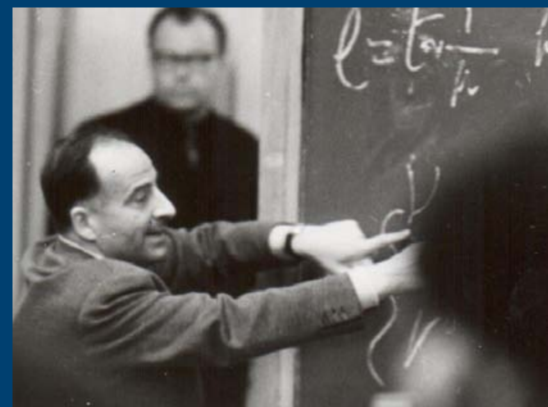
Введение

Бете и Пайерлс [1] в 1934 г. впервые дали оценку сечения образования β-частиц при столкновении свободных нейтрино с ядрами в области энергий около 1 МэВ. Как известно, сечение оказалось равным по порядку величины 10^{-44} см^2, на основании чего в течение долгого времени эффекты, вызваные свободными нейтрино, считались ненаблюдаемыми. Впоследствии автором и Альварецом [2,3] было показано, что постановка таких опытов является вполне реальной, и только недавно Райнесом и Коуэном, а также Дэвисом успешно были выполнены опыты, в которых использовались свободные антинейтрино от реакторов. Эти опыты показали наблюдаемость и, тем самым, «реальность» нейтрино, их двухкомпонентную природу [4], а также показали, что нейтрино и антинейтрино — разные частицы [5].

Цель настоящей работы — подчеркнуть возможность решения некоторых физических задач при помощи исследований до сих пор не обсуждавшихся эффектов, вызванных свободными нейтрино. Соответствующие опыты могут оказаться не выполнимыми сегодня, но обсуждение их постановки, как нам кажется, не является более преждевременным, чем обсуждение в свое время опытов с антинейтрино из реактора.

Обсуждается принципиальная возможность ответить на вопрос, являются ли нейтрино, испускаемые в $\pi \to \mu$-распаде (ν_μ), и нейтрино, испускаемые в β-распаде (ν_e), тождественными частицами.

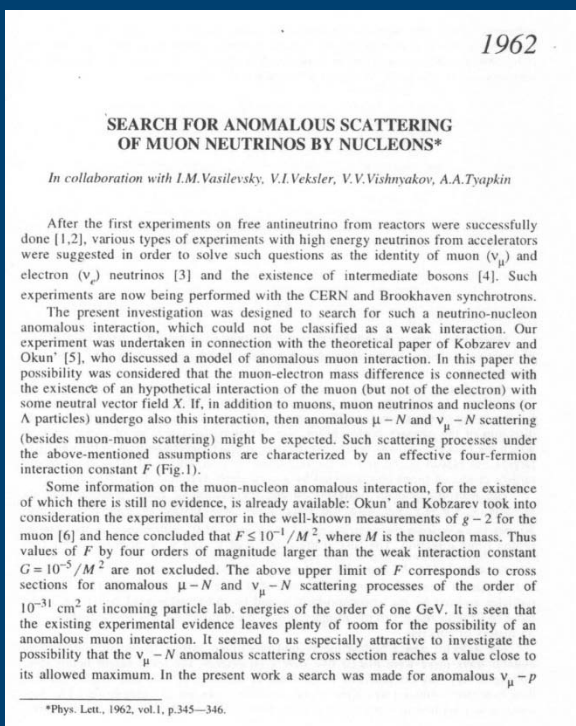
*ЖЭТФ, 1959, т.37, вып.6, с.1751—1757.



1961 - on the initiative of B.Pontecorvo, an attempt was taken at the JINR synchrophasotron to detect the reaction of neutral weak currents

$$\nu_\mu + N \to \nu_\mu + N,$$

that were later discovered in 1973 at CERN with much more intense neutrino beams.



1962

SEARCH FOR ANOMALOUS SCATTERING OF MUON NEUTRINOS BY NUCLEONS*

In collaboration with I.M.Vasilevsky, V.I.Veksler, V.V.Vishnyakov, A.A.Tyapkin

After the first experiments on free antineutrino from reactors were successfully done [1,2], various types of experiments with high energy neutrinos from accelerators were suggested in order to solve such questions as the identity of muon (ν_μ) and electron (ν_e) neutrinos [3] and the existence of intermediate bosons [4]. Such experiments are now being performed with the CERN and Brookhaven synchrotrons.

The present investigation was designed to search for such a neutrino-nucleon anomalous interaction, which could not be classified as a weak interaction. Our experiment was undertaken in connection with the theoretical paper of Kobzarev and Okun' [5], who discussed a model of anomalous muon interaction. In this paper the possibility was considered that the muon-electron mass difference is connected with the existence of an hypothetical interaction of the muon (but not of the electron) with some neutral vector field X. If, in addition to muons, muon neutrinos and nucleons (or Λ particles) undergo also this interaction, then anomalous $\mu - N$ and $\nu_\mu - N$ scattering (besides muon-muon scattering) might be expected. Such scattering processes under the above-mentioned assumptions are characterized by an effective four-fermion interaction constant F (Fig.1).

Some information on the muon-nucleon anomalous interaction, for the existence of which there is still no evidence, is already available: Okun' and Kobzarev took into consideration the experimental error in the well-known measurements of $g - 2$ for the muon [6] and hence concluded that $F \leq 10^{-1}/M^2$, where M is the nucleon mass. Thus values of F by four orders of magnitude larger than the weak interaction constant $G = 10^{-5}/M^2$ are not excluded. The above upper limit of F corresponds to cross sections for anomalous $\mu - N$ and $\nu_\mu - N$ scattering processes of the order of 10^{-31} cm^2 at incoming particle lab. energies of the order of one GeV. It is seen that the existing experimental evidence leaves plenty of room for the possibility of an anomalous muon interaction. It seemed to us especially attractive to investigate the possibility that the $\nu_\mu - N$ anomalous scattering cross section reaches a value close to its allowed maximum. In the present work a search was made for anomalous $\nu_\mu - p$

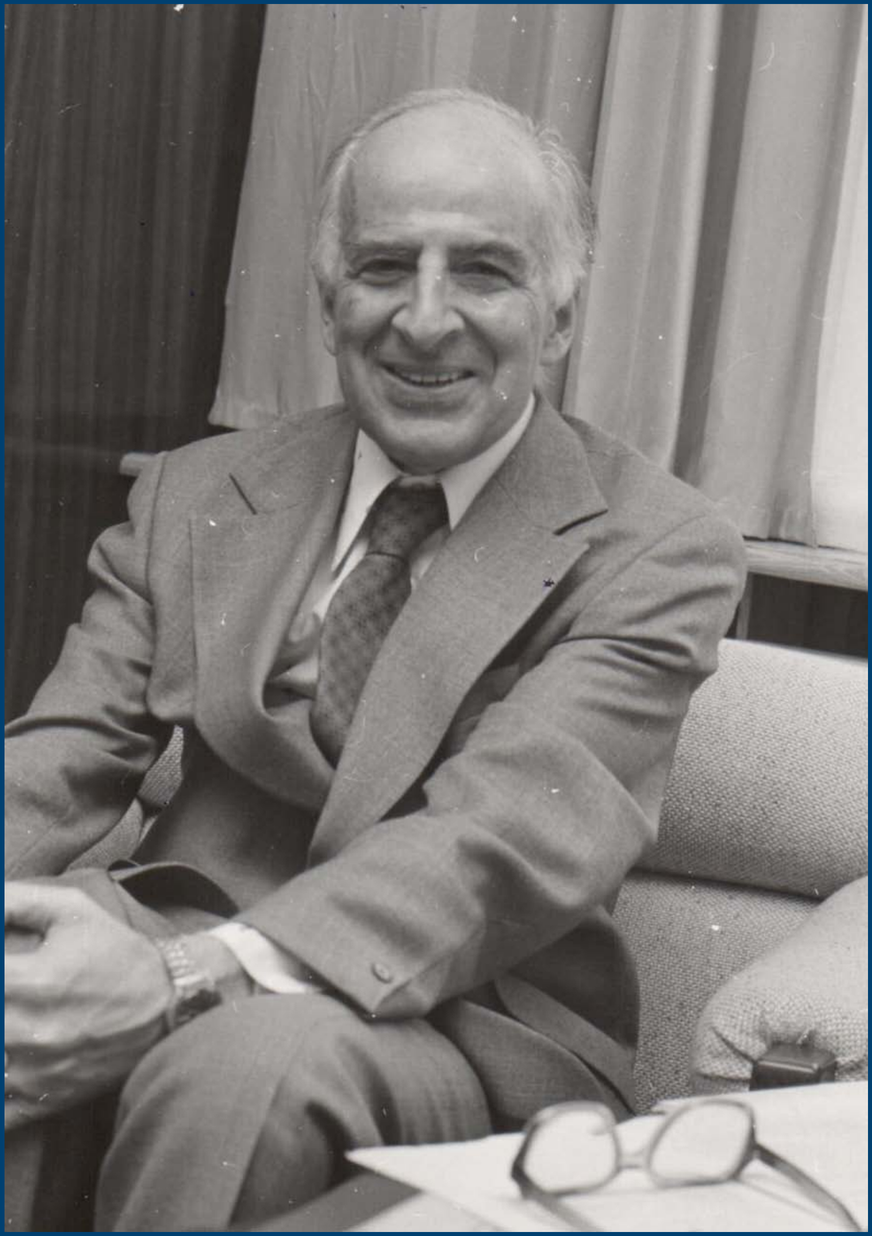
*Phys. Lett., 1962, vol.1, p.345—346.

Undoubtedly, neutrino oscillations is the most outstanding idea of B.Pontecorvo. He devoted many years to its development.

It took years and efforts for the tiny neutrino masses to become reality.

The discovery of neutrino oscillations is the triumph of Bruno Pontecorvo idea.

Now his name is eternized in the title of the neutrino mixing matrix – the Pontecorvo-Maki-Nakagawa-Sakata matrix.



Neutrino Properties

- ✓ Processes (decays, scattering) with neutrinos pushed forward the **Fermi theory, SM**.
- ✓ Neutrinos (together with photons) are the **most abundant particles in the Universe**.
- ✓ Relic neutrinos **should be after Big Bang (together with relic background radiation)**.
- ✓ Massive neutrinos are crucial for **construction of theories beyond the SM**.
- ✓ They are **hot Dark matter and responsible for Large scale Structure**.
- ✓ Solar neutrinos inform us about the **Sun interior and how the Sun works**.
- ✓ Supernovae exposures are **impossible without neutrinos, there are nuclear synthesis r-processes governed by neutrinos**.
- ✓ Only neutrinos could supply us with the **most distant cosmic signals**.
- ✓ Neutrinos are **very accurate probes of the structure of hadrons (strangeness, charm, spin, 5Q, ...), they allow test of QCD**.
- ✓ There is already **practical use of neutrinos: nuclear plant control (diagnostics),outer space, geo-neutrinos, communications ("neutrino" was coded and decoded!)…..**

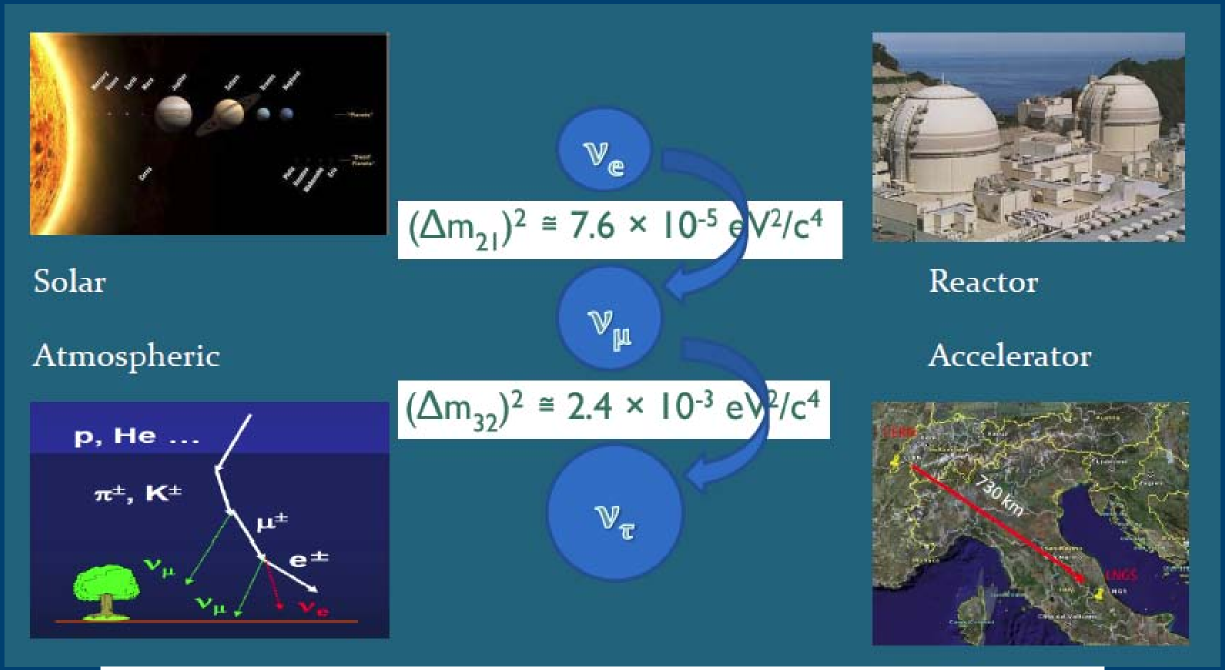
- ✓ Why are neutrino mixing angles **so large (contrary to quarks)?**
- ✓ What is a **source of too small neutrino masses, is it connected with a new huge mass scale?**
- ✓ What is a correct **ordering (hierarchy) of neutrino masses?**
- ✓ Do neutrinos have **CP-phases and could they "save" Baryogenesis (by means of Leptogenesis)?**
- ✓ Could we check directly that the **matter effect really works?**
- ✓ Is the neutrino **mass term Majorana or Dirac (neutrino = antineutrino, or not)?**
- ✓ How does the **Sun really shine?**
- ✓ Is oscillation already a **unique description of neutrino flavor changes?**
- ✓ How do the neutrino properties affect the **other (very)rare weak processes?**
- ✓ Where are the **relic neutrinos?**
- ✓ Do neutrinos have **magnetic moments (diagonal or transition)?**
- ✓ When we measure **coherent low-energy neutrino scattering off nuclei?**
- ✓ Could neutrinos explain **beyond-GZK Cosmic Rays?**
- ✓ Is there any **real possibility of seeing new (heavy) neutrinos with the LHC?**

Neutrino seems to be one of the most abundant fundamental and interdisciplinary objects. The studies of the neutrino properties may significantly influence our understanding of basic principles and evolution of the Universe.

Neutrino Physics at JINR

Neutrino Oscillations

Are well established in different experiments
with disappearance of neutrino flux



Pontecorvo-Maki-Nakagawa-Sakata matrix:

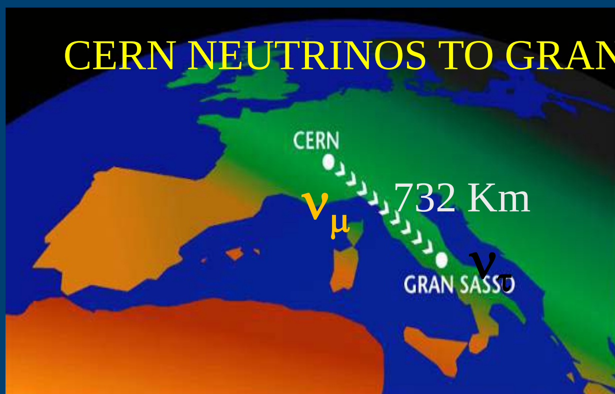
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathbf{V}_{e1} & \mathbf{V}_{e2} & \mathbf{V}_{e3} \\ \mathbf{V}_{\mu 1} & \mathbf{V}_{\mu 2} & \mathbf{V}_{\mu 3} \\ \mathbf{V}_{\tau 1} & \mathbf{V}_{\tau 2} & \mathbf{V}_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\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

Weak eigenstates — Mass eigenstates

Amplification of oscillations by MSW effect

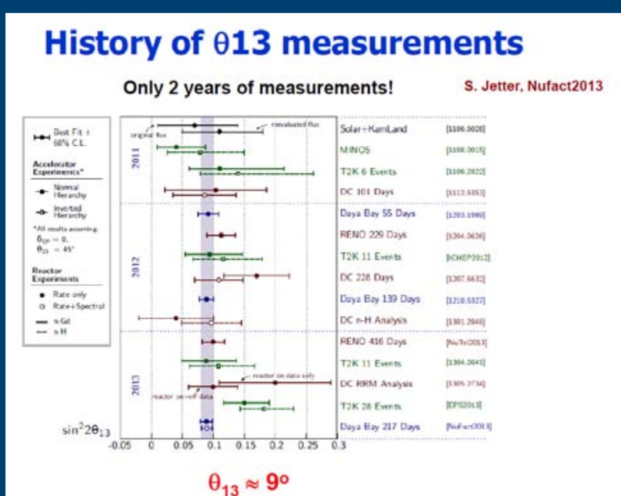
JINR Neutrino Physics Program

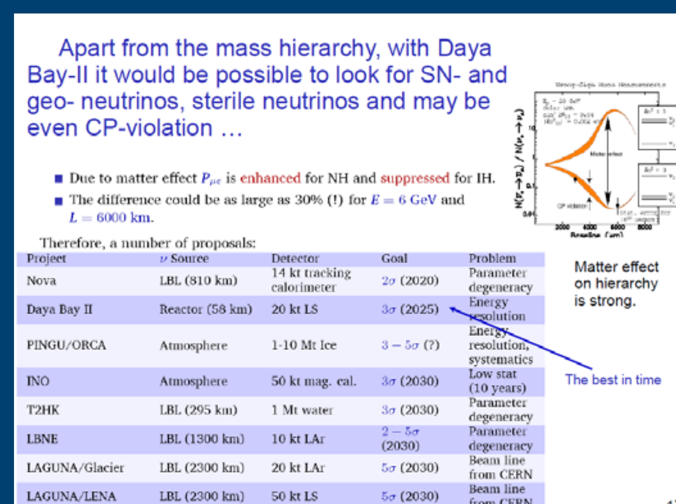
- Study of Neutrino mixing parameters
  - OPERA at Gran Sasso Underground Laboratory



up to now: 3 tau-candidates seen (~50% of data analyzed)

- Daya Bay θ_{13} measurement and prospects for mass Hierarchy and CPV





Apart from the mass hierarchy, with Daya Bay-II it would be possible to look for SN- and geo- neutrinos, sterile neutrinos and may be even CP-violation …

- Due to matter effect $P_{\mu e}$ is enhanced for NH and suppressed for IH.
- The difference could be as large as 30% (!) for $E = 6$ GeV and $L = 6000$ km.

Therefore, a number of proposals:

Project	ν Source	Detector	Goal	Problem
Nova	LBL (810 km)	14 kt tracking calorimeter	2σ (2020)	Parameter degeneracy
Daya Bay II	Reactor (58 km)	20 kt LS	3σ (2025)	Energy resolution
PINGU/ORCA	Atmosphere	1-10 Mt Ice	$3-5\sigma$ (?)	Energy resolution, systematics
INO	Atmosphere	50 kt mag. cal.	3σ (2030)	Low stat (10 years)
T2HK	LBL (295 km)	1 Mt water	3σ (2030)	Parameter degeneracy
LBNE	LBL (1300 km)	10 kt LAr	$2-5\sigma$ (2030)	Parameter degeneracy
LAGUNA/Glacier	LBL (2300 km)	20 kt LAr	5σ (2030)	Beam line from CERN
LAGUNA/LENA	LBL (2300 km)	50 kt LS	5σ (2030)	Beam line from CERN

Matter effect on hierarchy is strong.

The best in time

17

The Physics of Rare Decays

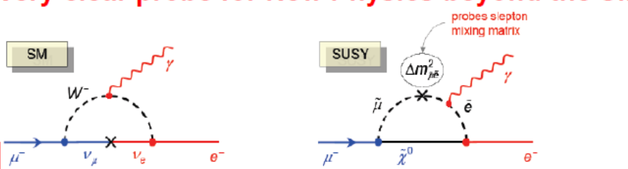
There is lepton flavor violation search at JINR with MEG. Good results are obtained.

Very clear probe for New Physics beyond the SM!

$\mu \to e \gamma$

Present Limit:

2.4×10^{-12} (90% C.L.).



$BR(\mu^- \to e^- \gamma)|_{SM} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-60}$

$BR(\mu^- \to e^- \gamma)|_{SUSY} \approx 10^{-5} \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\tilde{m}^2_{\tilde{l}}} \left(\frac{100\ \text{GeV}}{m_{SUSY}}\right)^4 \tan^2\beta \approx 10^{-12}$

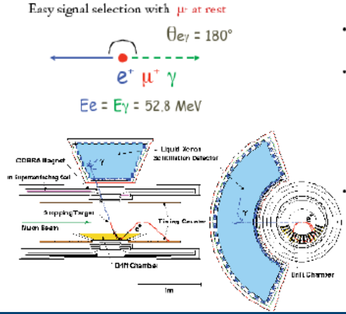
MEG experimental method

Easy signal selection with μ^+ at rest

$\theta_{e\gamma} = 180°$

$e^+ \ \mu^+ \ \gamma$

$E_e = E_\gamma = 52.8$ MeV

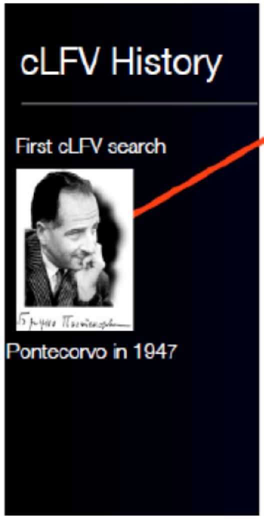


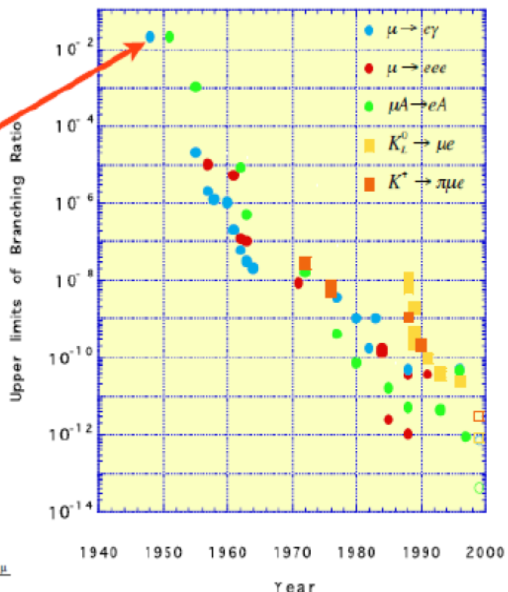
- Stopped beam of $>10^7$ μ /sec in a 175 μm target
- γ detection
  Liquid Xenon calorimeter based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm
- e+ detection
  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum
  scintillation counters for timing

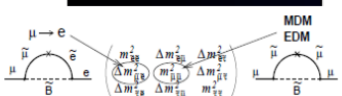
Plans

- Present Data taking to reach 10^{-13}
- Obtain a "significant" result before the LHC era
- Eventual reach of 10^{-14} during LHC era

Right time to recall:
The experimental history of charged lepton flavor violation search started from Bruno Pontecorvo **as well** !







(*) Phy. Rev. Lett. 110, 201801 (2013)

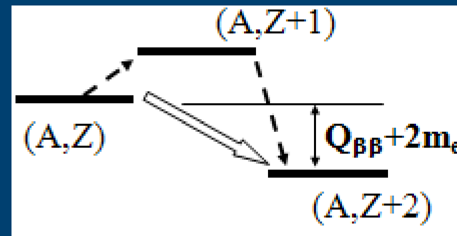
Summary of Results

(**) 90% C.L. upper limit averaged over pseudo-experiments based on null-signal hypothesis with expected rates of RMD and BG

	Best fit	Upper Limit (90% C.L.)	Sensitivity **
2009+10	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009+10+11	-0.06×10^{-12}	5.7×10^{-13}	7.7×10^{-13}

$B(\mu^+ \to e^+ \gamma) < 5.7 \times 10^{-13}$ (all combined data) *

Double beta decay



$\beta\beta2\nu$ - allowed in SM

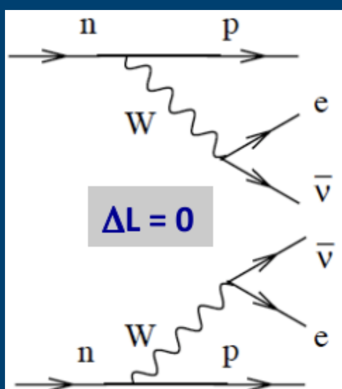
$T_{1/2} \sim 10^{20}$y

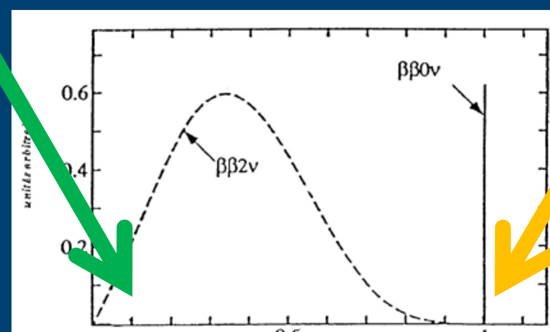
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu$

$\beta\beta0\nu$ - forbidden in SM

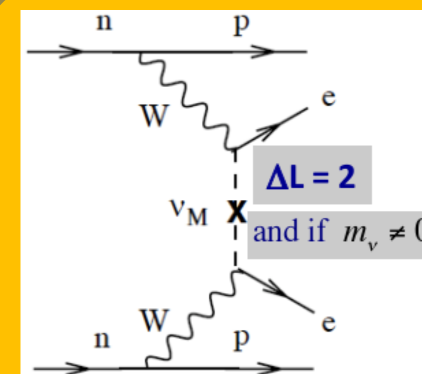
$T_{1/2} \geq 10^{25}$y

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 0\nu$



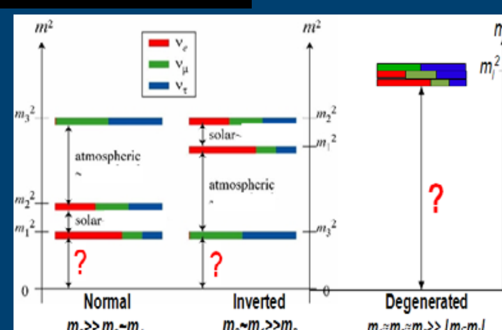


$(E_1+E_2)/Q\beta\beta$



Detection of $\beta\beta0\nu$ will mean:

- Majorana neutrino
- Absolute mass scale
- Hierarchy of neutrino masses

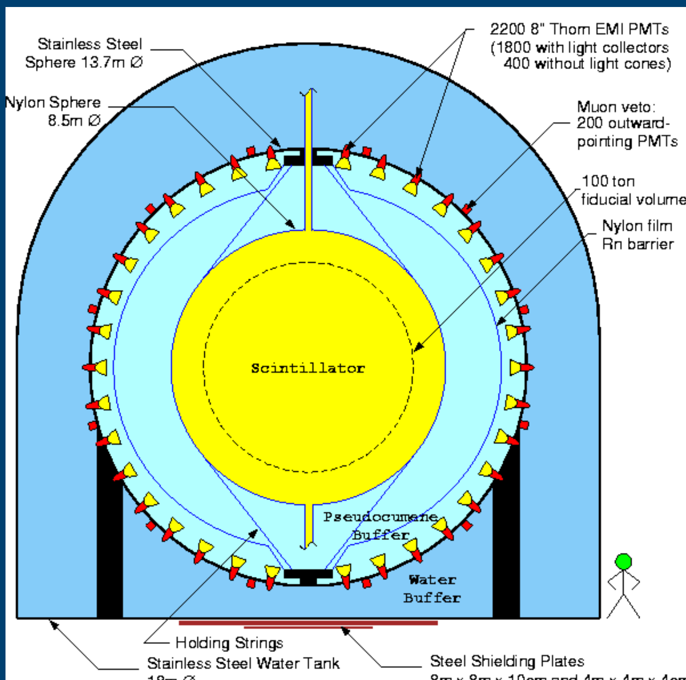


✓Super Nemo
and
✓GERDA/Majorana

Collaborations

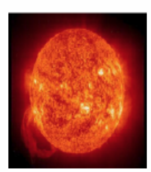
Neutrino Astronomy

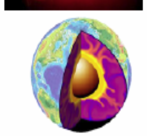
Borexino detector at Gran Sasso:
300 t of L S, 3500 MWE overburden



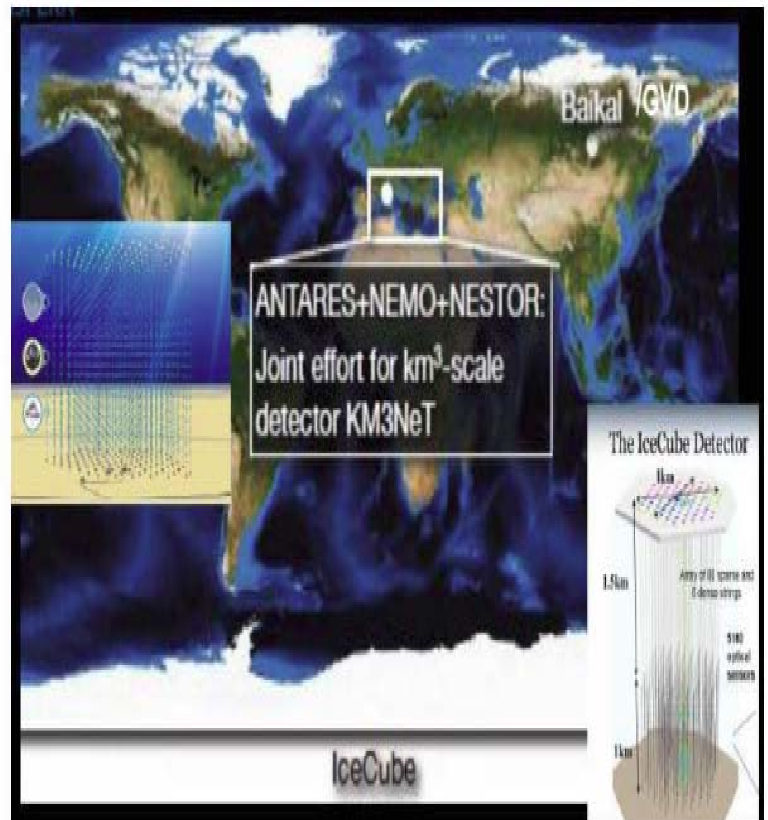
Physics Programme of Borexino-II includes:

SOLAR Neutrino study.
Improvement of ^{7}Be neutrino flux measurement (3%) and seasonal variations.
pp-neutrino flux measurement with 10% precision
pep neutrino measurement with better precision (>3σ)
B-8 neutrino measurement with x4 statistics (10%)
Measurement (or establishing strong limits) on the CNO neutrino flux.
Borexino-II measurements will allow discrimination of solar models.
Geoneutrino flux measurement with higher statistics
Measurements with artificial neutrino source
(search for sterile neutrino, neutrino magnetic moment).
Project SOX: Short distance Oscillations with BoreXino.





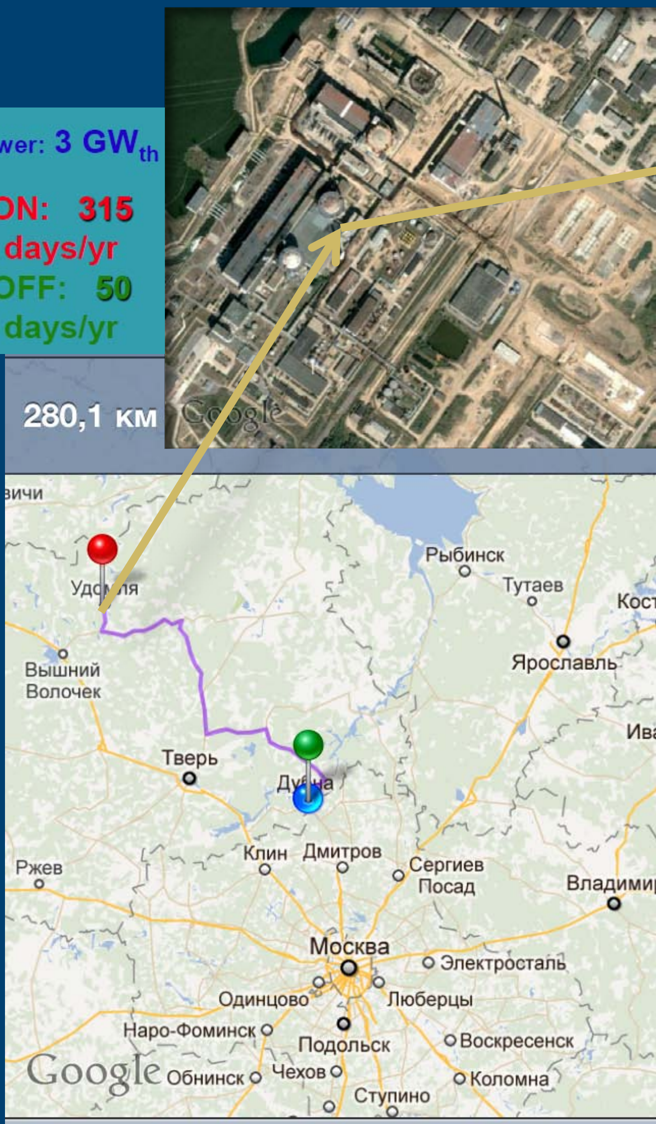
Northern Hemisphere projects and IceCube move through coordination towards a future Global Neutrino Observatory. Baikal-GVD is involved.

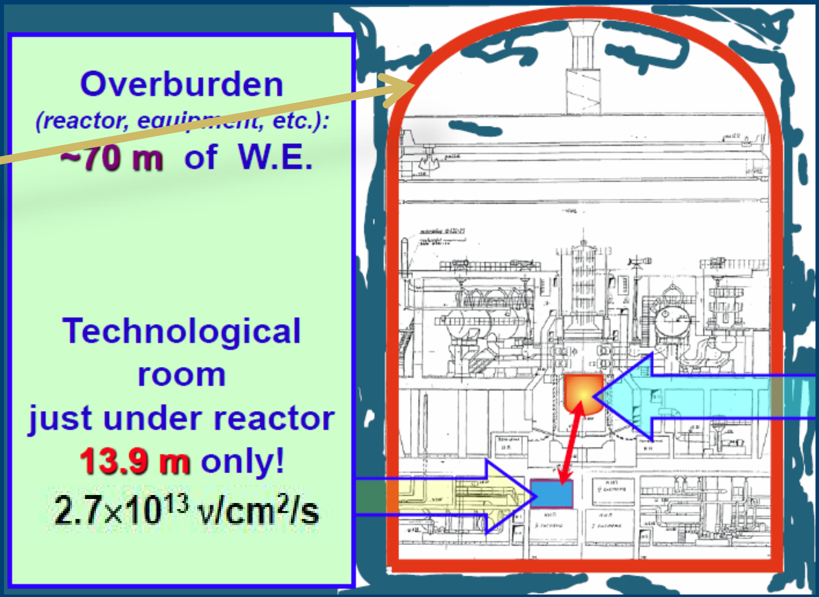


Experiments at Kalinin NPP

Power: 3 GW_{th}

ON: 315 days/yr
OFF: 50 days/yr





Fundamental and Applied Research:

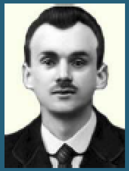
- ✓ Search for Neutrino Magnetic Moment
- ✓ Measurement of Neutrino Fluxes and Spectra
- ✓ Search for Sterile Neutrino States

Neutrino Magnetic Moment

In the (extended) Standard Model
Magnetic moment of neutrino is connected to the neutrino mass
and is very small.

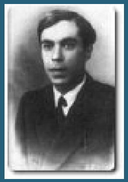
$\mu_\nu \sim 10^{-19} \mu_B \times (m_\nu / 1\text{eV})$

$\mu_\nu \equiv 0$



if neutrino
Dirac

if neutrino
Majorana



But some models predict:

$\mu_\nu \leq 10^{-14} \mu_B \times (m_\nu / 1\text{eV})$

$\mu_\nu \sim 10^{-10} - 10^{-11} \mu_B$

And this is already in the present sensitivity region

Detection of the Neutrino Magnetic Moment could be an argument in support of Majorana neutrino nature

GEMMA: Results and Prospects
HpGe detector

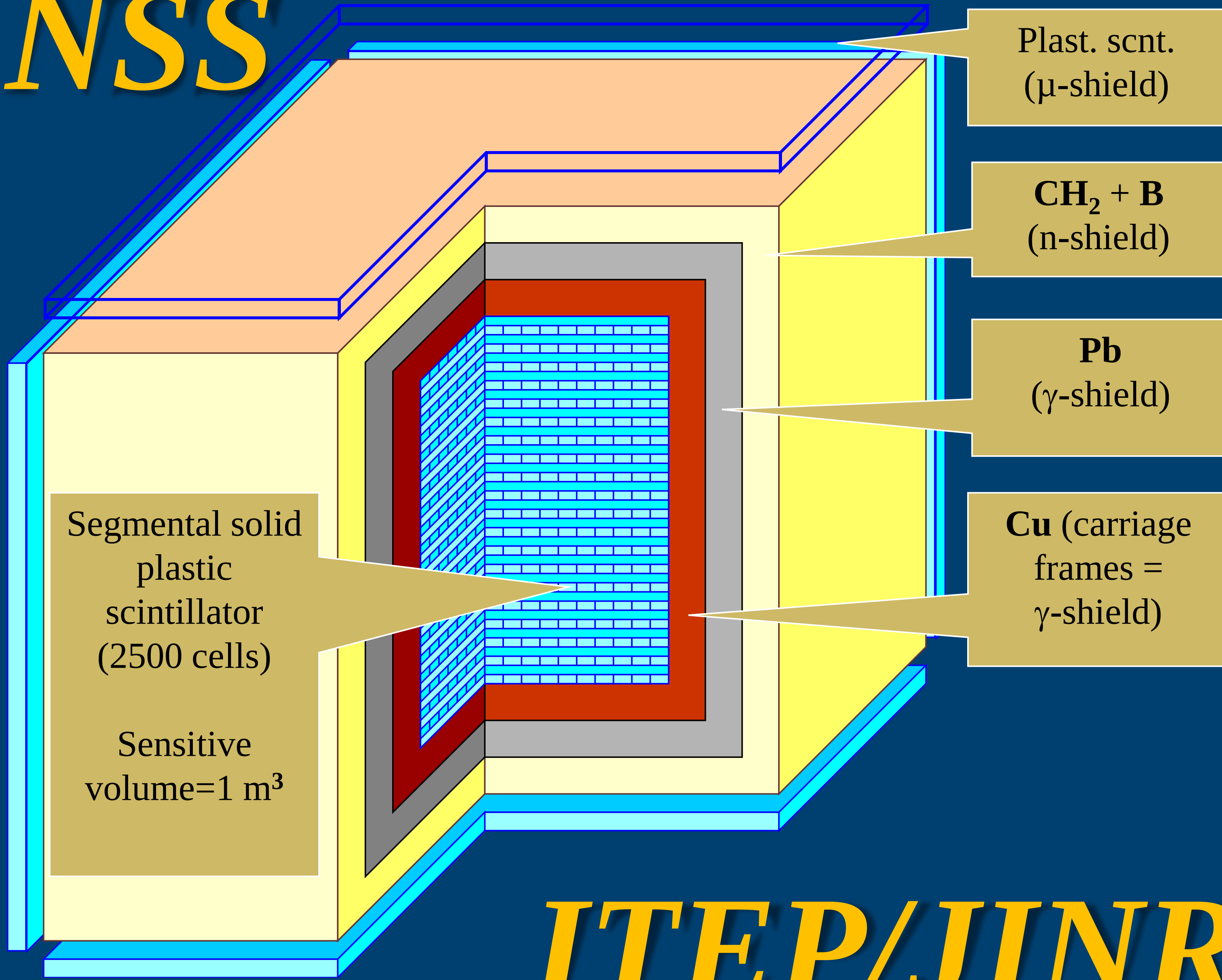
Present:
1.5kg, 14m

$\mu_\nu \leq 2.9\times10^{-11} \mu_B$

Future:
6.0kg, 10m

$\mu_\nu \leq 1.0\times10^{-11} \mu_B$

DANSS



ITEP/JINR

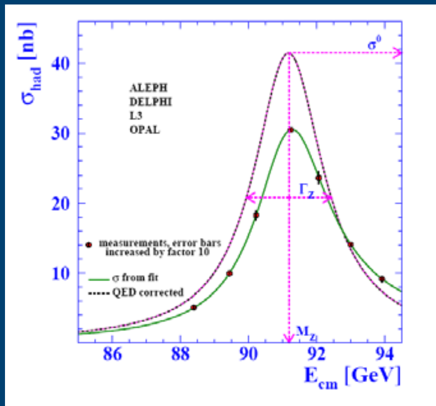
Direct detection of the reactor (anti) neutrino would allow:

- **Measure the actual reactor power (N_ν)**
- **Deduce the actual fuel composition (E_ν)**
- **On-line reactor monitoring (tomography)**
- **Non-proliferation** ***(to prevent unauthorized extraction of ^{239}Pu)***

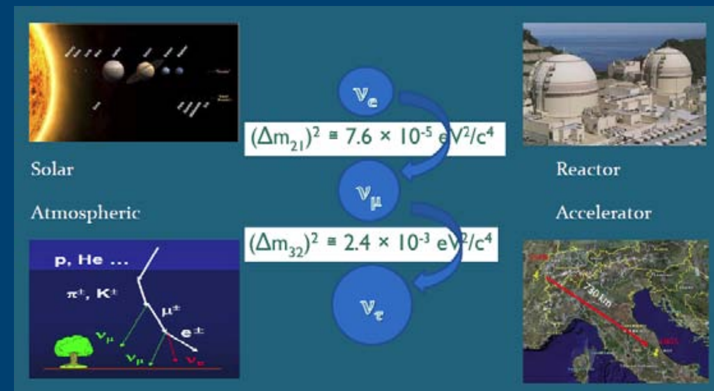
But also

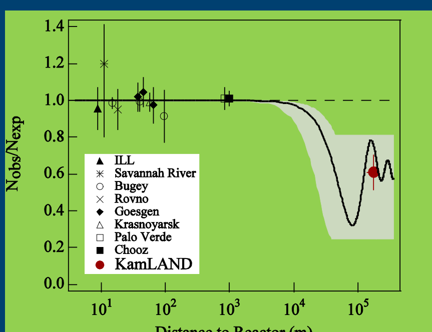
Search for Sterile neutrino

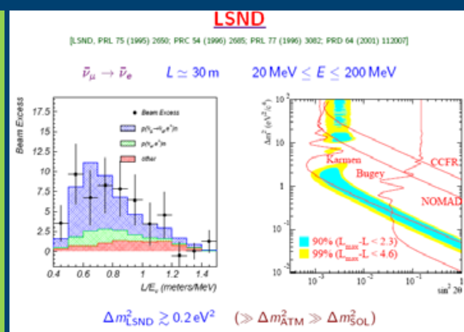
What do we know about the number of neutrino types?

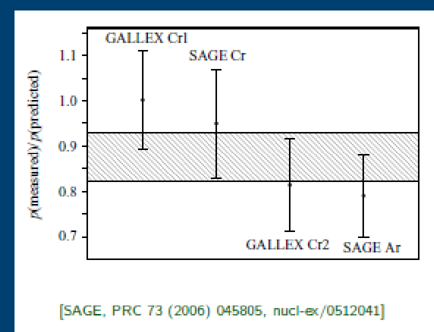


LEP: $N_{\bar{\nu}}$ = 2.9840±0.0082









Another Δm^2 ??

Cosmology:

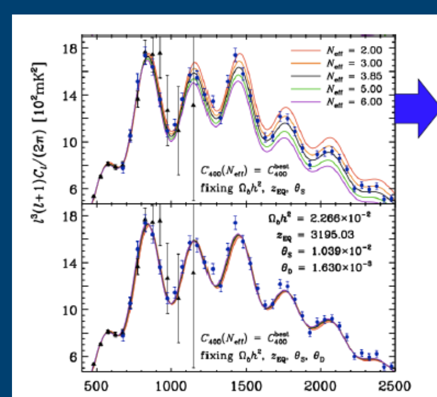
Num of Nus:

N_{eff} = 3.62 ± 0.48 (SPT+WMAP7)

N_{eff} = 3.71 ± 0.35 (SPT+WMAP7+H_0+BAO)

N_{eff} = 2.97 ± 0.56 (ACT+WMAP7)

N_{eff} = 3.50 ± 0.42 (ACT+WMAP7+H_0+BAO)

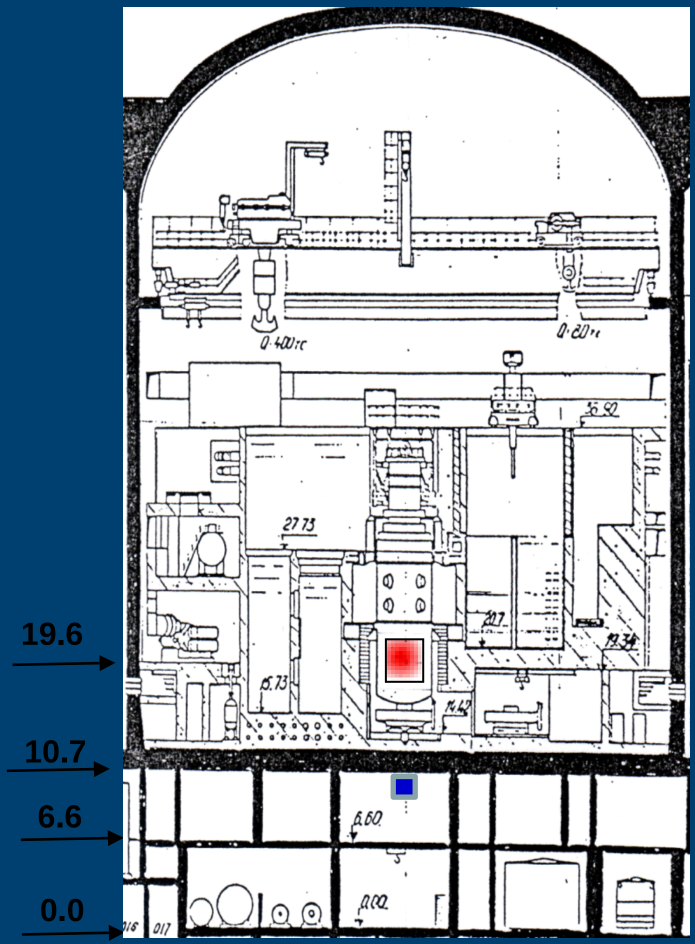


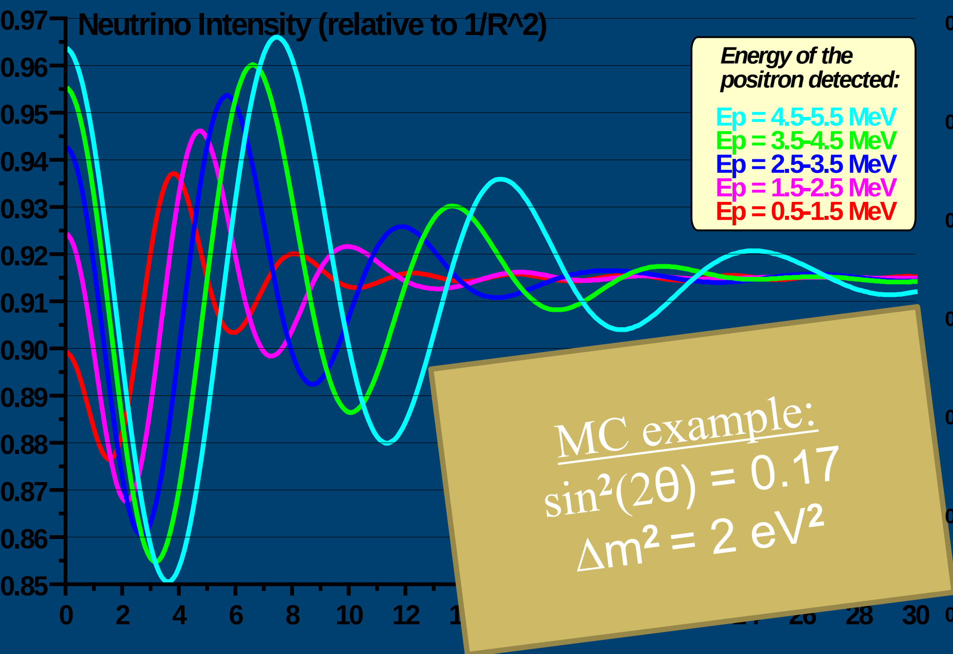
Objective:
Search for neutrino sterile states in oscillations at very short distances

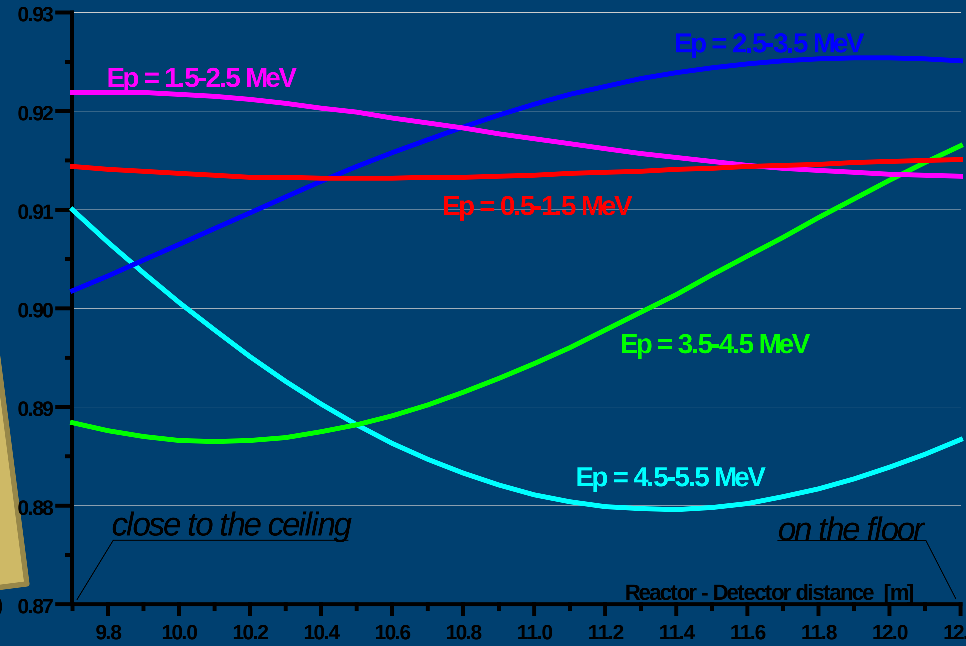
Sterile Neutrinos:
Testing Reactor Anomaly

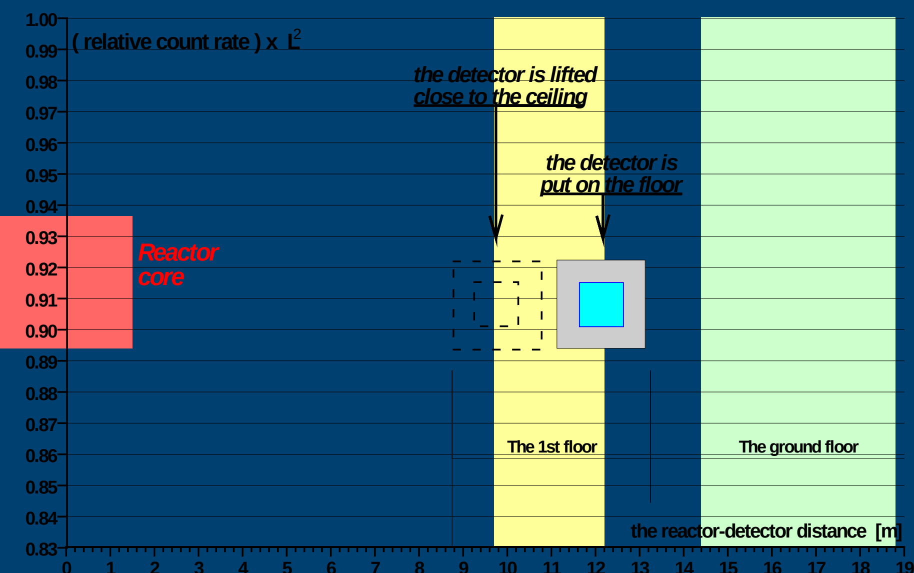
- Possible to move DANSS by ~2.5 m (from 9.7 to 12.2) <u>on-line</u>

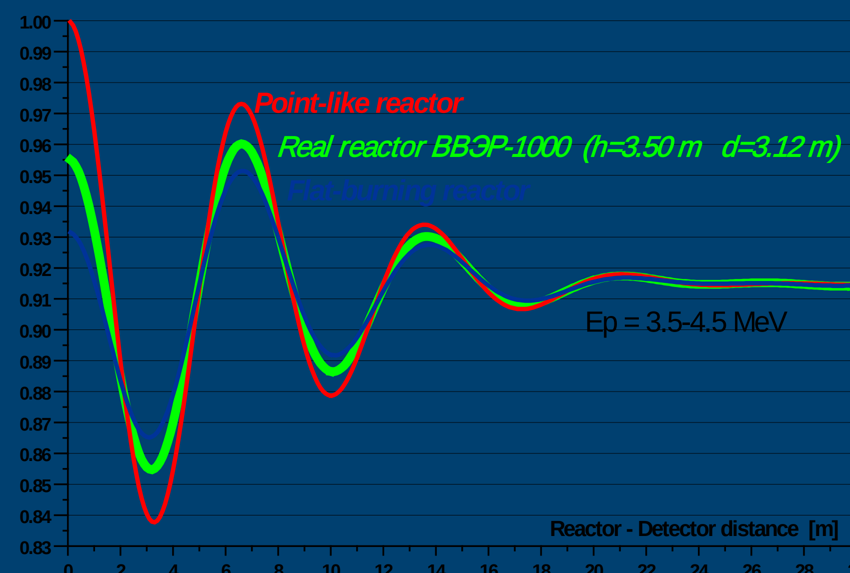
- Or by longer distance (up to 18.8 m), but with partial dismounting




Neutrino Intensity (relative to 1/R^2)
Energy of the positron detected:
Ep = 4.5-5.5 MeV
Ep = 3.5-4.5 MeV
Ep = 2.5-3.5 MeV
Ep = 1.5-2.5 MeV
Ep = 0.5-1.5 MeV
MC example:
sin²(2θ) = 0.17
Δm² = 2 eV²


Ep = 2.5-3.5 MeV
Ep = 1.5-2.5 MeV
Ep = 0.5-1.5 MeV
Ep = 3.5-4.5 MeV
Ep = 4.5-5.5 MeV
close to the ceiling
on the floor
Reactor - Detector distance [m]


(relative count rate) x L²
the detector is lifted close to the ceiling
the detector is put on the floor
Reactor core
The 1st floor
The ground floor
the reactor-detector distance [m]


Point-like reactor
Real reactor ВВЭР-1000 (h=3.50 m d=3.12 m)
Flat-burning reactor
Ep = 3.5-4.5 MeV
Reactor - Detector distance [m]

CM-3 research reactor

(НИИАР, Димитровград)

Operation: since 1961

Reconstructions: 1965, 1974, 1992

Core: 35x42x42 cm

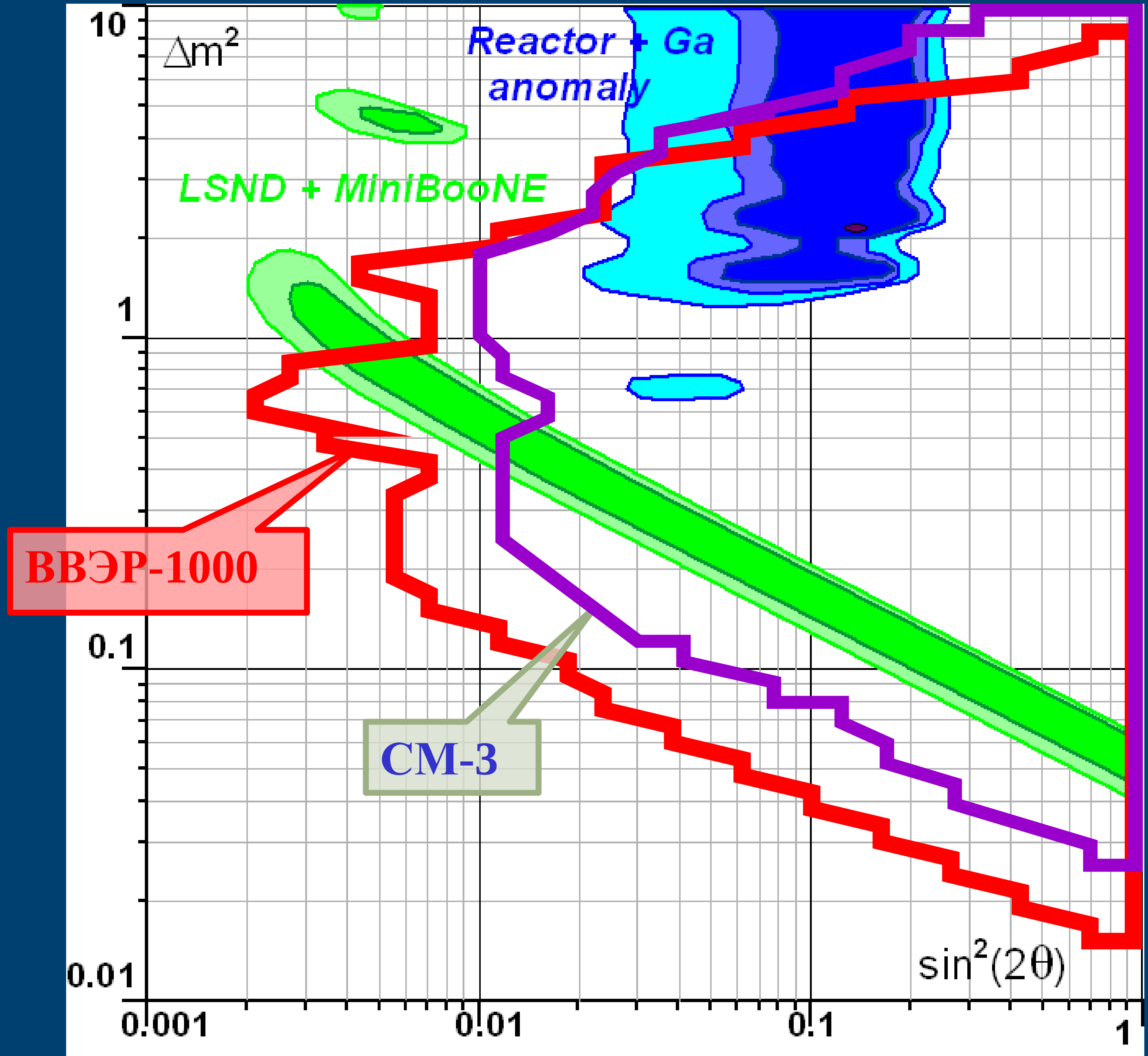
Thermal power: 100 MW

Fuel: ^{235}U (90%)

Distance available: 5.17 - ~15 m

Background in the room: ~x4

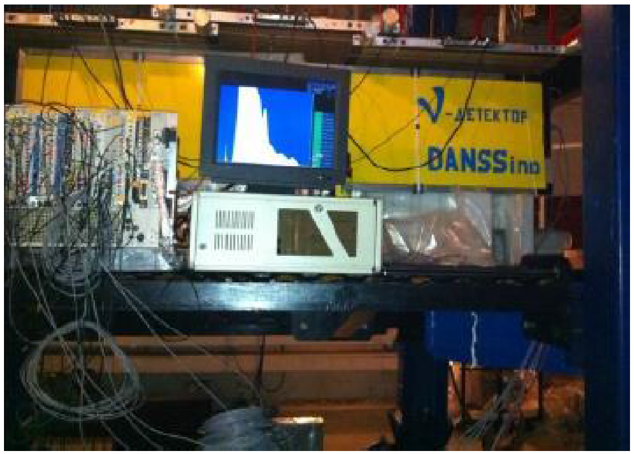
ON/OFF: ~2/1



Δm²
10
1
0.1
0.01
Reactor + Ga
anomaly
LSND + MiniBooNE
ВВЭР-1000
СМ-3
sin²(2θ)
0.001
0.01
0.1
1

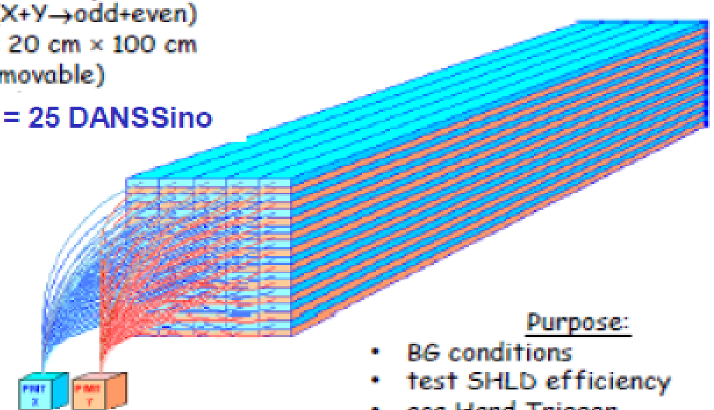
There is already a well working prototype:

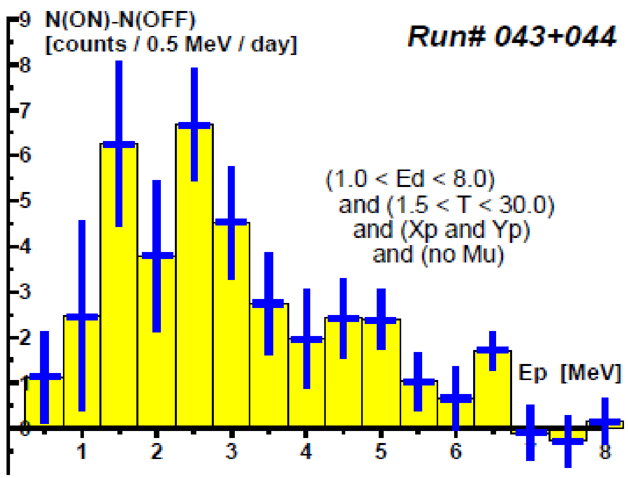
DANSSino



50+50=100 strips
2 PMT (X+Y→odd+even)
20 cm × 20 cm × 100 cm
40 kg (movable)

DANSS = 25 DANSSino

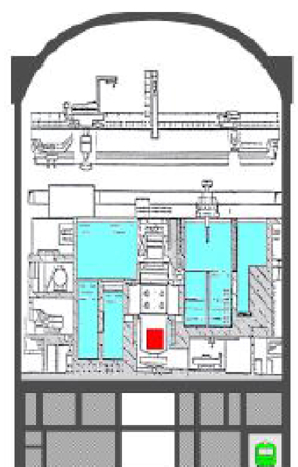




This is already measured reactor (anti)neutrino spectrum!

Purpose:

- BG conditions
- test SHLD efficiency
- acq Hard Trigger
- btw IBD count rate ~400/day



Conclusions :

- It works!!! ☺ *(even without flash ADCs and MPPC)*
- In spite of huge edge-effects, we see ν ☺
- 10 cm of (Pb+Cu) is enough to shield against γ
  The main (important) BG = fast *n*
- Impossible to operate on-ground ☹
- ВВЭР-1000 shields well against cosmic *n* ☺
- μ-produced (secondary) fast neutrons = ☹
- Improve eff. of μ-veto (4π + "sandwich")
- Avoid heavy materials inside. *Change the shield composition (and mechanical construction?)*

Expected parameters:

- Sensitive volume: $1\ m^3$
- Total mass: 13 t + lift + …
- Composition: 5 sections (1m × 1m × 0.2m)
  of (5**X** + 5**Y**) modules = 2500 cells
  { 1 module = 5 × 10 = 50 cells }
- IBD detection efficiency: **~72%**
- Count rate: **$\sim 10^4$ IBD-events/day @11 m**
- Background: 40-50 events/day
- Energy resolution: ***$\sigma \leq 30\%$ @ $E_\nu = 4$ MeV***
- Due date: section №0 - 4 – ***2010 – 2012***
- Installation at KNPP
  DANSS+lifting gear + shielding – ***2012***
- Start tests and data taking – ***2013***

CONCLUSION TO THE PREVIOUS PART

- ✓ The Neutrino Physics and Astroparticle Physics, in general, are among the main flagship topics of the JINR research program.

- ✓ It is a pleasure to acknowledge the contribution to this field of a great scientist and a man of the XXth century – Bruno Pontecorvo.

- ✓ We are very proud that the scientific program of our Institute has been influenced by his outstanding talent, genius intuition and human personality.

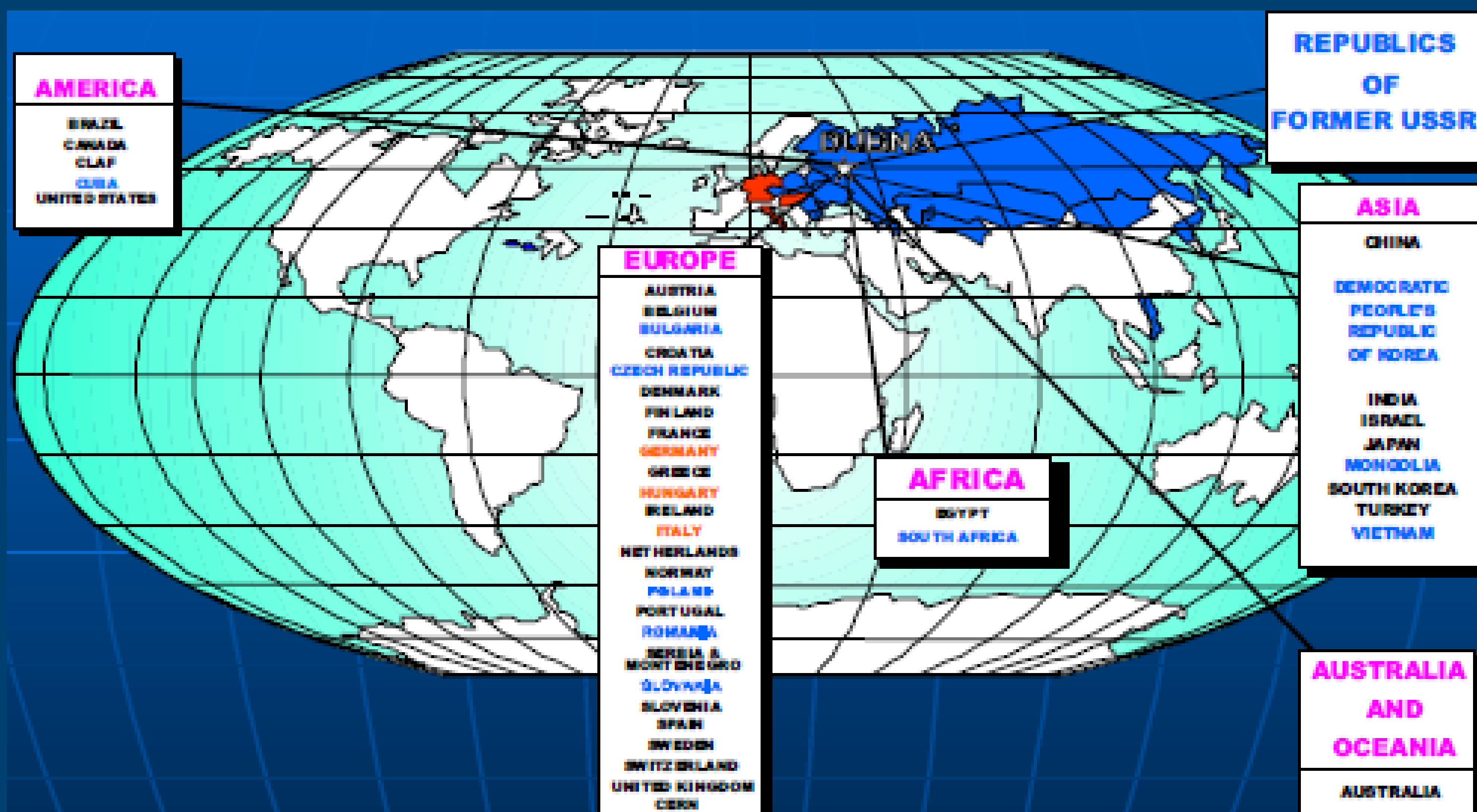
JINR has at present 18 Member States:

Armenia
Azerbaijan
Belarus
Bulgaria
Cuba
Czech Republic
Georgia
Kazakhstan
D. P. Republic of Korea
Moldova
Mongolia
Poland
Romania
Russian Federation
Slovakia
Ukraine
Uzbekistan
Vietnam

Participation of Egypt, Germany, Hungary, Italy, the Republic of South Africa and Serbia in JINR activities is based on bilateral agreements signed on the governmental level.

International collaboraton

In total, the JINR collaborates with more than 700 scientific centers and universities in 63 countries all over the world.



Russia–JINR–European Commission

A working meeting with representatives of the European Commission – the Executive Committee for development of research infrastructure and coordination of joint mega-science projects, which are being implemented in Russian scientific centers and JINR, was held on 16 May 2013 in the Ministry of education and science of the Russian Federation. Meeting participants were received in the JINR Directorate in Dubna on 17 May 2013.

Head of the Department of development of priority scientific and technical fields Sergei Salikhov and his colleagues Head of European Commission Research Infrastructures Department Anna Arano Antelo, European Union experts Ex-Director-General of CERN Robert Aymar, CEA representative Suzanne Gotha Goldman, member of the European Strategy Forum on Research Infrastructures Jean Moulin (ESFRI), Professor Steve Myers (CERN), GSI Director Horst Stocker (Germany), Science and Innovation Advisor Richard Burger **took part in the negotiations**.

The members of JINR Directorate have presented JINR's programme of scientific and research activities, they spoke about international cooperation and participation of the JINR member states and JINR associate members in projects of the JINR Seven-Year Development Plan, focusing on the mega-project NICA.

The guests visited the Veksler and Baldin Laboratory of High Energy Physics and main scientific and technical sites, where working process on the NICA project is being held, met leading scientists.

The large scale of design and research activities as well as extensive cooperation with leading scientific centers and experts, in particular, with specialist from Germany, who design the accelerator complex FAIR, which is supplement to the collider NICA, made deep impression on visitors.

Professor Horst Stocker, who is well informed about working process in VBLHEP, noted the significant progress at all sites, which were visited by members of the European Commission delegation.

During the final exchange of opinions participants expressed interest of the European Commission in participation in the Dubna's mega-science project, enhancing international cooperation in this direction. .

The 1st meeting of the Standing Committee on Cooperation between the National Institute of Nuclear Physics (INFN, Italy) and the JINR was held on 22 February 2013 in the Dzhelepov Laboratory of Nuclear Problems.

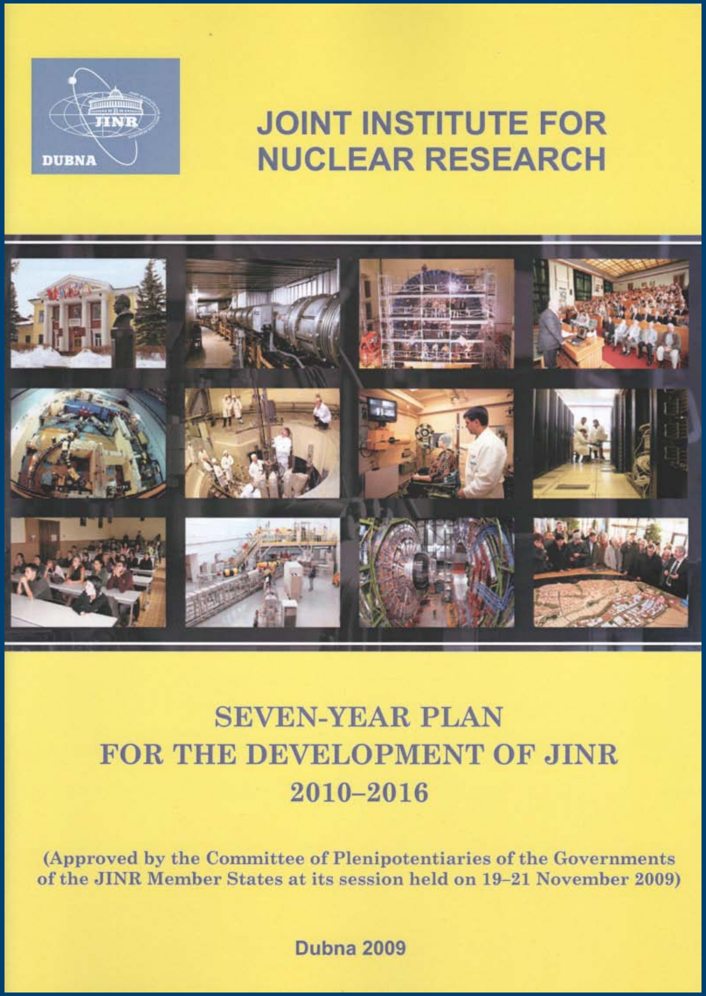
- The meeting was attended by Representatives of INFN and the Italian Embassy in Russia and by members of the JINR Directorate and representatives of laboratories: DLNP, FLNR, BLTP and VBLHEP.
- Members of the INFN delegation made presentations on research in various areas of particle physics, nuclear physics and INFN applied research. JINR Director and representatives of JINR laboratories also gave overviews of the JINR activities, which are interesting for cooperation.
- The Committee identified the prospects of cooperation between the two research centers. In the frame of the INFN-JINR collaboration, an Agreement on cooperation between INFN (Section in Pisa) and JINR was signed during the meeting.

Celebration of 100th anniversary of Bruno Pontecorvo

- Members of the JINR Scientific Council, members of the Committee on JINR-INFN cooperation, DLNP staff members participated in the opening ceremony of the memorial board of the European Physical Society (EPS) at the office of B.M. Pontecorvo on 22 February 2013 at the Dzhelepov Laboratory of Nuclear Problems.
- EPS President Luisa Chifarelli (National Institute for Nuclear Research, Italy) opened the ceremony.
- If Bruno Pontecorvo were alive today, he undoubtedly would have received the Nobel Prize.
- He had a lot of ideas - the existence of different types of neutrinos and their oscillations, and these ideas came to him when only one type of neutrino was known.

The research policy of JINR is determined by the Scientific Council, which consists of eminent scientists from the Member States and worldwide (at present from China, France, Germany, Greece, Hungary, India, Italy, and CERN).

7-Year Plan (2010 – 2016)



The concept of the Seven-Year Plan is based on the concentration of resources to upgrade the own infrastructure and to participate in major international projects with visible contributions. The key elements of the JINR research infrastructure are the following basic facilities:

– the ion collider NICA (Nuclotron-based Ion Collider fAcility) for research in the field of high-energy heavy-ion physics ;

– the cyclotron complex DRIBs-III (Dubna Radioactive Ion Beams) for the search for new superheavy elements of Mendeleev's Periodic Table and for studies of the properties of radioactive and exotic neutron-rich nuclei;

– the modernized reactor IBR-2M for research in condensed matter physics and particularly in the fields of nanoscience and nanotechnology.

7Y plan: implementation & update
JINR @ CERN, BNL, Fermilab, GSI/FAIR, KEK

I. CERN (LHC): LHC development – consolidation of SC magnets;
CMS, ALICE and ATLAS – data taking & analysis;
upgrade of all 3 detectors – moderate ***additional resources***;

II. CERN (SPS):
COMPASS – finished 1st phase. Detector modification to measure GPD (DVCS) and polarized/unpolarized D-Y;
NA61 – neutrino and heavy-ion programs;
NA62 – measurement of extremely rare decays **($K^+ \rightarrow \pi^+ \nu\nu$)** ;
DIRAC – lifetime measurement of $\pi\pi$ and πK atoms completed at PS; collaboration formed to continue at SPS;

III. BNL (RHIC):
STAR - energy scan HI program and physics with polarized beams (important experience for future research at NICA)

IV. Fermilab: CDF, D0 – finishing the data analysis
Mu2e **($\mu \rightarrow e$)**, ORKA **($K^+ \rightarrow \pi^+ \nu\nu$)** – in discussion

V. GSI, FAIR (SIS-18/100/300): HADES – on the beam
CBM, PANDA – in preparation

VI. J-PARC & KEK: COMET **($\mu \rightarrow e$)**, in progress

Main targets of the "NICA Project":

- study of hot and dense baryonic matter

& nucleon spin structure

- development of accelerator facility

for HEP in JINR providing

*intensive beams of relativistic ions from **p** to **Au***

*polarized **protons** and **deutrones***

with max energy up to

$\sqrt{S_{NN}}$ = ***11 GeV (Au^{79+})*** *and =**26 GeV (p)***

NICA Collaboration

UHV test bench (up to 10^{-11} Torr) (with Czech assistance)

HTSC current leads 12 kA (China) – for test bench and for the Booster

Curved UHV vacuum chambers for Booster (Germany, Belarus,

Laser metrology for Booster alignment: Belarus

Budker INP :
RF systems for NICA, beam diagnostics, beam transportation channels, electron cooling for Booster,

CERN, NRC KI (KI, ITEP, IHEP), FNAL, BNL, INR RAS, FZJ, AEI,...

One of the main partners-Germany: (GSI/FAIR) + BMBF. New Test facility for assembly and cold test of SC magnets for NICA and FAIR

NICA project at JINR is additionally strongly supported by Russian Federation. It was accepted for financing among the mega-science infrastructural projects.

Developing the Fixed Target program at NICA / Nuclotron

- 45^{th} and 46^{th} Nuclotron Run demonstrated stable and reliable operation of the accelerator complex;

- two test runs with a 3.42 A·GeV carbon beam and a 4 A·GeV deuteron beam have been performed for the BM@N project;

- total run durations were 1650 hours;
- more than 1000 hours were delivered for the physics (FAZA-3, Quinta, DSS, Delta-LNS).

BM@N, CBM-0 @ NICA & FAIR, SPIN Physics @ NICA

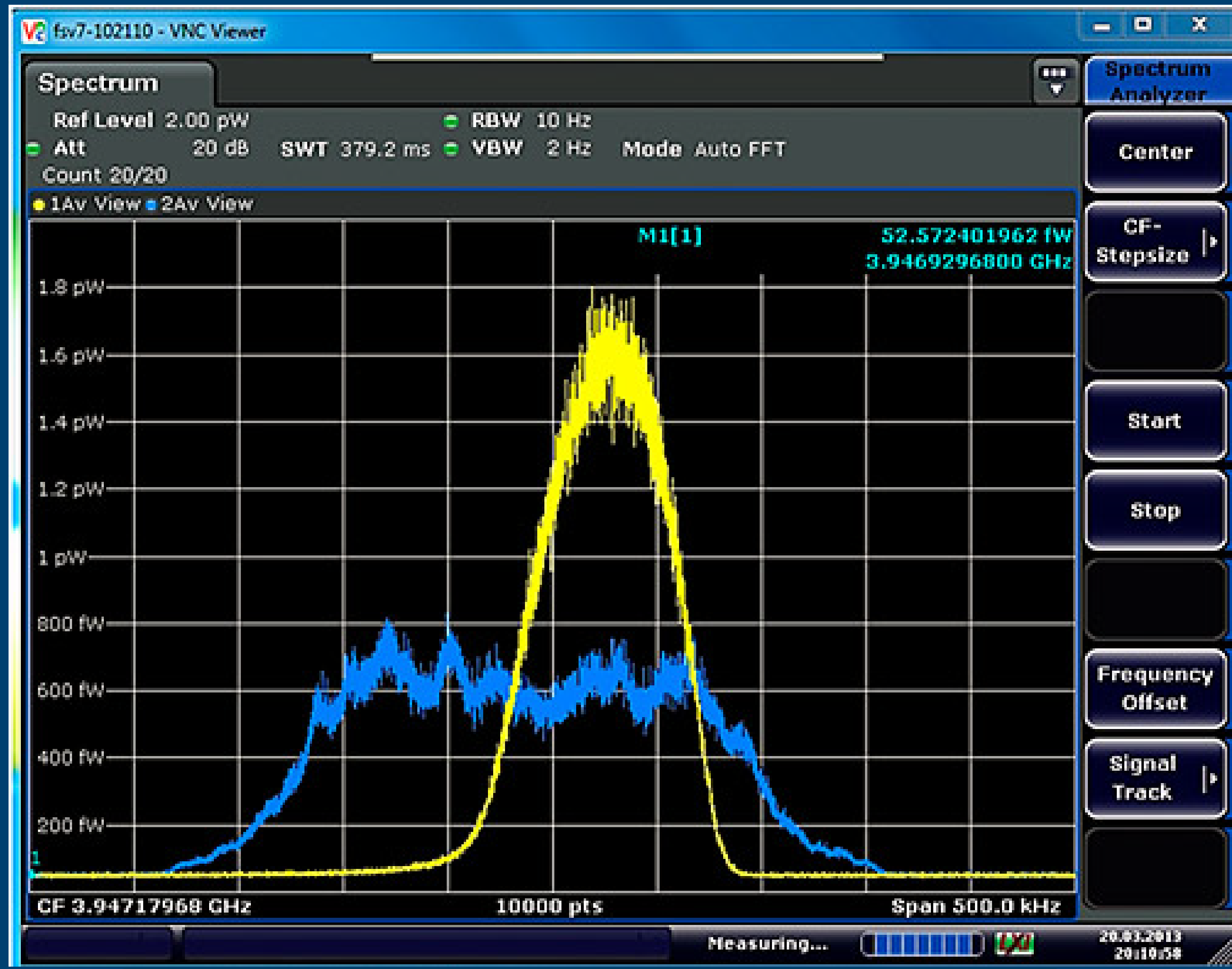
NUCLOTRON, March 2013

Stochastic Cooling (Van der Meer S., 1984) of the ion beam (deutrons)

First time in Russia in collaboration with IKP FZJ (Juelich)

Spectrum of transverse noise
E_d = 3 GeV/n,
I ~ 10^9 particles

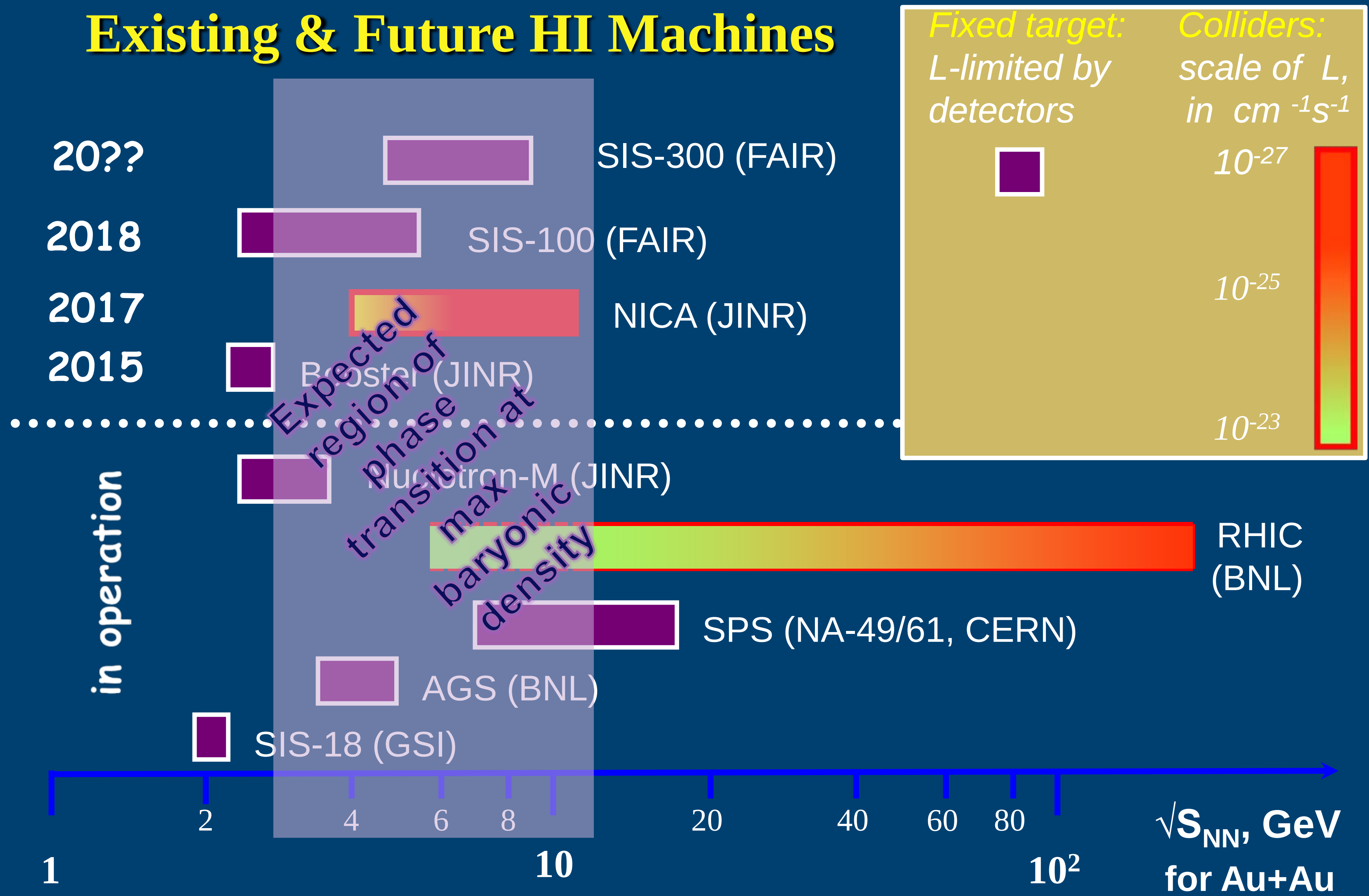
Blue – just after injection
Yellow – after 8 min's of cooling



Signal of the beam dP/P distribution evolution (~300 sec)

NICA schedule

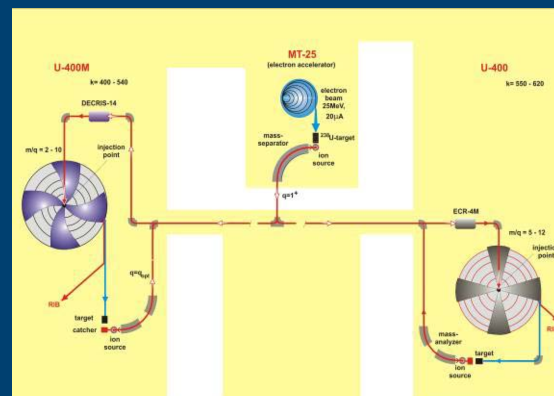
Existing & Future HI Machines



Heavy Ion Physics at Low Energies

U-400: energy factor K 305÷650
mass-to-charge ratio range 5÷12

U-400M: accelerated ion mass 4÷238
energy 20÷120 MeV/n;
mass-to-charge ratio 2÷5



DRIBs (I,II,III) –
Dubna Radioactive Ion Beams

U400 and U400M isochronous cyclotrons are combined into accelerator complex – the project DRIBs – which deals with production of beams of exotic light neutron-deficient and neutron-rich nuclei in reactions with light ions.

D.I. Mendeleev
1834 - 1907

113

Discovered at JINR in 2003

114

Discovered at JINR in 1999

115

Discovered at JINR in 2003

116

Discovered at JINR in 2000

117

Discovered at JINR in 2009

118

Discovered at JINR in 2001

Dubnium and Flerovium

As recognition of the outstanding contribution of JINR scientists to the research in the modern physics and chemistry, the International Union of Pure and Applied Chemistry named element 105 of the D.Mendeleev Periodic system of chemical elements "***Dubnium***".

Very recently IUPAC has officially approved the name ***Flerovium***, with symbol Fl, for the element of atomic number 114 and the name ***Livermorium***, with symbol Lv, for the element of atomic number 116. Priority for the discovery of these elements was assigned to the collaboration between the JINR (Dubna, Russia) and the Lawrence Livermore National Laboratory (Livermore, California, USA).

104 Резерфордий **Rf** [261] Rutherfordium	105 Дубний **Db** [262] Dubnium	106 Сиборгий **Sg** [266] Seaborgium
114 Флеровий **Fl** [287] Flerovium	115	116 Ливерморий **Lv** [291] Livermorium

PROSPECTS

Road map
Superheavy elements (SHE)

- Nuclear structure and properties of SHE
- Chemical properties of SHE
- Electron structure of SH atoms
- Search for new nuclear shells
- Search for SHE in nature

Project «DRIBs-III»
experimental base

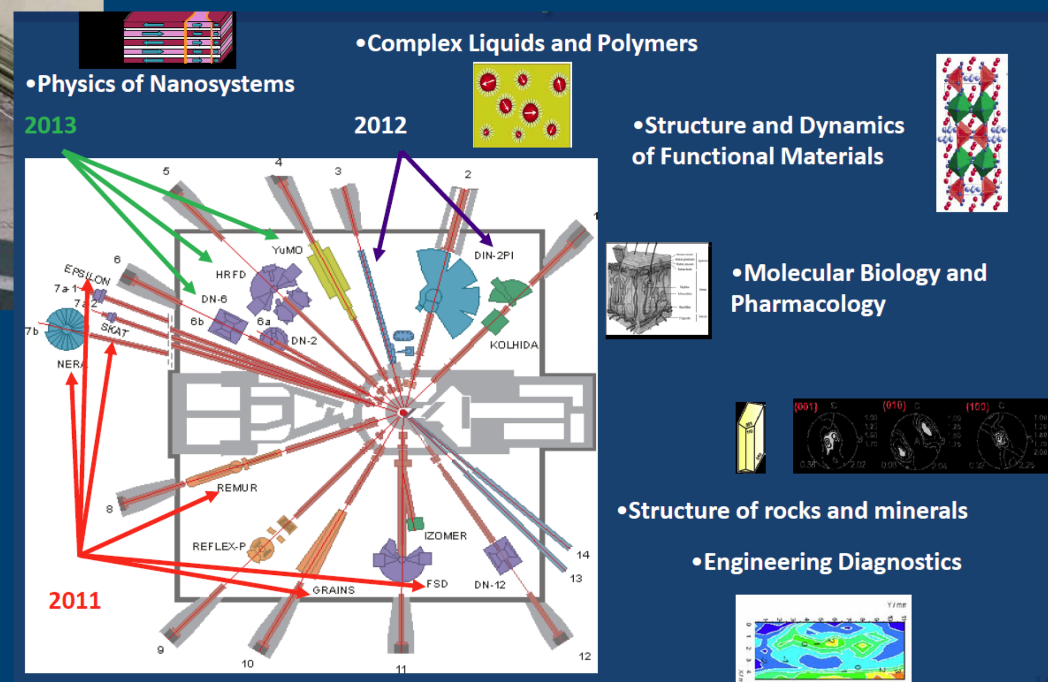
- Upgrade of the running accelerators U400 and U400M
- Construction of the new experimental hall (≈ 2600 м^2)
- Development and construction of the next-generation set-ups
- Development of high current heavy ion accelerator

Upgraded IBR-2

Pulsed reactor with fast neutrons

mean power ***2 MW***
pulse frequency ***5 Hz***
pulse width for fast neutrons ***200 μs***
thermal neutrons flux density on the moderator surface: ***10^{13} n/cm^2/s***
maximum in pulse: ***10^{16} n/cm^2/s***

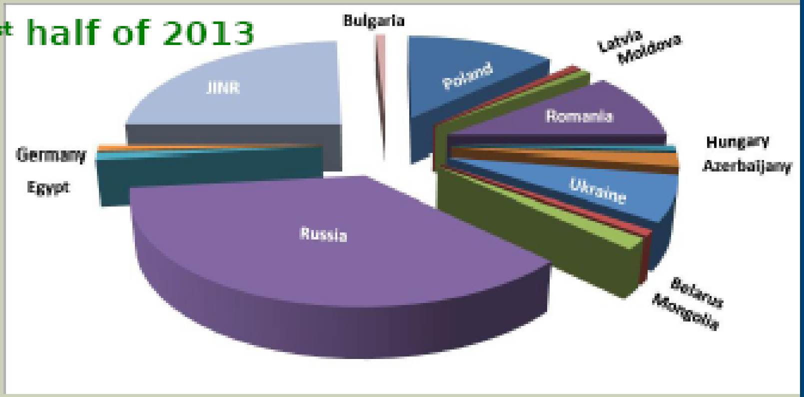
and spectrometer complex



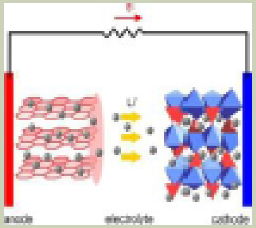
FULFILLMENT OF THE USER PROGRAMME AT THE SPECTROMETER COMPLEX OF THE MODERNIZED IBR-2 FACILITY

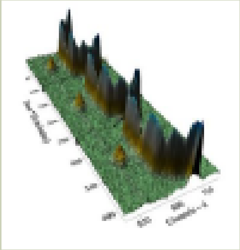
2013

- 195 proposals received for realization in 2013 during two calls (20% increase compared to 2012)
- 70 % accepted for realization according to recommendations of Expert Committees
- Most of the proposals accepted for the first half of 2013 were realized .



Proposals from 14 countries and JINR

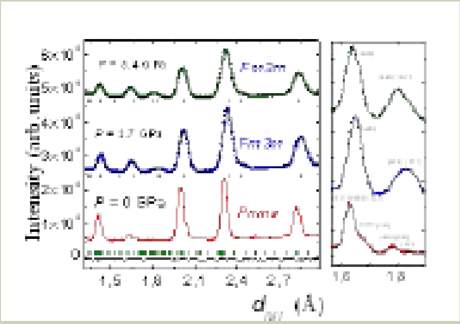


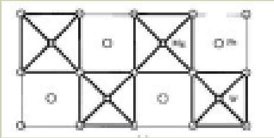


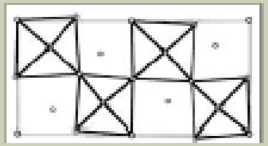
Real-time studies

charging/recharging processes in Li accumulators for improving the technological processes in production of accumulators

(proposal from National Tsing-Hua Univ., Hsinchu, Taiwan)







Neutron diffraction studies of structural phase transition in $PbMg_{1/2}W_{1/2}O_3$ perovskite under pressure

(proposal from Institute of Physics, Azerbaijan)

Basic Supporting activities

- Theory of PP, NP, CMP
- Networking and computing
- Training of young staff

Theoretical Physics

Main fields of research

- Theory of Elementary Particles and Fields
- Nuclear Theory, Nuclear Structure and Dynamics
- Theory of Condensed Matter and New Materials
- Modern Mathematical Physics
- Research and Education Project "Dubna International School of Theoretical Physics (DIAS-TH)"

Publications, 2012

Total ~ 430

Journals ~ 250

Conferences and Schools

Total - 15 (> 1000 participants)

DIAS-TH and Helmholtz Schools - 3

(> 20 countries were represented)

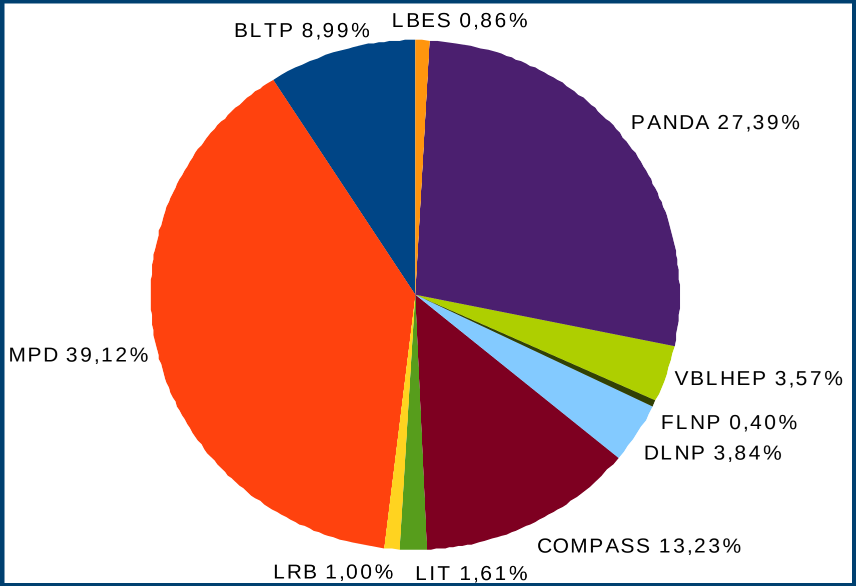
Educational Activity

> 50 lecture courses at JINR UC, DIAS-TH, Moscow U., Dubna U., MPTI, etc.

JINR Central Information and Computing Complex (CICC) works very well!

Local JINR users (no grid)

Jobs run by JINR Laboratories and experiments executed at CICC January - September 2013.

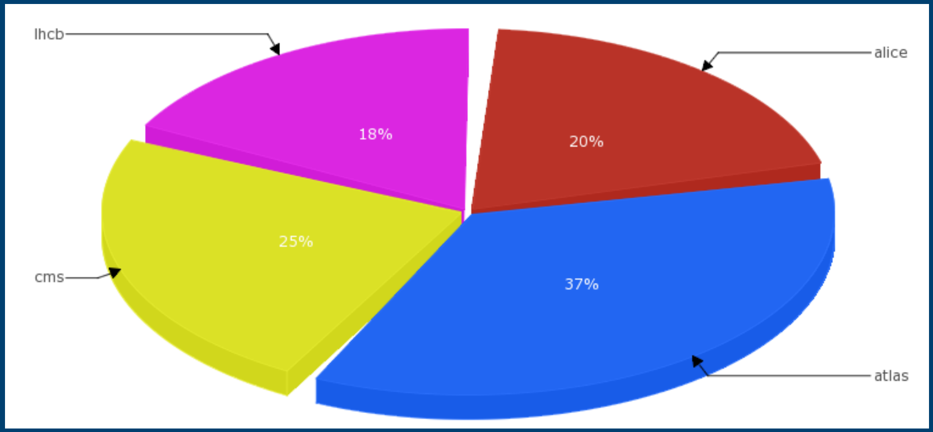


56 800 jobs run (Jan. – Sep. 2013)

Total normalised CPU time – 2 081 683 kSI2K-hours

Grid users (WLCG)

<u>JINR-LCG2</u> Normalised CPU time by LHC VOs. January - September 2013.



More than 3 million jobs run

Total normalised CPU time – 20 346 183 kSI2K-hours

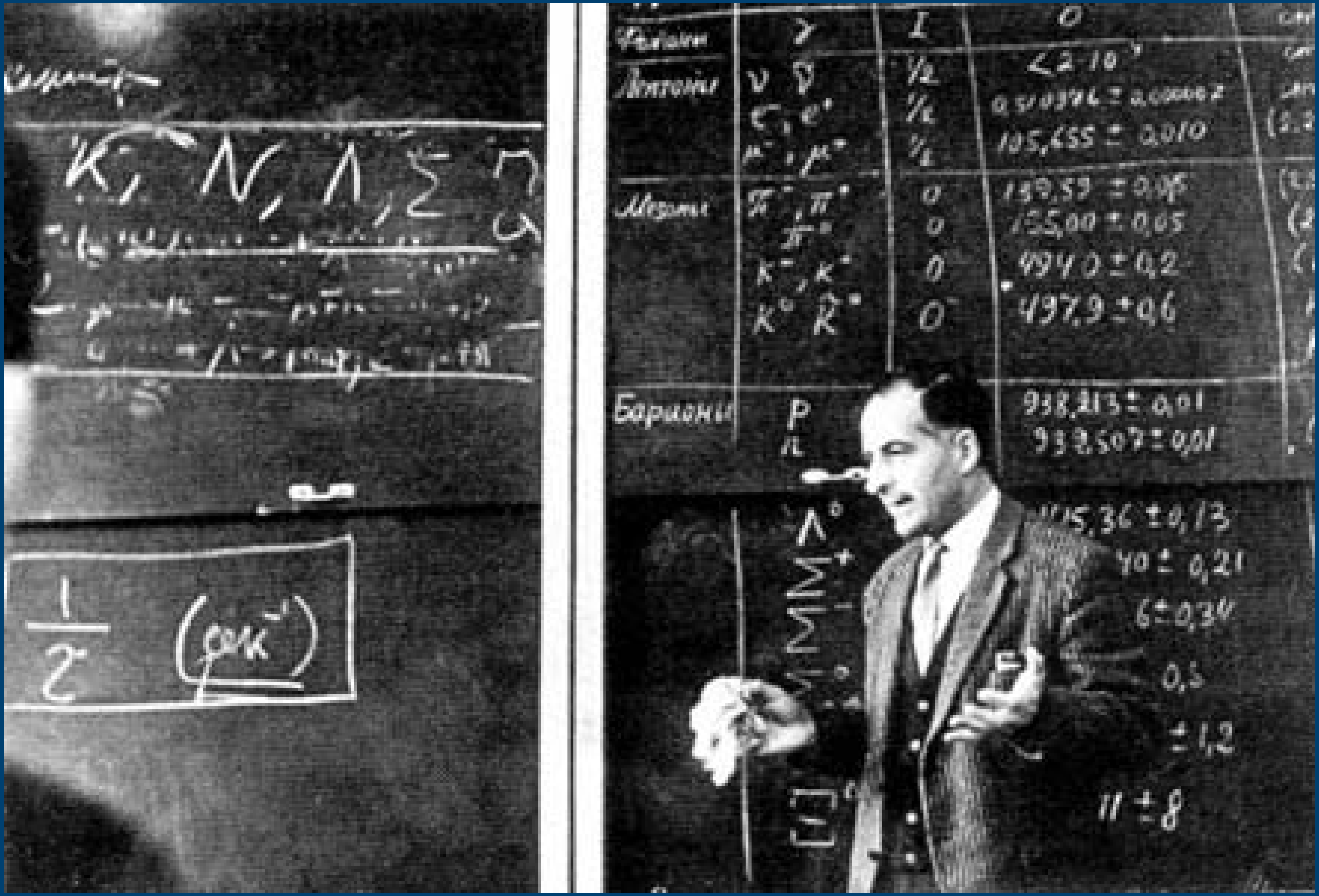
JINR Students statistics

University	09/10	10/11	11/12	12/13
MPhTI	16	28	36	31
MSU	24	27	23	34
MSTU MIREA	166	64	56	19
NRNU MEPhI	3	2	3	6
Dubna IU	229	232	261	253
Other Universities	116	83	121	108
Total	554	436	500	451

Distribution of students over JINR Laboratories

DLNP	BLTP	FLNR	FLNP	VBLHEP	LIT	LRB
90	47	74	60	86	46	48

Dubna branch of Moscow State University



Bruno Pontecorvo was leading for 20 years the Chair of Elementary Particle Physics at Physics Department of Moscow State University

Opening of the monument to Bruno Pontecorvo and Venedict Dzhelepov at Dubna on 20 September 2013

Conclusions

- **To stay at the forefront of Science, JINR has proposed and is realizing the ambitious projects within the 7-year planning horizon and beyond it.**

- **This main mission of JINR as International Research Center is strongly supported by the JINR's Member States and governing bodies.**