Present status and future prospect of Neutrino-4 experiment search for sterile neutrino

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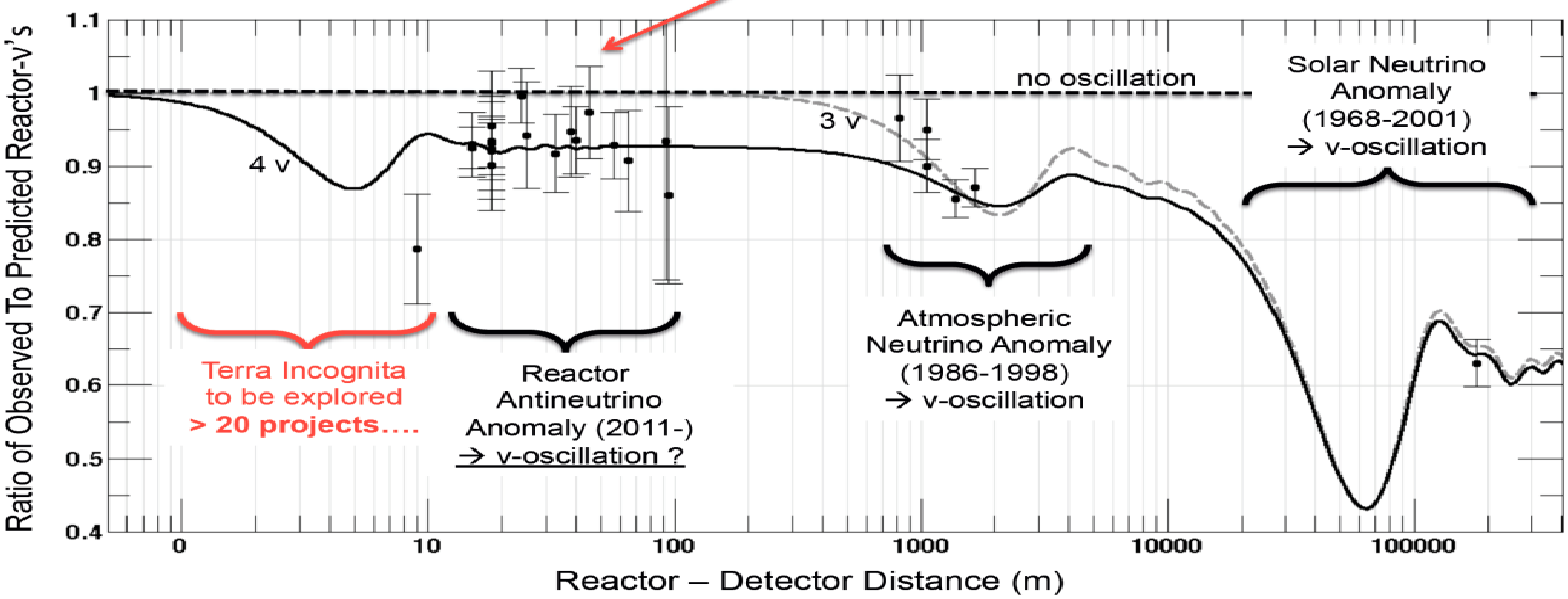
20-25 October 2019 PSI

Reactor antineutrino anomaly

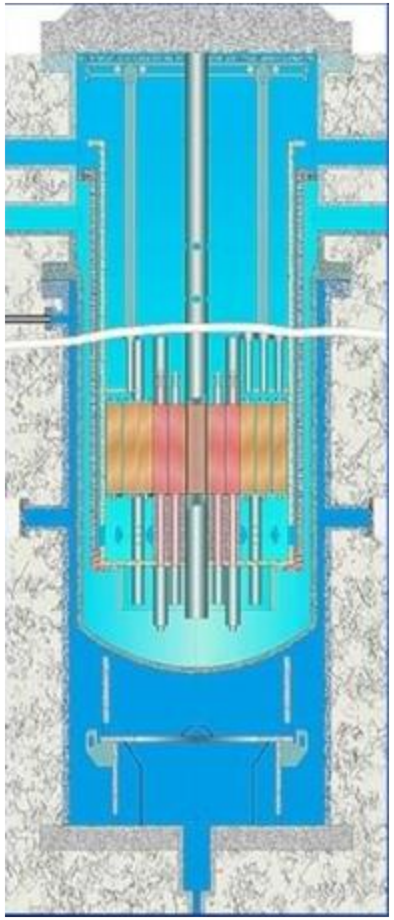
- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



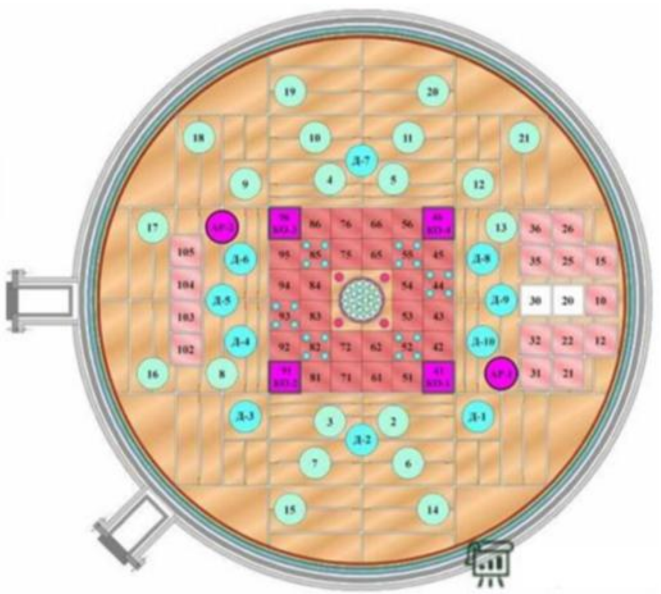
$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \ \sin^2\left(1.27 \frac{\Delta m^2_{14}[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\tilde{\nu}}[\mathrm{MeV}]}\right)$$

SM-3 research reactor

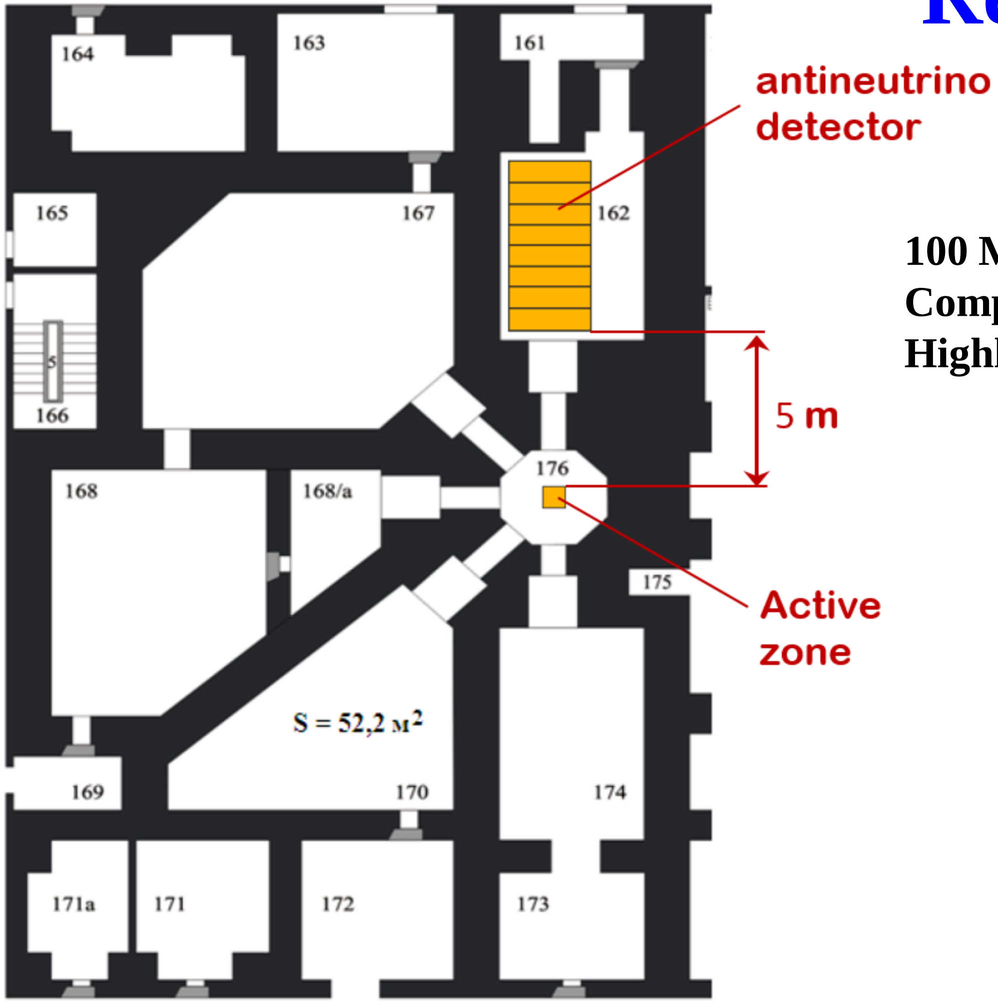
- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched ^{235}U fuel
- Separated rooms for experimental setup
- The laboratory is poorly protected from cosmic rays



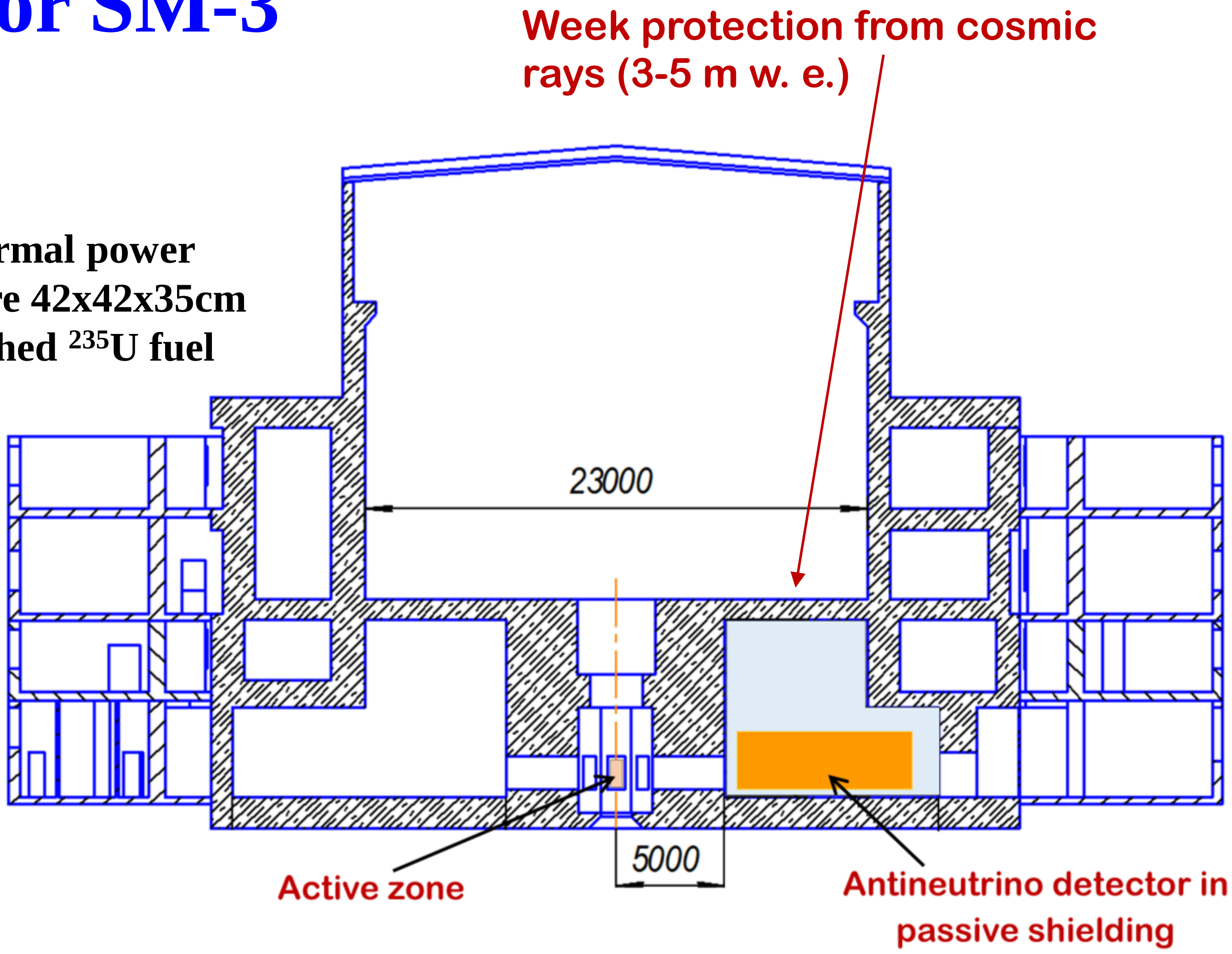
Vertical and horizontal sections of SM-3 reactor



Reactor SM-3

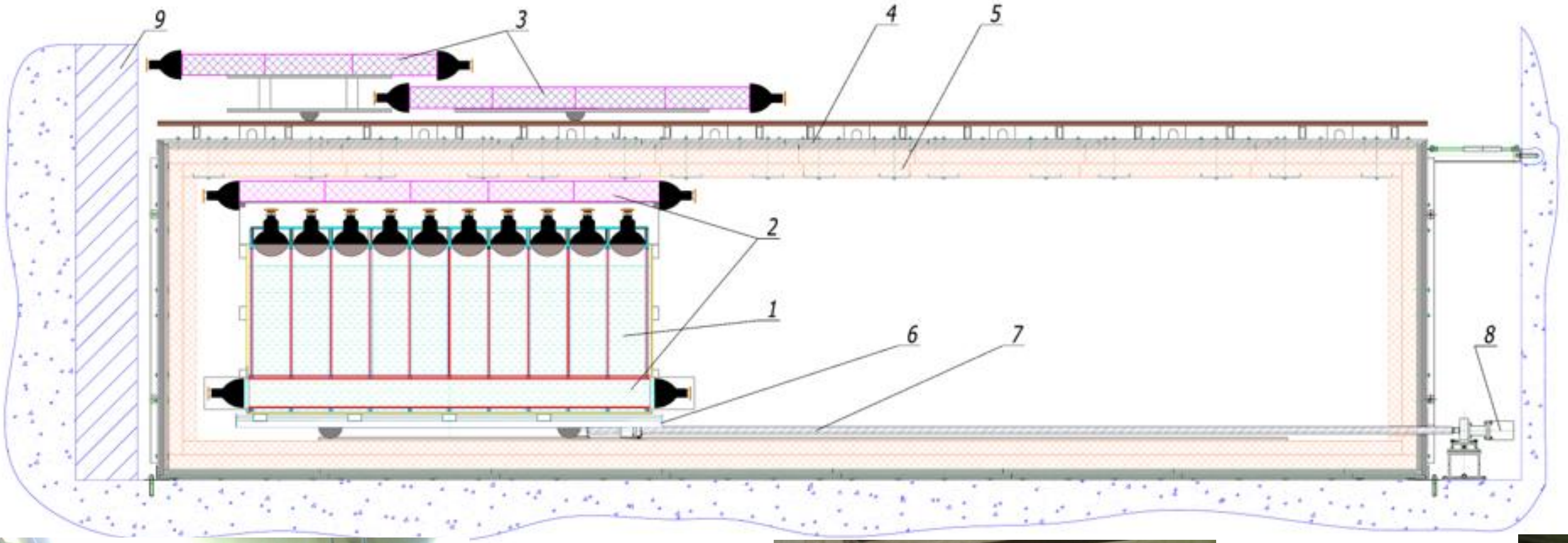


100 MW thermal power
Compact core 42x42x35cm
Highly enriched ^{235}U fuel

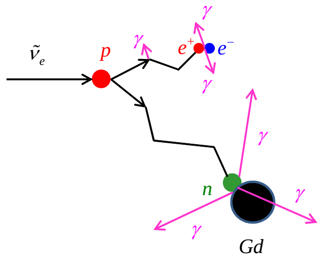


Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth's surface, hence, cosmic background is the major difficulty in considered experiment.

Movable and spectrum sensitive antineutrino detector



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



1. detector (5x10 cells)
2. internal active shielding
3. external active shielding
4. steel and lead
5. borated polyethylene
6. moveable platform
7. feed screw
8. step motor
9. shielding

Passive shielding - 60 tons

Neutrino channel outside and inside

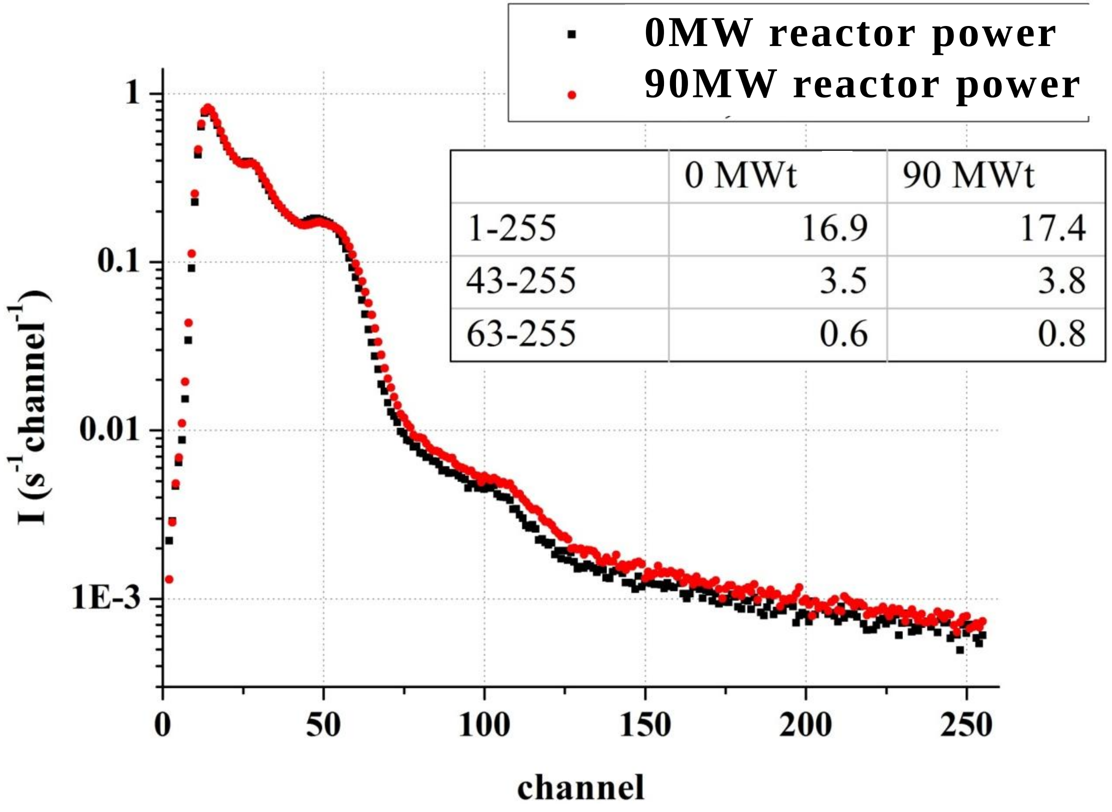
Range of measurements is 6 – 12 meters

Detector prototype

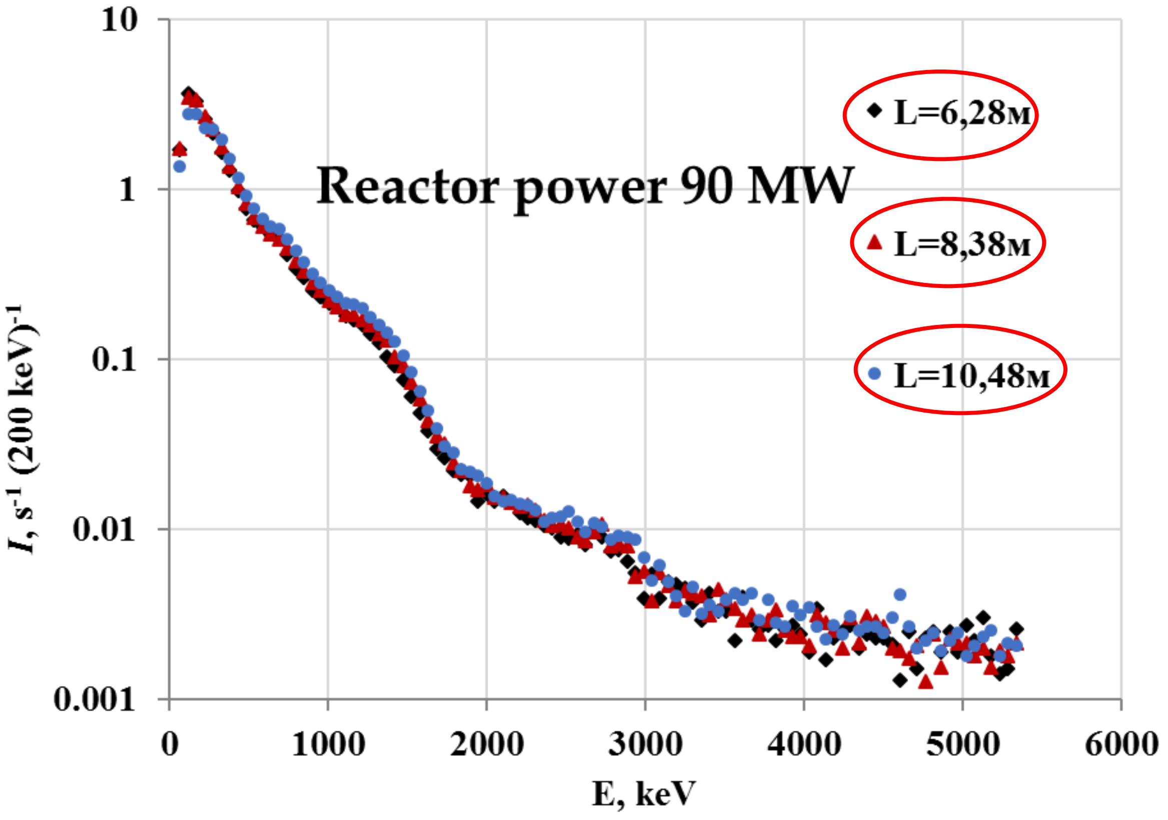
Full-scale detector

Liquid scintillator detector
50 sections 0.235x0.235x0.85м³

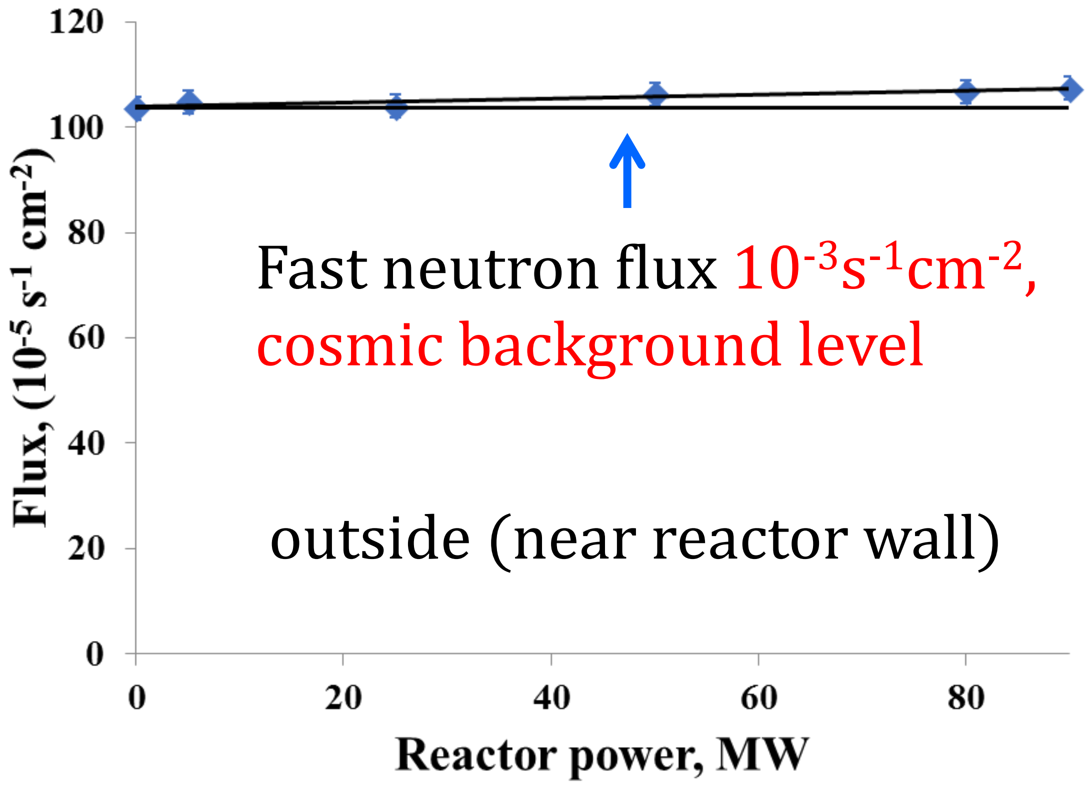
Gamma background in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor

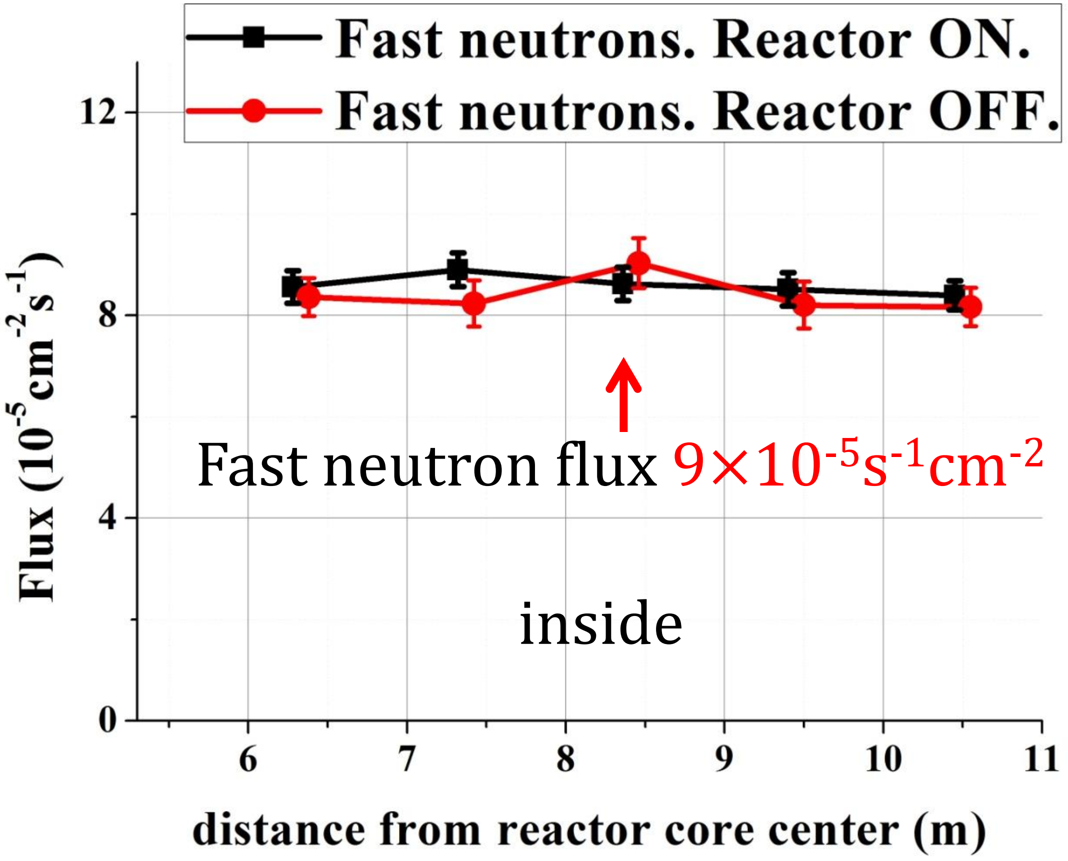


	0 MWt	90 MWt
1-255	16.9	17.4
43-255	3.5	3.8
63-255	0.6	0.8



The background of fast neutrons in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor





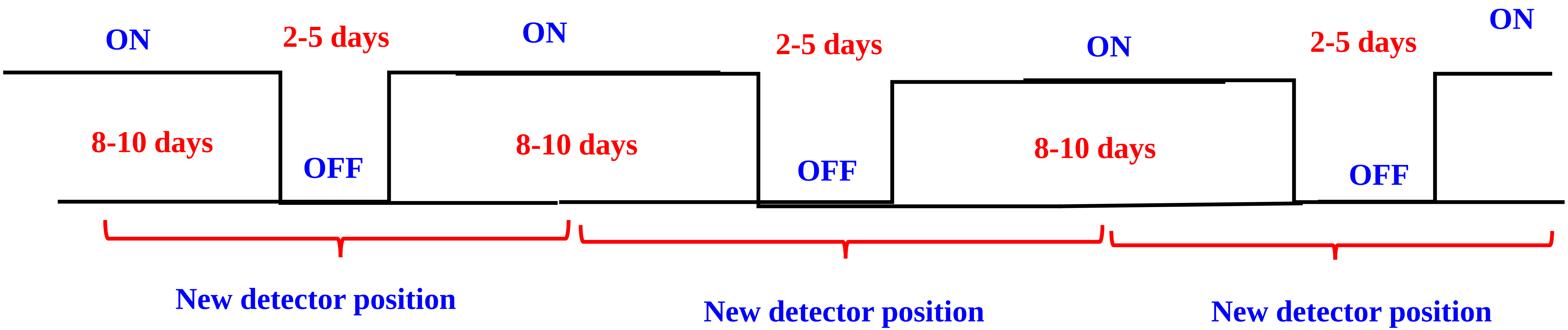
The background of fast neutrons in passive shielding is 10 times less than outside.
The background of fast neutrons outside of passive shielding is defined by cosmic rays and practically does not depend on reactor power.

Absence of noticeable dependence of the background on both distance and reactor power was observed. As a result, we consider that difference in reactor ON/OFF signals appears mostly due to antineutrino flux from operating reactor.

ON
90 MW

Measurements with the detector have started in June 2016. Measurements with the reactor ON were carried out for 480 days, and with the reactor OFF- for 278 days. In total, the reactor was switched on and off 58 times.

(ON – OFF)/ OFF = 50%



Probability of antineutrino disappearance

$N(E_i, L_k)$

Number of antineutrino events

$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \ \sin^2\left(1.27 \frac{\Delta m^2_{14}[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\tilde{\nu}}[\mathrm{MeV}]}\right) \quad (1)$$

The method of the analysis of experimental data

$$R^{\exp}_{i,k} = \frac{N(E_i, L_k)L_k^2}{K^{-1}\sum_k^K N(E_i, L_k)L_k^2} = \frac{[1 - \sin^2 2\theta_{14} \sin^2(1.27\Delta m^2_{14} L_k / E_i)]}{K^{-1}\sum_k^K [1 - \sin^2 2\theta_{14} \sin^2(1.27\Delta m^2_{14} L_k / E_i)]} = R^{th}_{i,k} \quad (2)$$

The method of the analysis of experimental data should not rely on precise knowledge of spectrum. One can carry out model independent analysis using equation (2), where numerator is the rate of antineutrino events with correction to geometric factor $1/L^2$ and denominator is its value averaged over all distances.

$$\sum_{i,k} [(R^{\exp}_{i,k} - R^{th}_{i,k})^2 / (\Delta R^{\exp}_{i,k})^2] = \chi^2(\sin^2 2\theta_{14}, \Delta m^2_{14})$$

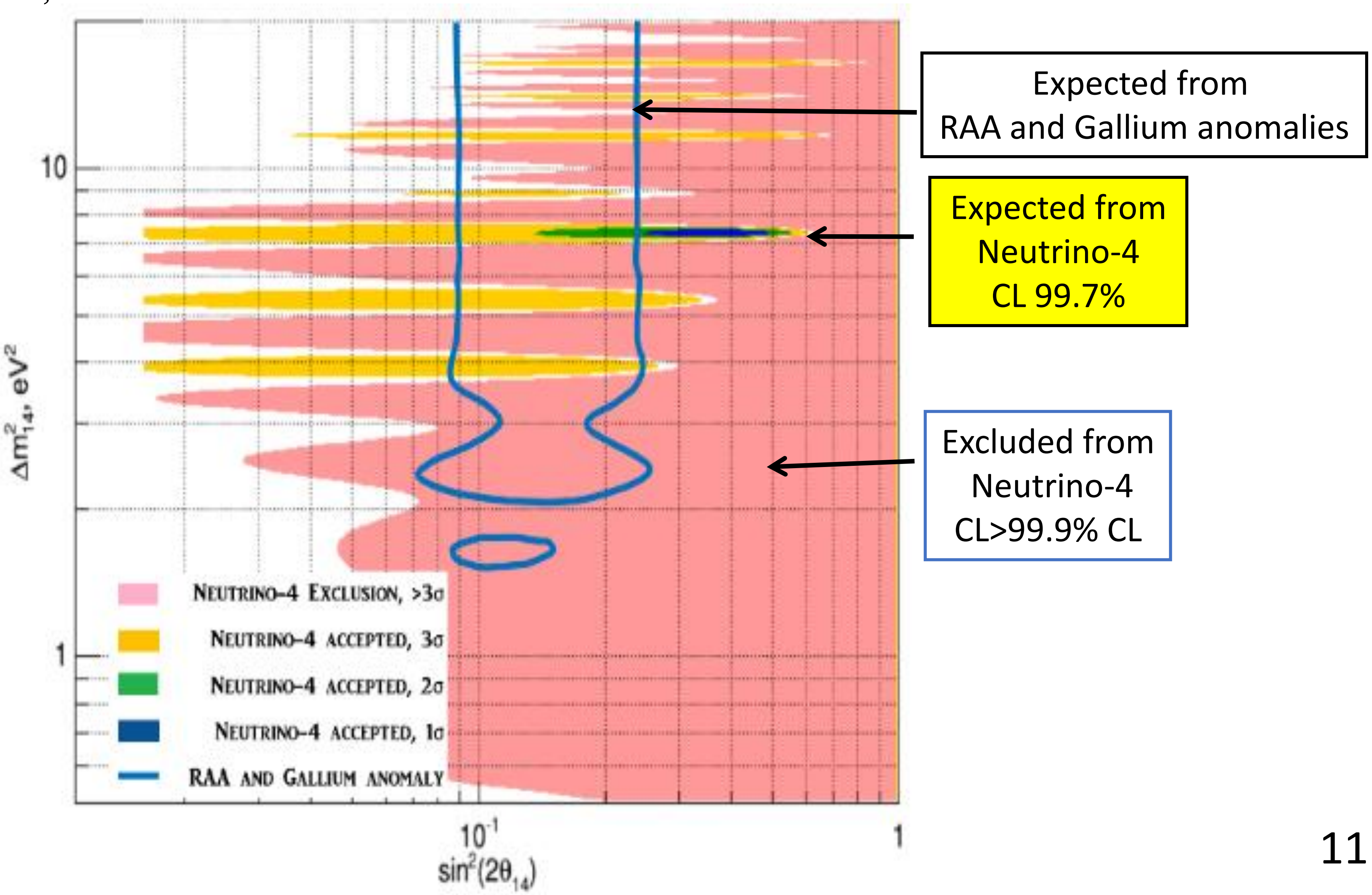
The results of the analysis of optimal parameters Δm_{14}^2 and $\sin^2 2\theta_{14}$ using χ^2 method

$$\sum_{i,k}[(R_{i,k}^{\exp} - R_{i,k}^{th})^2 / (\Delta R_{i,k}^{\exp})^2] = \chi^2(\sin^2 2\theta_{14}, \Delta m_{14}^2)$$

We observed the oscillation effect at C.L. 99.7% (3σ) in vicinity of :

$$\Delta m_{14}^2 \approx 7 eV^2$$

$$\sin^2 2\theta_{14} \approx 0.4$$

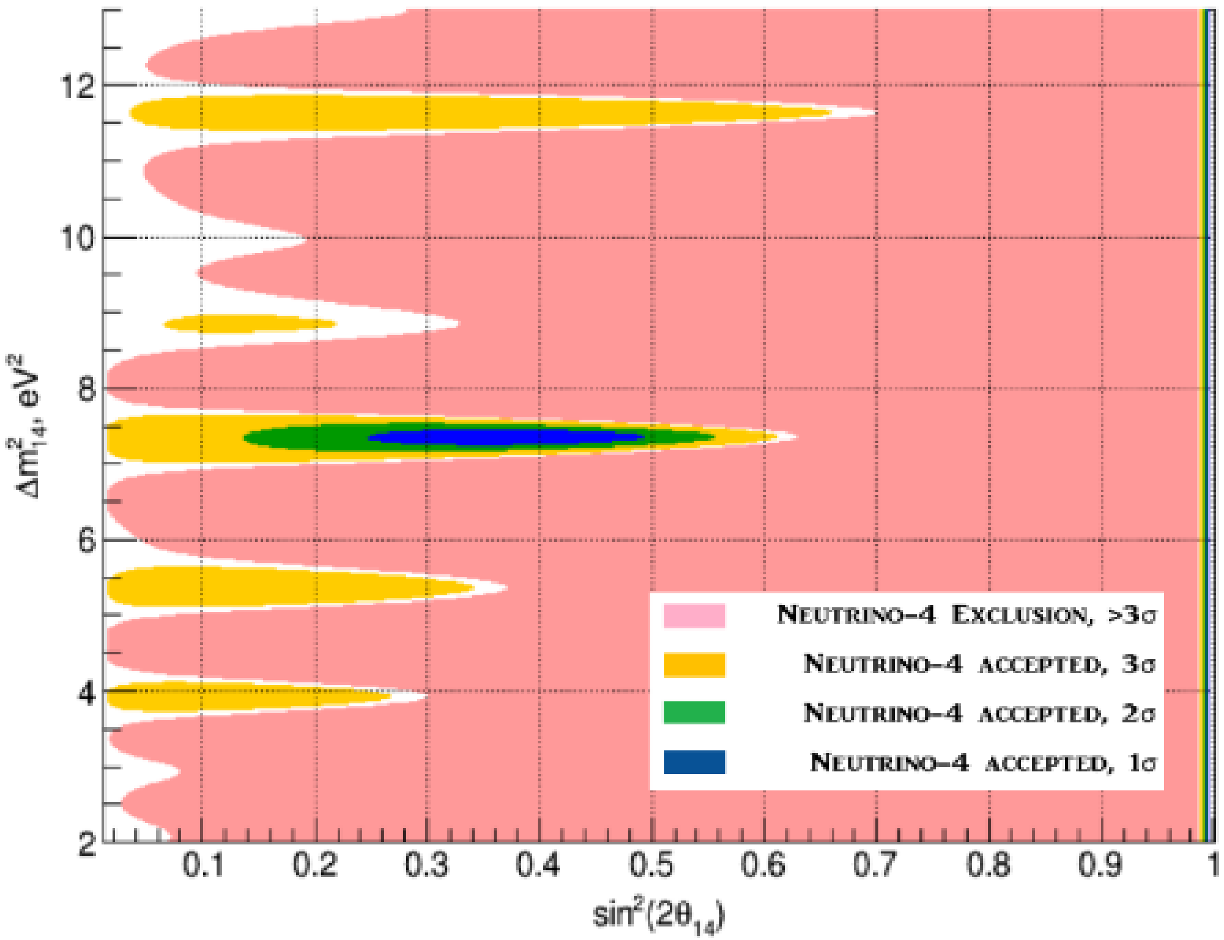


It seems that the effect predicted in gallium and reactor experiments is confirmed, but at sufficiently large values

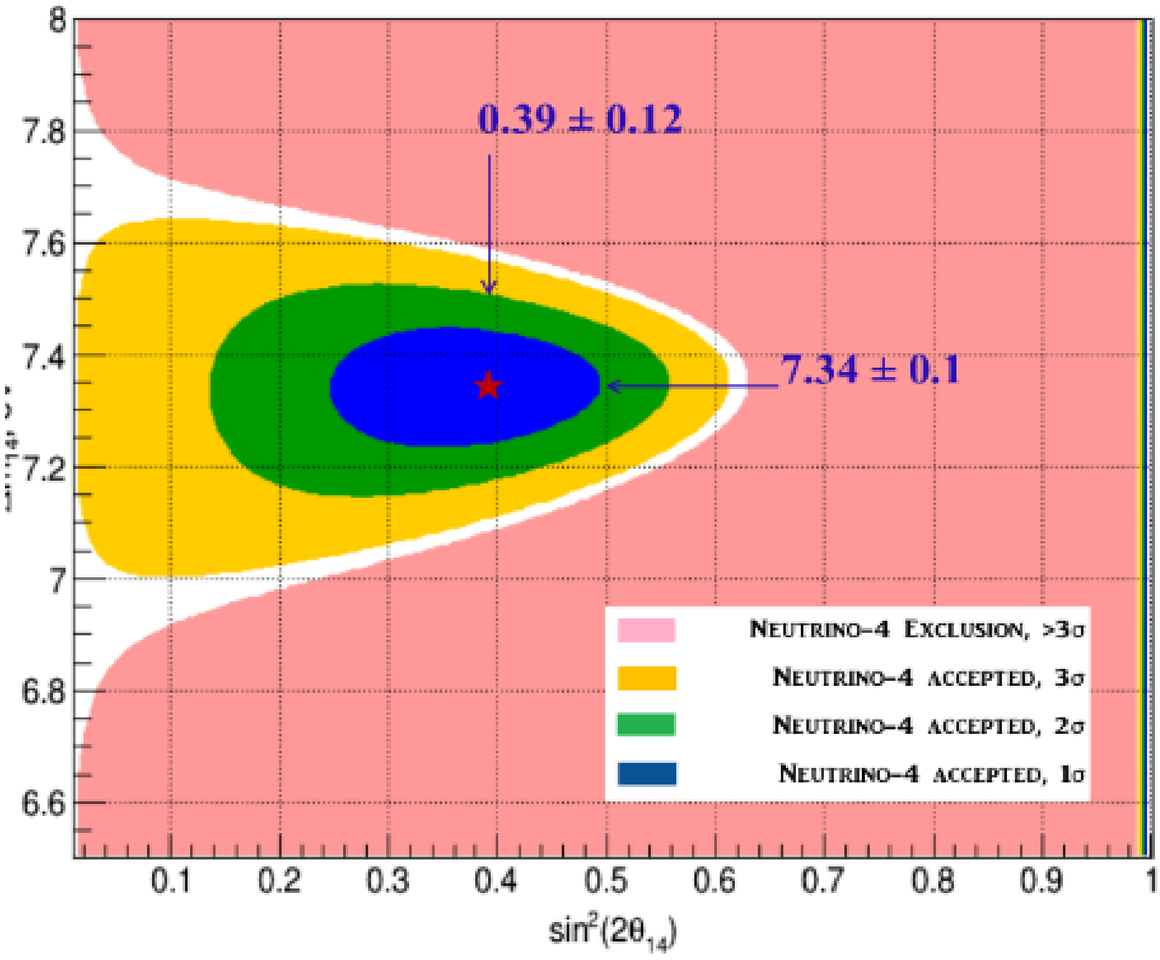
$$\Delta m_{14}^2 \approx 7.3\text{эВ}^2 \qquad\qquad \sin^2 2\theta_{14} = 0.39 \pm 0.12$$

The mixing parameter appears to be large enough in comparison with existing limitations from the Daya Bay and Bugey-3 experiments, but the difference between the results is 0.19 ± 0.18, i.e. one standard deviation. Therefore, there is no clear contradiction.

The results of the analysis of optimal parameters Δm_{14}^2 and $\sin^2 2\theta_{14}$ using χ^2 method

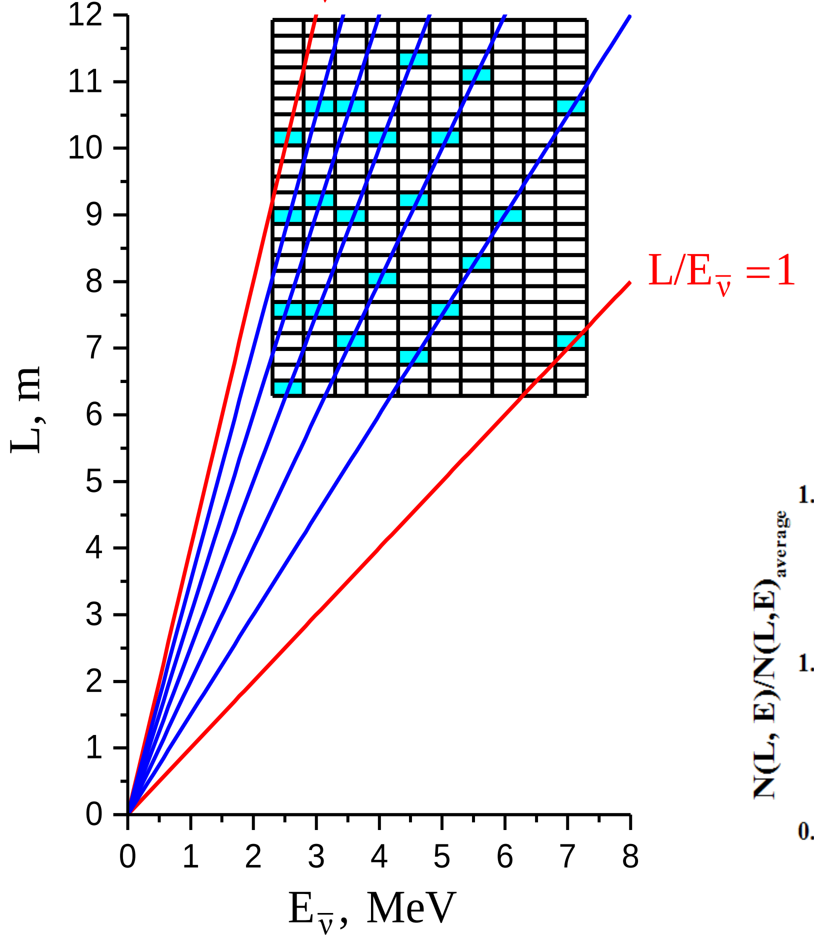


Area around central values in linear scale and significantly magnified

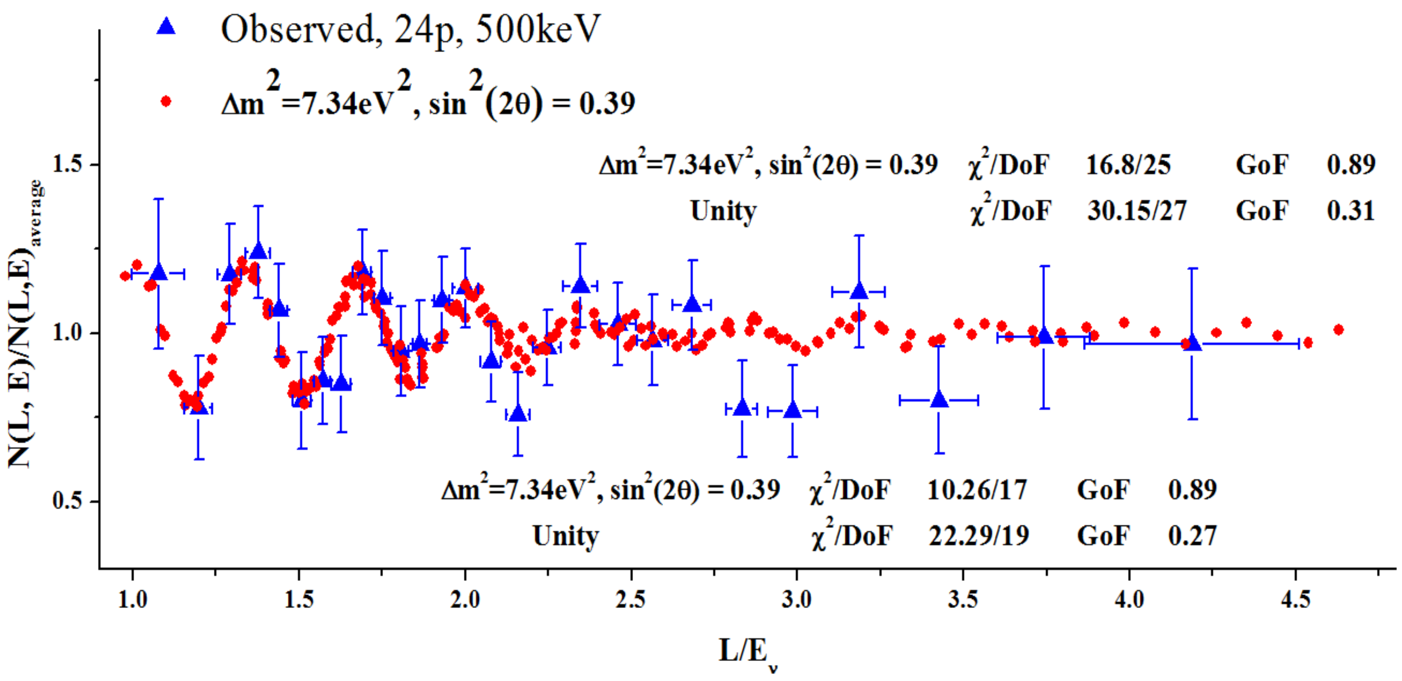


Central part even further magnified

The method of coherent addition of results of measurements allows us to directly observe the effect of oscillations



$$R^{\exp}_{i,k} = \frac{N(E_i^{\nu}, L_k)L_k^2}{K^{-1}\sum_k^K N(E_i^{\nu}, L_k)L_k^2} = \frac{[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 \boxed{L_k/E_i^{\nu}})]}{K^{-1}\sum_k^K [1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 \boxed{L_k/E_i^{\nu}})]} = R^{th}_{i,k} \quad (2)$$

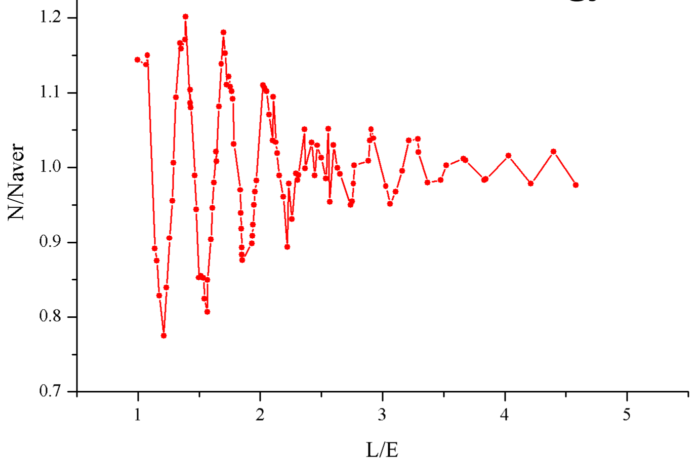


The expected effect at the different interval for distance and for energy (right part of equation 2)

$\Delta m^2_{14} \approx 7эВ^2$

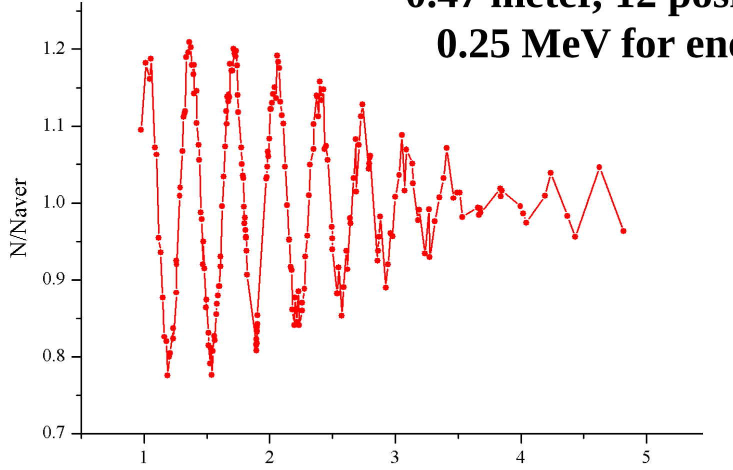
$\sin^2 2\theta_{14} \approx 0.4$

0.47 meter, 12 positions, 0.5 MeV for energy

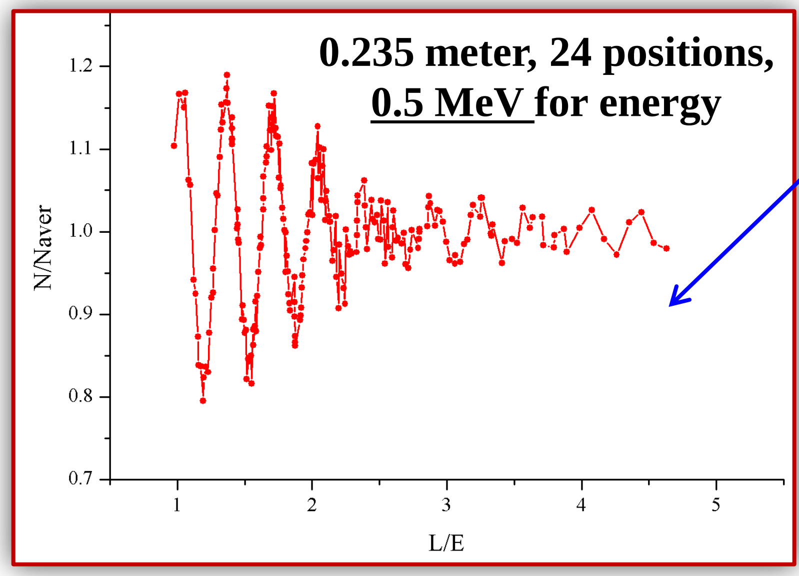


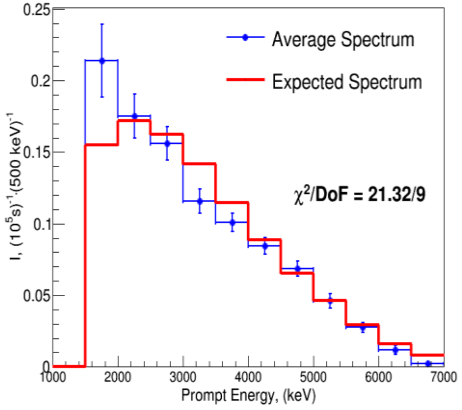
The attenuation of sinusoidal process for red curve in area L/E >2.5 is explained by taken energy interval 0.5MeV.
This energy interval corresponds to experimental energy resolution **±250keV**

0.47 meter, 12 positions, 0.25 MeV for energy

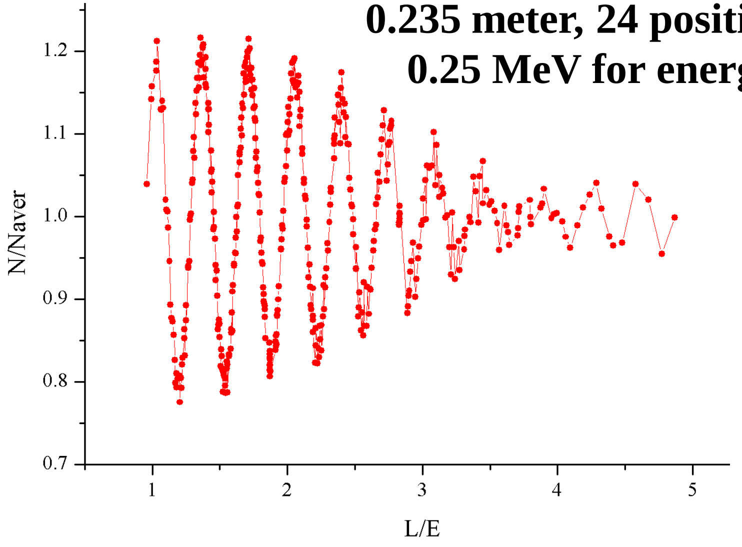


0.235 meter, 24 positions, <u>0.5 MeV</u> for energy

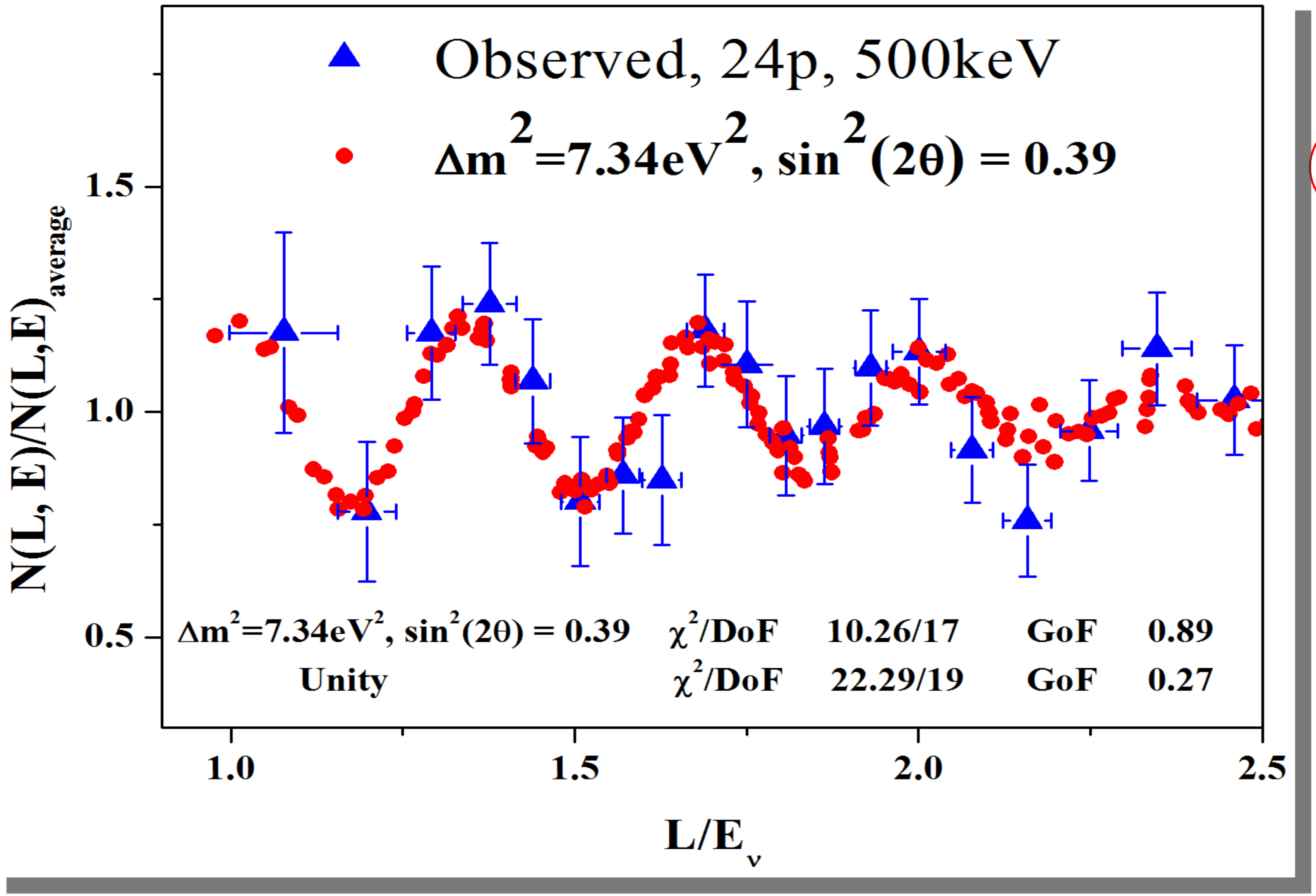




0.235 meter, 24 positions, 0.25 MeV for energy

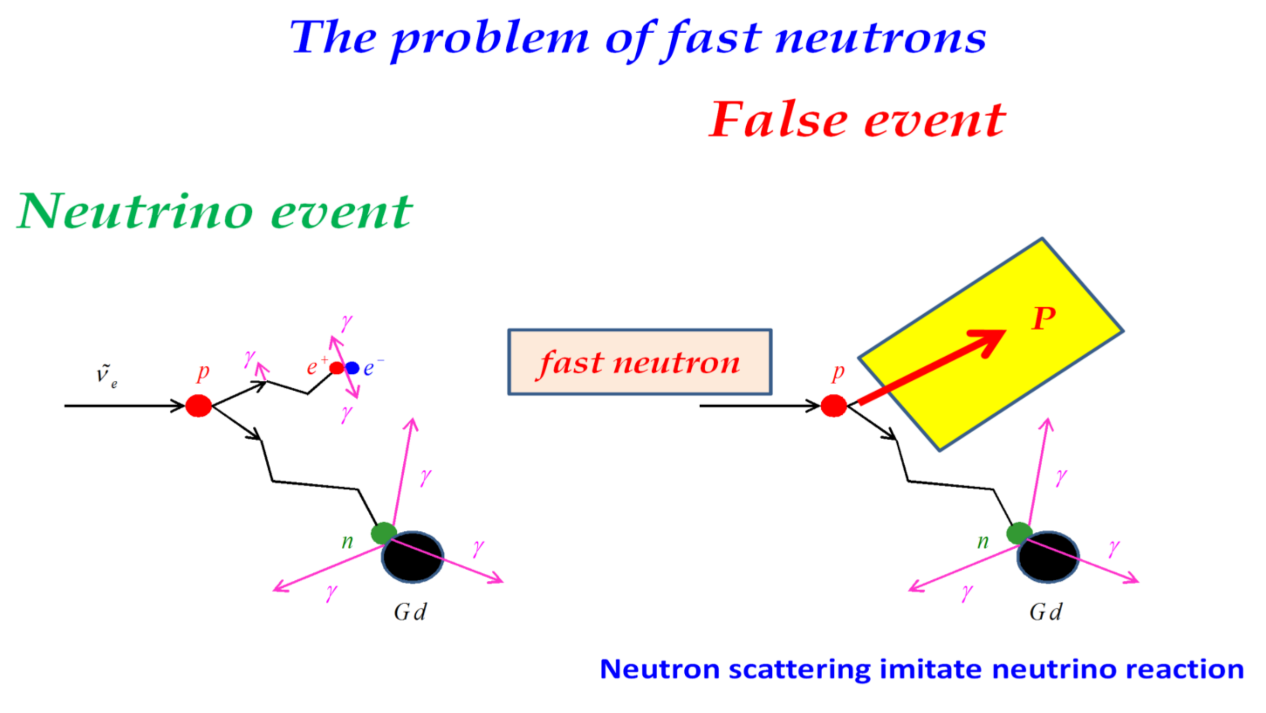


The first observation of oscillation of reactor antineutrino in sterile neutrino

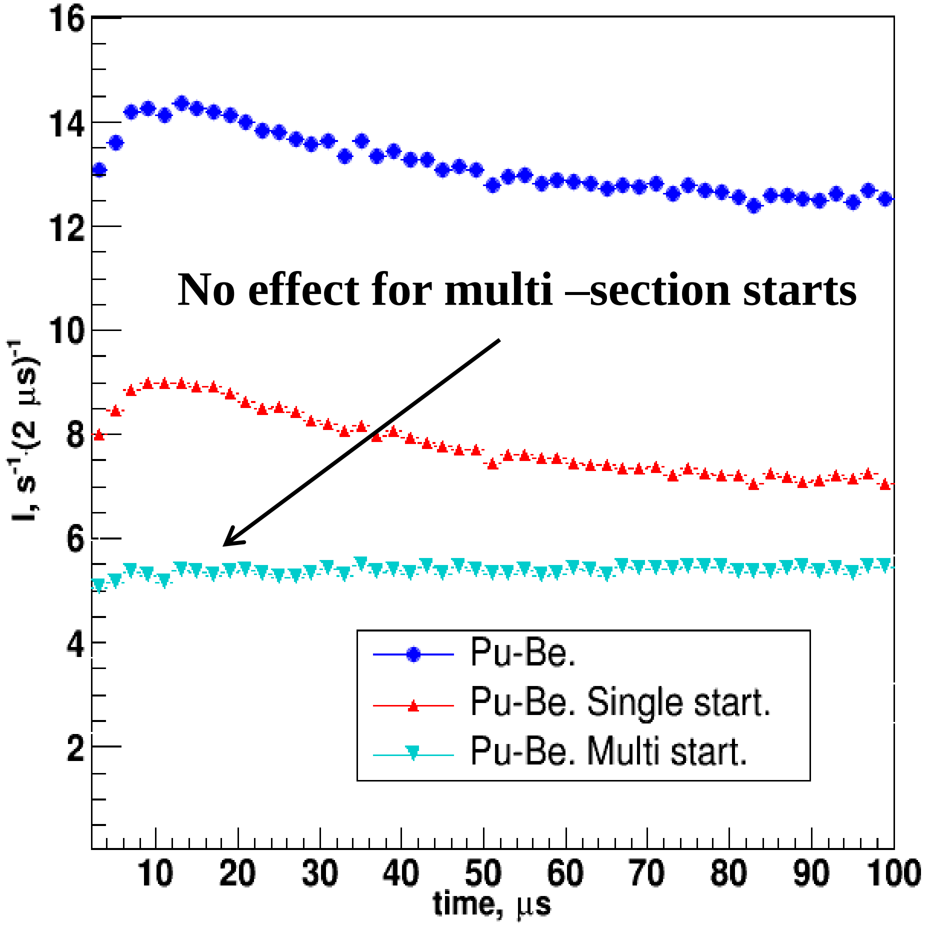


GoF 89%

- **Sectioning of the detector**
- **Problem of fast neutrons**
- **Allocation of a neutrino signal**



The test with a source of fast neutrons



24 central and 16 side cells for full-scale detector

central cell	side cell	angular cell	in all cells
42%	29%	19%	37%

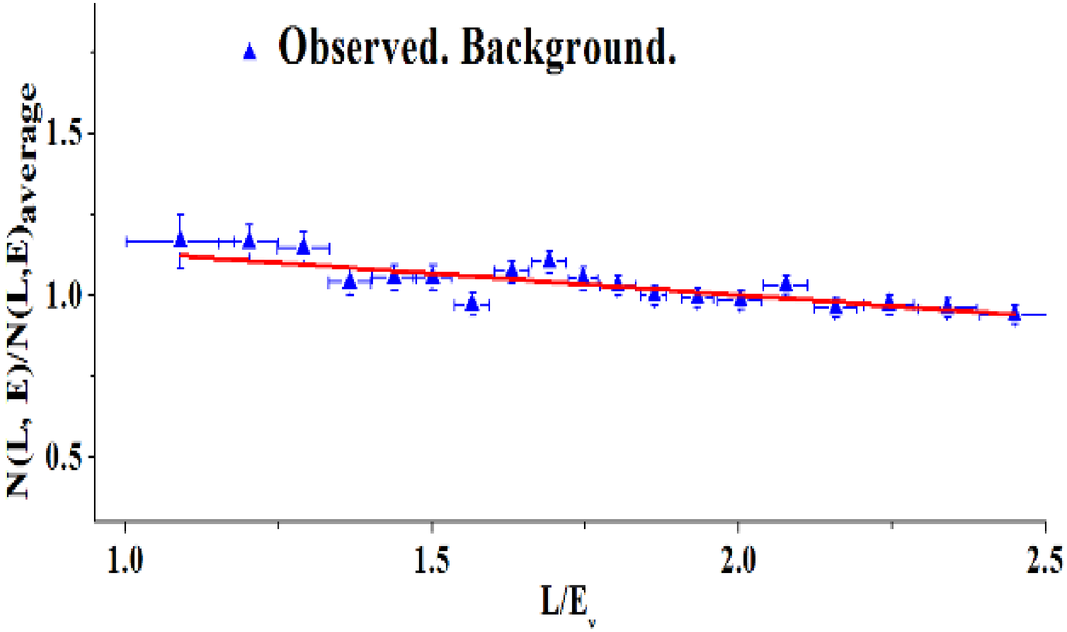
Calculated percentage of multi-start events

Experimental average percentage of multi-start events for full-scale detector

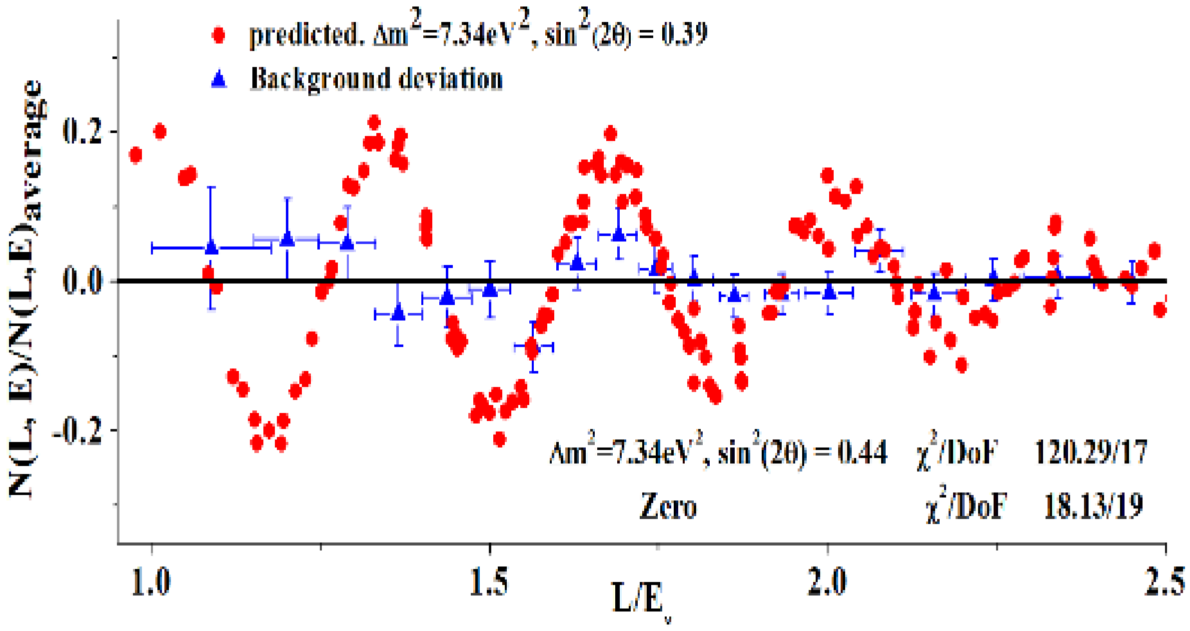
(37 ± 4)%

Test of systematic effects

To carry out analysis of possible systematic effects one should turn off antineutrino flux (reactor) and perform the same analysis of obtained data



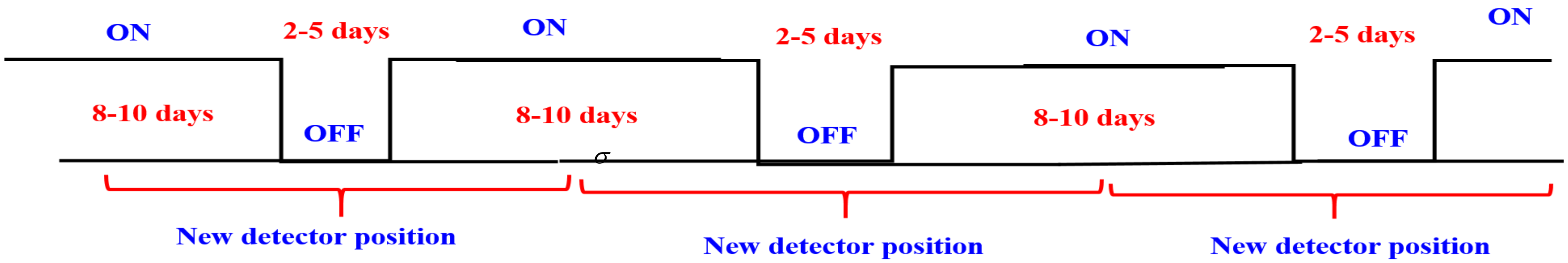
data analysis using coherent summation method

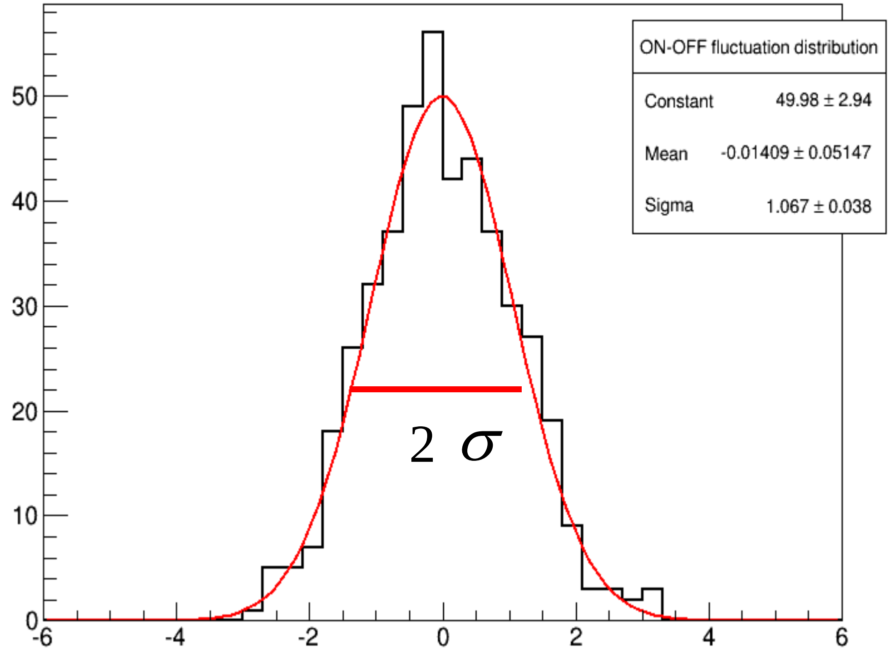


analysis of the results on oscillation parameters plane

Thus no instrumental systematic errors were observed.

Additional dispersion of measurement result which appears due to fluctuations of cosmic background





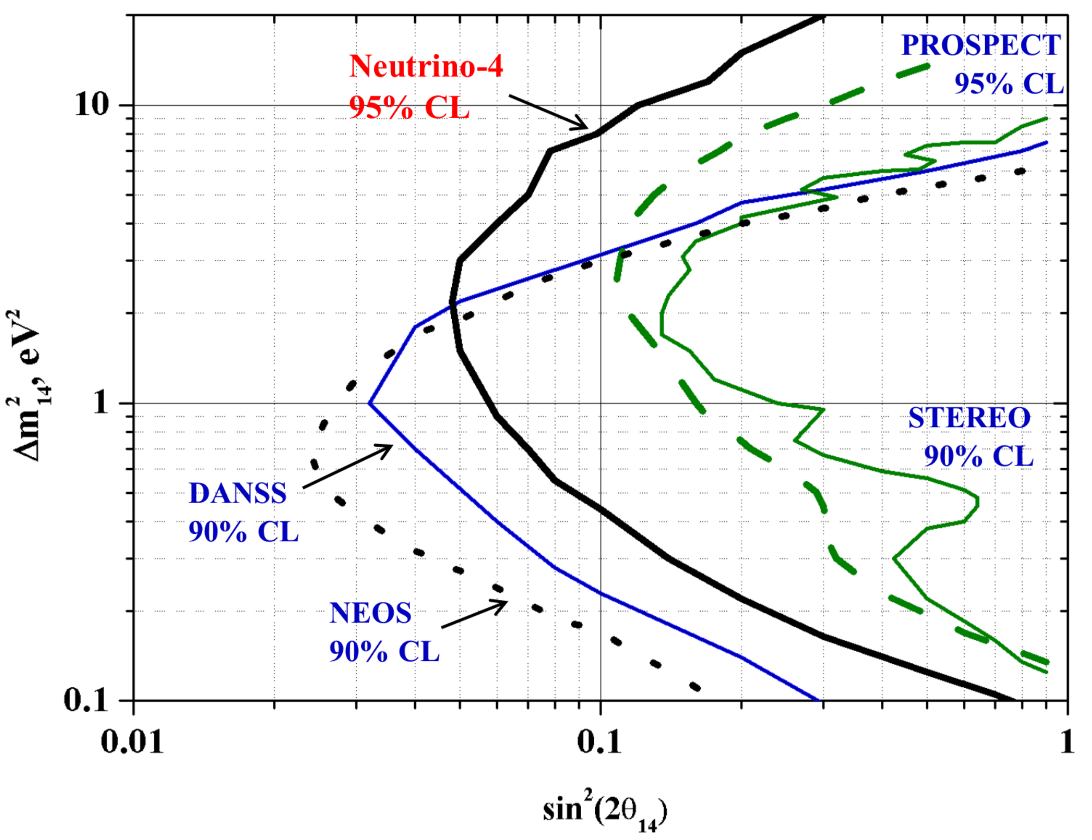
$$\sigma = 1.067 \pm 0.038$$

Since the measurements of the background carried out during the annual scheduled reactor repair works, then total additional dispersion is increased up to ~ **9%**.

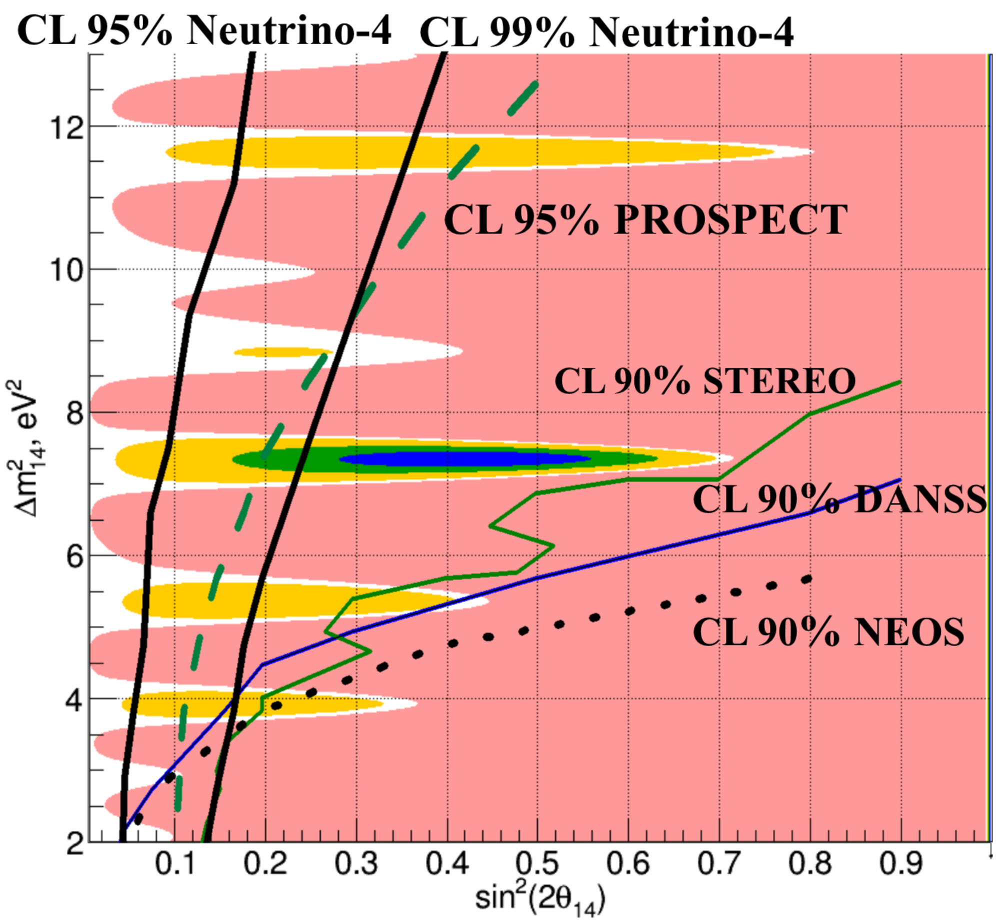
That is considered as systematic correction of uncertainties of results of measurements and it results in decreasing of confidence level of the results to 2.8σ.

That distribution has the form of normal distribution, but its width exceeds unit by ~ **7%.**

Sensitivity of other experiments NEOS , DANSS , STEREO and PROSPECT together with Neutrino-4



sensitivity regions of various experiments
(logarithmic scale)



region of oscillation effect in linear scale.

Experiment Neutrino-4 has some advantages in sensitivity to big values of Δm^2_{14} owing to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements. Next highest sensitivity to large values of Δm^2_{14} belongs to PROSPECT experiment. Currently its sensitivity is two times lower than Neutrino-4 sensitivity, but it recently has started data collection so it possibly can confirm or refute our result.

Some advantages of experiment Neutrino-4

Experiment Neutrino-4 has some advantages in sensitivity to big values of Δm^2_{14} owing to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements. In total, the reactor was switched on and off 58 times.

Present status of Neutrino-4 experiment search for sterile neutrino

Publications

А.П. Серебров, В.Г. Ивочкин, Р.М. Самойлов и др.
Первое наблюдение эффекта осцилляций в эксперименте Нейтрино-4 по поиску стерильного нейтрино.
Письма в ЖЭТФ, том 109, вып. 4, с. 209 – 218

A.P.Serebrov, et al. The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino. JETP Letters, Volume 109, Issue 4, pp 213–221. https://doi.org/10.1134/S0021364019040040, arxiv:1809.10561

A.P.Serebrov, The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino. Journal of Physics: Conference Series, In presss.

Conference talks

A.P.Serebrov, The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino. Applied Antineutrino Physics 2018 Workshop, Livermore, California, USA, 10-11 October 2018

A.P.Serebrov, The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino . IV international conference on particle physics and astrophysics, ICPPA-2018, Moscow, Russia, 22-26 October 2018

A.P.Serebrov, The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino. Particle Physics with Neutrons at the ESS, Stockholm, Sweden, 10-14 December 2018

Seminars: NRC “Kurchatov institute” – PNPI, INR

Future prospect of experiment search for sterile neutrino

1. **New measurements with detector Neutrino-4 and new scintillator with more high concentration of Gd and with PSD quality**

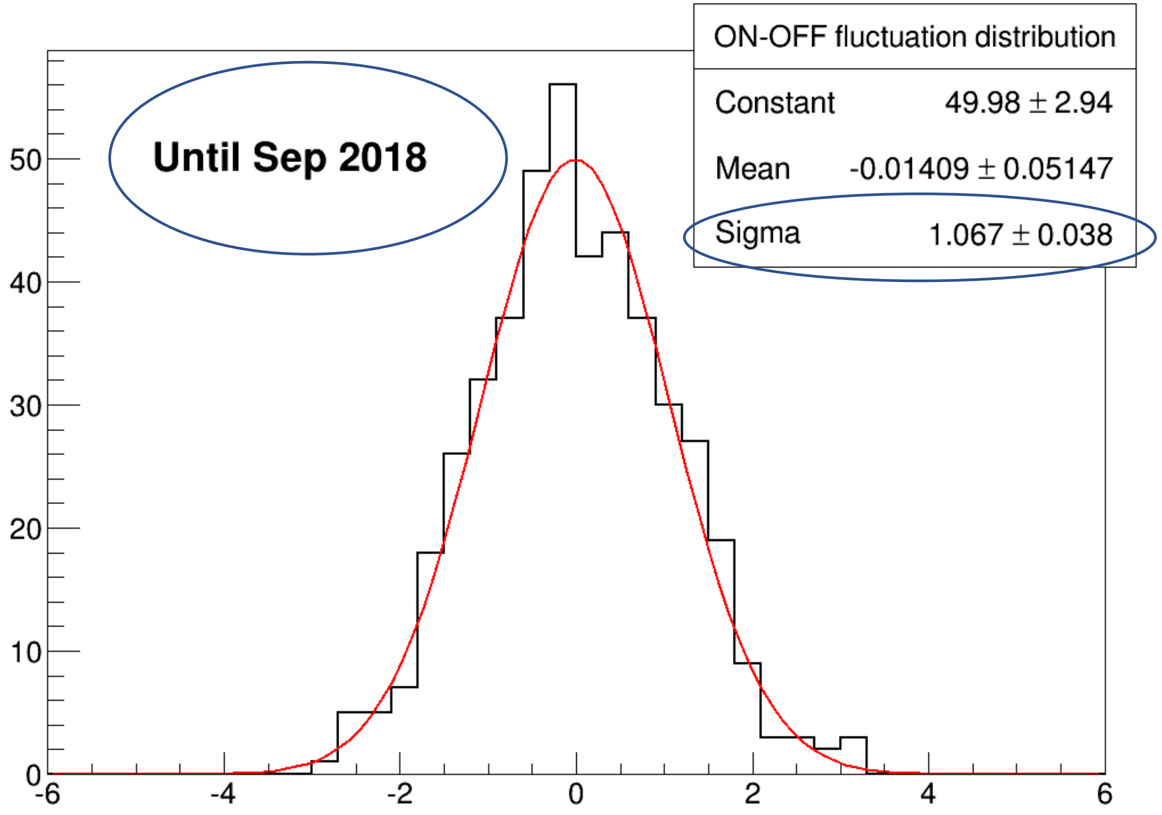
2. **Creation of the second neutrino laboratory at the reactor CM-3**

3. **The development and manufacture of a new detector Neutrino-6 with a sensitivity of 3.1 times higher**

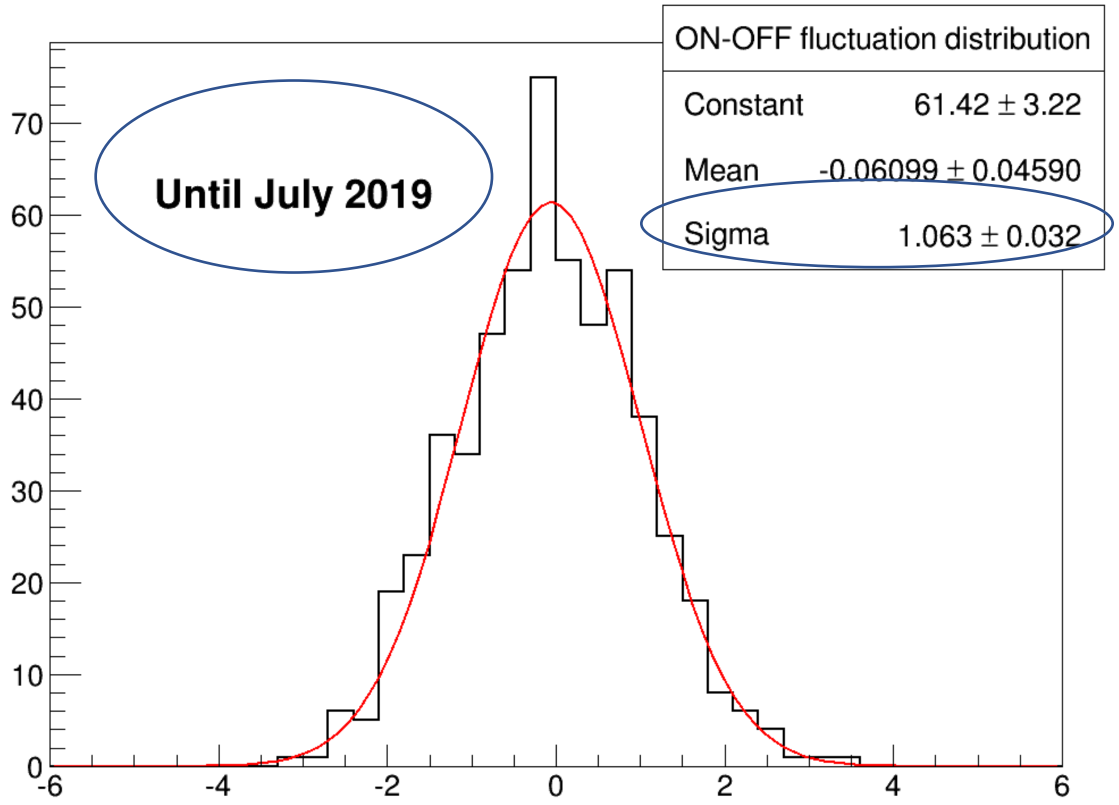
New measurements

ON – OFF fluctuation distribution

Deviation from statistic distribution 6.7 +_ 3.8 %



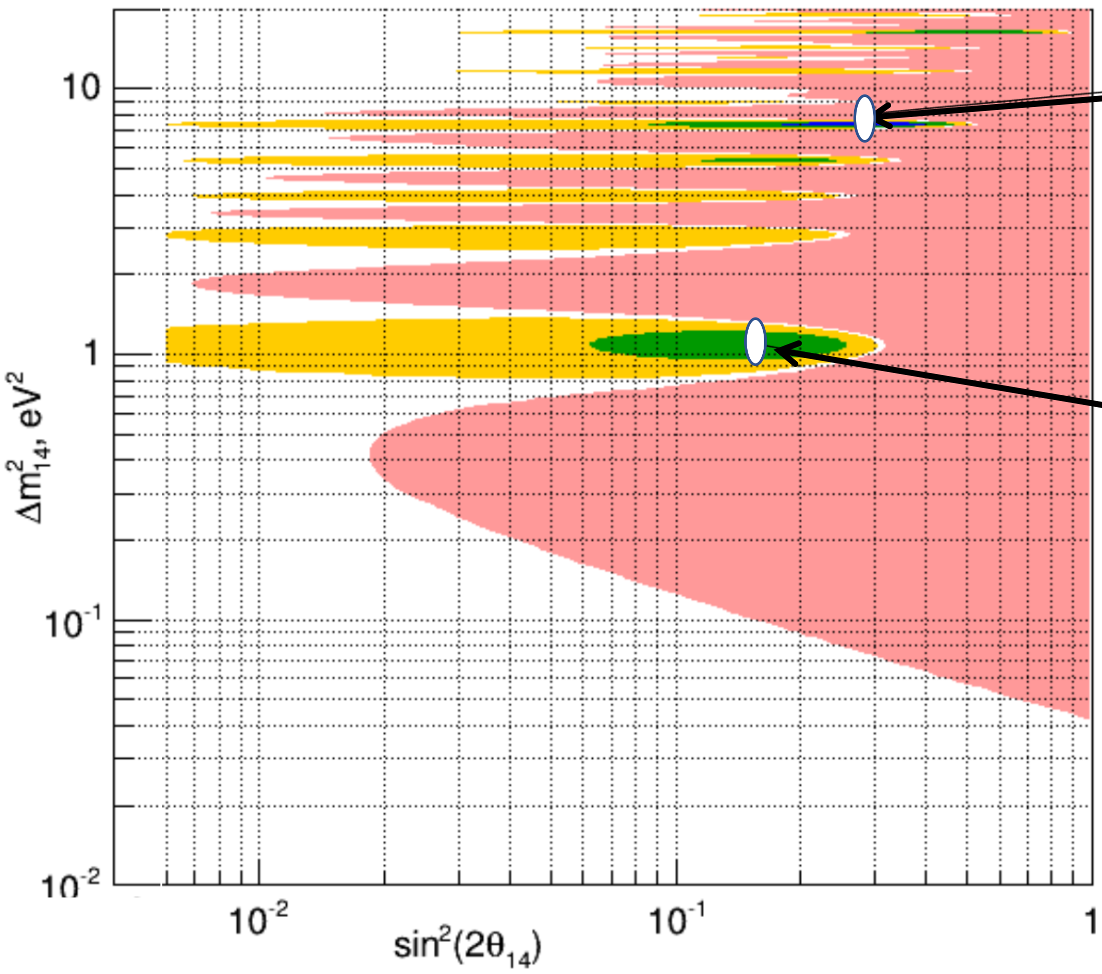
Deviation from statistic distribution 6.3+_ 3.2 %



The results of the analysis of optimal parameters Δm^2_{14} **and** $\sin^2 2\theta_{14}$

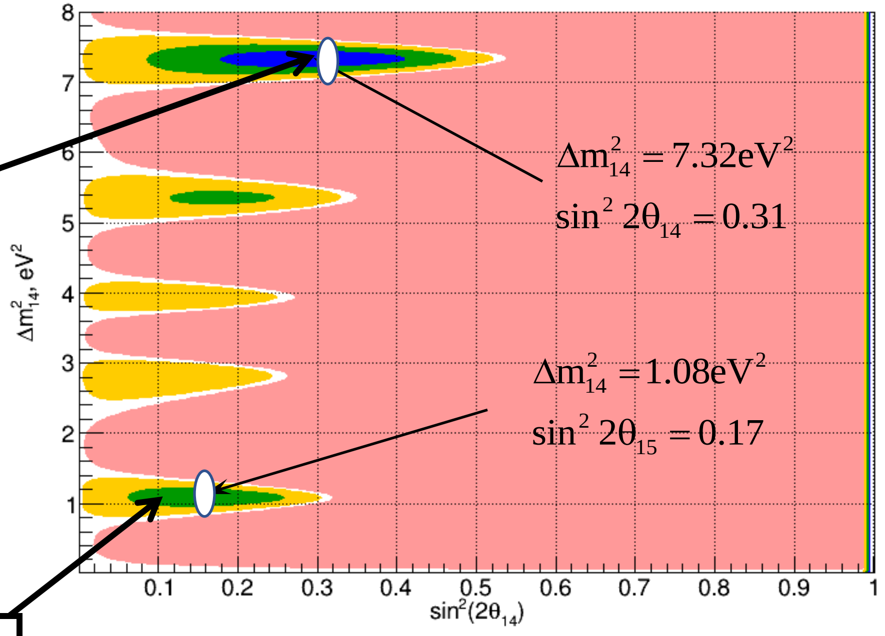
June 2016 – Julv 2019

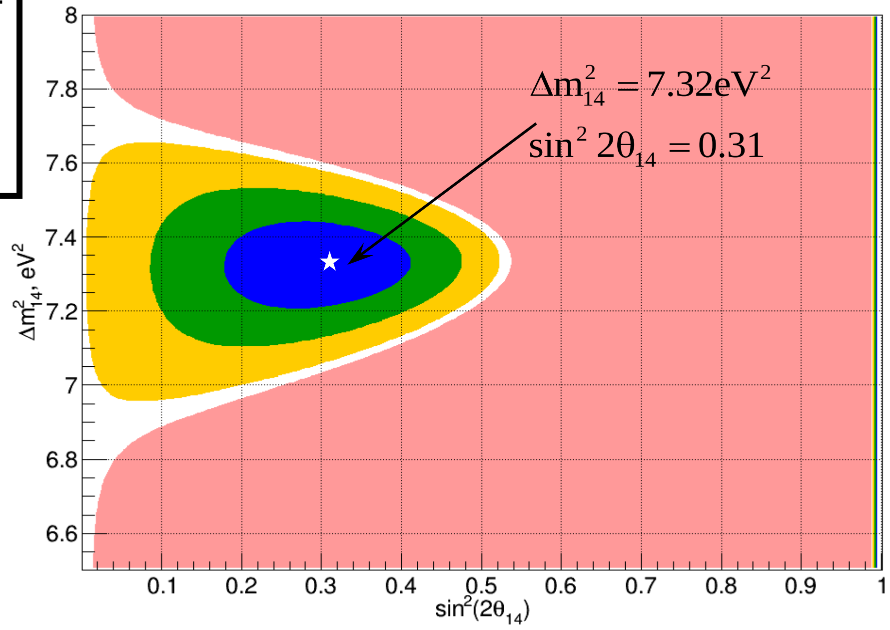
$$\sum_{i,k}[(R^{\exp}_{i,k}-R^{th}_{i,k})^2/(\Delta R^{\exp}_{i,k})^2]=\chi^2(\sin^2 2\theta_{14},\Delta m^2_{14})$$



$$\Delta m^2_{14}=7.32 eV^2$$
$$\sin^2 2\theta_{14}=0.31$$

$$\Delta m^2_{14}=1.08 eV^2$$
$$\sin^2 2\theta_{15}=0.17$$





Analysis of experimental data with two sterile neutrino

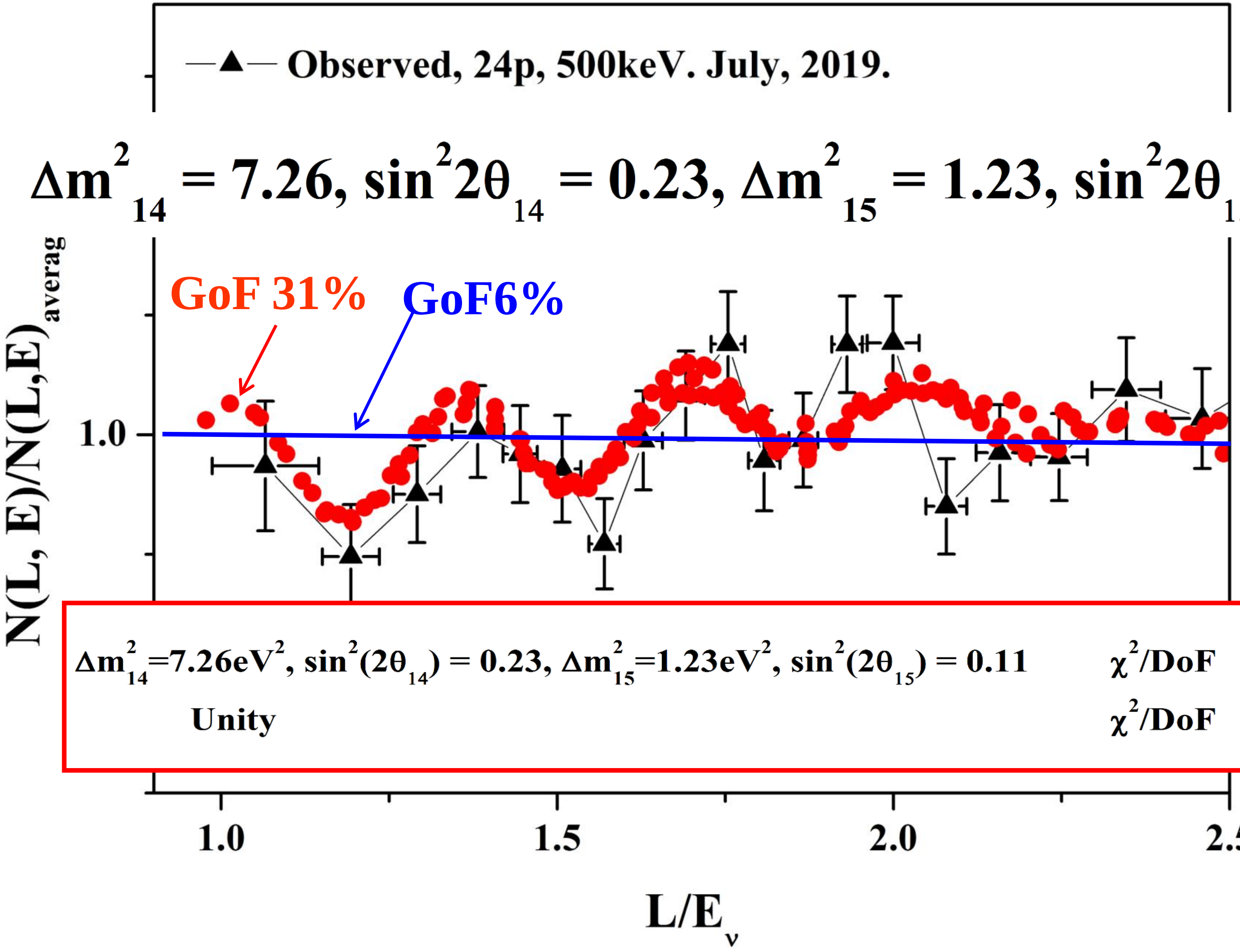
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{14} \sin^2 \frac{1.27\Delta m^2_{14}[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}$$

$$-\sin^2 2\theta_{15} \sin^2 \frac{1.27\Delta m^2_{15}[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}$$

$\boxed{\Delta m^2_{14} = 7.26,\ \sin^2 2\theta_{14} = 0.23,}$ $\boxed{\Delta m^2_{15} = 1.23,\ \sin^2 2\theta_{15} = 0.11}$

Analysis of experimental data with two sterile neutrino

$$\Delta m^2_{14} = 7.26,\ \sin^2 2\theta_{14} = 0.23,\ \Delta m^2_{15} = 1.23,\ \sin^2 2\theta_{15} = 0.11$$



Δm^2_{14}=7.26eV^2, $\sin^2(2\theta_{14})$ = 0.23, Δm^2_{15}=1.23eV^2, $\sin^2(2\theta_{15})$ = 0.11	χ^2/DoF	19.36/17	GoF	0.31
Unity	χ^2/DoF	29.13/19	GoF	0.06

V.Egorov DLNP JINR, Dubna
(on behalf of the DANSS collaboration)

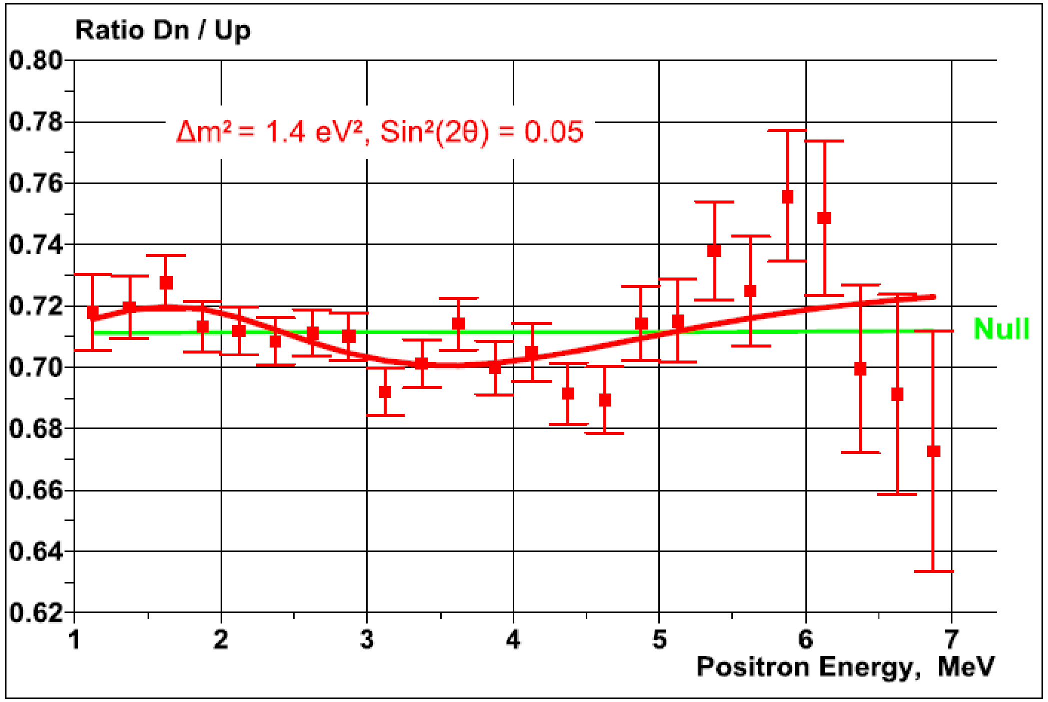
JINR Dubna

ITEP Moscow

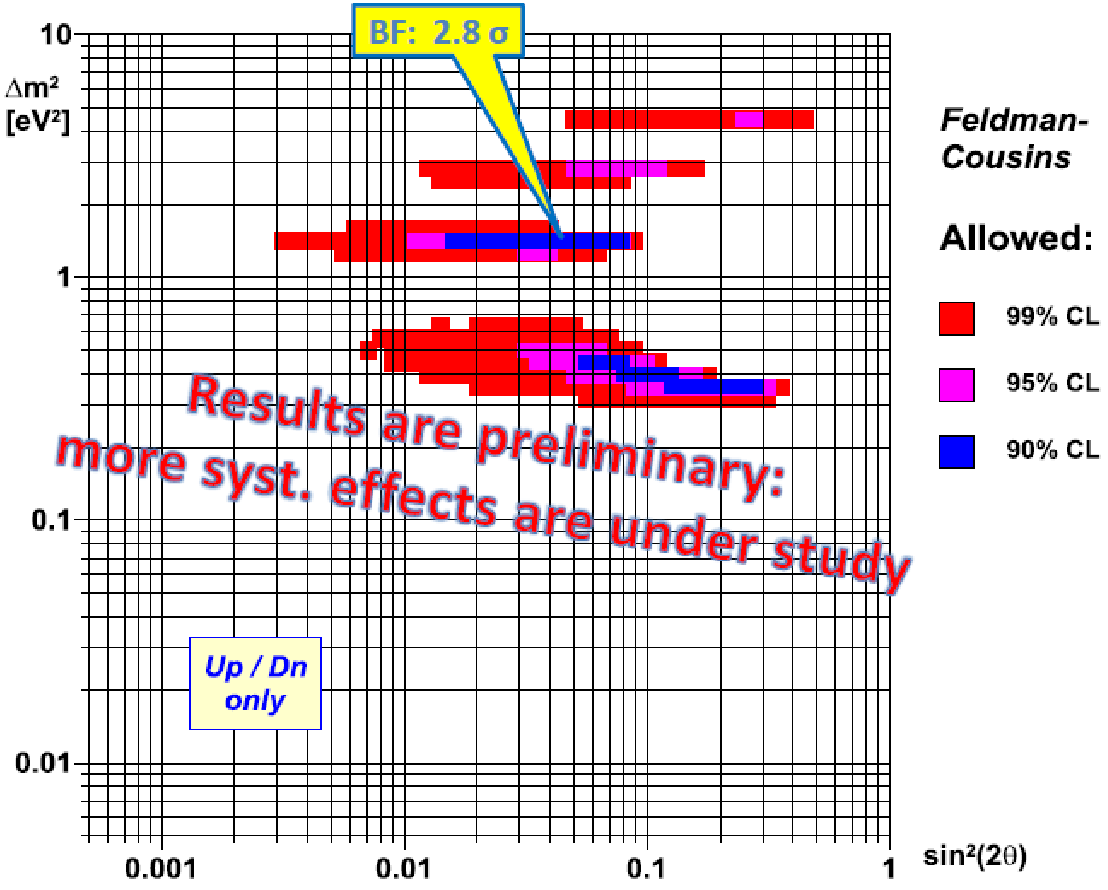
DANSS

Detector of the reactor AntiNeutrino based on Solid-state Scintillator

Best Fit: $\Delta m^2 = 1.4\ eV^2$, $Sin^2(2\theta) = 0.05$



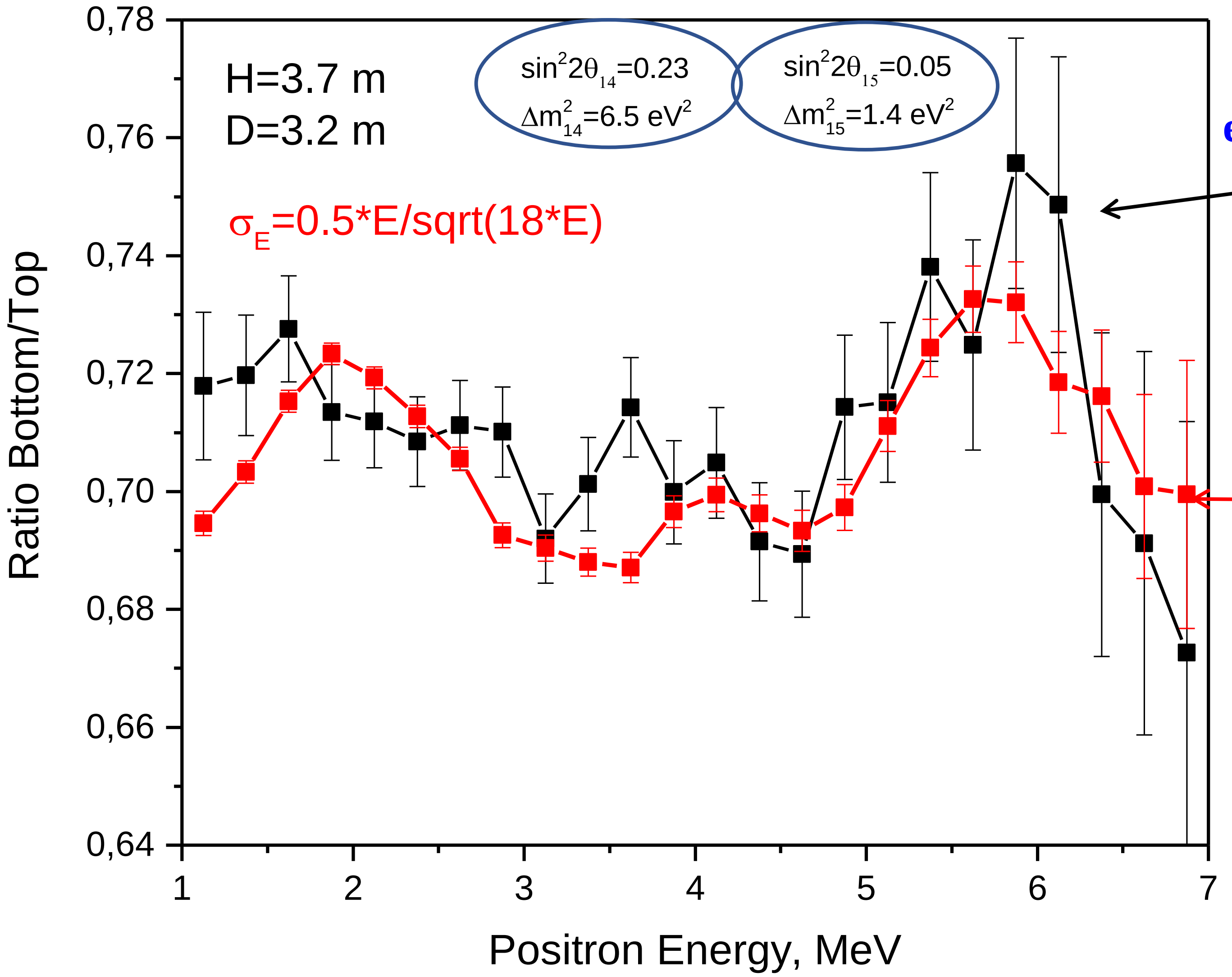
Significance of the best regions



MC simulation of experiment DANSS
and analysis of experimental data DANSS with two sterile neutrino

Possible confirmation of effect of anti-neutrino oscillations with

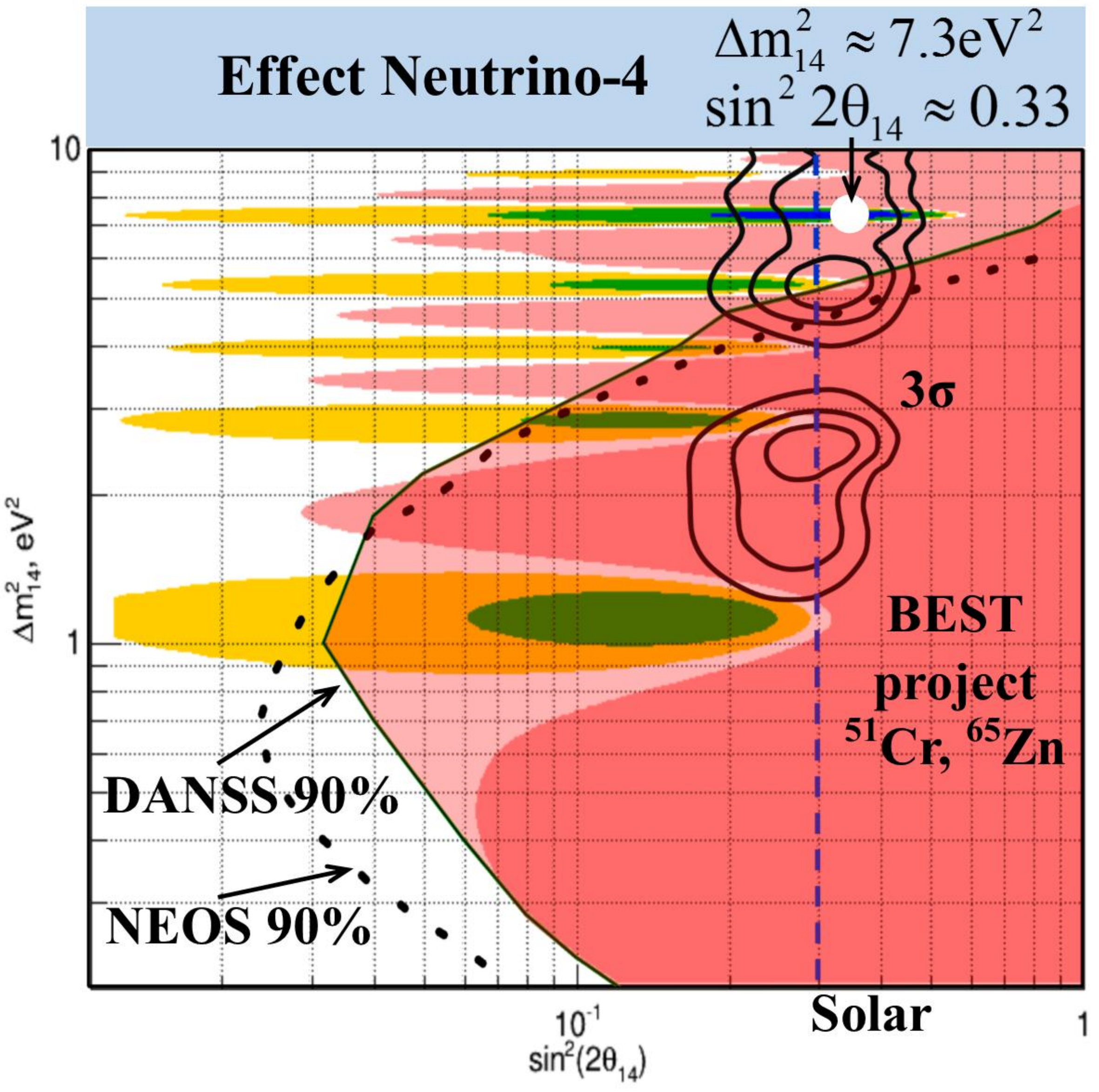
$$\Delta m_{14}^{2} \approx 7.3 эВ^{2}$$



experimental data DANSS

MC simulation of experimental data DANSS

BEST Experiment - Sensitivity Area



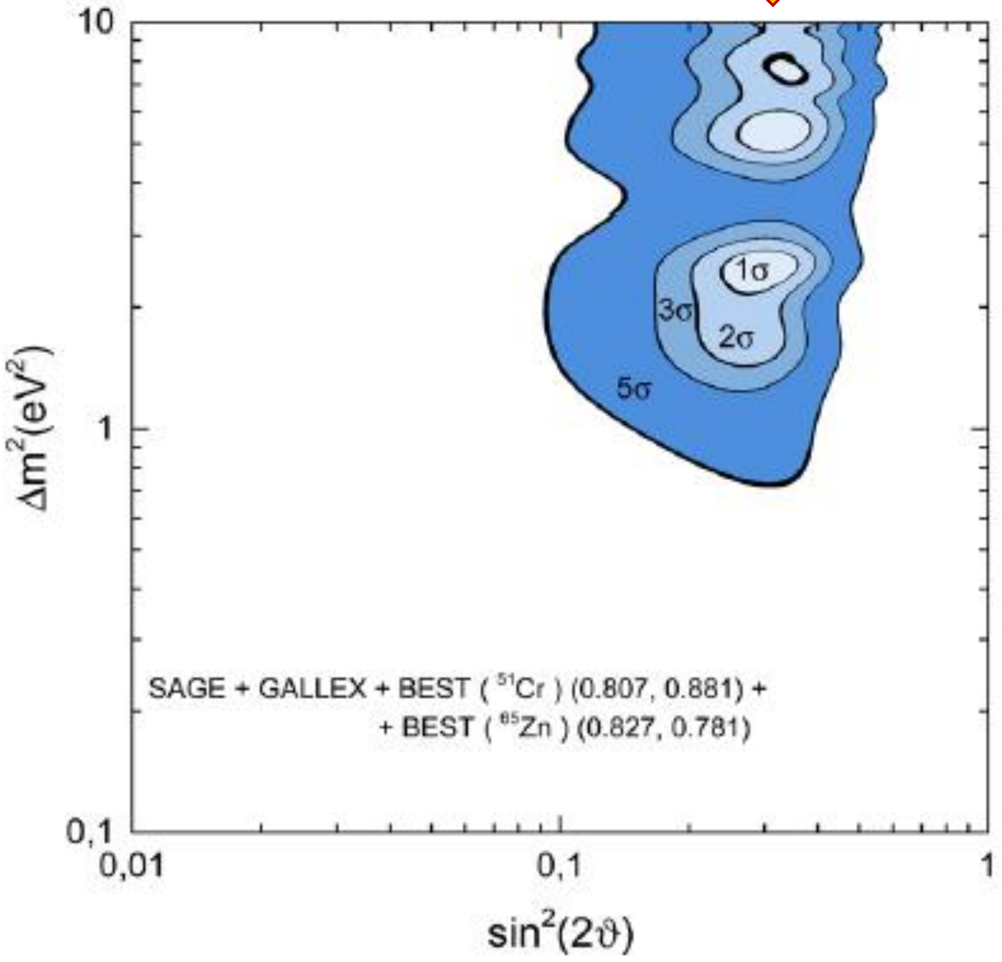
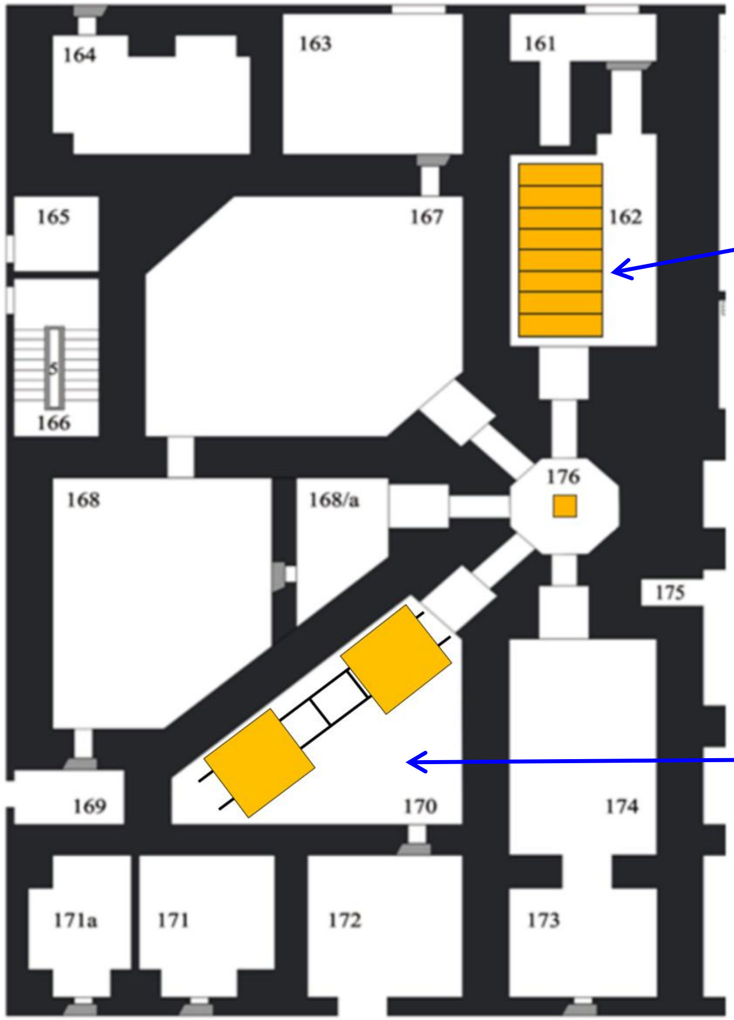


FIG. 7. Allowed regions of oscillation parameters, built on the basis of new data, in the case of combining the results of SAGE + GALLEX with the result of BEST for two sources (^{51}Cr and ^{65}Zn), which corresponds to the best fit point.

Future plans: Experiment Neutrino-6



Neutrino Laboratory No. 1

Neutrino Laboratory No. 2

Neutrino laboratory on the SM-3 reactor in room №170

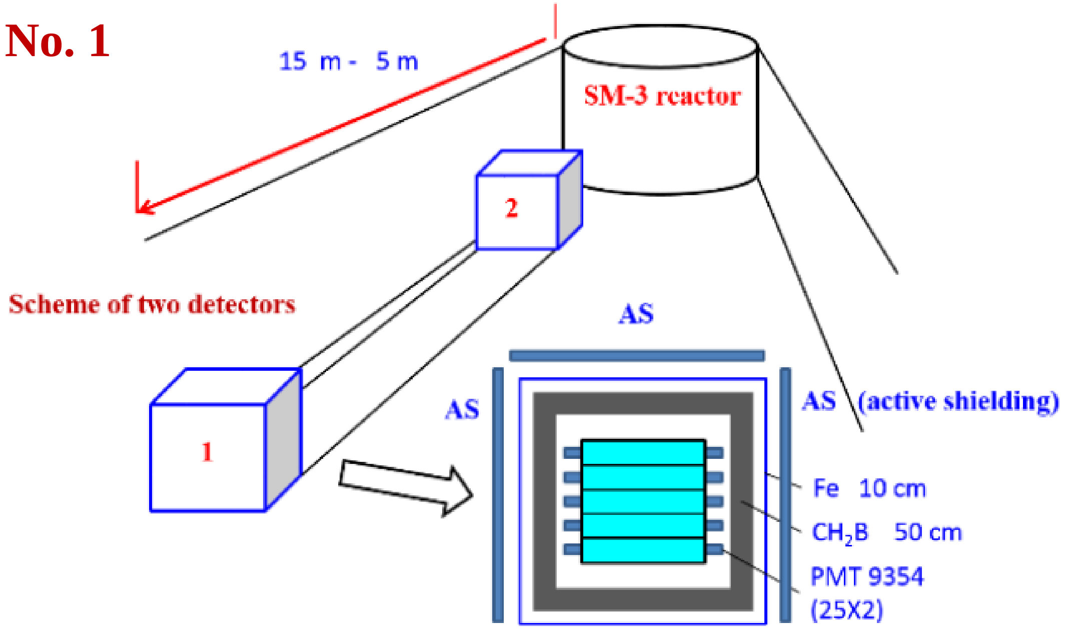
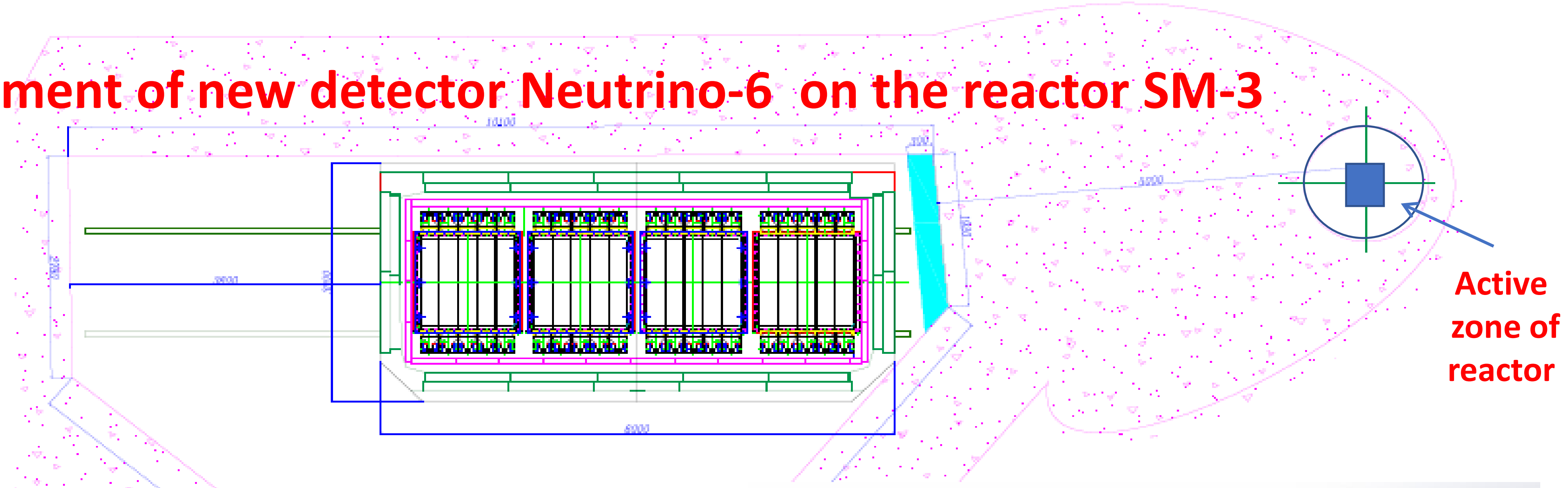
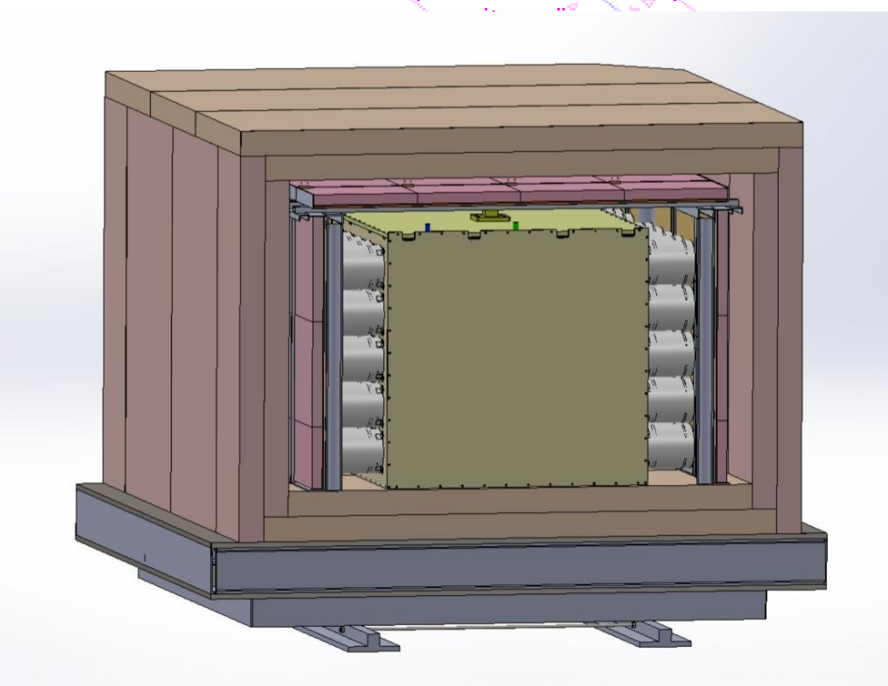
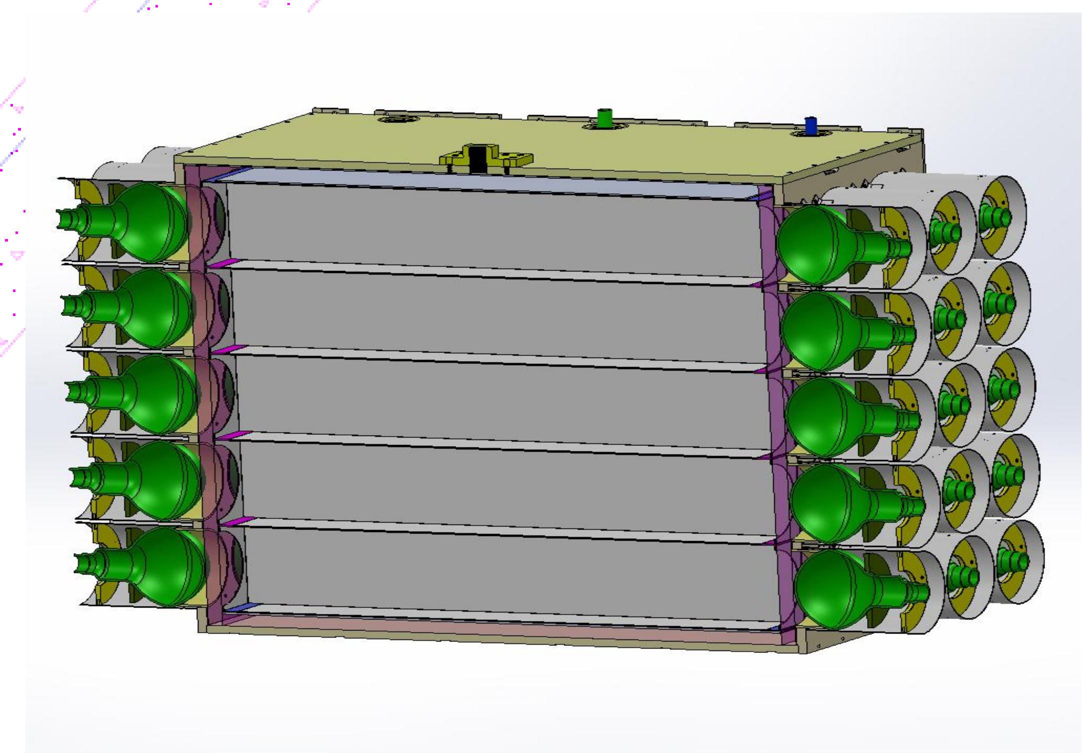


FIG. 22. Scheme of a new experiment on search for neutrino oscillations in room No. 170 of the SM-3 reactor.

Arrangement of new detector Neutrino-6 on the reactor SM-3





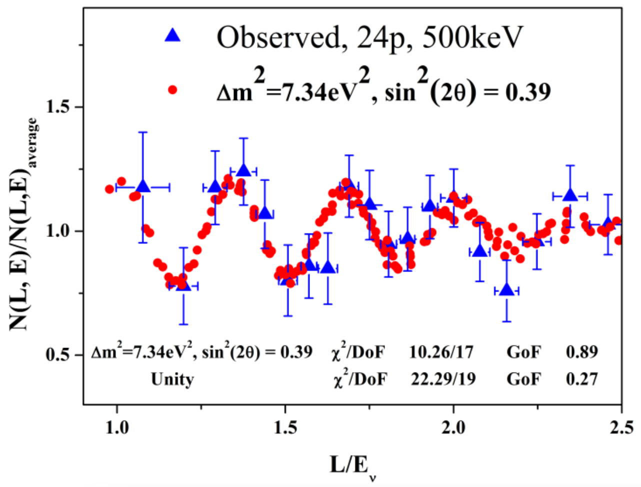


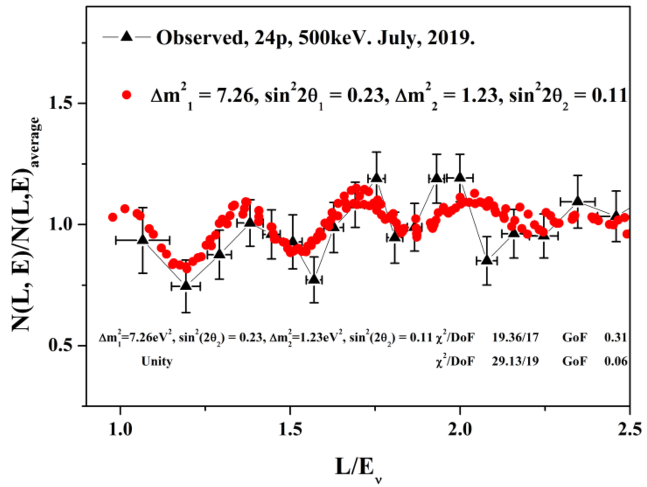
Expected increasing of accuracy for NEUTRINO-6 experiment

Method	Consequence	Increasing accuracy factor
4 detectors	3x larger volume	**1.6**
Gd concentration	4x less accidental background	**1.5**
PSD	4x less correlated background	**1.3**
Total		**3.1**

The project is planned to be implemented with participation of colleagues from DANSS and NEOS collaborations.

Thank you for attention

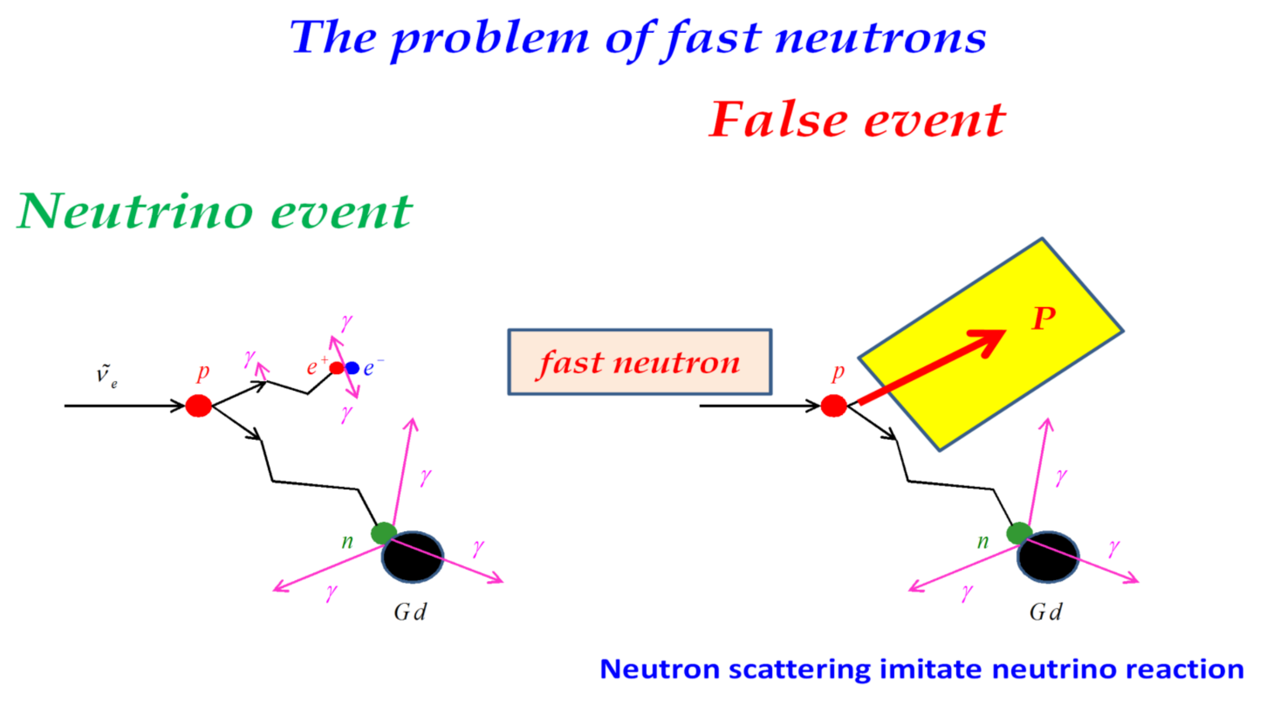




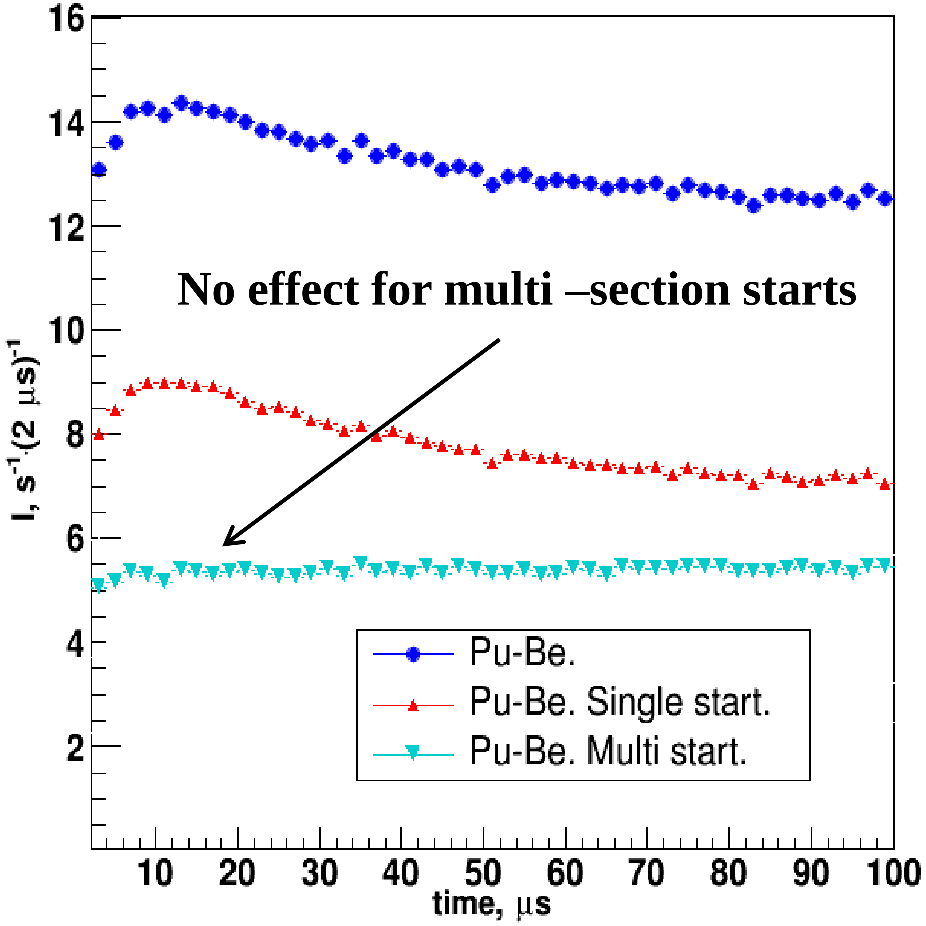
Best regards from Gatchina

Best regards from Dimitrovgrad

- **Sectioning of the detector**
- **Problem of fast neutrons**
- **Allocation of a neutrino signal**



The test with a source of fast neutrons



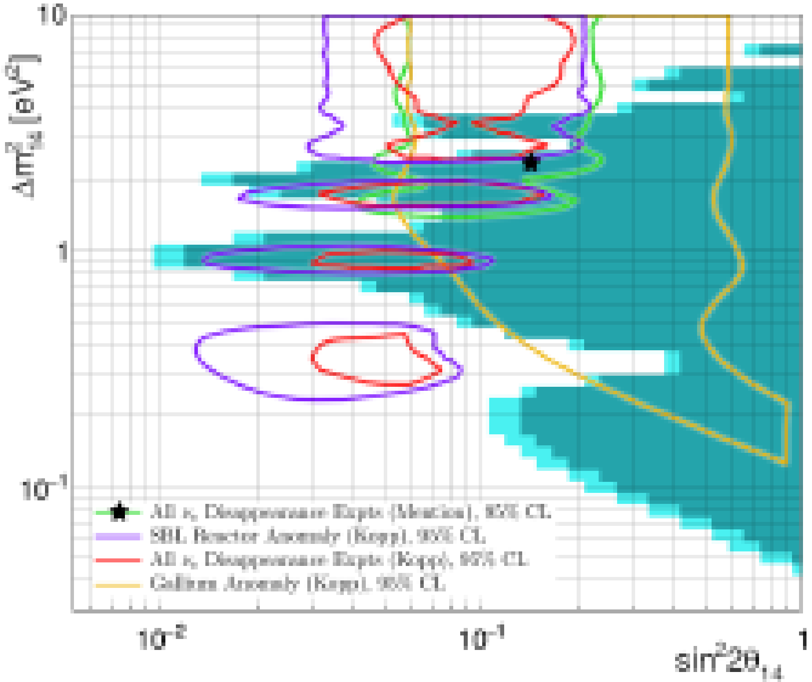
24 central and 16 side cells for full-scale detector

central cell	side cell	angular cell	in all cells
42%	29%	19%	37%

Calculated percentage of multi-start events

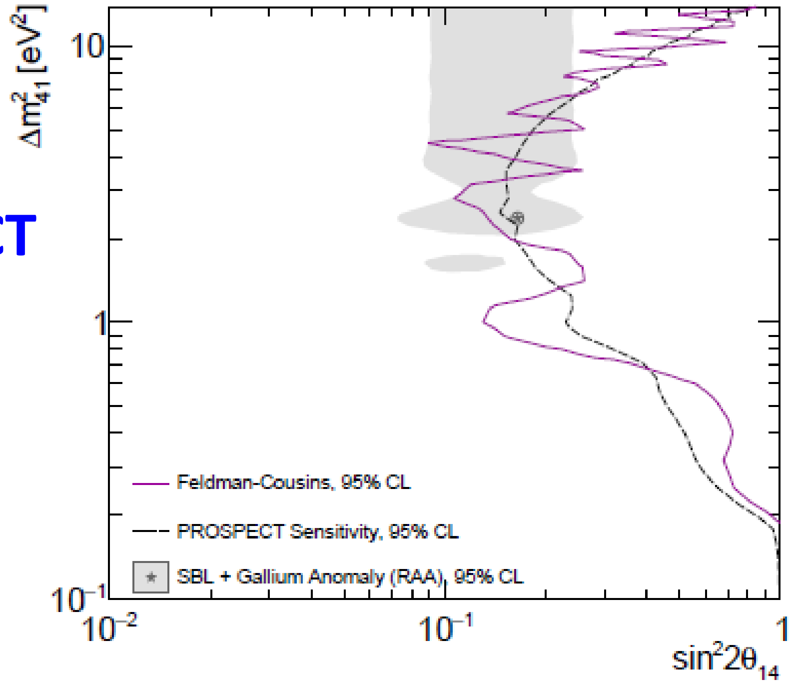
Experimental average percentage of multi-start events for full-scale detector

(37 ± 4)%

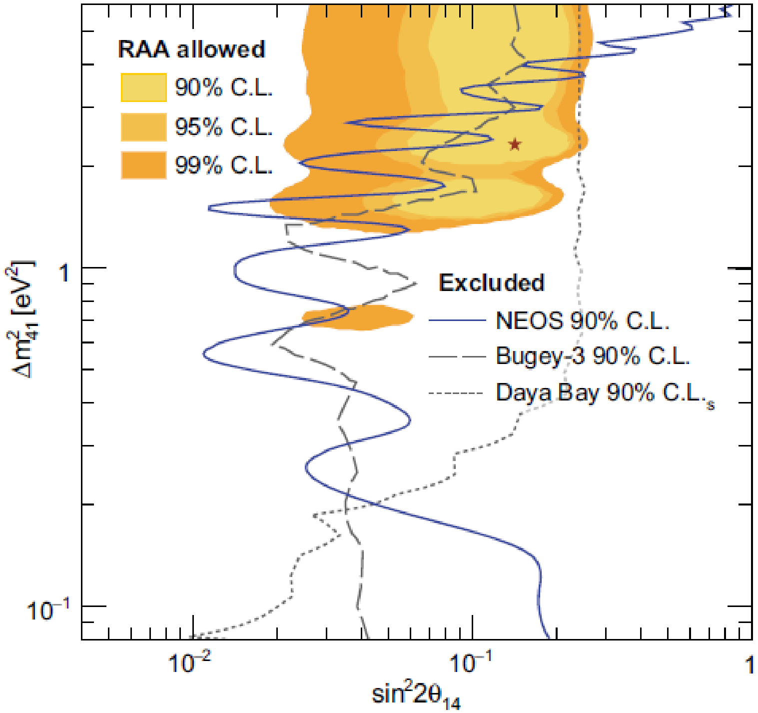


DANSS
90%

PROSPECT
95%

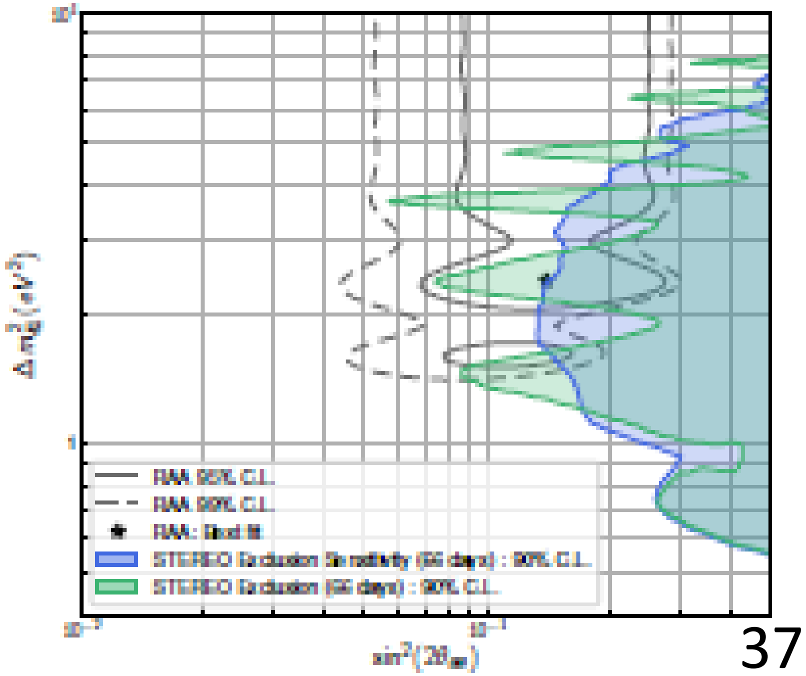


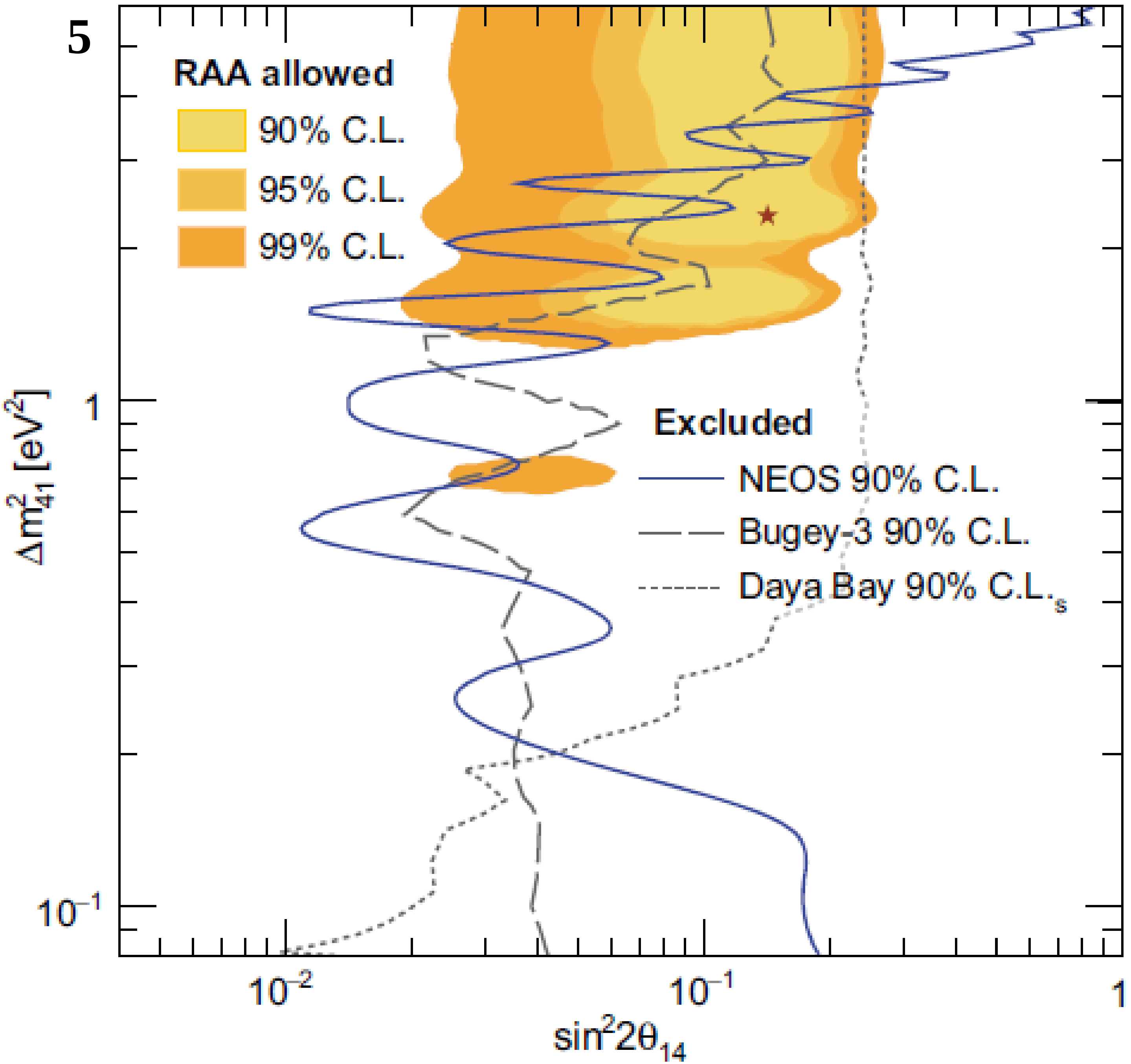
The slide illustrates sensitivity of other experiments: NEOS , DANSS , STEREO and PROSPECT



NEOS
90%

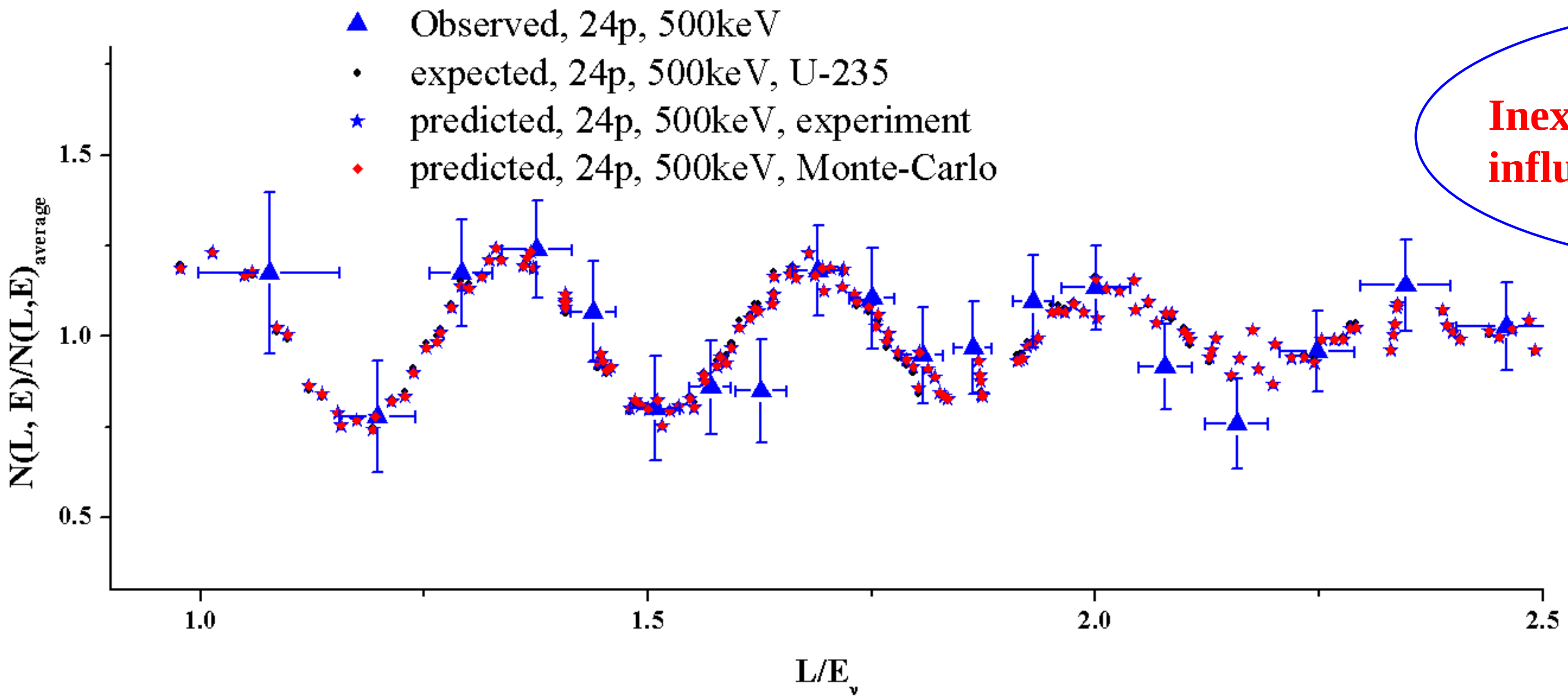
STEREO
90%




5
RAA allowed
90% C.L.
95% C.L.
99% C.L.
Excluded
NEOS 90% C.L.
Bugey-3 90% C.L.
Daya Bay 90% C.L.s
Δm^2_{41} [eV^2]
1
10^{-1}
10^{-2}
10^{-1}
1
$\sin^2 2\theta_{14}$

Independence of identification of effect of oscillations of a form of a neutrino spectrum

3 different ranges were chosen : 1) U-235, 2) Expetiment, 3) Monte-Carlo



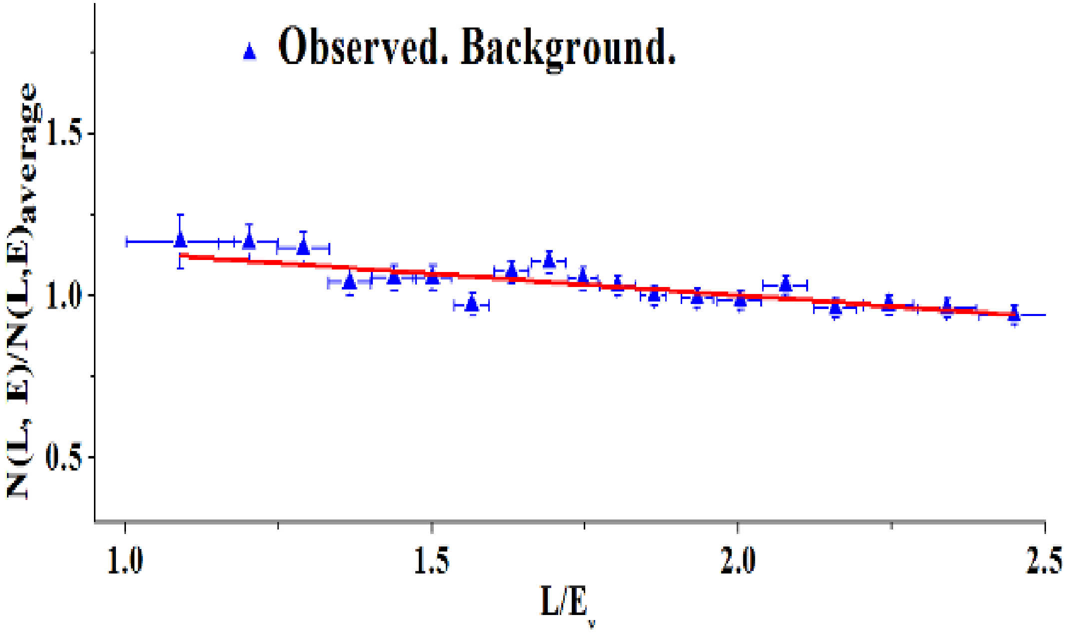
Inexact measurement of energy influences to definition of: Δm^2_{14}

Apparently there is no difference. It also should not be because spectra are strictly canceled in formula (2)

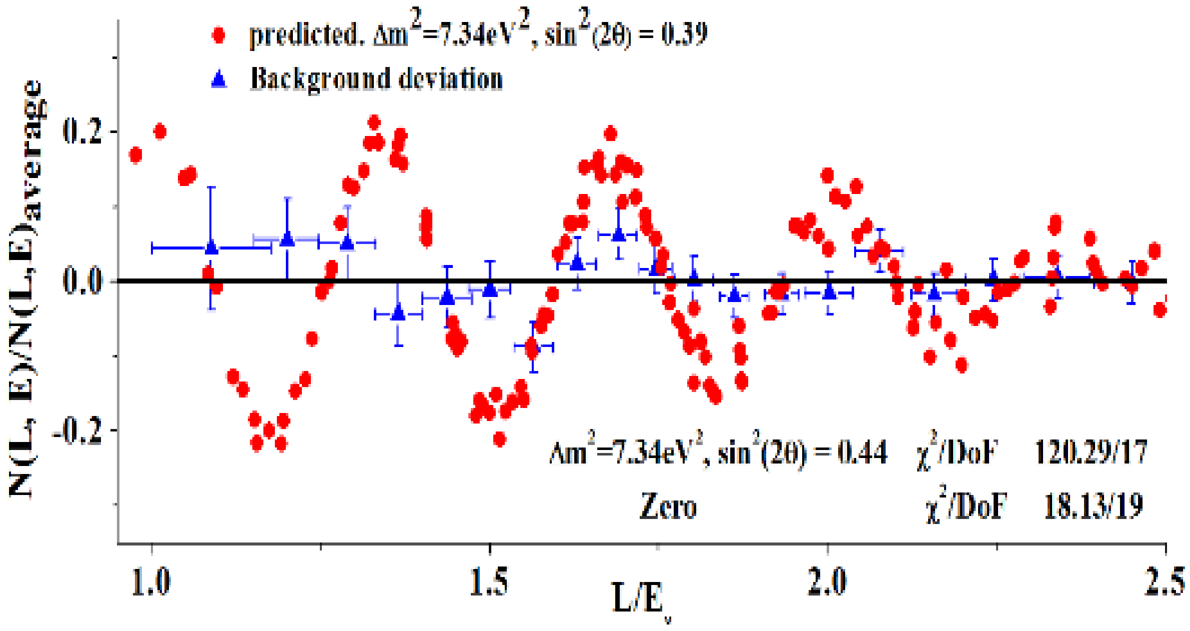
$$R^{\exp}_{i,k} = \frac{N(E_i, L_k) L_k^2}{K^{-1}\sum_k^K N(E_i, L_k) L_k^2} = \frac{[1-\sin^2 2\theta_{14} \sin^2(1.27\Delta m^2_{14} L_k / E_i)]}{K^{-1}\sum_k^K [1-\sin^2 2\theta_{14} \sin^2(1.27\Delta m^2_{14} L_k / E_i)]} = R^{th}_{i,k} \qquad (2)$$

Test of systematic effects

To carry out analysis of possible systematic effects one should turn off antineutrino flux (reactor) and perform the same analysis of obtained data



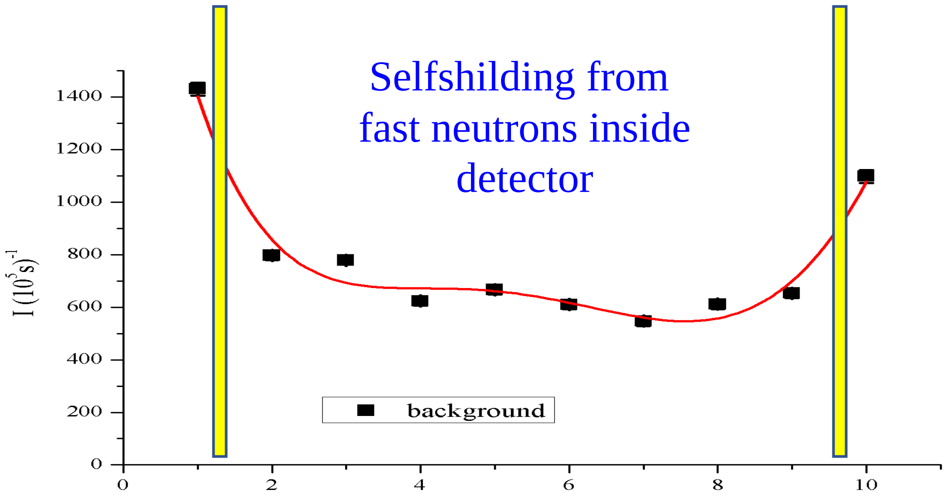
data analysis using coherent summation method

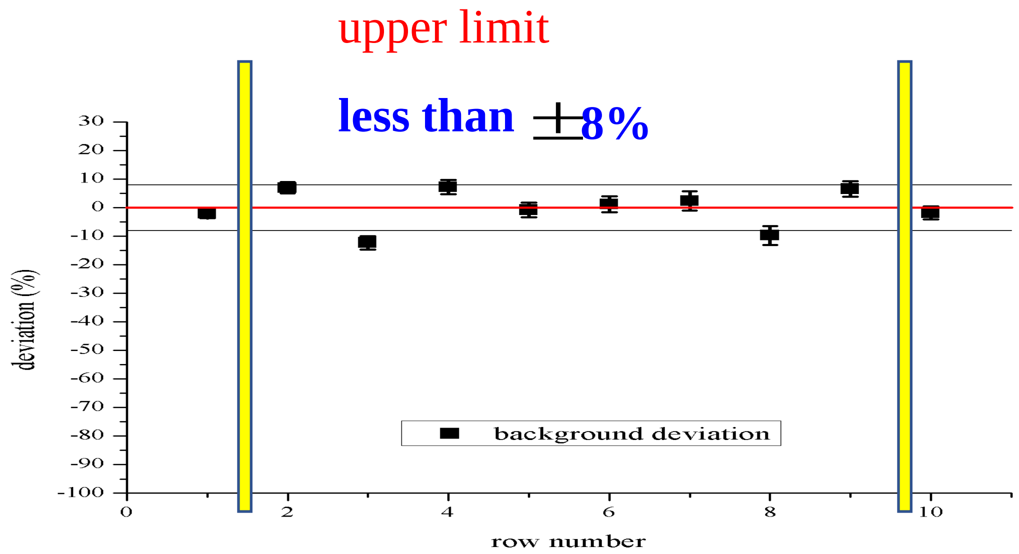


analysis of the results on oscillation parameters plane

Thus no instrumental systematic errors were observed.

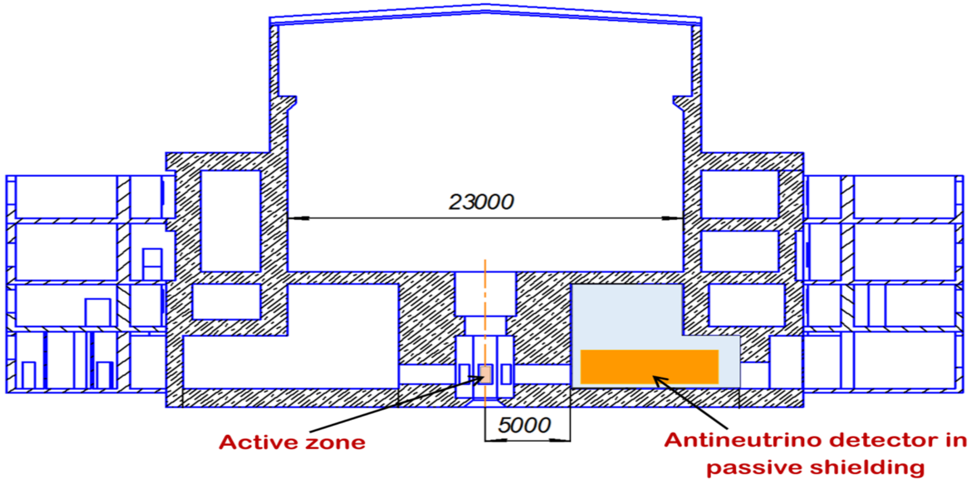
Analysis of possible difference in efficiency of rows of the detector, using the background of fast neutrons which is given rise into the building from cosmic muons.

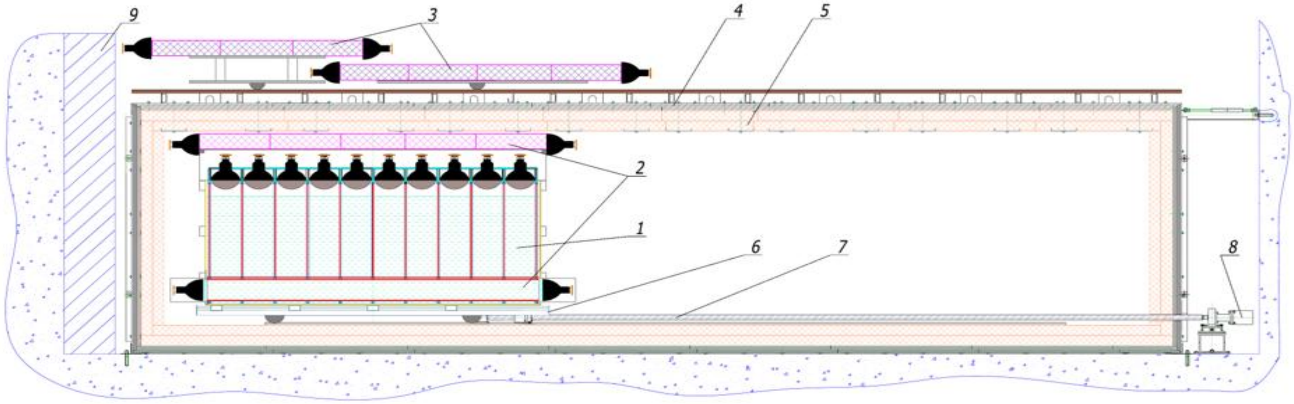




The background of fast neutrons is asymmetric because of structure of the building.

The dispersion on a background when moving the detector is within the same 8%.





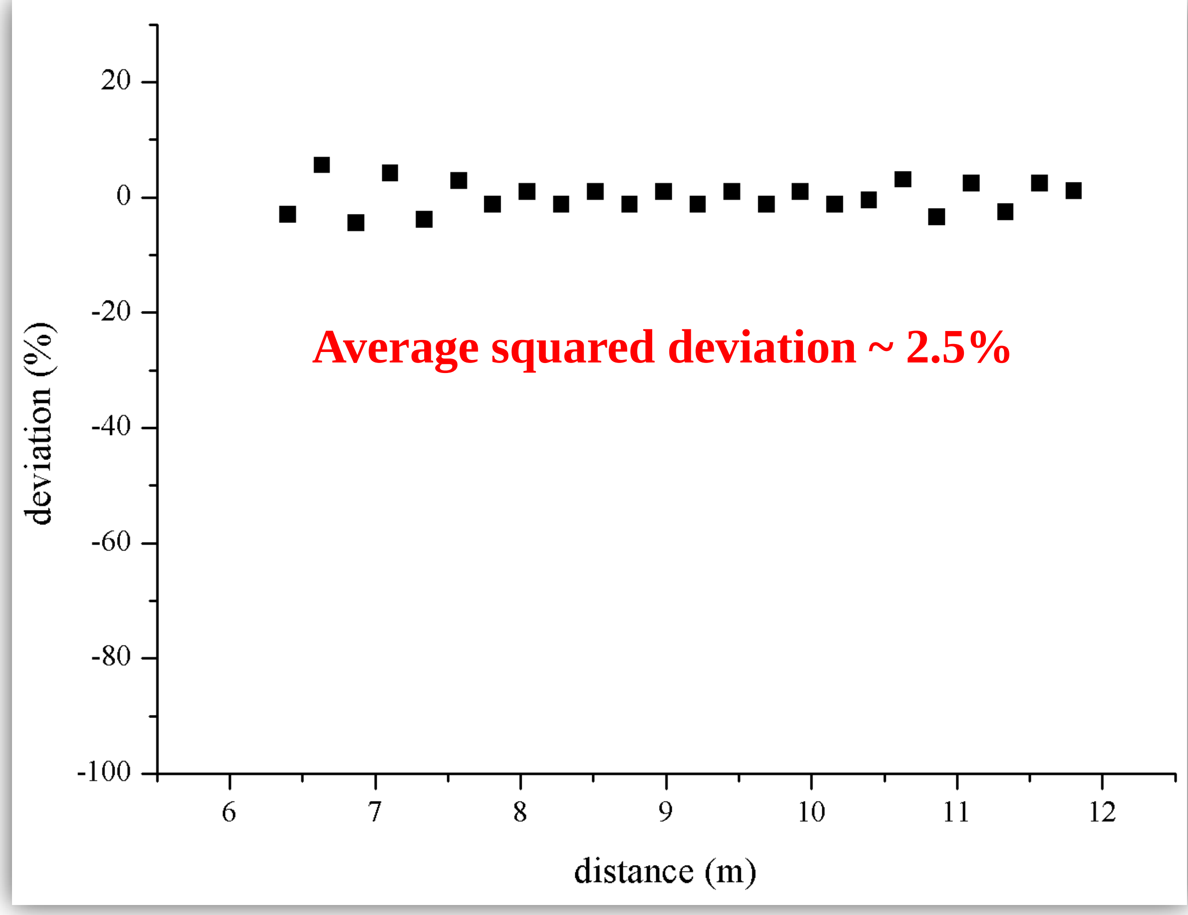
We use only 8 internal rows, the first and tenth are protective.

Averaging of detector rows efficiencies due to movements (above estimation)

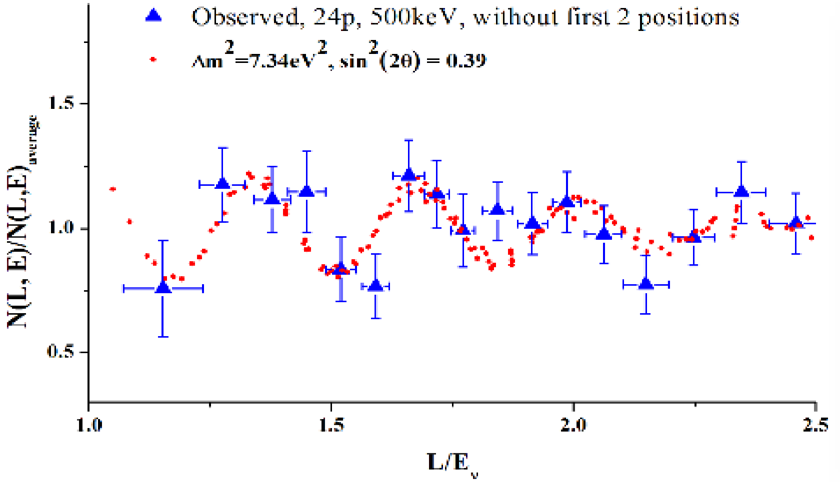
L(m) **Numbers of detector row**

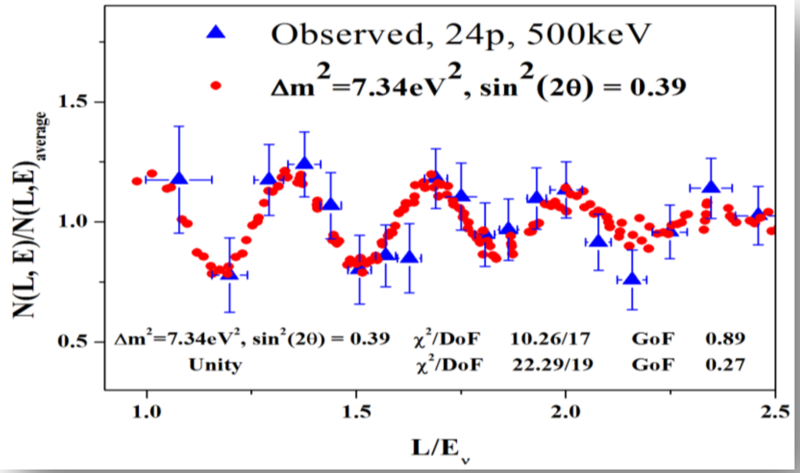
L(m)					
6.4025	2				
6.6375	3				
6.8725	4	2			
7.1075	5	3			
7.3425	6	2	4		
7.5775	7	3	5		
7.8125	8	4	6	2	
8.0475	9	5	7	3	
8.2825	6	2	8	4	
8.5175	7	3	9	5	
8.7525	8	4	6	2	
8.9875	9	5	7	3	
9.2225	6	2	8	4	
9.4575	7	3	9	5	
9.6925	8	4	6	2	
9.9275	9	5	7	3	
10.1625	6	2	8	4	
10.3975	7	3	9	5	2
10.6325	8	4	6	3	
10.8675	9	5	7	4	
11.1025	6	8	5		
11.3375	7	9	6		
11.5725	8	7			
11.8075	9	8			

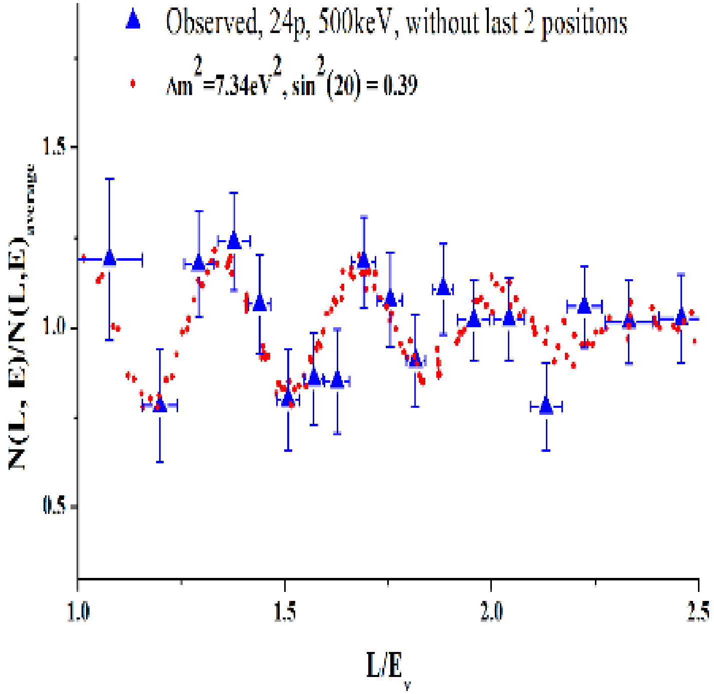
Average efficiency at various distances

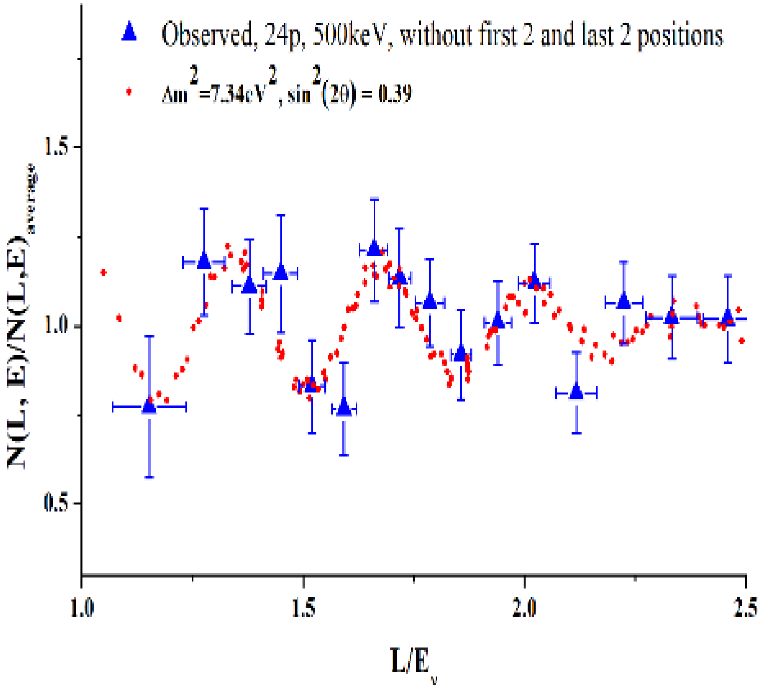


Test of stability of the effect by means of removal of extreme positions







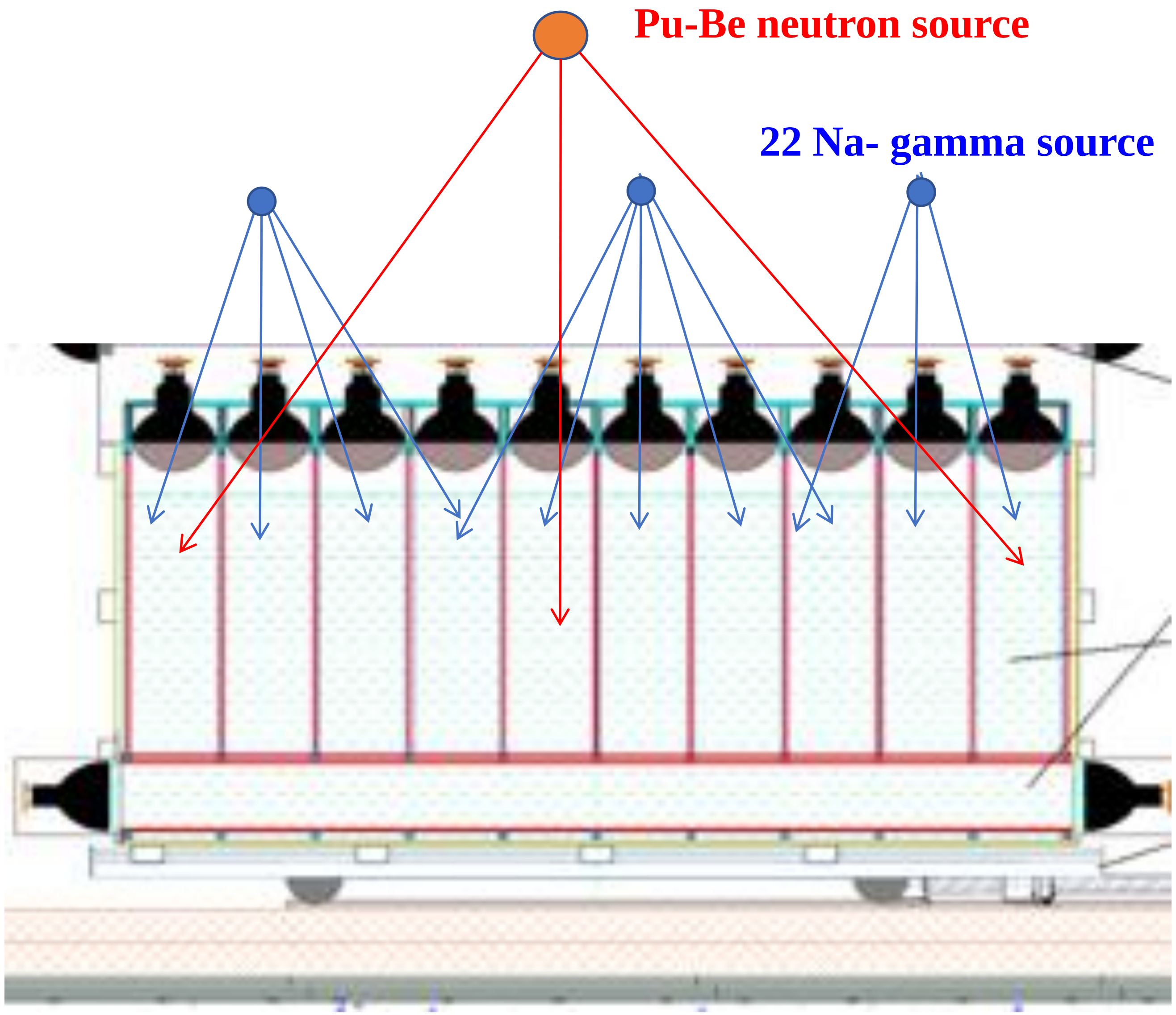


Conclusion

There is no reason to consider that the effect can be caused by structure of the detector. The possibility of averaging of efficiency of various sections by placing them at the same distance is the advantage of our experiment.

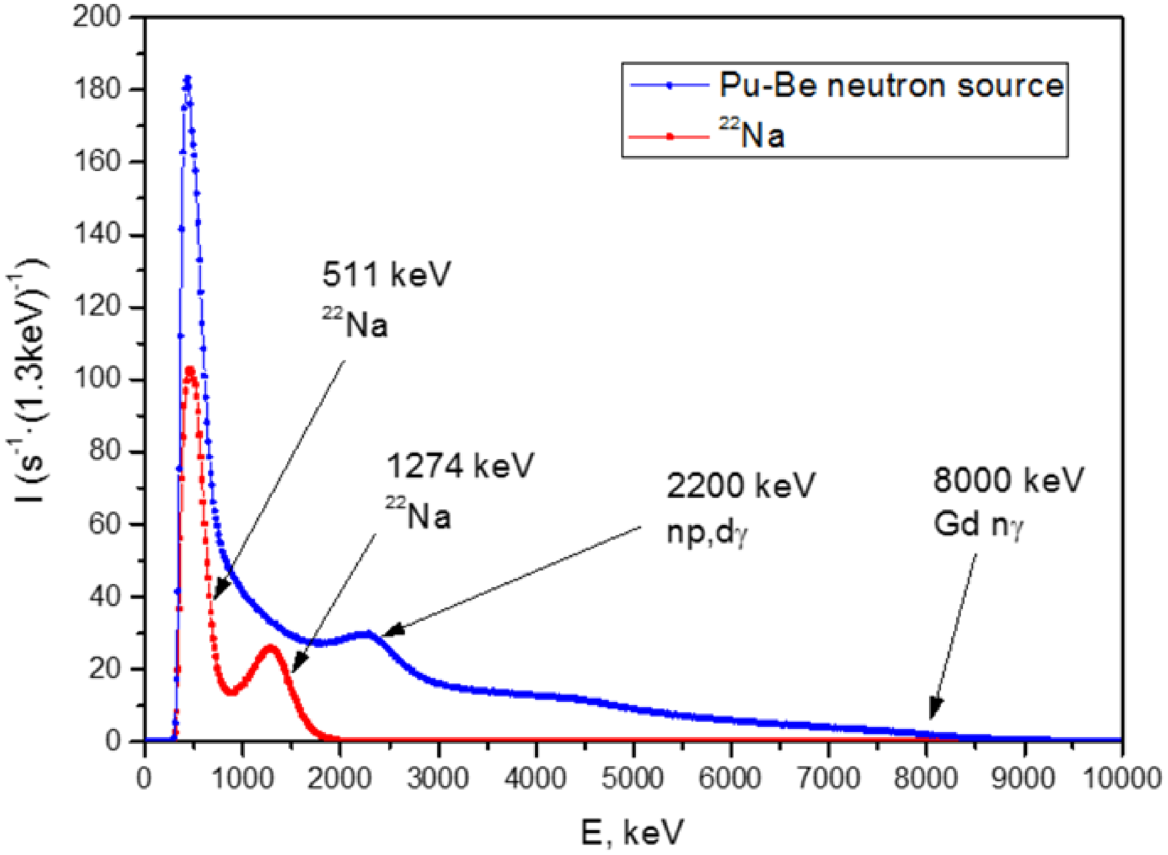
Energy calibration of the full-scale detector

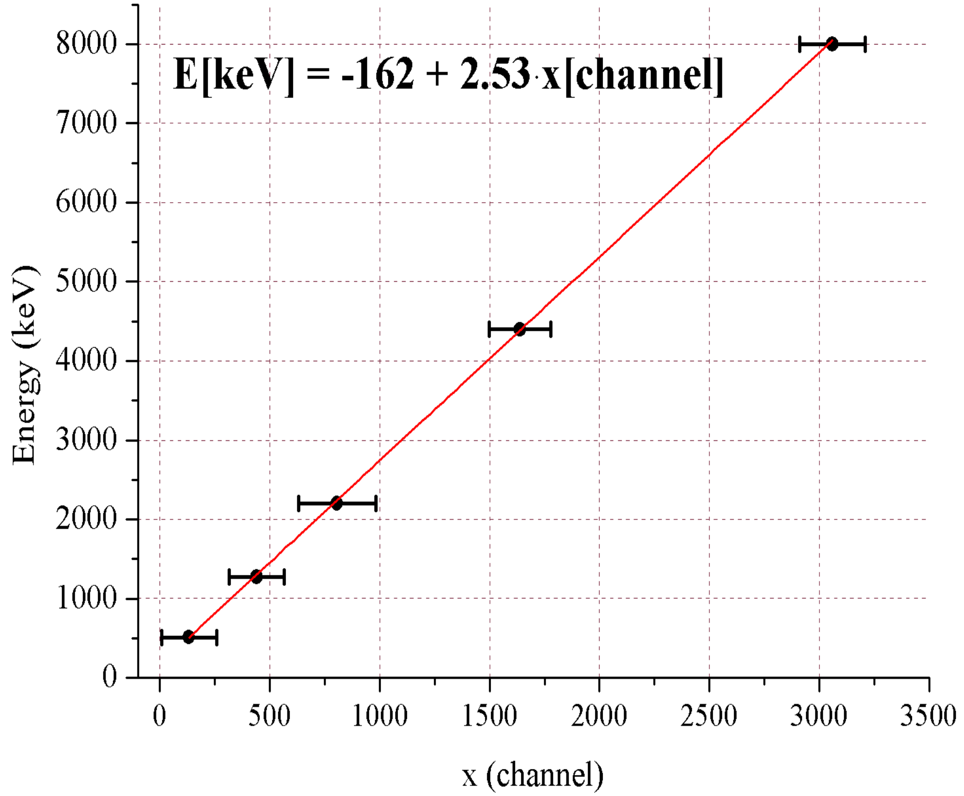
The source 22Na is installed above the detector at distance about 0.8 meters and irradiate about 16 sections at once. PMTs were normalized to one energy scale by selecting voltage on them. Simultaneous calibration of several sections is required. For all detector only 6 positions of the source were used.
Overlapping of the irradiated sections unifies the calibration.



The neutron Pu-Be source irradiated all sections at once. This method has advantage relatively to using of internal sources. The difficulty of calibration at energy 8MeV is that quanta from neutron capture by gadolinium can't be absorbed in the same row. Therefore the detector calibration should be conducted on a diffuse edge of spectrum.

Energy calibration of the full-scale detector





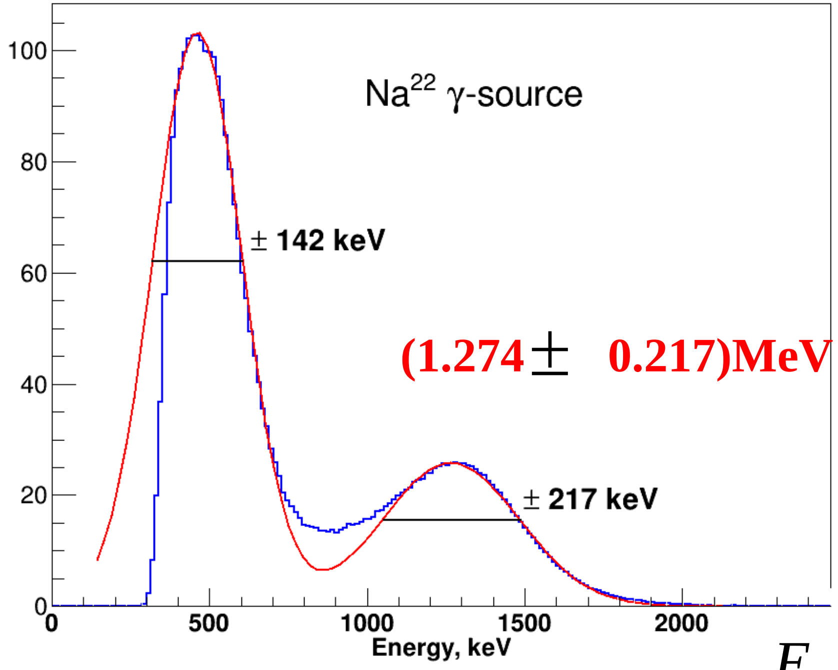
In the left - ranges of sources. In the right - the calibration of gamma quanta scale.
Registration of positrons includes inevitable loss of a part of energy of 511keV gamma-quanta. Because of the threshold of registration in the adjacent section we have to increase errors up to **±250 keV**.

It is the calibration which needs to be used at data processing.

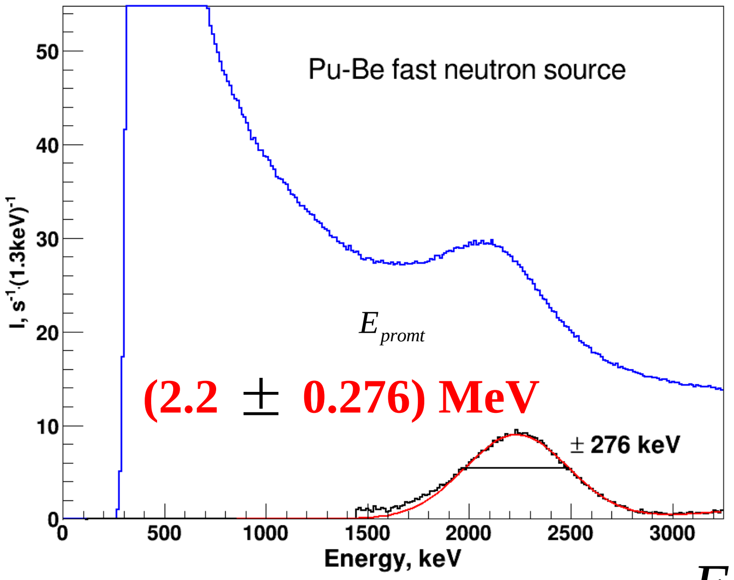
Energy calibration of the full-scale detector

$$E_\nu = E_{promt} + 0.8MeV$$

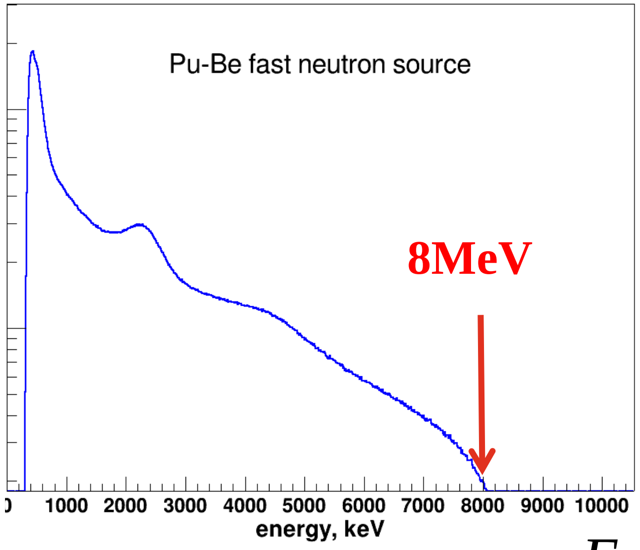
(0.511± 0.142) MeV



E_{promt}



E_{promt}



E_{promt}

$$\Delta E_\nu / E_\nu(2MeV) = 21\%$$

$$\Delta E_\nu / E_\nu(3MeV) = 18\%$$

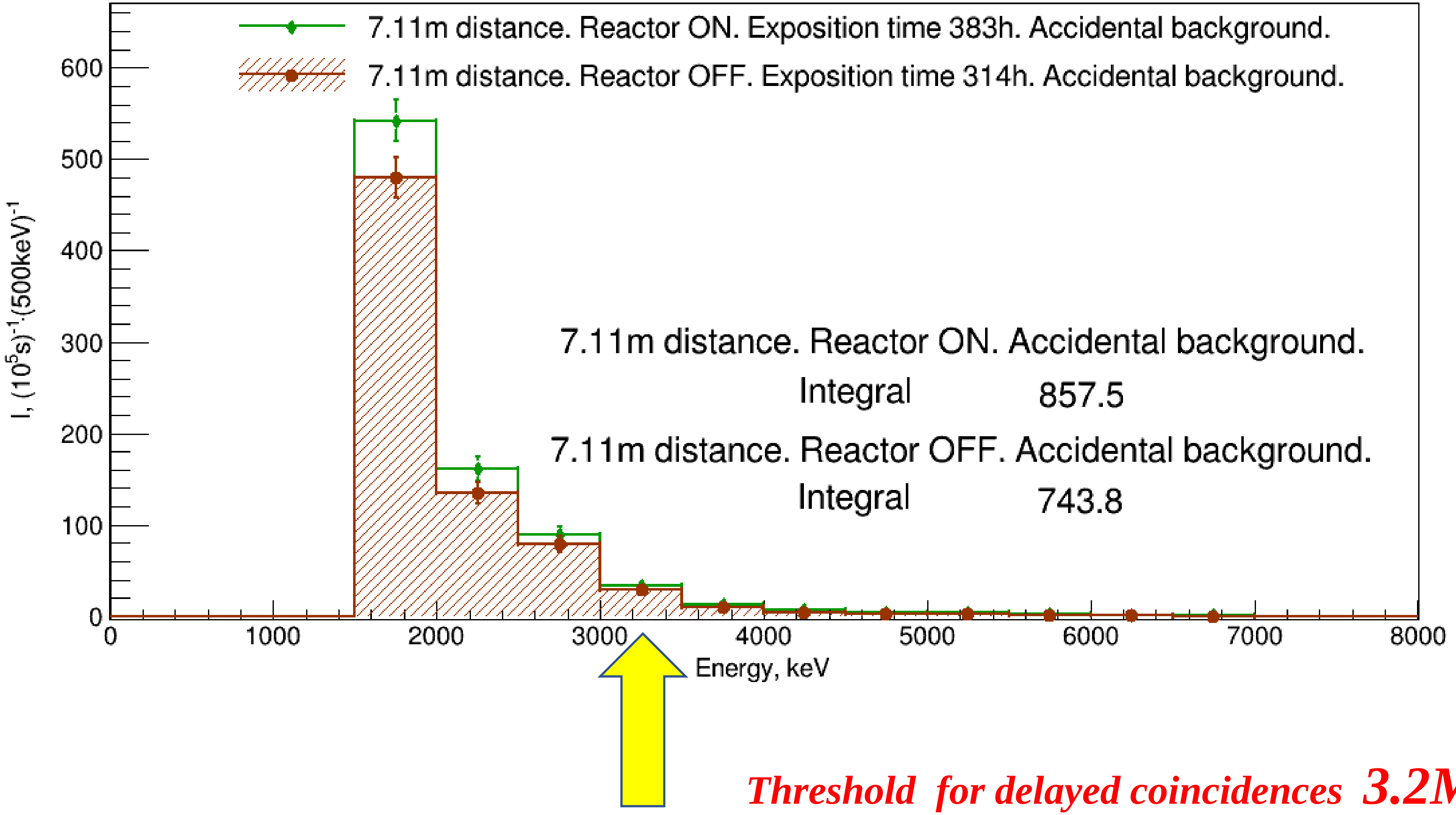
$$\Delta E_\nu / E_\nu(6MeV) = 14\%$$

$$\Delta E_\nu(2MeV) = 440keV$$

$$\boxed{\Delta E_\nu(3MeV) = 550keV}$$

$$\Delta E_\nu(6MeV) = 830keV$$

Accidental background practically does not depend on reactor, but it is rather big at low energies.



Threshold for delayed coincidences ***3.2MeV***