The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino

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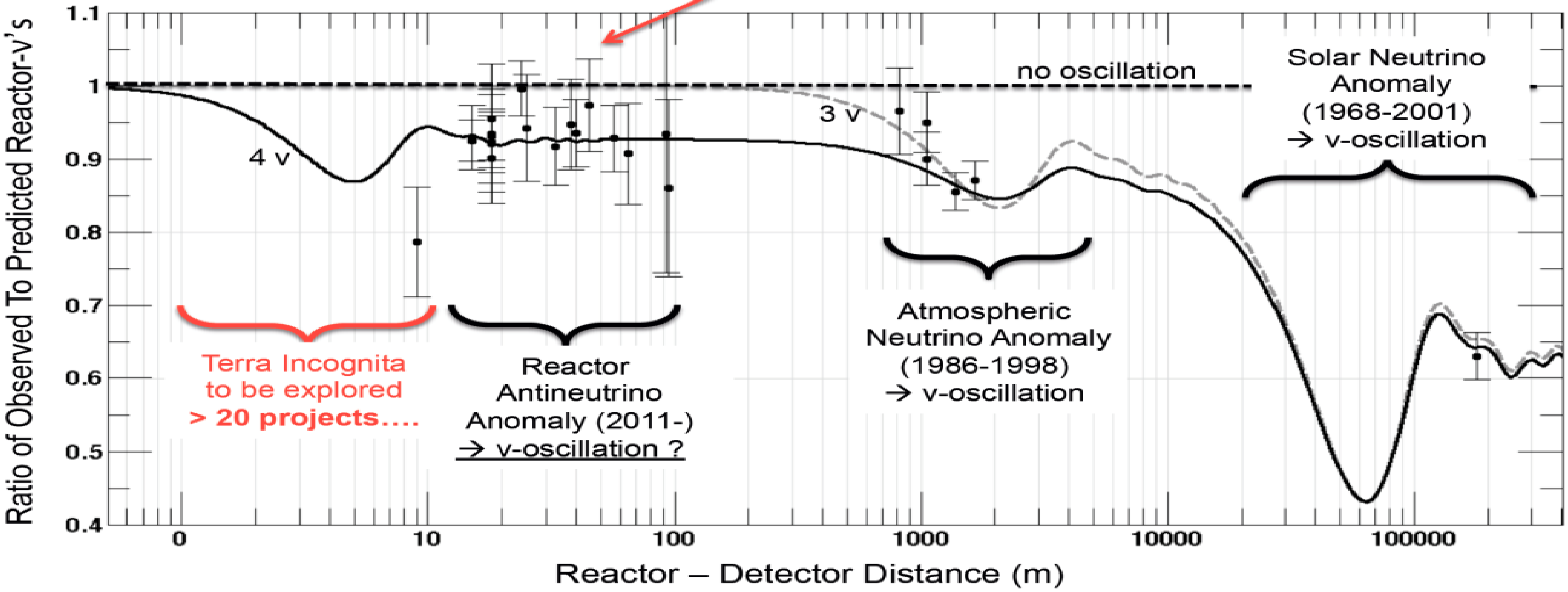
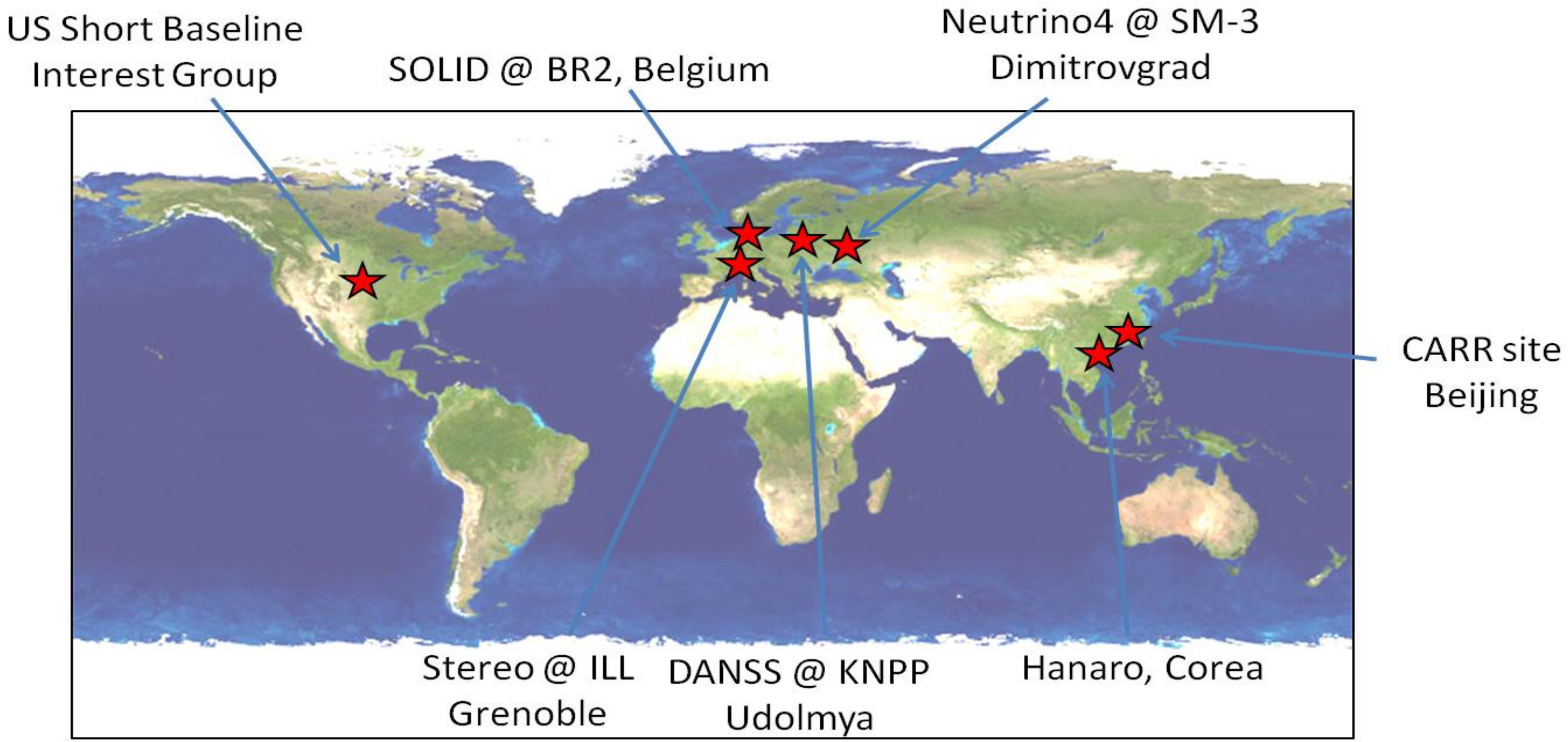
Reactor antineutrino anomaly

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



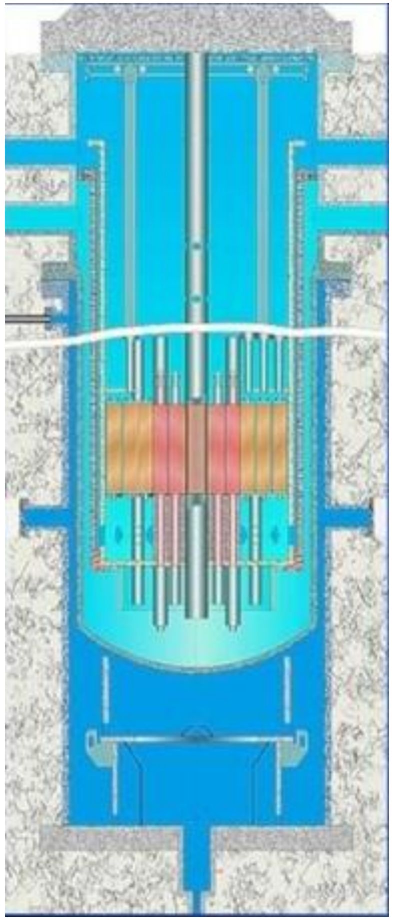
$$P(\tilde{\nu}_e \rightarrow \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \ \sin^2\left(1.27 \frac{\Delta m^2_{14}[eV^2]L[m]}{E_{\tilde{\nu}}[MeV]}\right)$$

New Short Baseline Reactor Experiments

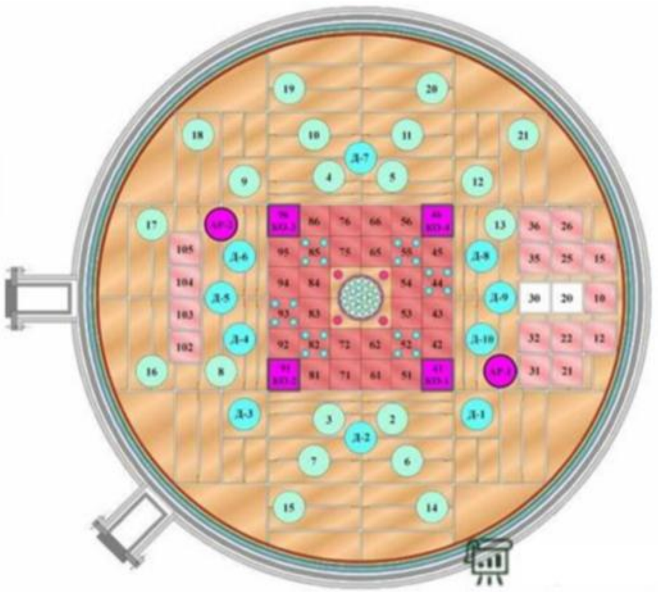


SM-3 research reactor

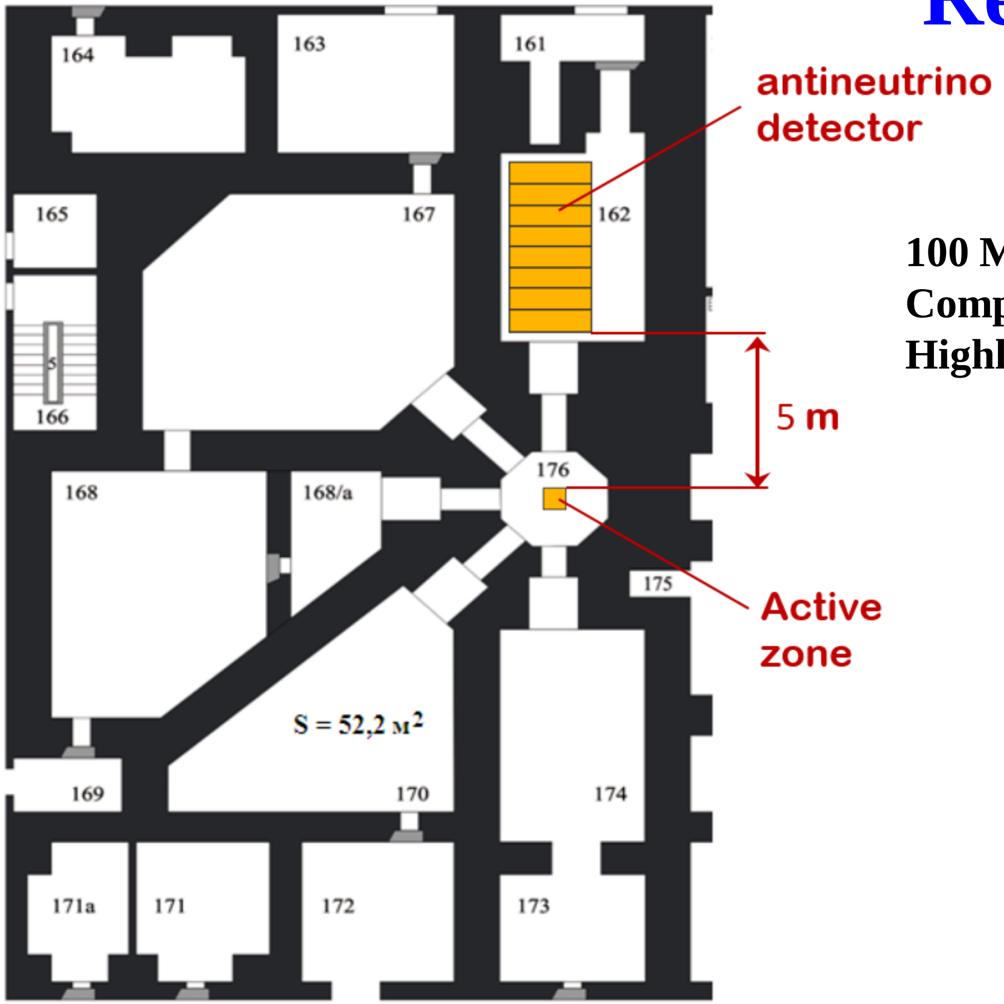
- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched ^{235}U fuel
- Separated rooms for experimental setup
- The laboratory is poorly protected from cosmic rays



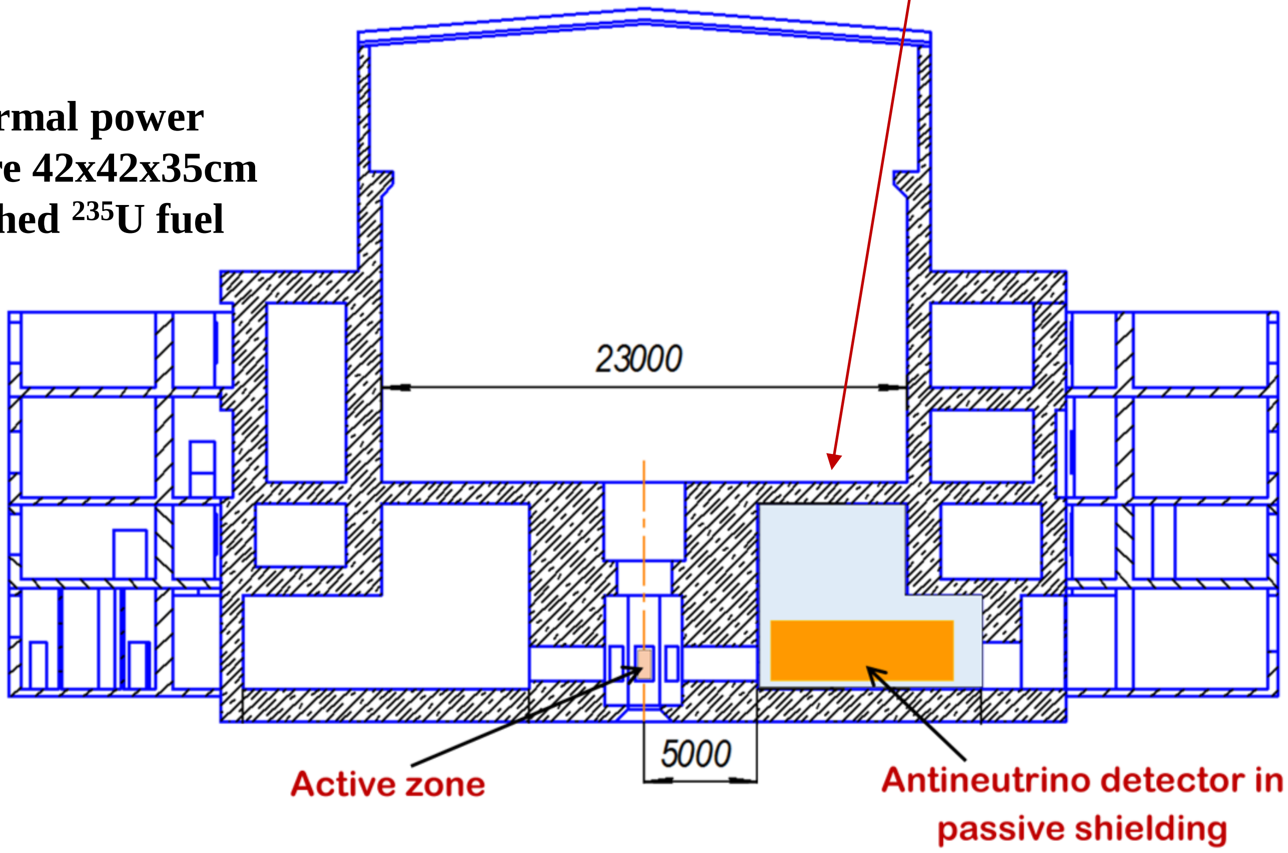
Vertical and horizontal sections of SM-3 reactor



Reactor SM-3



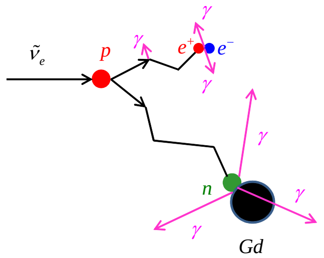
100 MW thermal power
Compact core 42x42x35cm
Highly enriched ^{235}U fuel

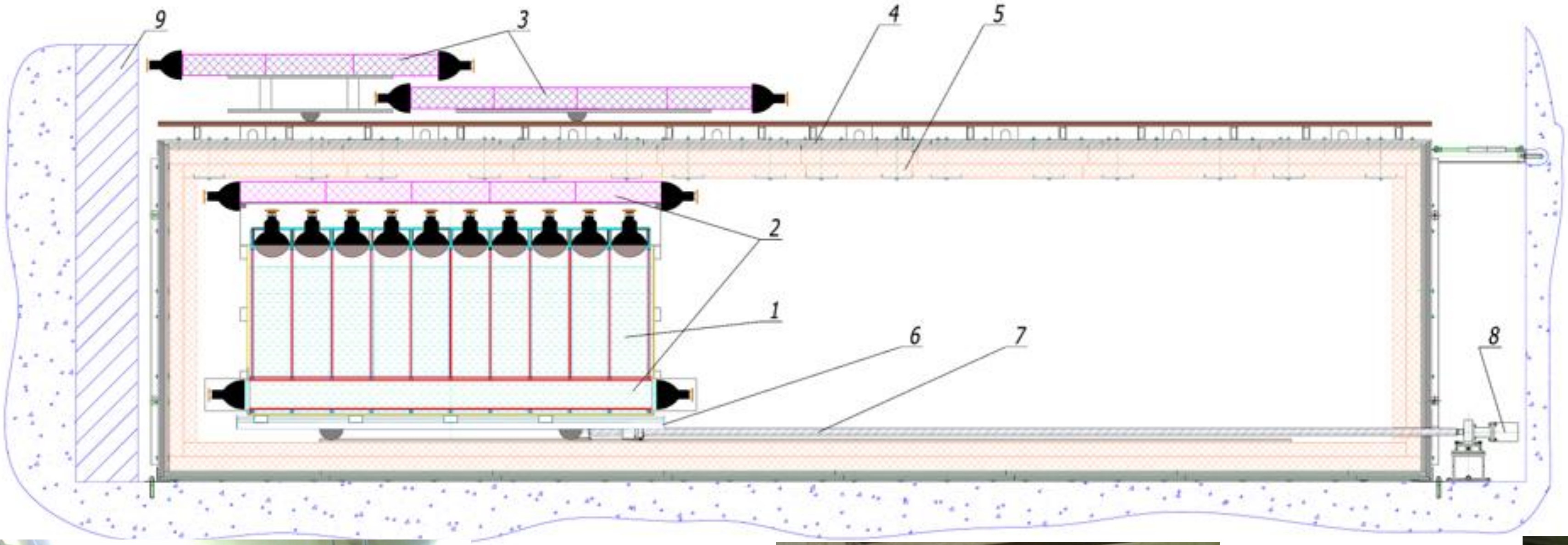


Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth's surface, hence, cosmic background is the major difficulty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

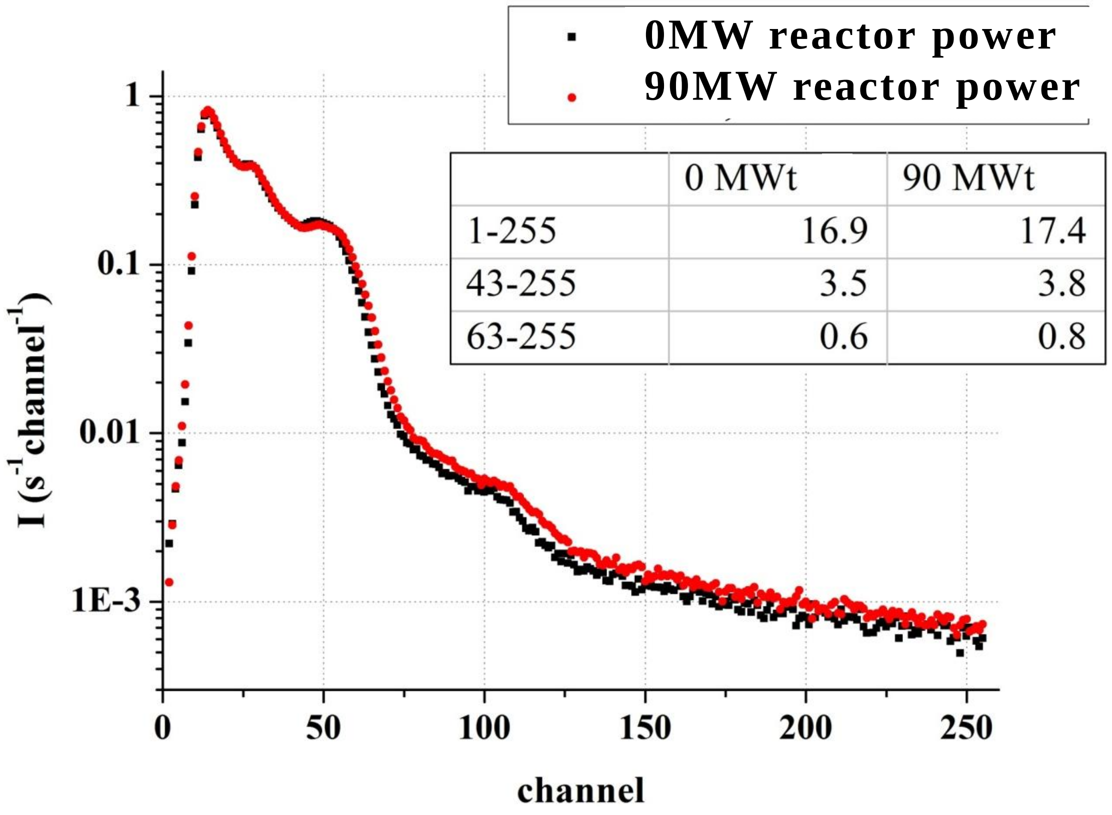
Range of measurements is 6 – 12 meters

Detector prototype

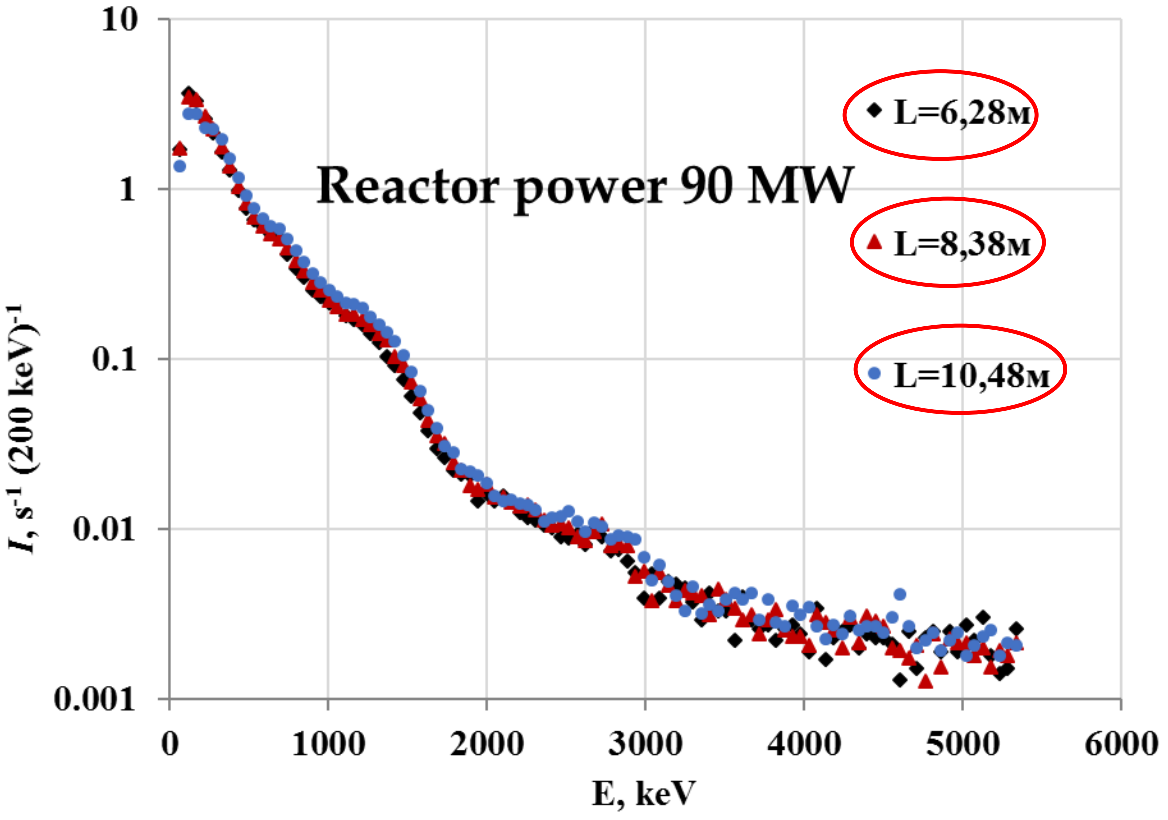
Full-scale detector

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

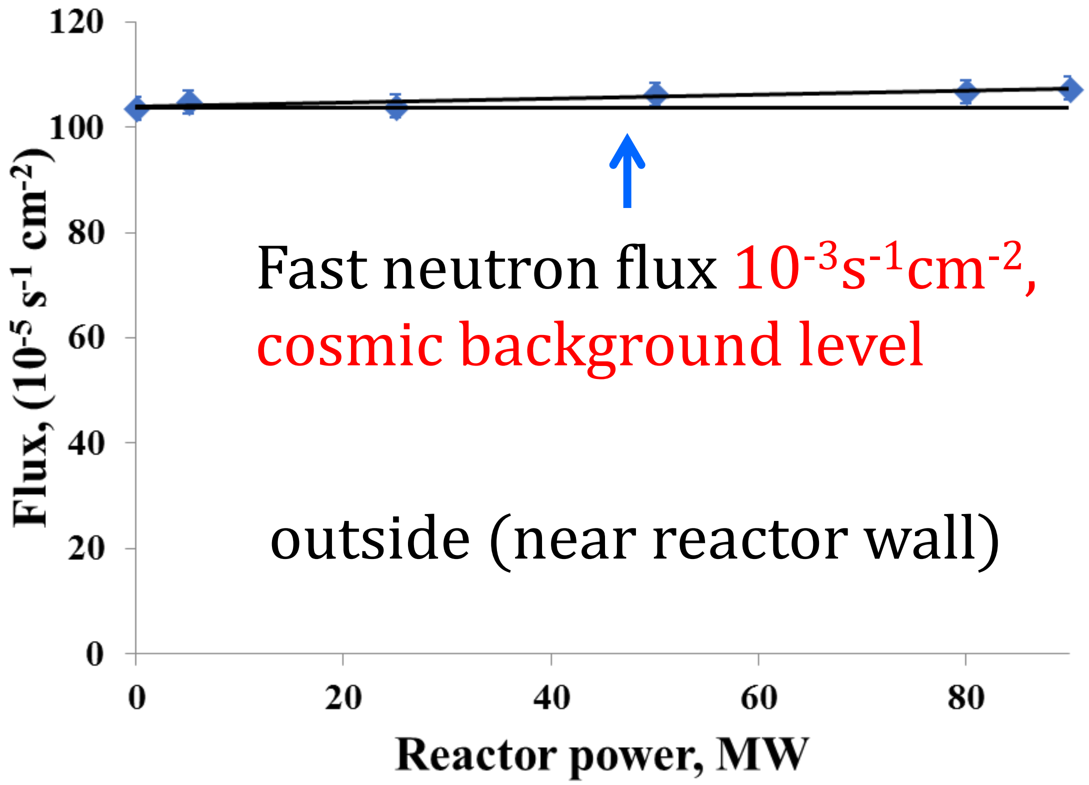
Gamma background in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor

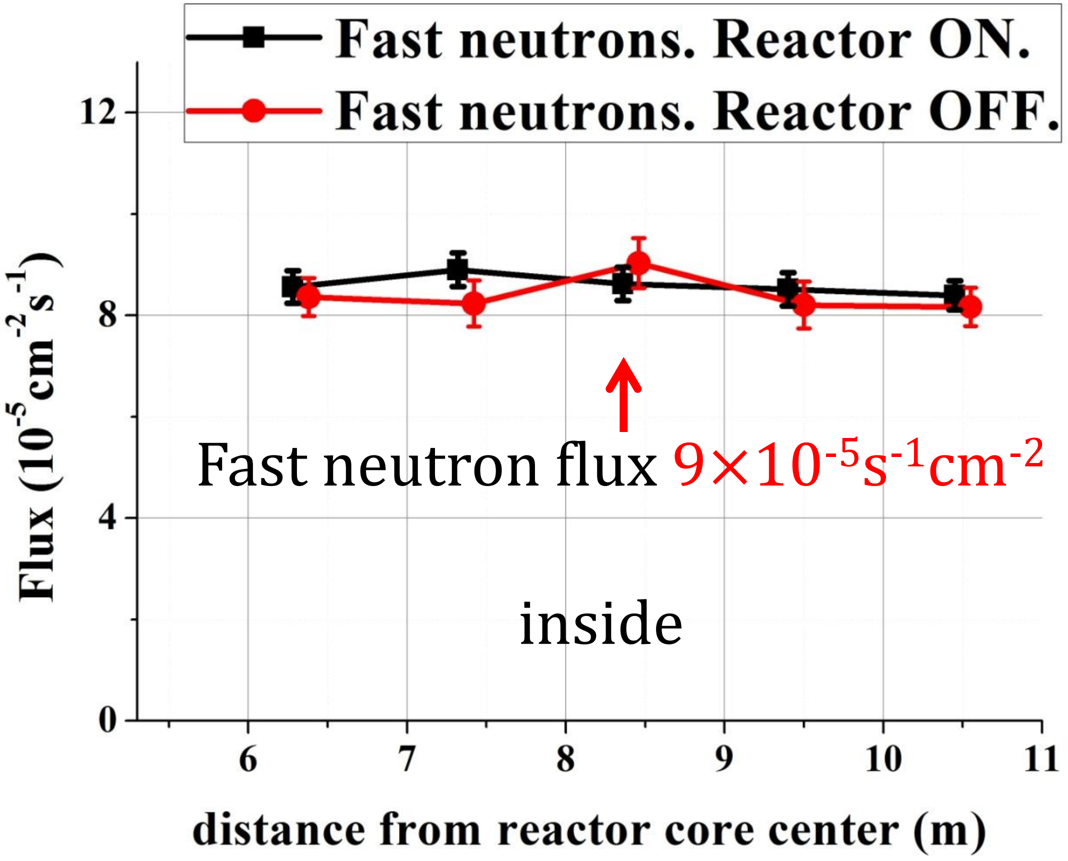


	0 MWt	90 MWt
1-255	16.9	17.4
43-255	3.5	3.8
63-255	0.6	0.8



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





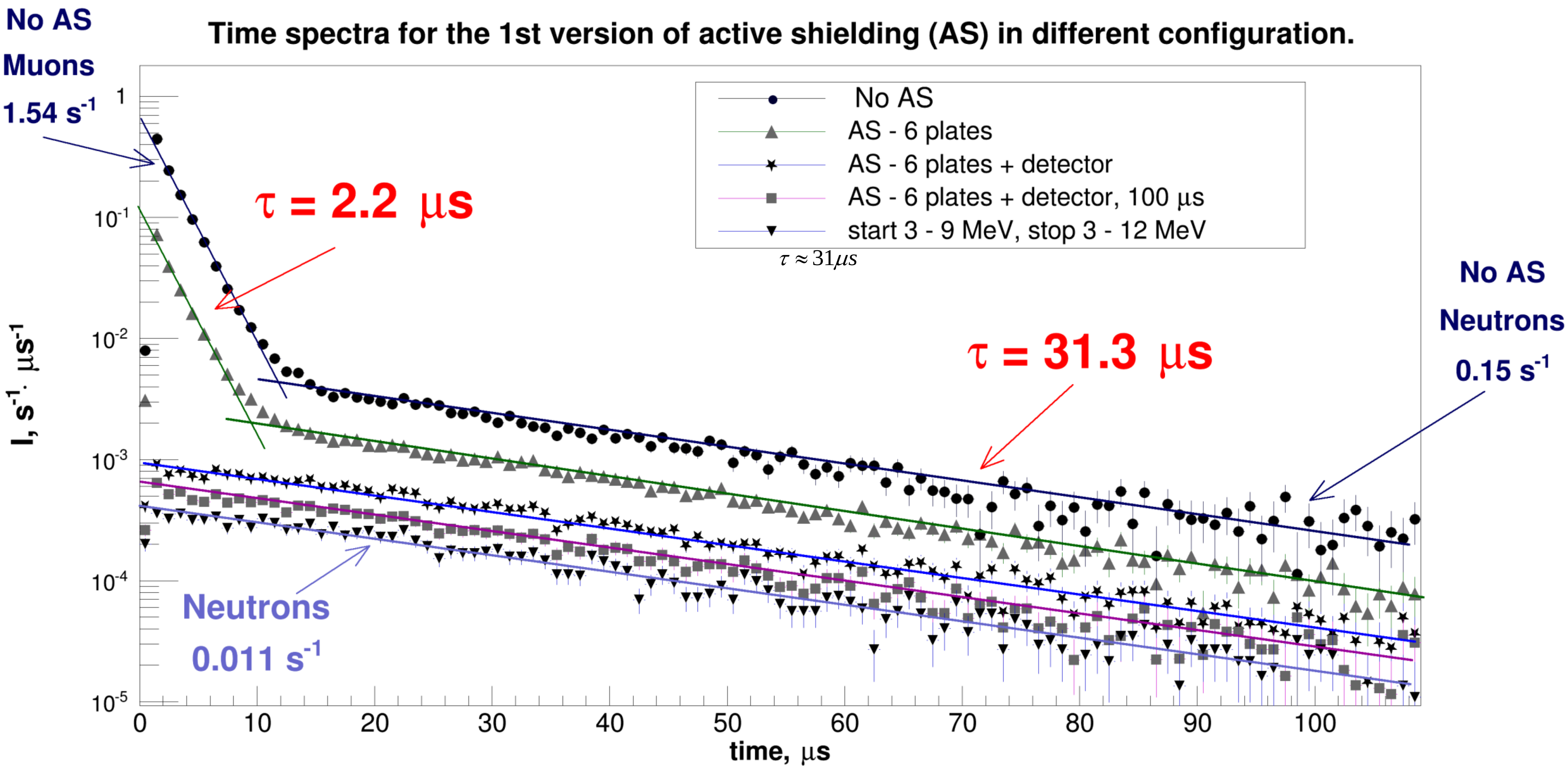
The background of fast neutrons in passive shielding is 10 times less than outside.
The background of fast neutrons outside of passive shielding is defined by cosmic rays and practically does not depend on reactor power.

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.

However, SM-3 reactor is located on the Earth's surface. Cosmic background is the major difficulty in the experiment.

Cosmic background

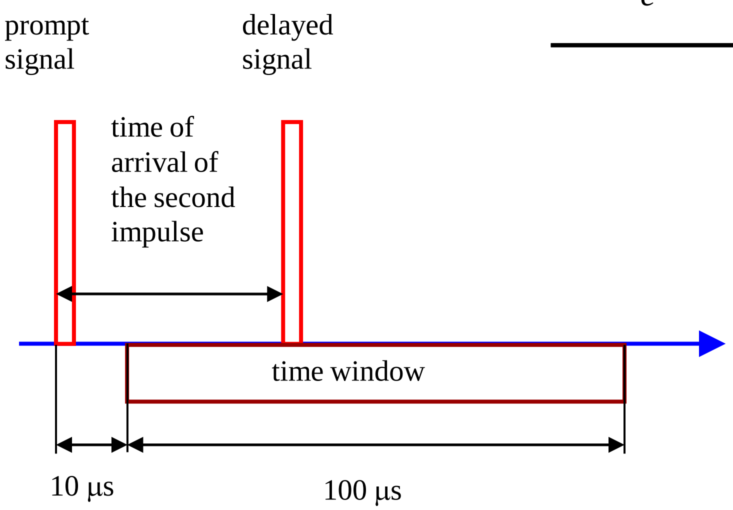
First AS version suppress background by an order of magnitude

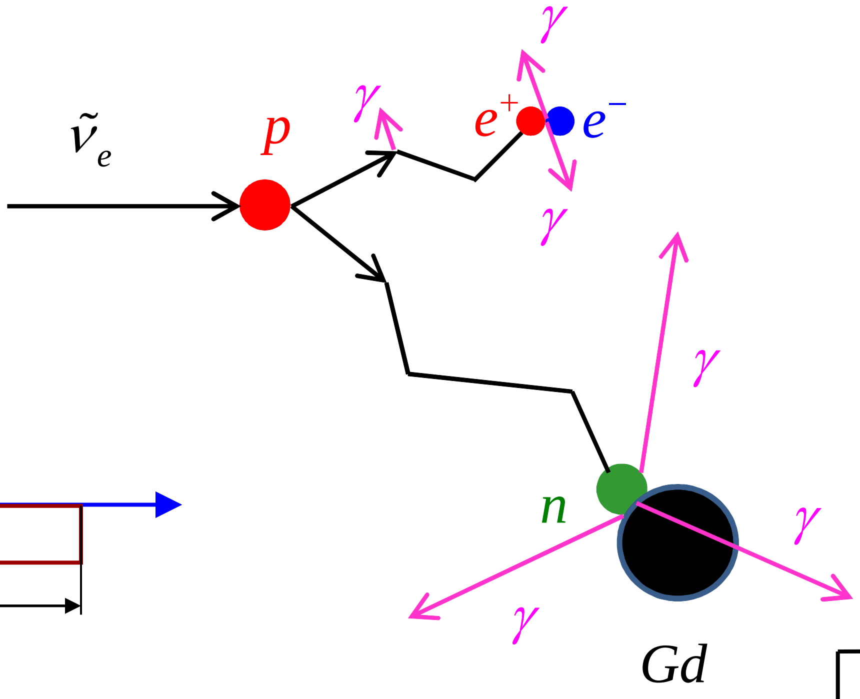


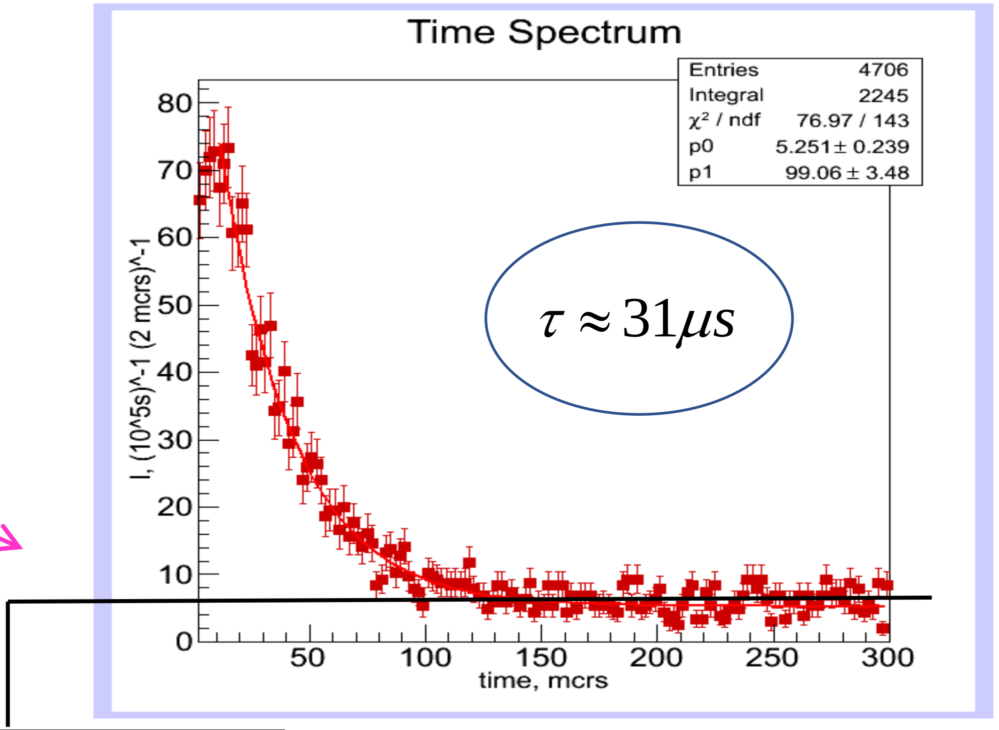
Scintillator with gadolinium concentration 0.1% was using to detect inverse beta decay (IBD) events

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

The method of antineutrino registration is to select correlated pare of signals: prompt positron signal and delayed signal of neutron captured by gadolinium.

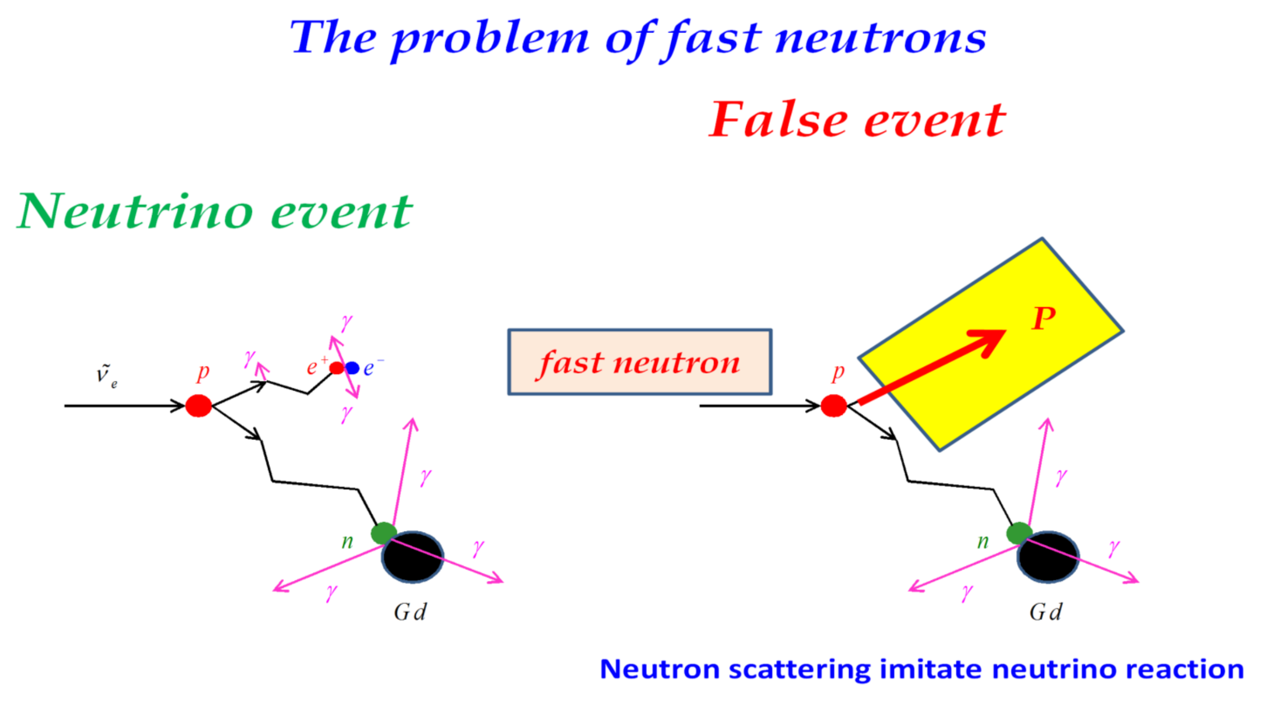




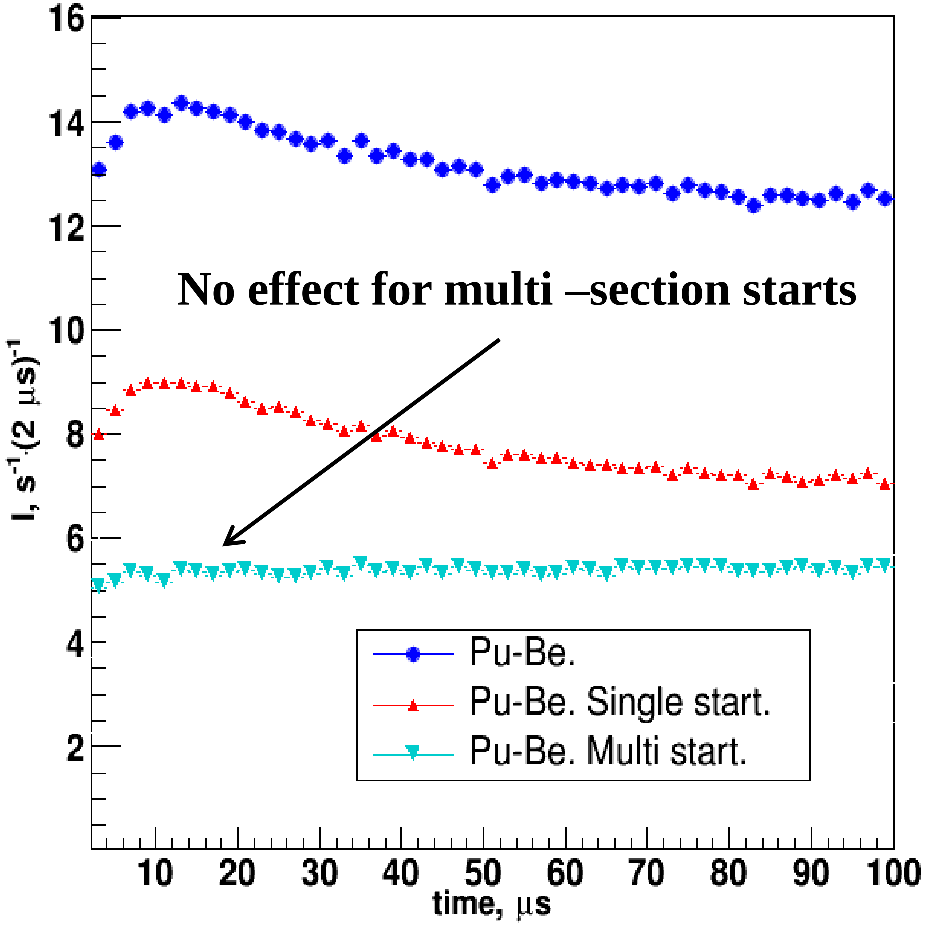


Accidental background

- **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

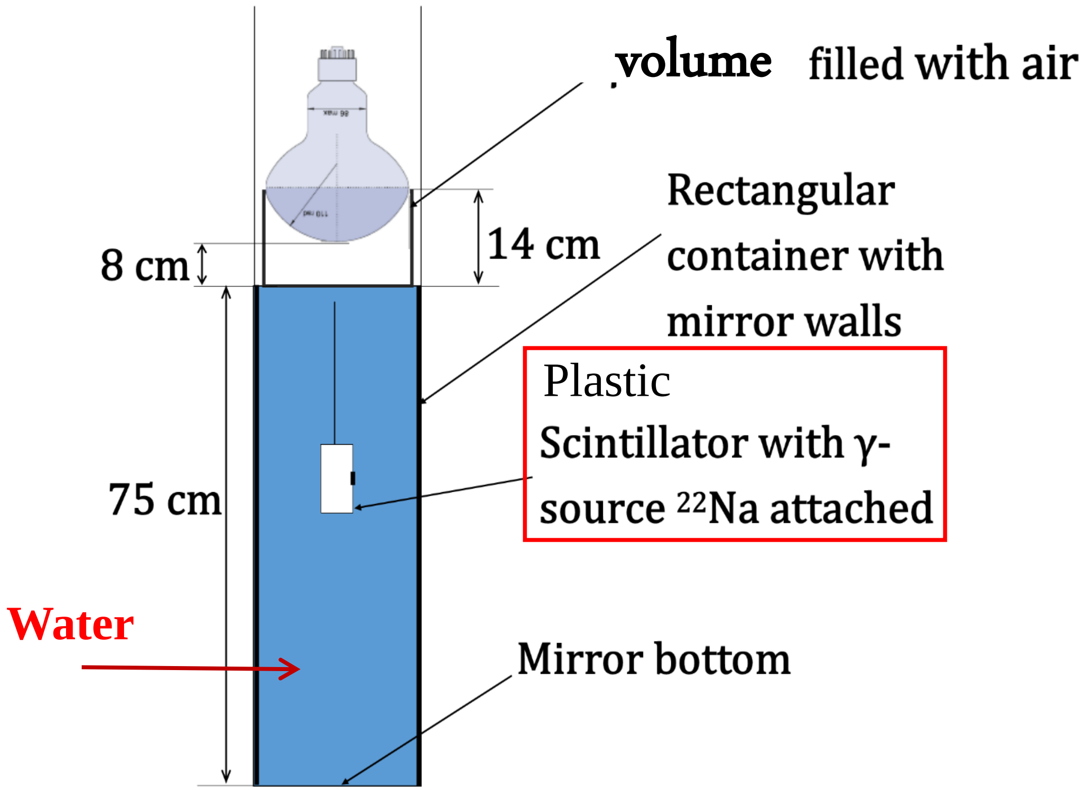
$(37 \pm 4)\%$

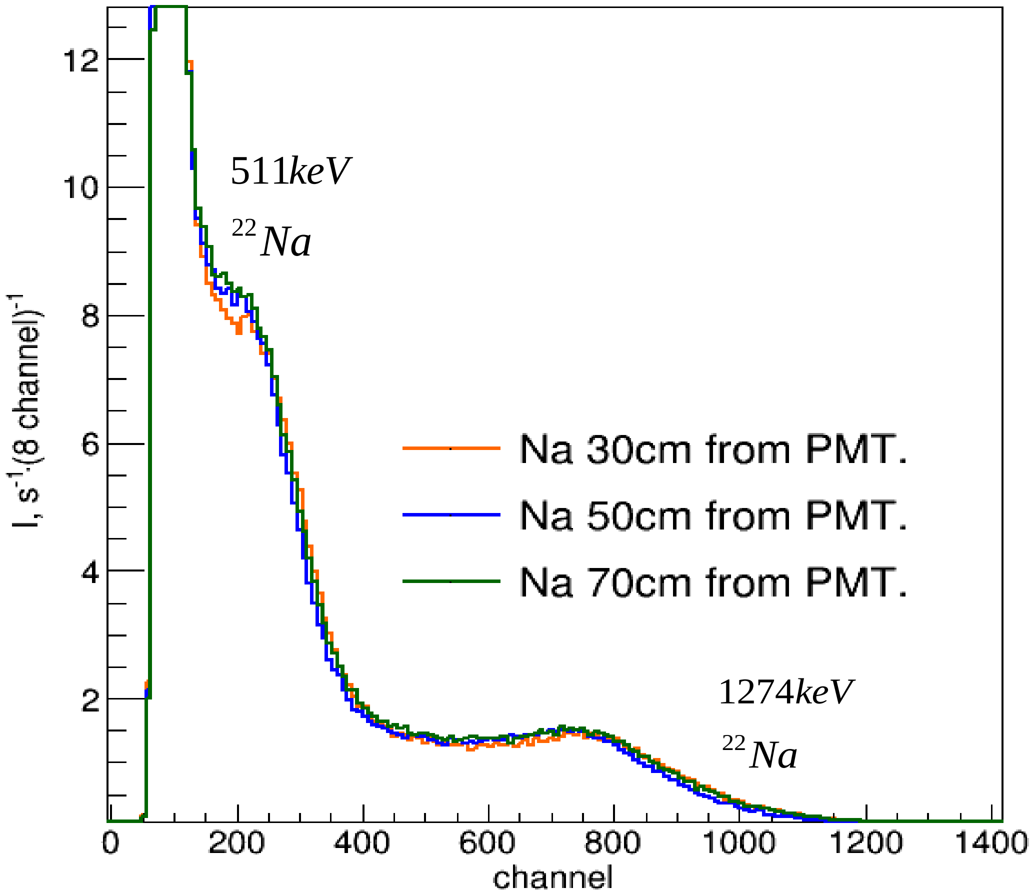
Monte Carlo calculations has shown that 63% of prompt signals from neutrino events are recorded within one section and only 37% of events has signal in another section. In our measurements, the signal difference at the reactor ON and OFF has ratio of double and single prompt events integrated over all distances $(37 \pm 4)\%$ **and** $(63 \pm 7)\%$ **.**

This ratio allows us to interpret the recorded events as neutrino events within current experimental accuracy.

Energy calibration on model of single section

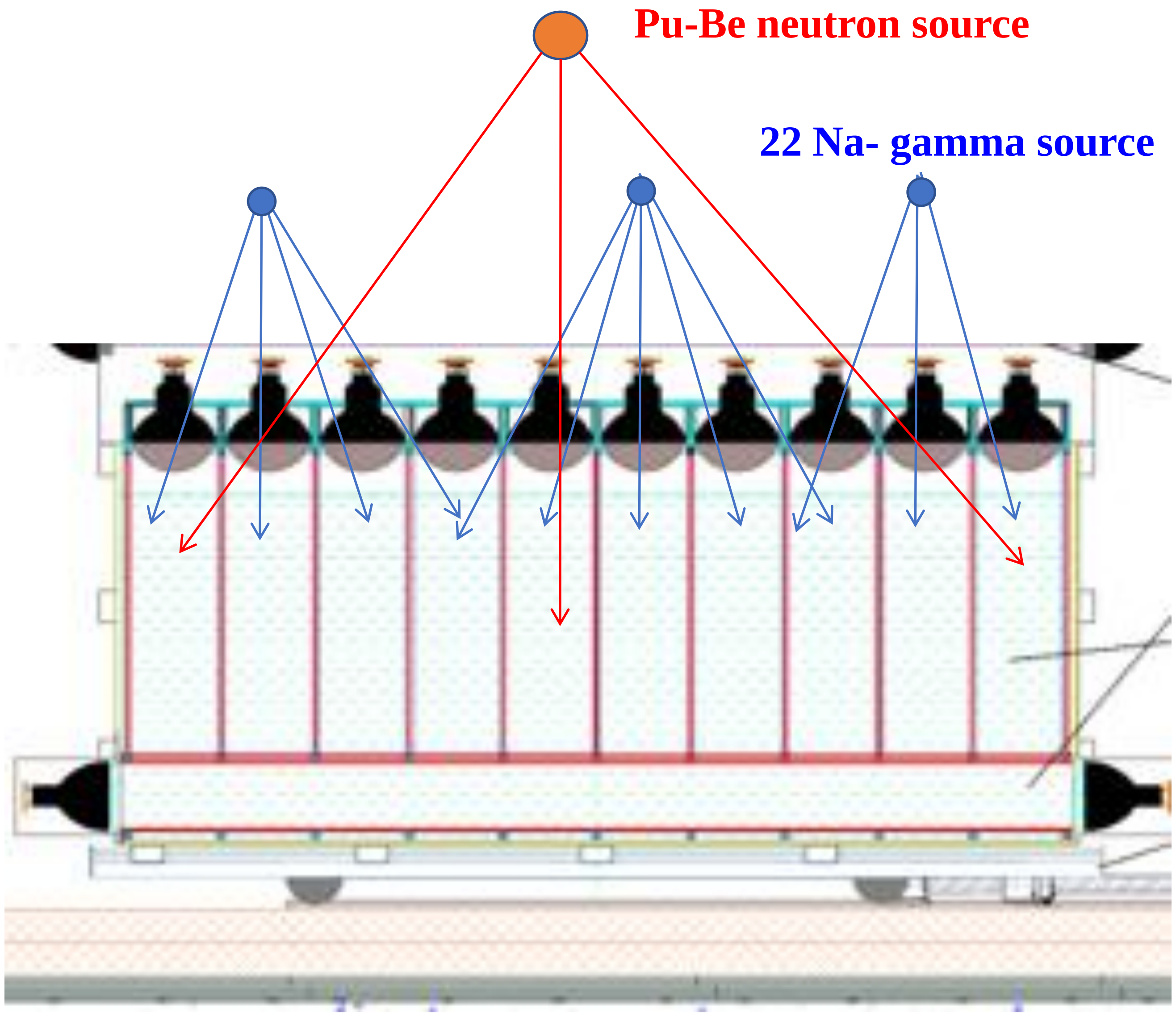
We use effect of full internal reflection of light on the border scintillator - air at small angeles to improve the light collection from different distances. Therefore calibration can be done using the sources located outside – above section.





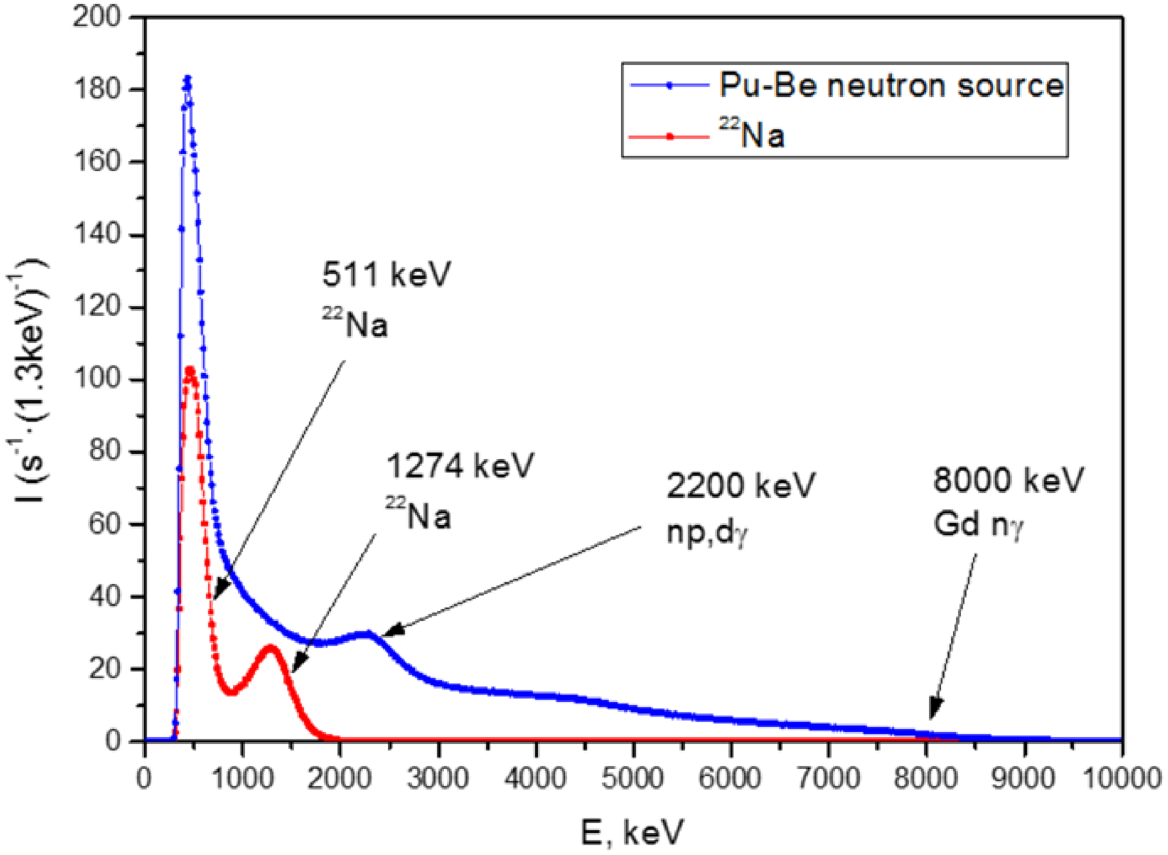
Energy calibration of the full-scale detector

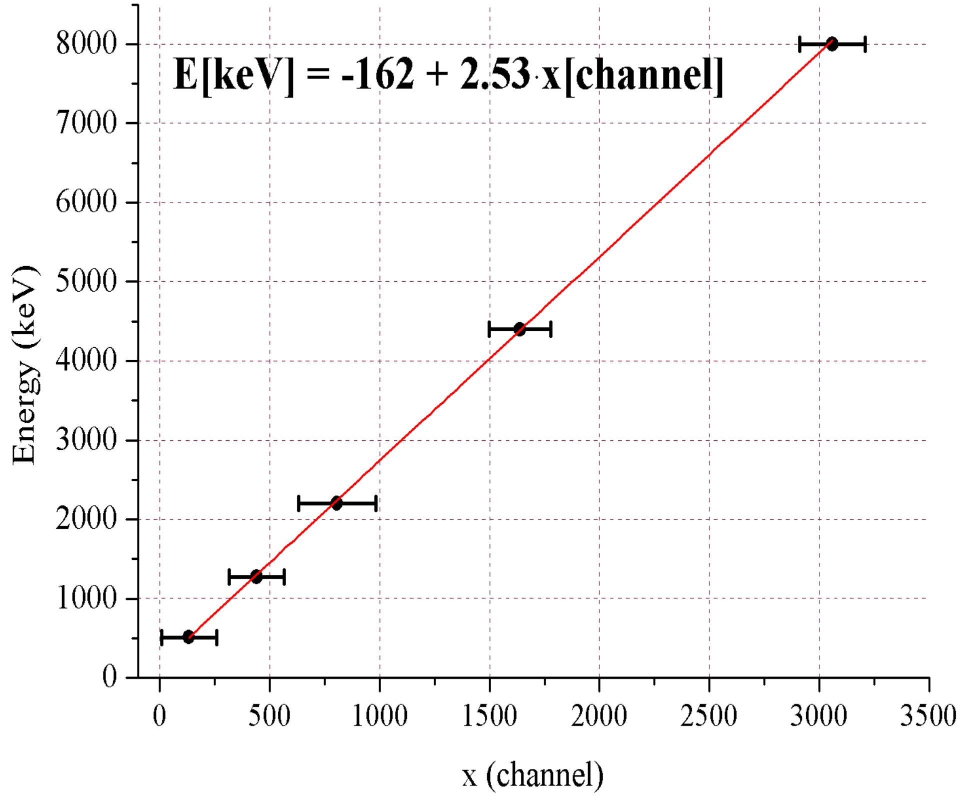
The source 22Na is installed above the detector at distance about 0.8 meters and irradiate about 16 sections at once. PMTs were normalized to one energy scale by selecting voltage on them. Simultaneous calibration of several sections is required. For all detector only 6 positions of the source were used.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





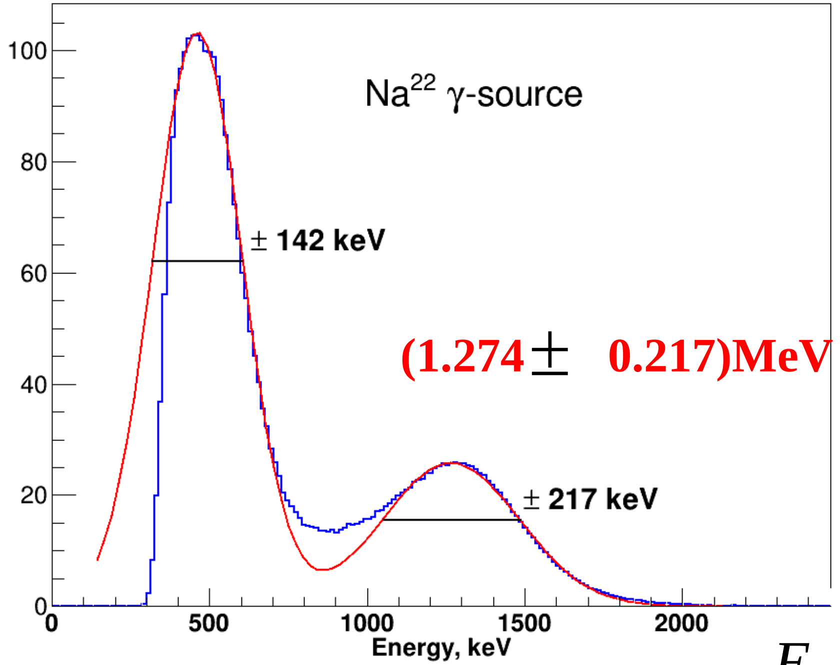
In the left - ranges of sources. In the right - the calibration of gamma quanta scale.
Registration of positrons includes inevitable loss of a part of energy of 511keV gamma-quanta. Because of the threshold of registration in the adjacent section we have to increase errors up to **±250 keV**.

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

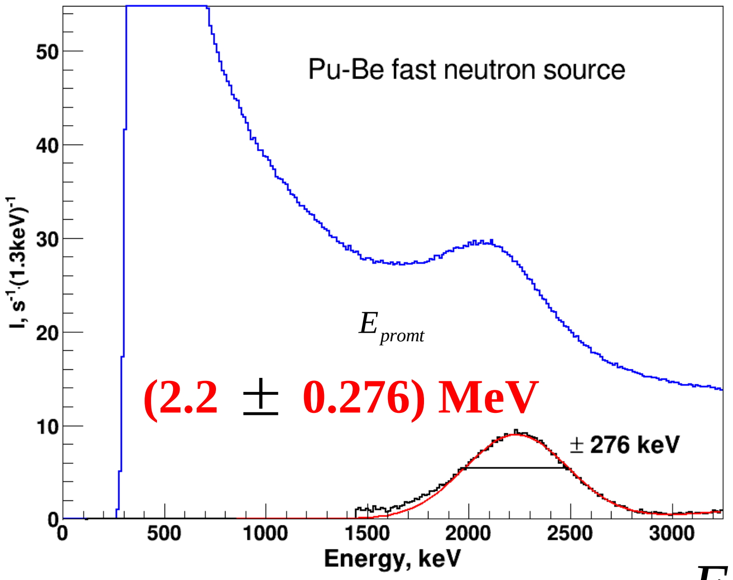
Energy calibration of the full-scale detector

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

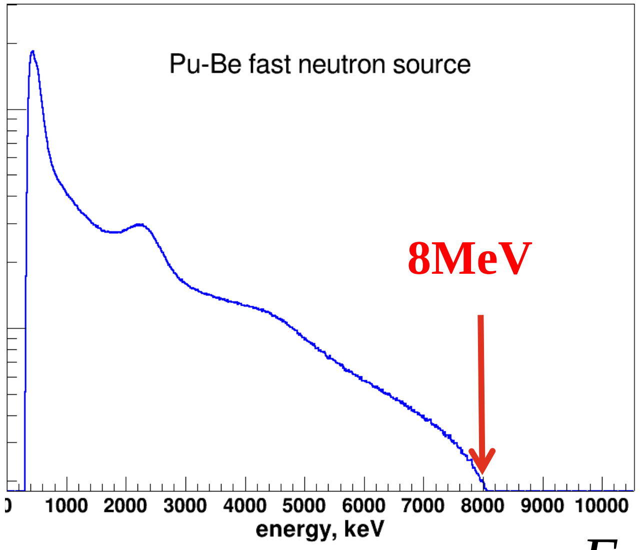
(0.511 ± 0.142) MeV



E_{promt}



E_{promt}



E_{promt}

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

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

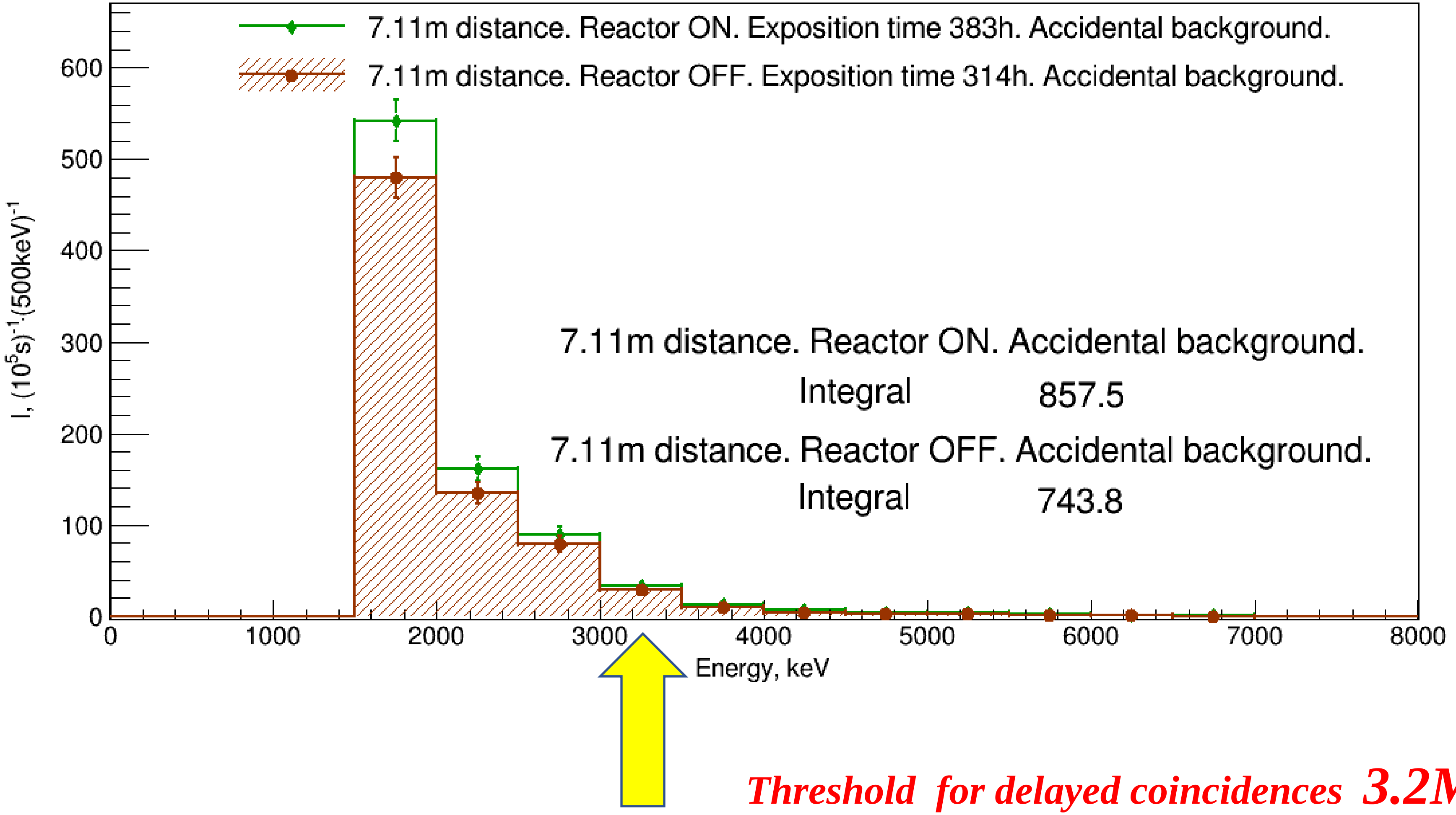
$$\Delta E_\nu / E_\nu (3MeV) = 18\%$$

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

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

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

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



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

Energy spectrum and signal /background ratio

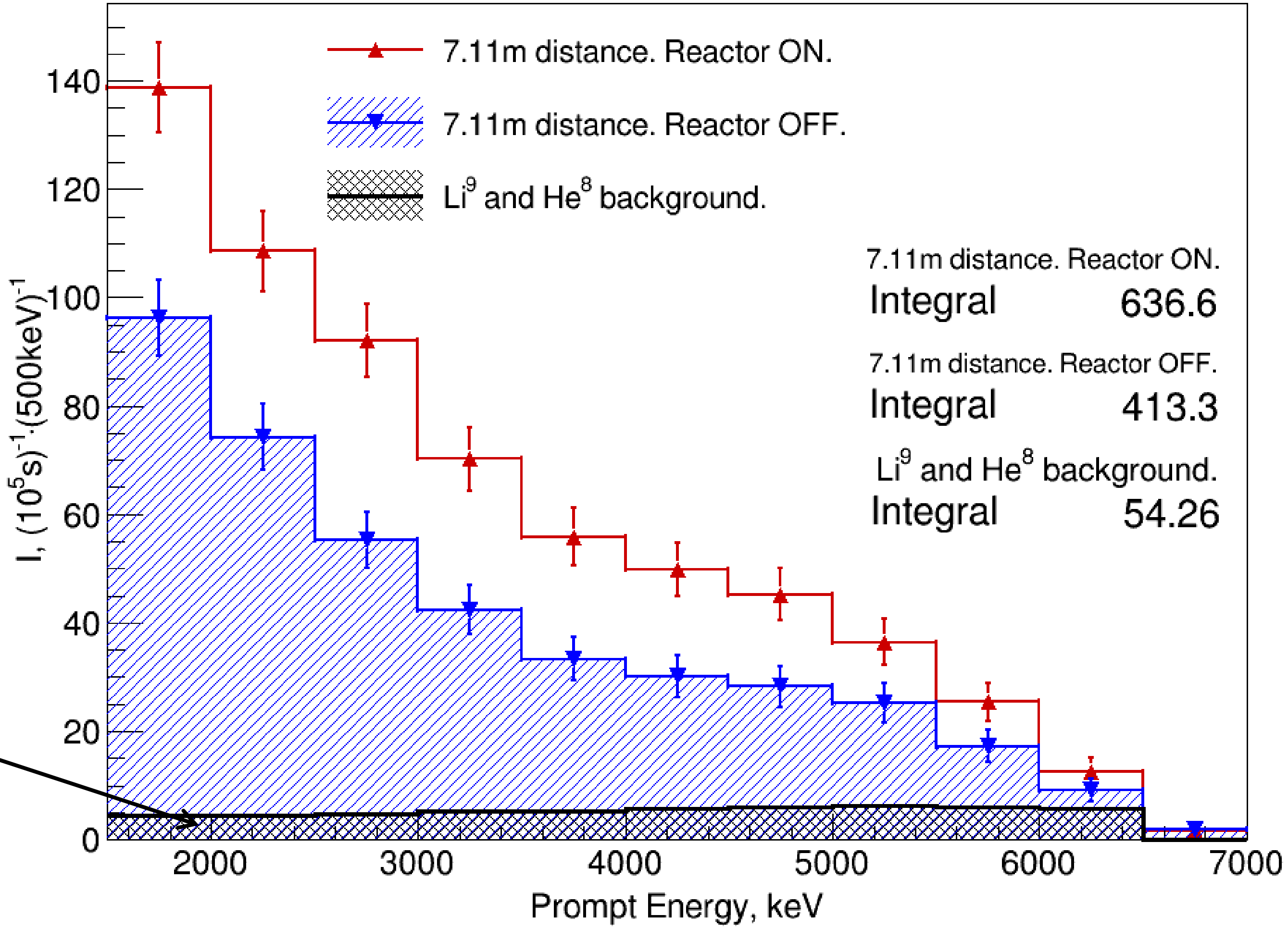
Reactor ON and OFF spectra after 2 months exposition at 7.11m

213 neutrino events/10^5 s

(ON - OFF)

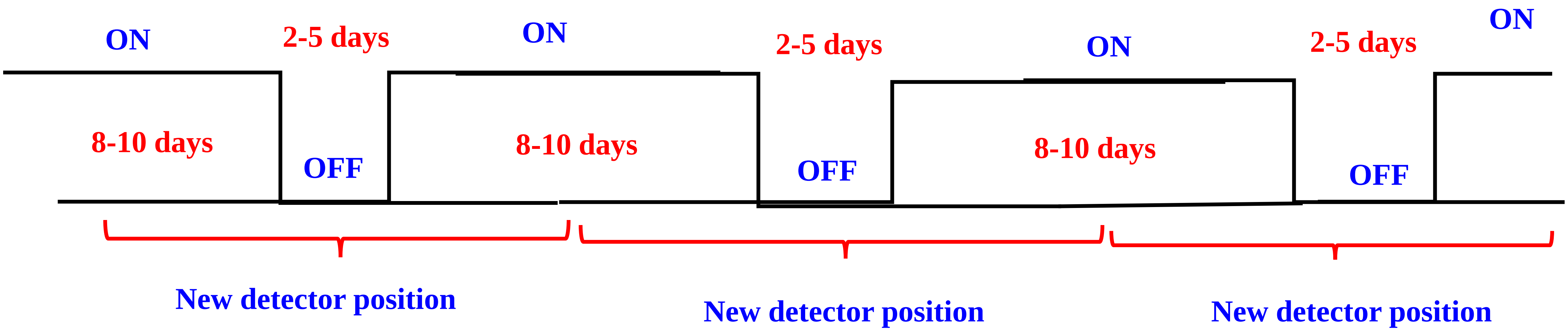
signal /background ratio 0.54

Unavoidable background of Li^9 and He^8 is 54 events/10^5s

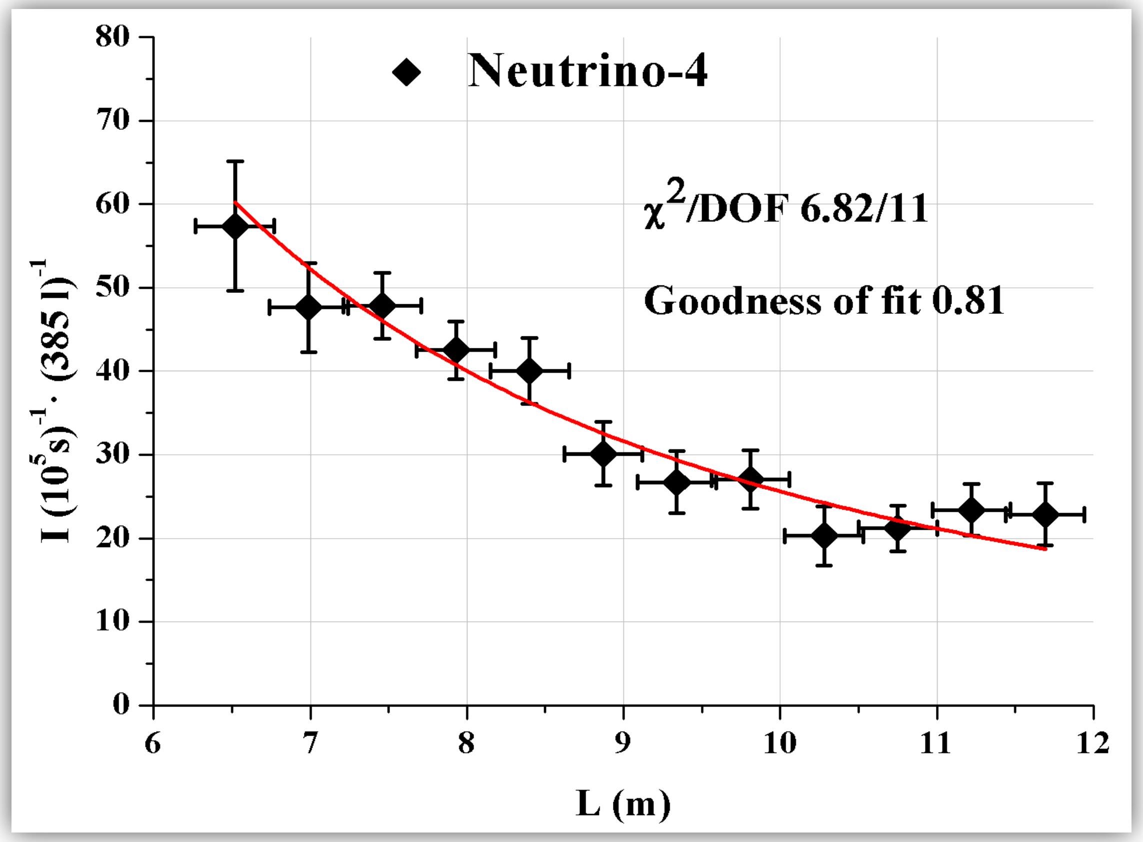


ON
90 MW

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.



Results of measurements of the difference in counting rates of neutrino-like events for the detector as dependence on the distance to the reactor core.

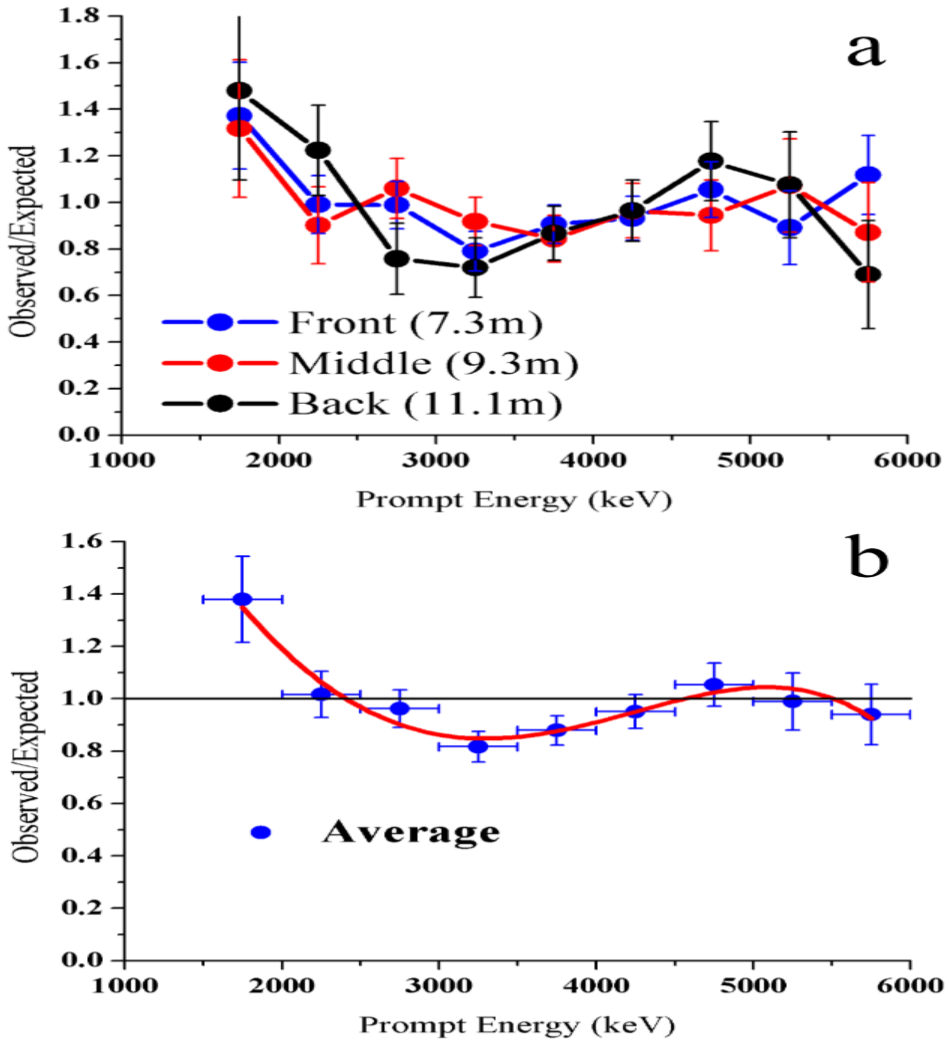


Fit of an experimental dependence with the law A/L^2 yields satisfactory result. Goodness of that fit is 81%. Corrections for finite size of reactor core and detector sections are negligible – 0.3%, and correction for difference between detector movement axes and direction to center of reactor core is also negligible – about 0.6%.

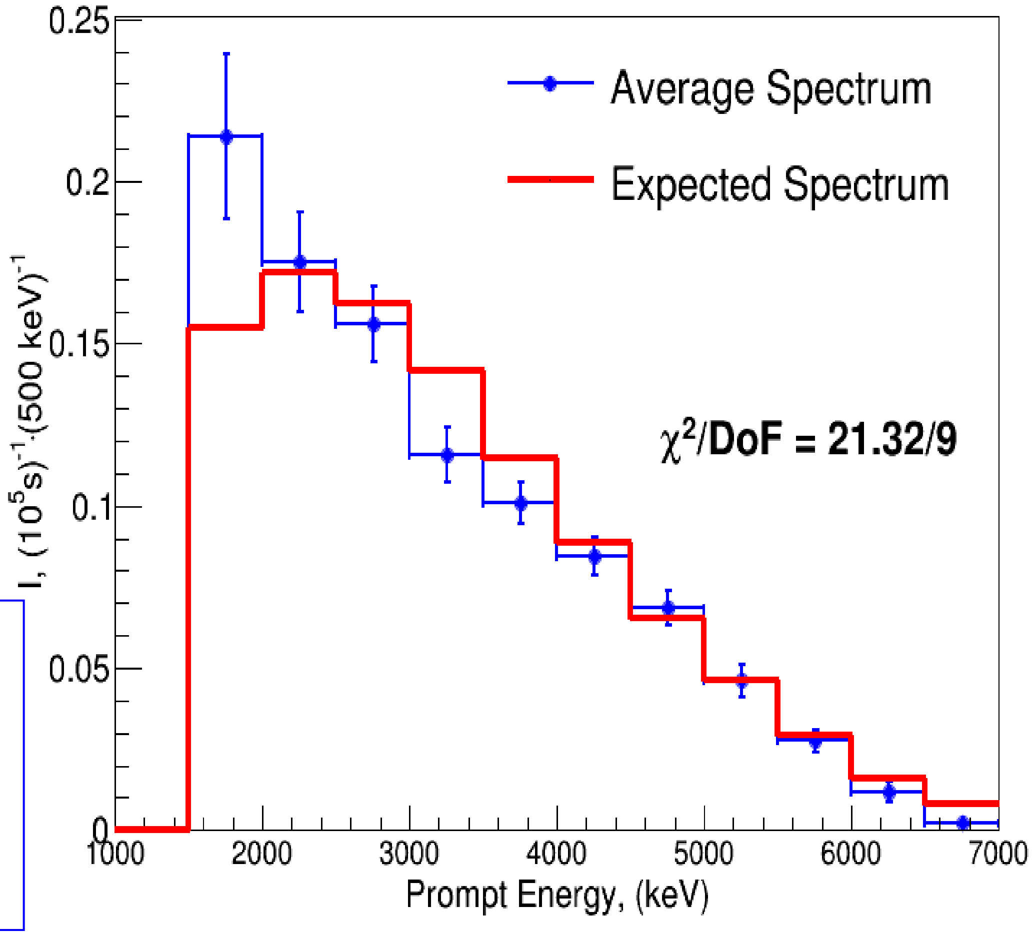
The analysis of distance dependence without energy spectrum is not enough to observe oscillations because of spectral averaging .

a) The ratio of an experimental spectrum of prompt signals to the spectrum, expected from MC calculations for 3 ranges (~2m) with centers 7.3m, 9.3m and 11.1m

b) polynomial fit of results averaged by distance (red curve)



Problems with energy spectrum



Spectrum of prompt signals in the detector for a total cycle of measurements summed over all distances (average distance — 8.6 meters). The red line shows Monte -Carlo simulation with neutrino spectrum of ^{235}U, as the SM-3 reactor works on highly enriched uranium.

The model-independent method of the analysis of experimental data

Probability of antineutrino disappearance

$N(E_i, L_k)$

Number of antineutrino events

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

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.

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

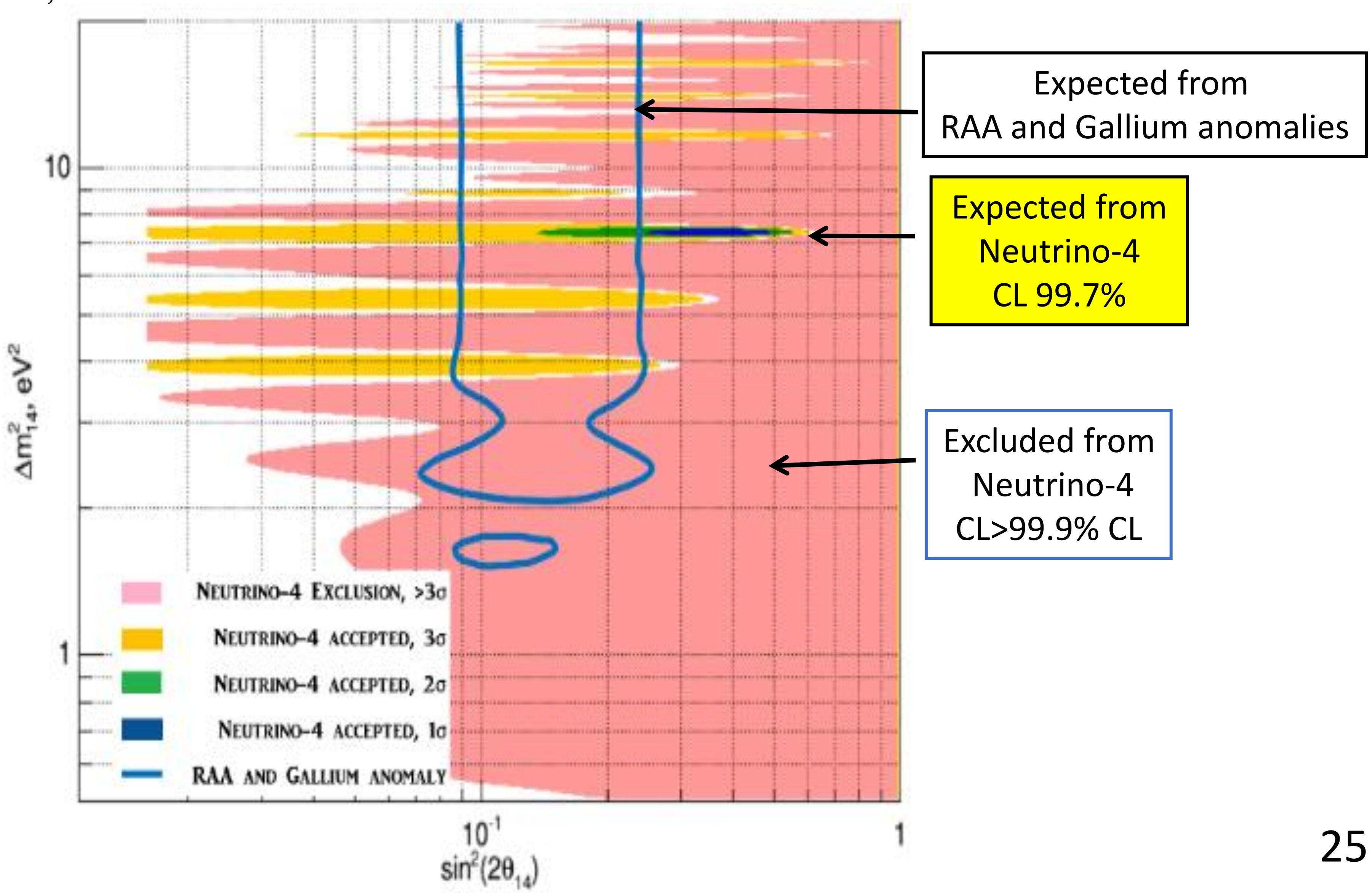
The results of the analysis of optimal parameters Δm^2_{14} and $\sin^2 2\theta_{14}$ using χ^2 method

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

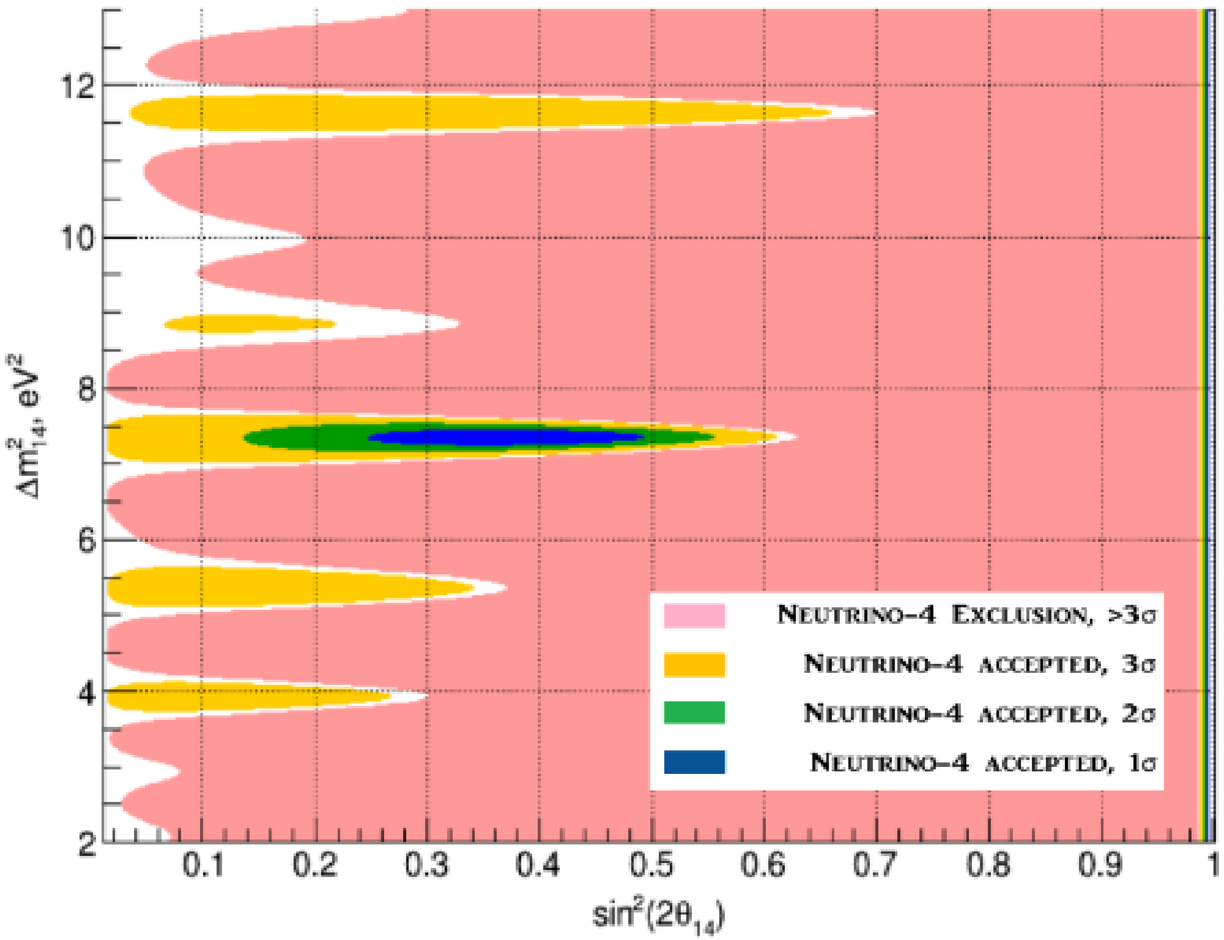
We observed the oscillation effect at C.L. 99.7% (3σ) in vicinity of :

$$\Delta m^2_{14} \approx 7 eV^2$$

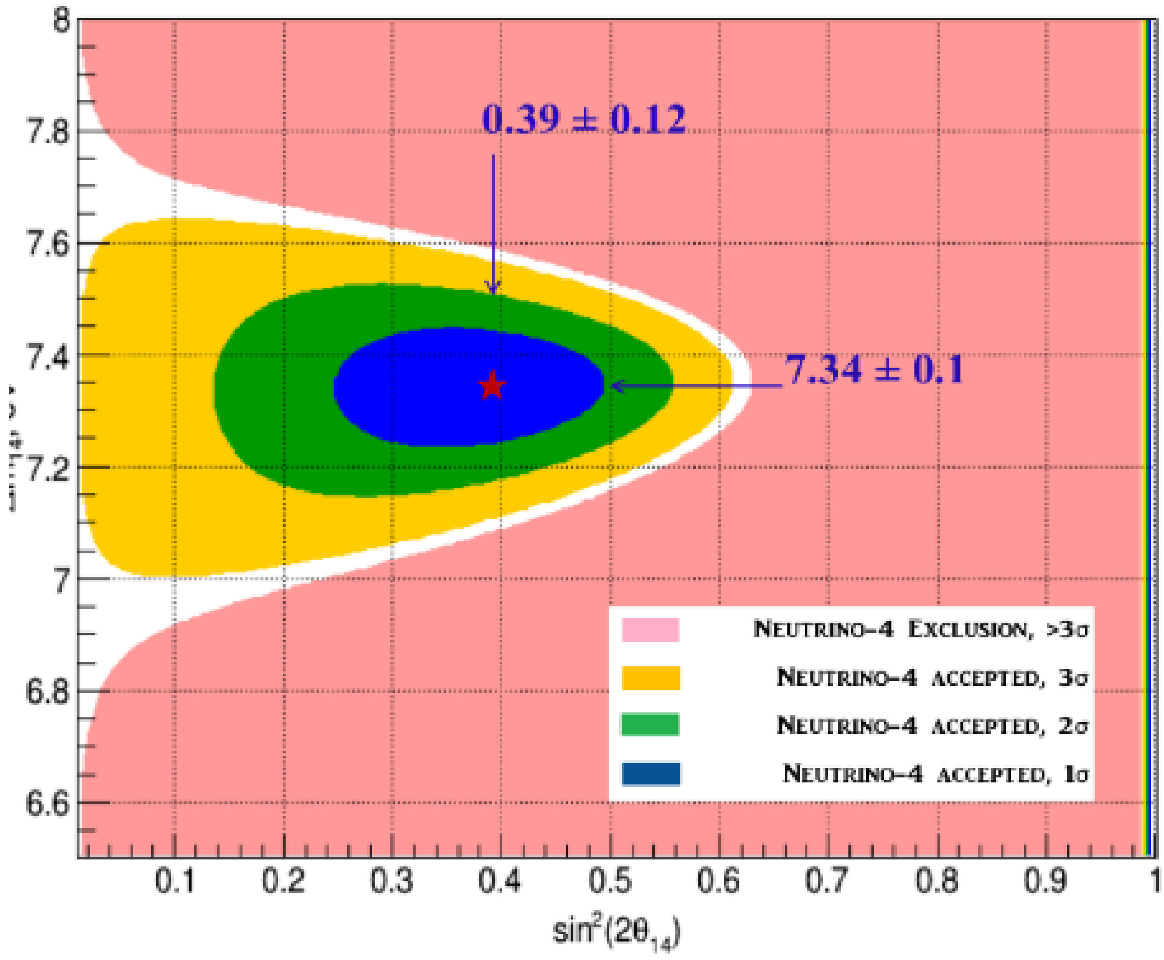
$$\sin^2 2\theta_{14} \approx 0.4$$



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

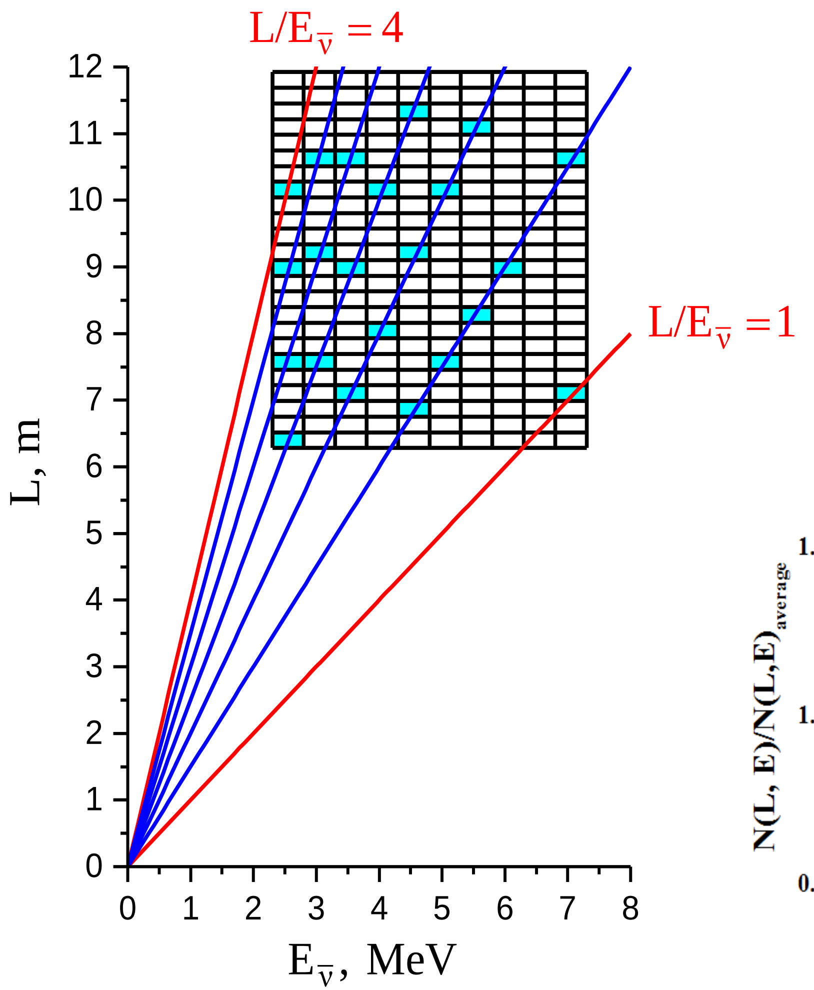


Area around central values in linear scale and significantly magnified

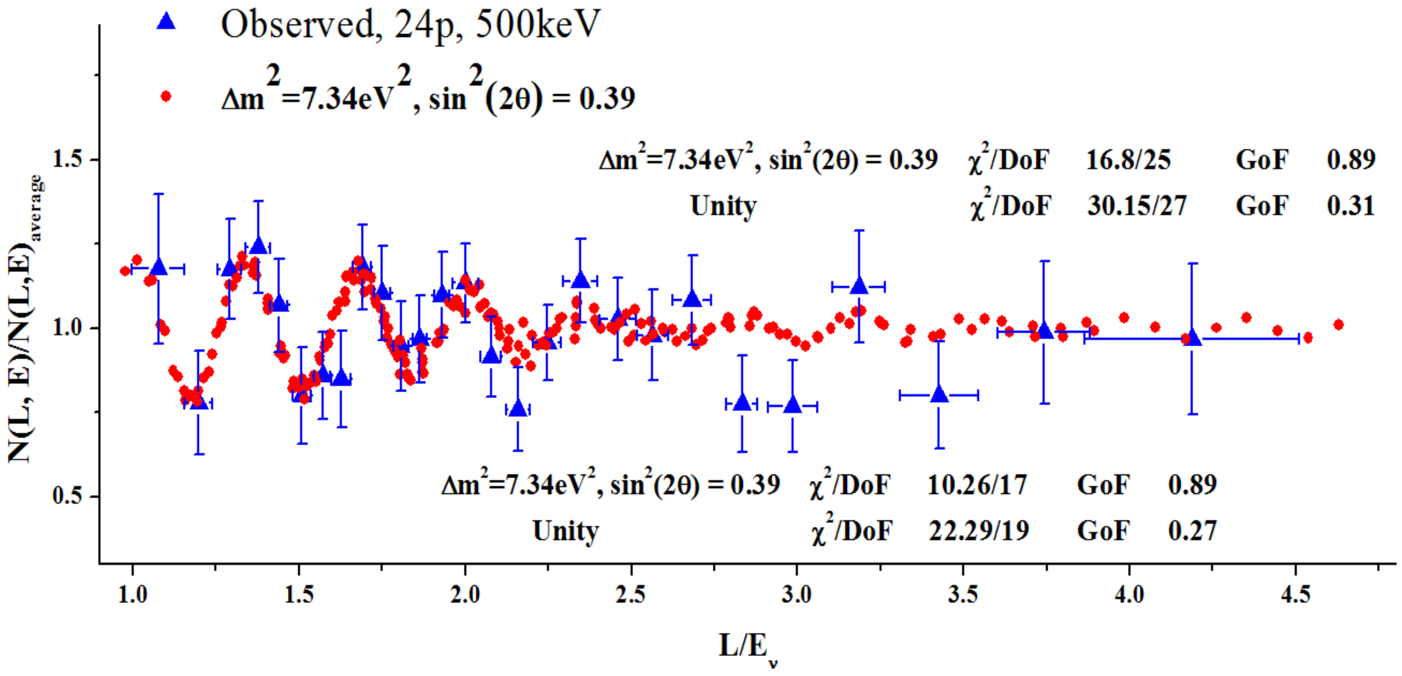


Central part even further magnified

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



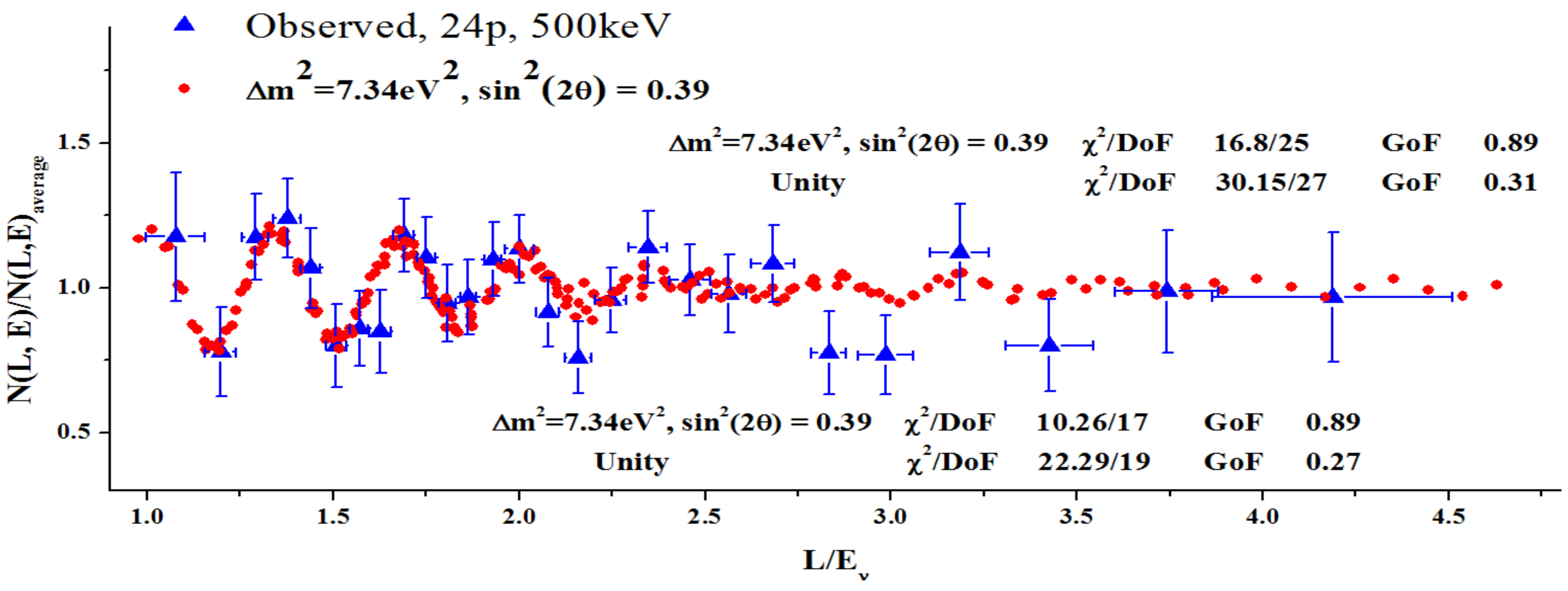
$$R_{i,k}^{\exp} = \frac{N(E_i^{\nu}, L_k)L_k^2}{K^{-1}\sum_k^K N(E_i^{\nu}, L_k)L_k^2} = \frac{[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 \boxed{L_k/E_i^{\nu}})]}{K^{-1}\sum_k^K[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 \boxed{L_k/E_i^{\nu}})]} = R_{i,k}^{th} \quad (2)$$



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

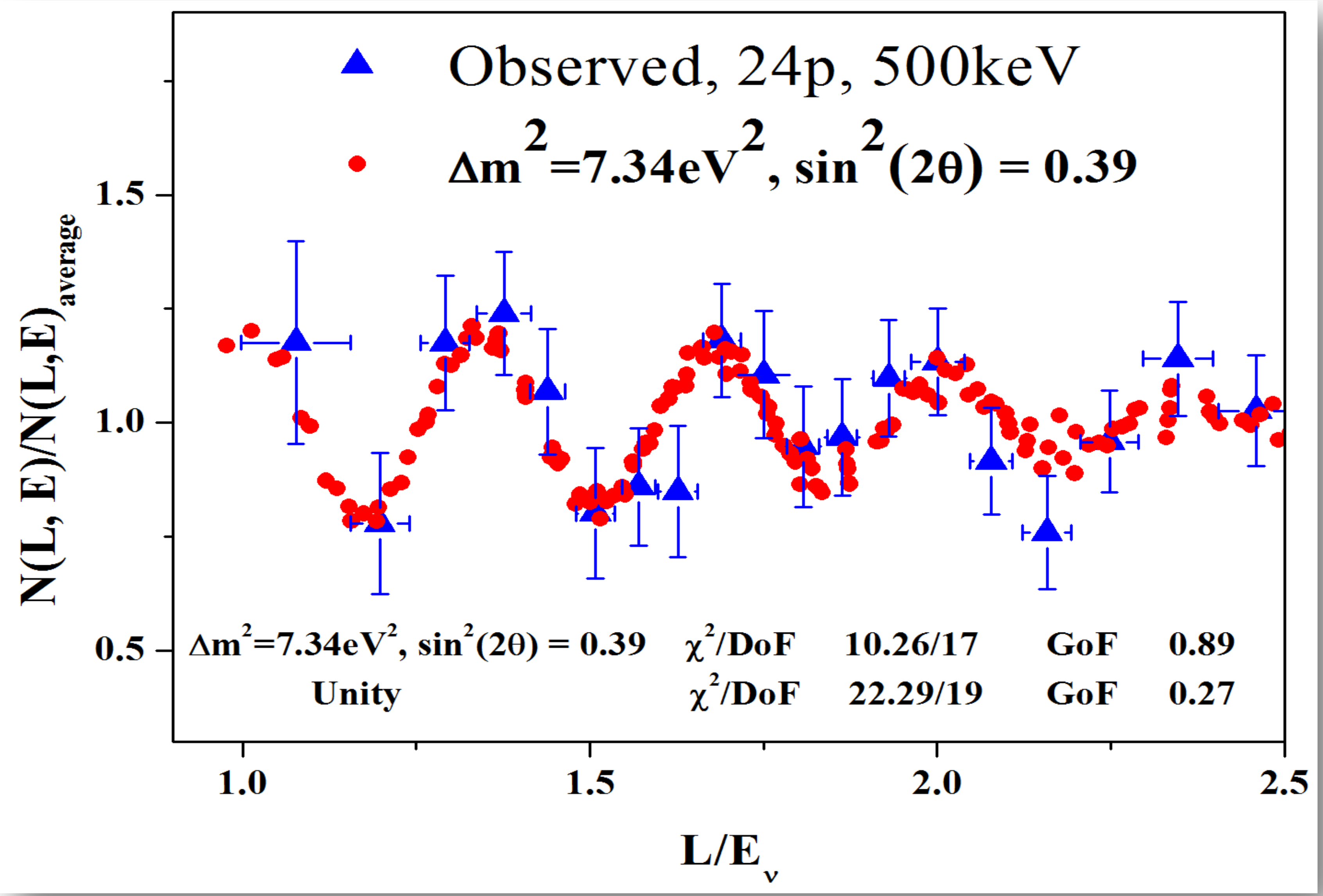
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{14}\ \sin^2\left(1.27\frac{\Delta m_{14}^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}}[\mathrm{MeV}]}\right) \qquad (1)$$

Since, according to equation (1), oscillation effect depends on ratio L/E, it is beneficial to make experimental data selection using that parameter.



Comparison of the blue experimental triangles and the red calculated dots with optimal oscillation parameters.

The first observation of oscillation of reactor antineutrino in sterile neutrino



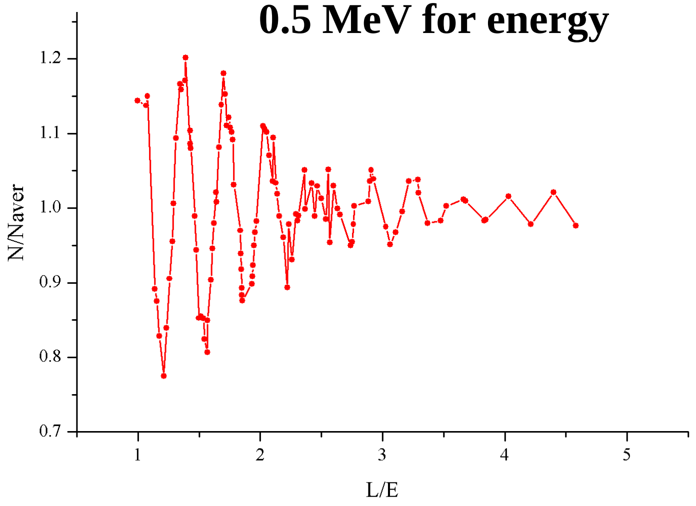
GoF 89%

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

$$\Delta m_{14}^{2} \approx 7\,\text{эВ}^{2}$$

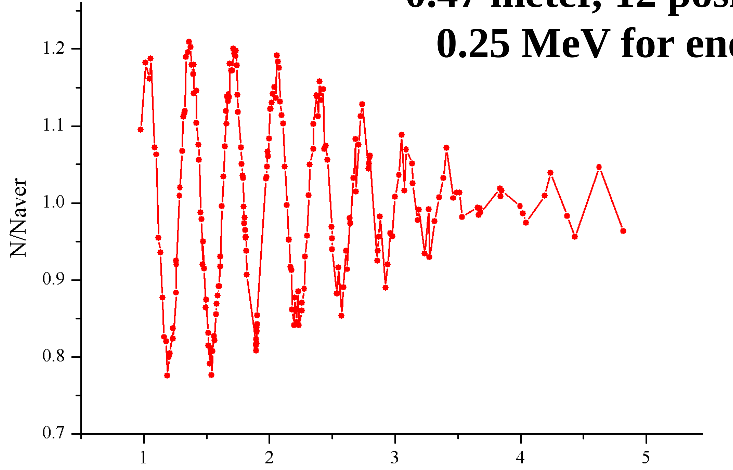
$$\sin^{2} 2\theta_{14} \approx 0.4$$

0.47 meter, 12 positions, 0.5 MeV for energy

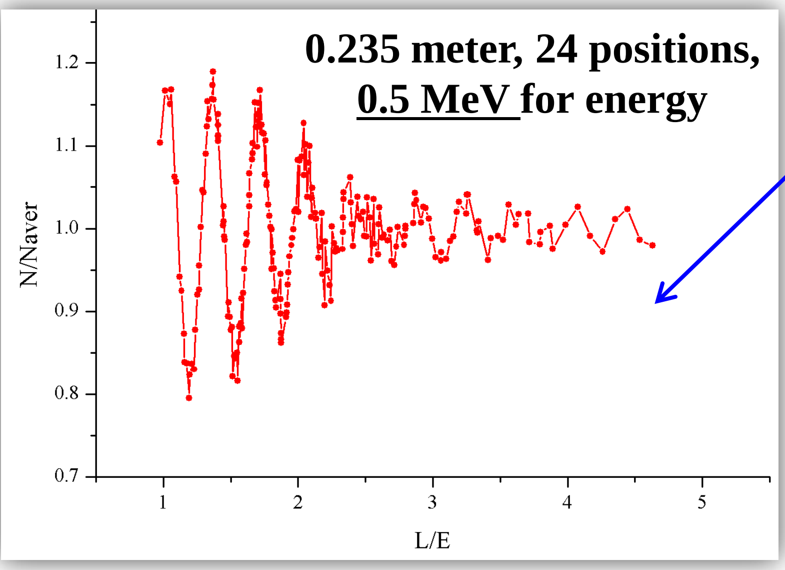


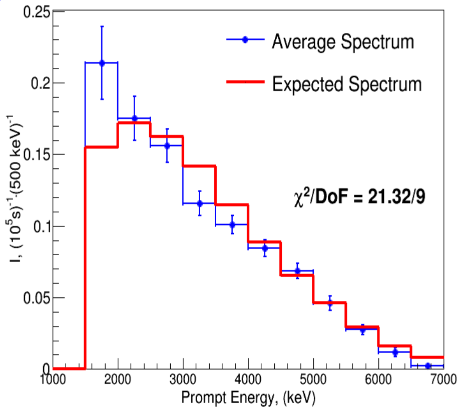
The attenuation of sinusoidal process for red curve in area L/E >2.5 is explained by taken energy interval 0.5MeV.
This energy interval corresponds to experimental energy resolution **±250keV**

0.47 meter, 12 positions, 0.25 MeV for energy

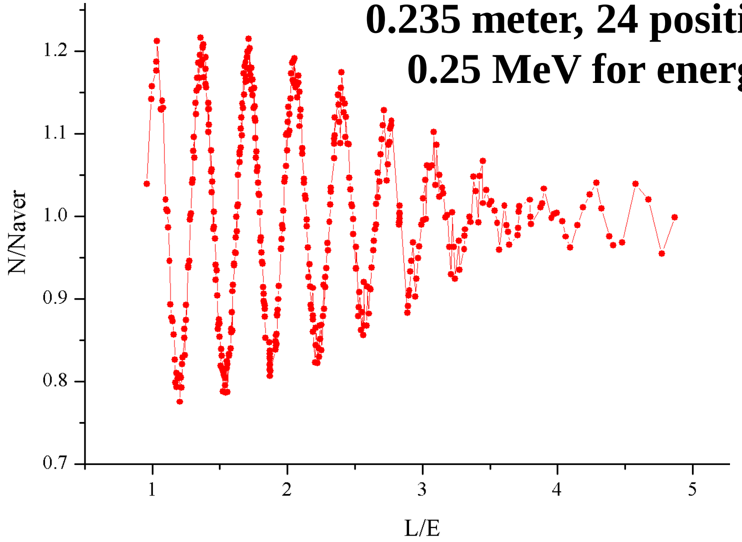


0.235 meter, 24 positions, <u>0.5 MeV</u> for energy

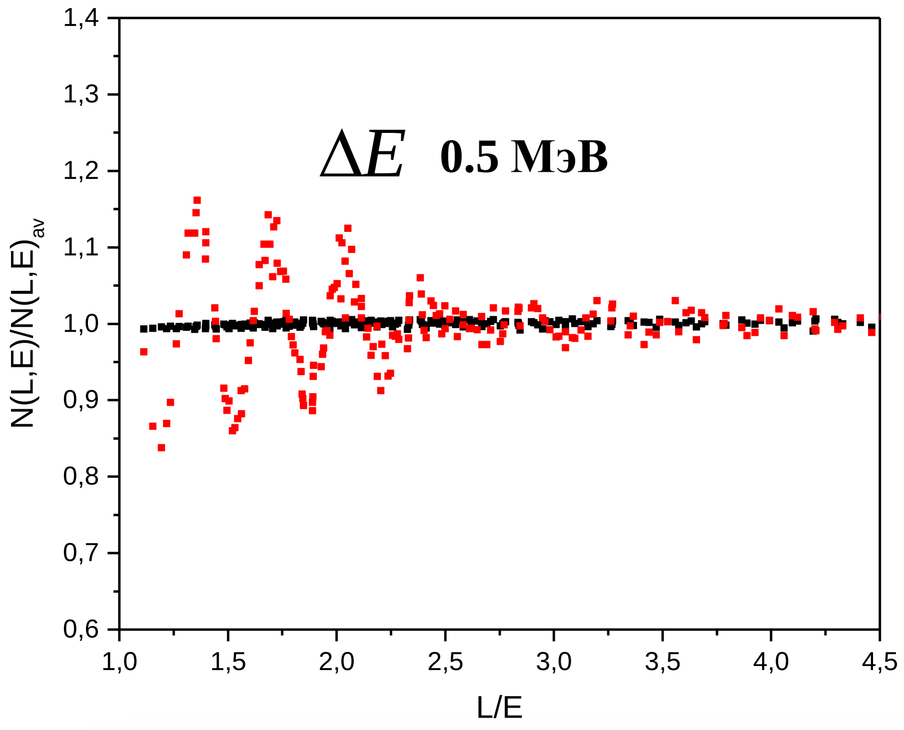


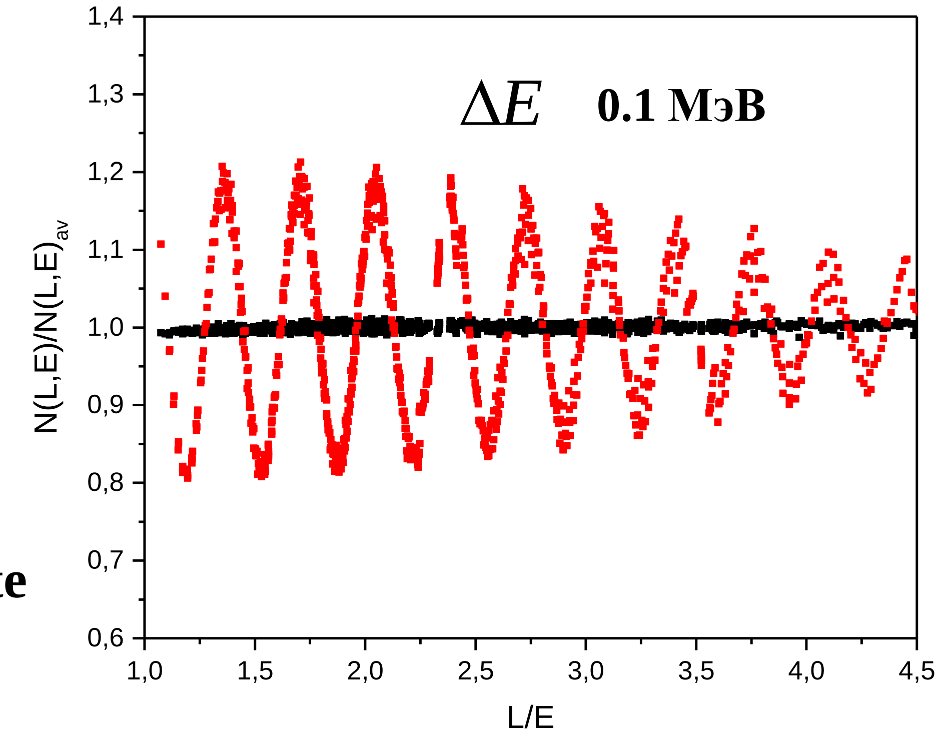


0.235 meter, 24 positions, 0.25 MeV for energy



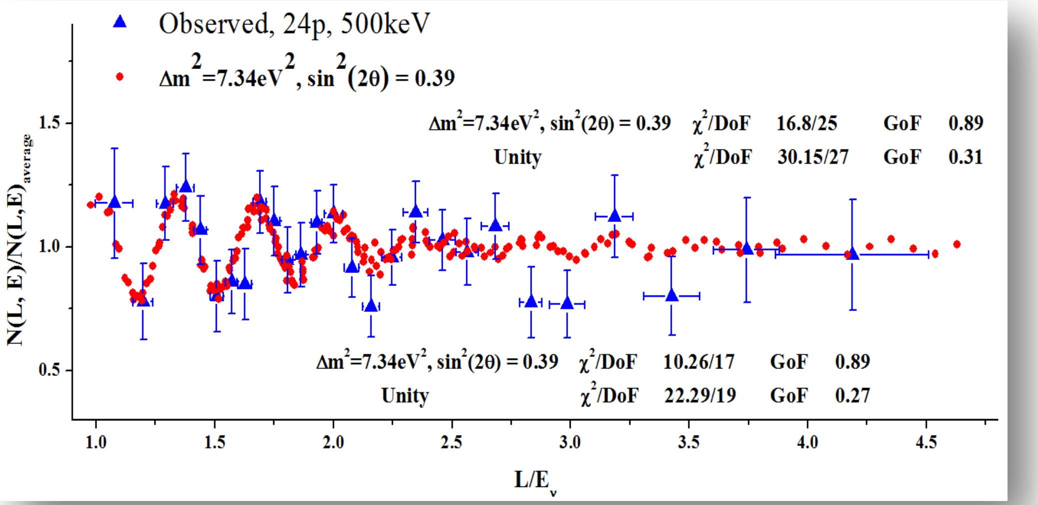
Monte Carlo calculations taking into account the sizes of the zone of the reactor of 42x42x35 cm3.

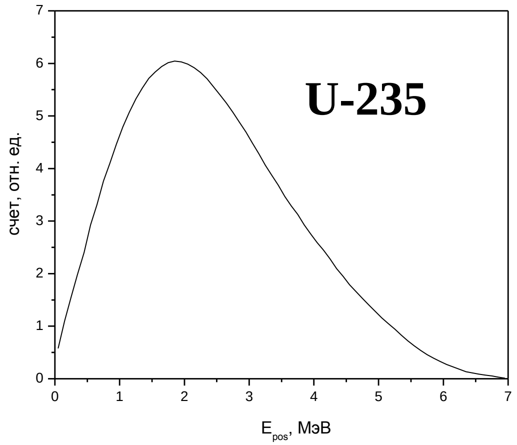




For

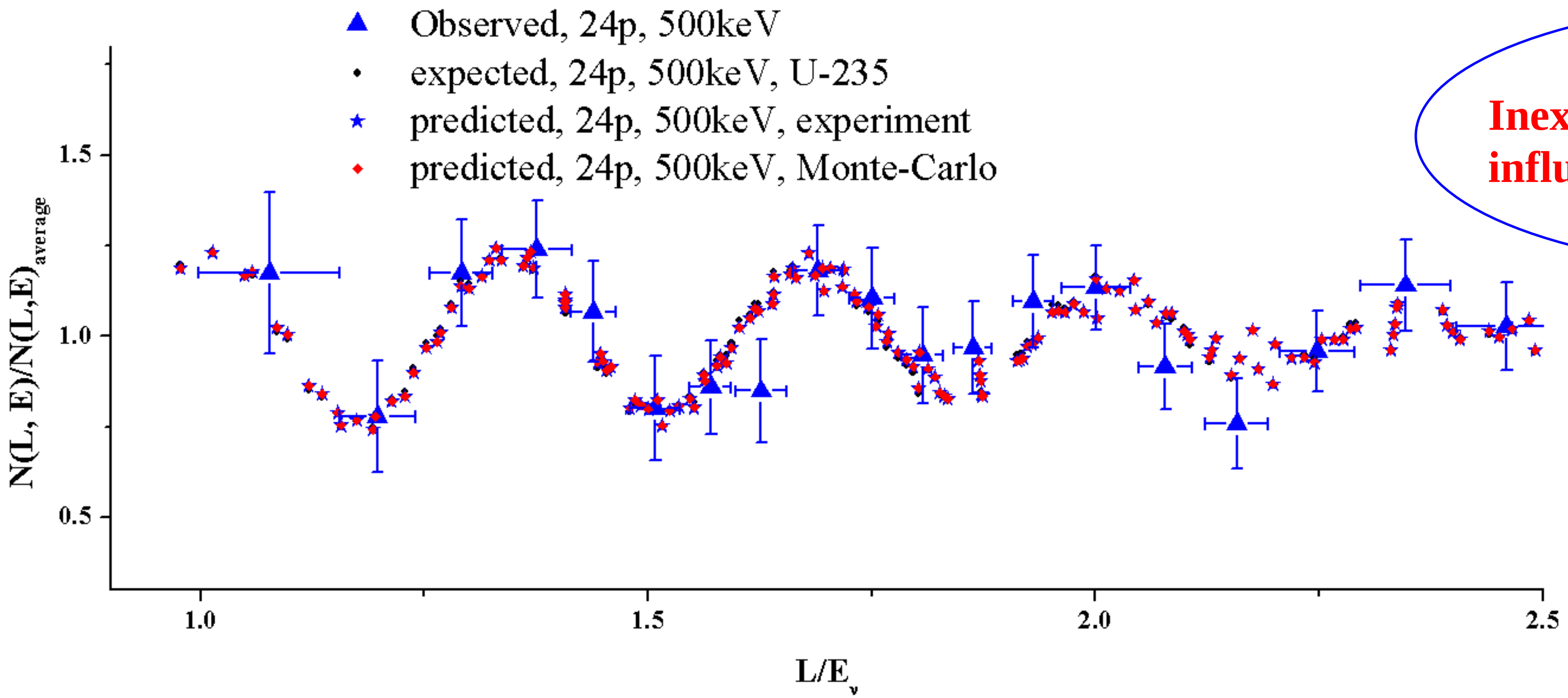
ΔE = 0.5MeV the picture of Monte Carlo of calculation is quite similar to the experimental picture.





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



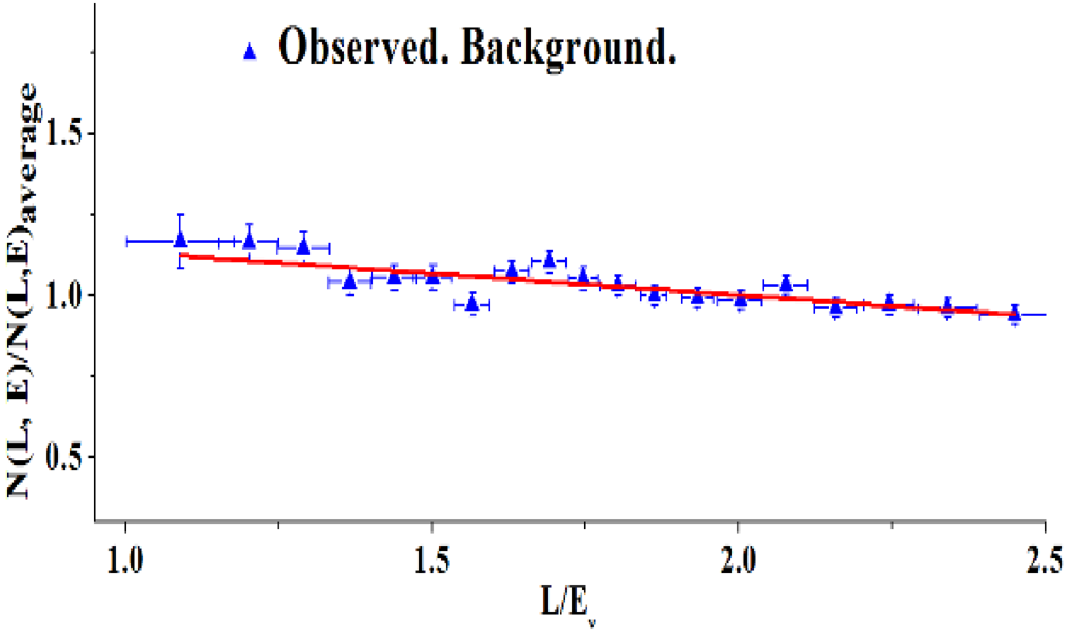
Inexact measurement of energy influences to definition of: Δm^2_{14}

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

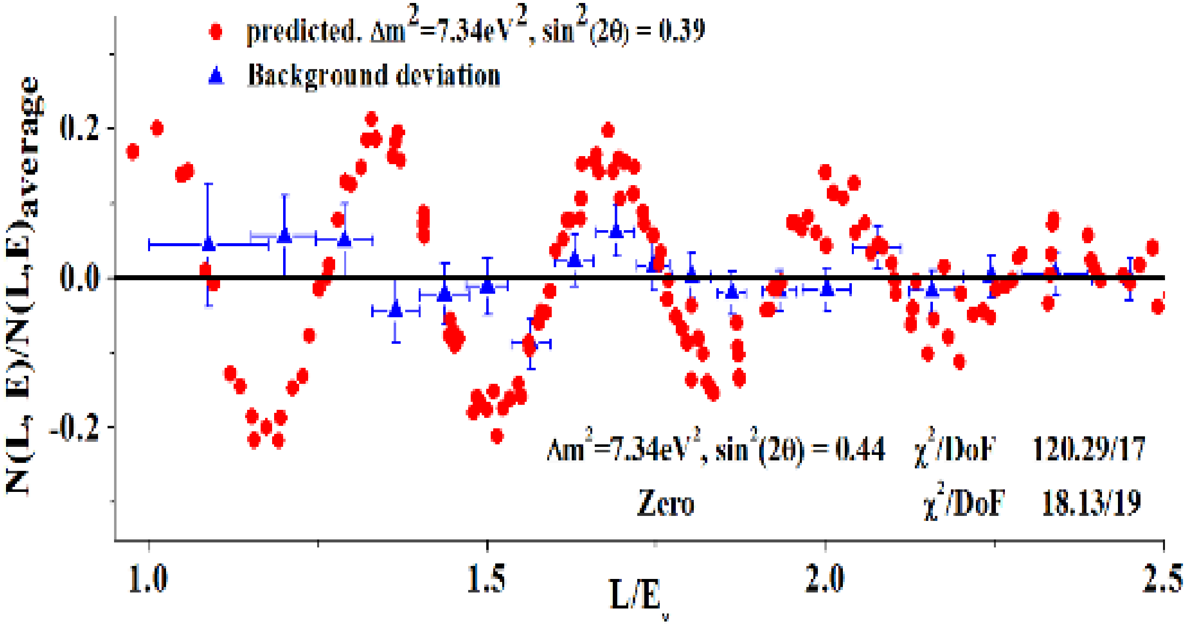
$$R^{\exp}_{i,k}=\frac{N(E_i,L_k)L_k^2}{K^{-1}\sum\limits_k^K N(E_i,L_k)L_k^2}=\frac{[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m^2_{14}L_k/E_i)]}{K^{-1}\sum\limits_k^K[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m^2_{14}L_k/E_i)]}=R^{th}_{i,k} \qquad (2)$$

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



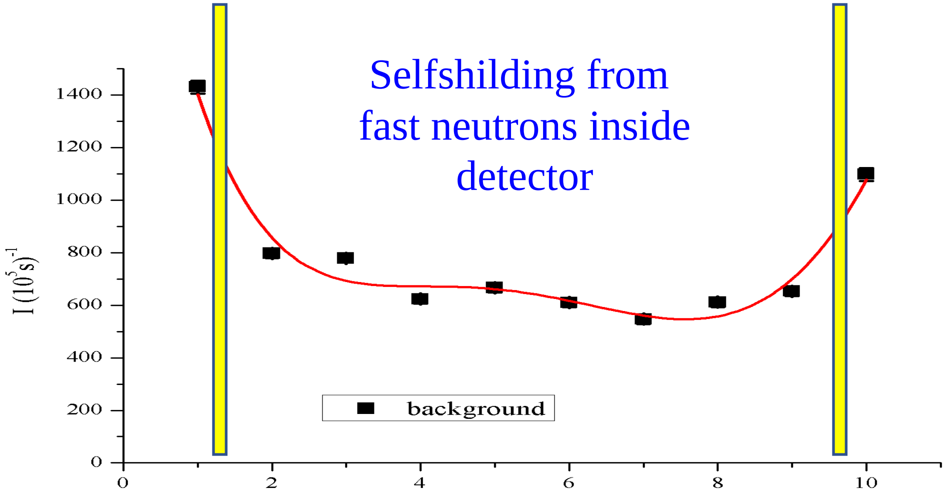
data analysis using coherent summation method



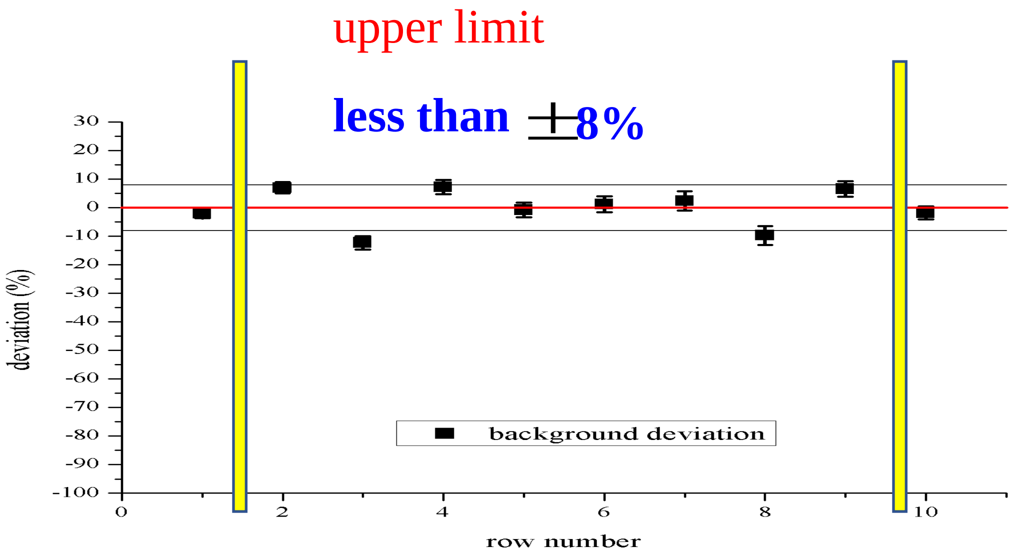
analysis of the results on oscillation parameters plane

Thus no instrumental systematic errors were observed.

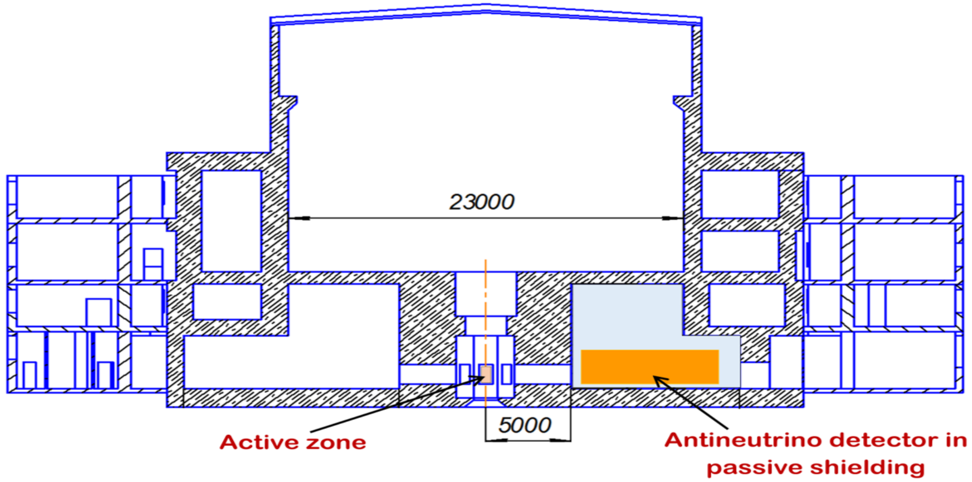
Analysis of possible difference in efficiency of rows of the detector, using the background of fast neutrons which is given rise into the building from cosmic muons.

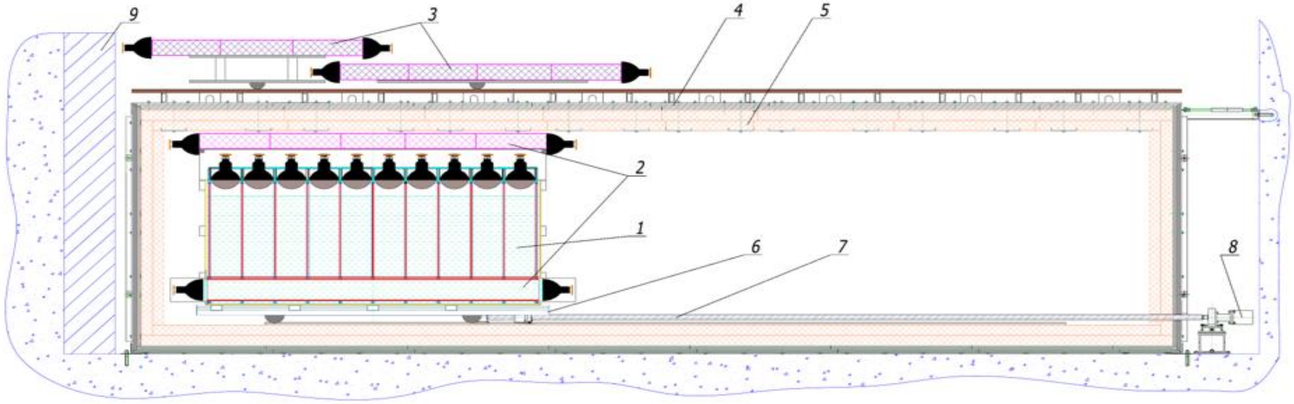


The background of fast neutrons is asymmetric because of structure of the building.



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



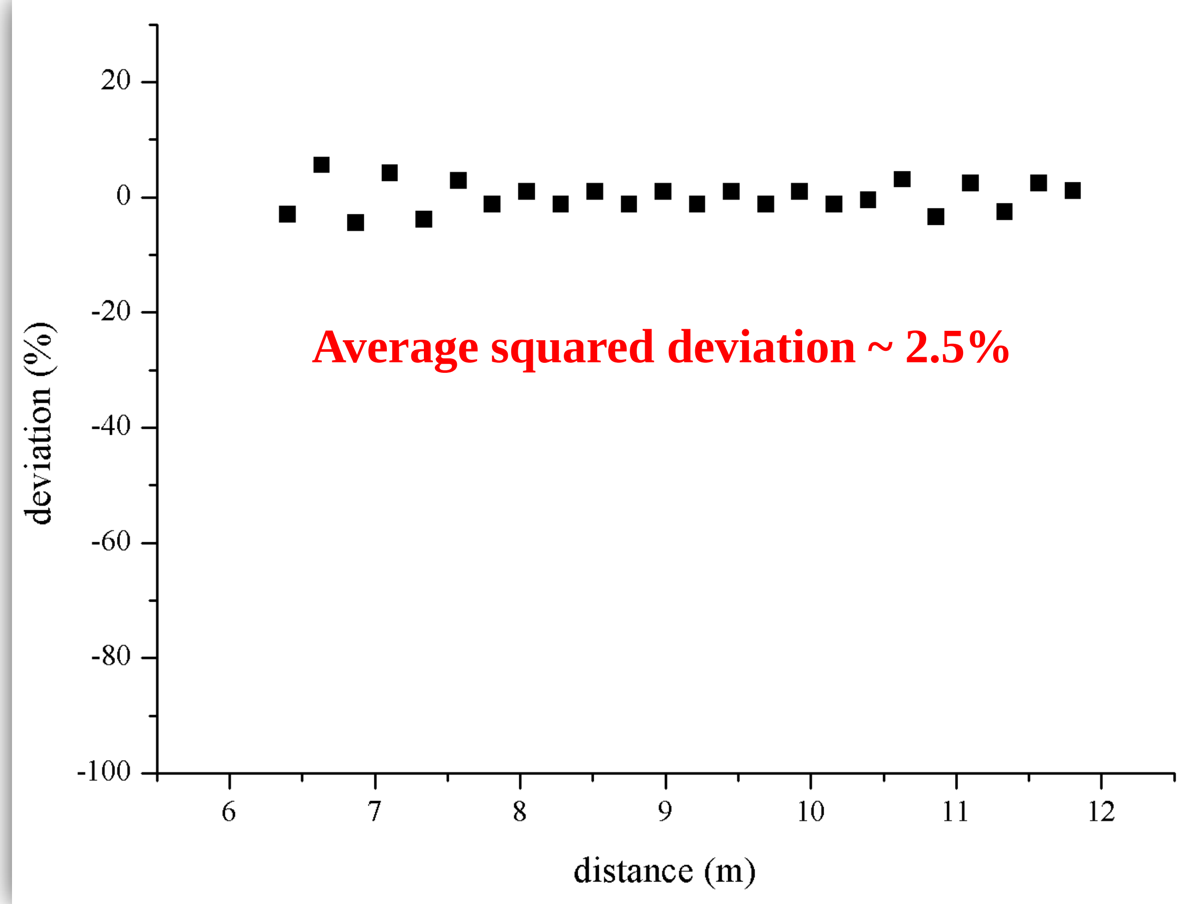


We use only 8 internal rows,
the first and tenth are protective.

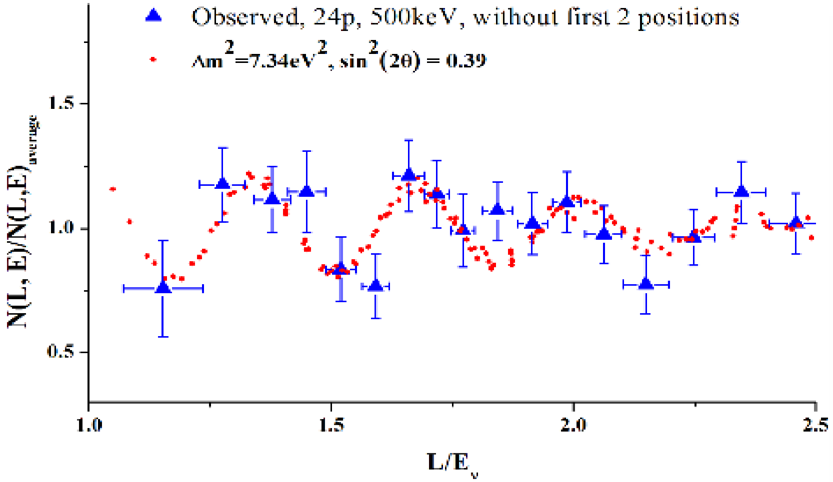
Averaging of detector rows efficiencies due to movements (above estimation)

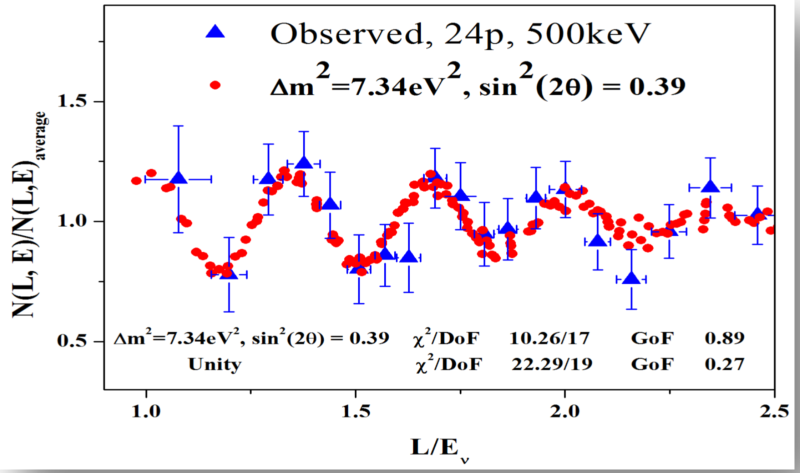
L(m)	Numbers of detector row				
6.4025	2				
6.6375	3				
6.8725	4	2			
7.1075	5	3			
7.3425	6	2	4		
7.5775	7	3	5		
7.8125	8	4	6	2	
8.0475	9	5	7	3	
8.2825	6	2	8	4	
8.5175	7	3	9	5	
8.7525	8	4	6	2	
8.9875	9	5	7	3	
9.2225	6	2	8	4	
9.4575	7	3	9	5	
9.6925	8	4	6	2	
9.9275	9	5	7	3	
10.1625	6	2	8	4	
10.3975	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			

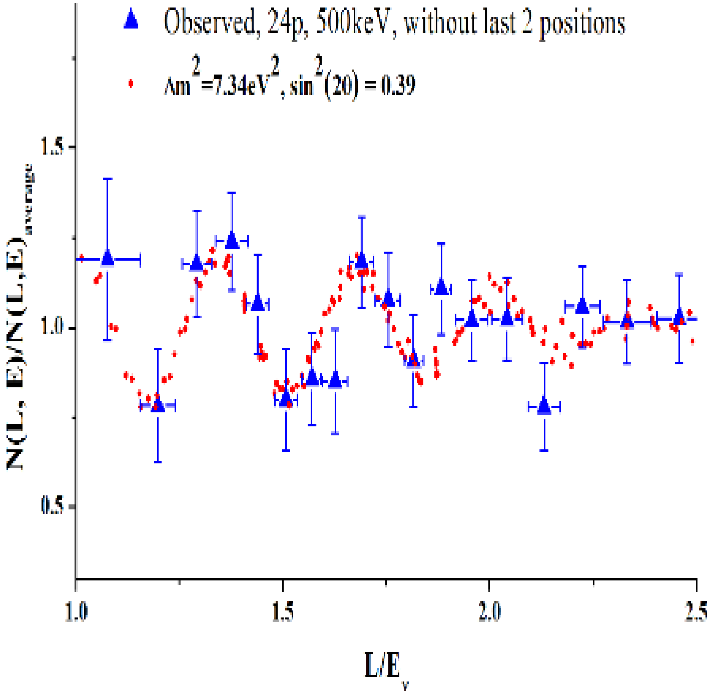
Average efficiency at various distances

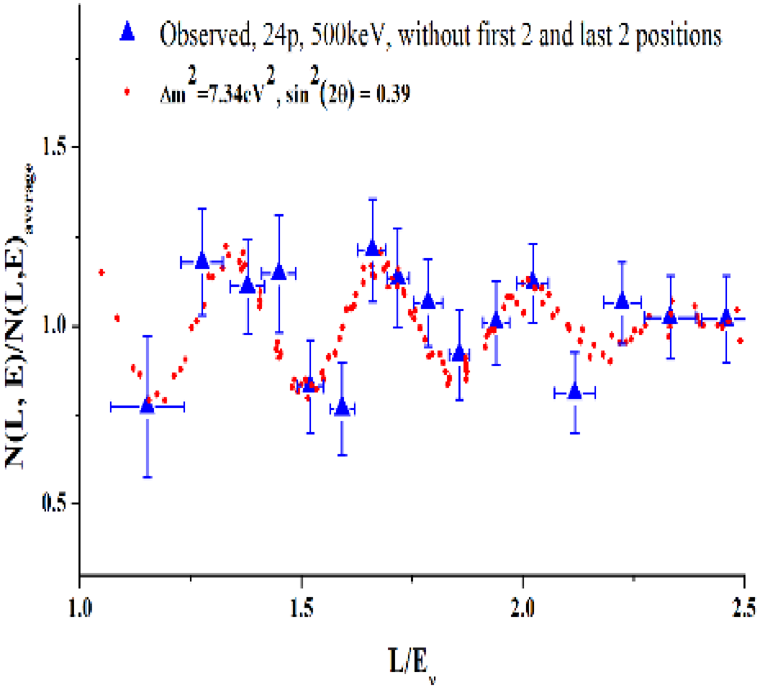


Test of stability of the effect by means of removal of extreme positions





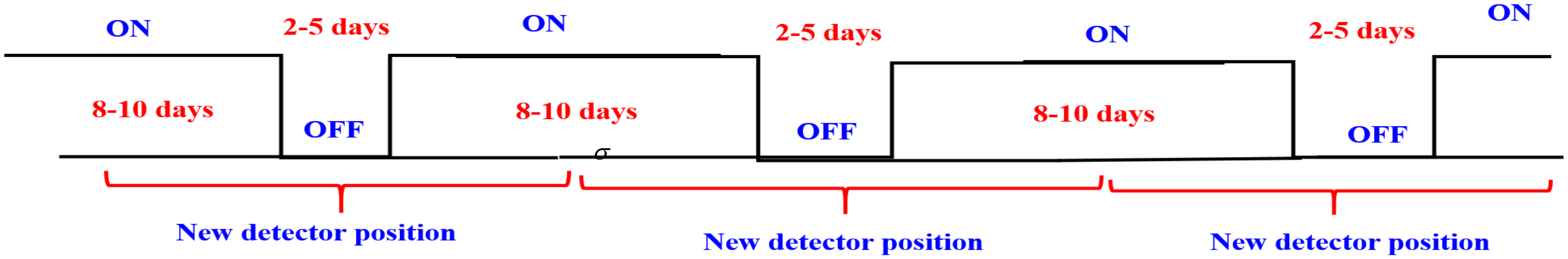


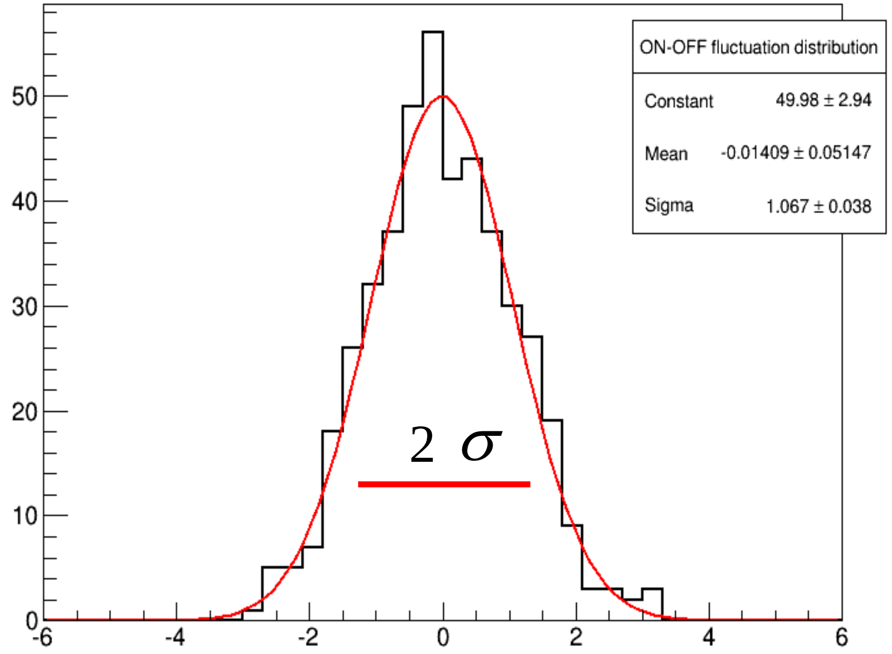


Conclusion

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.

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





$$\sigma = 1.067 \pm 0.038$$

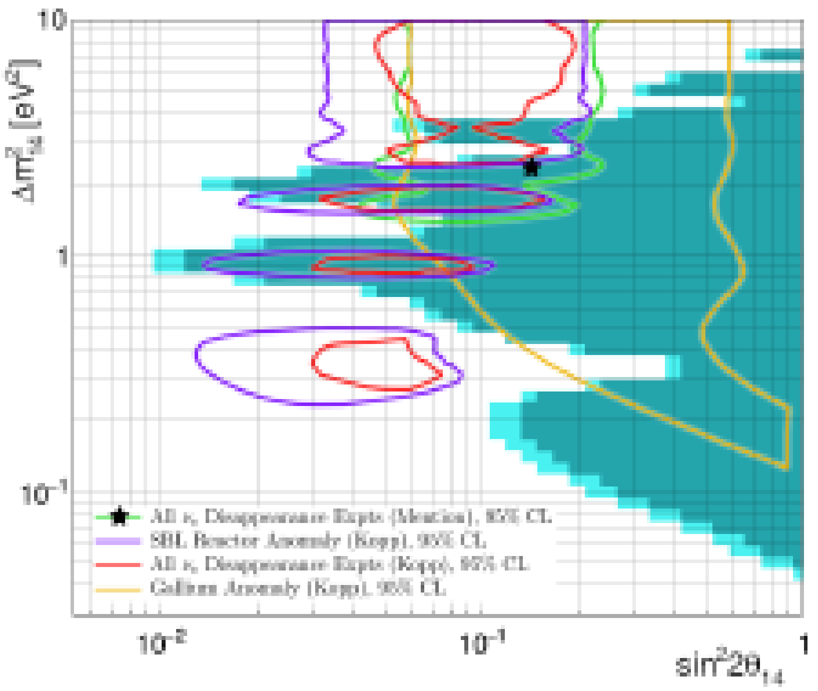
Since the measurements of the background carried out during the annual scheduled reactor repair works, then total additional dispersion is increased up to ~ **9%**.

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%.**

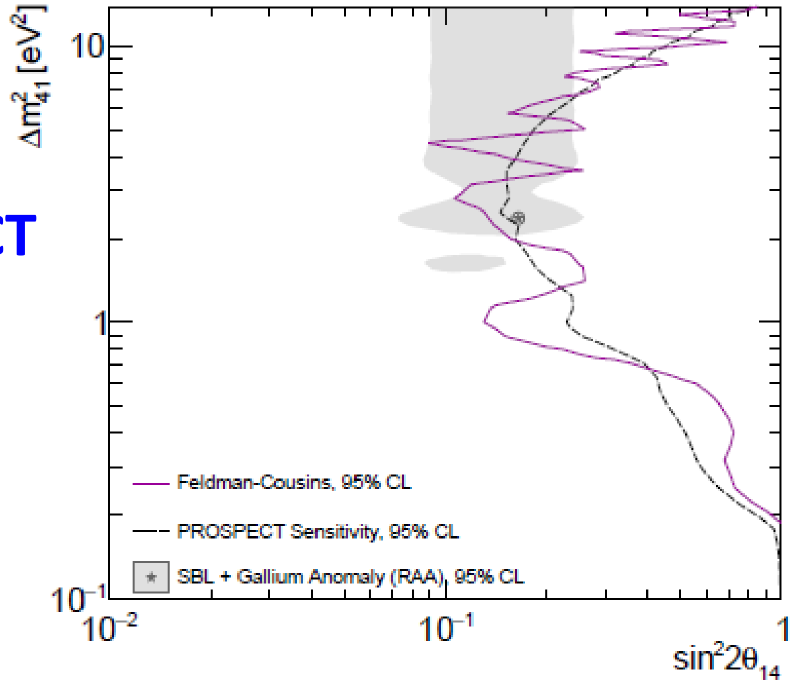
Obtained results should be compared with other results of experiments with short base line carried out at research reactors and nuclear power plants.

Next slide illustrates sensitivity of other experiments NEOS , DANSS , STEREO and PROSPECT together with Neutrino-4.

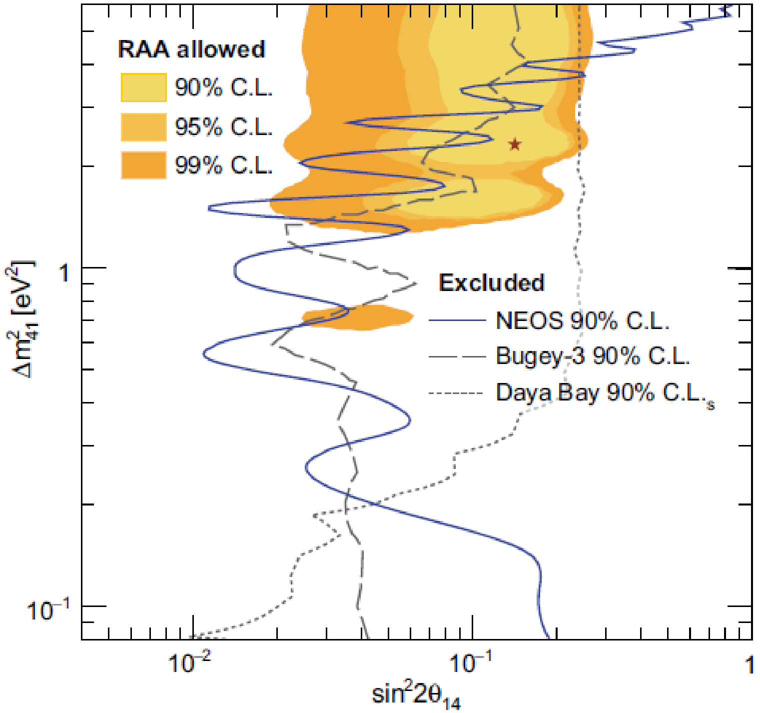


DANSS
90%

PROSPECT
95%

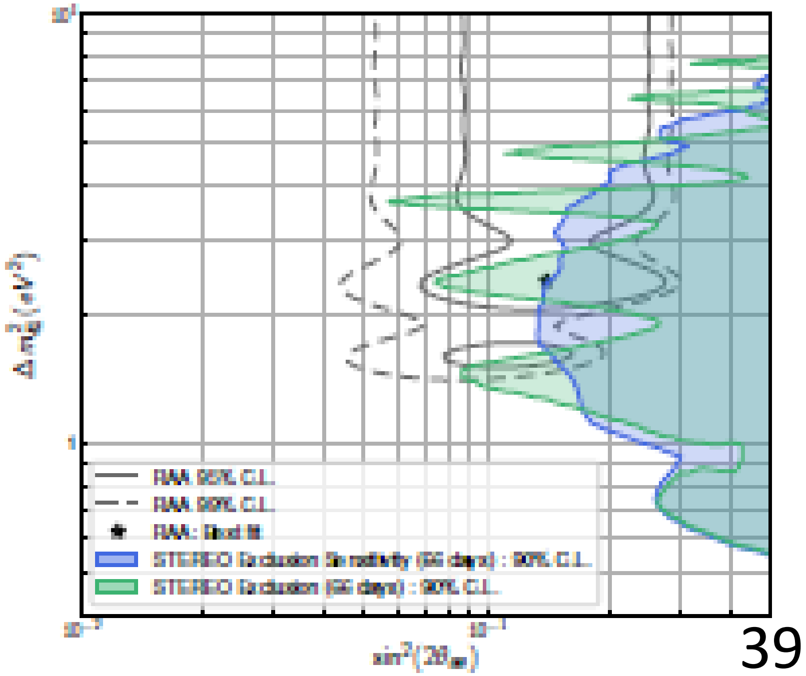


The slide illustrates sensitivity of other experiments: NEOS , DANSS , STEREO and PROSPECT

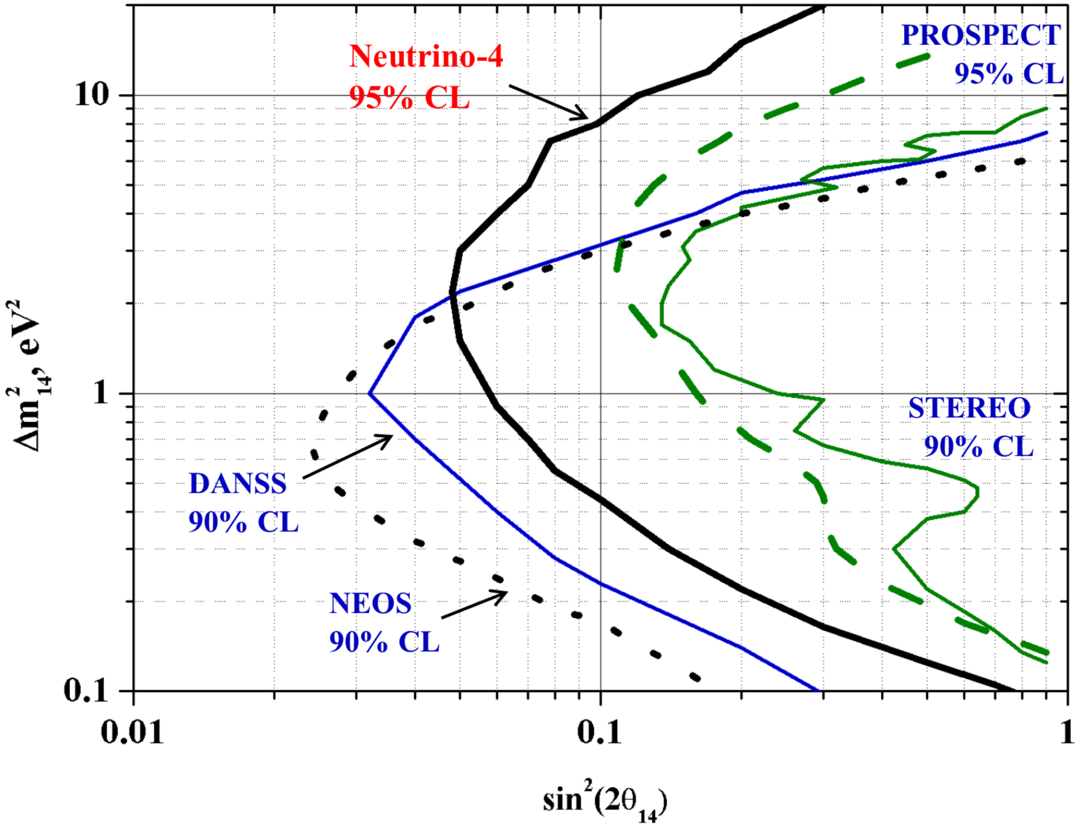


NEOS
90%

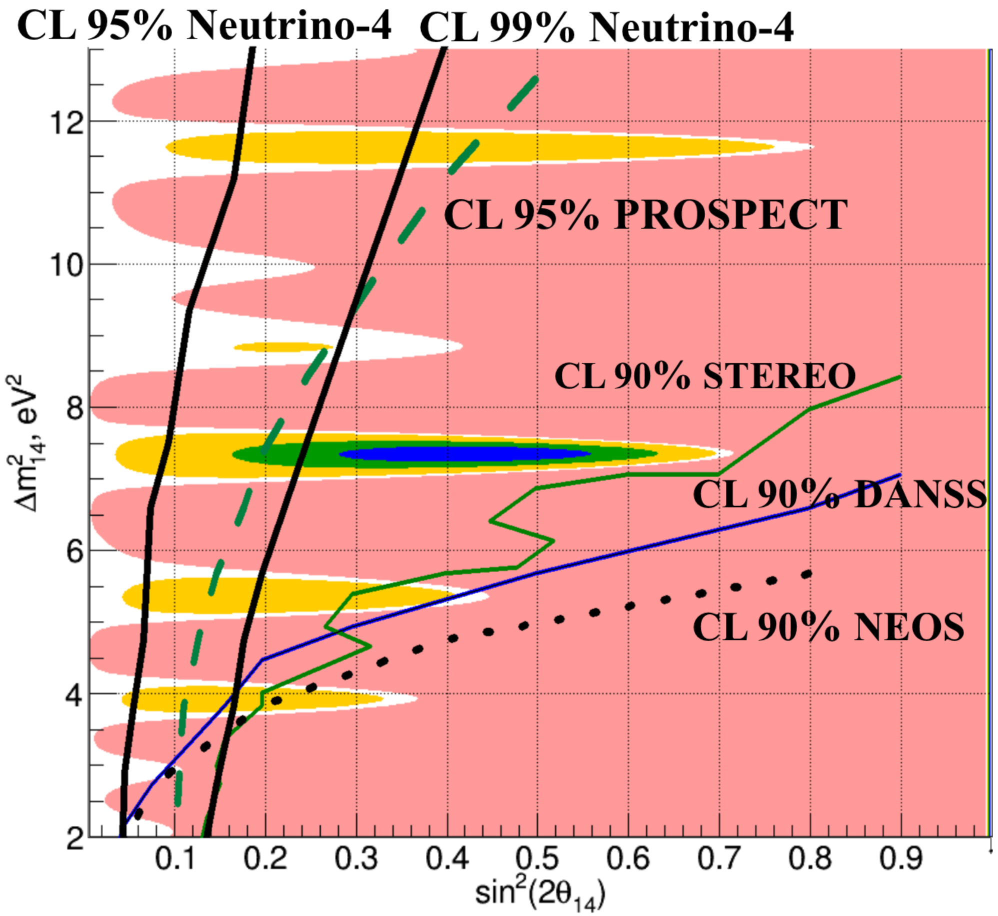
STEREO
90%



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.

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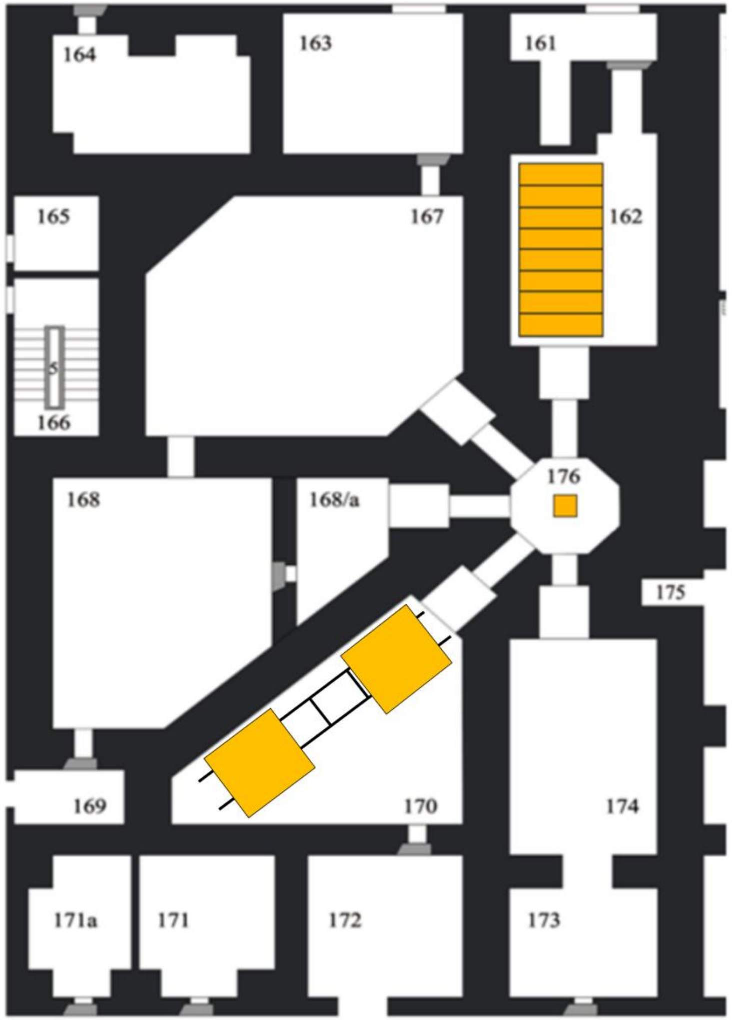
Future plans: Experiment Neutrino-6



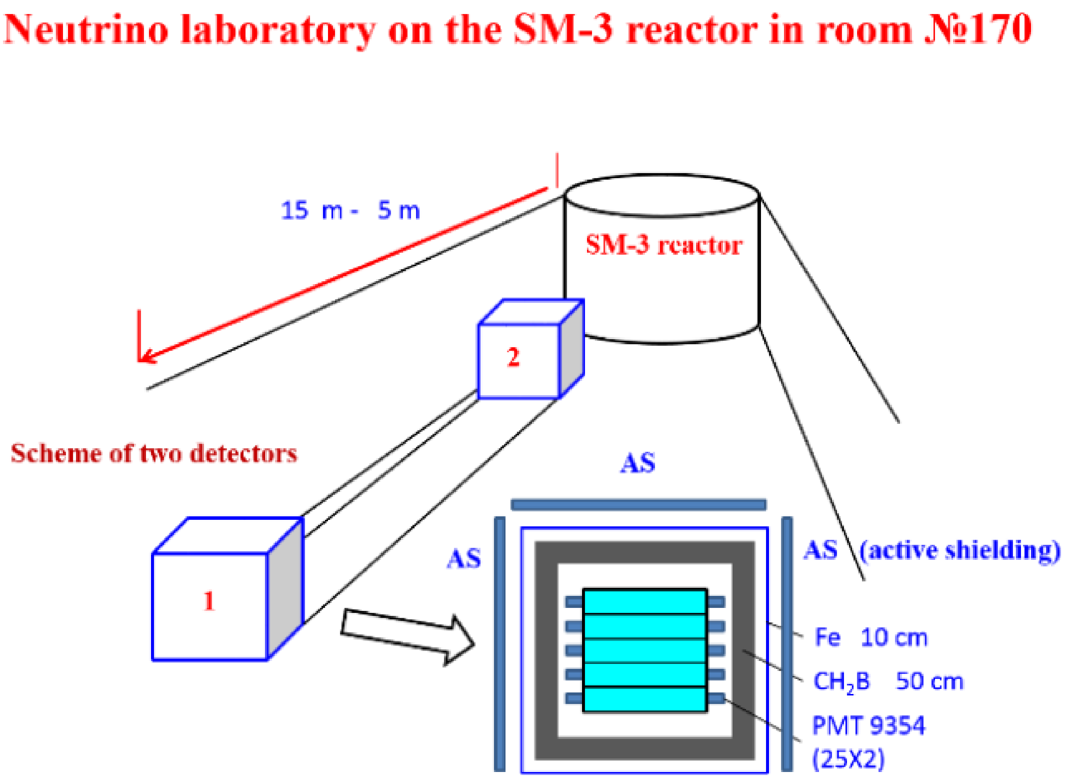
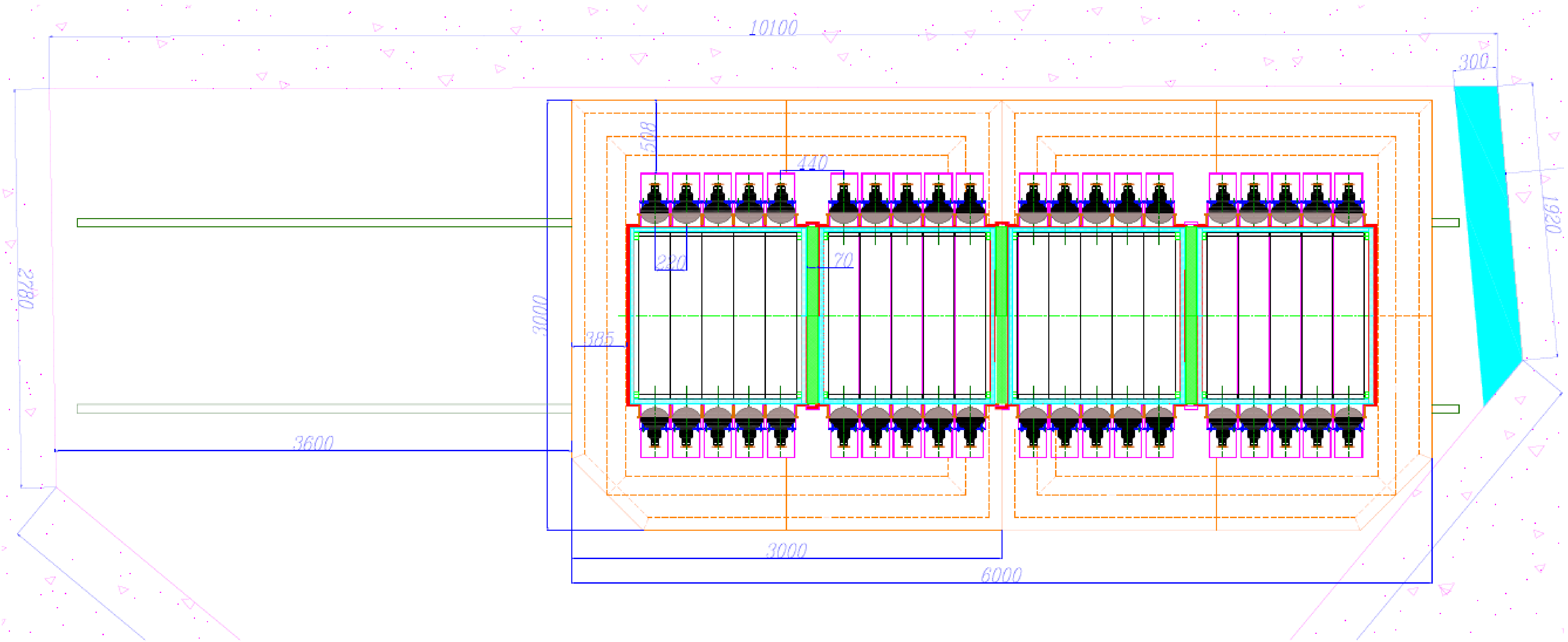


FIG. 22. Scheme of a new experiment on search for neutrino oscillations in room No. 170 of the SM-3 reactor.

Future plans: Experiment Neutrino-6



For conclusion

In general, it seems that the effect predicted in gallium and reactor experiments is being confirmed but at sufficiently large value

$$\Delta m_{14}^2 \approx 7.3 эВ^2$$

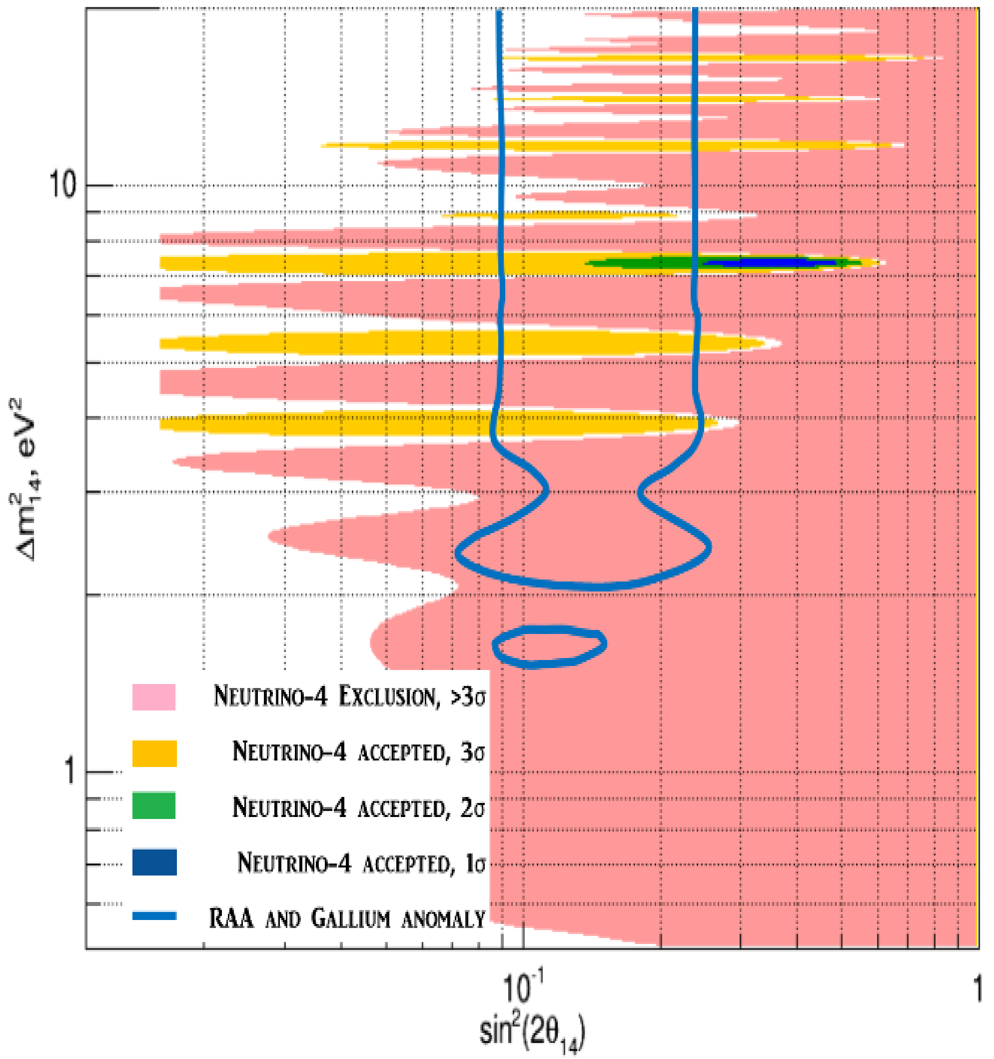
Moreover, presented mixing parameter

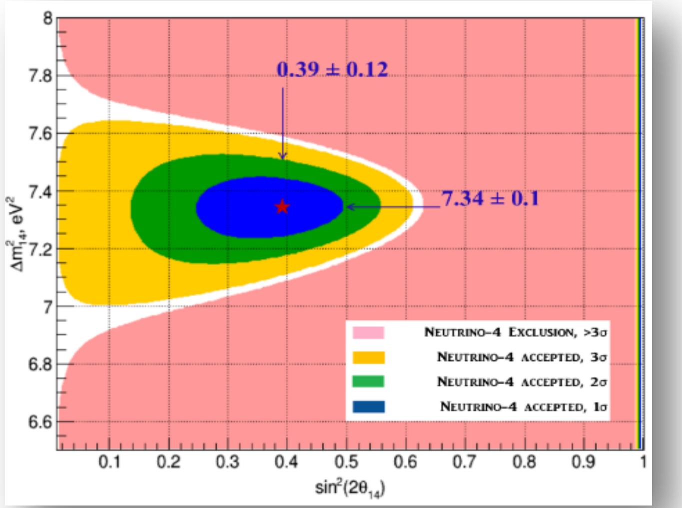
$$\sin^2 2\theta_{14} = 0.39 \pm 0.14$$

is rather big in comparison with existing limits obtained in experiments Daya Bay and Bugey-3, which gave an upper limit at level 0.2 with 90% C.L. i.e. 0.20±0.12.

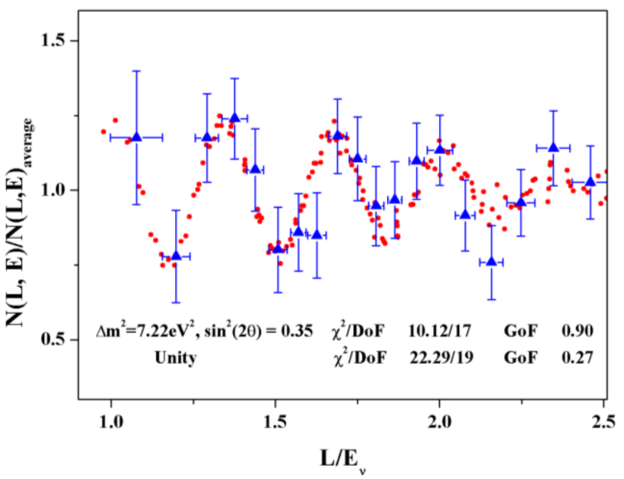
Therefore, discrepancy between the results is 0.19±0.18 i.e. one standard deviation. Thus, there is no obvious contradiction.

However, confidence level is not sufficient. Therefore, increasing of experimental accuracy is essential as well as additional analysis of possible systematic errors of the experiment.



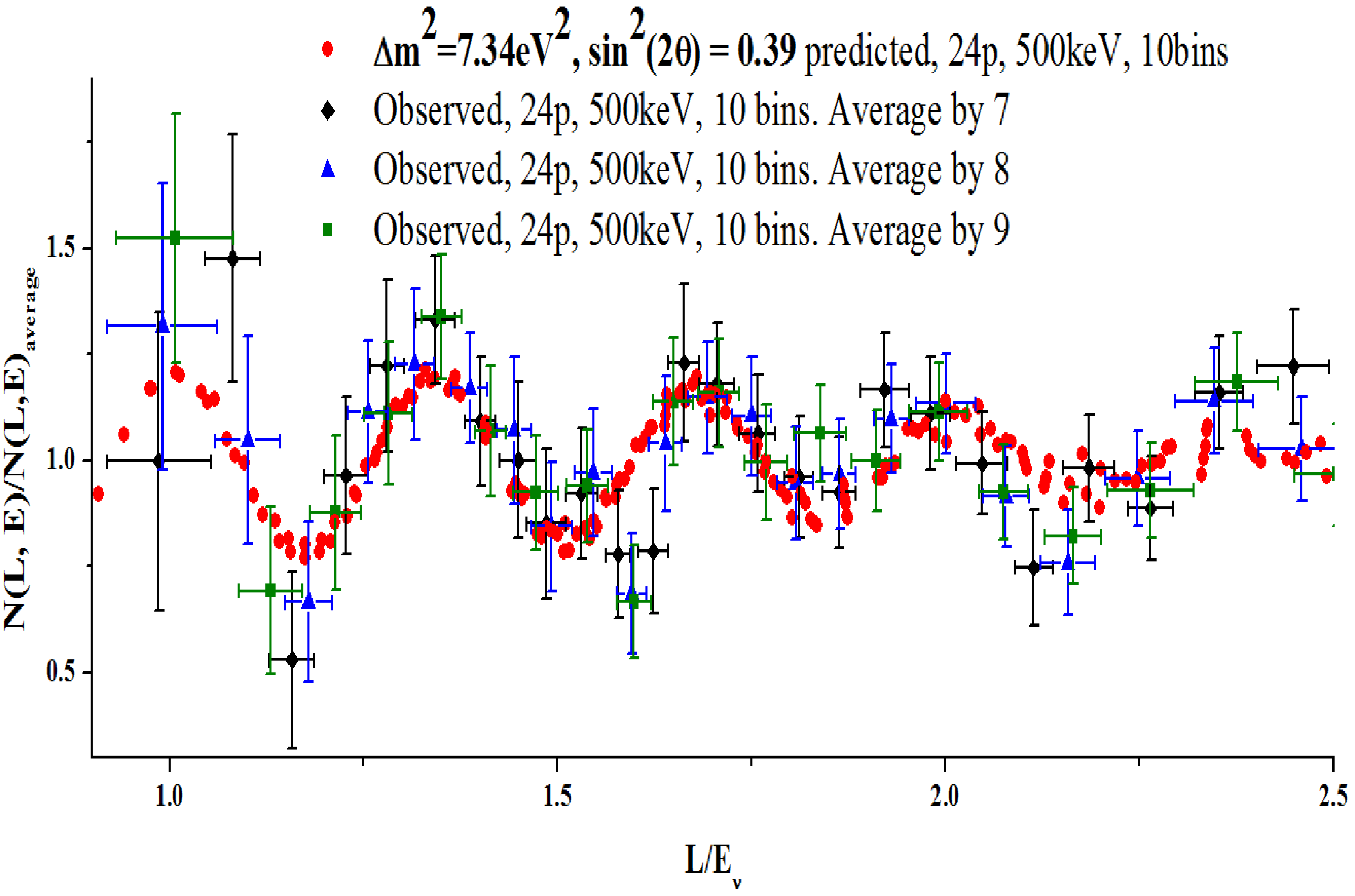


Thank you for attention

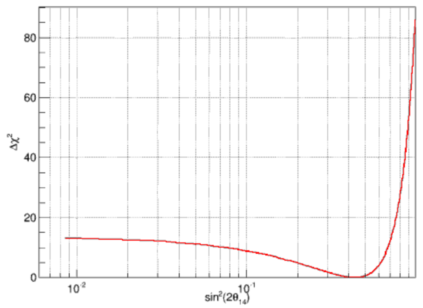


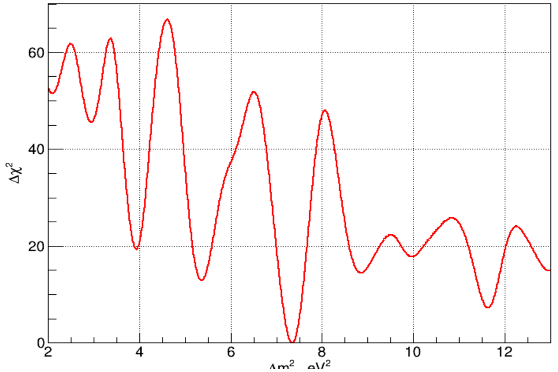
Best regards from Gatchina

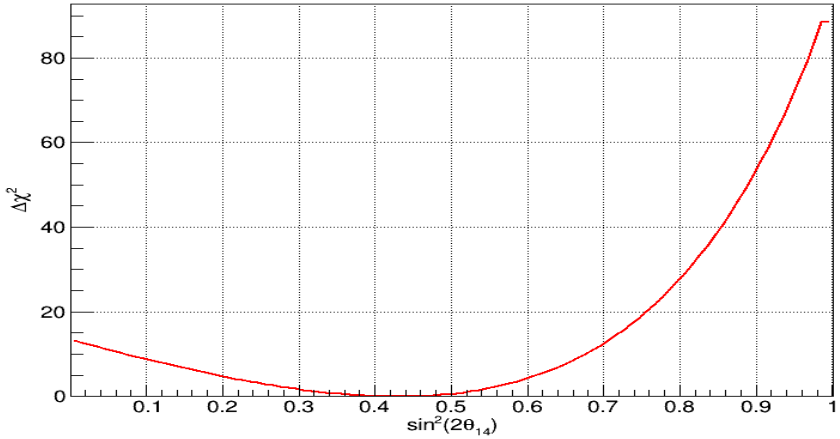
Best regards from Dimitrovgrad

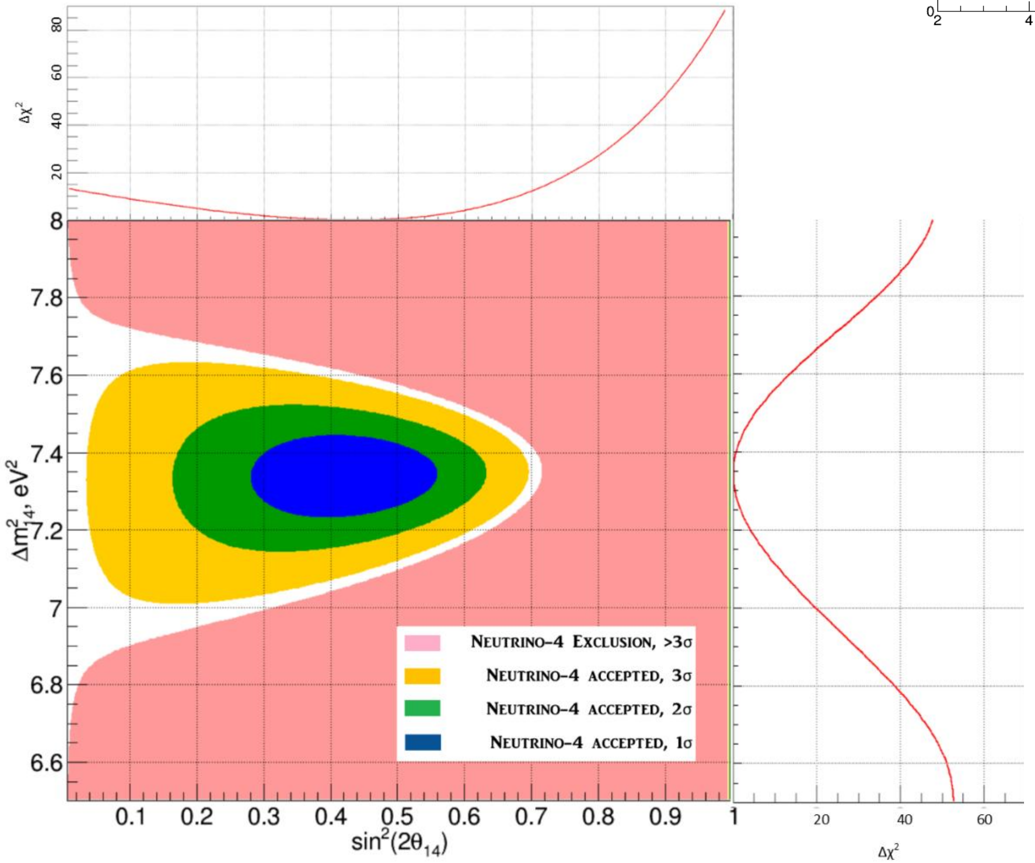


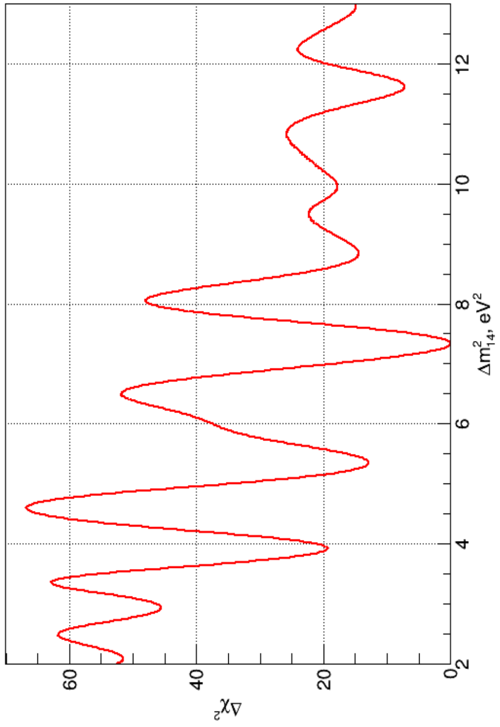
Δm^2=7.34eV^2, sin^2(2θ) = 0.39 predicted, 24p, 500keV, 10bins
Observed, 24p, 500keV, 10 bins. Average by 7
Observed, 24p, 500keV, 10 bins. Average by 8
Observed, 24p, 500keV, 10 bins. Average by 9
N(L, E)/N(L, E)$_{average}$
1.5
1.0
0.5
1.0
1.5
2.0
2.5
L/E$_\nu$

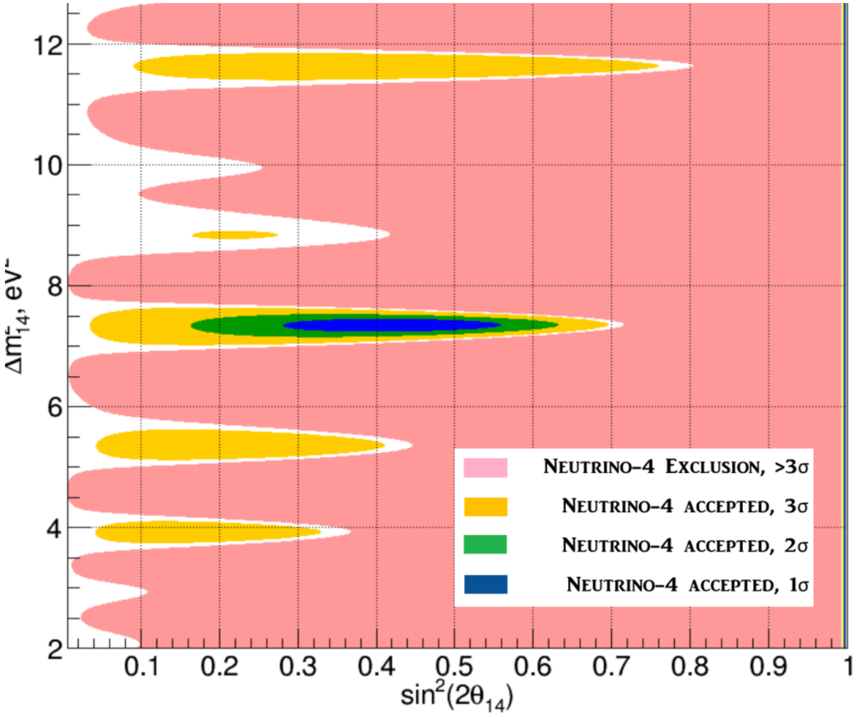




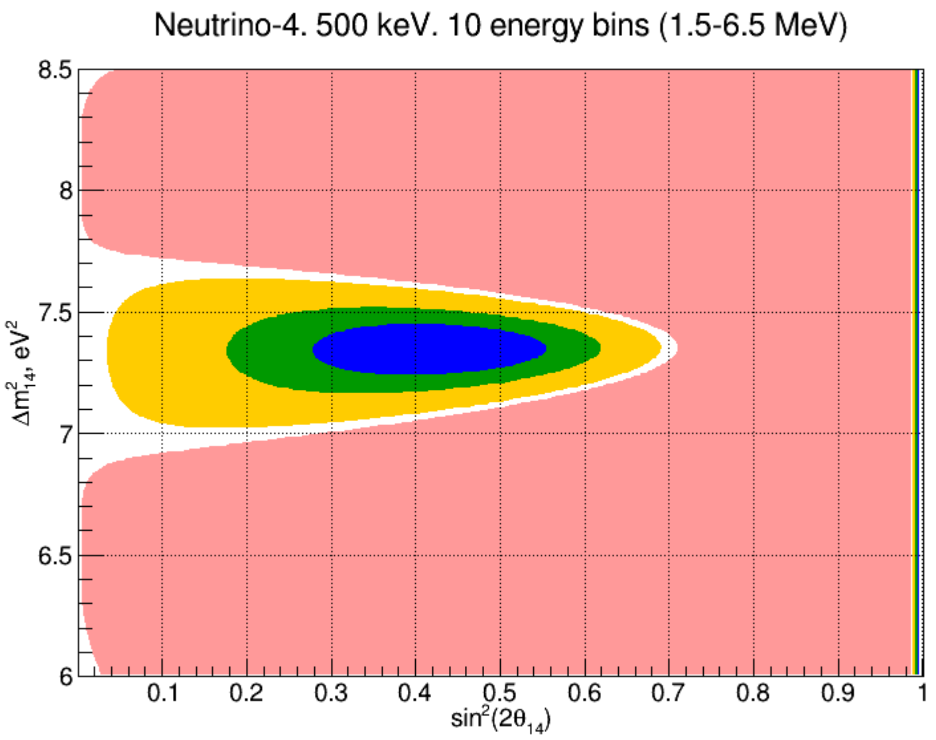


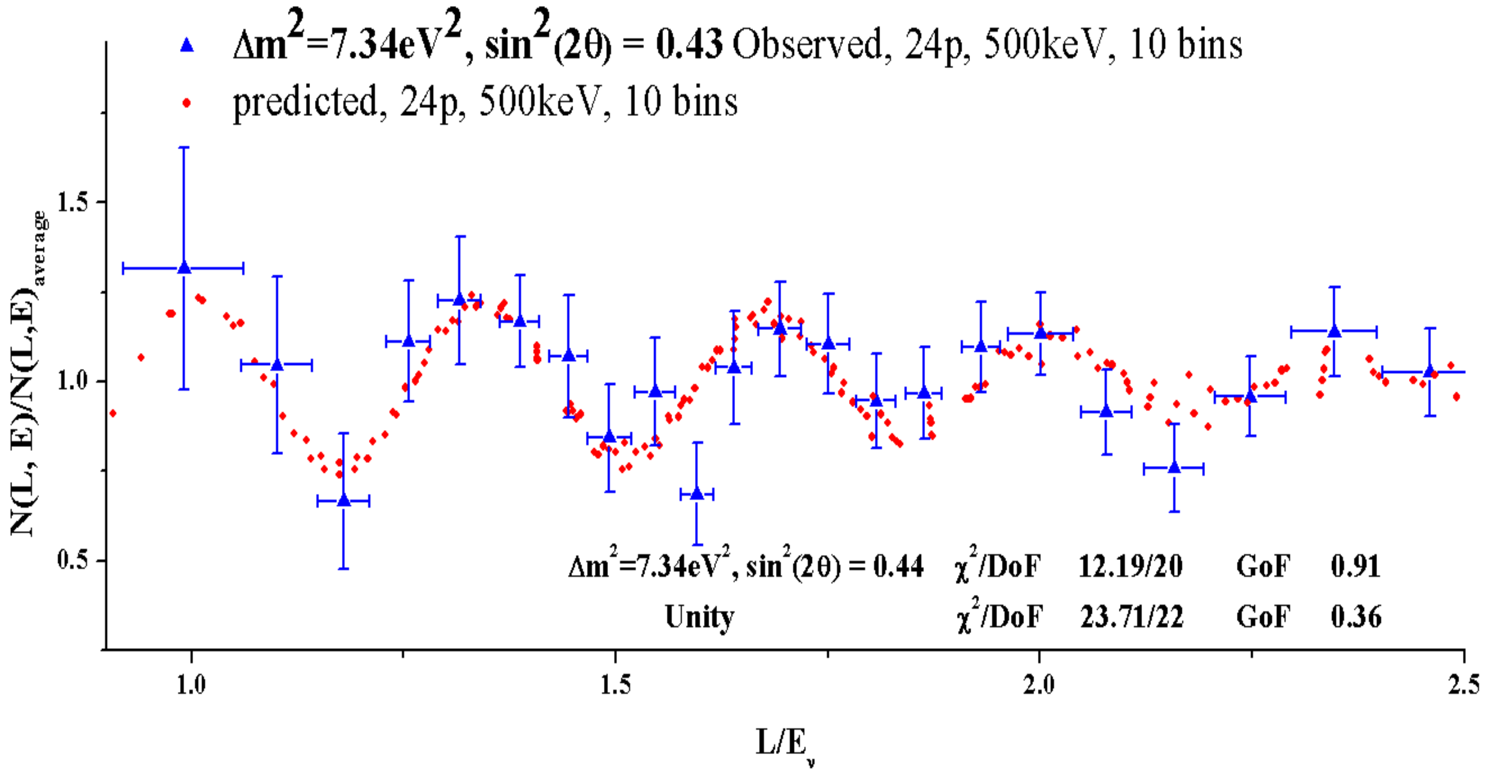

Neutrino-4 Exclusion, >3σ
Neutrino-4 accepted, 3σ
Neutrino-4 accepted, 2σ
Neutrino-4 accepted, 1σ
Δm^2_{14}, eV^2
$\sin^2(2\theta_{14})$
$\Delta\chi^2$


Δm^2_{14}, eV^2
$\Delta\chi^2$


Neutrino-4 Exclusion, >3σ
Neutrino-4 accepted, 3σ
Neutrino-4 accepted, 2σ
Neutrino-4 accepted, 1σ
Δm^2_{14}, eV^2
$\sin^2(2\theta_{14})$

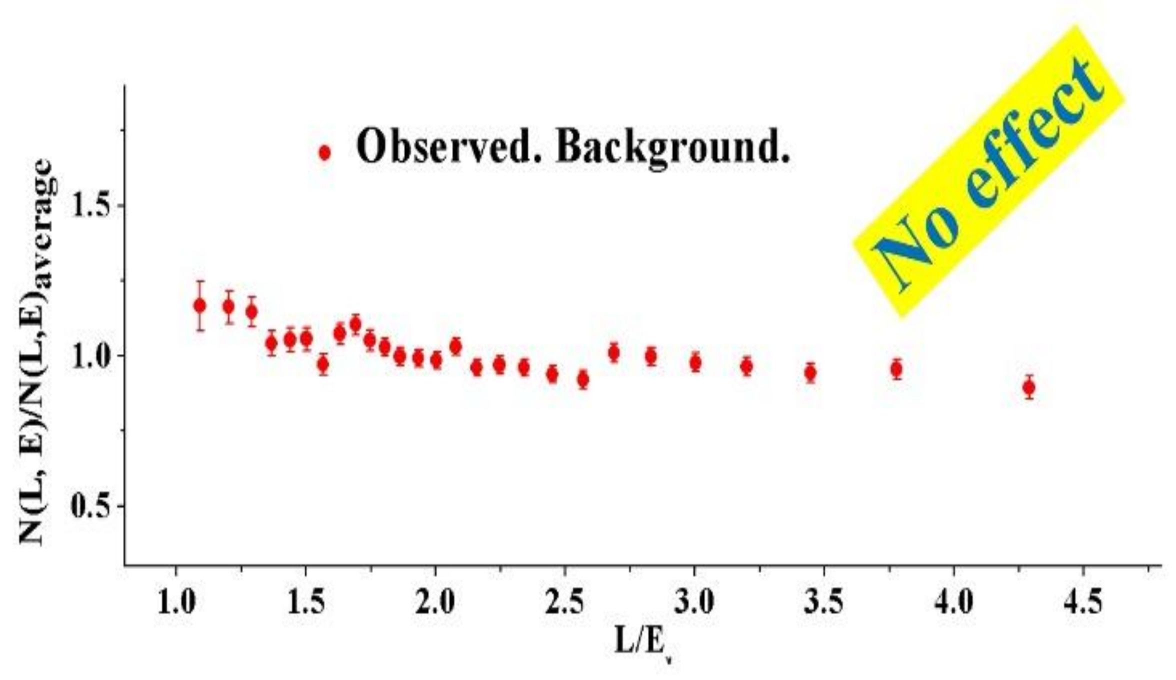
10 energy bins (1.5-6.5 MeV)



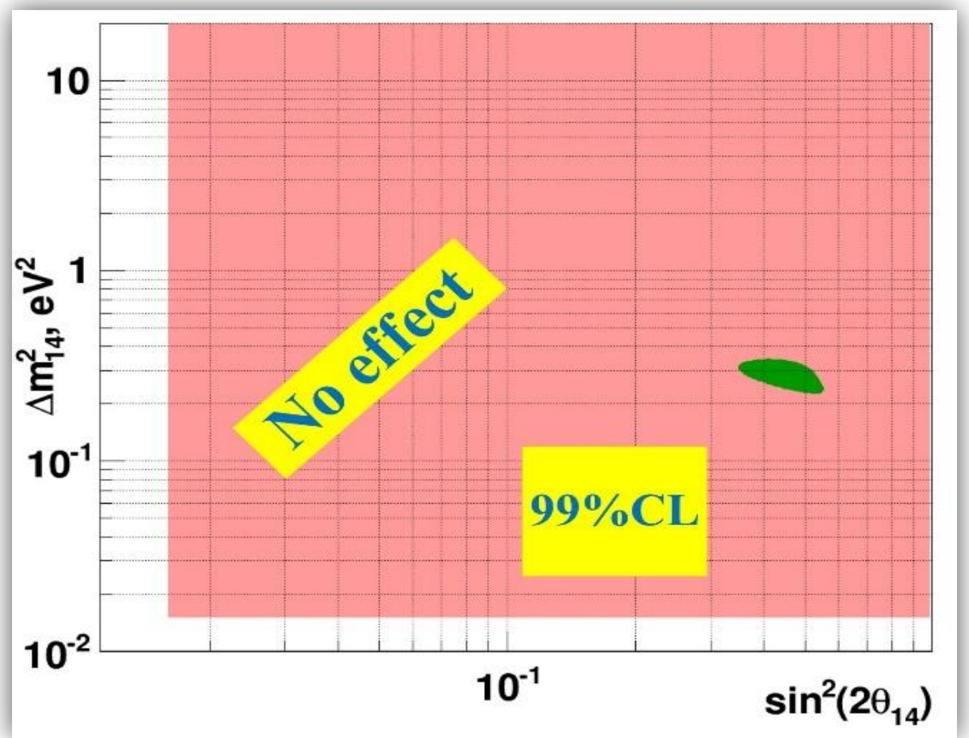


Test of systematic effects

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.

Problems with energy spectrum

1. Calculations of reactor flux can be one of the possible reasons for discrepancy. Taking into consideration 0.934 deficiency for an experimental antineutrino flux with respect to the calculated one, we should discuss not the «bump» in 5 MeV area, but the «hole» in 3 MeV area.

2. We should also consider possibility of systematic errors in calibration of energy scale or Monte-Carlo calculations of prompt signal spectrum in low energy region. There is a problem of precise registration of annihilation gamma energy (511 keV) in adjacent sections. Thus, energy point 1.5 MeV is the most problematic one.

3. Finally, one should take into account influence of oscillations with high Δm^2_{14} because we use 2m interval in analysis. Using such averaging, if $\Delta m^2_{14} > 5eV^2$ then spectrum would be suppressed by factor $1-0.5\sin^2 2\theta_{14}$ starting from low energies.

Conclusion: The method of the analysis of experimental data should not rely on precise knowledge of spectrum.

About accounting of correlations in the equation 2

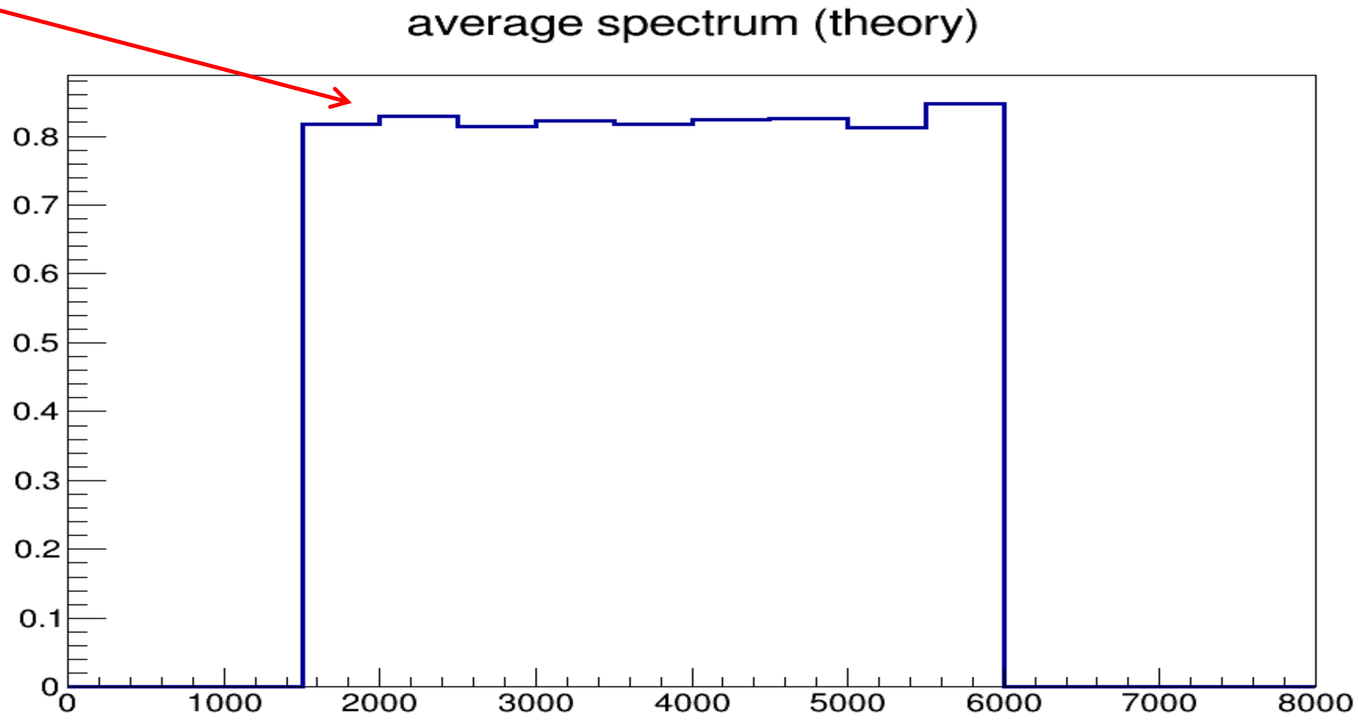
$$R_{i,k}^{\exp} = \frac{N(E_i, L_k)L_k^2}{K^{-1}\sum_k^K N(E_i,L_k)L_k^2} = \frac{[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 L_k / E_i)]}{K^{-1}\sum_k^K [1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 L_k / E_i)]} = R_{i,k}^{th} \qquad (2)$$

$$K^{-1}\sum_k^K [1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m_{14}^2 L_k / E_i)]$$

average 0.82 +-0.01 on dispersion

On the average on all distances from 6 to 12 meters with optimum parameters:

$$\Delta m_{14}^2 \sim 7эВ^2 \qquad \sin^2 2\theta_{14} \sim 0.4$$

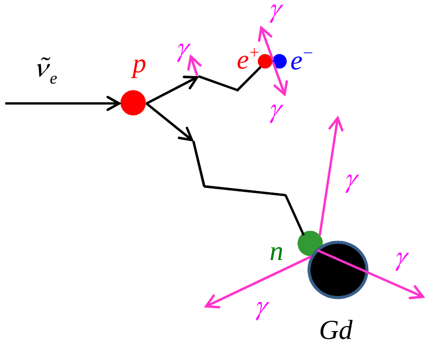


Conclusion: correlations on the spectrum are, but they much less statistical errors and we do not consider them yet.

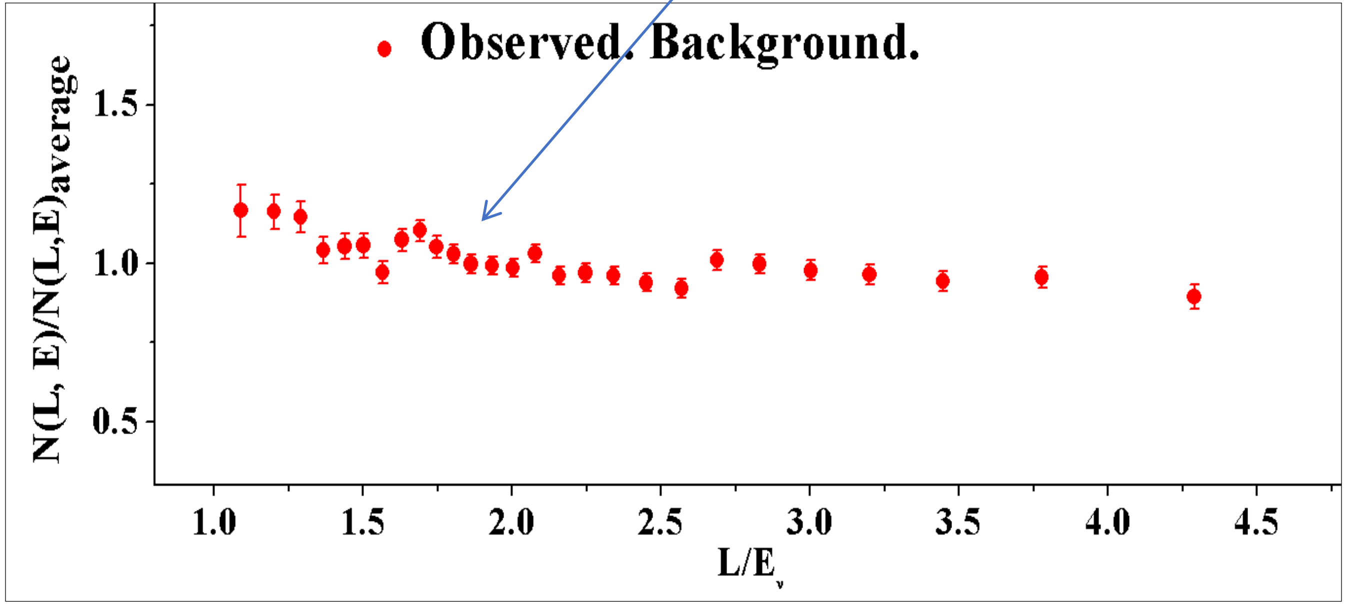
The liquid scintillator detector has volume of 1.8 m^3 (5x10 sections 0.225x0.225x0.85м^3, filled to the height of 70 cm). Scintillator with gadolinium concentration 0.1% was using to detect inverse beta decay (IBD) events. The first and last detector rows were also used as an active shielding and at the same time as a passive shielding from the fast neutrons. Thus, fiducial volume of scintillator is **1.42 m^3**.

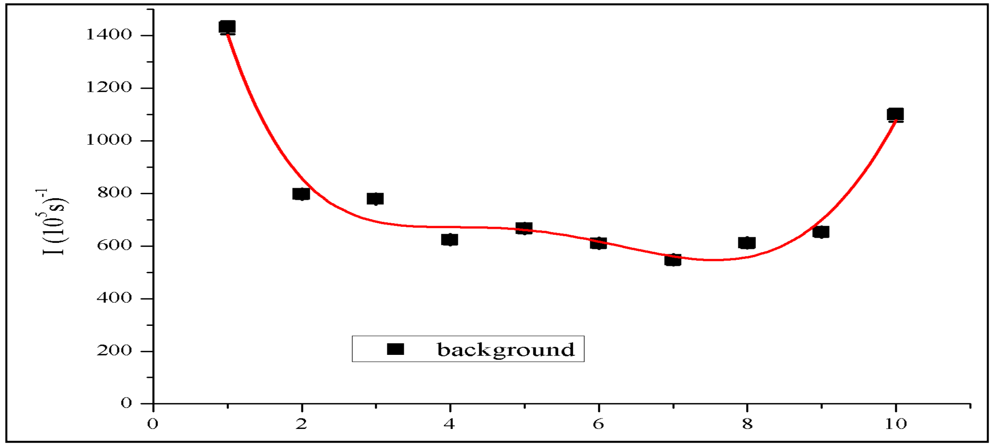
The method of antineutrino registration is to select correlated pare of signals: prompt positron signal and delayed signal of neutron captured by gadolinium.

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



Explanation of variations in the L/E dependence for a background

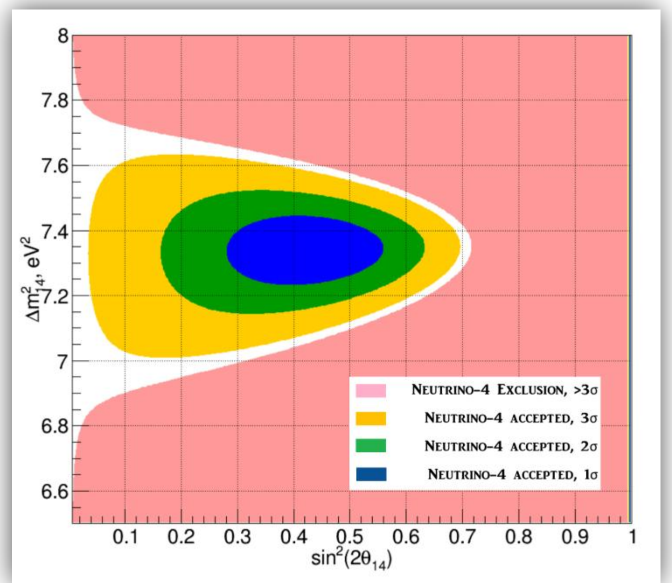




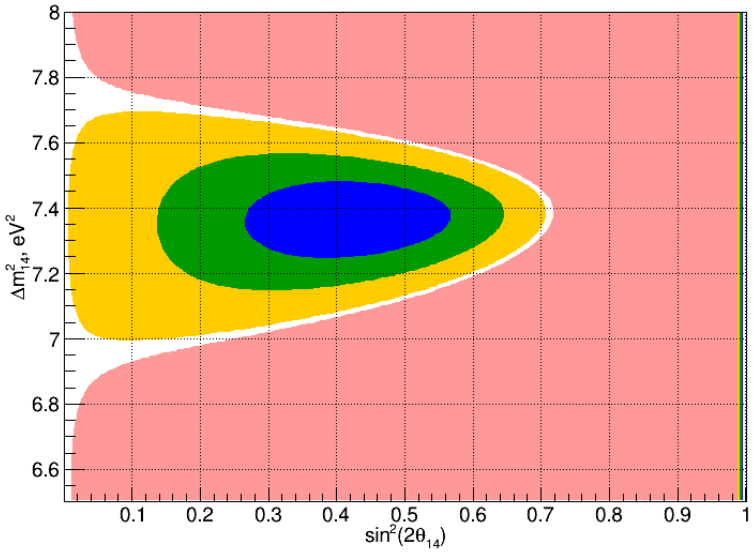
Reason - Different positions of the detector are looked through.

This effect in the difference of ON-OFF is subtracted.

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

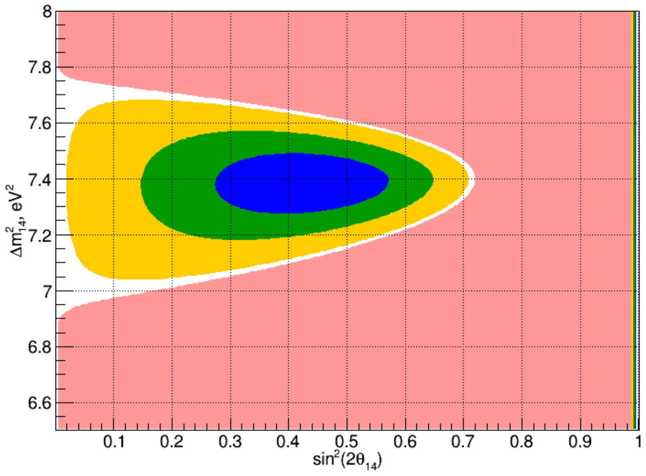


Neutrino-4. Without first 2 and last 2 positions.



After removal of extreme positions the effect still is in limits the 3rd sigma.

Neutrino-4. Without first 2 positions.



Neutrino-4. Without last 2 positions.