

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

**A.P. Serebrov *NRC “KI” PNPI, Gatchina, Russia***

A.P. Serebrov<sup>1</sup>, R.M. Samoilov<sup>1</sup>, V.G. Ivochkin<sup>1</sup>, A.K. Fomin<sup>1</sup>, A.O. Polyushkin<sup>1</sup>, V.G. Zinoviev<sup>1</sup>, P.V. Neustroev<sup>1</sup>, V.L. Golovtsov<sup>1</sup>, A.V. Chernyj<sup>1</sup>, O.M. Zhrebtsov<sup>1</sup>, M.E. Chaikovskii<sup>1</sup>, V.P. Martemyanov<sup>2</sup>, V.G. Tarasenkov<sup>2</sup>, V.I. Aleshin<sup>2</sup>, A.L. Petelin<sup>3</sup>, A.L. Izhutov<sup>3</sup>, A.A. Tuzov<sup>3</sup>, S.A. Sazontov<sup>3</sup>, M.O. Gromov<sup>3</sup>, V.V. Afanasiev<sup>3</sup>, M.E. Zaytsev<sup>1, 4</sup>, A.A. Gerasimov<sup>1</sup>, D.K. Ryazanov<sup>4</sup>

1. *NRC “KI” Petersburg Nuclear Physics Institute, Gatchina, Russia*

2. *NRC “Kurchatov Institute”, Moscow, Russia*

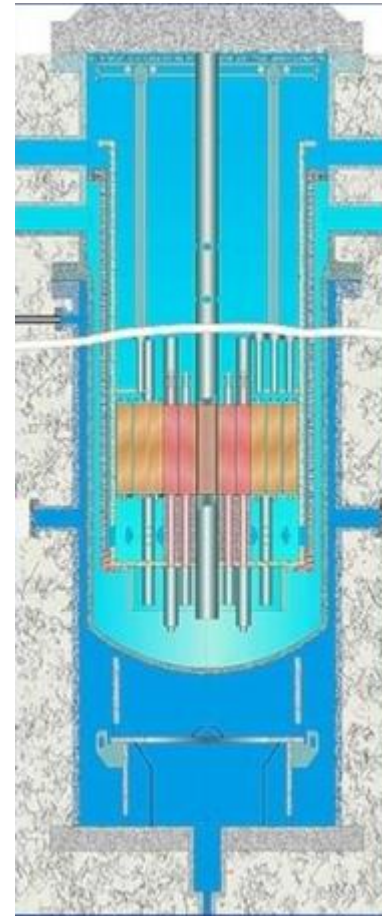
3. *JSC “SSC Research Institute of Atomic Reactors”, Dimitrovgrad, Russia*

4. *Dimitrovgrad Engineering and Technological Institute MEPhI, Dimitrovgrad, Russia*

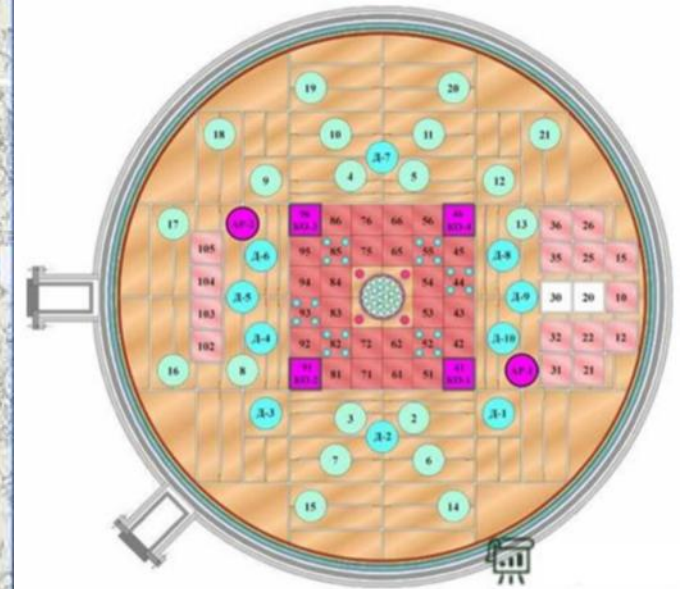
**IV International Conference on Particle Physics and Astrophysics  
(ICPPA-2018) Moscow, Russia, (22 – 26, October)**

# SM-3 research reactor

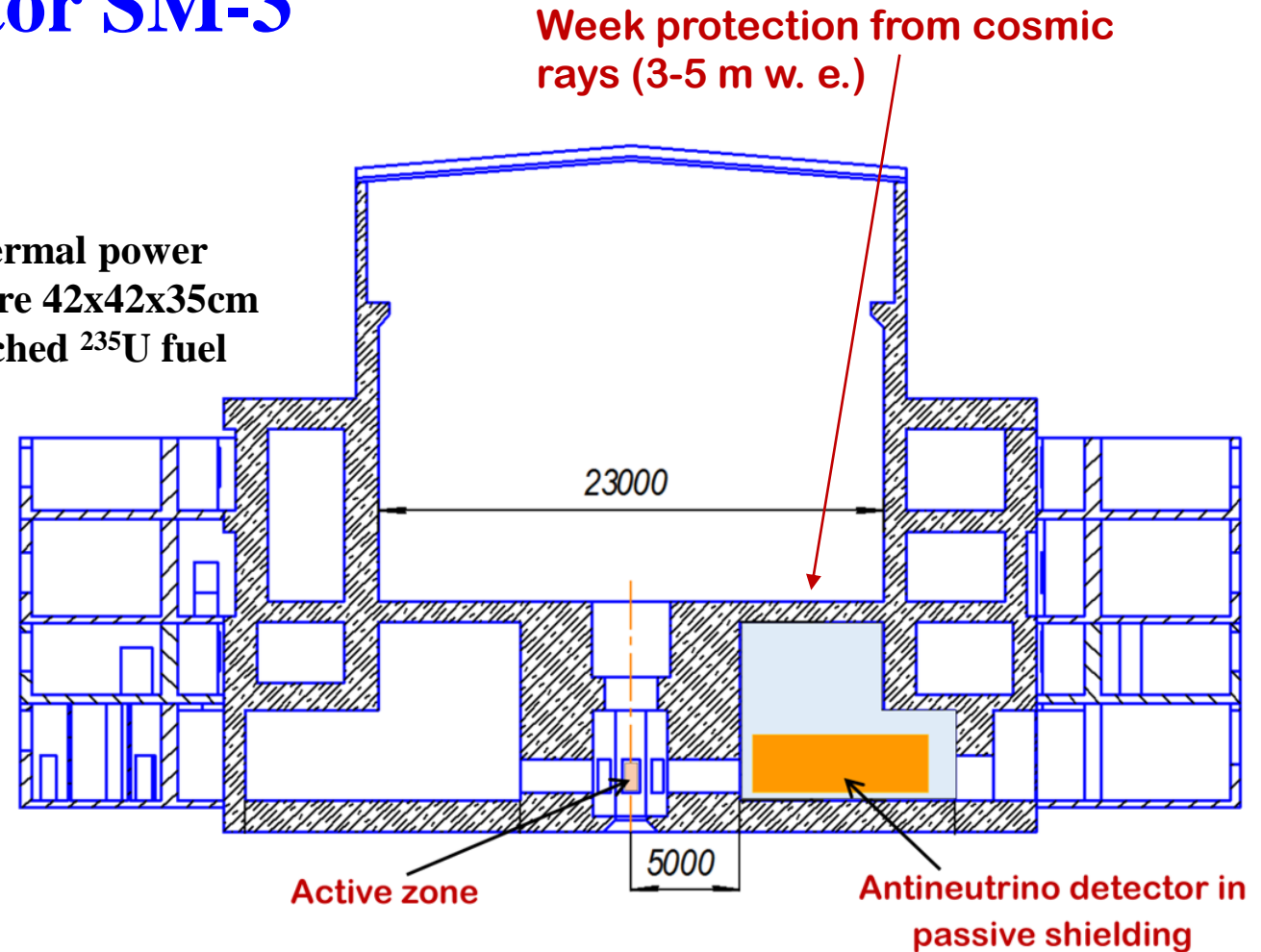
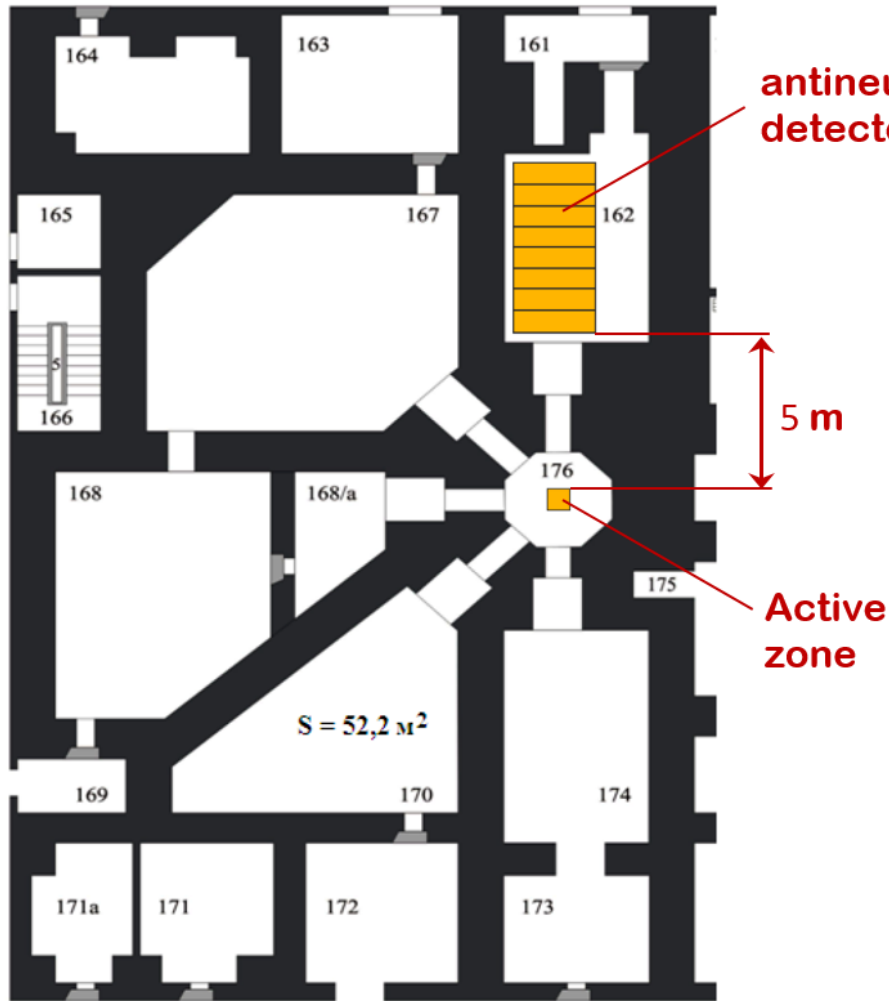
- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched  $^{235}\text{U}$  fuel
- Separated rooms for experimental setup
- The laboratory is poorly protected from cosmic rays



Vertical and horizontal sections of SM-3 reactor



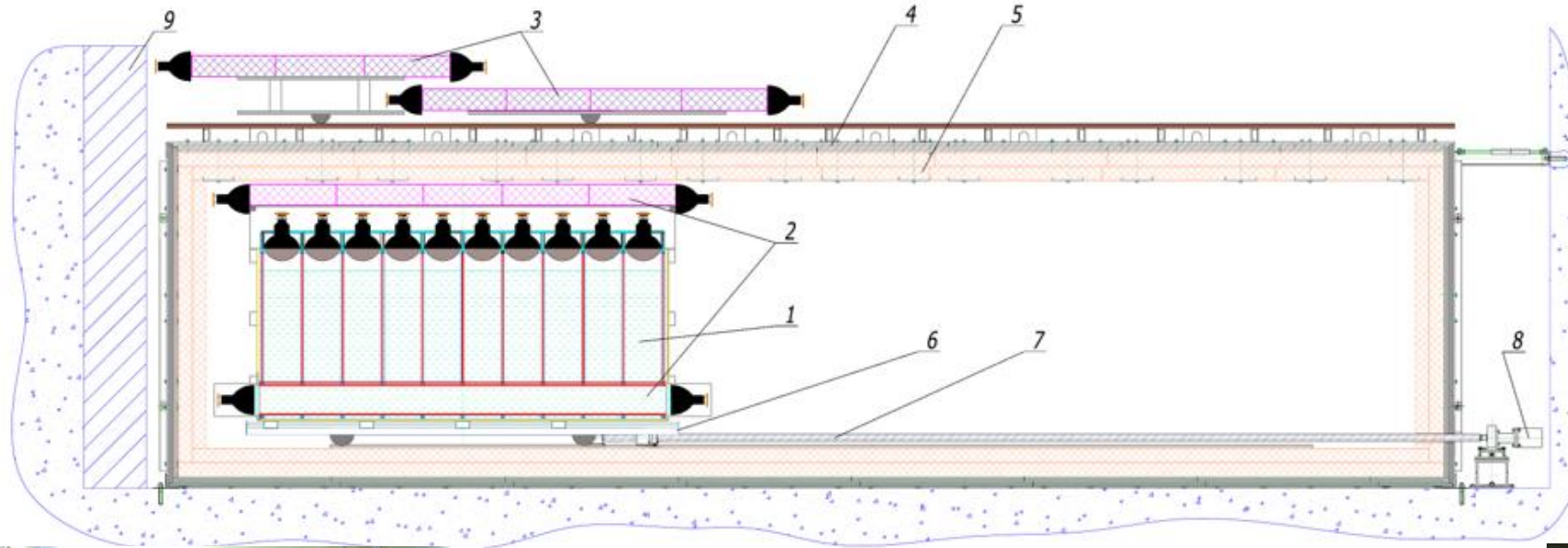
# Reactor SM-3



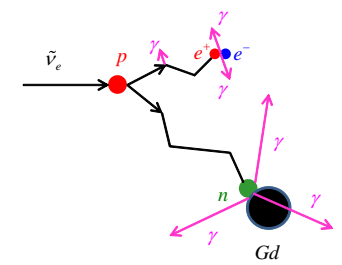
Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth's surface, hence, cosmic background is the major difficulty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



*Detector  
prototype*

*Full-scale  
detector*

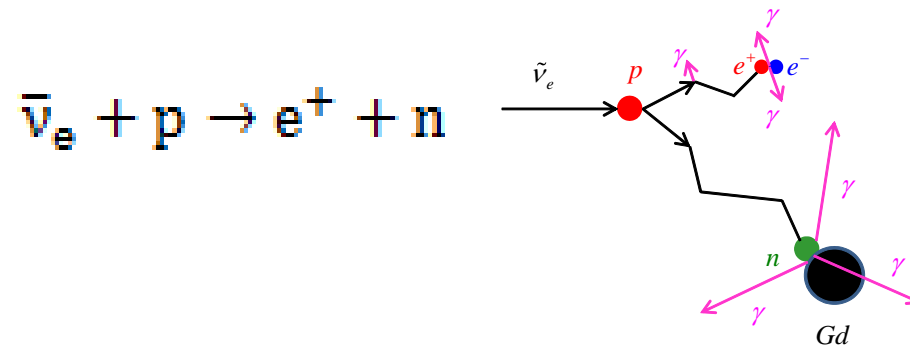


*Liquid scintillator detector  
50 sections 0.235x0.235x0.85m<sup>3</sup>*

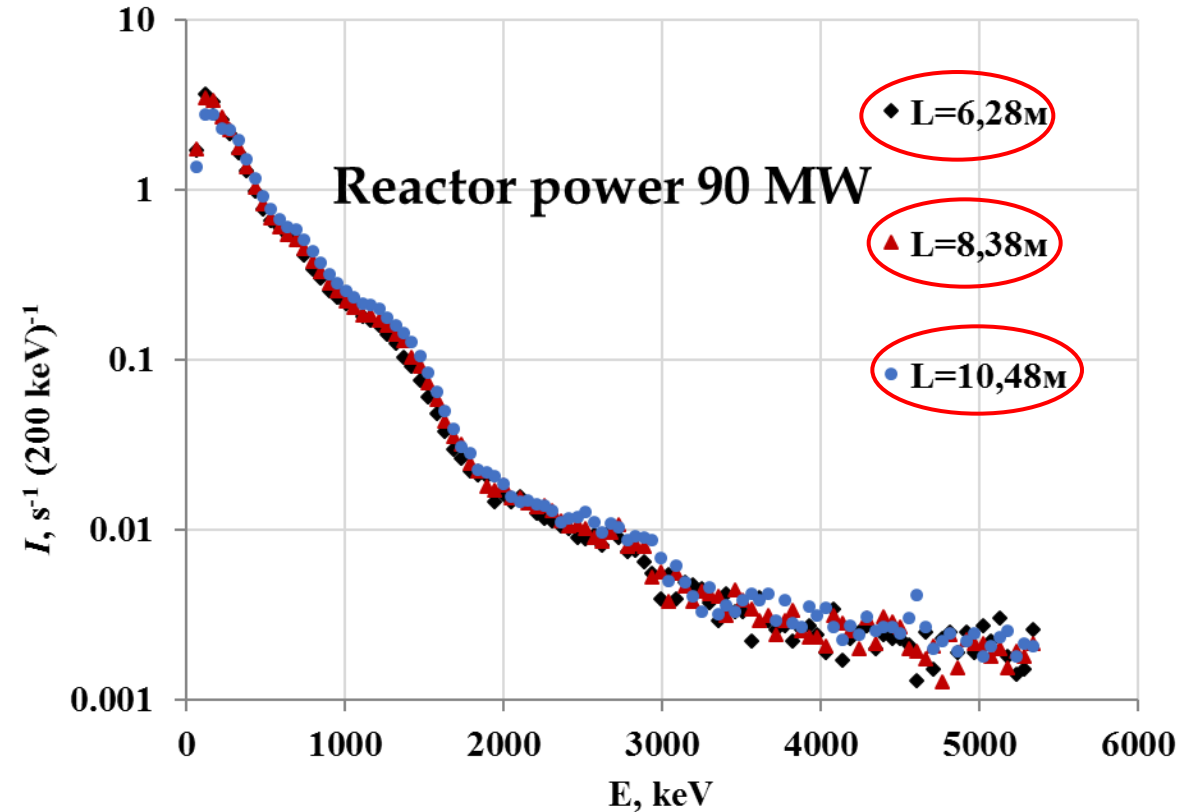
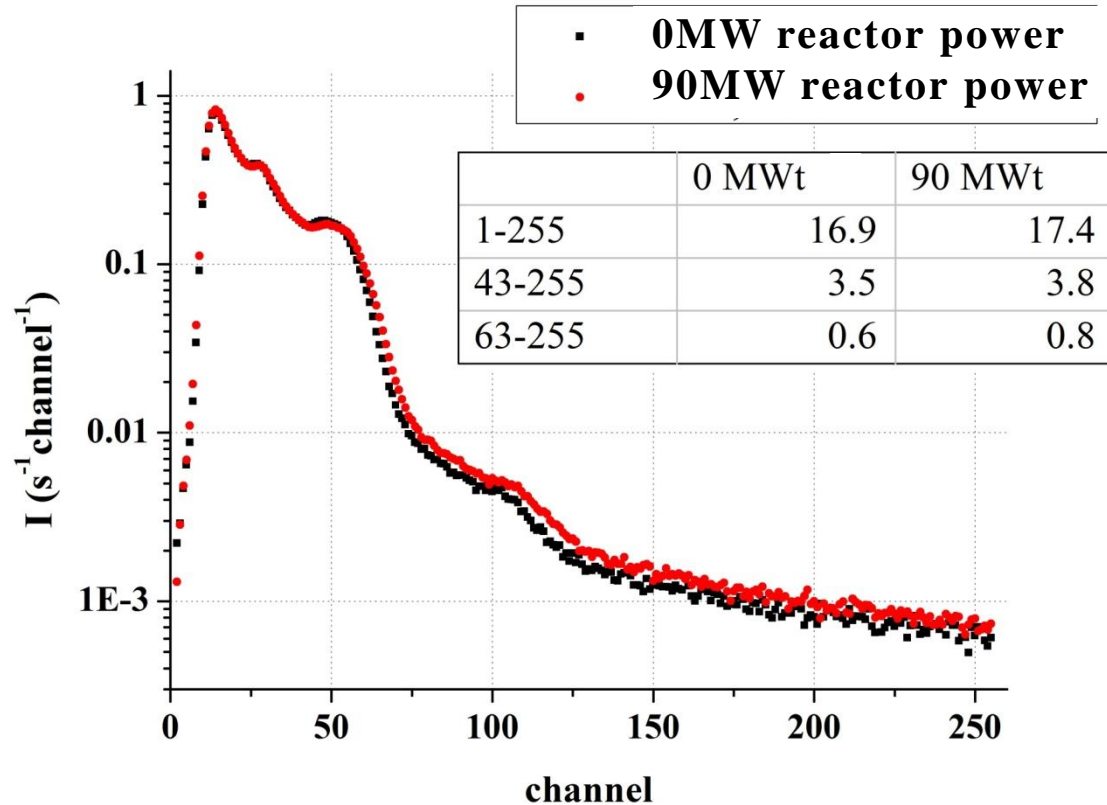
*Range of measurements is 6 – 12 meters*

The liquid scintillator detector has volume of 1.8 m<sup>3</sup> (5x10 sections 0.225x0.225x0.85m<sup>3</sup>, 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<sup>3</sup>.

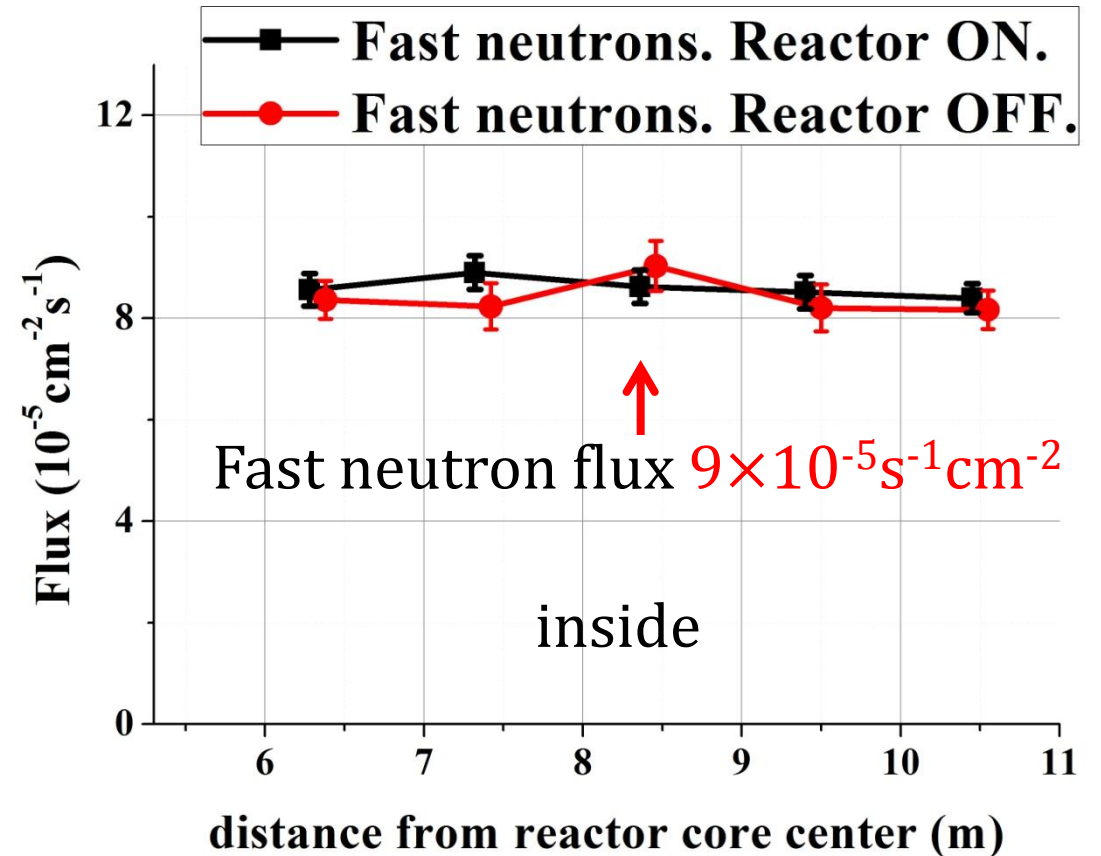
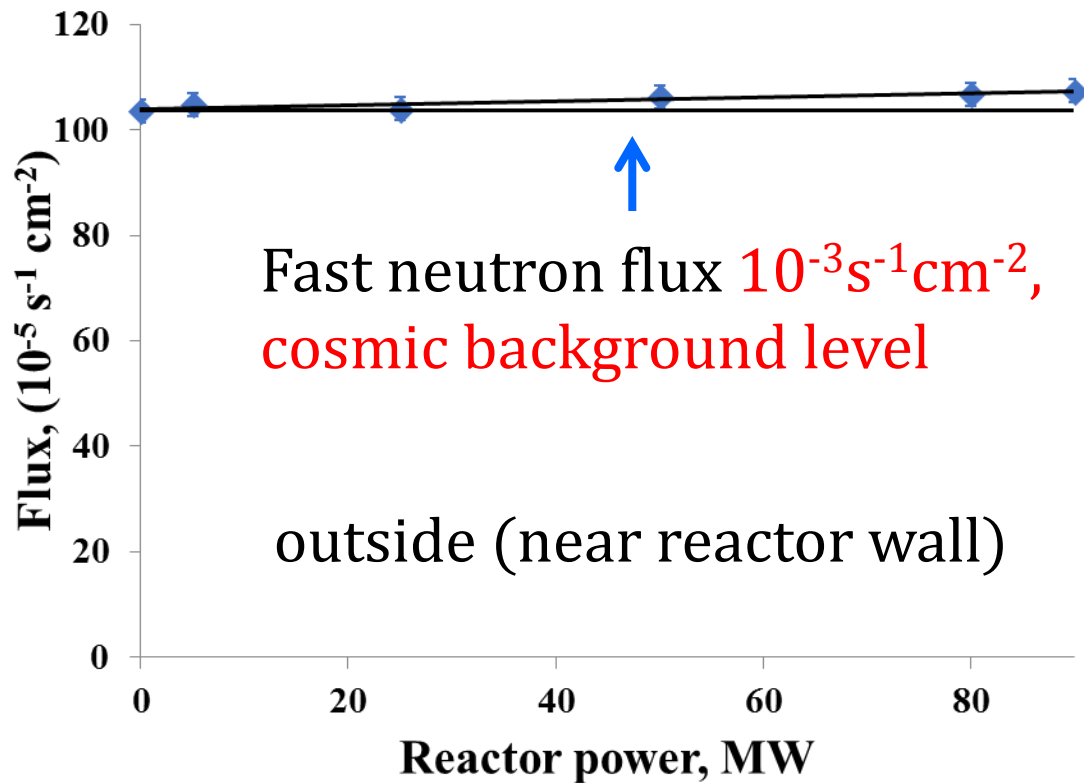
The method of antineutrino registration is to select correlated pare of signals: prompt positron signal and delayed signal of neutron captured by gadolinium.



Gamma background 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 **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.**



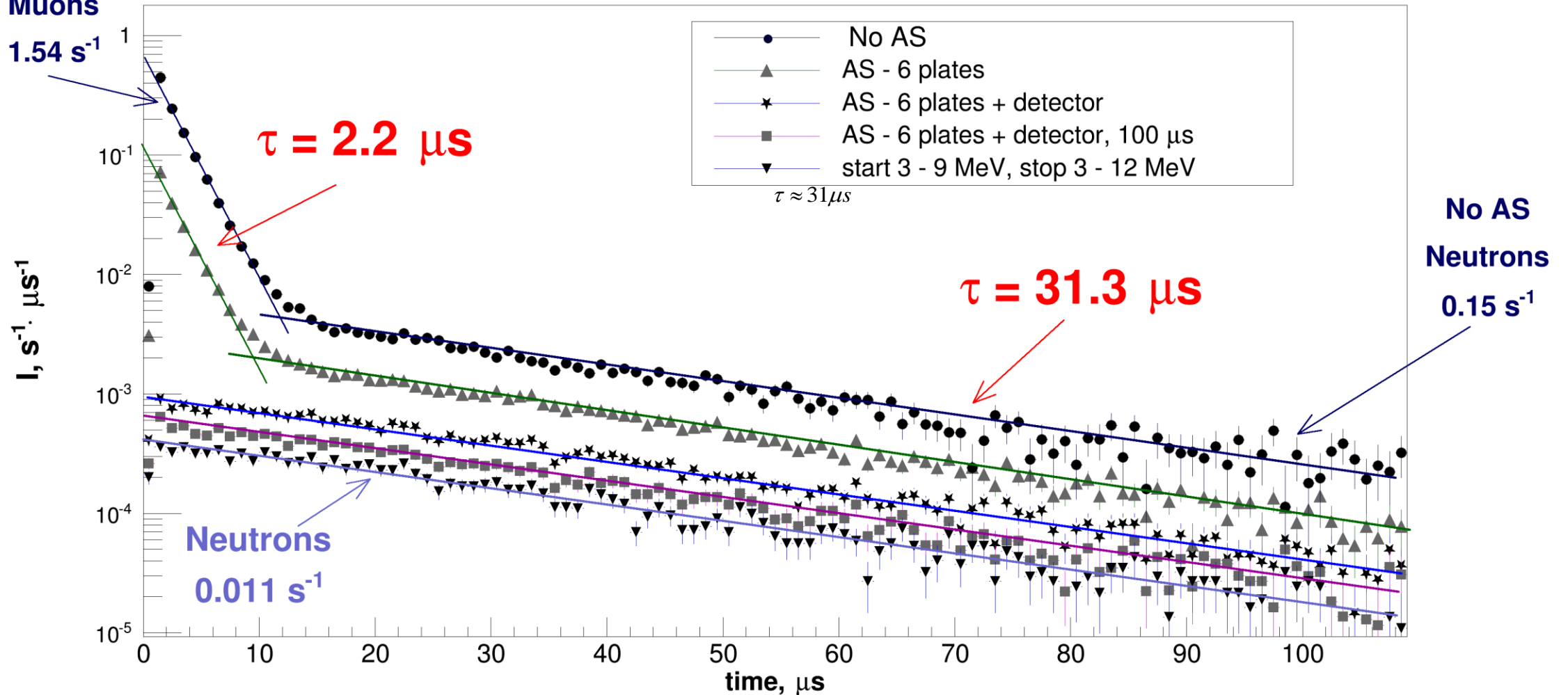
# Cosmic background

First AS version suppress  
background **by an order** of magnitude

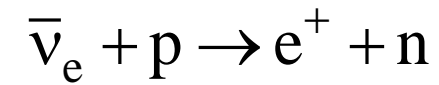
No AS  
Muons

$1.54 \text{ s}^{-1}$

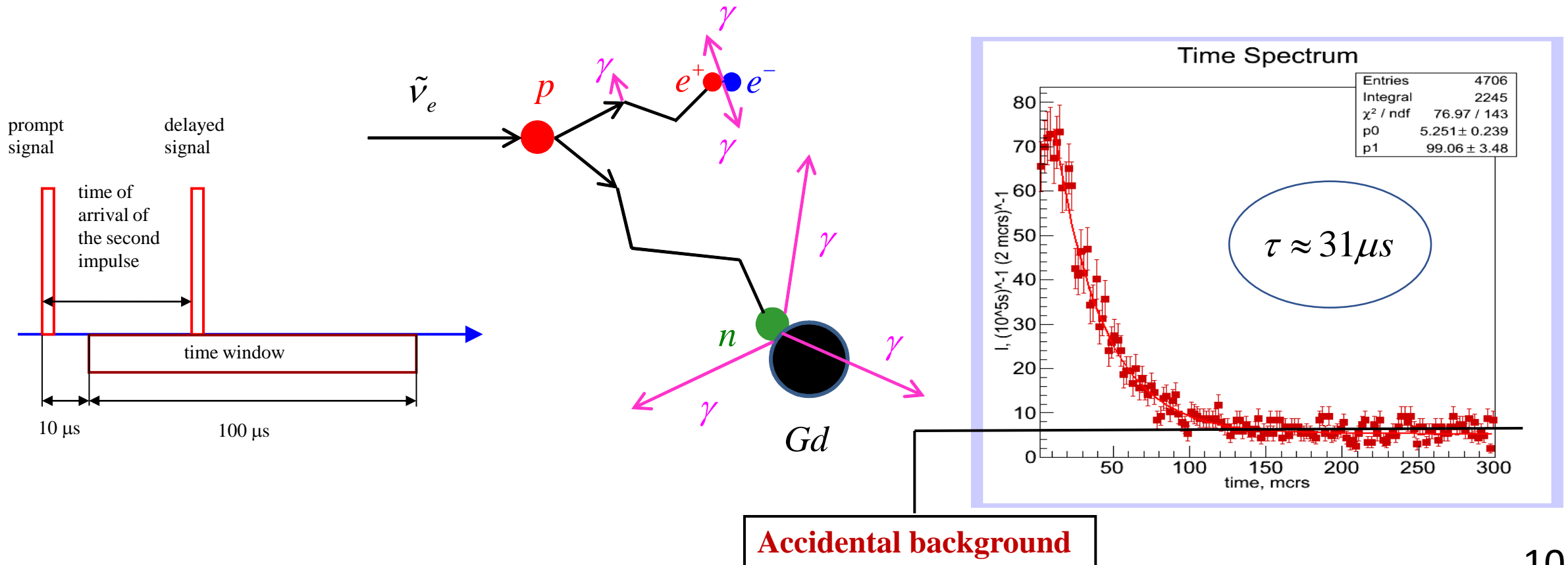
Time spectra for the 1st version of active shielding (AS) in different configuration.



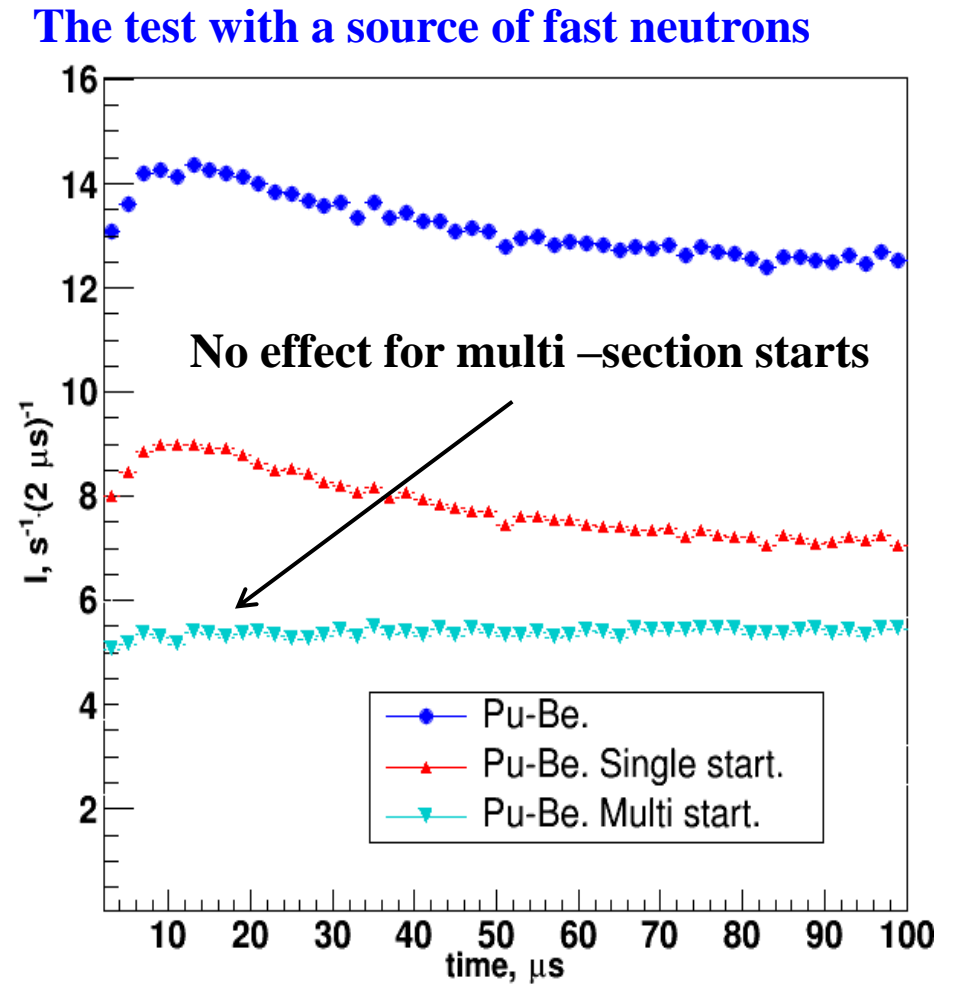
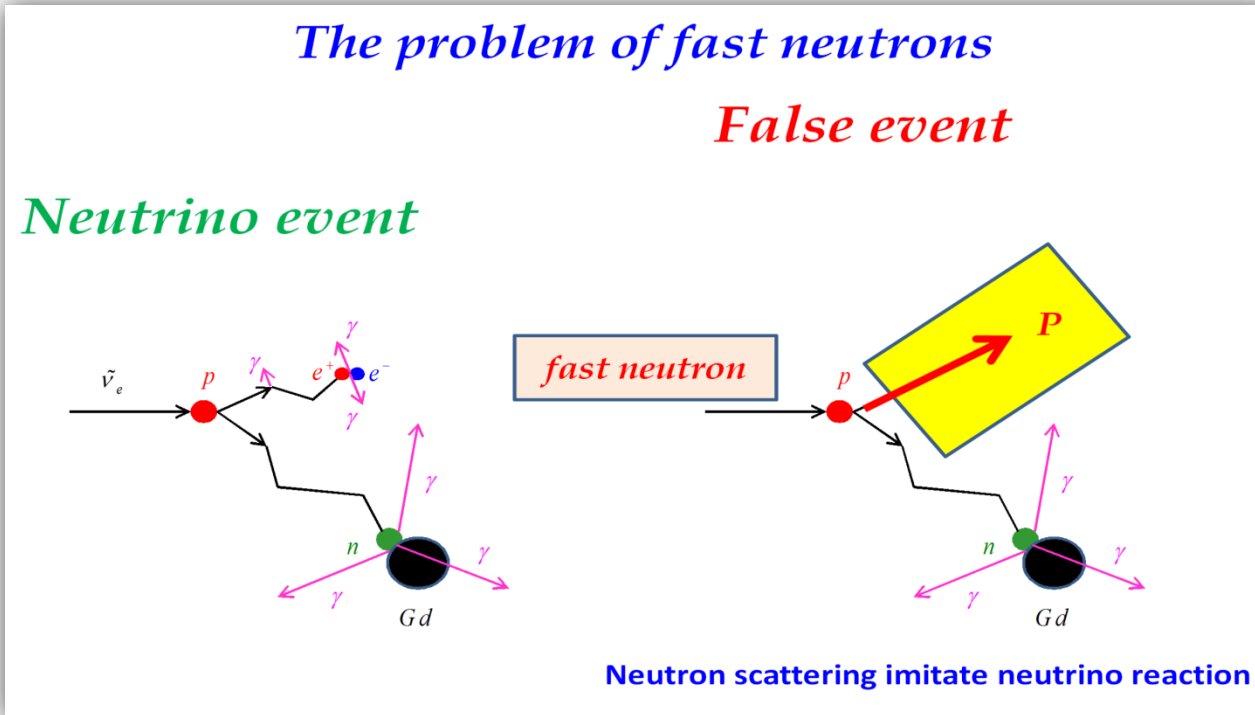
Scintillator with gadolinium concentration 0.1% was using to detect inverse beta decay (IBD) events



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



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



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**

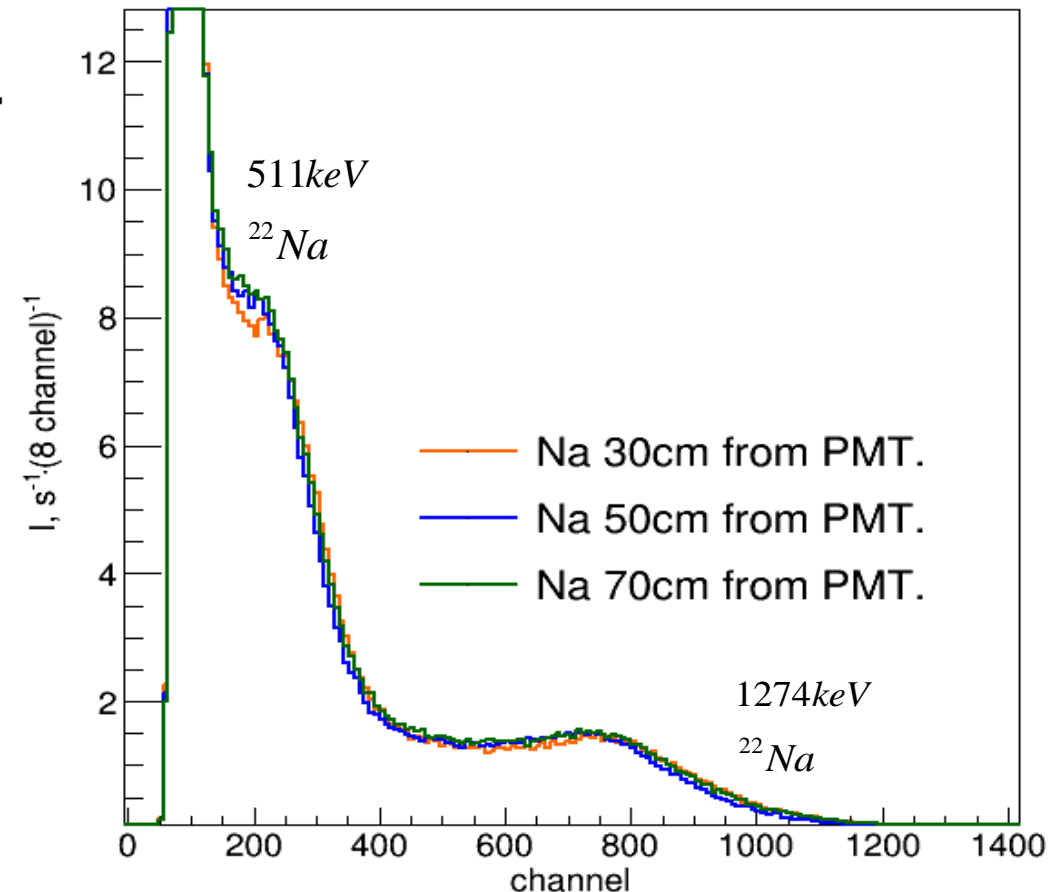
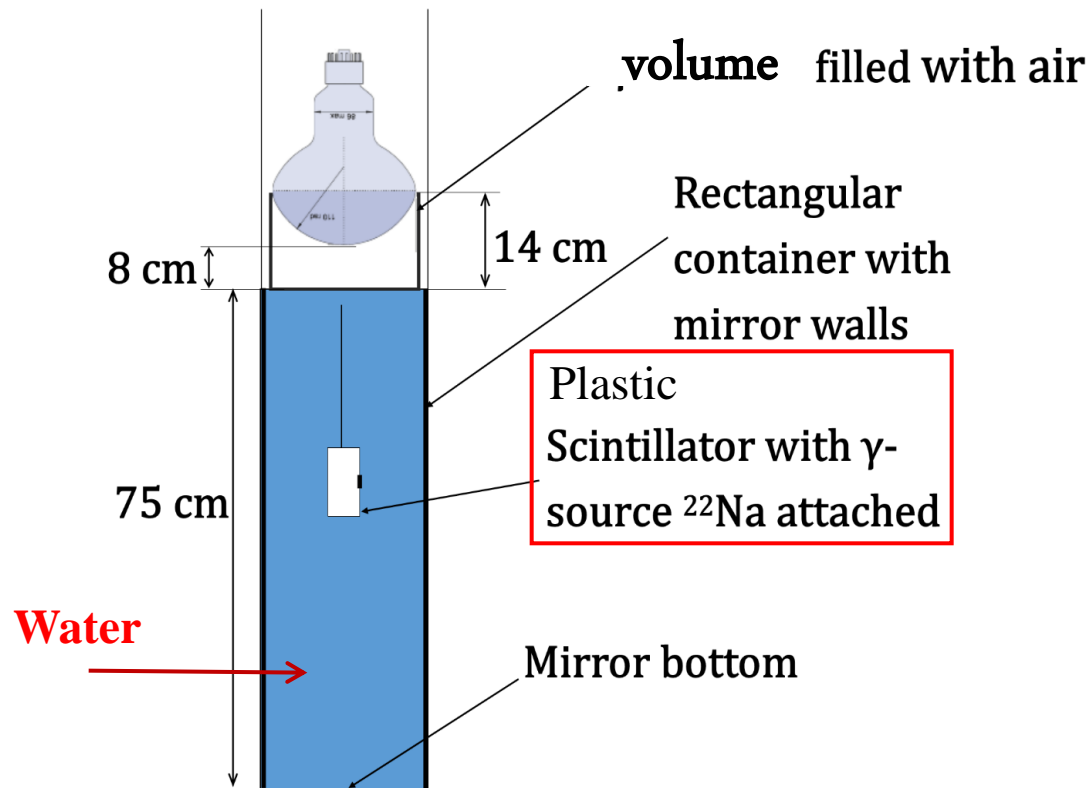
**(37 ± 4)%**

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 angles to improve the light collection from different distances. Therefore calibration can be done using the sources located outside – above section.

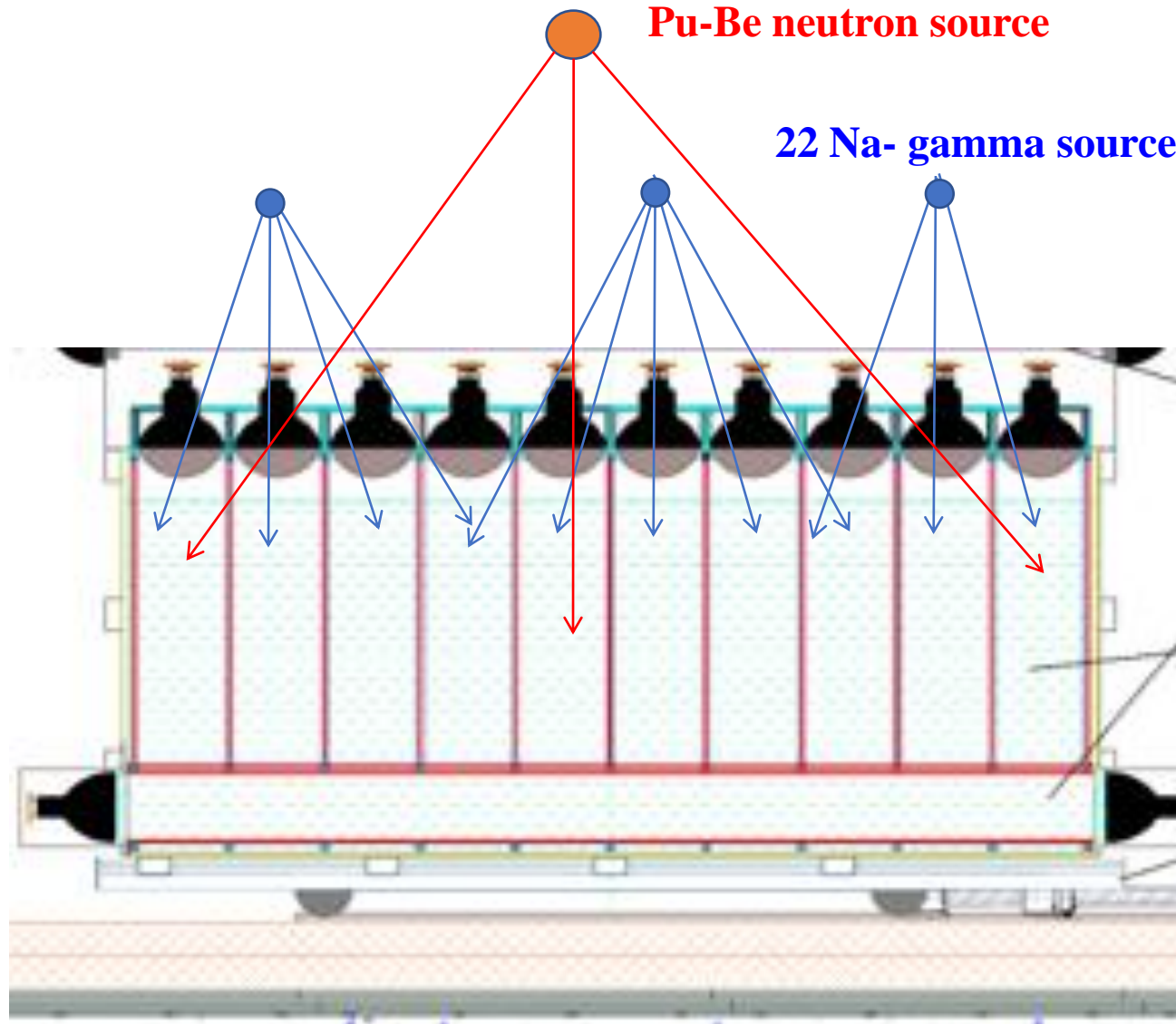




# Energy calibration of the full-scale detector

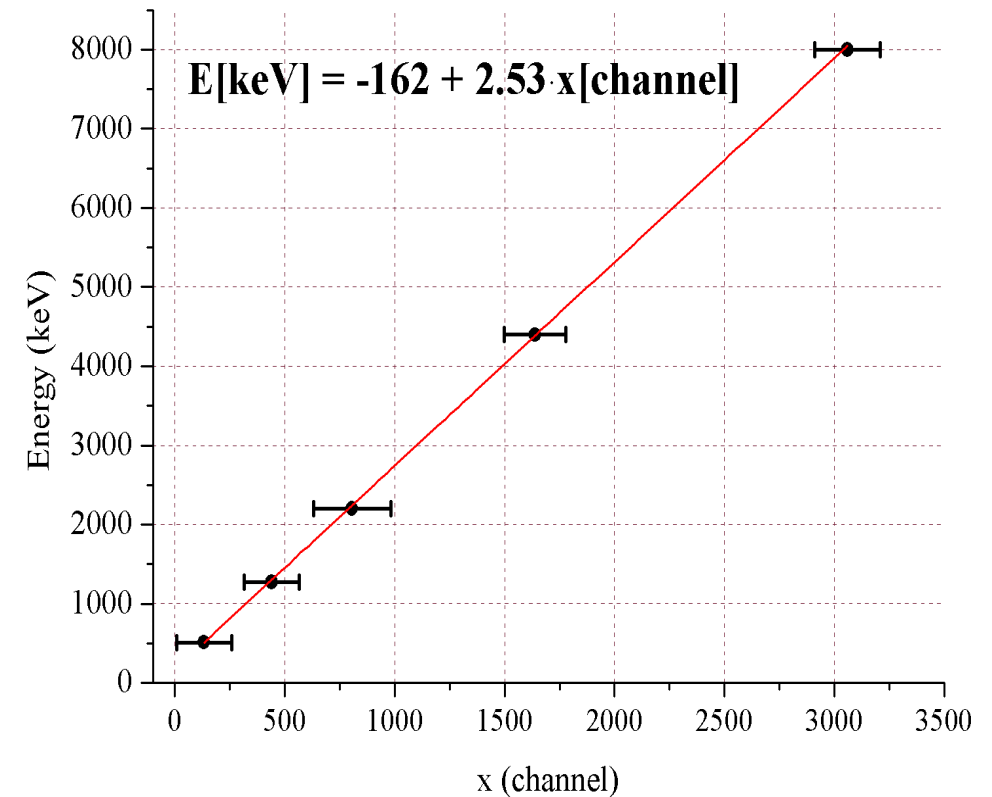
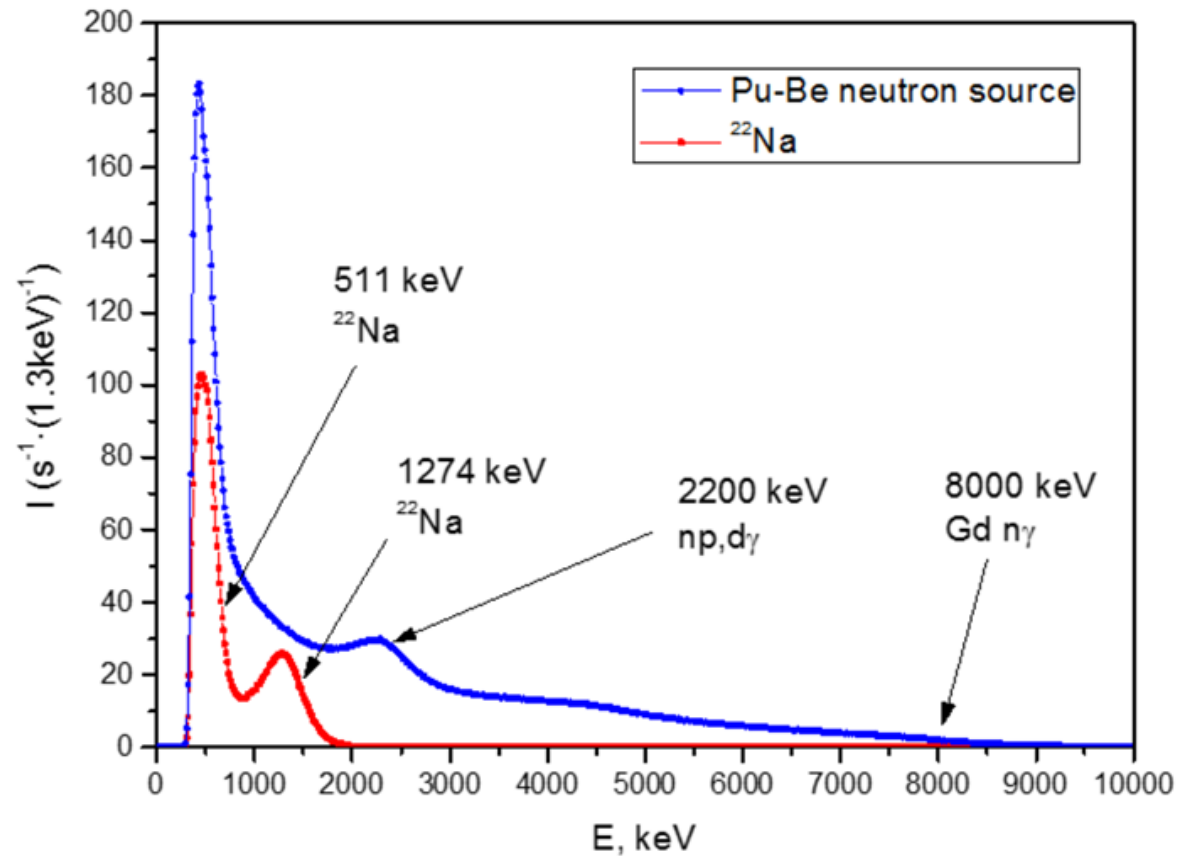
The source  $^{22}\text{Na}$  is installed above the detector at distance about 0.8 meters and irradiate about 16 sections at once. PMTs were normalized to one energy scale by selecting voltage on them. Simultaneous calibration of several sections is required. For all detector only 6 positions of the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

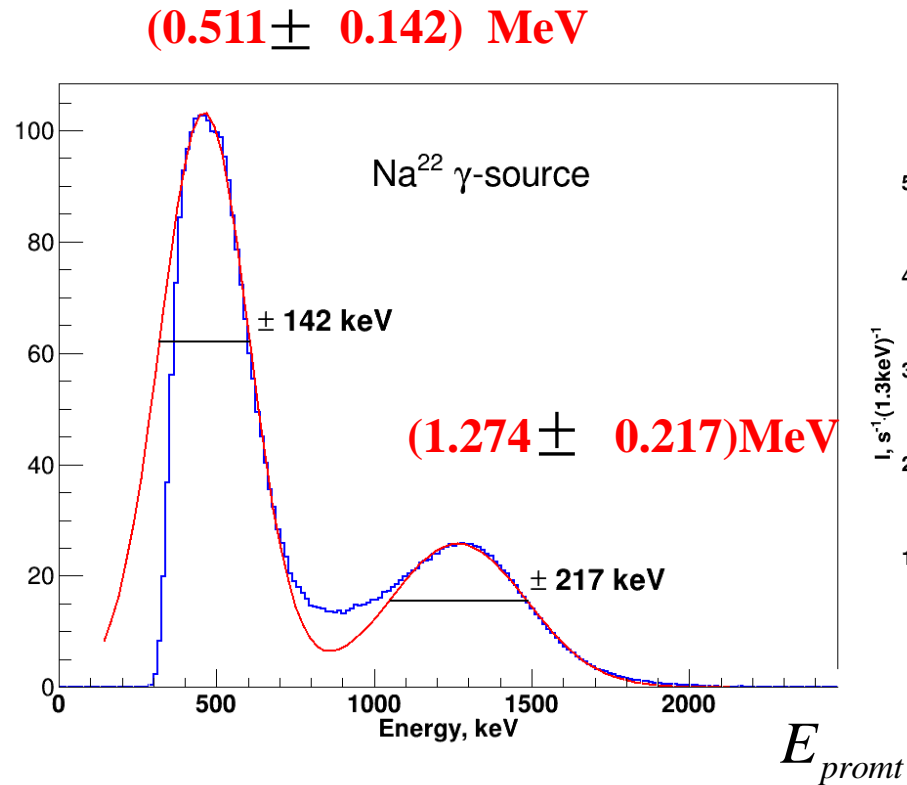


In the left - ranges of sources. In the right - the calibration of gamma quanta scale.

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  **$\pm 250$  keV**.

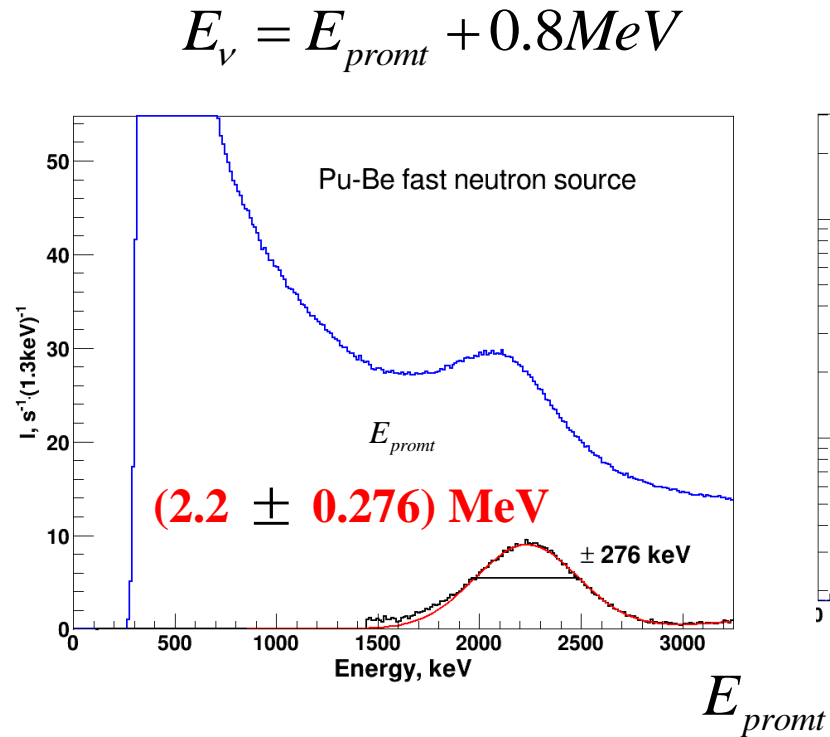
It is the calibration which needs to be used at data processing.

## Energy calibration of the full-scale detector



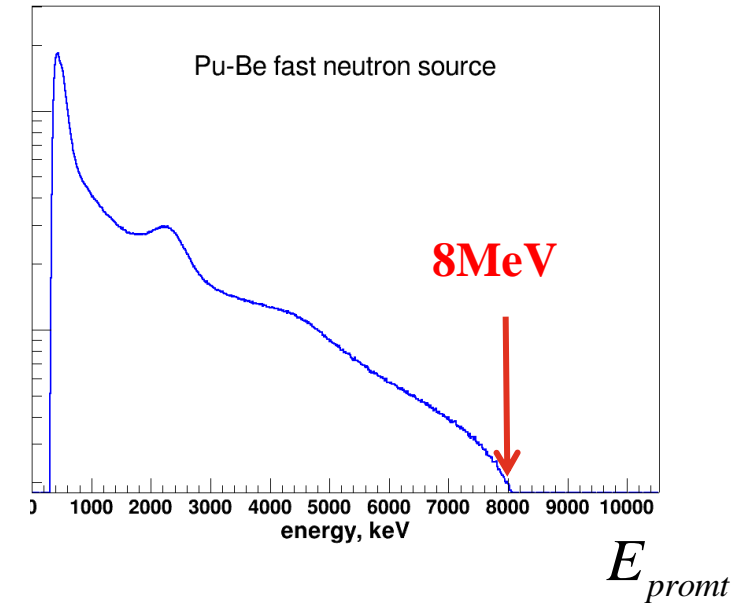
$$\Delta E_\nu / E_\nu (2 \text{ MeV}) = 21\%$$

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



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

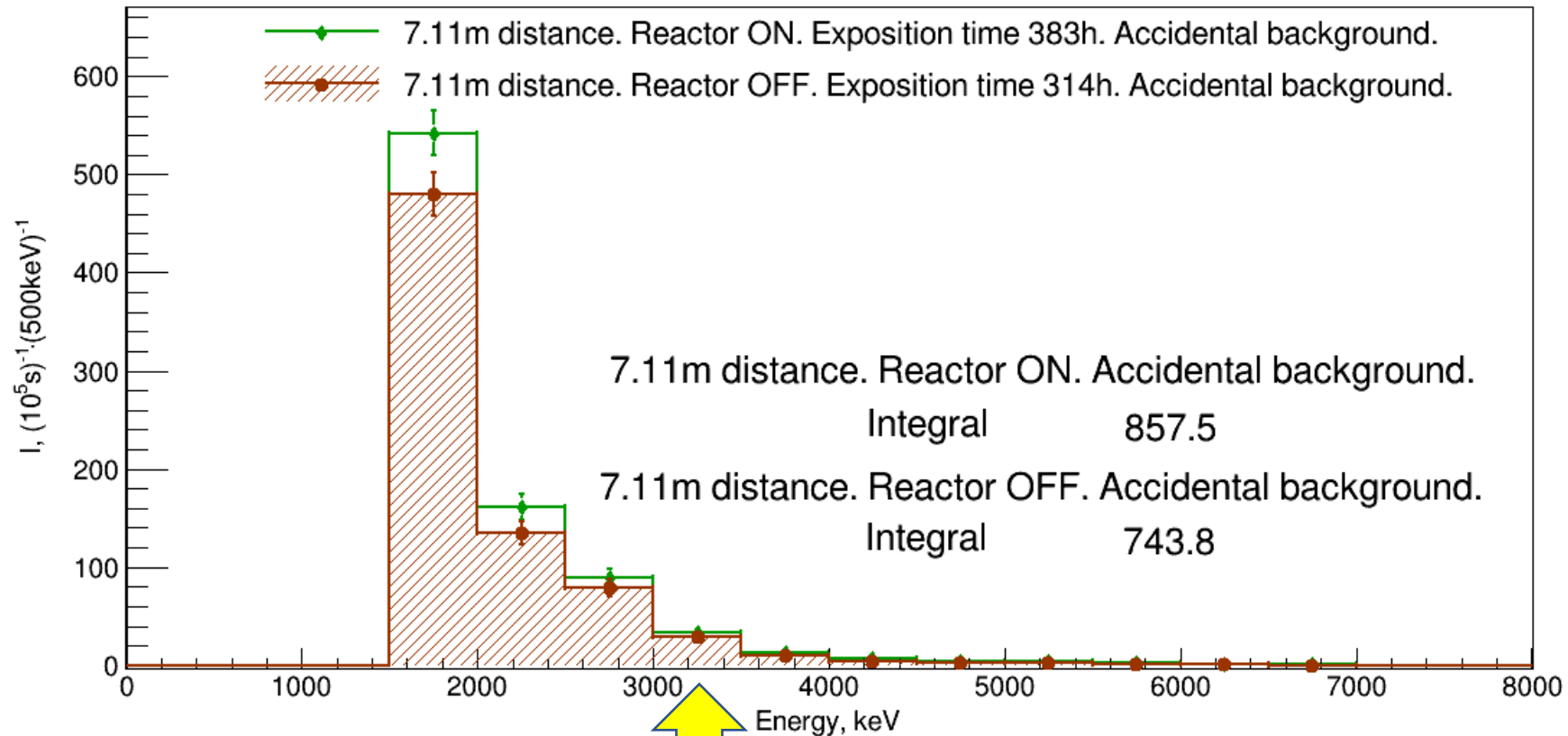
$$\Delta E_\nu (3 \text{ MeV}) = 550 \text{ keV}$$



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

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

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

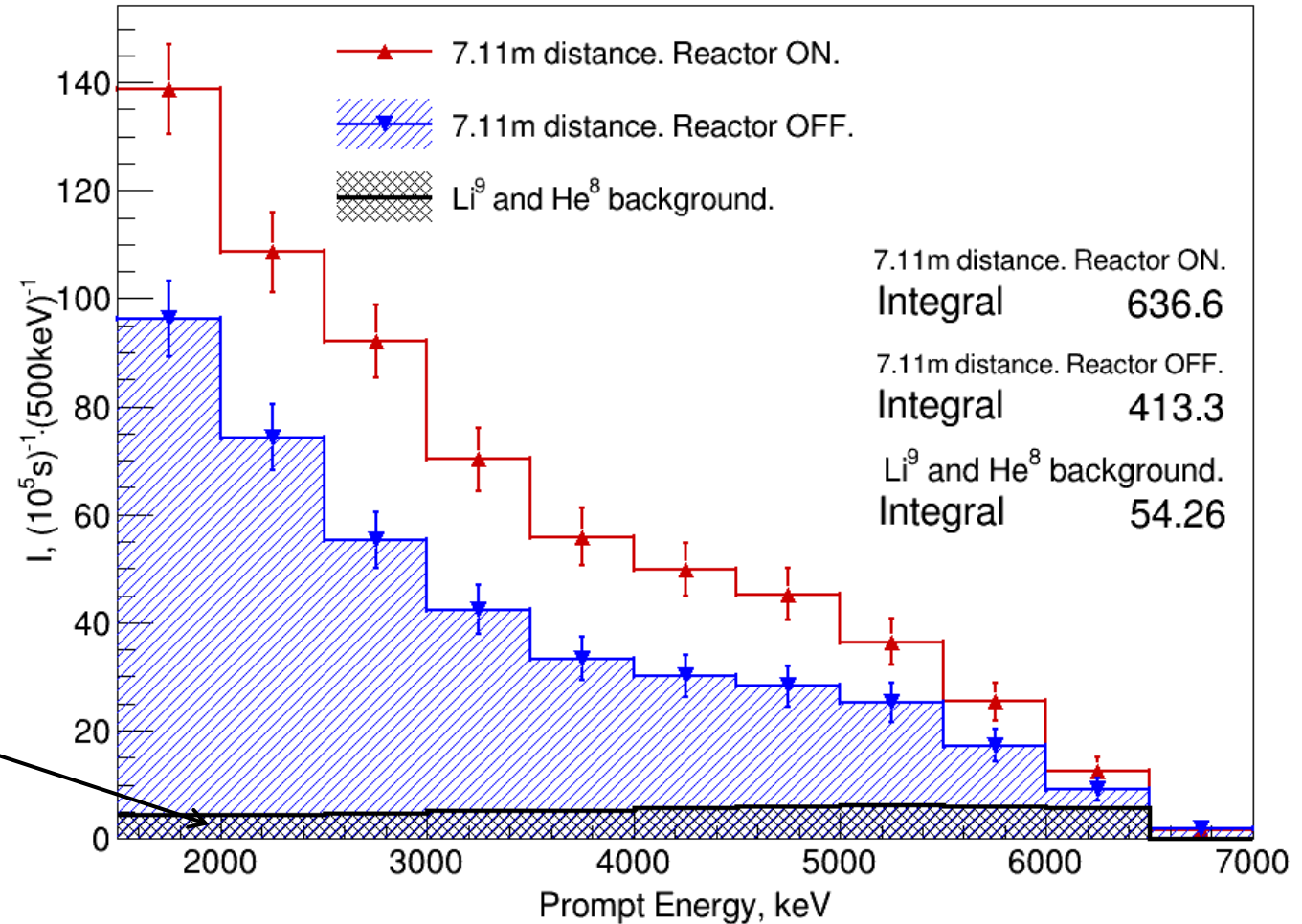


***Threshold for delayed coincidences 3.2MeV***

## 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**

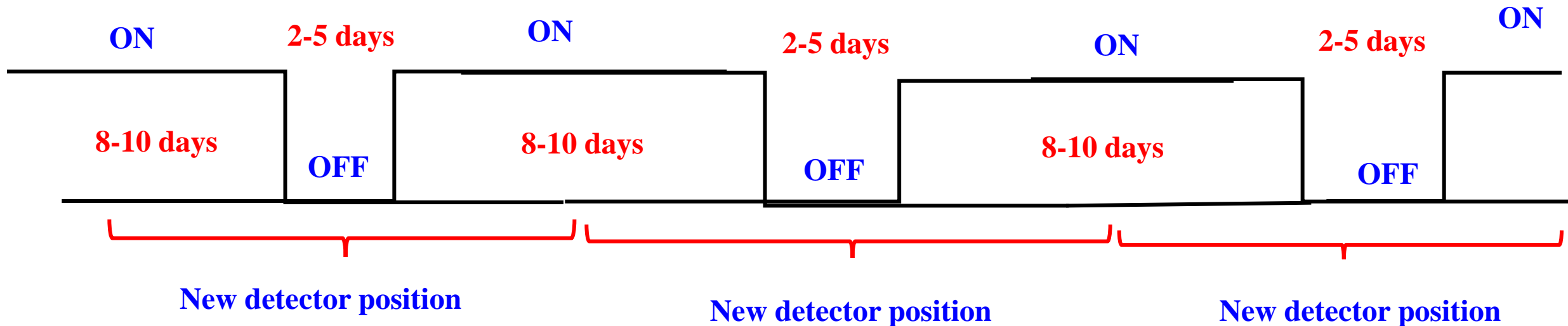
Unavoidable background of  $\text{Li}^9$   
and  $\text{He}^8$  is 54 events/ $10^5$ s



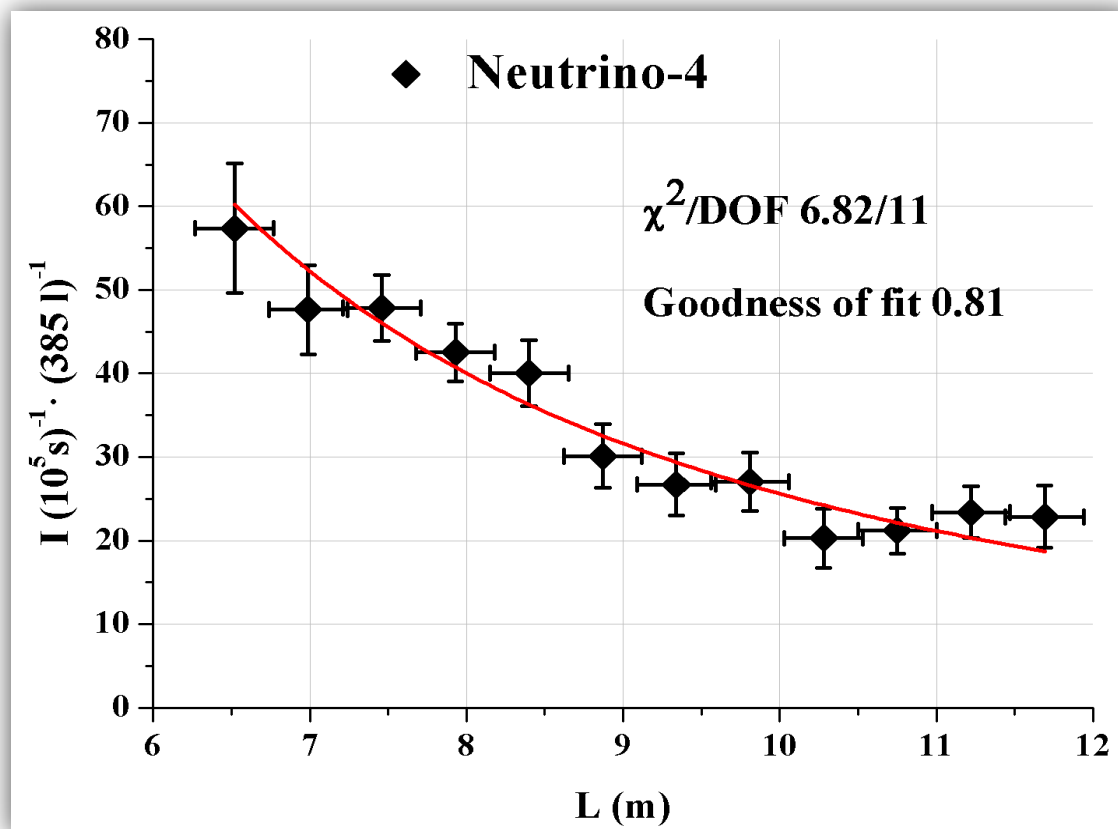


ON  
90 MW

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.

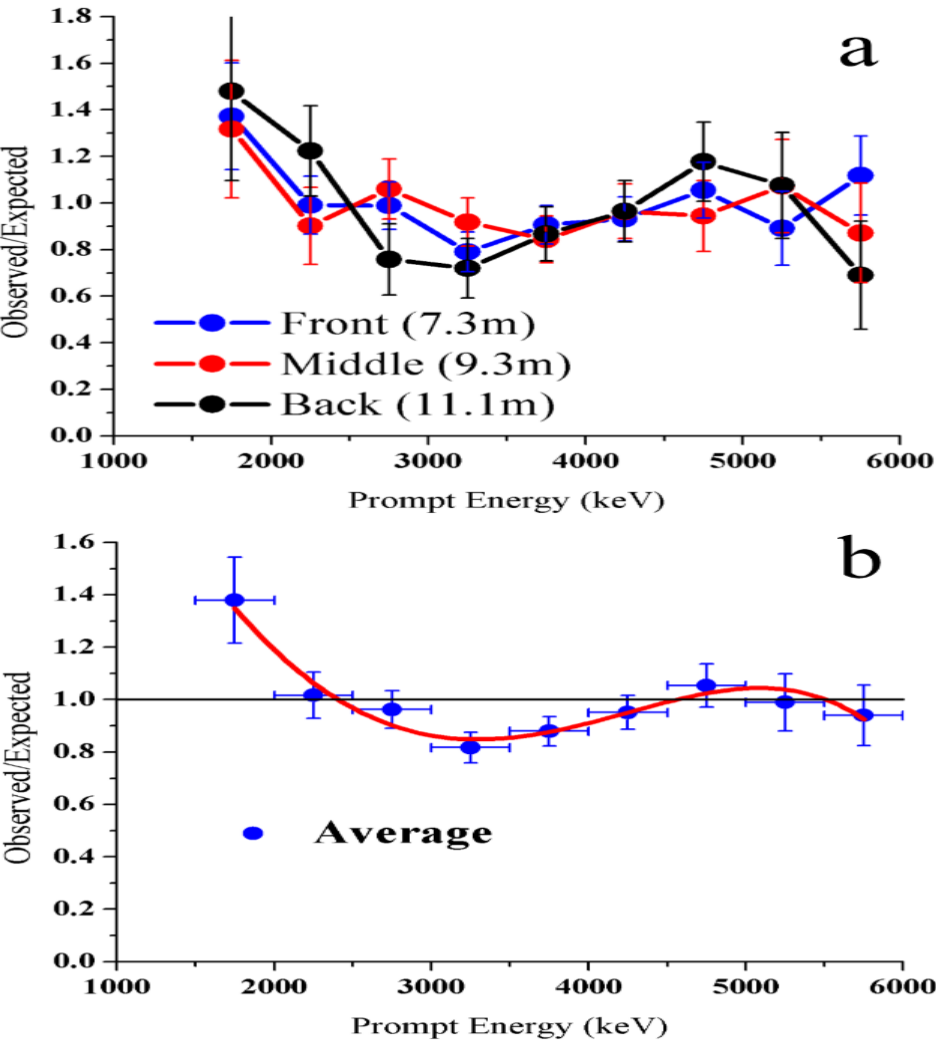


Fit of an experimental dependence with the law  $A/L^2$  yields satisfactory result. Goodness of that fit is 81%. Corrections for finite size of reactor core and detector sections are negligible – 0.3%, and correction for difference between detector movement axes and direction to center of reactor core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

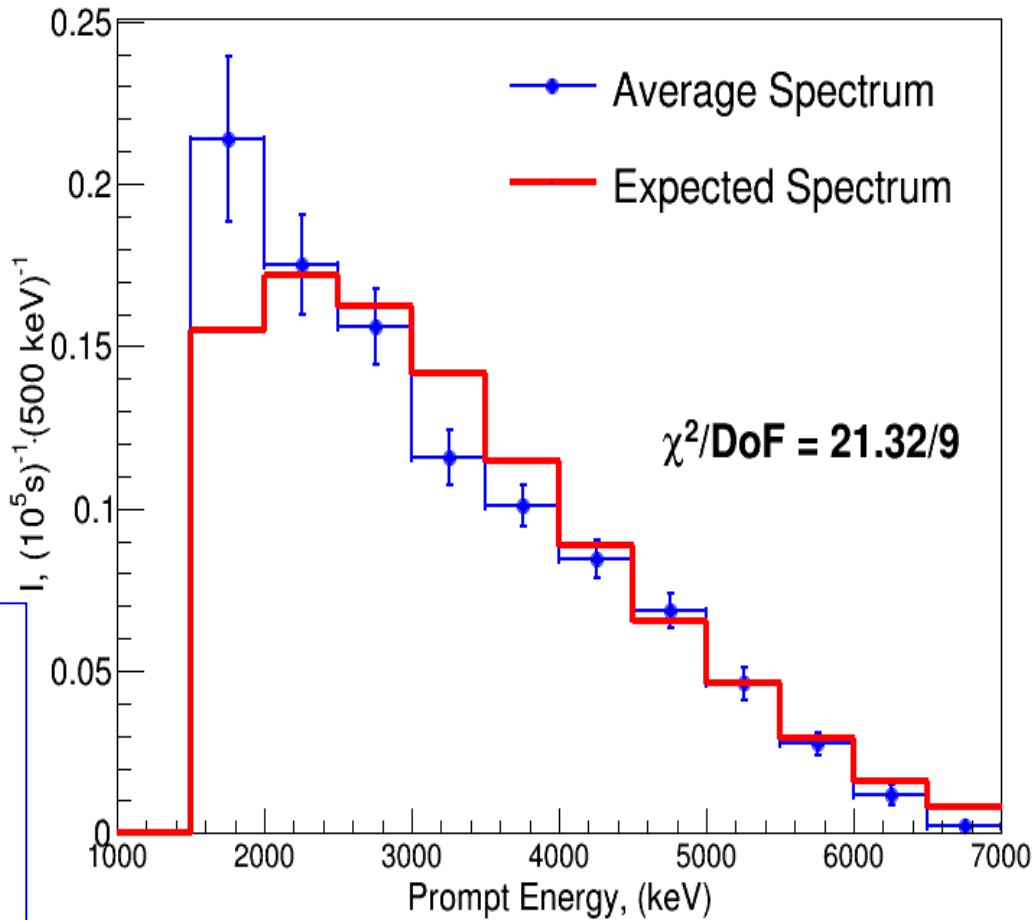
The analysis of distance dependence without energy spectrum is not enough to observe oscillations because of spectral averaging .

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 <sup>235</sup>U, as the SM-3 reactor works on highly enriched uranium.

## 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  $\Delta m_{14}^2$  because we use 2m interval in analysis. Using such averaging, if  $\Delta m_{14}^2 > 5eV^2$  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.**

# **The model-independent method of the analysis of experimental data**



## Probability of antineutrino disappearance

$N(E_i, L_k)$   
Number of  
antineutrino  
events

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

## The method of the analysis of experimental data

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

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.

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

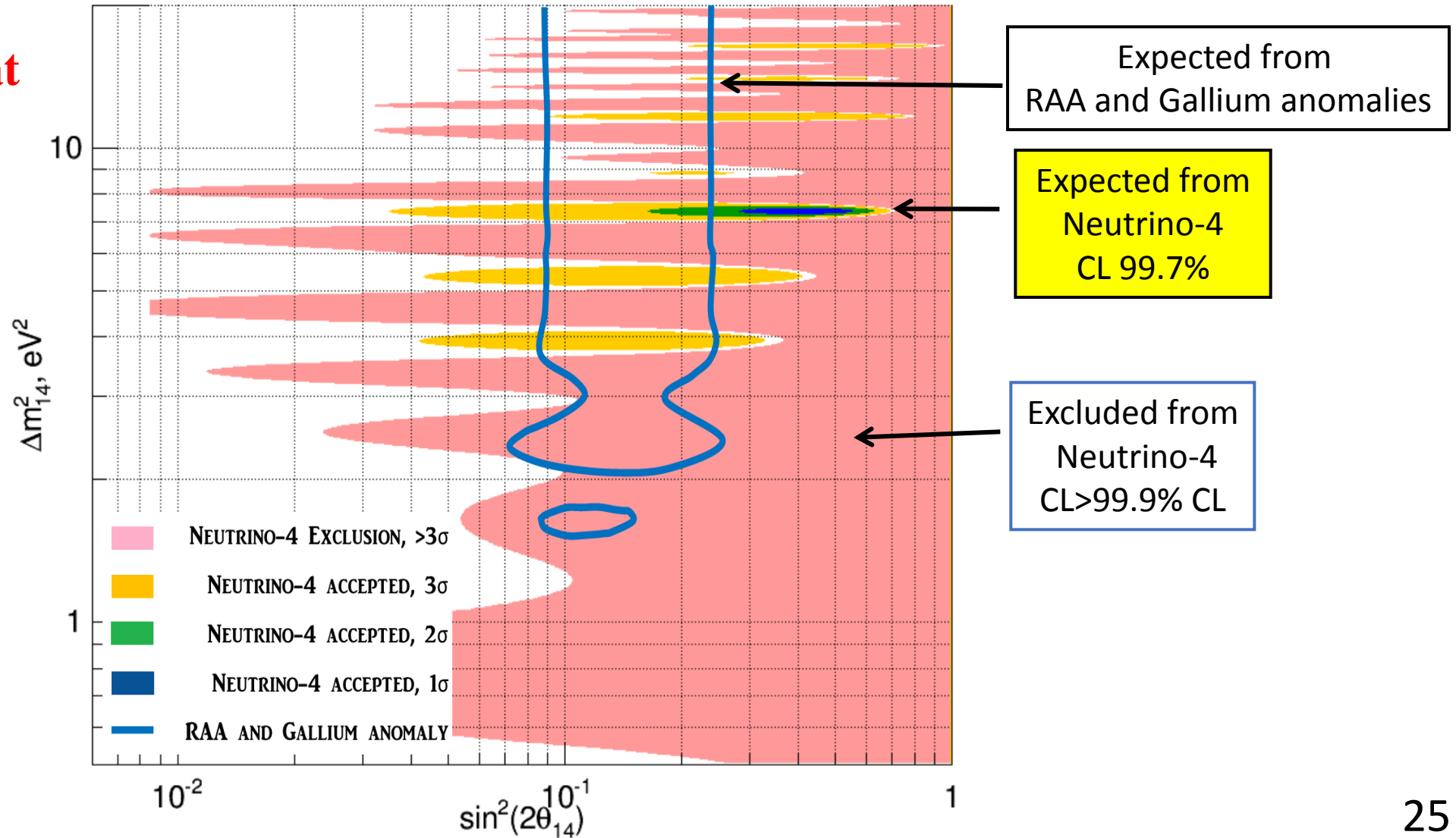
The results of the analysis of optimal parameters  $\Delta m_{14}^2$  and  $\sin^2 2\theta_{14}$  using  $\chi^2$  method

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

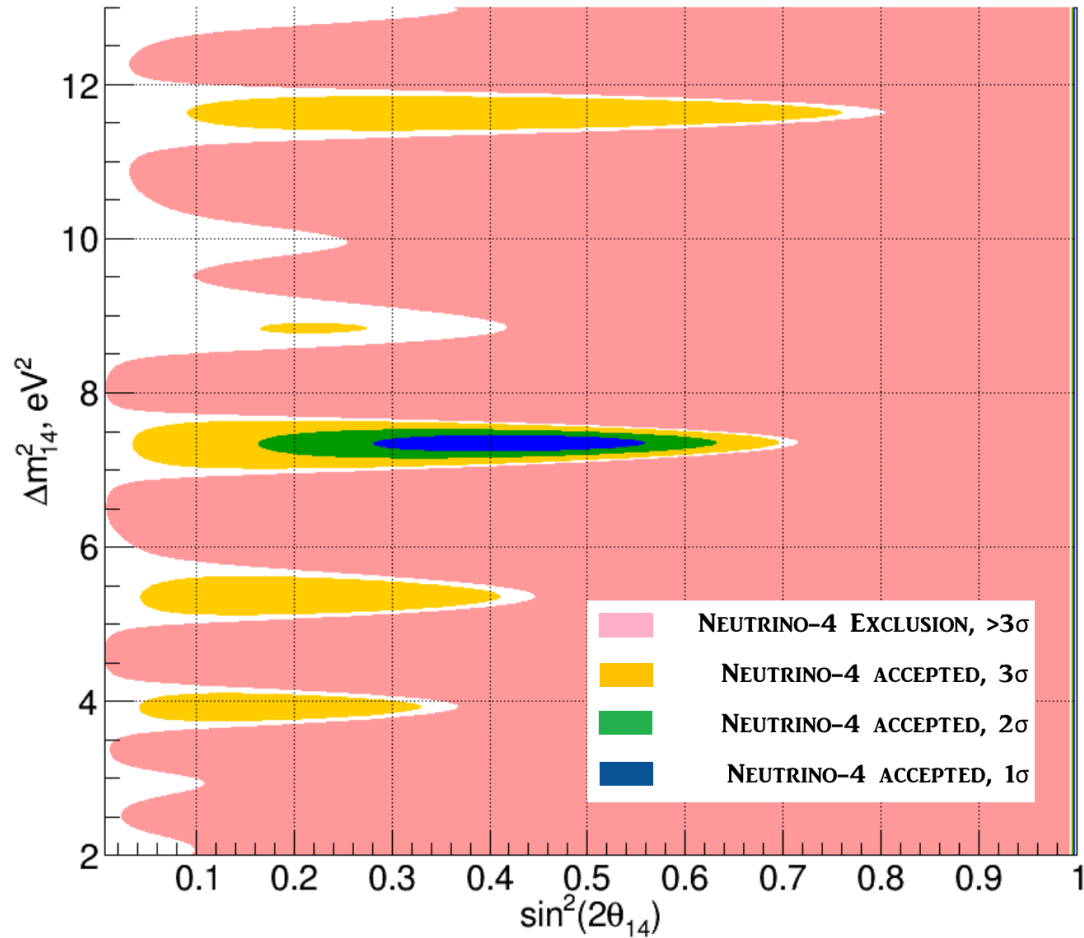
We observed the oscillation effect at C.L. 99.7% ( $3\sigma$ ) in vicinity of :

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

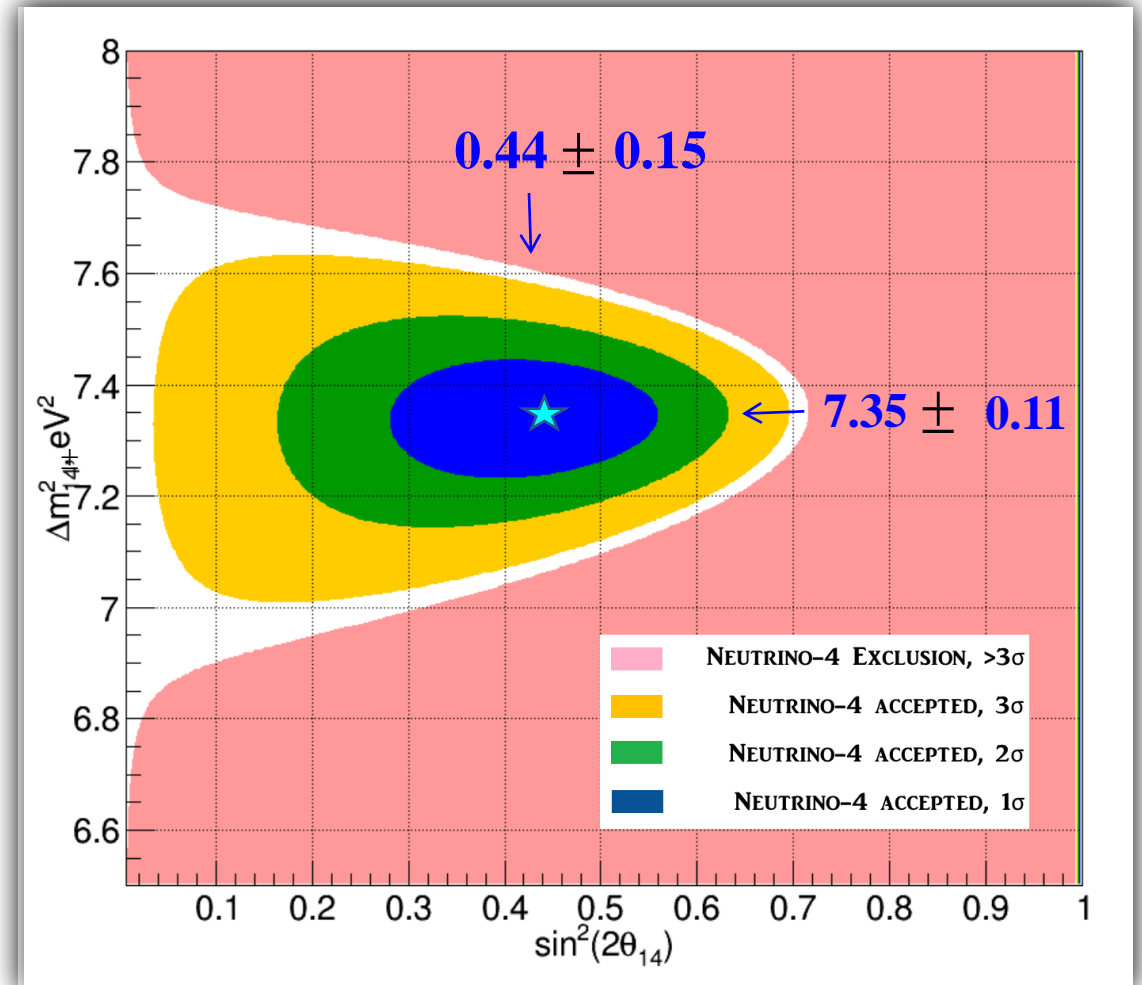
$$\sin^2 2\theta_{14} \approx 0.4$$



The results of the analysis of optimal parameters  $\Delta m_{14}^2$  and  $\sin^2 2\theta_{14}$  using  $\chi^2$  method

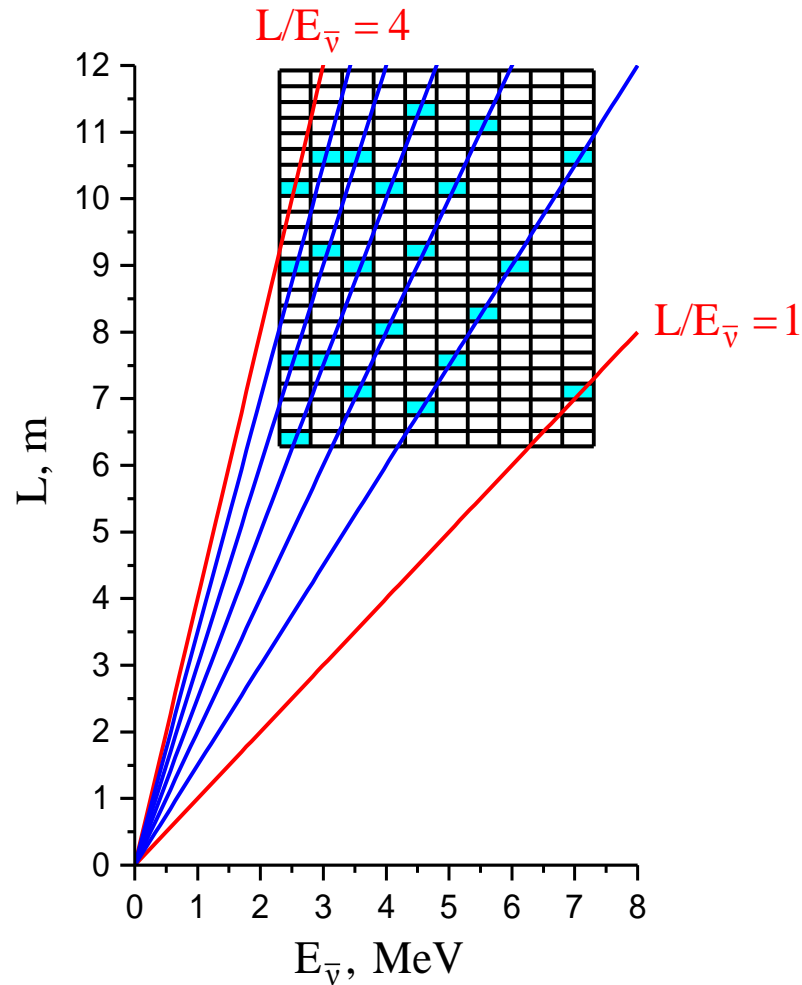


Area around central values in linear scale  
and significantly magnified

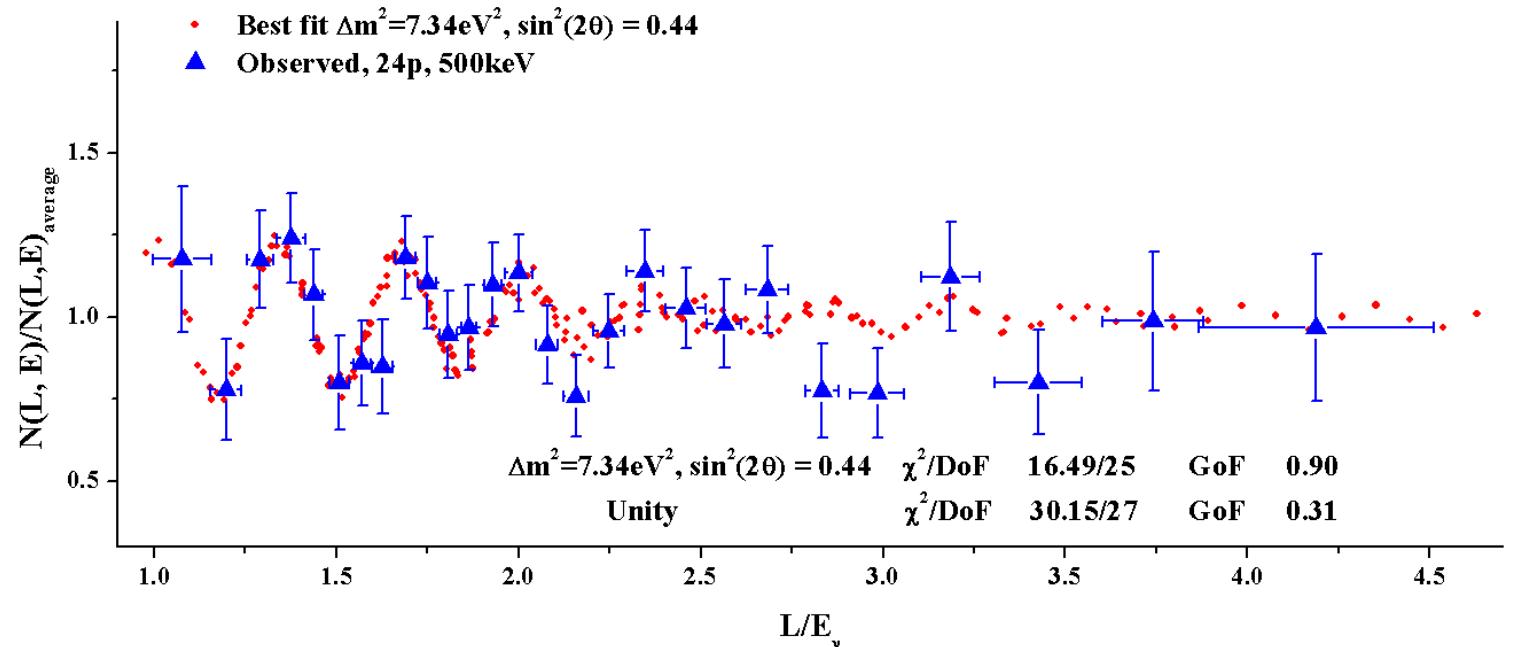


Central part even further magnified

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



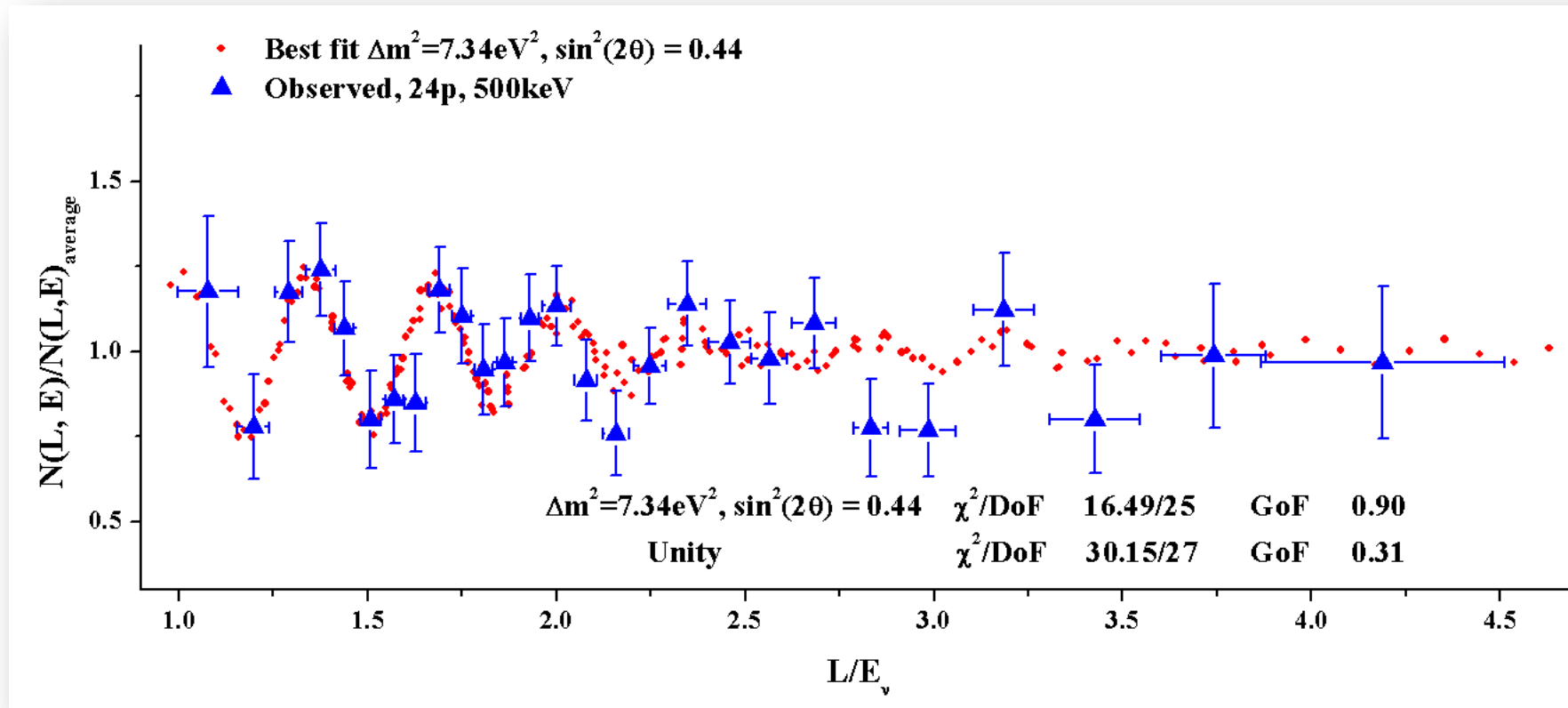
$$R_{i,k}^{\text{exp}} = \frac{N(E_i^\nu, L_k) L_k^2}{K^{-1} \sum_k N(E_i^\nu, L_k) L_k^2} = \frac{[1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i^\nu)]}{K^{-1} \sum_k [1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i^\nu)]} = R_{i,k}^{\text{th}} \quad (2)$$



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

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

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.

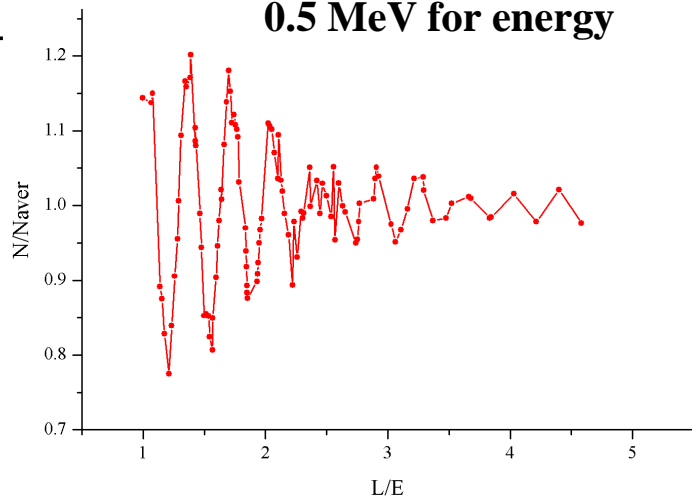


# The expected effect at the different interval for distance and for energy (right part of equation 2)

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

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

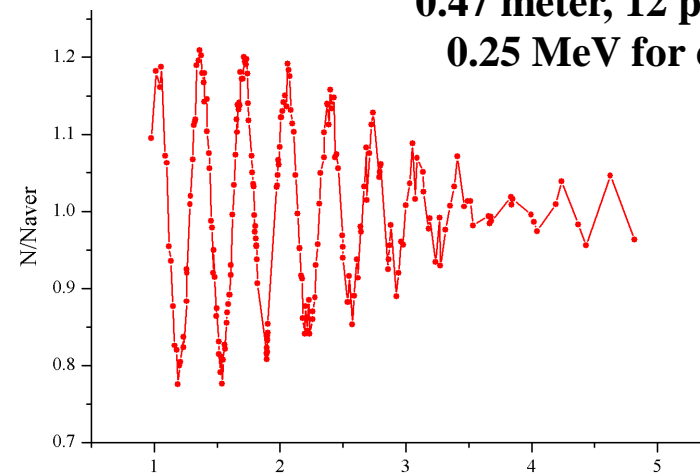
**0.47 meter, 12 positions,  
0.5 MeV for energy**



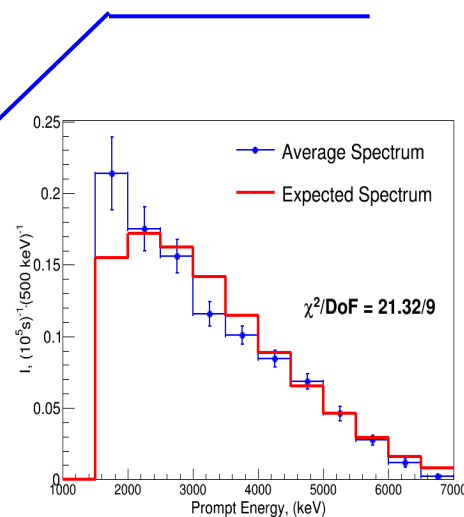
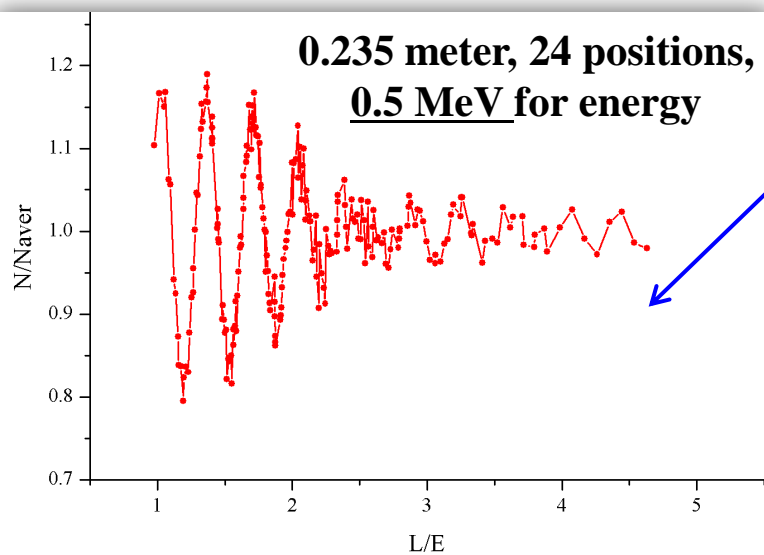
The attenuation of  
sinusoidal process for  
red curve in area  $L/E$   
 $>2.5$  is explained by  
taken energy interval  
0.5MeV.

This energy interval  
corresponds to  
experimental energy  
resolution  $\pm 250\text{keV}$

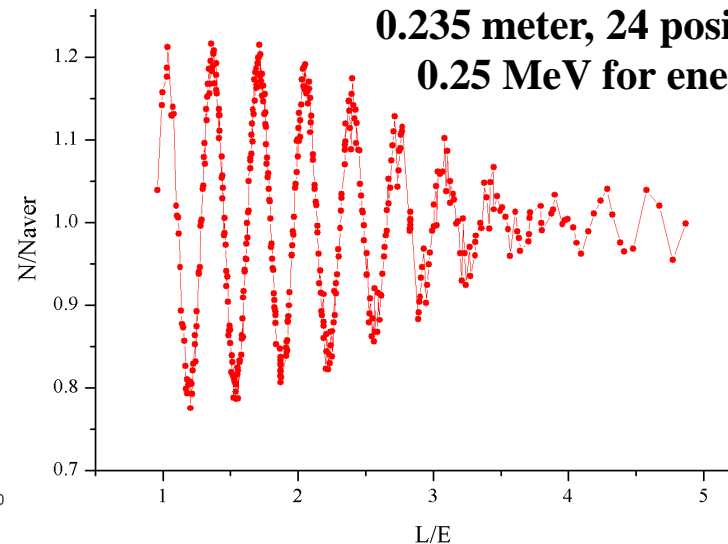
**0.47 meter, 12 positions,  
0.25 MeV for energy**



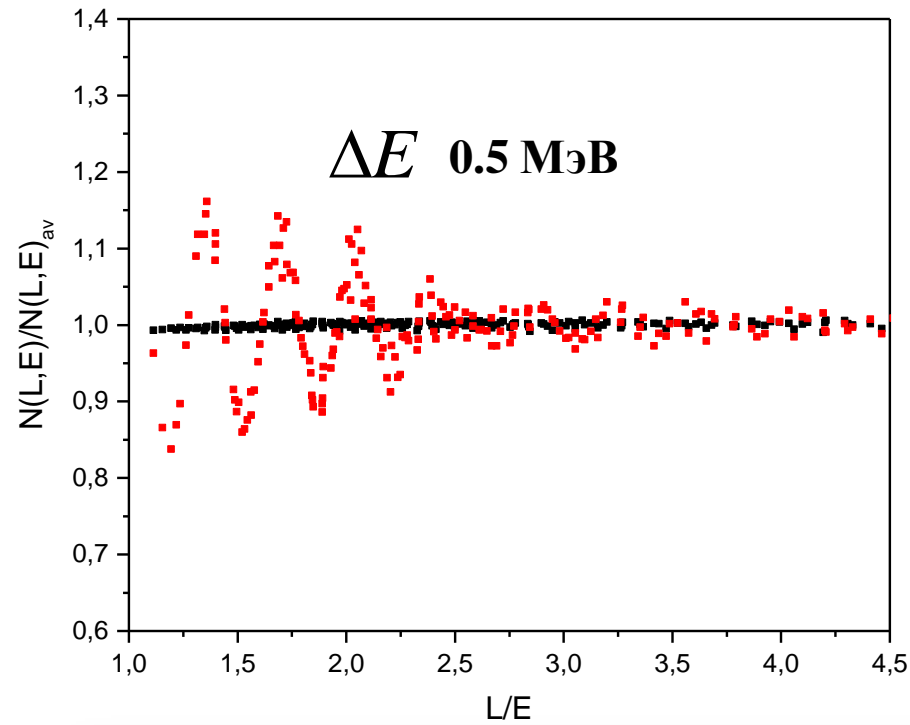
**0.235 meter, 24 positions,  
0.5 MeV for energy**



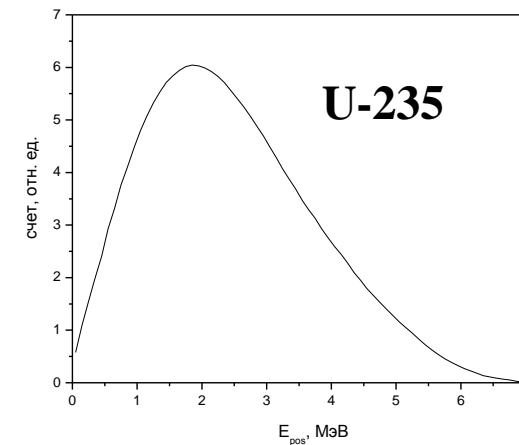
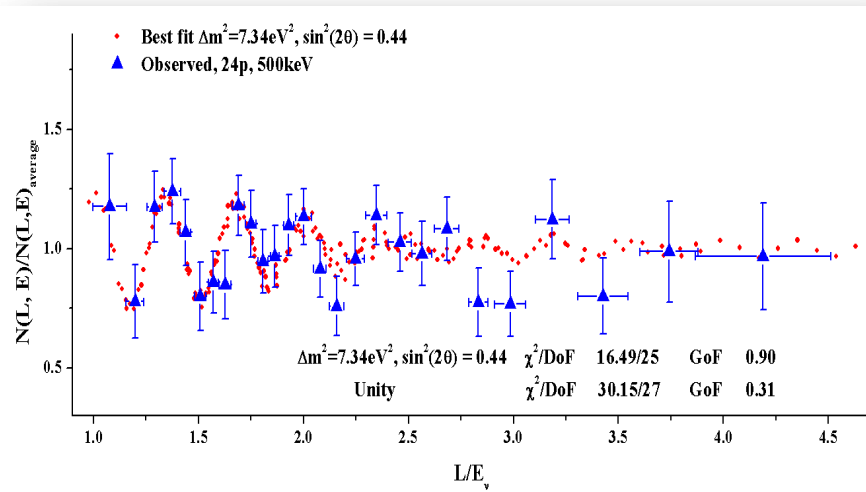
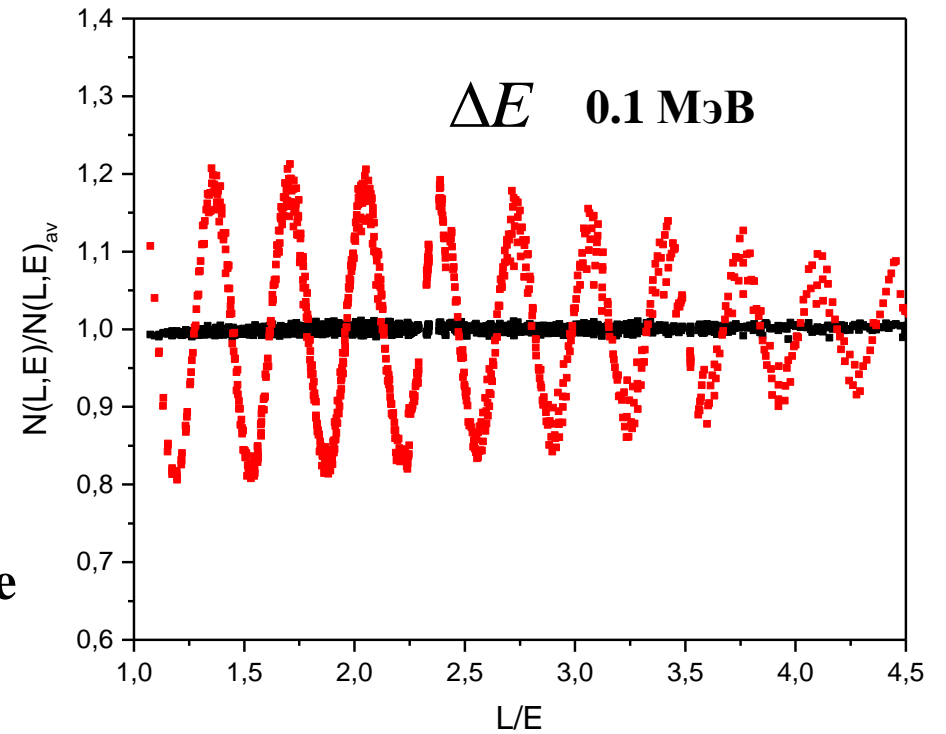
**0.235 meter, 24 positions,  
0.25 MeV for energy**



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

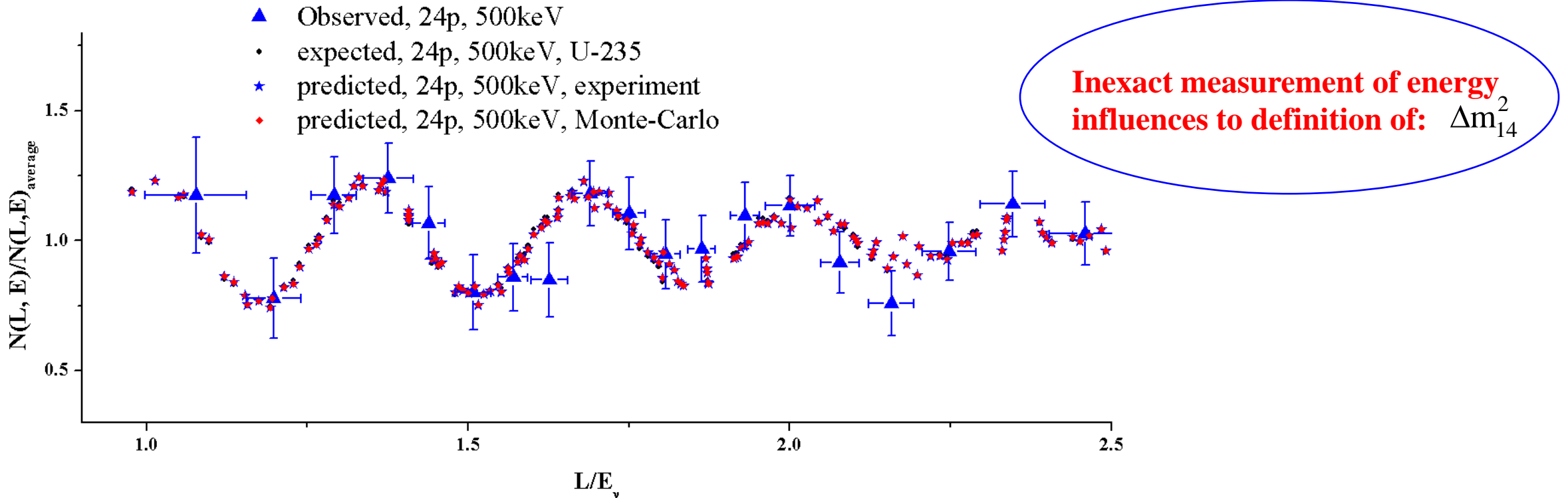


For  
 $\Delta E = 0.5 \text{ MeV}$   
 the picture of  
 Monte Carlo of  
 calculation is quite  
 similar to the  
 experimental  
 picture.



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

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



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

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

## About accounting of correlations in the equation 2

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

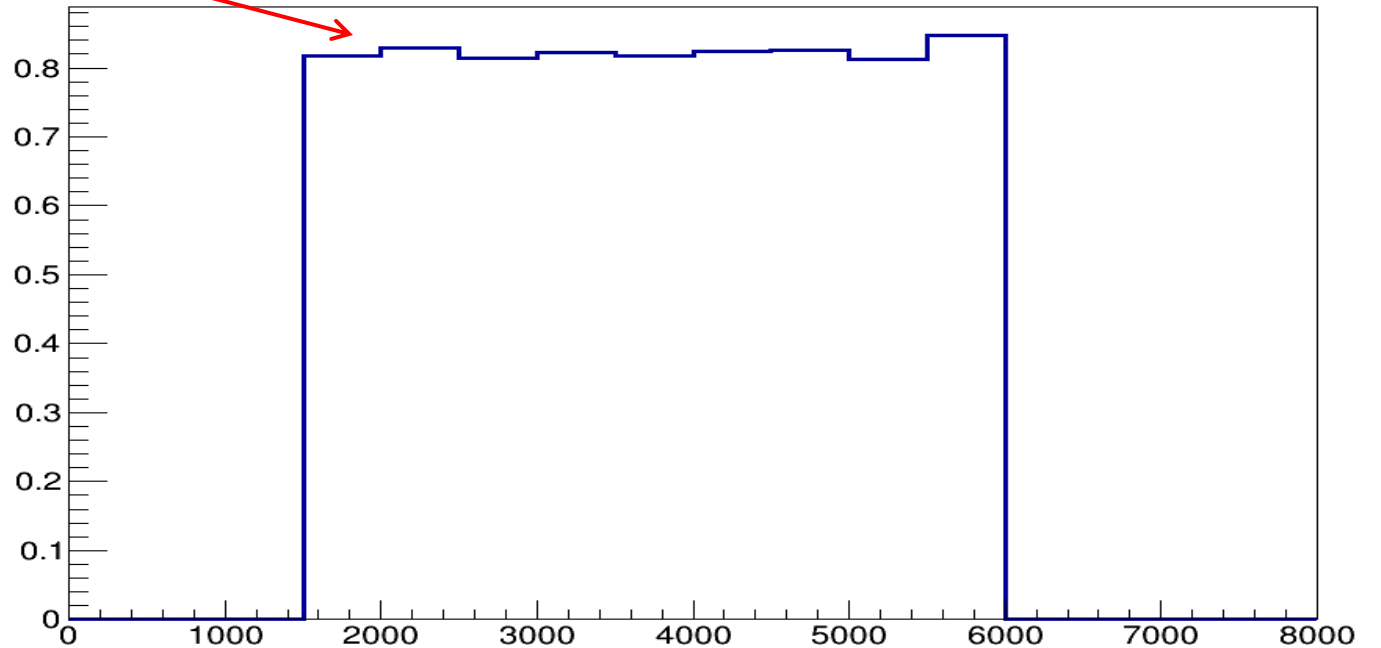
$$K^{-1} \sum_k [1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i)] \quad \text{average } 0.82 \pm 0.01 \text{ on dispersion}$$



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

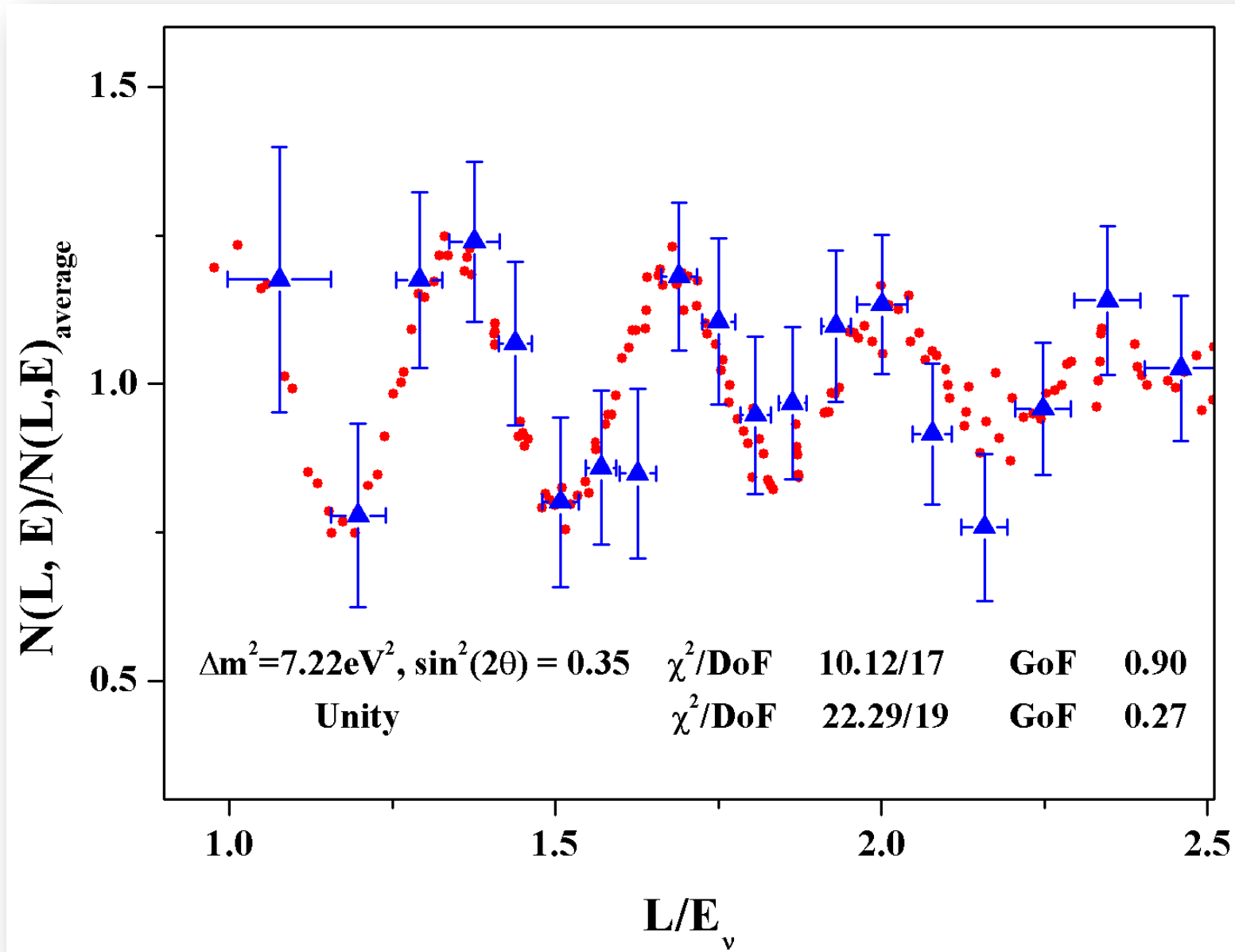
$$\Delta m_{14}^2 \sim 7 \text{ eV}^2 \quad \sin^2 2\theta_{14} \sim 0.4$$

average spectrum (theory)



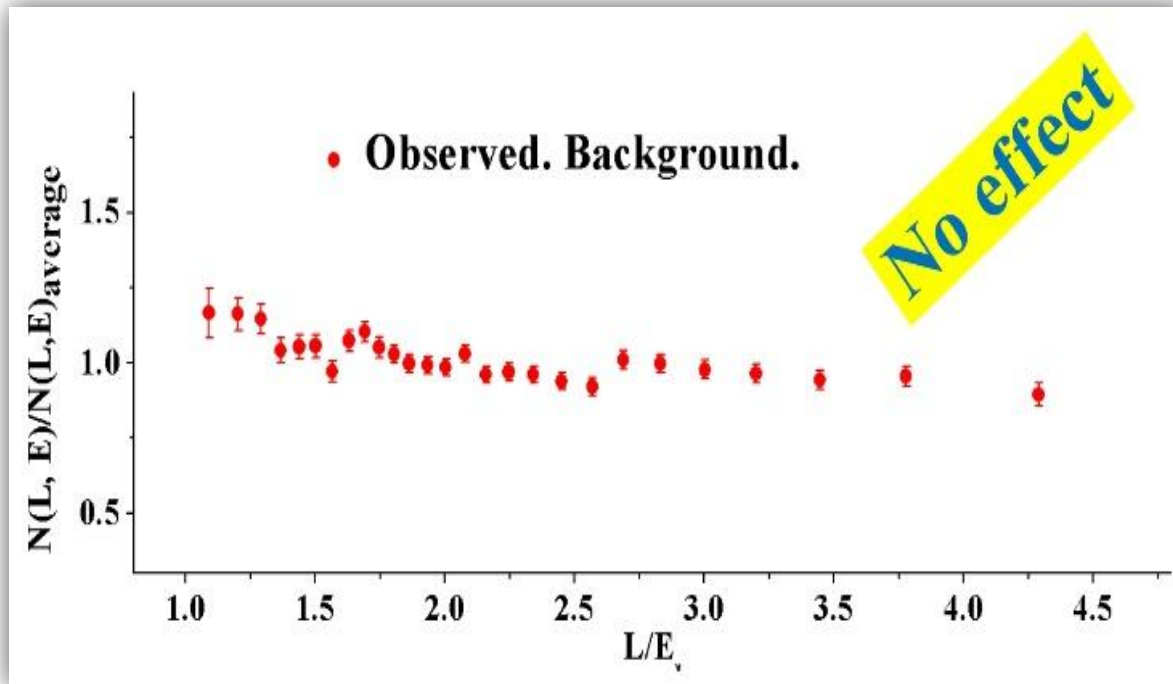
Conclusion: correlations on the spectrum are, but they much less statistical errors and we do not consider them yet.

# The first observation of oscillation of reactor antineutrino in sterile neutrino

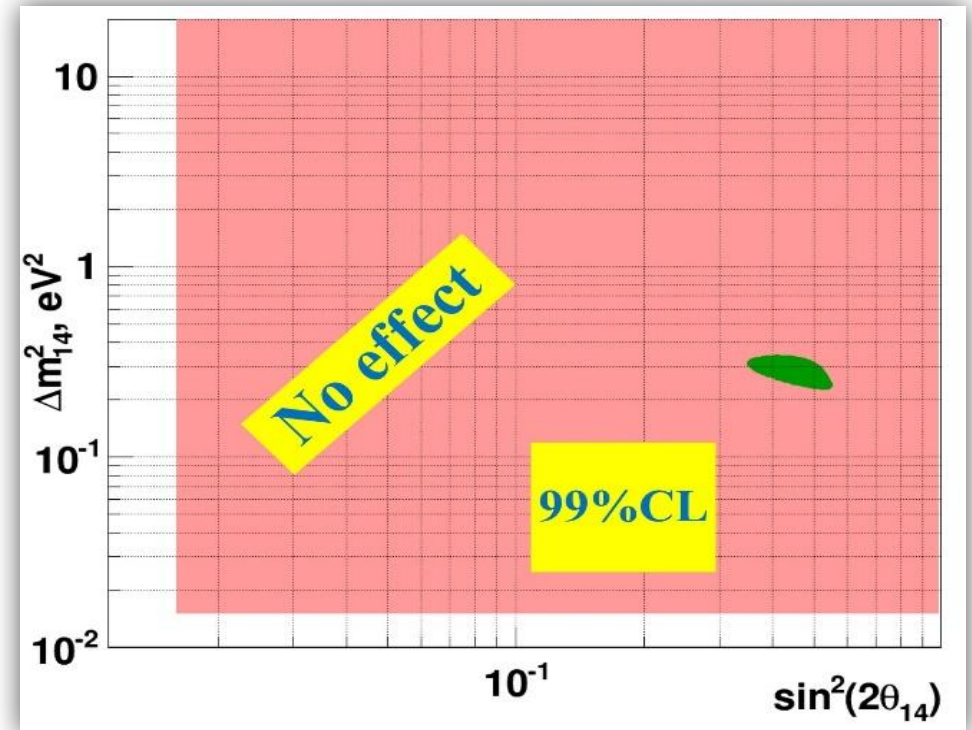


## Test of systematic effects

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



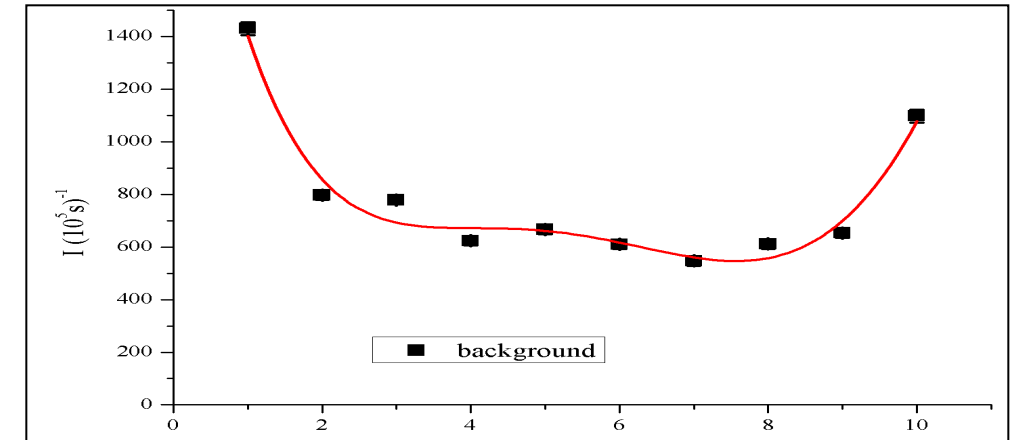
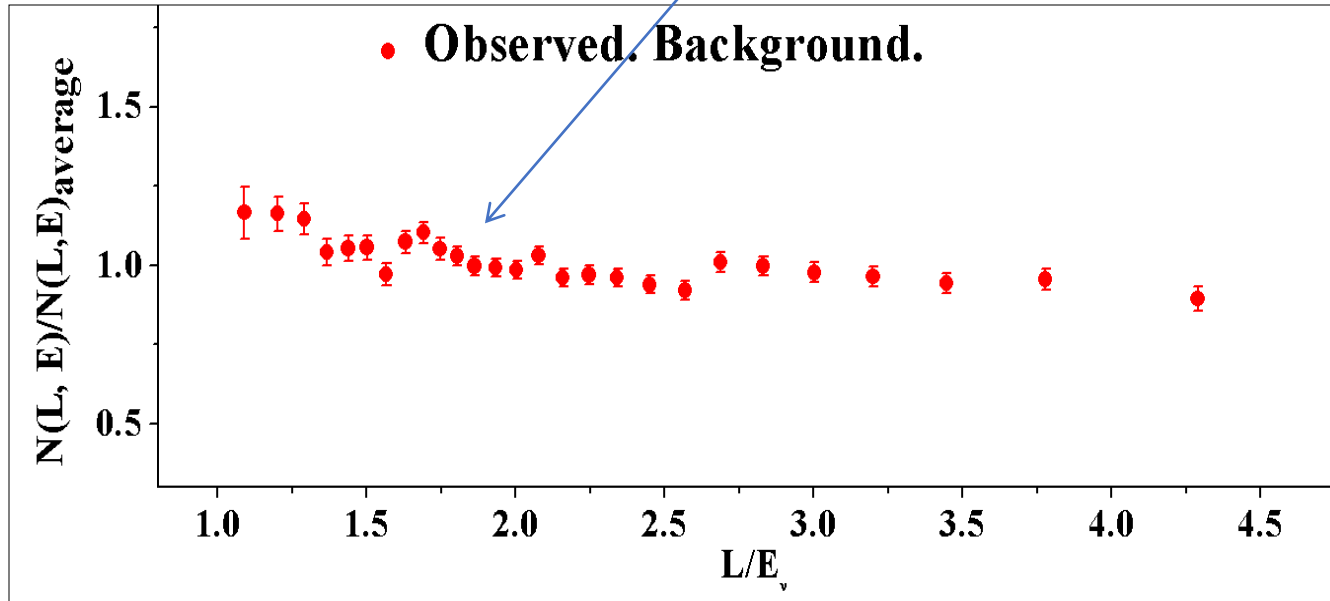
data analysis using coherent summation method



analysis of the results on oscillation parameters plane

**Thus no instrumental systematic errors were observed.**

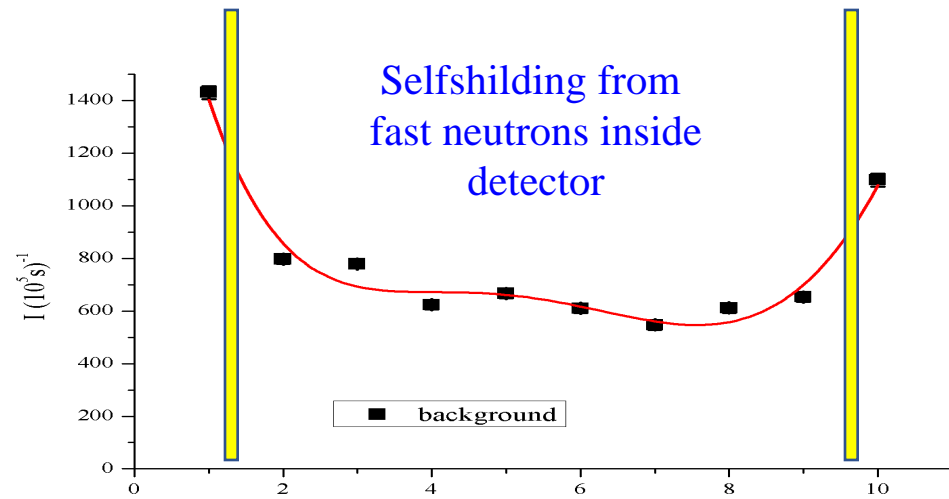
## Explanation of variations in the L/E dependence for a background



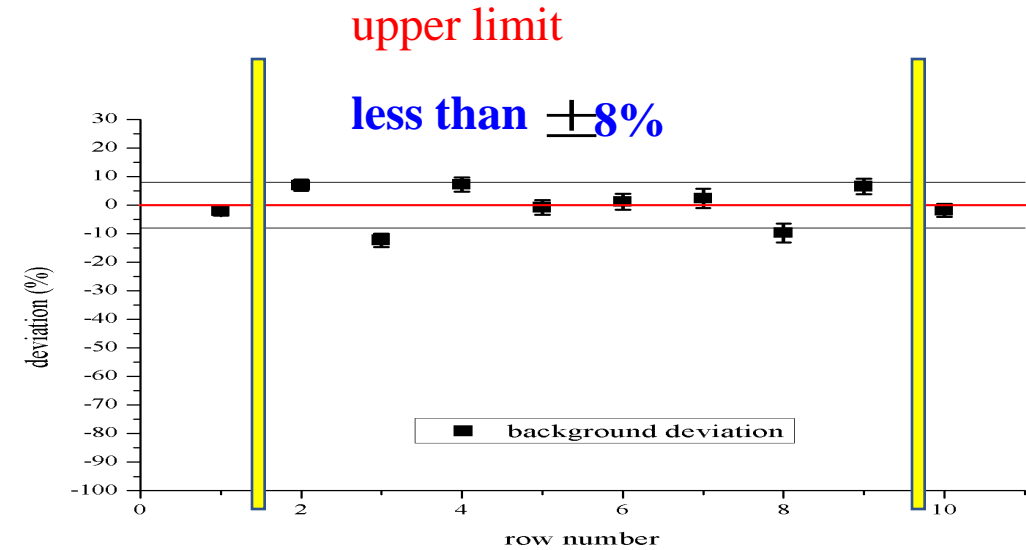
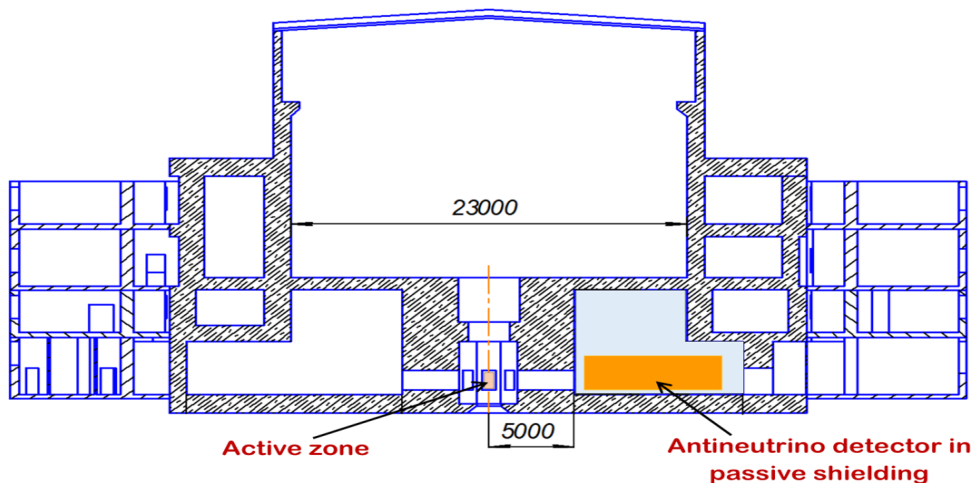
**Reason - Different positions of the detector are looked through.  
This effect in the difference of ON-OFF is subtracted.**



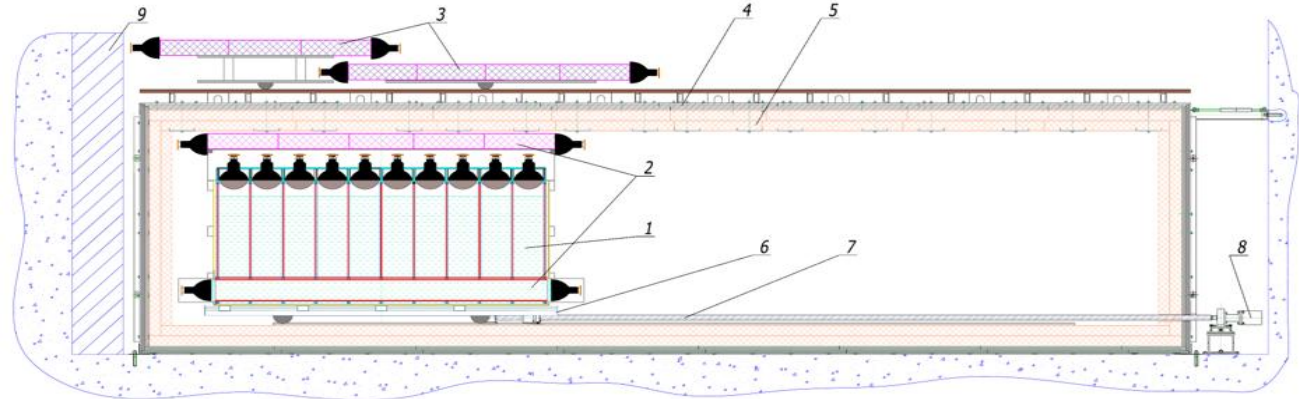
# Analysis of possible difference in efficiency of rows of the detector, using the background of fast neutrons which is given rise into the building from cosmic muons.



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%.

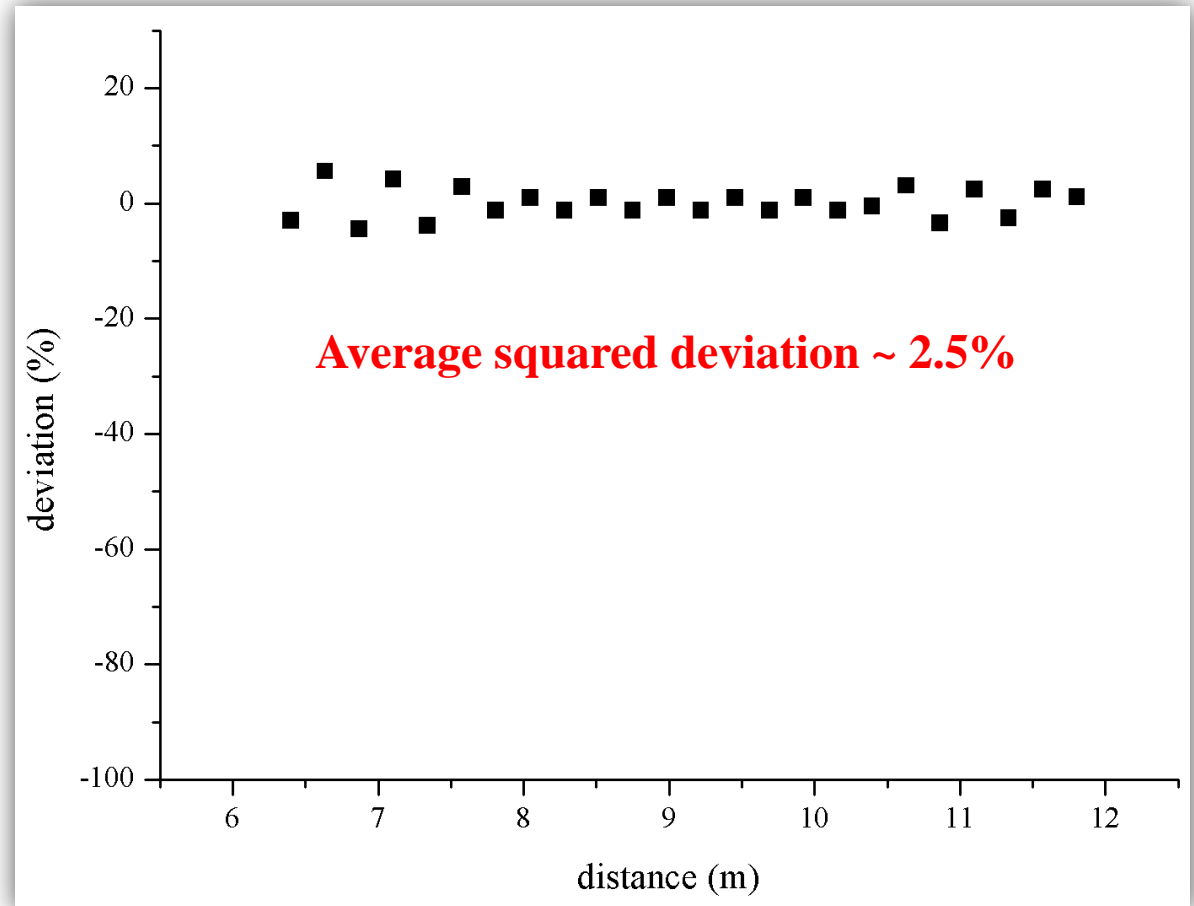


We use only 8 internal rows, the first and tenth are protective.

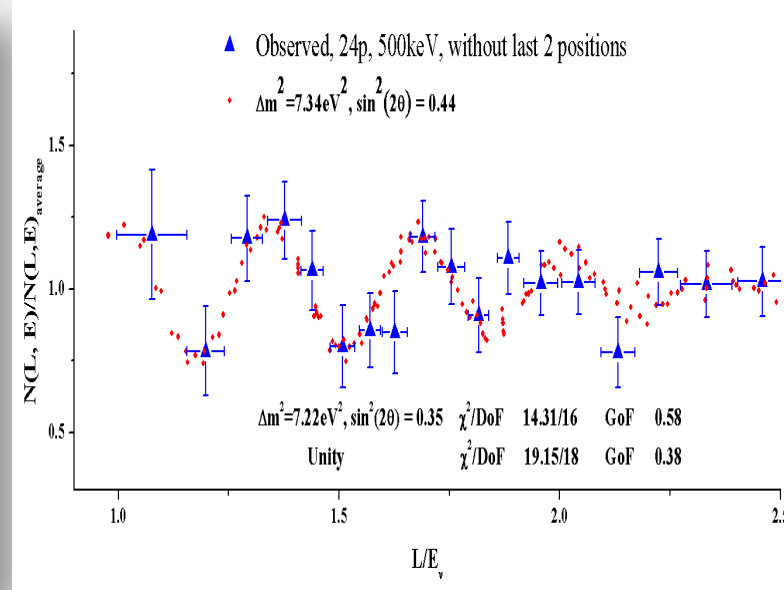
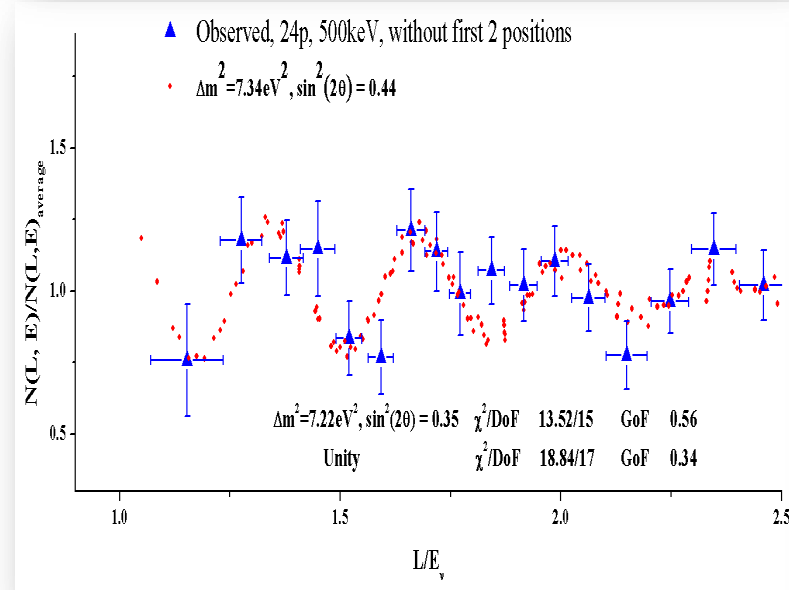
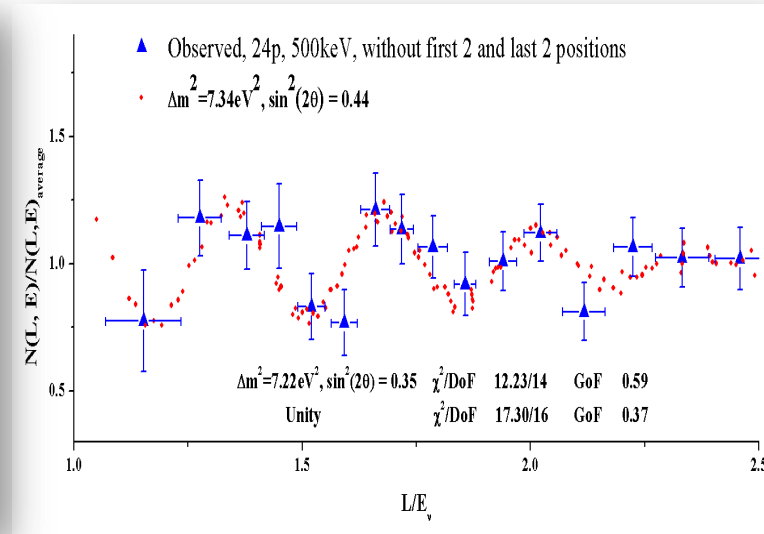
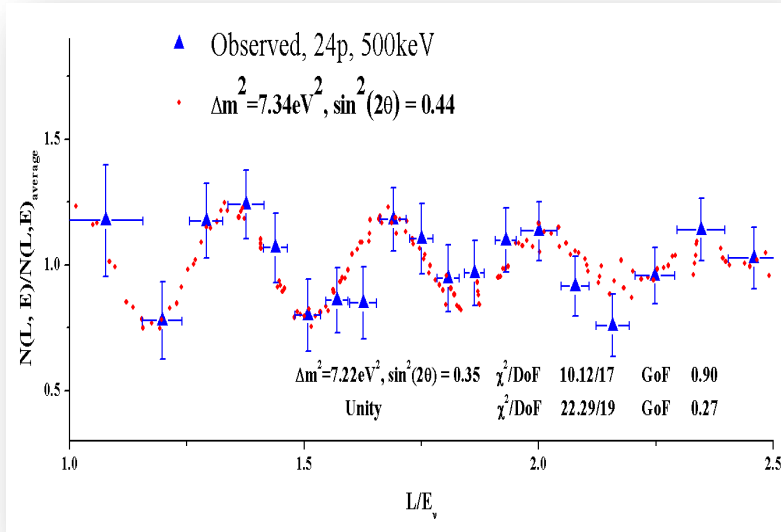
# Averaging of detector rows efficiencies due to movements (above estimation)

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

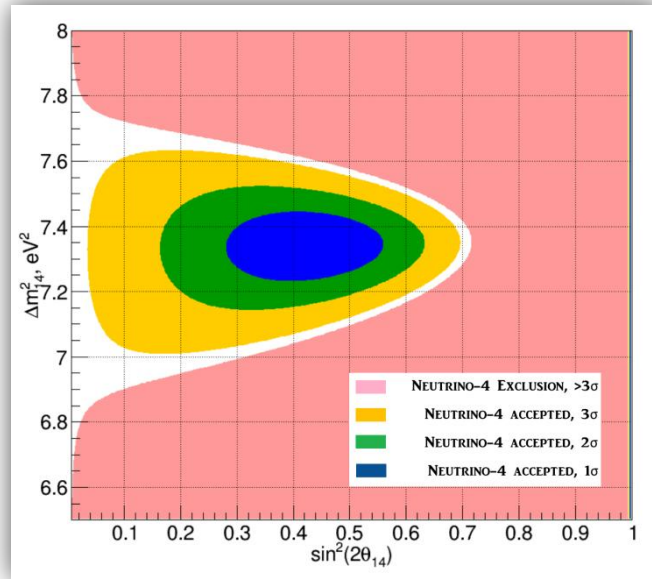


# Test of stability of the effect by means of removal of extreme positions



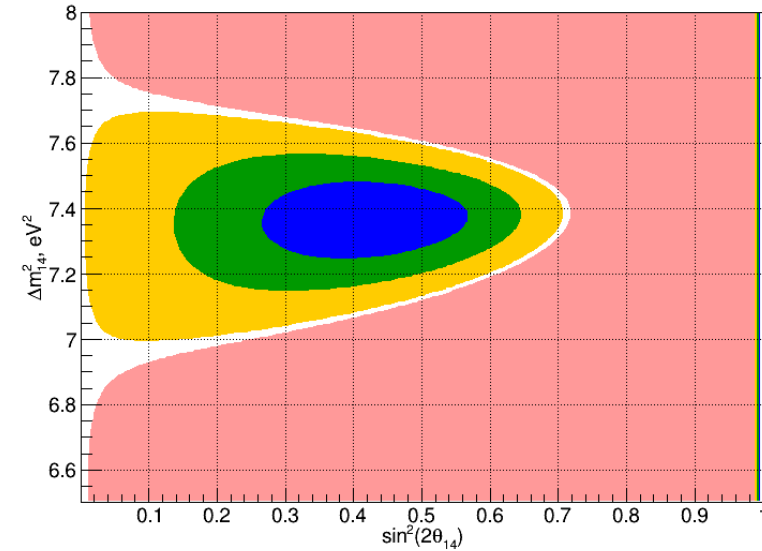
**Conclusion**  
 There is no reason to consider that the effect can be caused by structure of the detector. The possibility of averaging of efficiency of various sections by placing them at the same distance is the advantage of our experiment.

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

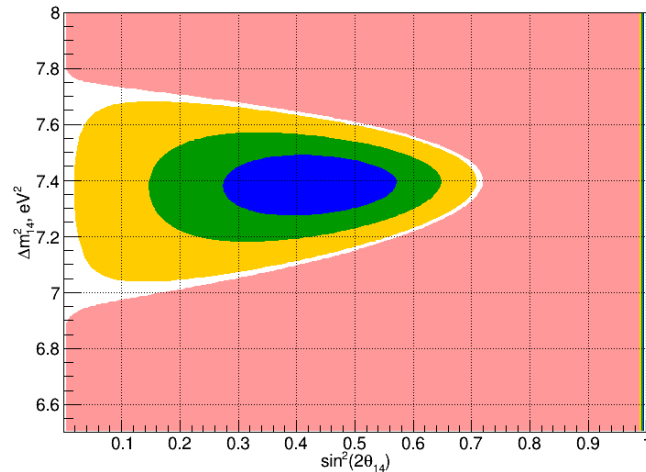


After removal  
of extreme  
positions the  
effect still is in  
limits the 3rd  
sigma.

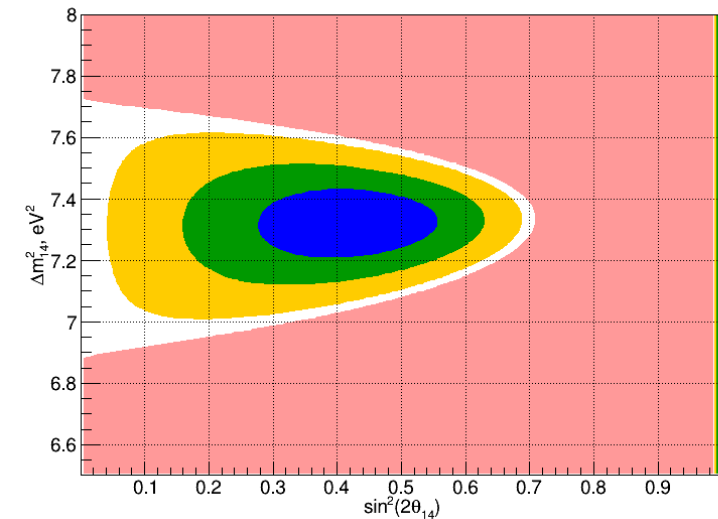
Neutrino-4. Without first 2 and last 2 positions.



Neutrino-4. Without first 2 positions.

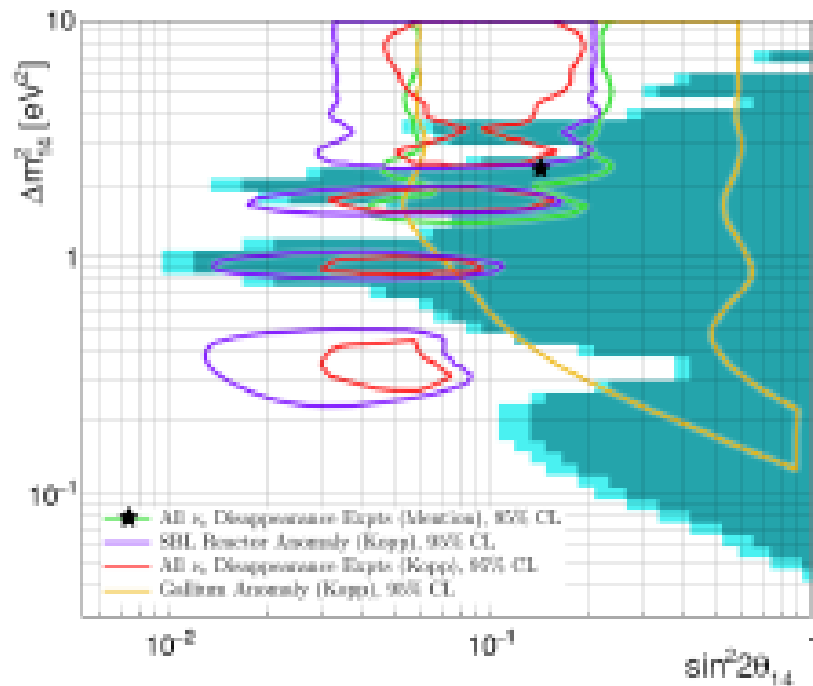


Neutrino-4. Without last 2 positions.



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

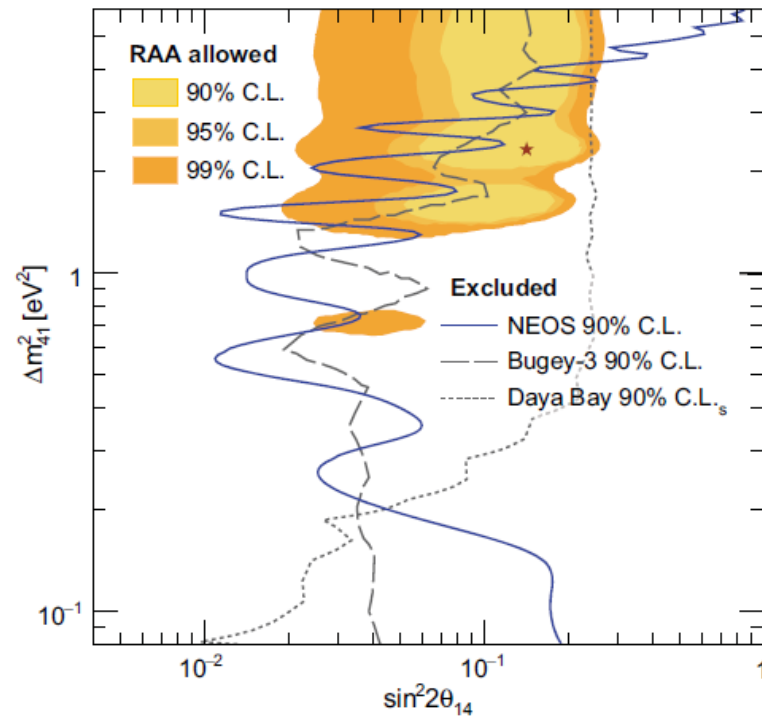
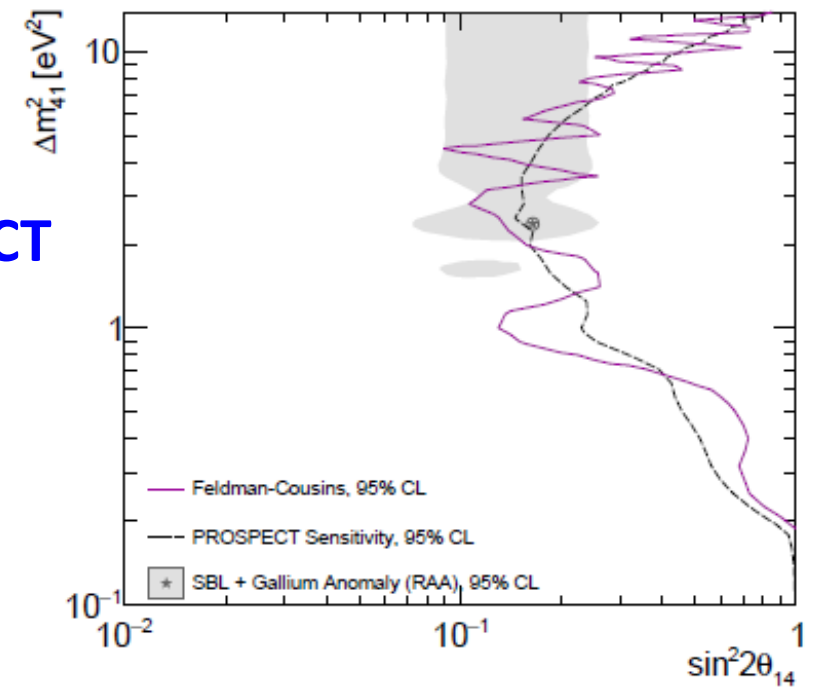
**Next slide illustrates sensitivity of other experiments NEOS , DANSS , STEREO and PROSPECT together with Neutrino-4.**



**DANSS**  
90%

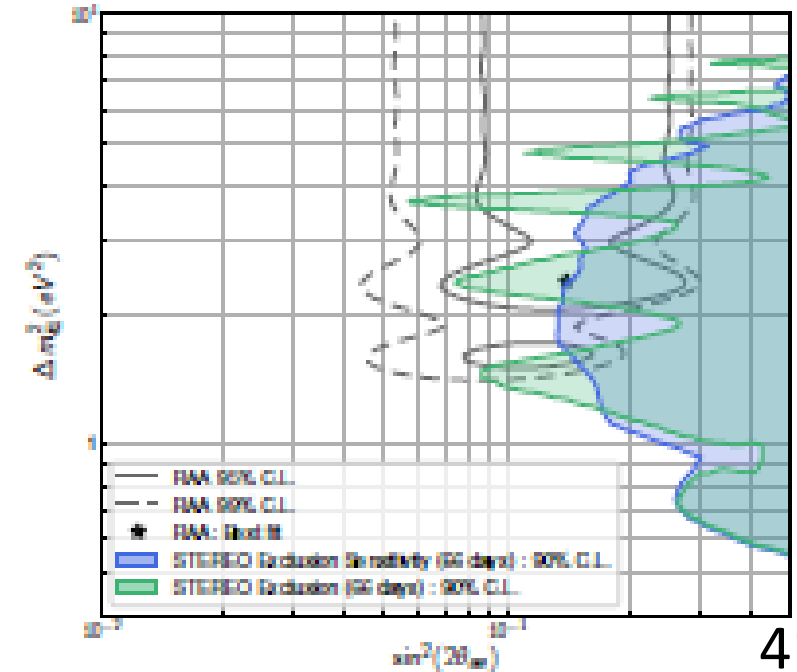
**PROSPECT**  
95%

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

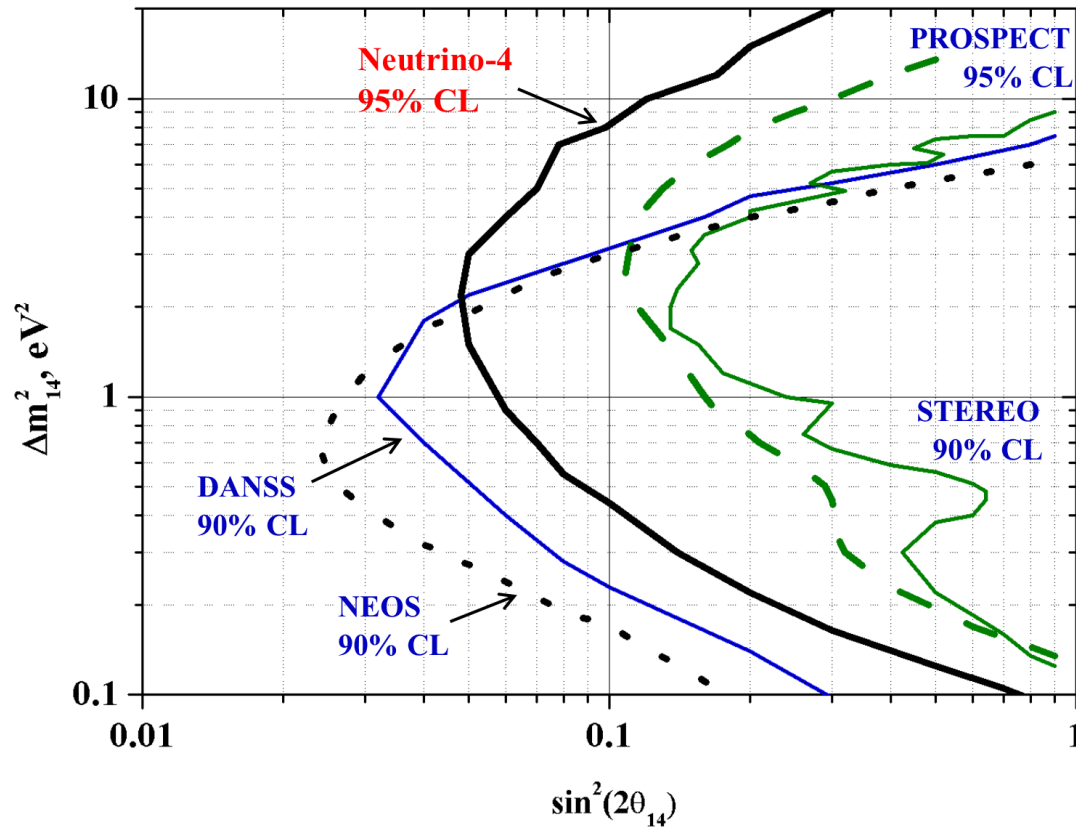


**NEOS**  
90%

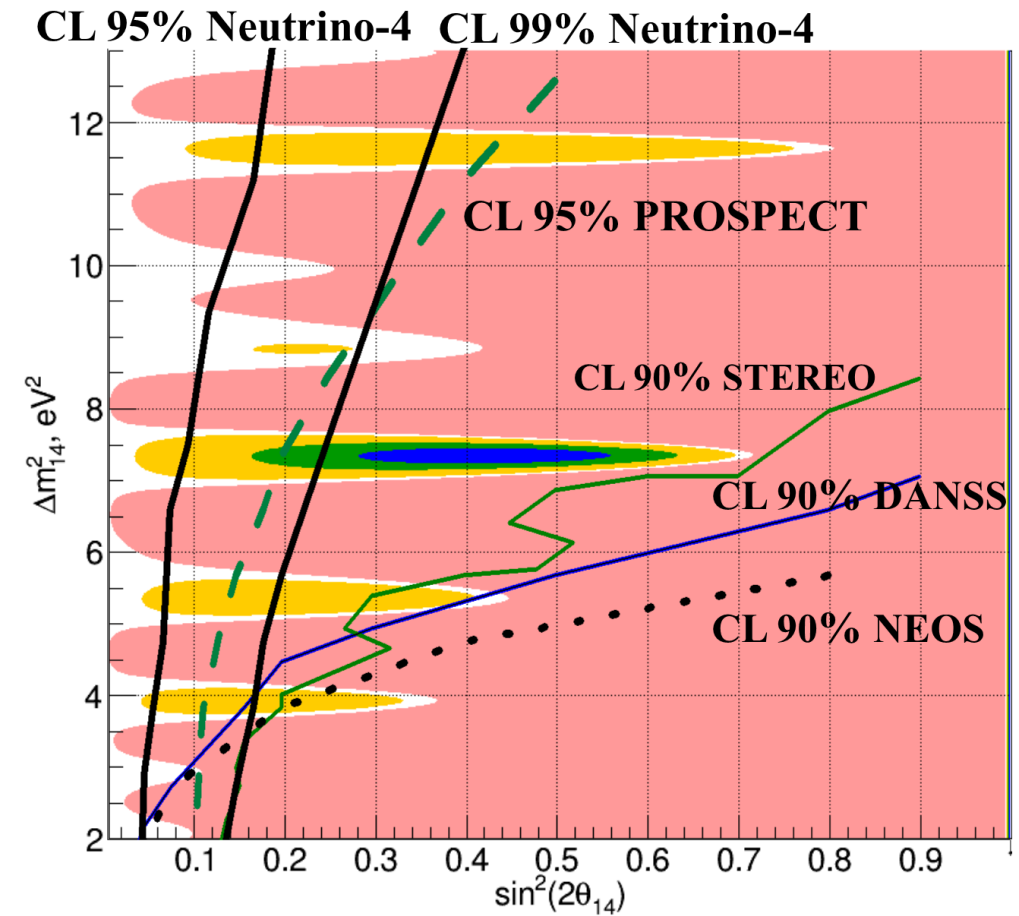
**STEREO**  
90%



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



sensitivity regions of various experiments  
(logarithmic scale)



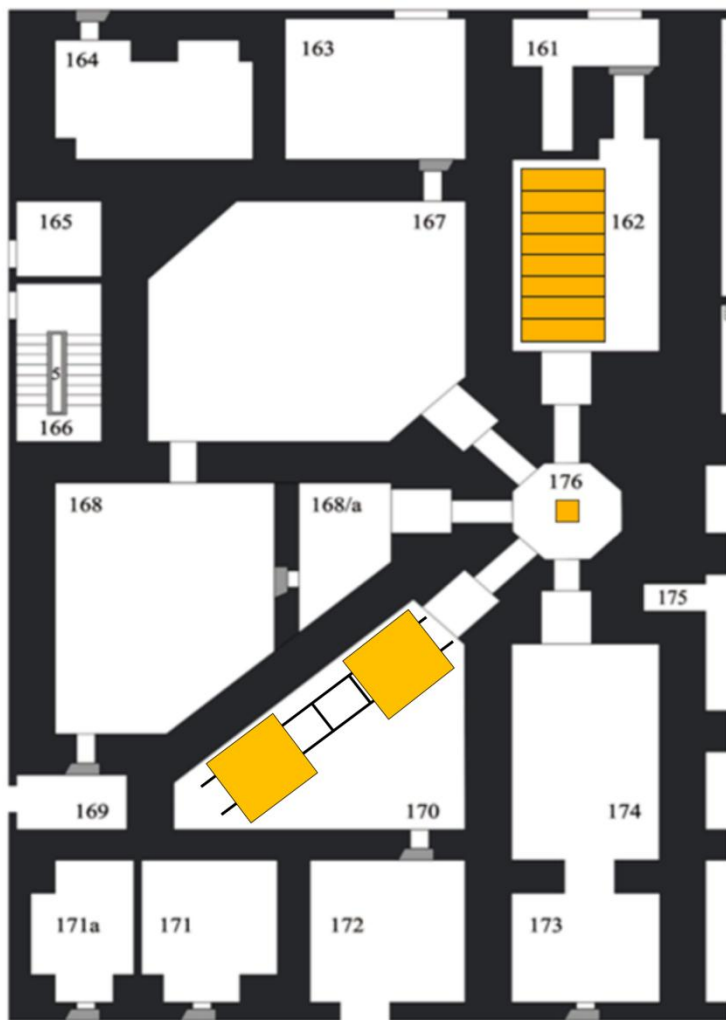
region of oscillation effect in linear scale.

Experiment Neutrino-4 has some advantages in sensitivity to big values of  $\Delta m_{14}^2$  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  $\Delta m_{14}^2$  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**.



**Experiment Neutrino-4 has some advantages in sensitivity to big values of  $\Delta m_{14}^2$  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  $\Delta m_{14}^2$  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.****

## Future plans: Experiment Neutrino-6



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

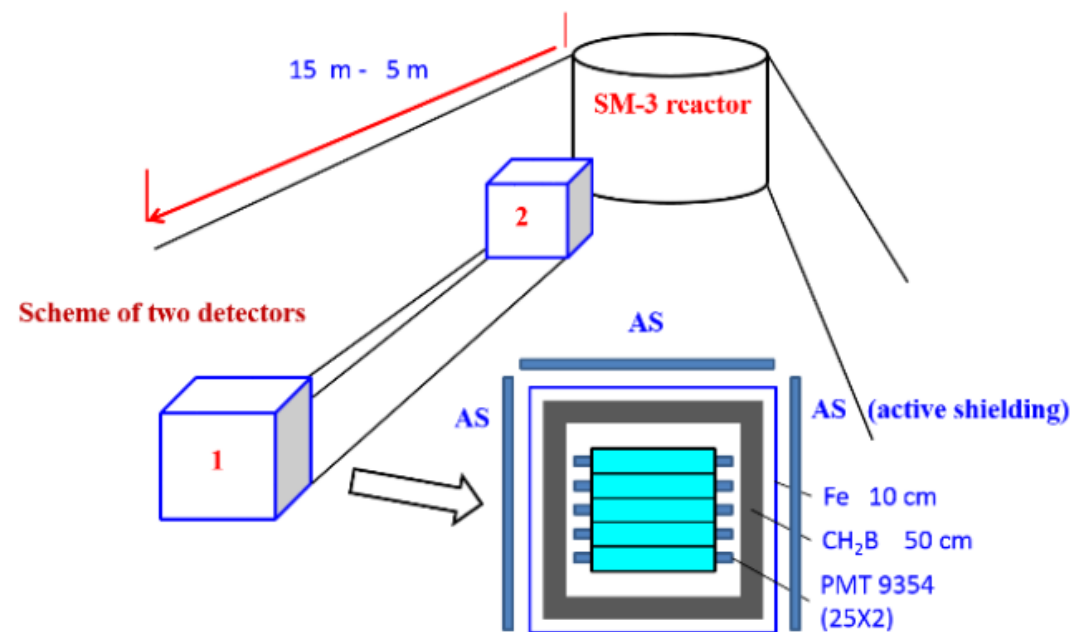
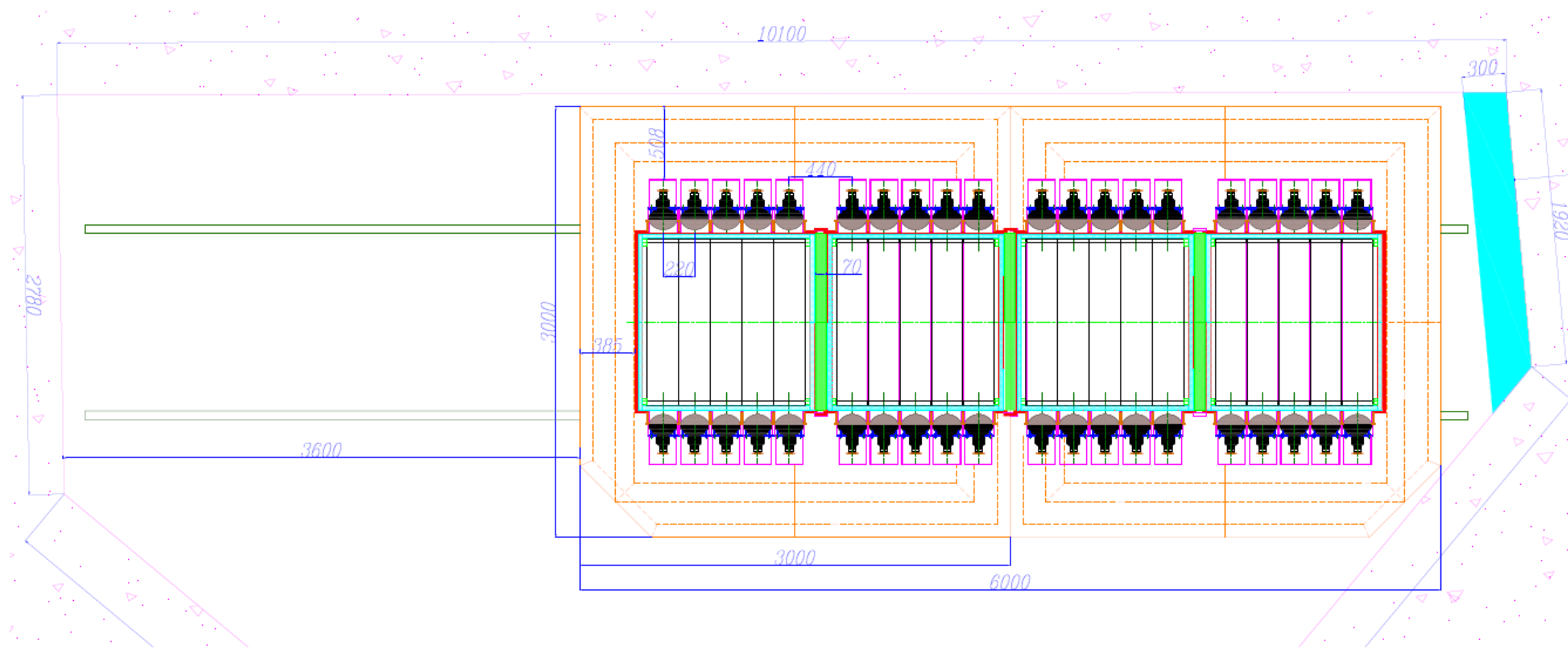
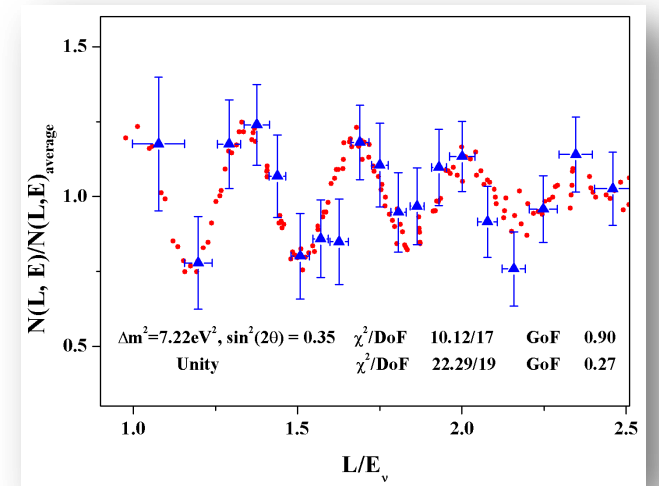
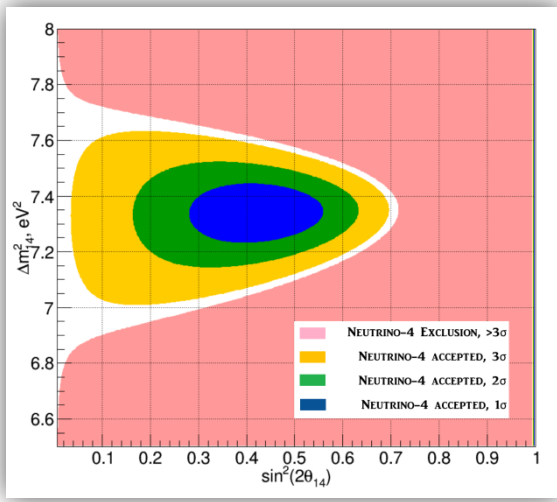


FIG. 22. Scheme of a new experiment on search for neutrino oscillations in room No. 170 of the SM-3 reactor.

## Future plans: Experiment Neutrino-6



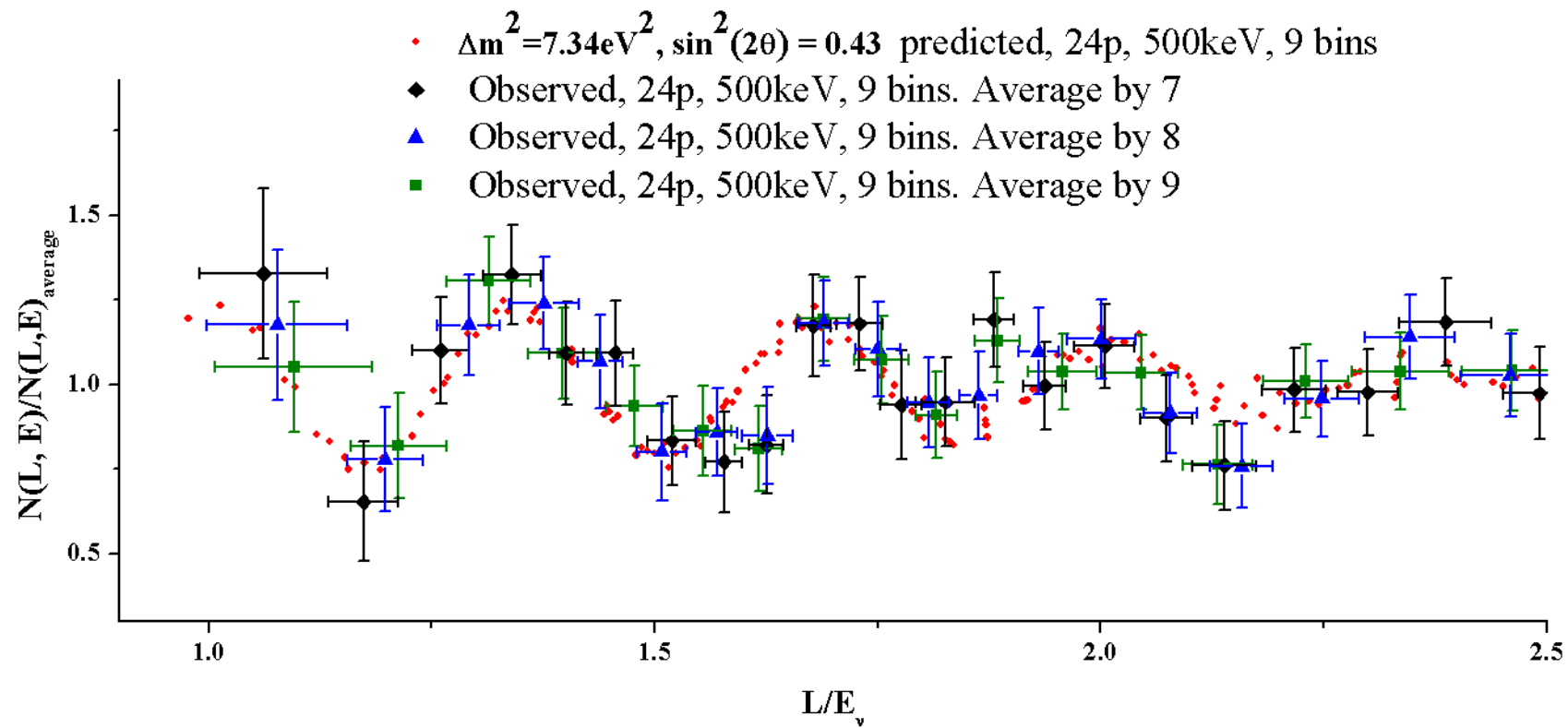
# Thank you for attention

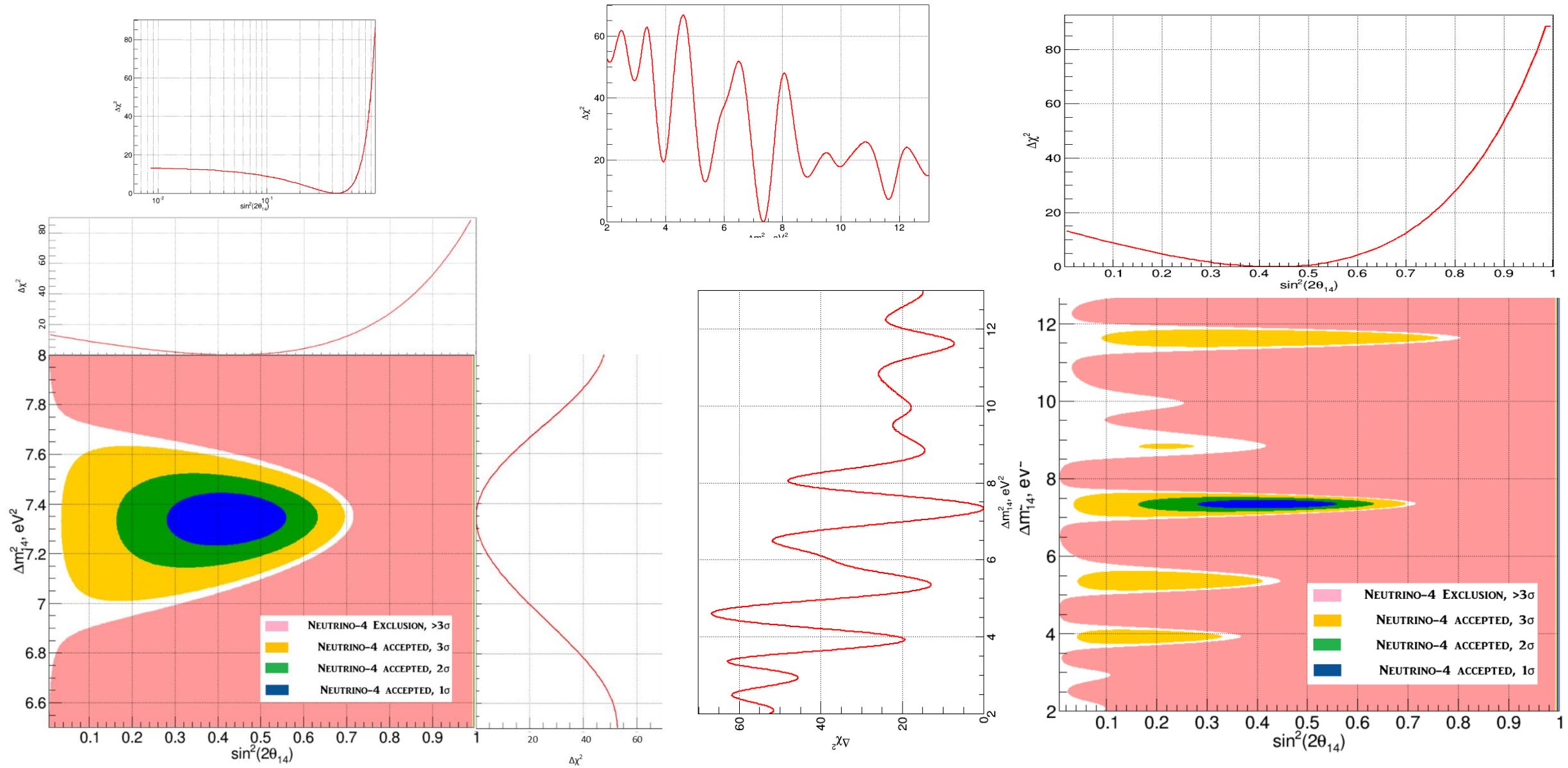


*Best regards from Gatchina*

*Best regards from Dimitrovgrad*









## 10 energy bins (1.5-6.5 MeV)

Neutrino-4. 500 keV. 10 energy bins (1.5-6.5 MeV)

