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

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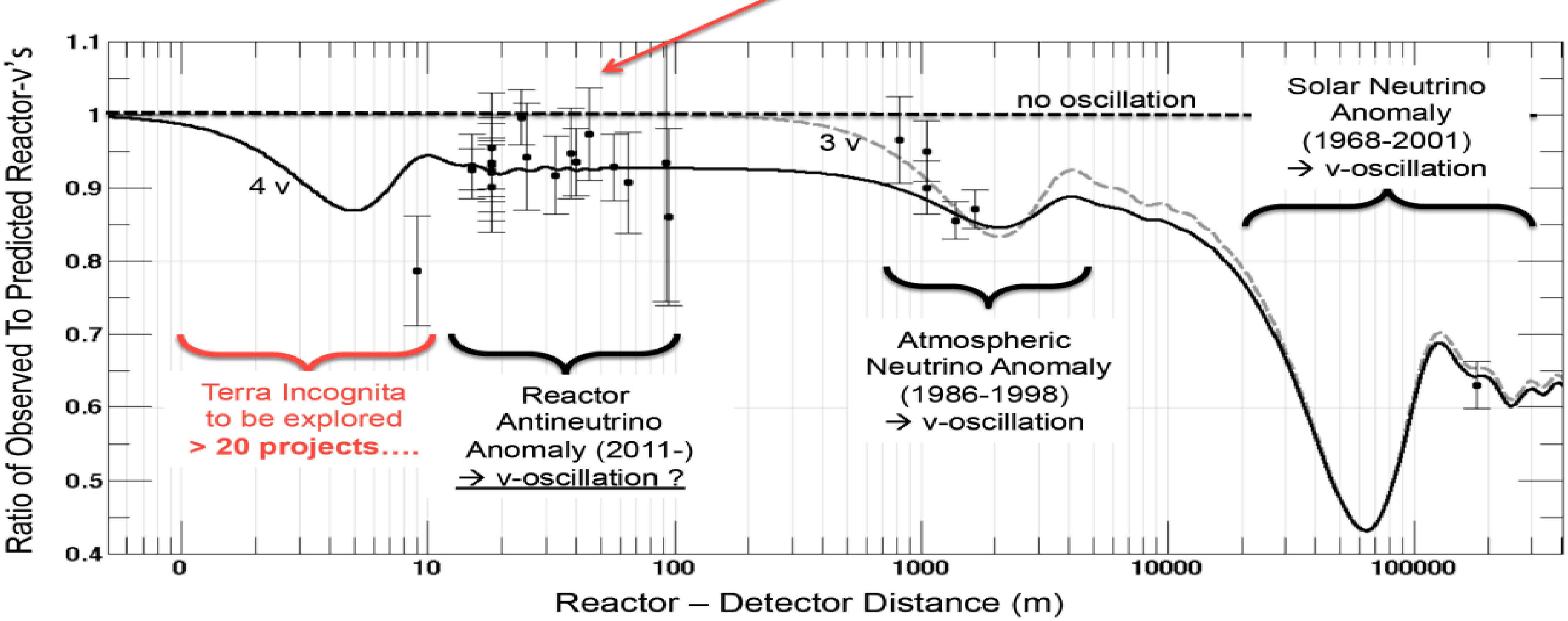
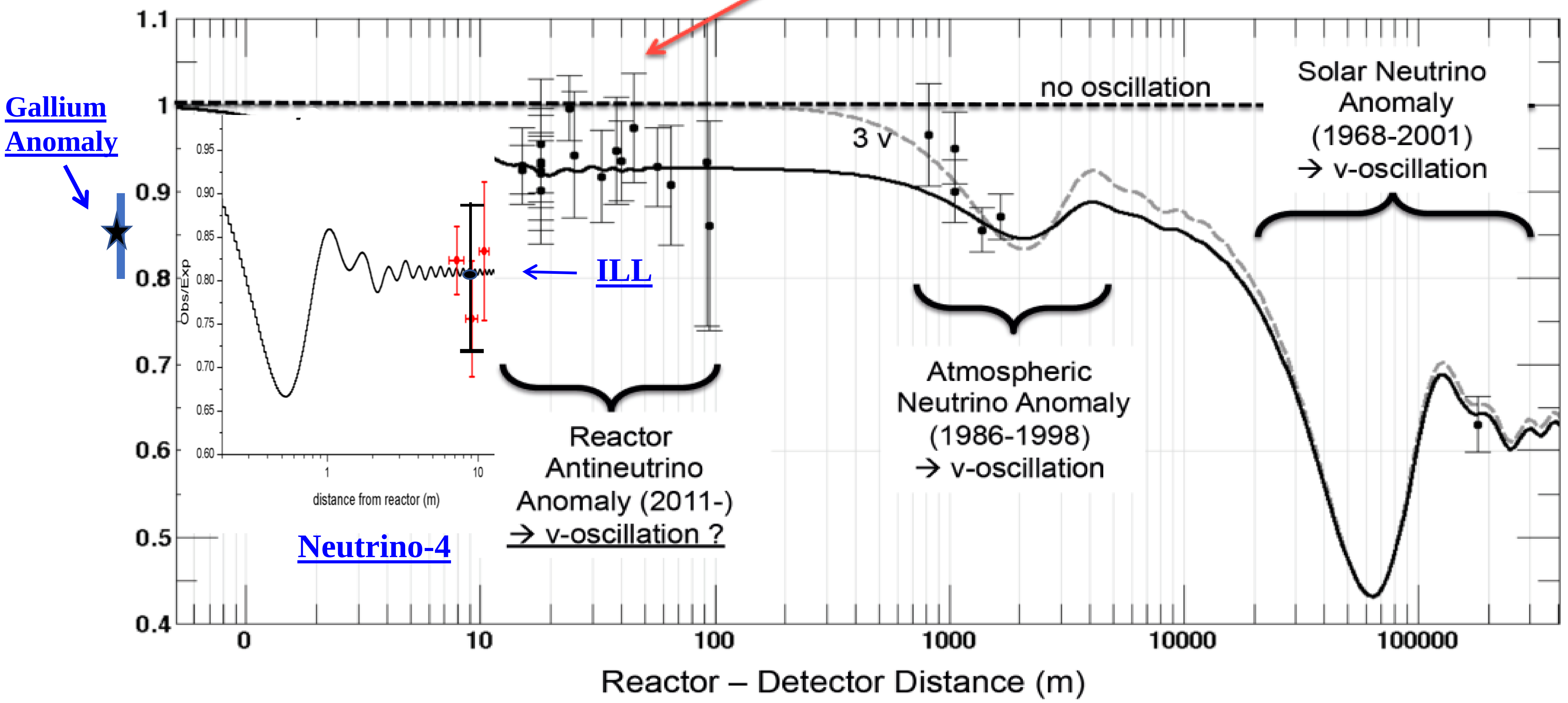
Reactor antineutrino anomaly

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

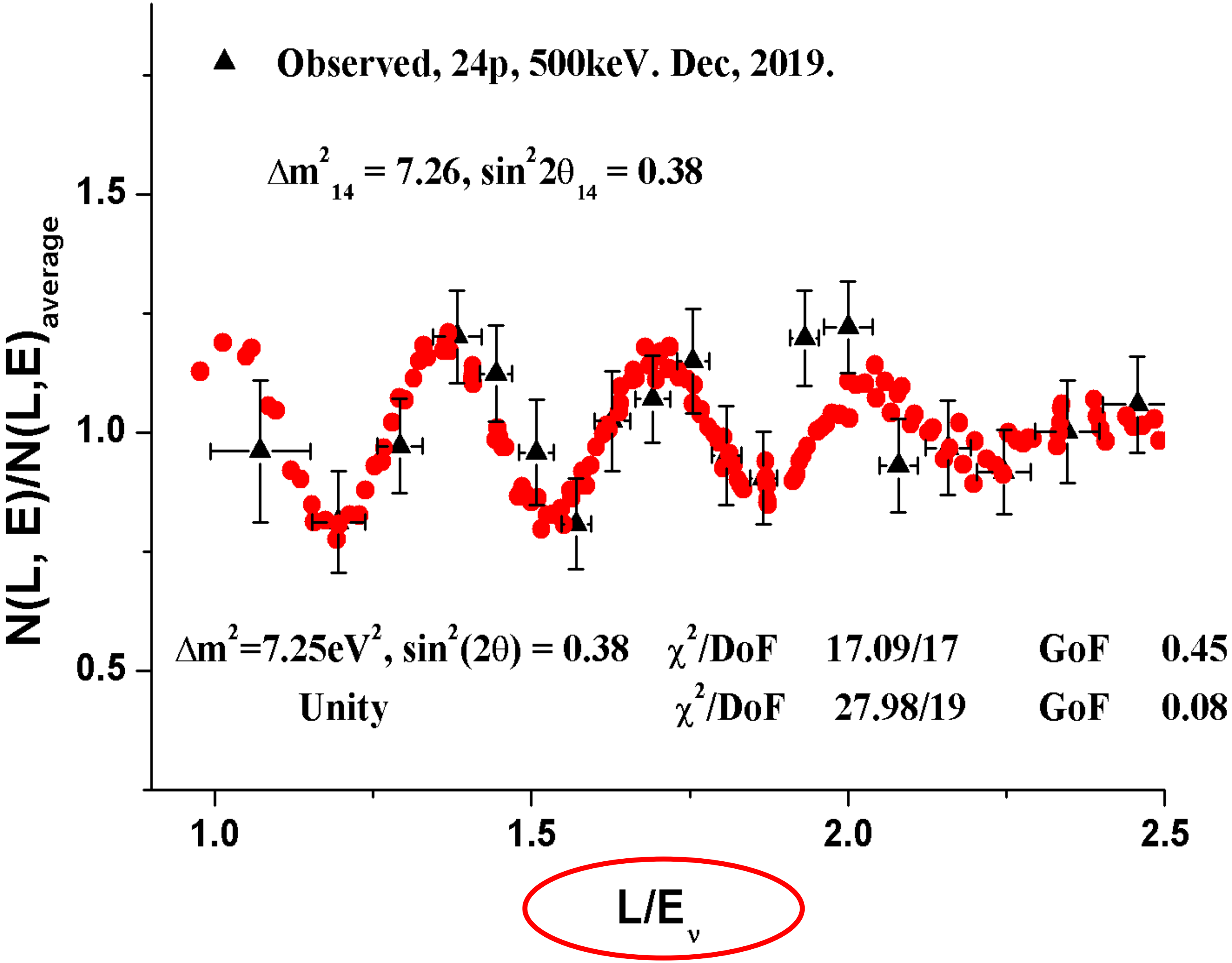


$$P(\tilde{\nu}_e \rightarrow \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \ \sin^2\left(1.27 \frac{\Delta m^2_{14}[eV^2]L[m]}{E_{\tilde{\nu}}[MeV]}\right)$$

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

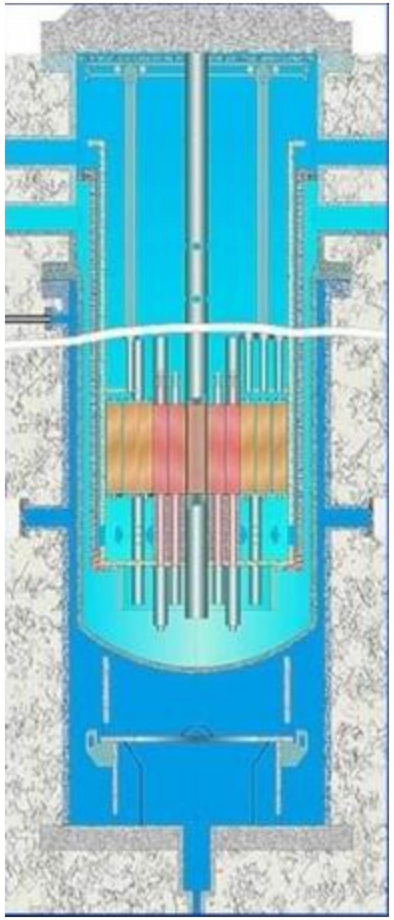


The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino

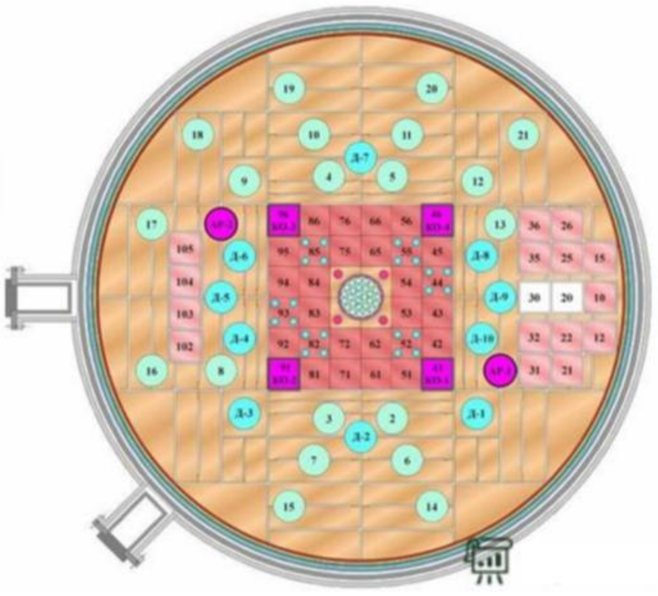


SM-3 research reactor

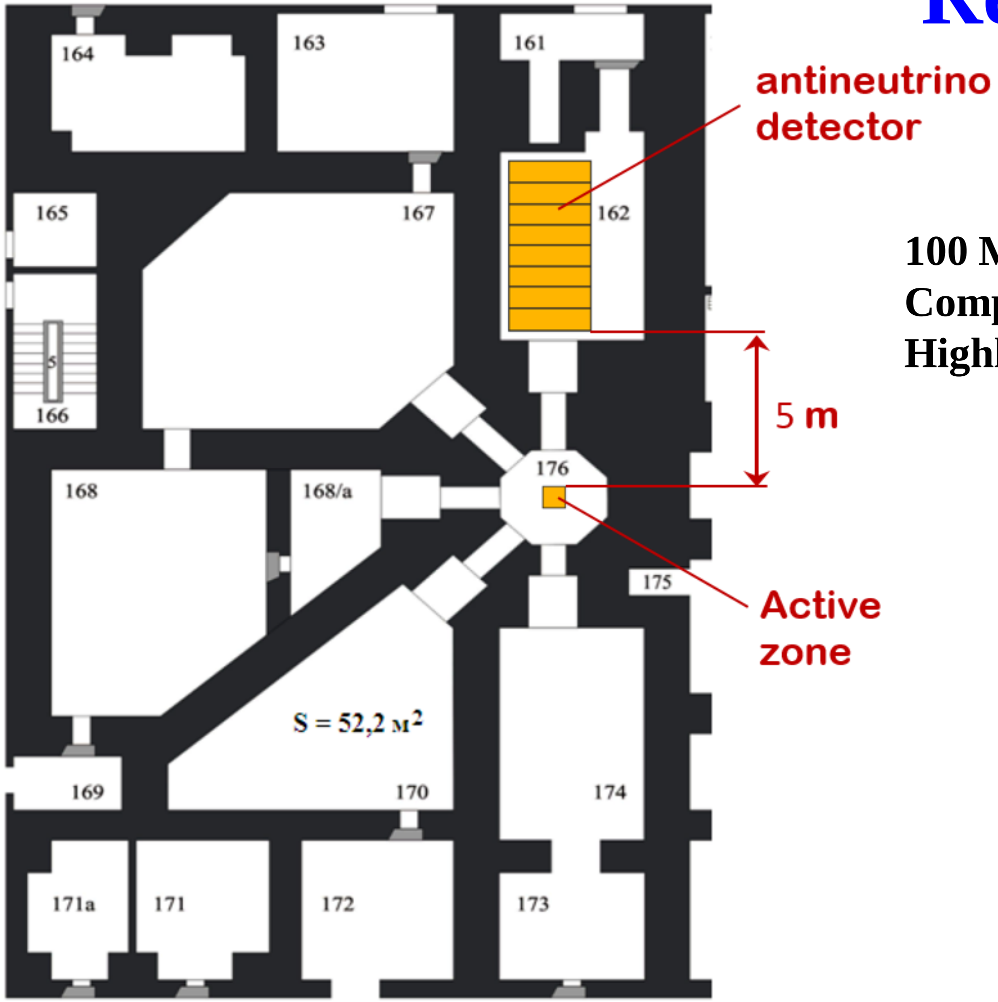
- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched ^{235}U fuel
- Separated rooms for experimental setup
- The laboratory is poorly protected from cosmic rays



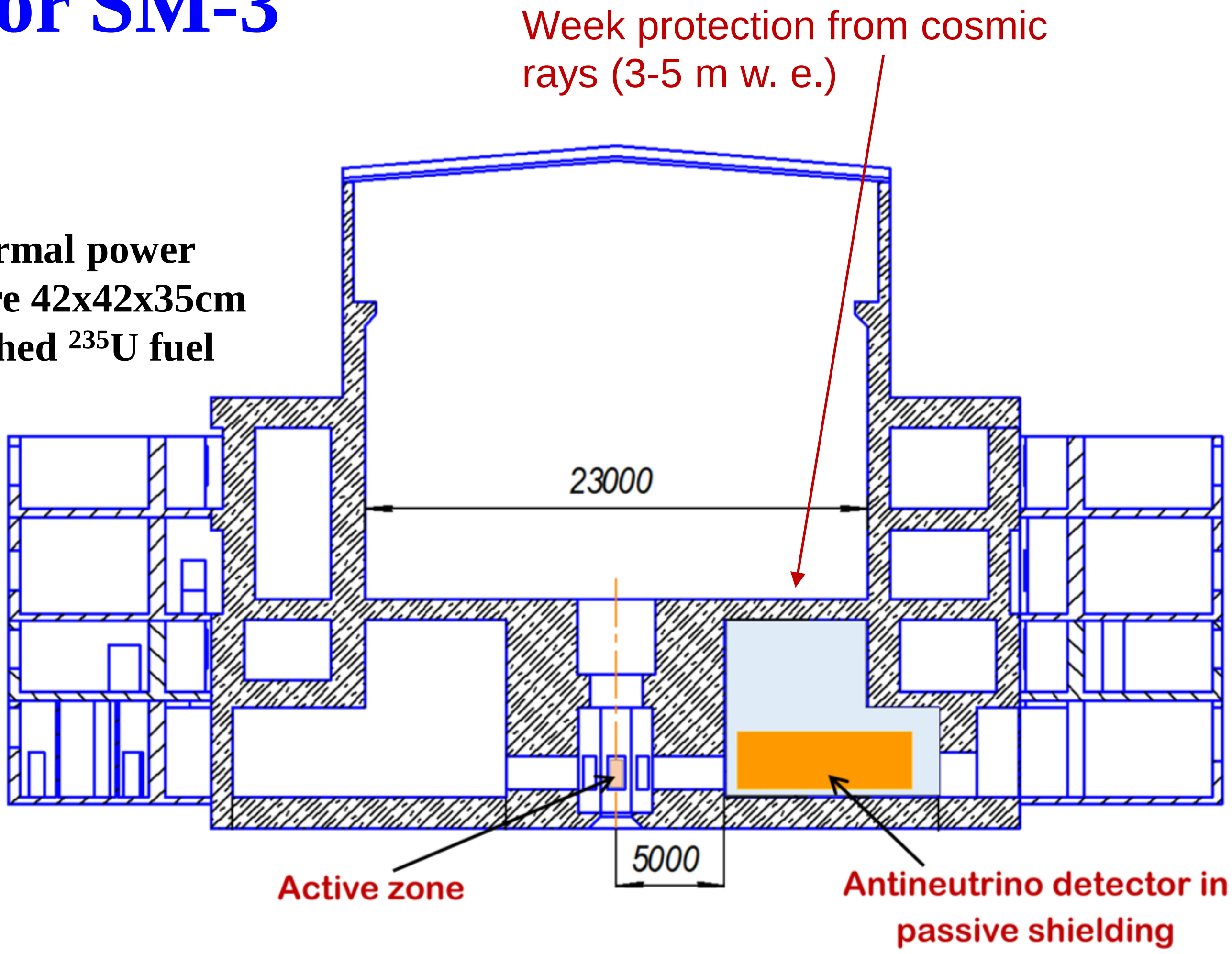
Vertical and horizontal sections of SM-3 reactor



Reactor SM-3

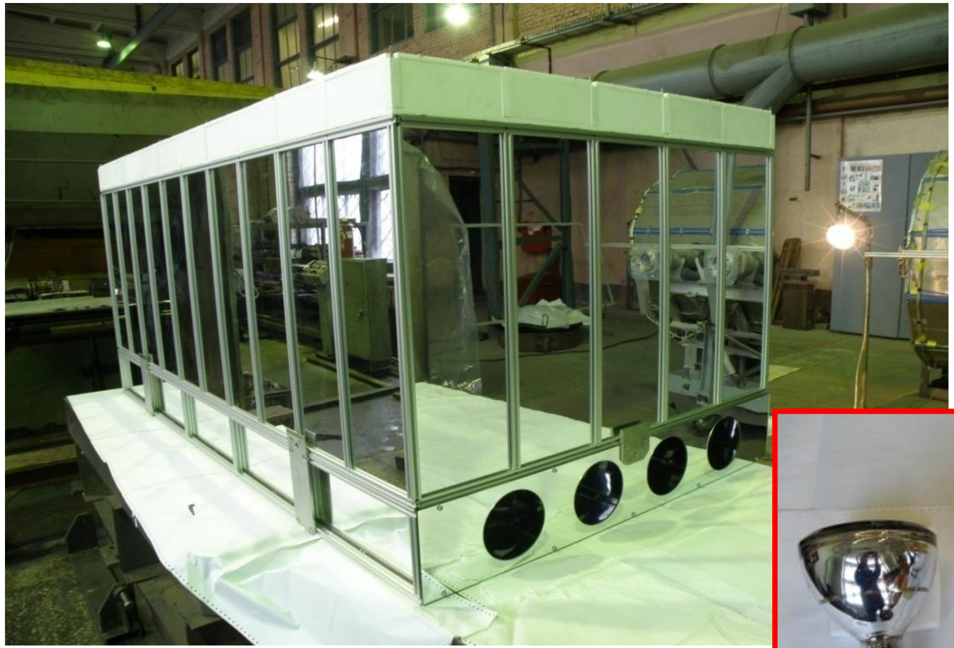


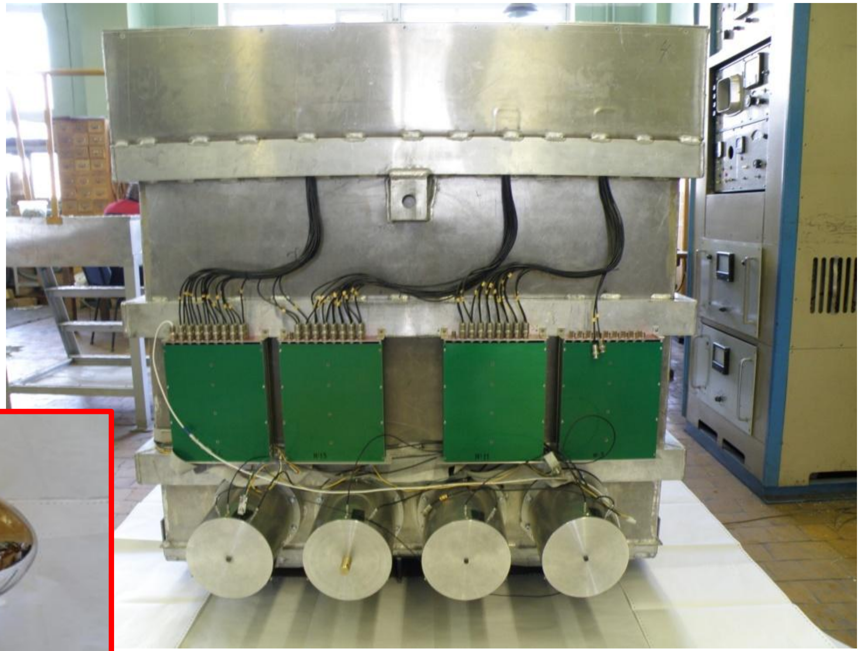
100 MW thermal power
Compact core 42x42x35cm
Highly enriched ^{235}U fuel



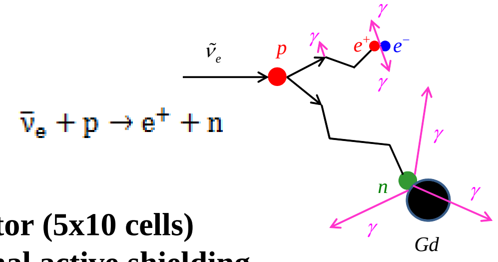
Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth's surface, hence, cosmic background is the major difficulty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

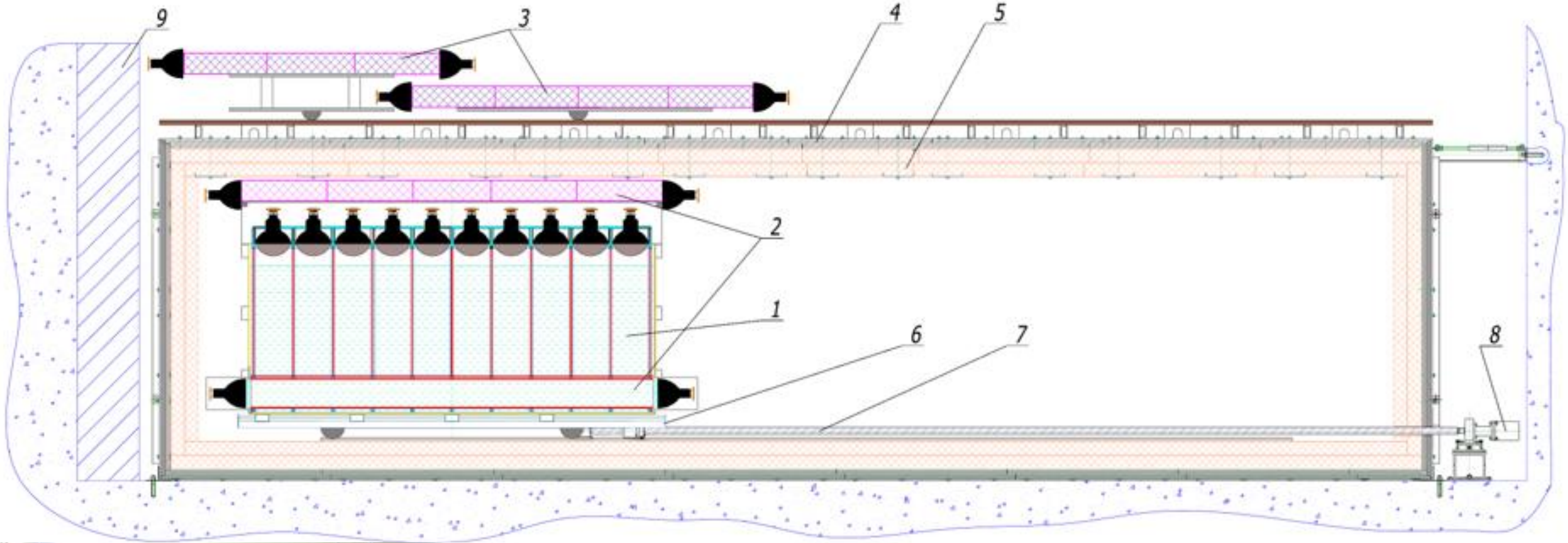
The full-scale detector with liquid scintillator volume of 3 m^3 (5x10 sections) have been prepared in NRC “KI” PNPI, Gatchina, Russia





Movable and spectrum sensitive antineutrino detector at SM-3 reactor





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

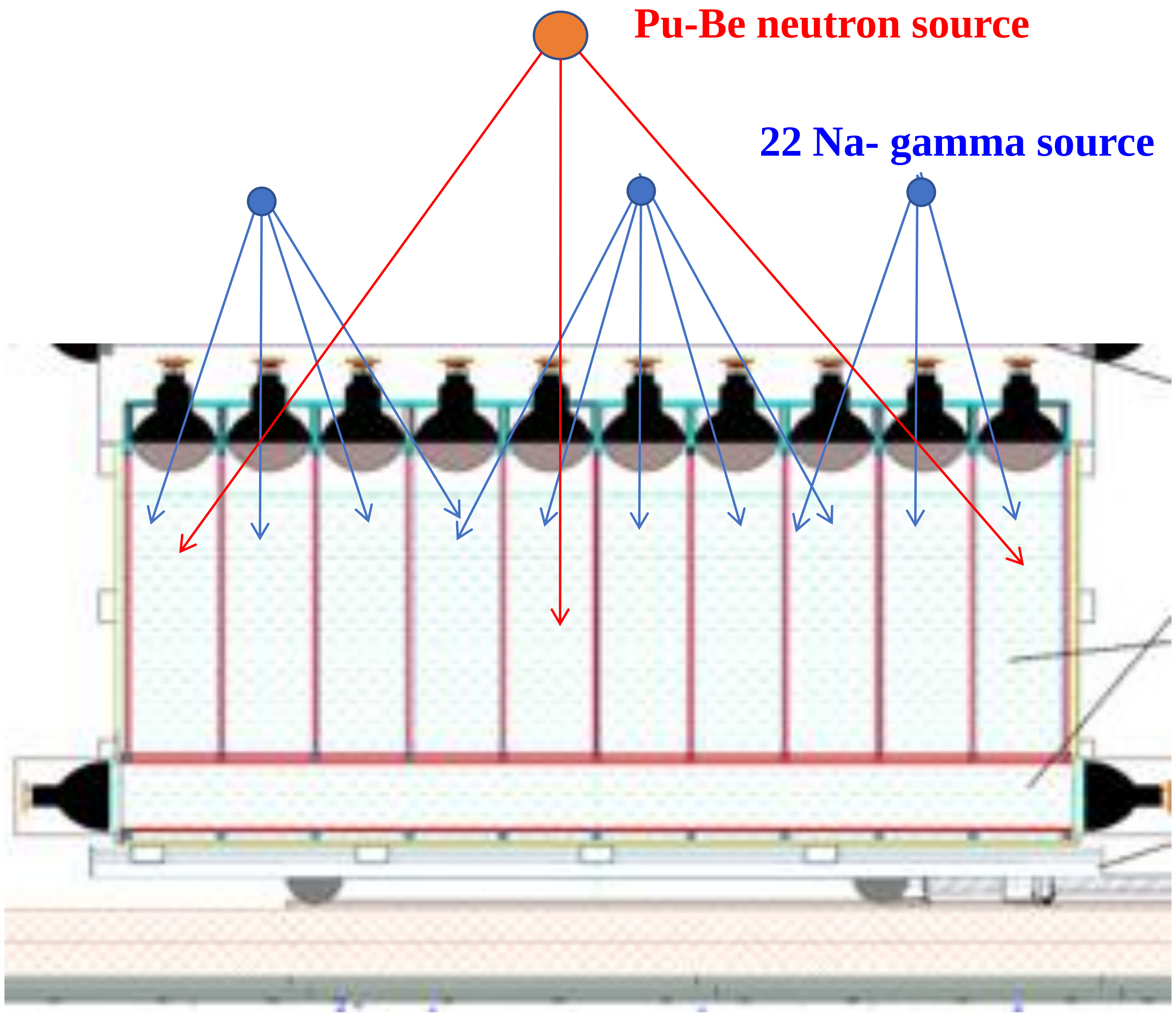
Full-scale detector

Liquid scintillator detector
50 sections 0.235x0.235x0.85м^3

Energy calibration of the full-scale detector

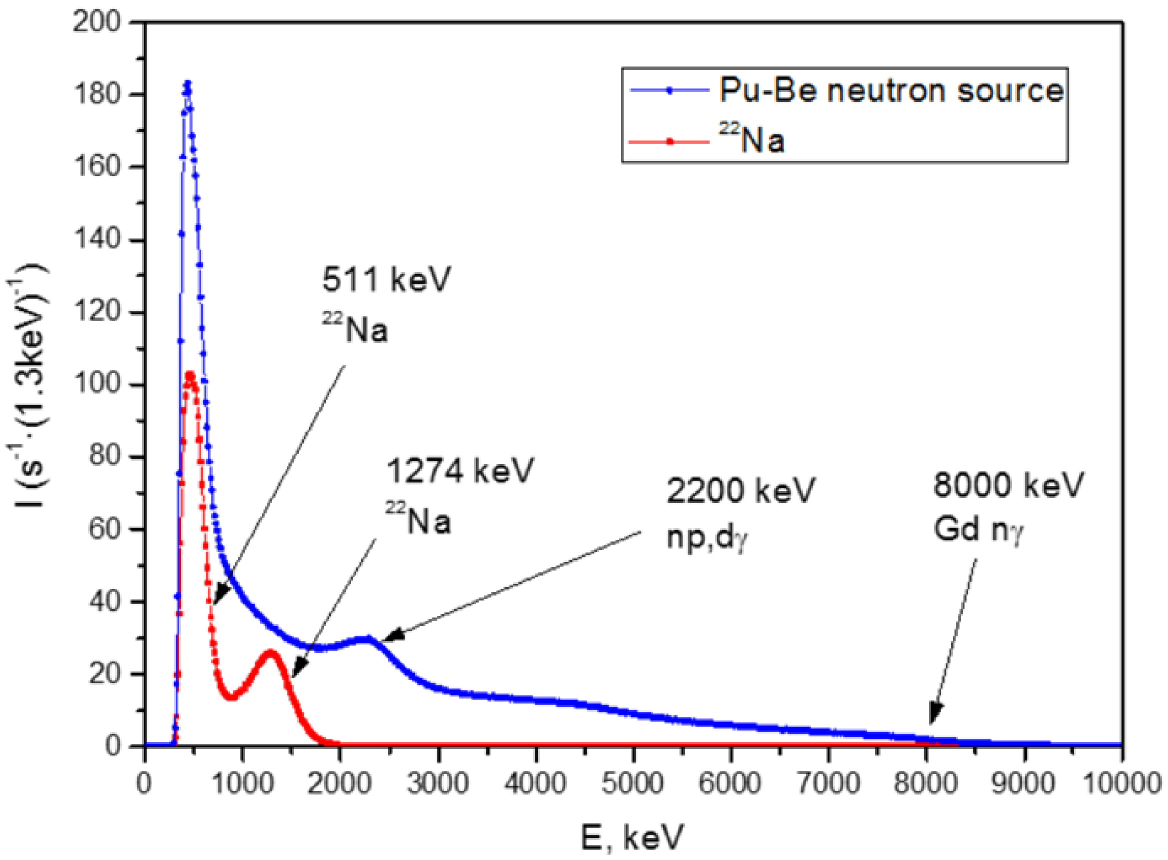
The source 22Na is installed above the detector at distance about 0.8 meters and irradiate about 16 sections at once. PMTs were normalized to one energy scale by selecting voltage on them. Simultaneous calibration of several sections is required. For all detector only 6 positions of the source were used.

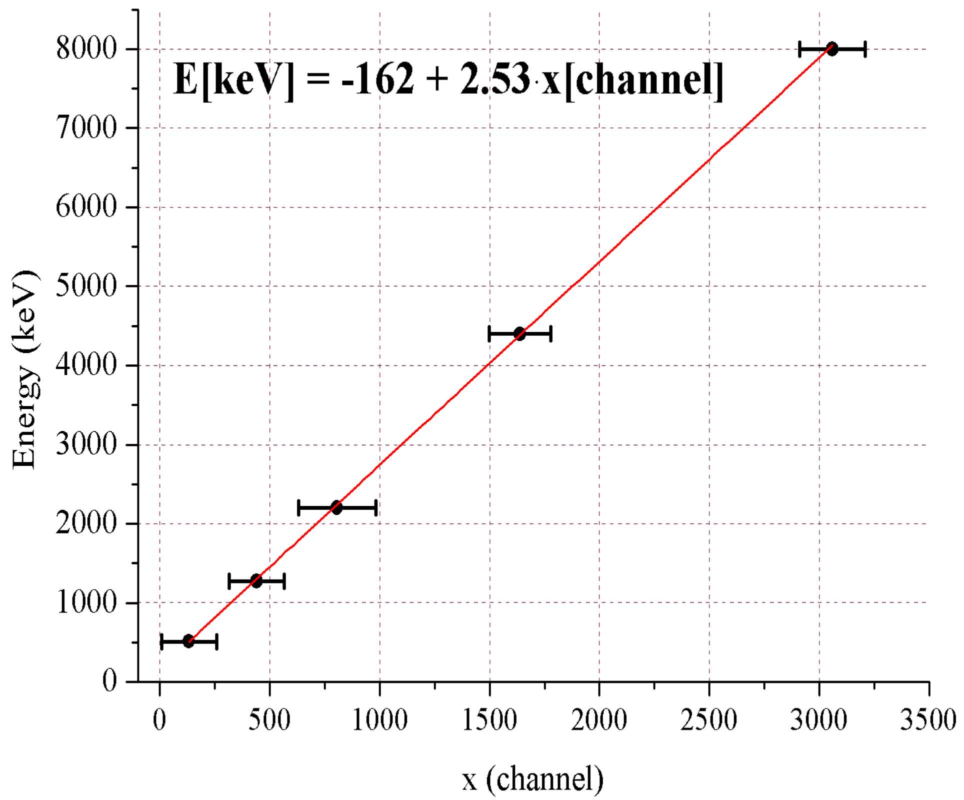
Overlapping of the irradiated sections unifies the calibration.



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.

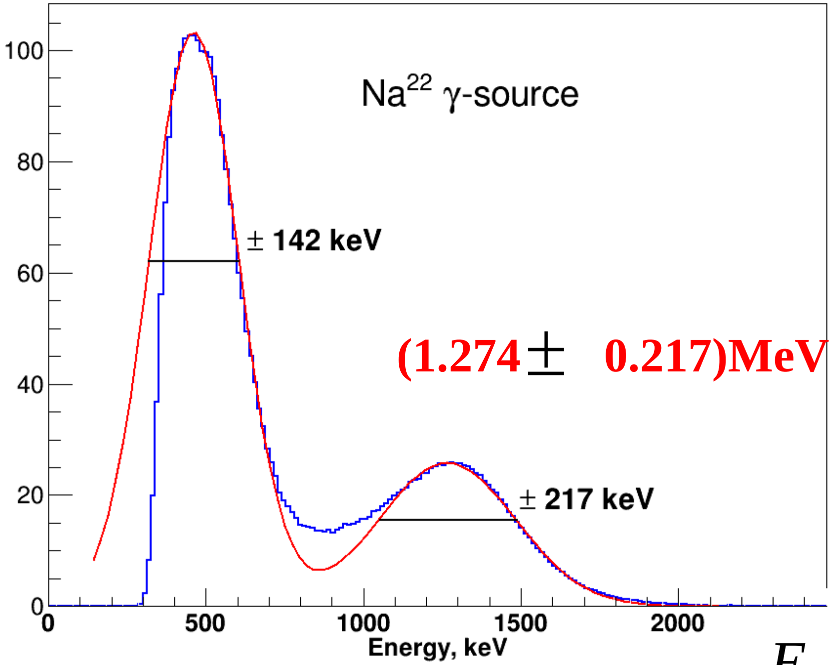
Registration of positrons includes inevitable loss of a part of energy of 511keV gamma-quanta. Because of the threshold of registration in the adjacent section we have to increase errors up to **±250 keV**.

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

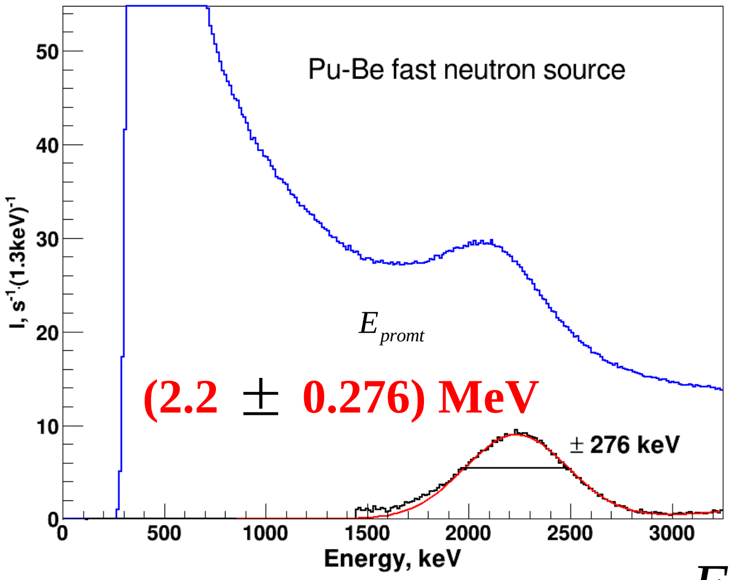
Energy calibration of the full-scale detector

(0.511 ± 0.142) MeV

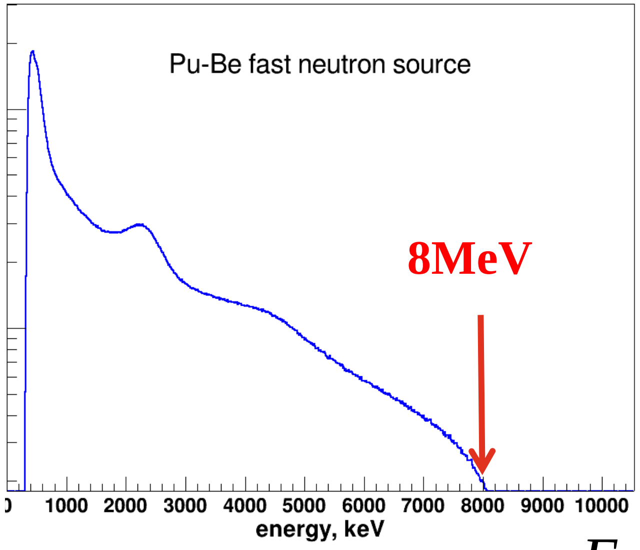
$$E_\nu = E_{promt} + 0.8 MeV$$



E_{promt}



E_{promt}



E_{promt}

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

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

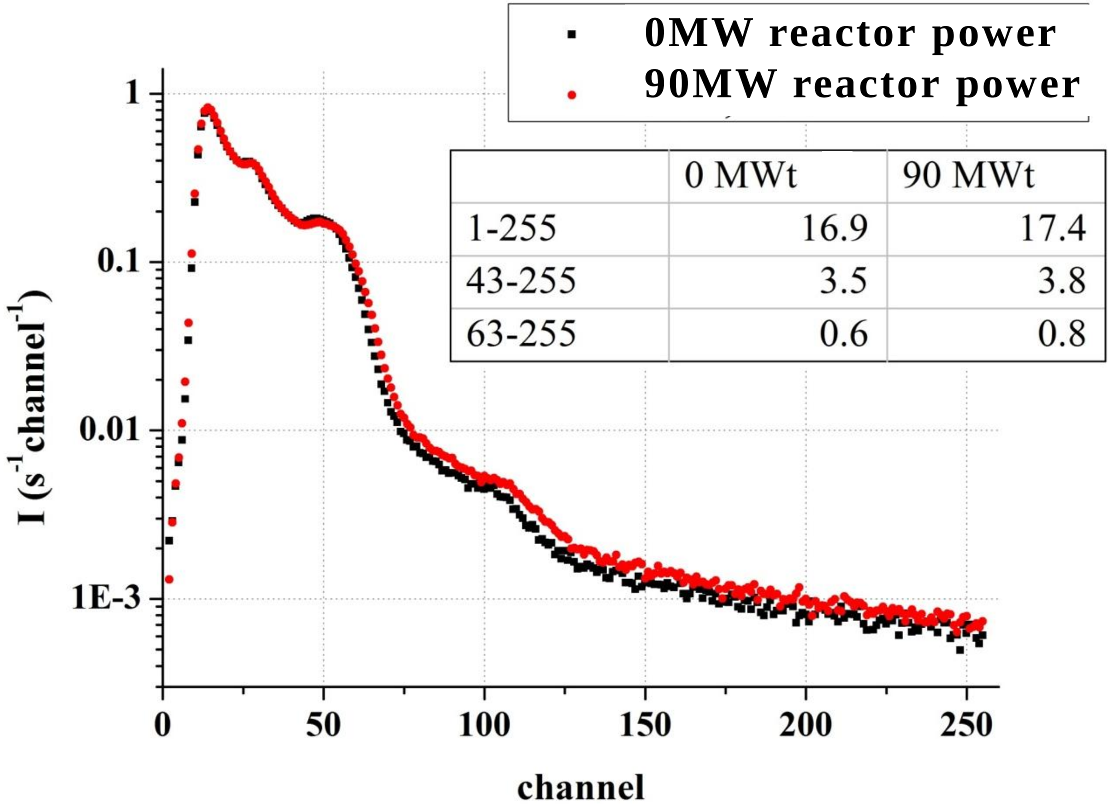
$$\Delta E_\nu / E_\nu(3MeV) = 18\%$$

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

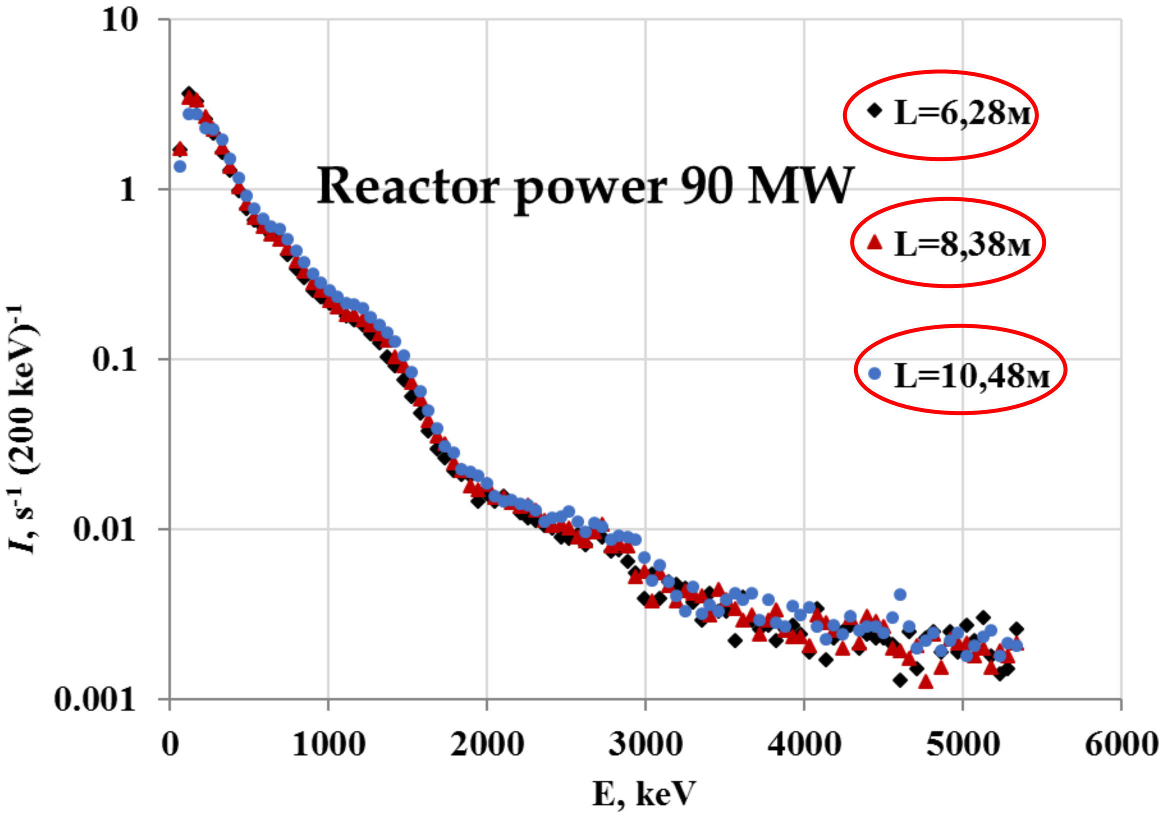
$$\Delta E_\nu / E_\nu(6MeV) = 14\%$$

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

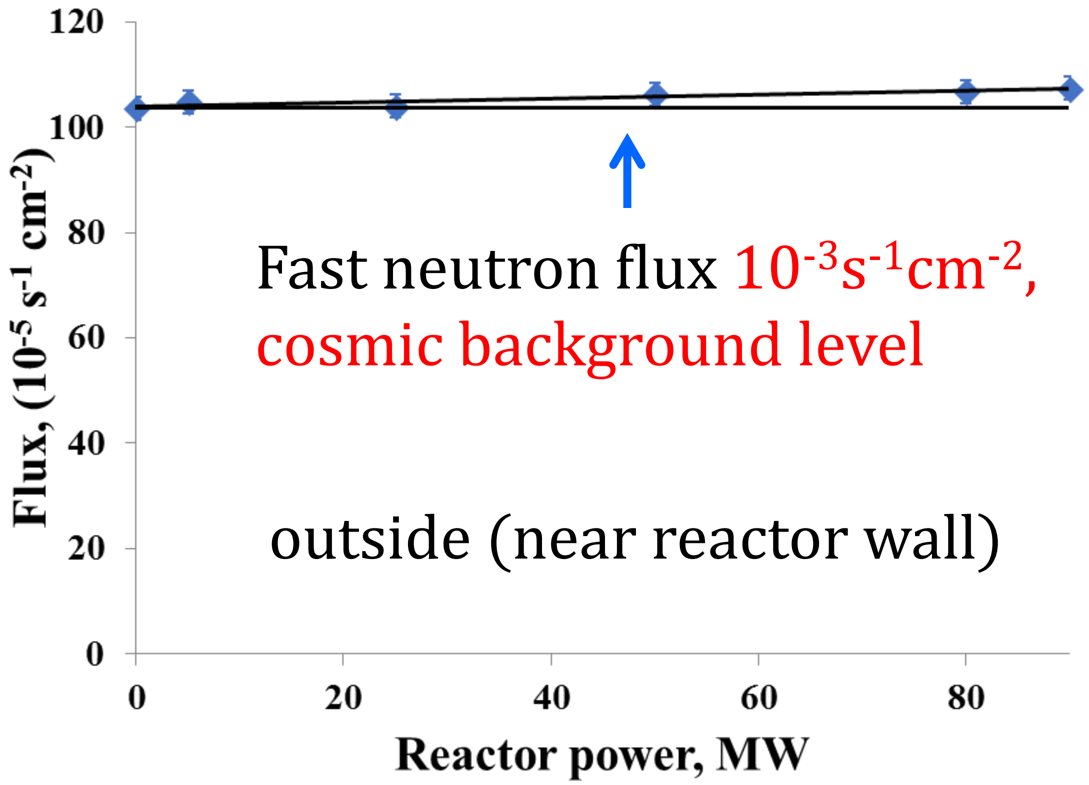
Gamma background in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor

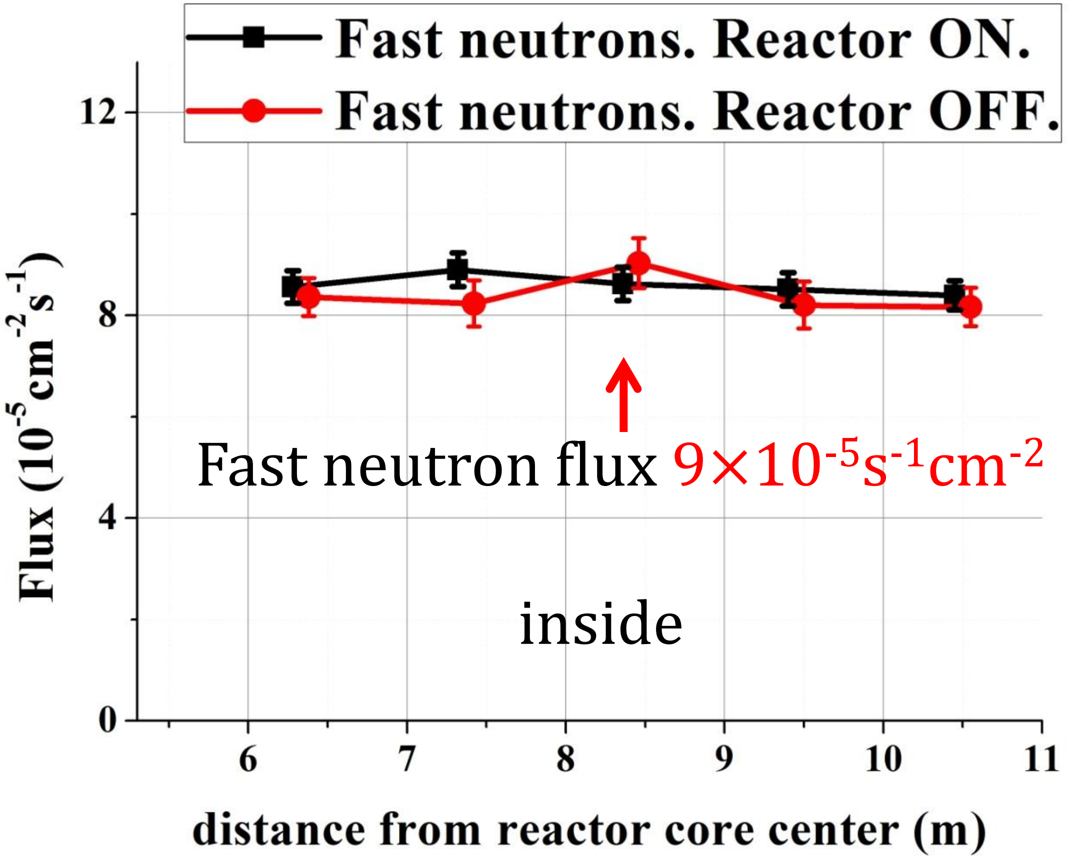


	0 MWt	90 MWt
1-255	16.9	17.4
43-255	3.5	3.8
63-255	0.6	0.8



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





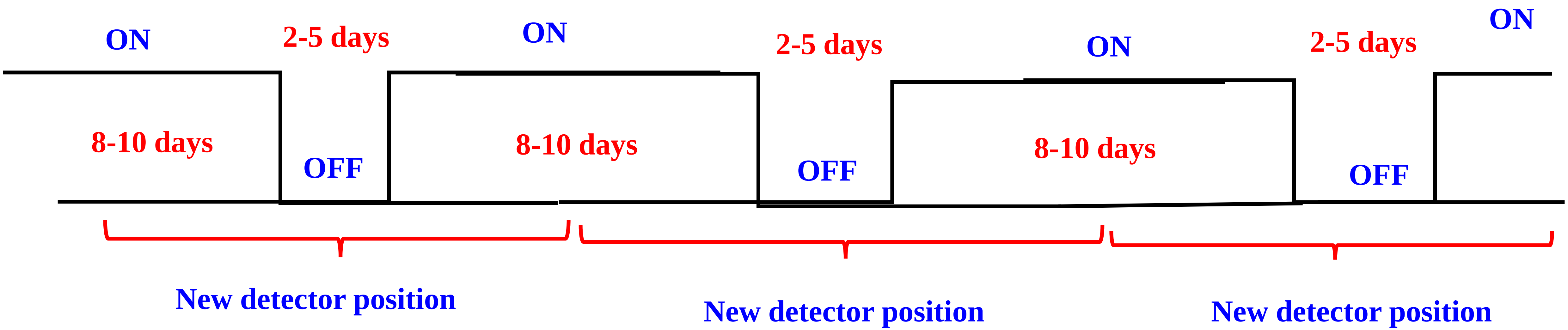
The background of fast neutrons in passive shielding is 10 times less than outside.
The background of fast neutrons outside of passive shielding is defined by cosmic rays and practically does not depend on reactor power.

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.

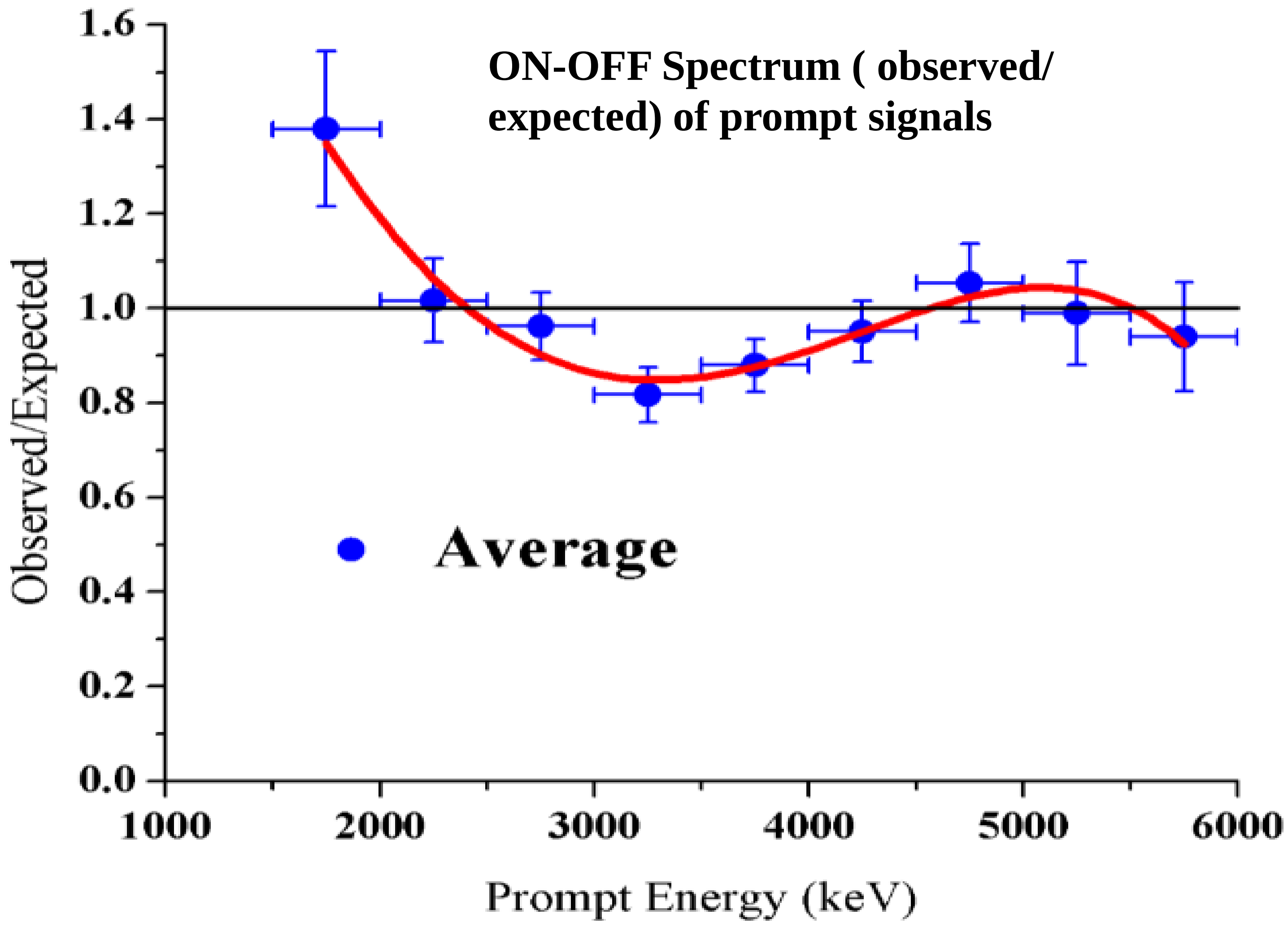
ON
90 MW

Measurements with the detector have started in June 2016. Measurements with the reactor ON were carried out for 720 days, and with the reactor OFF- for 417 days. In total, the reactor was switched on and off 87 times.

(ON – OFF)/ OFF = 50%



There is problems with energy spectrum therefore we proposed the spectrum independent method of the experimental data analysis



Spectrum (observed/ expected) of prompt signals in the detector for a total cycle of measurements summed over all distances (average distance — 8.6 meters).

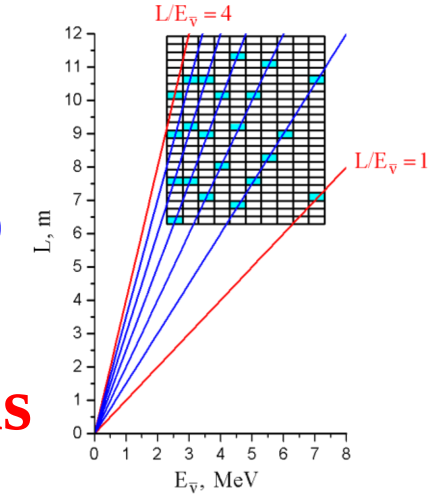
Expected - Monte -Carlo simulation with neutrino spectrum of ^{235}U, as the SM-3 reactor works on highly enriched uranium.

$$N(E_i, L_k)$$

Number of antineutrino events

Probability of antineutrino disappearance

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



The spectrum independent method of experimental data analysis

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

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.

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

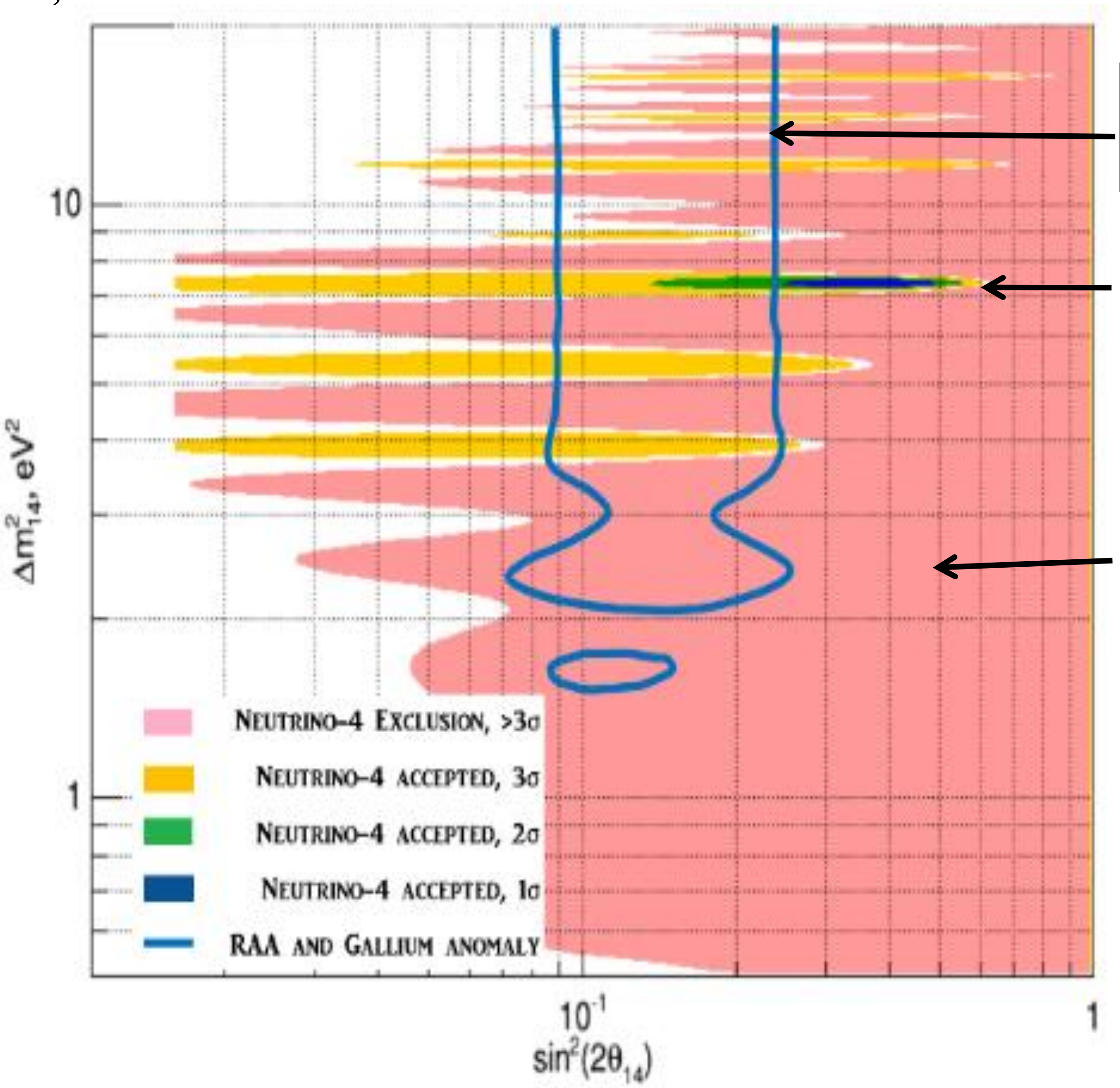
The results of the analysis of optimal parameters Δm^2_{14} and $\sin^2 2\theta_{14}$ using χ^2 method

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

We observed the oscillation effect at C.L. 99.7% (3.5 σ) in vicinity of :

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

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

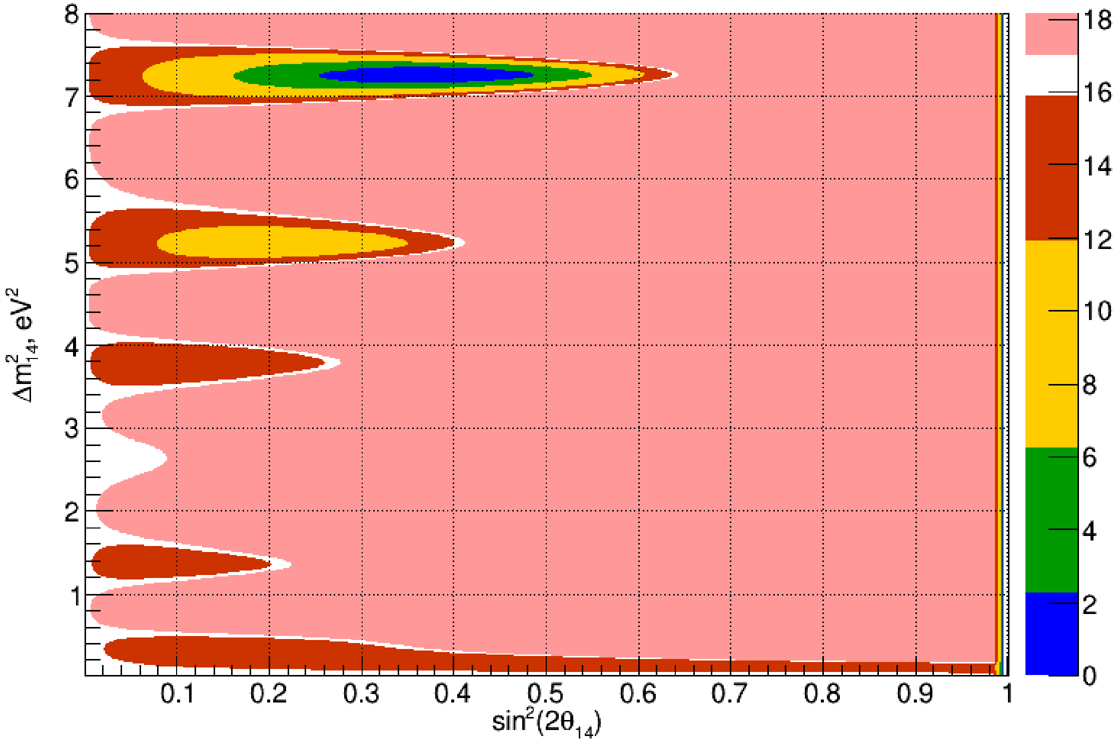


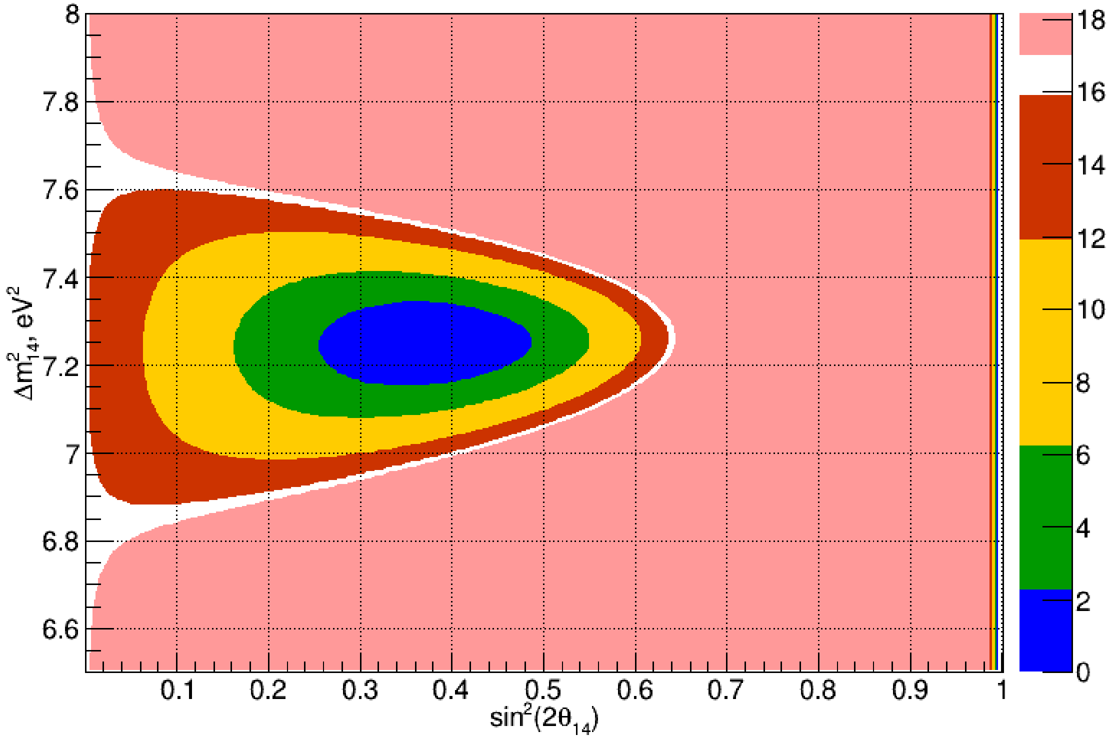
Expected from RAA and Gallium anomalies

Expected from Neutrino-4 CL 99.7%

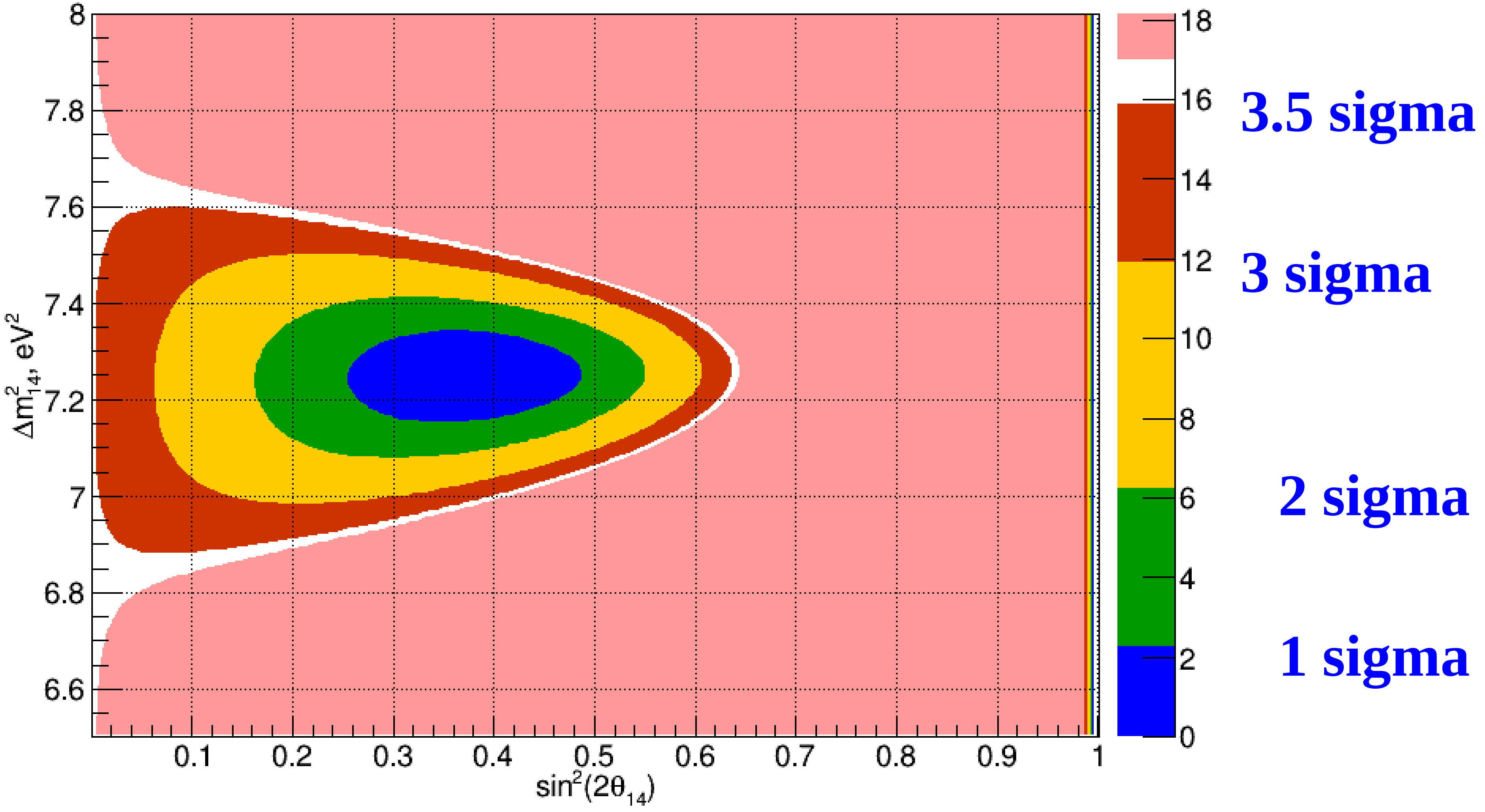
Excluded from Neutrino-4 CL>99.9% CL

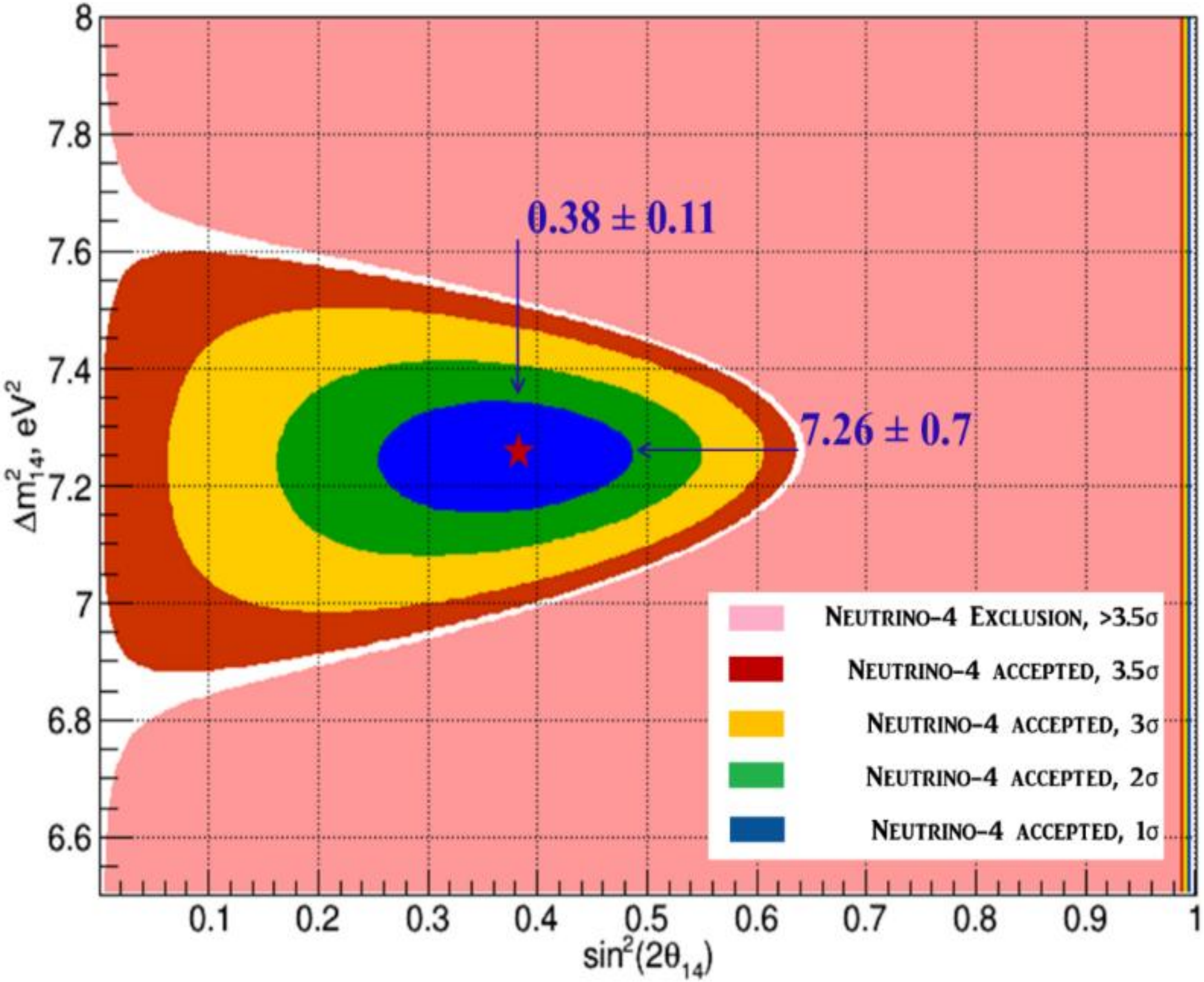
All data 2017 -2019 + background 2019



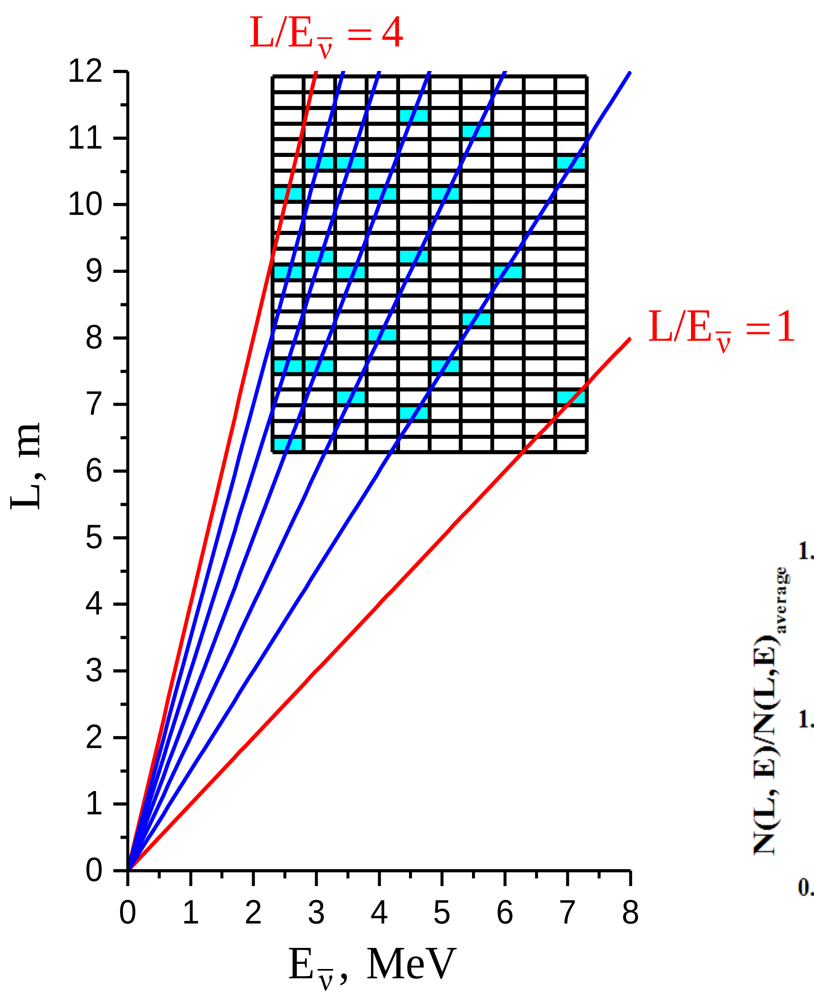


3.5 sigma


8
7.8
7.6
7.4
7.2
7
6.8
6.6
Δm^2_{14}, eV^2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2(2\theta_{14})$
18
16
14
12
10
8
6
4
2
0
3.5 sigma
3 sigma
2 sigma
1 sigma

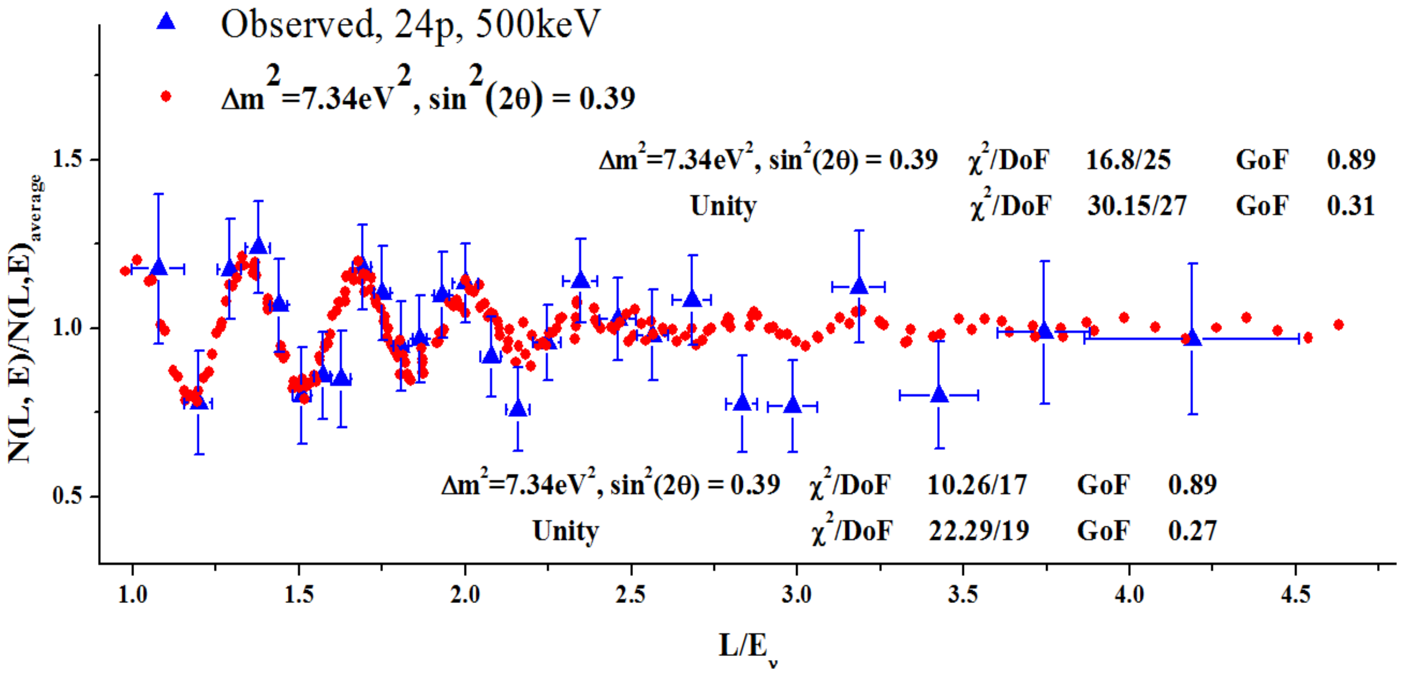

0.38 ± 0.11
7.26 ± 0.7
NEUTRINO-4 EXCLUSION, >3.5σ
NEUTRINO-4 ACCEPTED, 3.5σ
NEUTRINO-4 ACCEPTED, 3σ
NEUTRINO-4 ACCEPTED, 2σ
NEUTRINO-4 ACCEPTED, 1σ
Δm²₁₄, eV²
sin²(2θ₁₄)
8
7.8
7.6
7.4
7.2
7
6.8
6.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

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

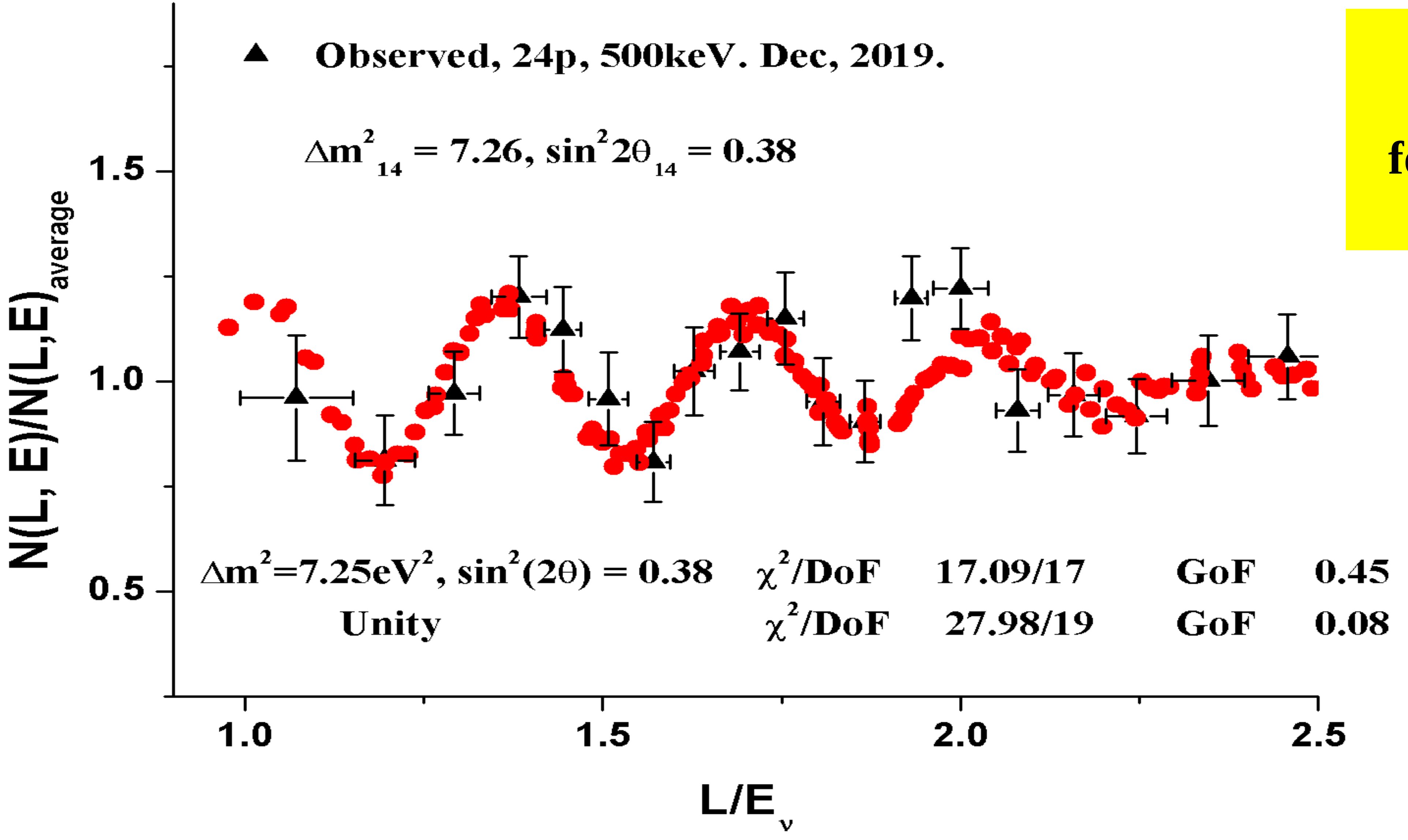


$$R_{i,k}^{\exp} = \frac{N(E_i^{\nu}, L_k)L_k^2}{K^{-1}\sum_k^K N(E_i^{\nu}, L_k)L_k^2} = $$

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



All data 2016 -2019 + background 20119

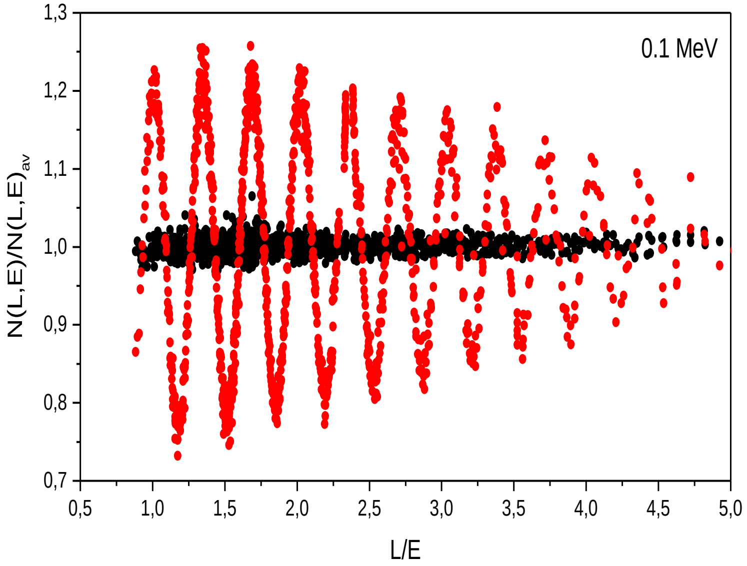


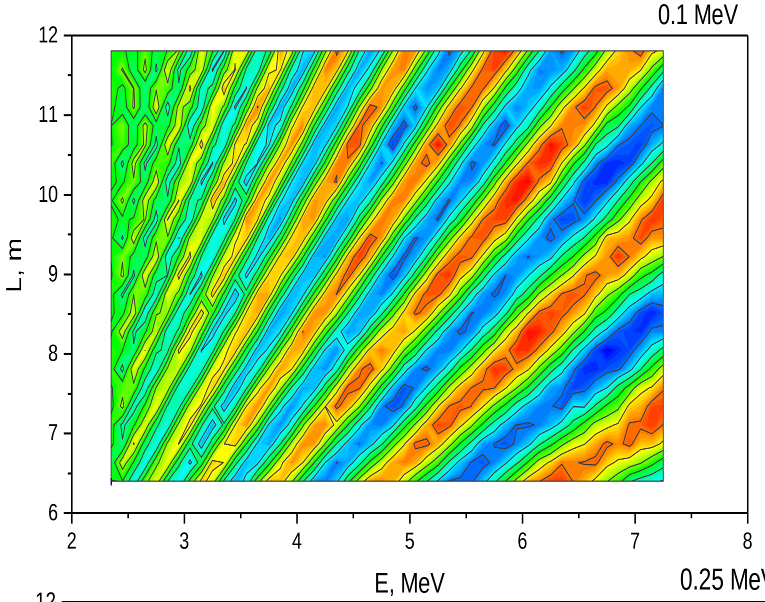
The period of oscillation for neutrino energy 4 MeV is 1.4 m

A.P.Serebrov, et al.
JETP Letters,
Volume 109,
Issue 4, pp 213–221.

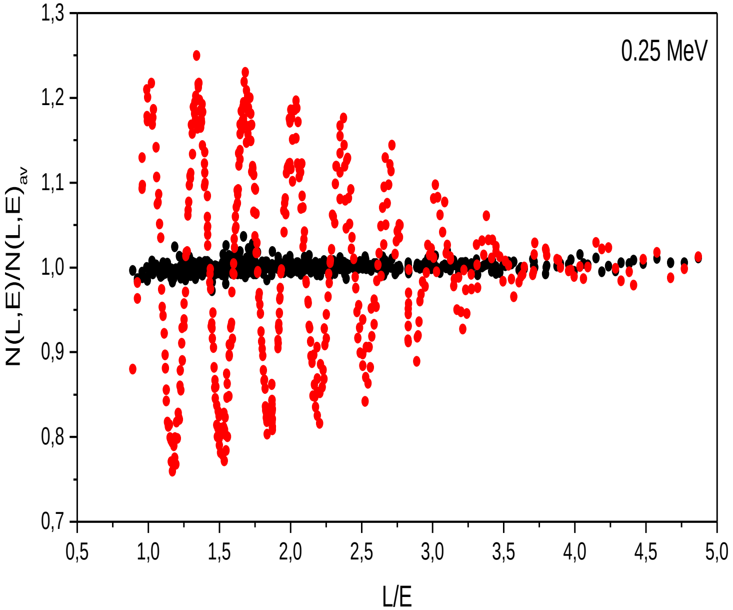
arxiv:1809.10561

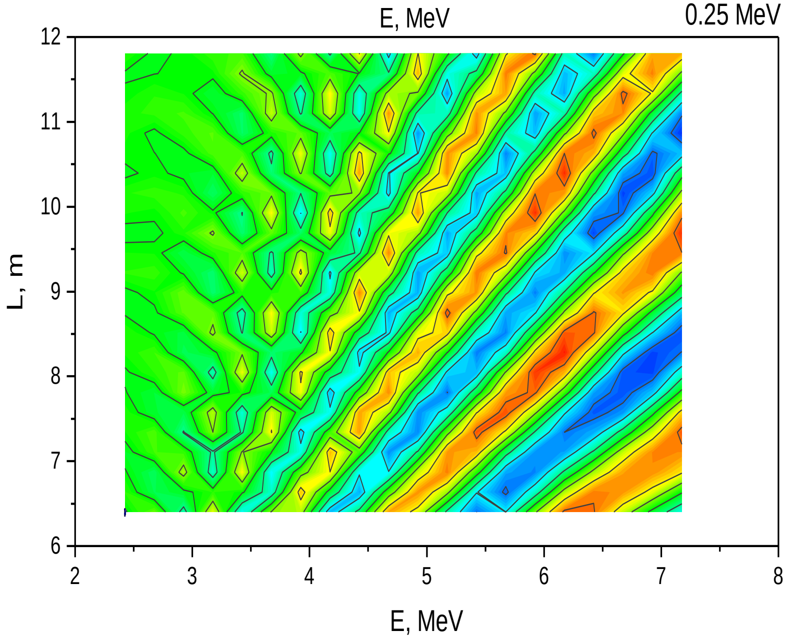
The expected effect for the different energy resolution from MC calculation





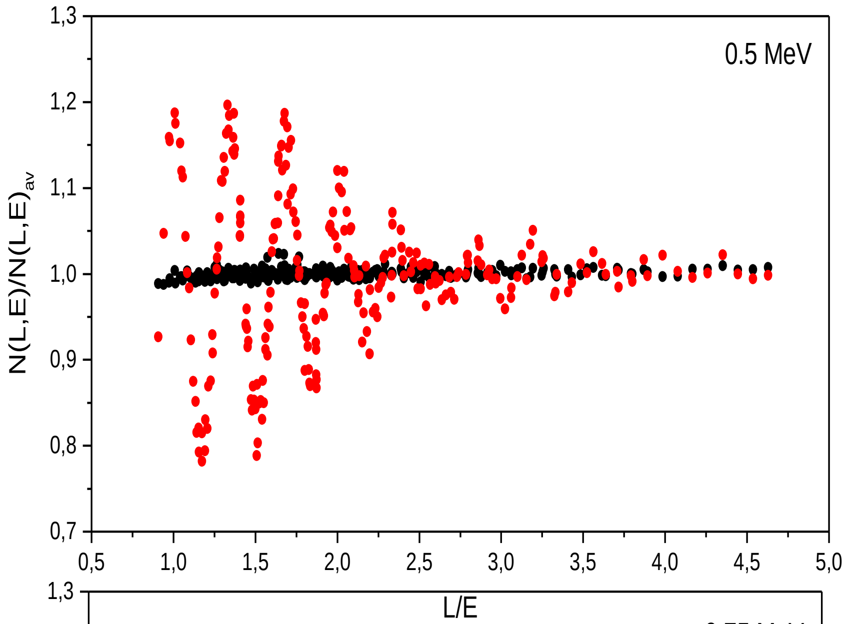
energy resolution 0.1 MeV

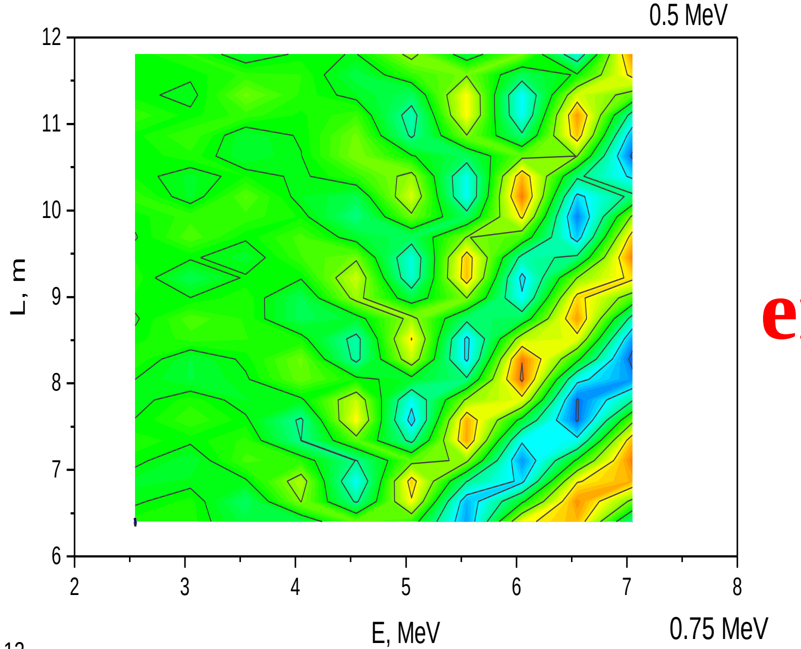




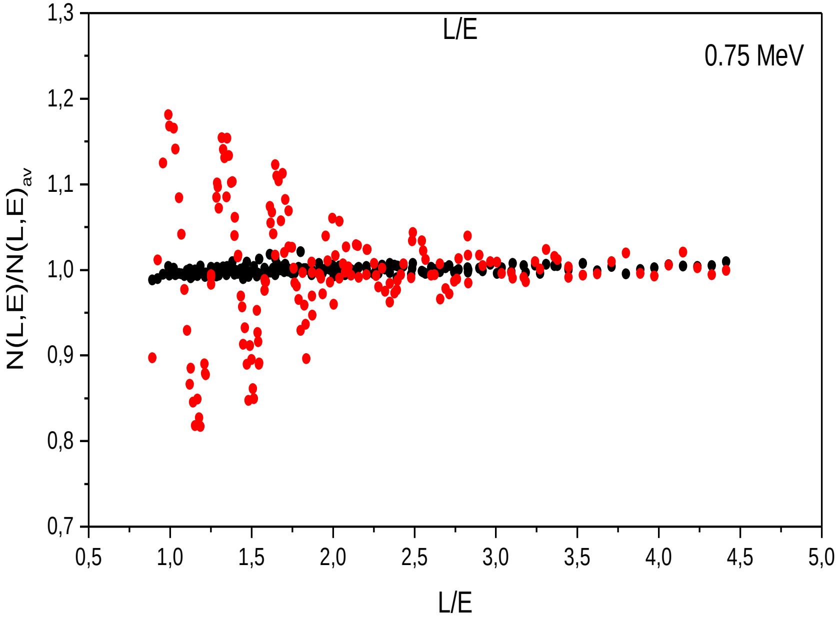
energy resolution 0.25 MeV

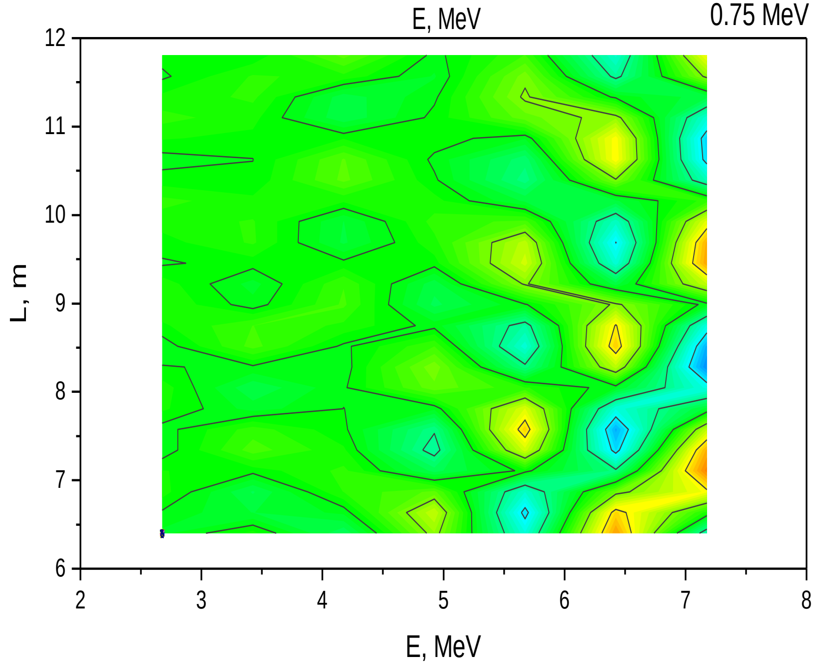
The expected effect for the different energy resolution from MC calculation





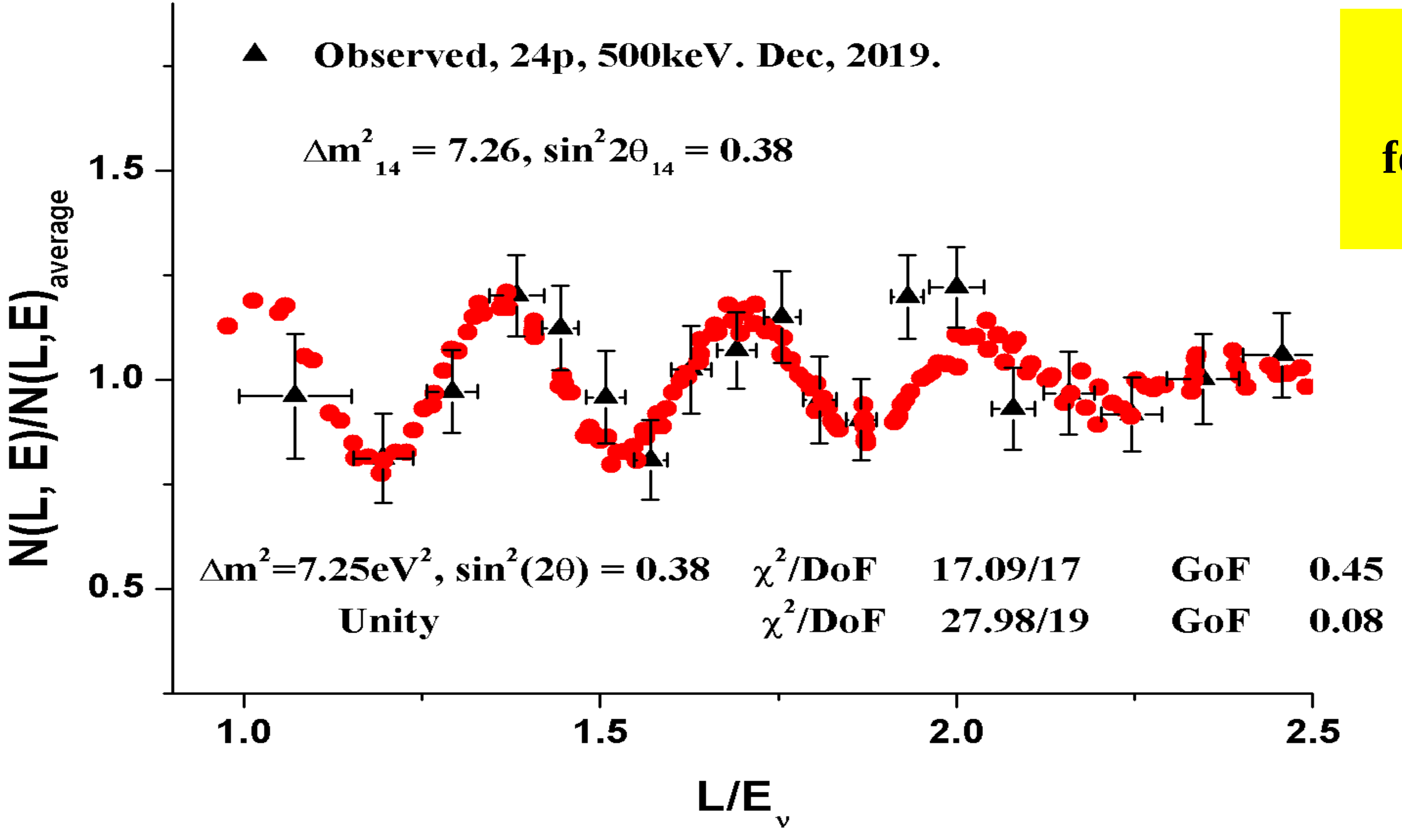
energy resolution 0.5 MeV (our case)





energy resolution 0.75 MeV

All data 2017 -2019 + background 20119



The period of oscillation for neutrino energy 4 MeV is 1.4 m

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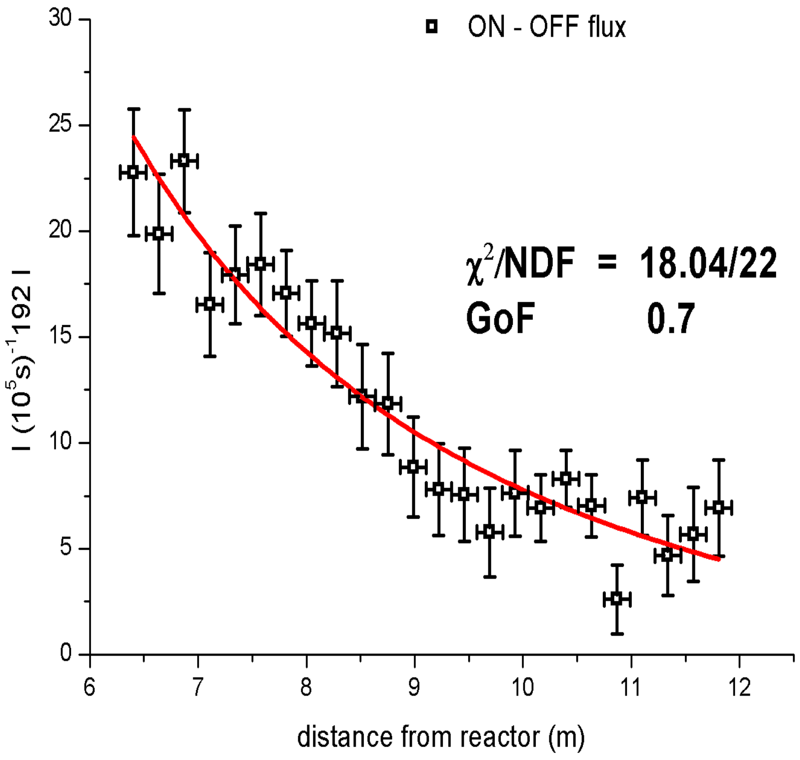
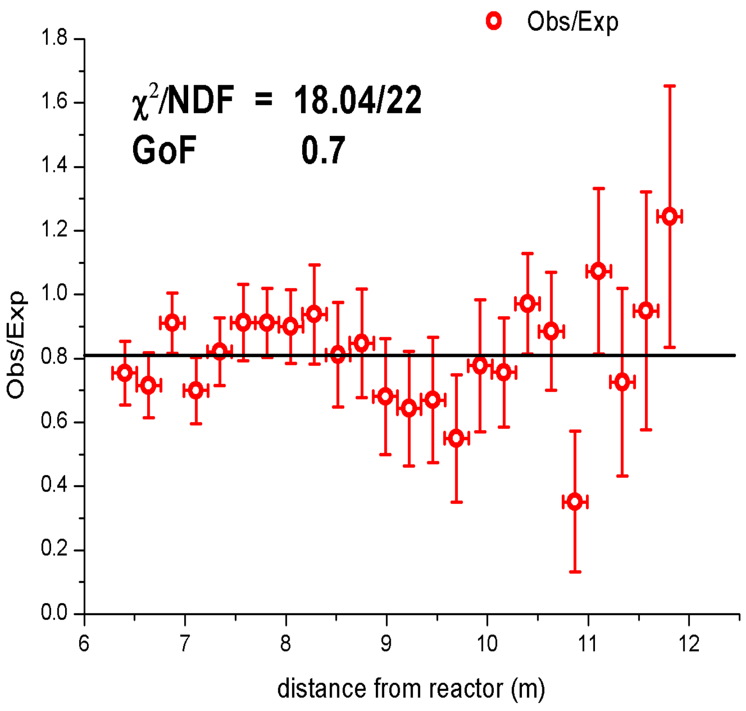
arxiv:1809.10561

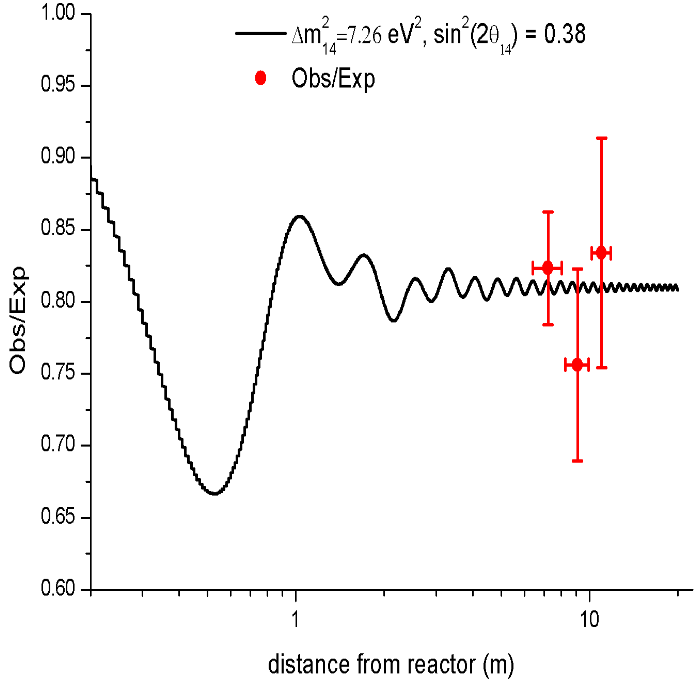
Dependence of antineutrino flux on the distance to the reactor core. a - direct experimental dependence, b – normalized experimental dependence, c - oscillation curve with the experimental results in range 6-12 m.



a



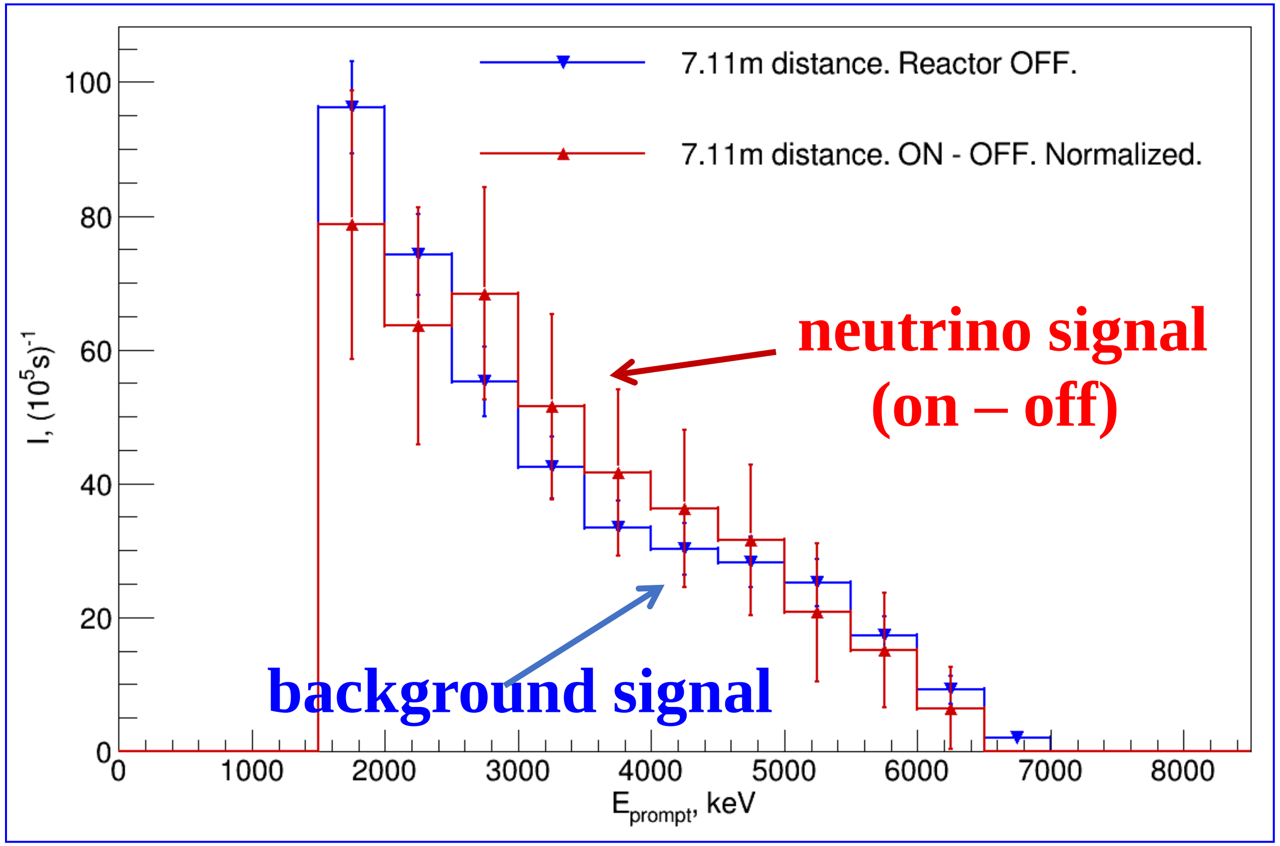
b



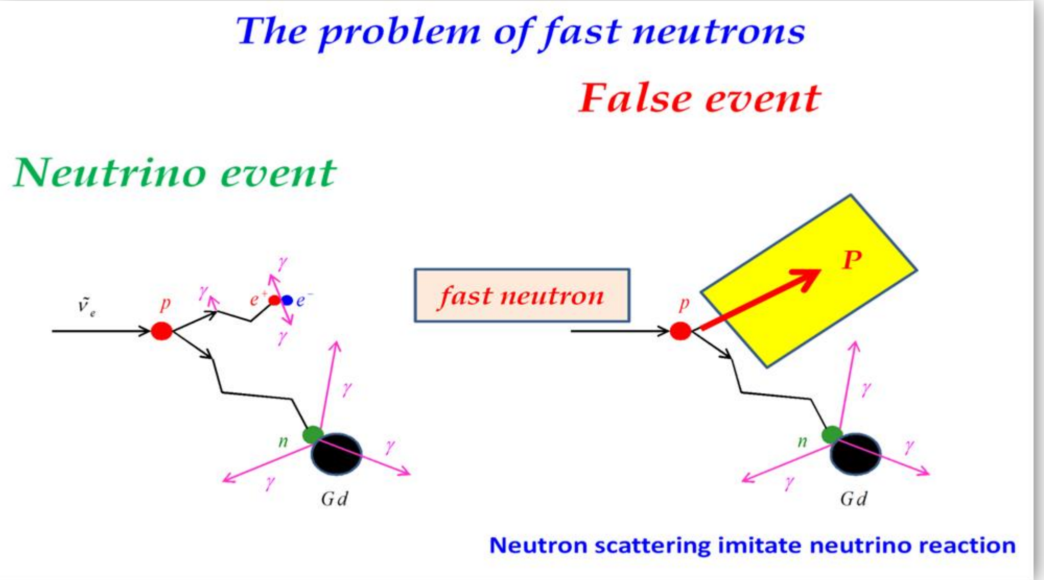
c

Analysis of possible systematic effects

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

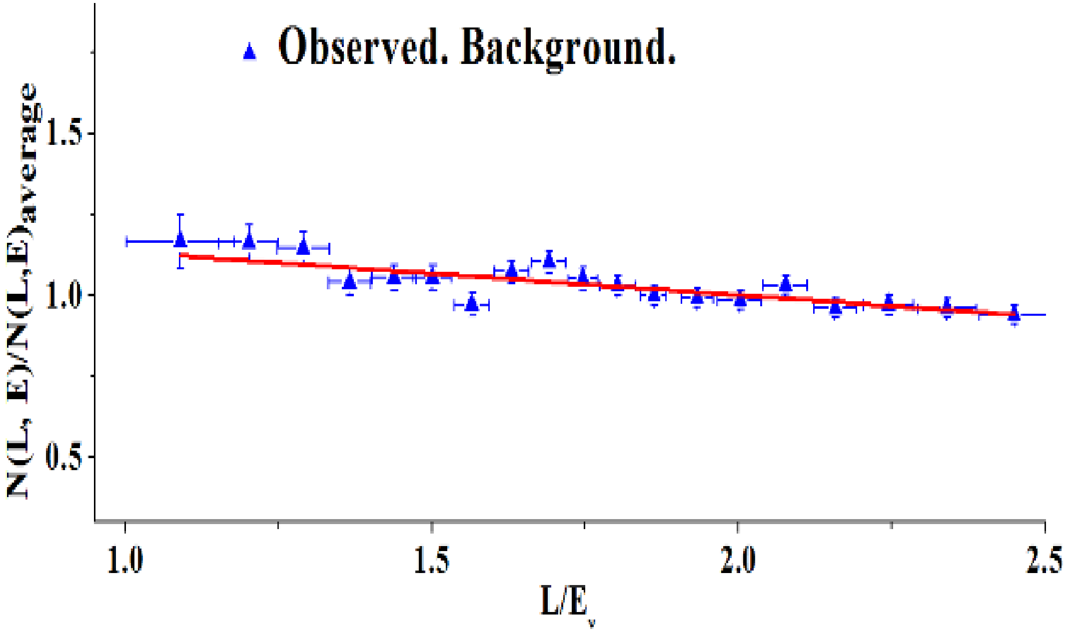


The spectrum for neutrino signal and background signal are similar therefore test for systematic effect have to be adequate .

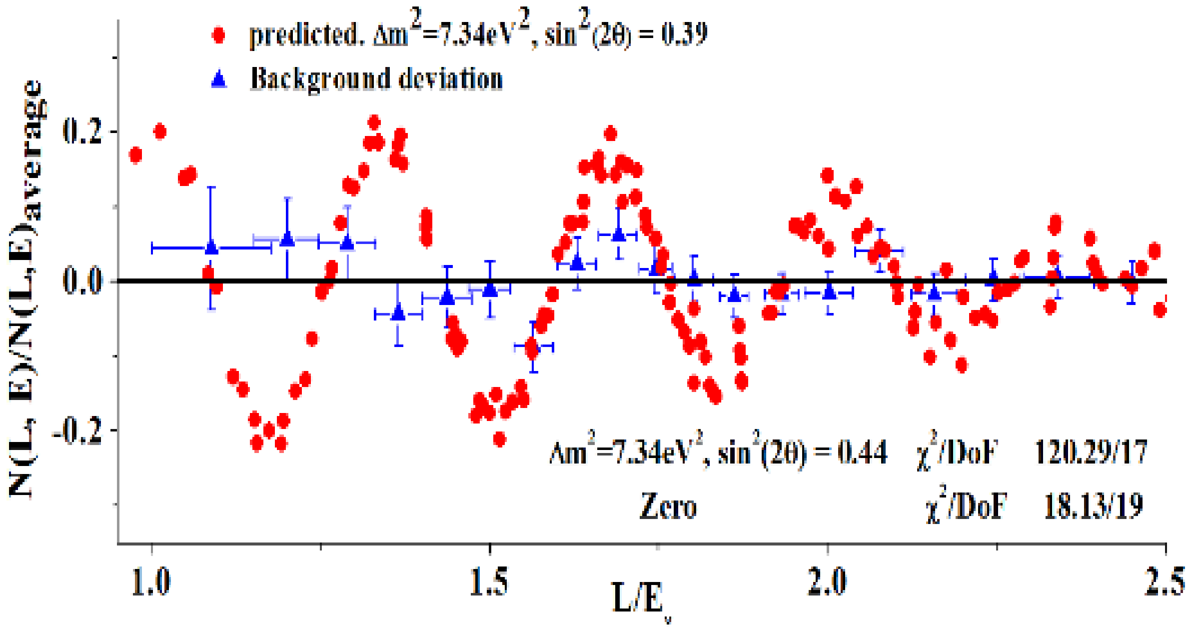


Test of systematic effects

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



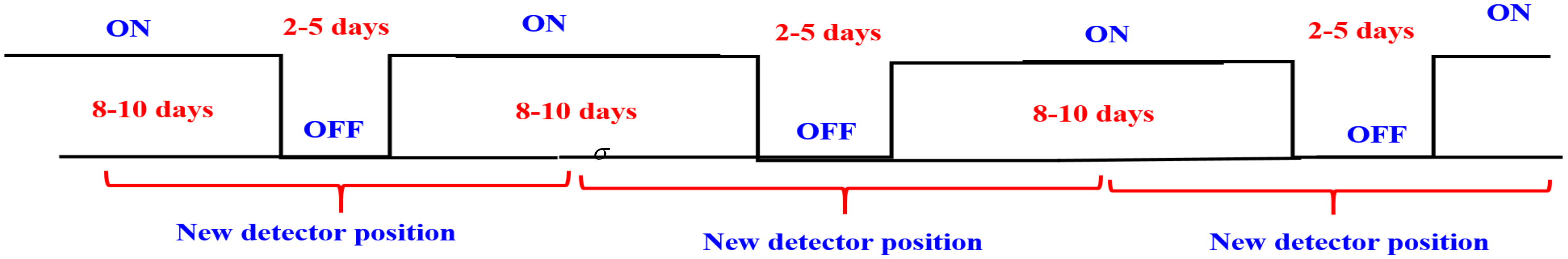
data analysis using coherent summation method

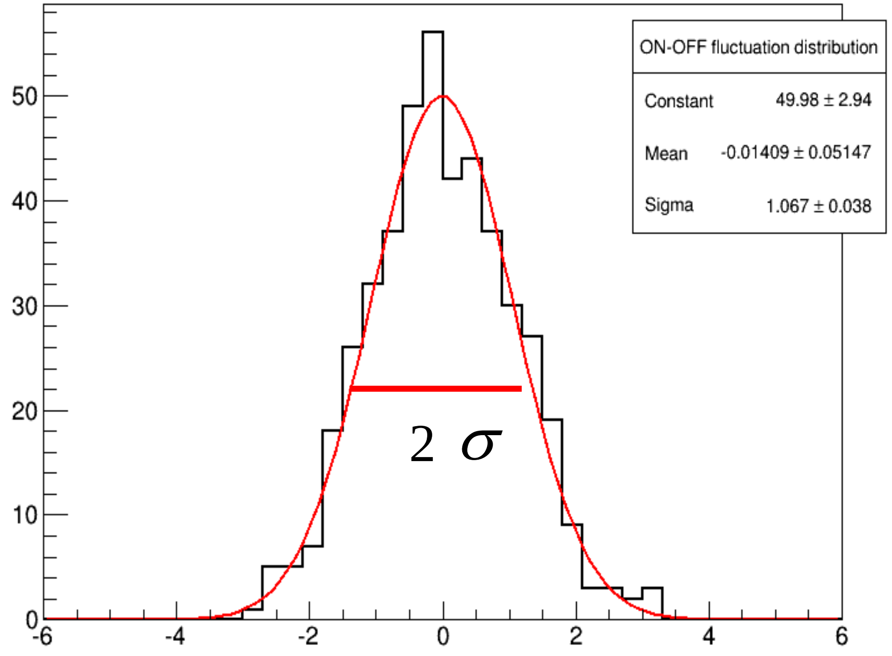


analysis of the results on oscillation parameters plane

Thus no instrumental systematic errors were observed.

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





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

$$\sigma = 1.070 \pm 0.045$$

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

Considering the instability of cosmic background, we increased the uncertainties of the experimental results by 9% relatively to statistical uncertainties, therefore the instability of cosmic background is already considered. It may be an overestimation, but this guarantees the reliability of the final result.

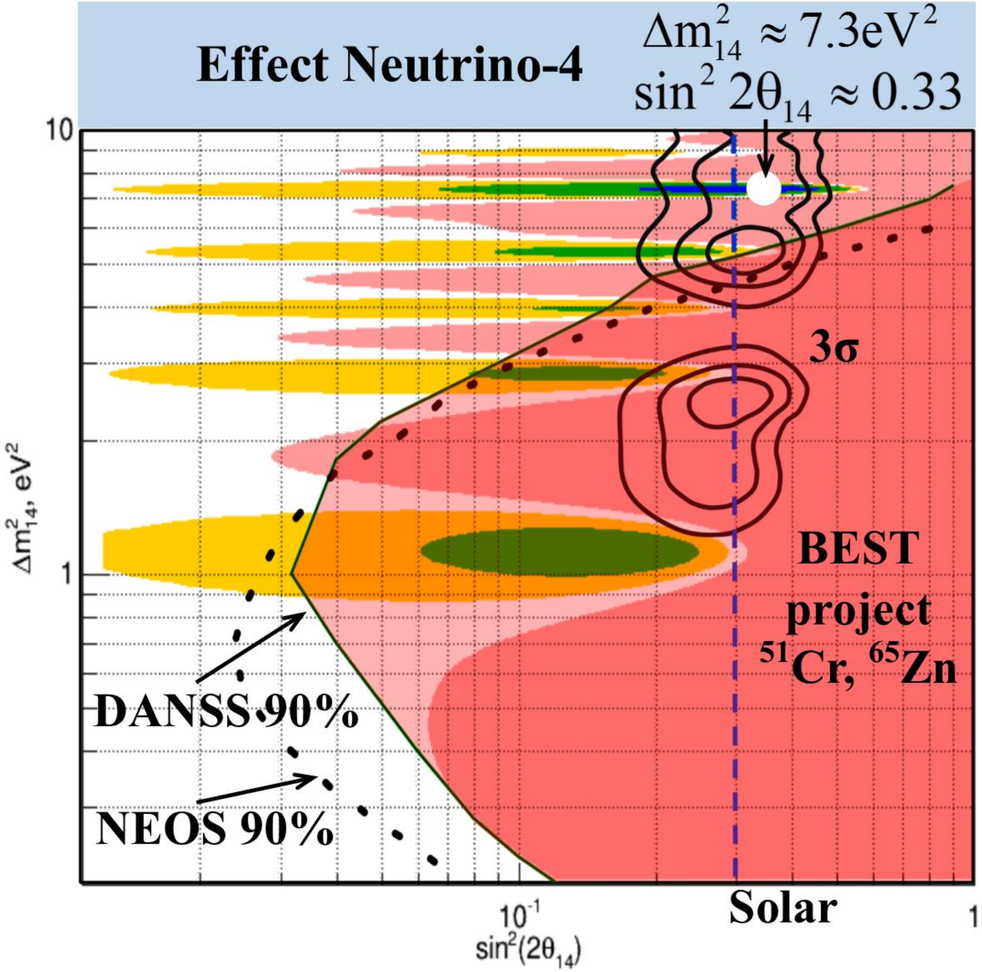
Possible conformation of our results

First of all there is no contradiction with Gallium Anomaly

The combined result of the Neutrino-4 and gallium anomaly gives

$$\sin^2 2\theta_{14} \approx 0.35 \pm 0.07 \; (5.0\sigma)$$

BEST experiment - Sensitivity Area



The BEST experiment started in August 2019 in BNO has good sensitivity at $\Delta m^2_{14} > 5 eV^2$ area

There is combined analysis of Neutrino-4 result and BEST potential in case of gallium anomaly confirmation in this experiment

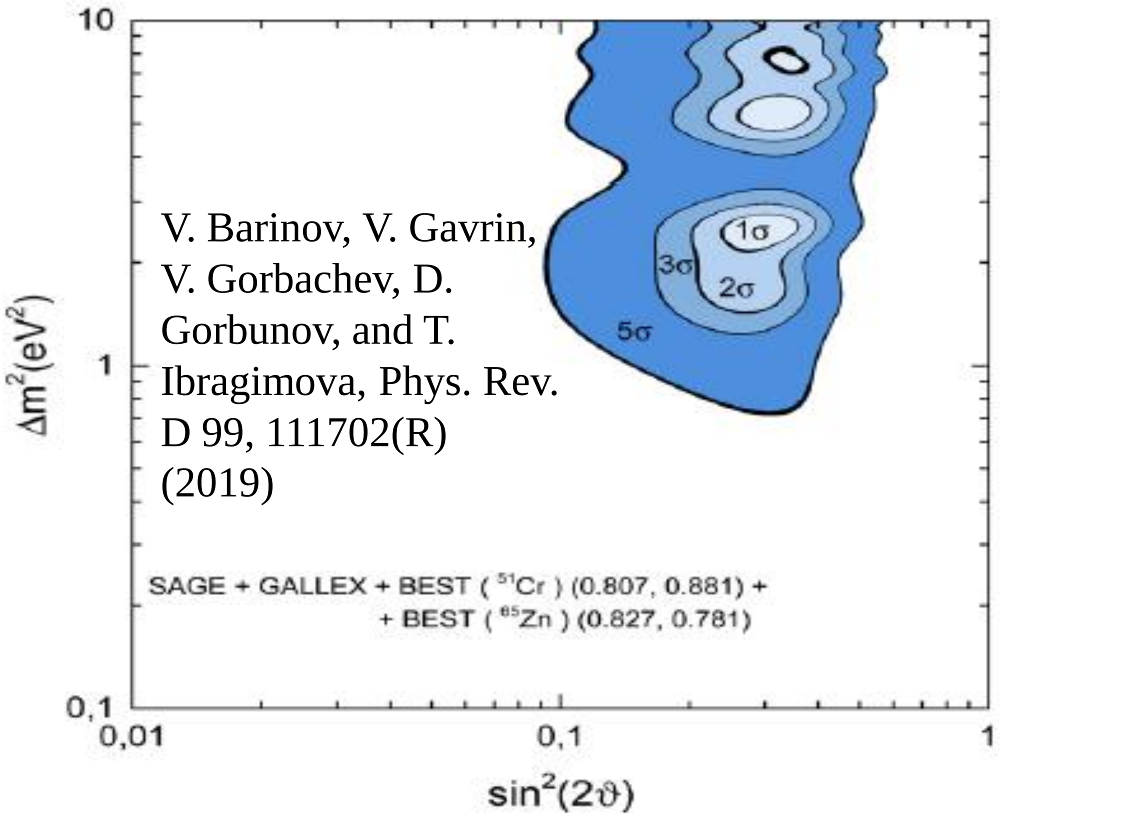
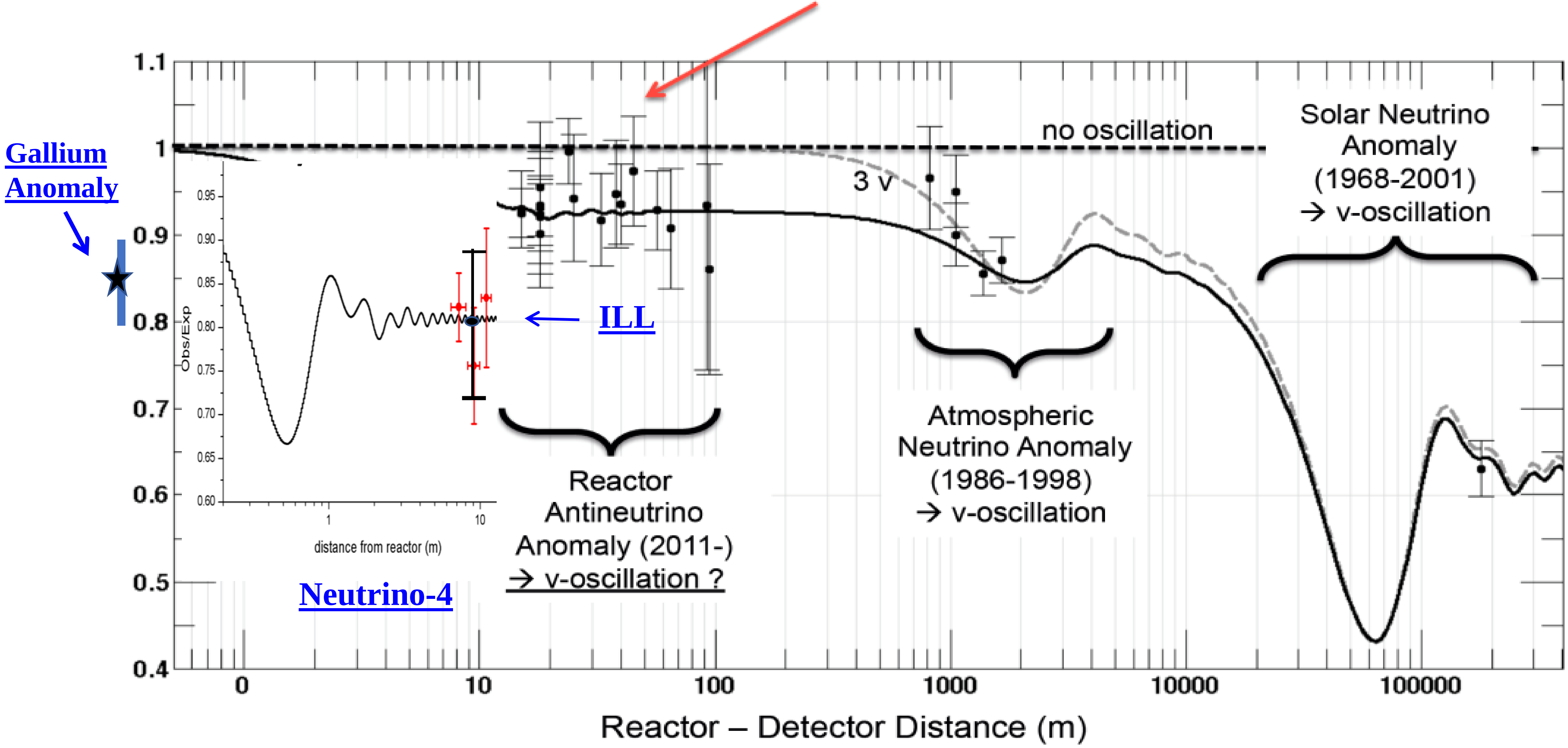


FIG. 7. Allowed regions of oscillation parameters, built on the basis of new data, in the case of combining the results of SAGE + GALLEX with the result of BEST for two sources (^{51}Cr and ^{65}Zn), which corresponds to the best fit point.

There is contradiction with reactor anomaly (2σ) . However, it should be noted that the results of the reactor anomaly do not yet include a systematic calculation error, which is currently under discussion.

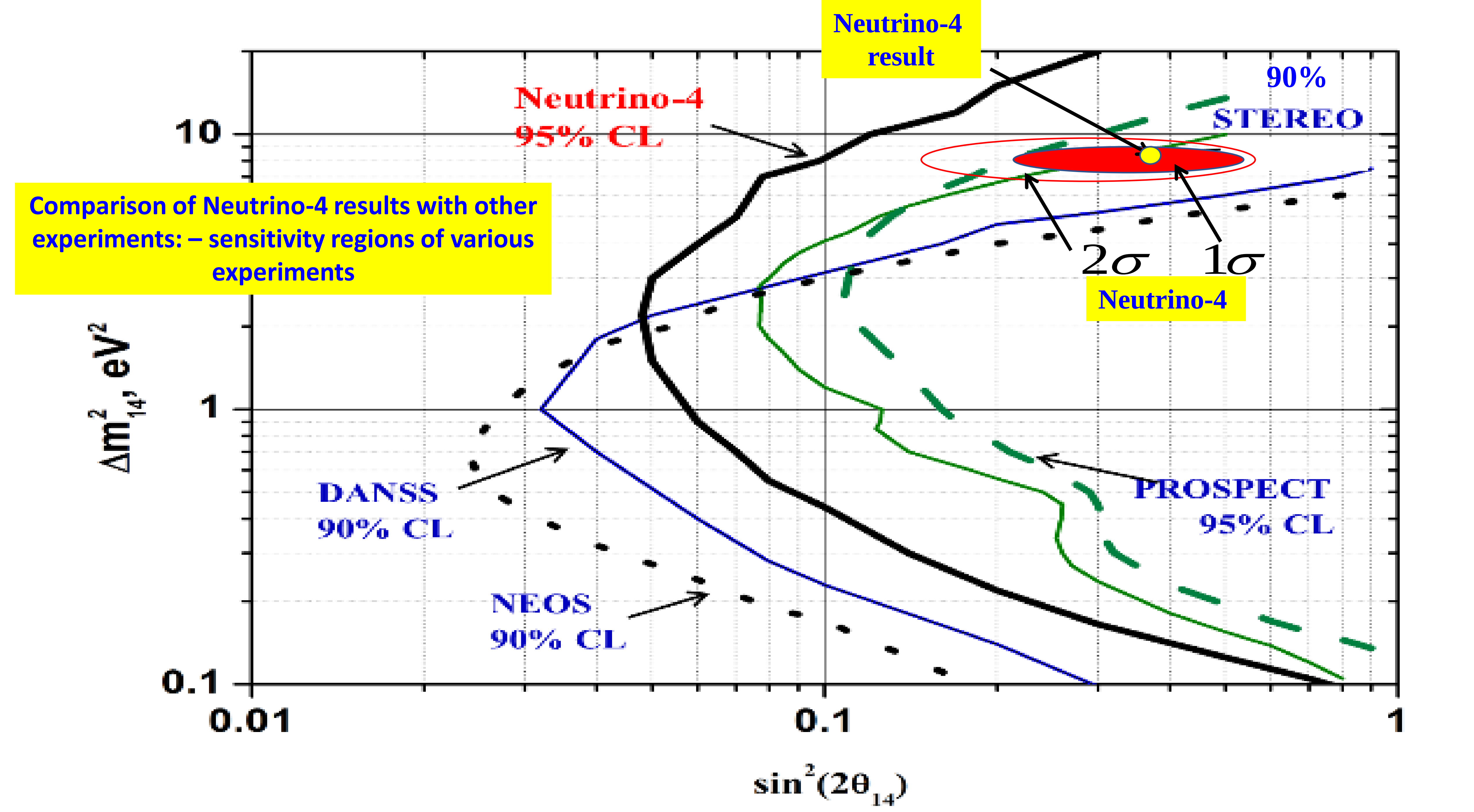
- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



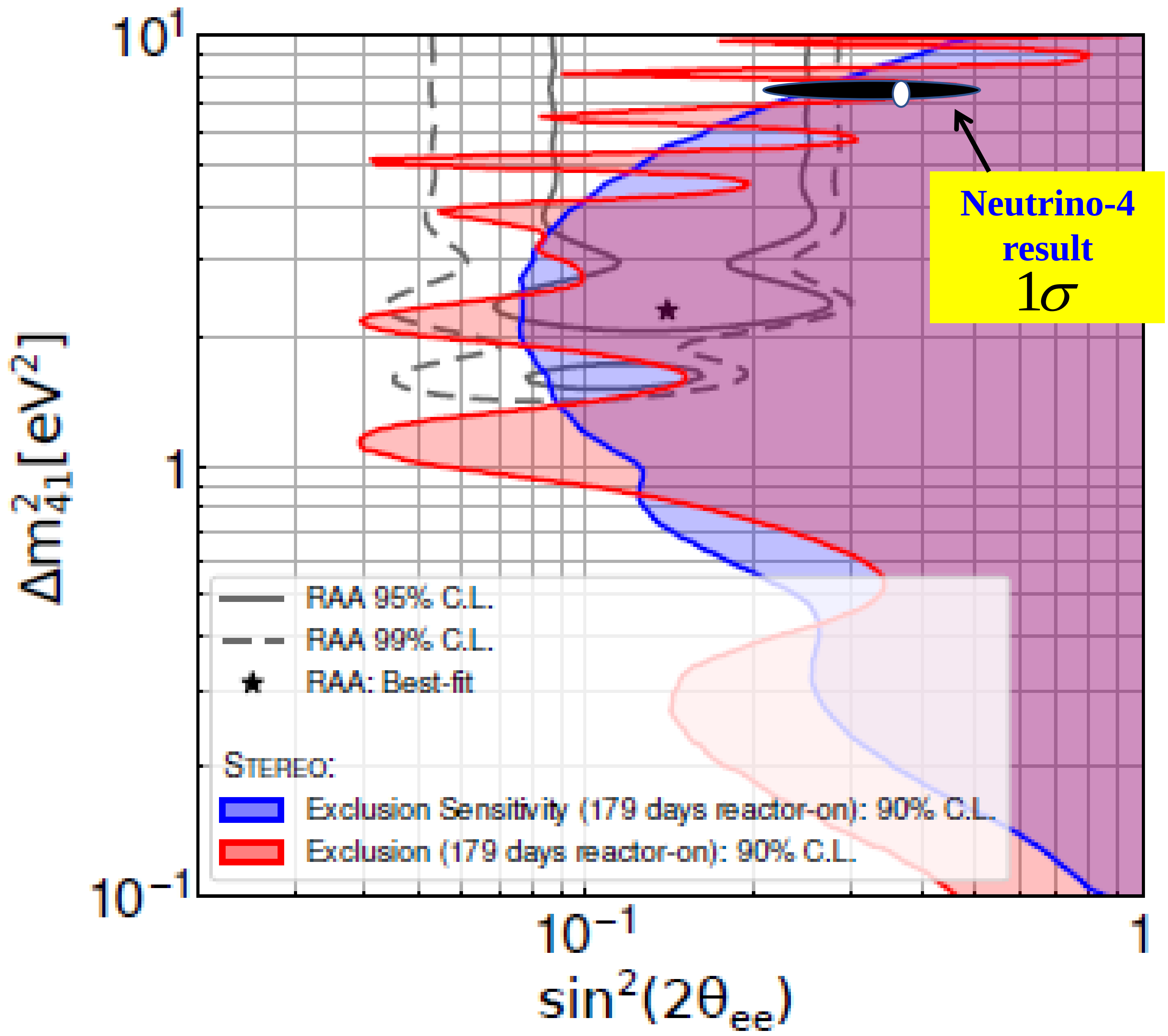
Where our result can be confirmed or refuted ?

1. PROSPECT, STEREO, SoLiD - can be …… because small size of reactor core.
2. DANSS –it is difficult because big size (3.7m) of reactor core.
3. NEOS – it is very difficult because big size of reactor core and distance 24 m.
4. BEST - new measurements is going right now.
5. KATRIN, Troisk

The period of oscillation for $\Delta m^2_{14} \approx 7.3эВ^2$ and neutrino energy 4 MeV is **1.4 m**

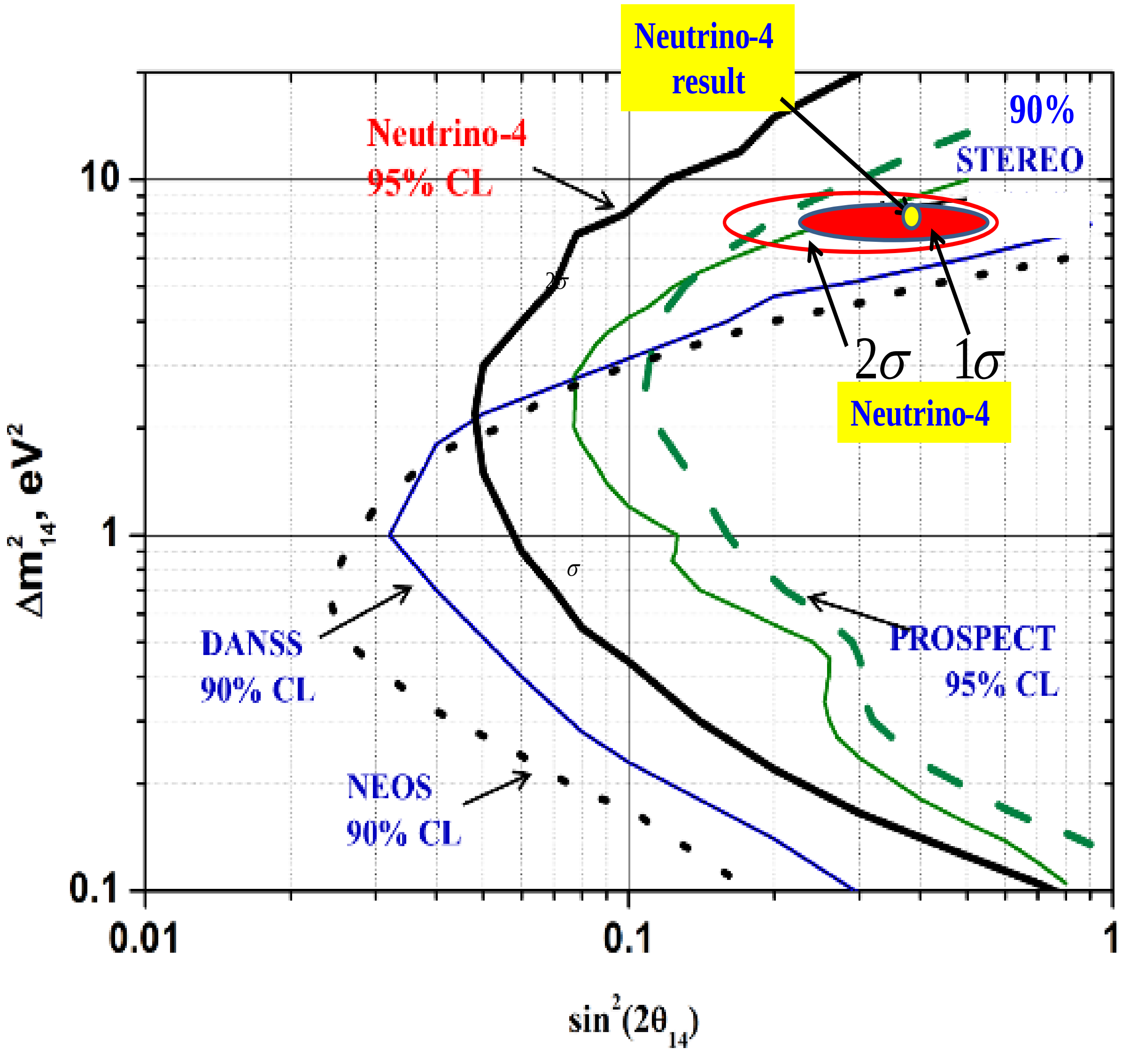


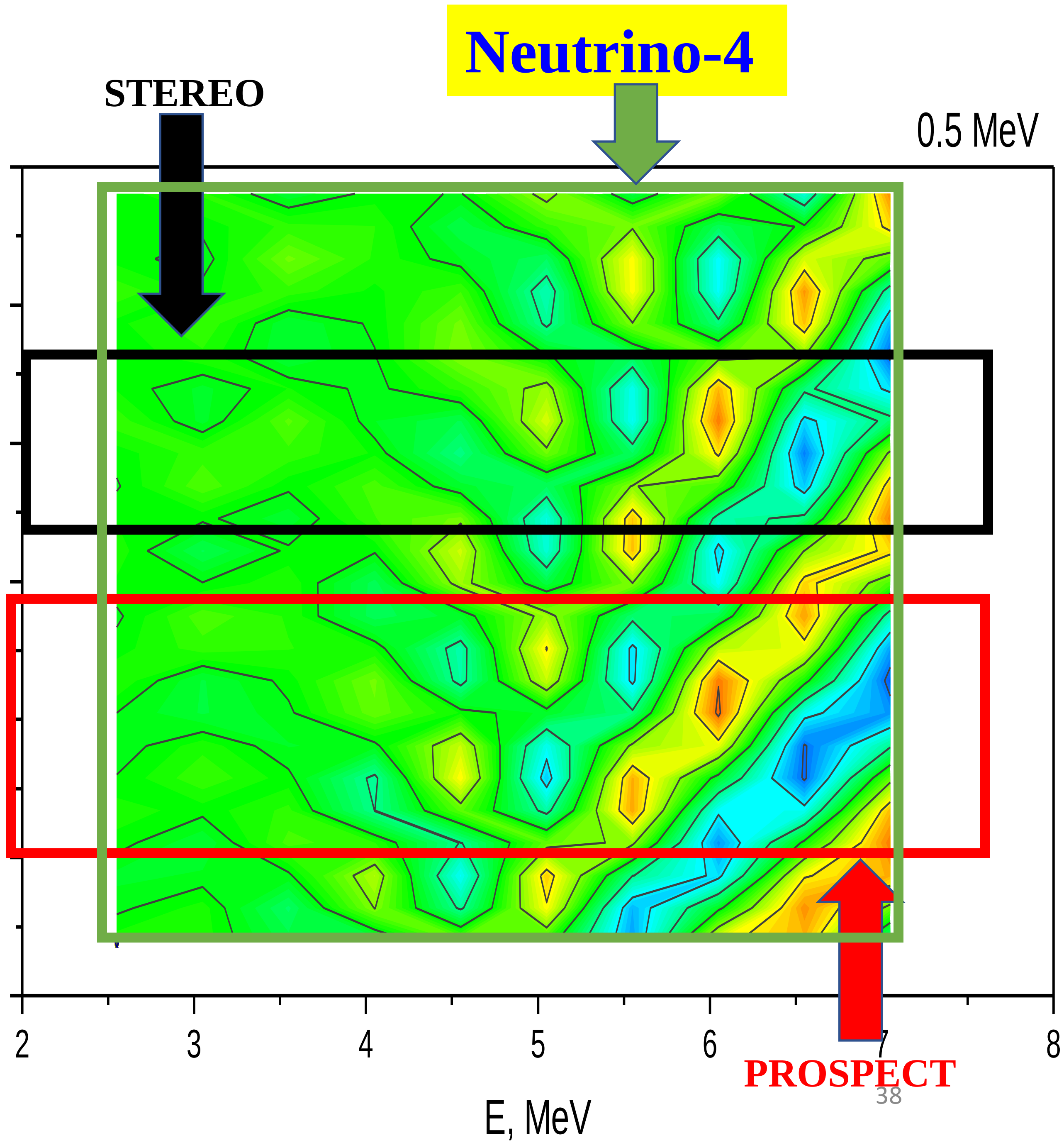
Neutrino-4 result
Neutrino-4 95% CL
90% STEREO
Comparison of Neutrino-4 results with other experiments: – sensitivity regions of various experiments
2σ
1σ
Neutrino-4
DANSS 90% CL
NEOS 90% CL
PROSPECT 95% CL
10
1
0.1
0.01
0.1
1
Δm²₁₄, eV²
sin²(2θ₁₄)



STEREO together with Neutrino-4.

Comparison with other results





Experiment Neutrino-4 has some advantages in sensitivity to big value Δm^2_{14} due to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements. It should be noted that without method of the coherent summation of data by L/E parameter, it is practically impossible to extract the effect of the oscillations. So far, the method of coherent summation of data by the parameter L/E has been actively used only by experimental Neutrino-4. This may determine the difference between the results of these experiments.

If effect of Neutrino-4 is correct
then it is possible to predict neutrino mass

Experiment KATRIN and sterile neutrino from Neutrino-4

$$\Delta m_{14}^2 = 7.26 eV^2,$$

$$Sin^2 2\vartheta_{14} = 0.38$$

$$m_\beta = \sqrt{\Sigma_i m_i^2 /U_{ei}/^2}$$

$$\Delta m_{14}^2 \approx m_4^2,$$

$$Sin^2 2\vartheta_{14} = 4/U_{14}/^2 (1 - /U_{14}/^2)$$

$$/U_{14}/^2 \ll 1$$

$$/U_{14}/^2 \approx \frac{1}{4} Sin^2 2\vartheta_{14}$$

$$m_\beta \approx \frac{1}{2}\sqrt{7.3 \cdot 0.38} \approx 0.87 eV$$

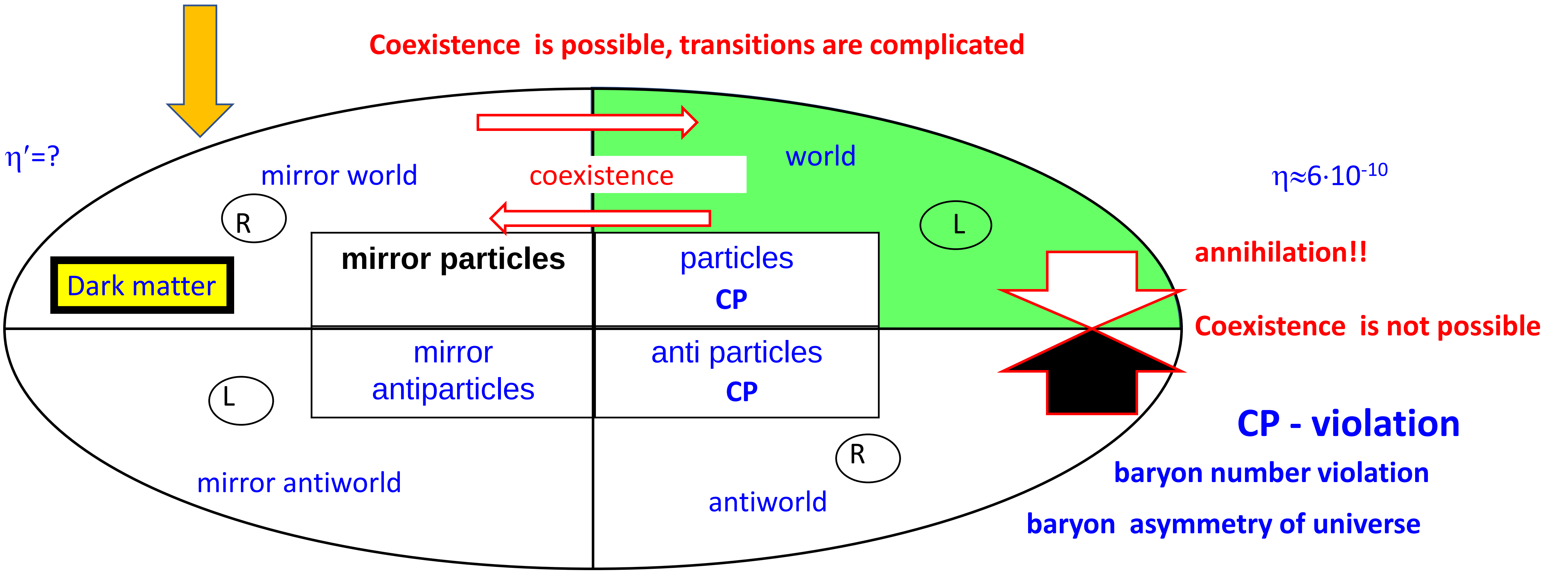
1. There is no contradiction with restriction from experiment KATRIN - $m_\beta \le 1 eV$

2. If effect of Neutrino-4 is correct then prediction for neutrino mass is $m_\beta \approx 0.87 eV$

Two problems of fundamental interaction – baryon asymmetry of the universe and dark matter

(left-right asymmetry in nature)

Sterile neutrino it is mirror neutrino – candidate for dark matter particle



Conclusion

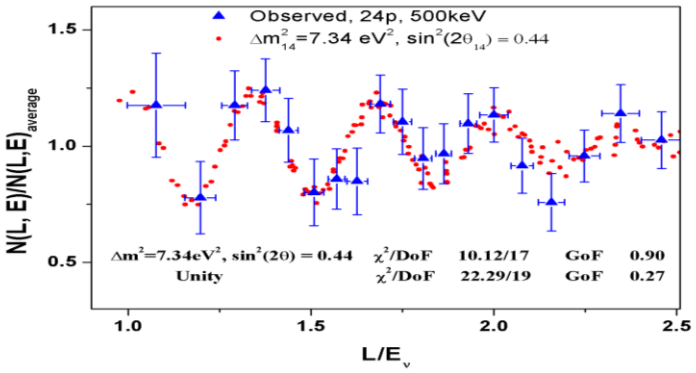
1. It is probable that sterile neutrino exist

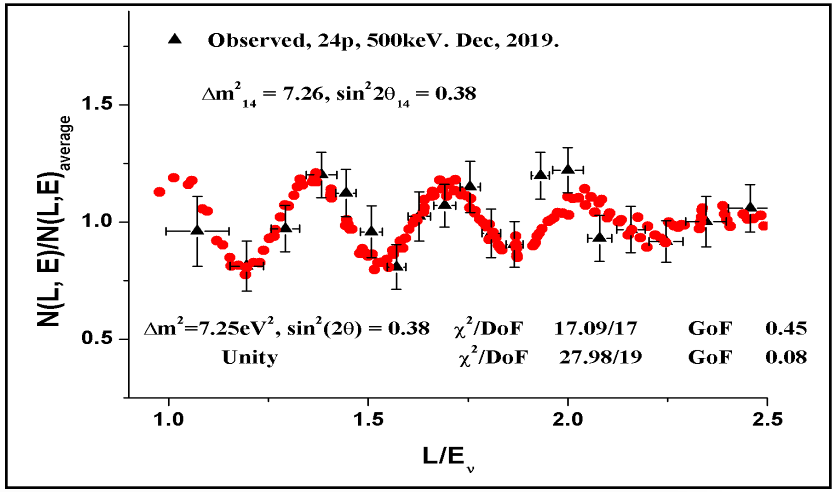
2. If effect of Neutrino-4 is correct then prediction for neutrino mass is

$$m_\beta \approx 0.87 eV$$

3. Sterile neutrino is probably a dark matter particle

Thank you for attention





Best regards from Gatchina

Best regards from Dimitrovgrad

Back up

More detailed analysis of comparison between Neutrino-4 and KATRIN gives the following estimations.

Upper $1.1\text{eV}(90\%)$ **limit for KATRIN result means neutrino mass estimation** $m_\beta = 0.30 \pm 0.49\text{eV}$ **;**

Neutrino-4 estimation for neutrino mass is $m_\beta = 0.87^{+0.07}_{-0.17}\text{eV}$

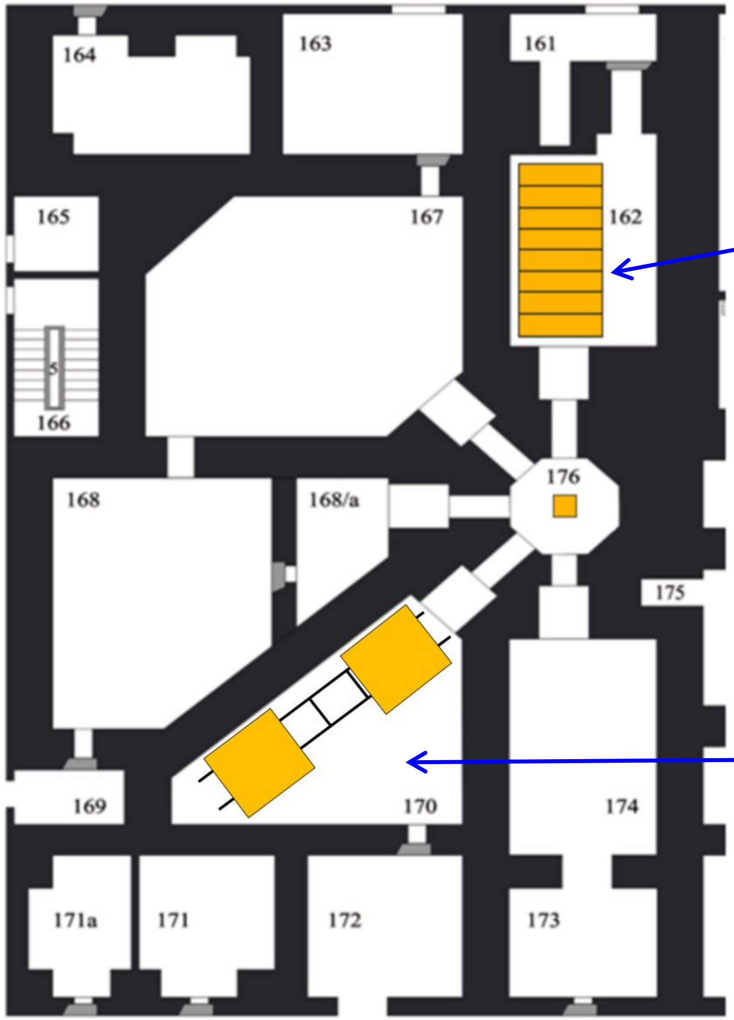
That means discrepancy is $\Delta m_\beta = 0.57 \pm 0.50\ (1\sigma)$

and it is not serious contradiction like it was declared in

C. Giunti, Y.F. Li, and Y.Y. Zhang. arXiv:1912.12956v2 [hep-ph]

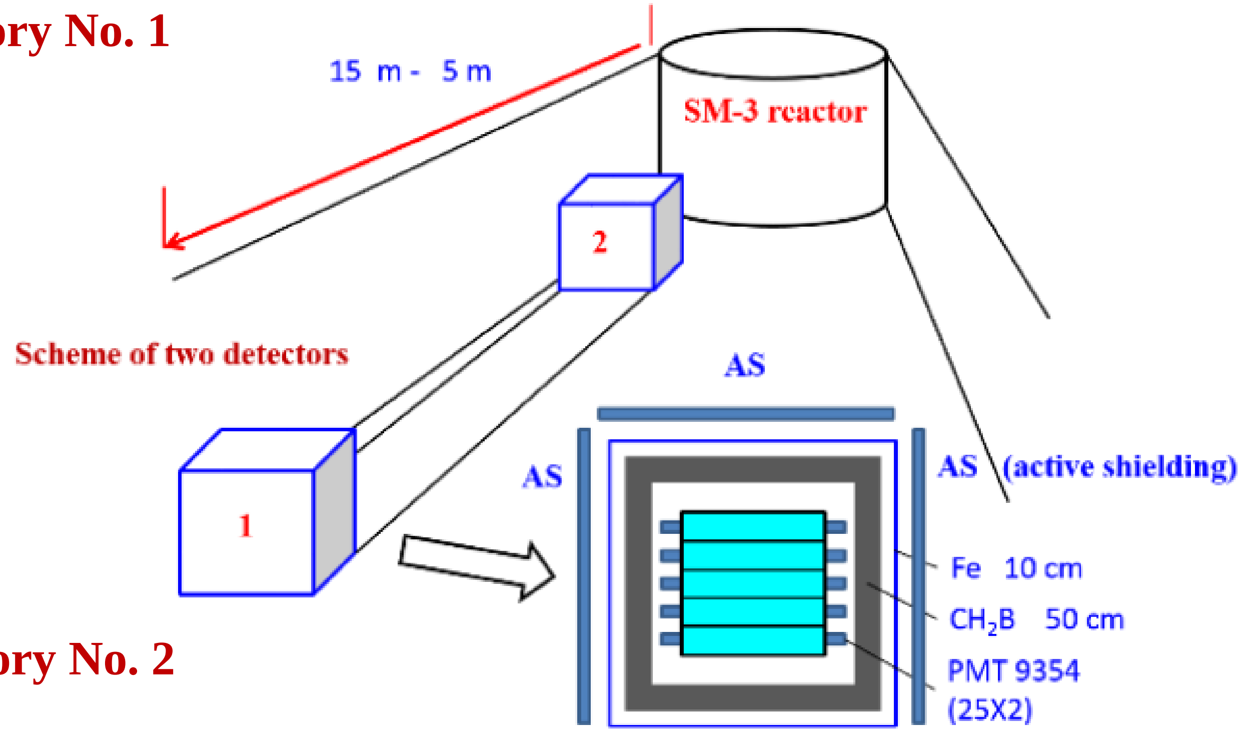
Future: Neutrino-6 experiment

Future: Neutrino-6 experiment

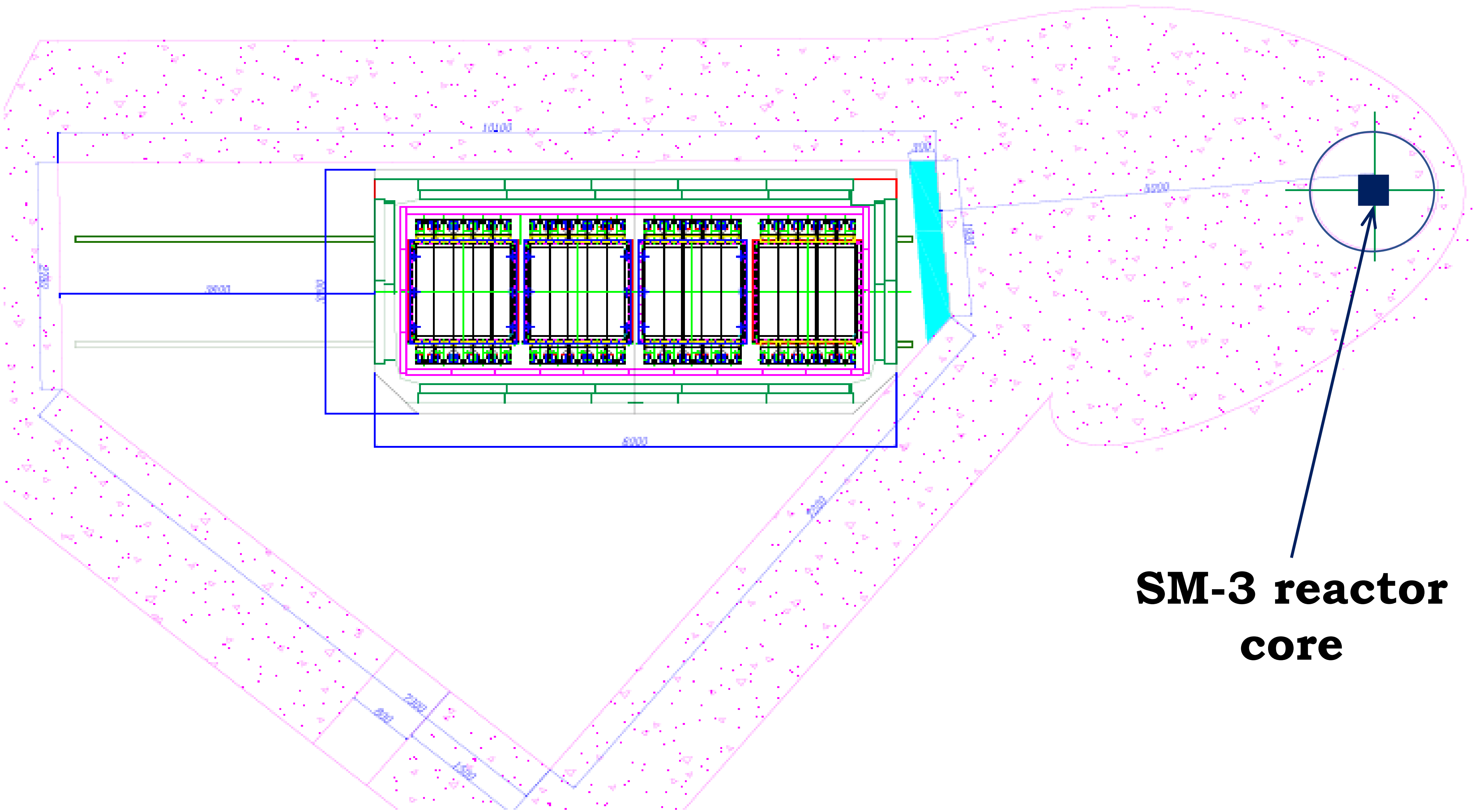


Neutrino
Laboratory No. 1

Neutrino
Laboratory No. 2



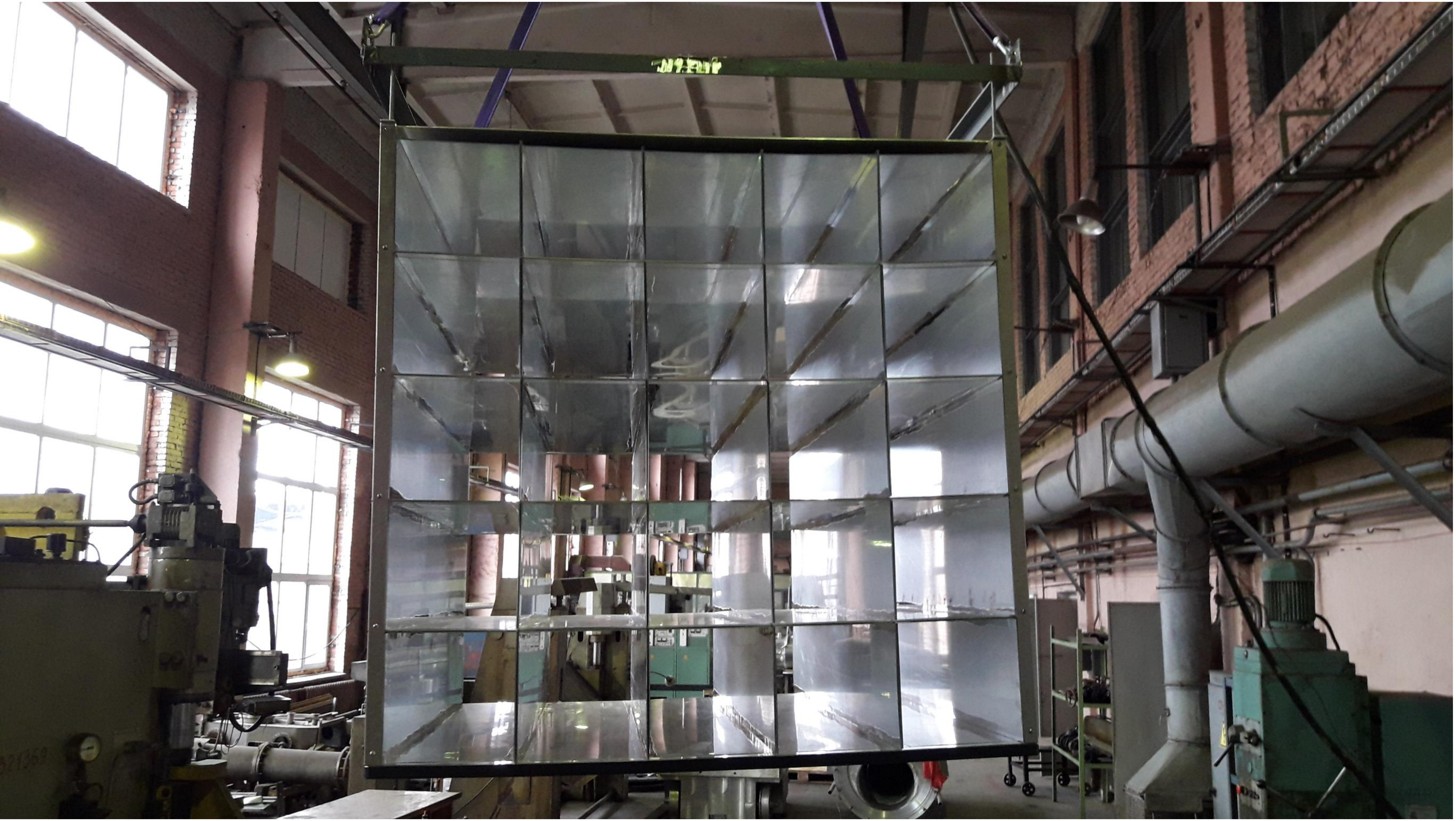
Neutrino-6 experiment location



Detector's design.
Transport system

Platforms

Inner cavities



Detector's design.
Transparent tank

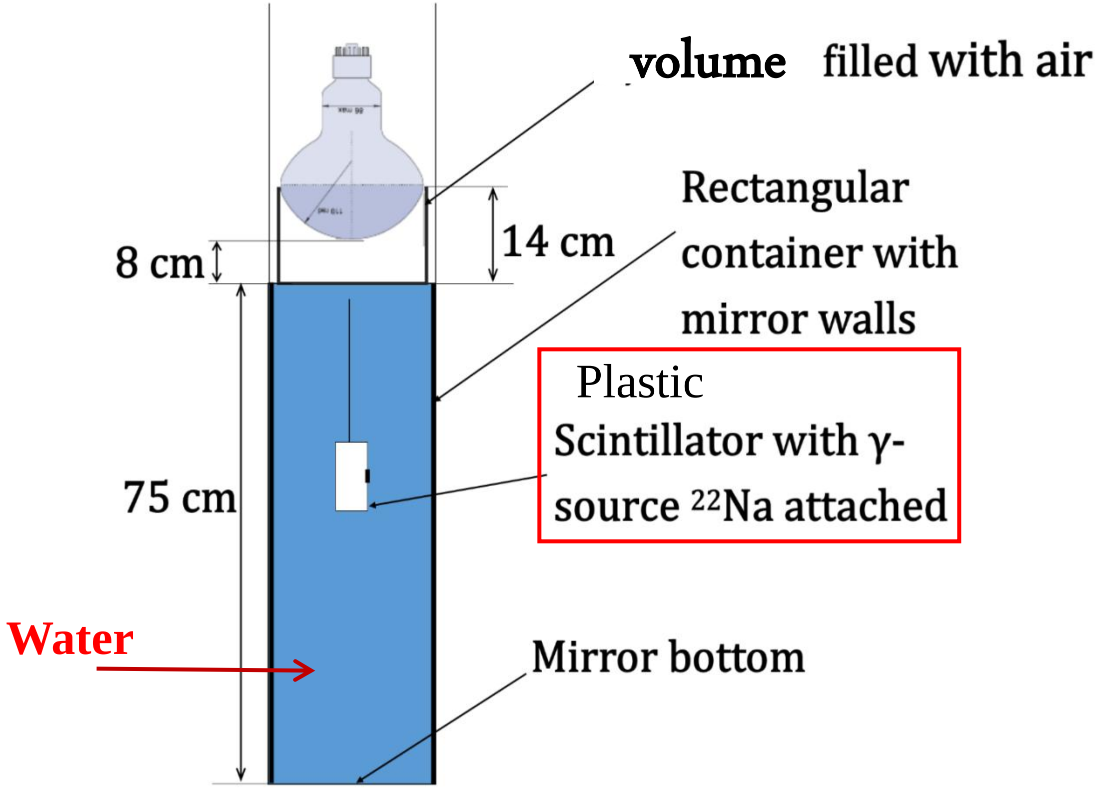
Detector's design.
Case

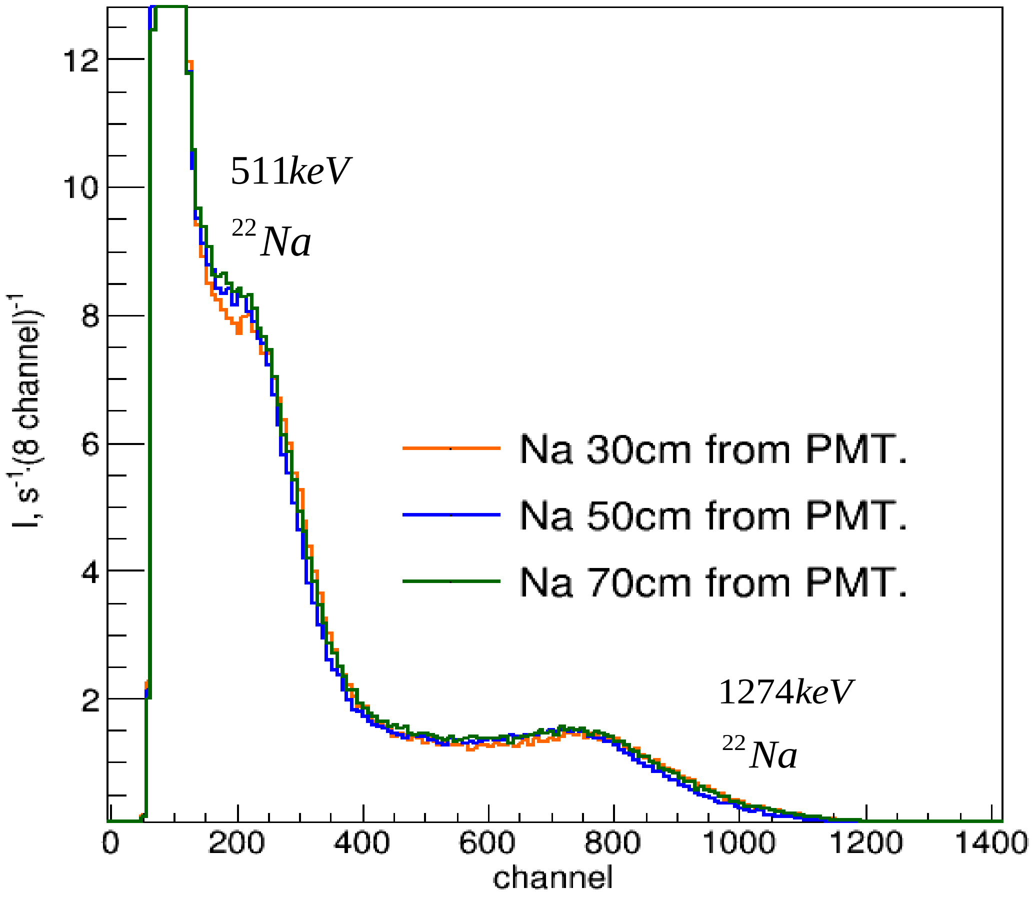
Expecting improvements of statistical accuracy for Neutrino-6

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**

Энергетическая калибровка на модели одной секции

Мы используем эффект полного внутреннего отражения света на границе сцинтиллятор - воздух при малых углах падения, чтобы улучшить сбор света с разных расстояний. Поэтому калибровка может быть сделана, используя источники, расположенные снаружи – над детектором.

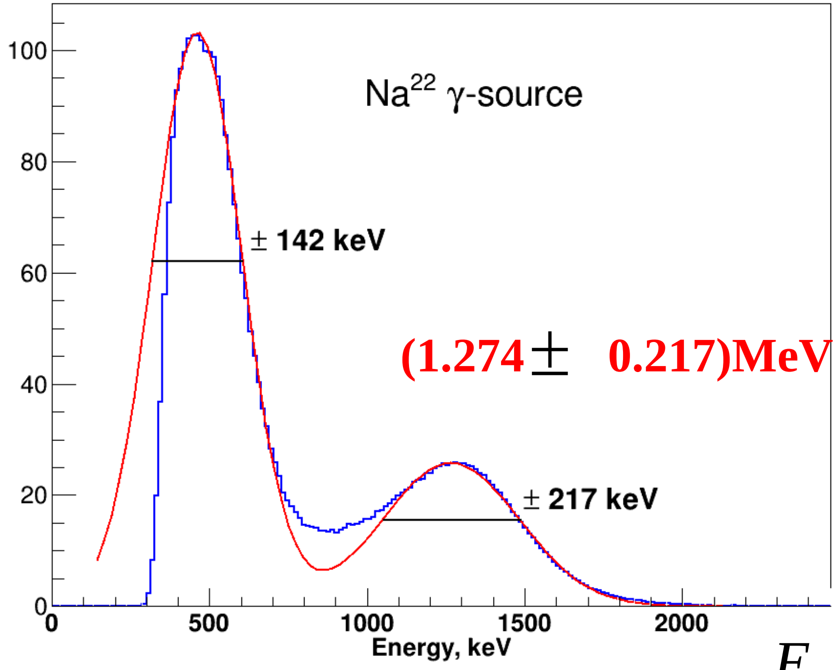




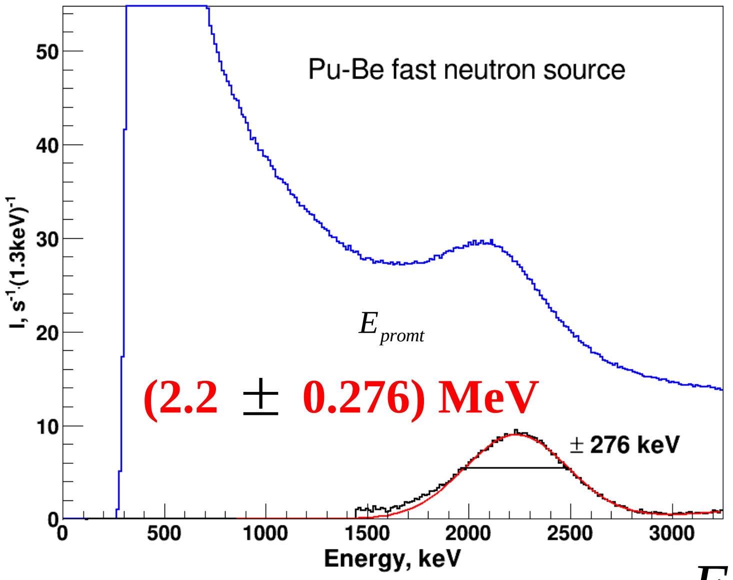
Energy calibration of the full-scale detector

(0.511 ± 0.142) MeV

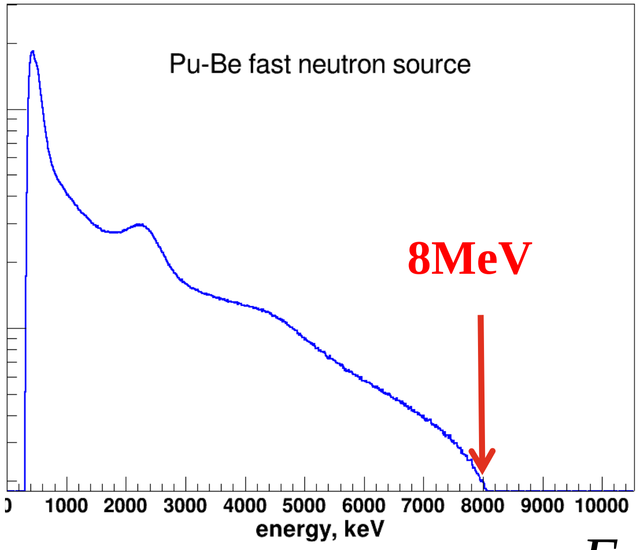
$$E_\nu = E_{promt} + 0.8 MeV$$



E_{promt}



E_{promt}



E_{promt}

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

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

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

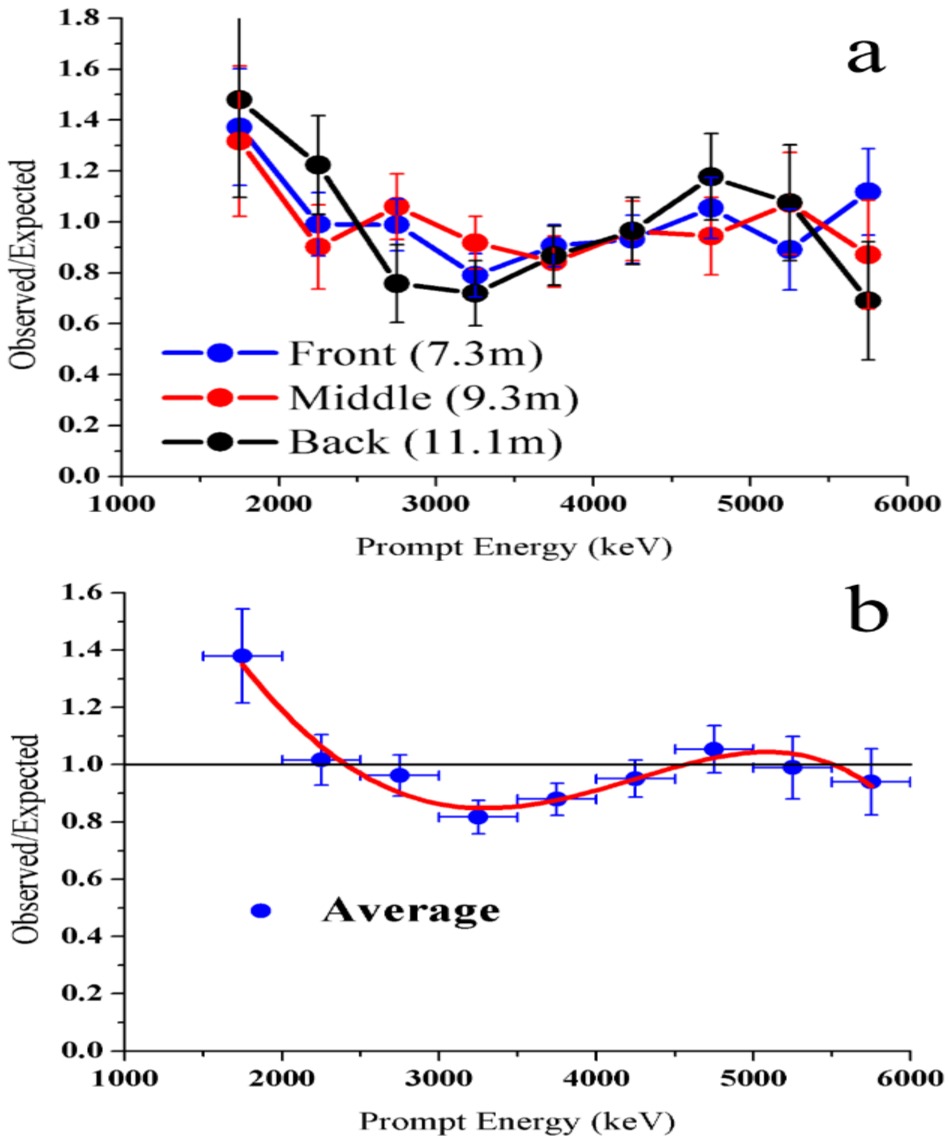
$$\Delta E_\nu(3MeV) = 550keV$$

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

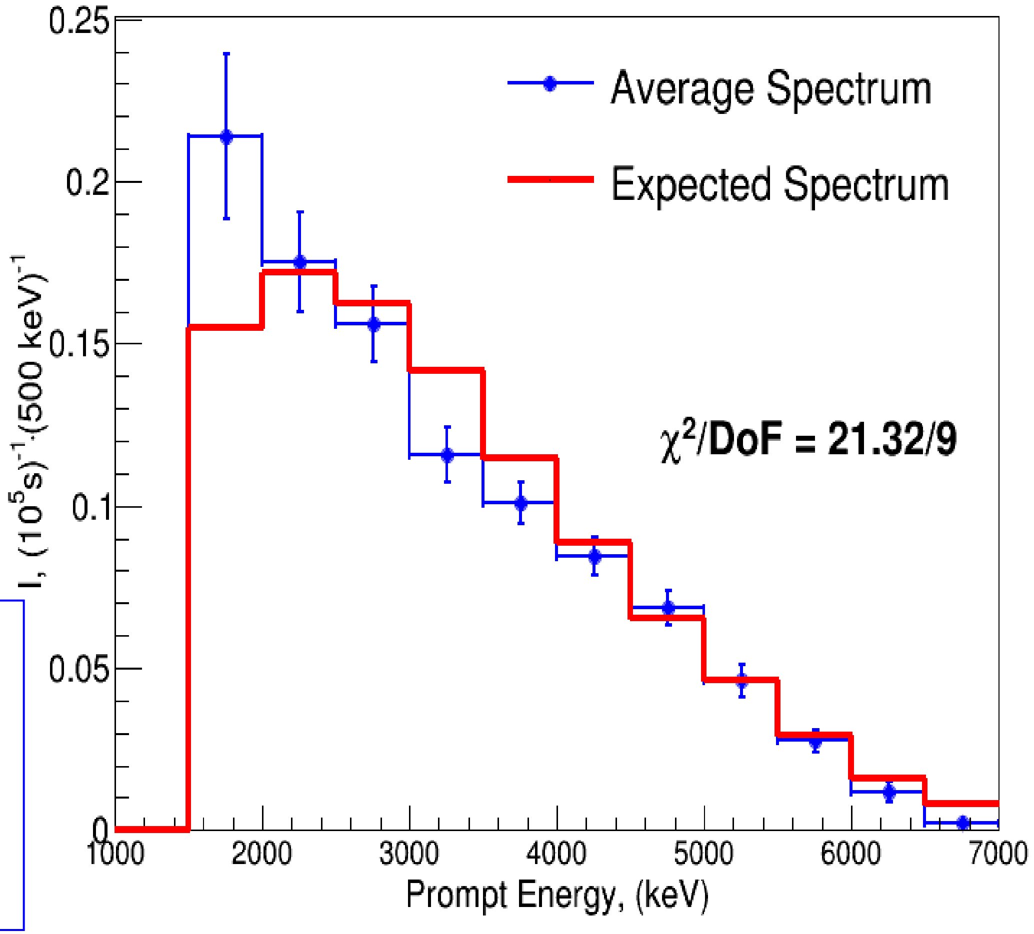
$$\Delta E_\nu(6MeV) = 830keV$$

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)

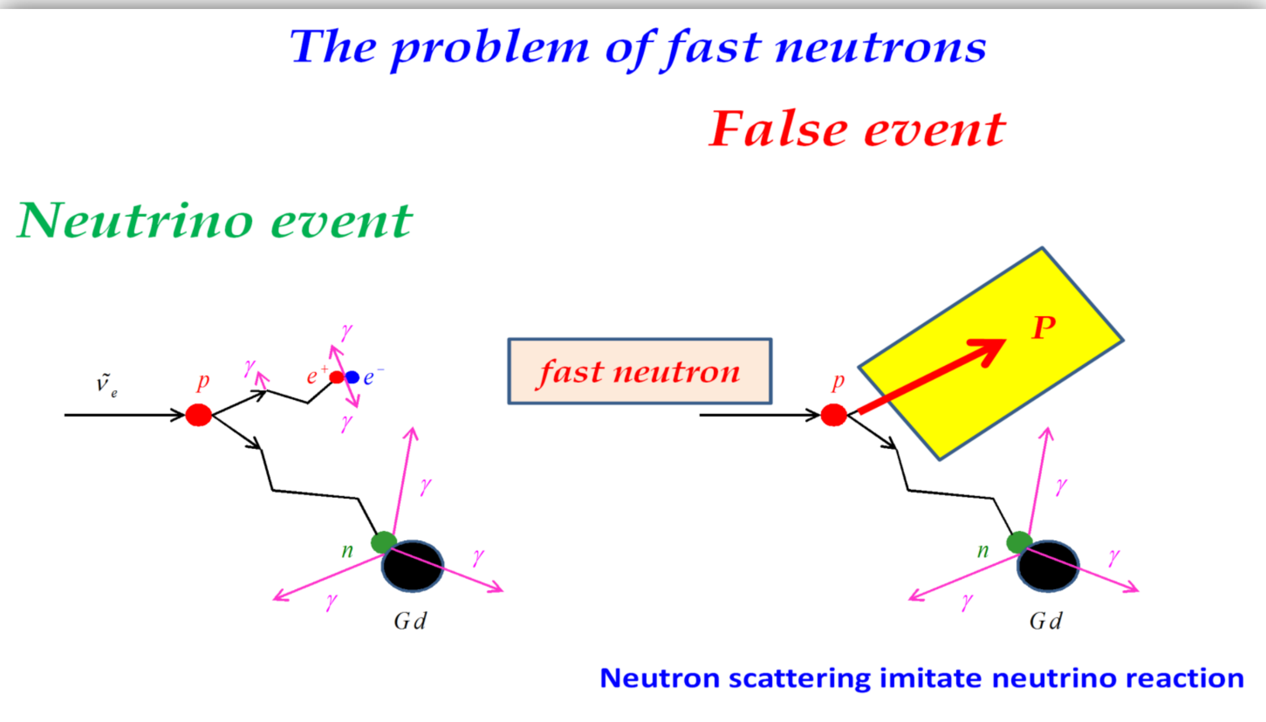


Problems with energy spectrum



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.

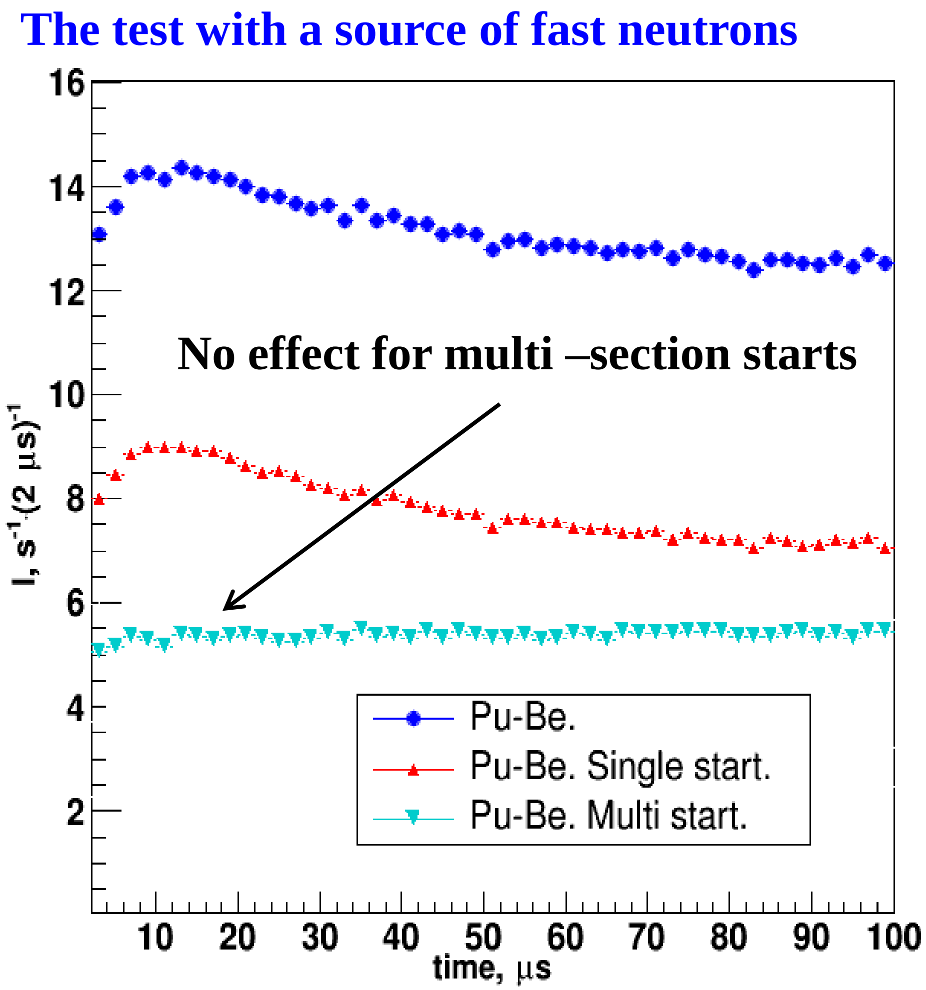
- **Sectioning of the detector**
- **Problem of fast neutrons**
- **Allocation of a neutrino signal**



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

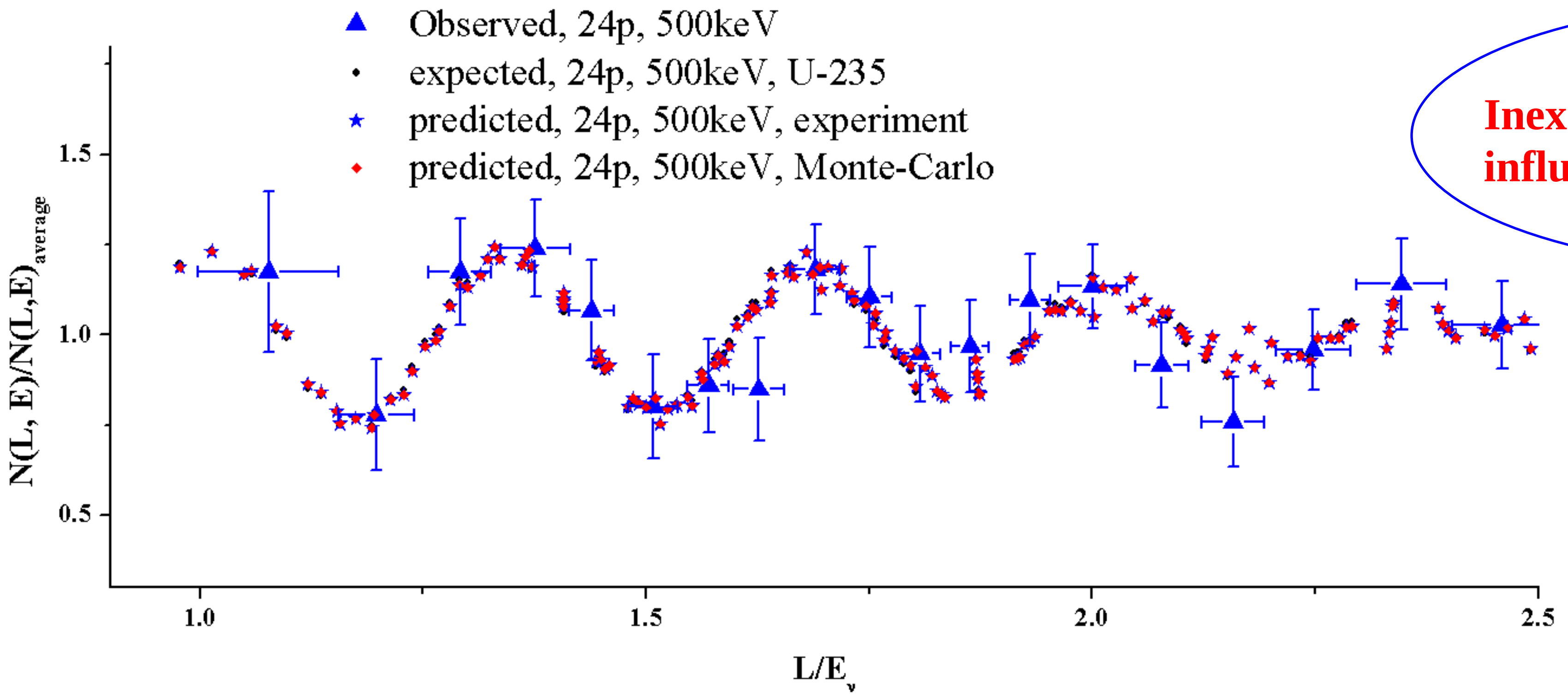


Experimental average percentage of multi-start events for full-scale detector

$(37 \pm 4)\%$

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

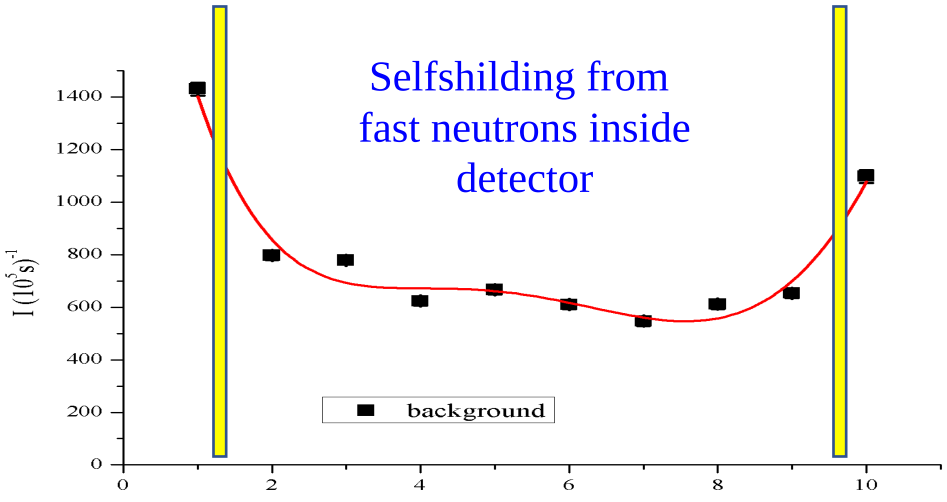


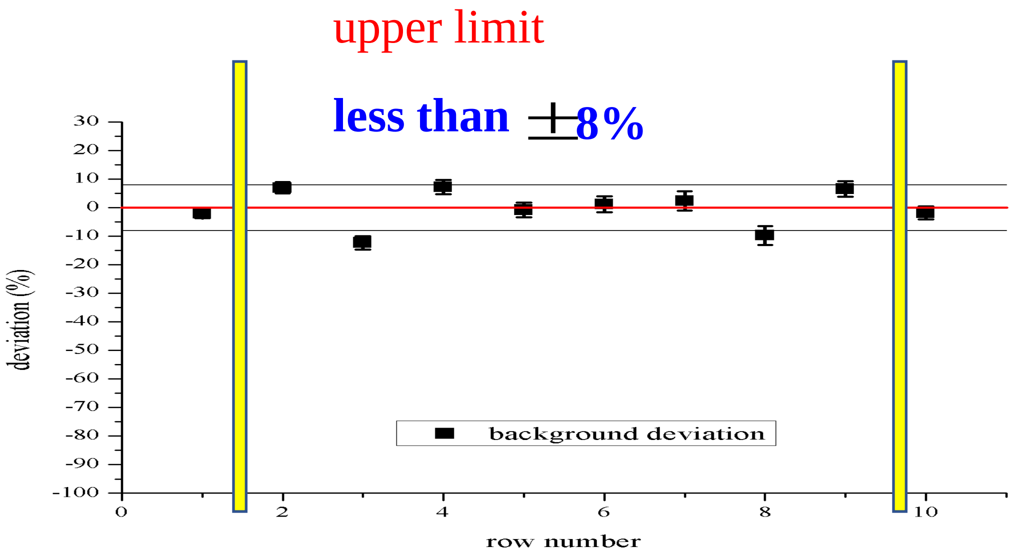
Inexact measurement of energy influences to definition of: Δm^2_{14}

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

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

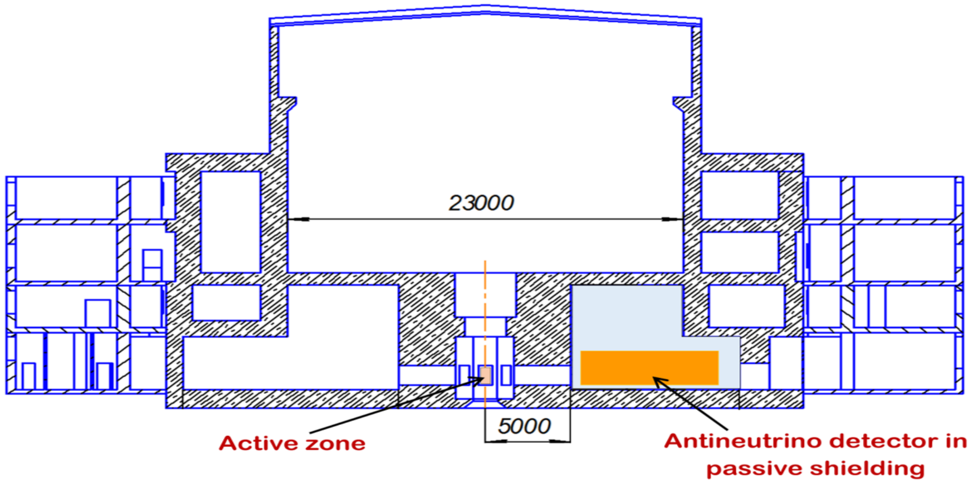
Analysis of possible difference in efficiency of rows of the detector, using the background of fast neutrons which is given rise into the building from cosmic muons.

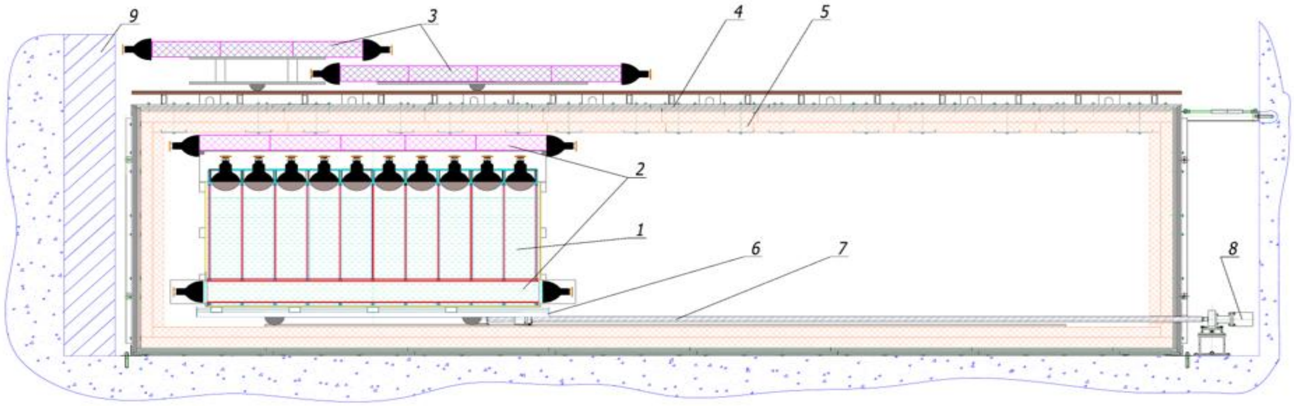




The background of fast neutrons is asymmetric because of structure of the building.

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



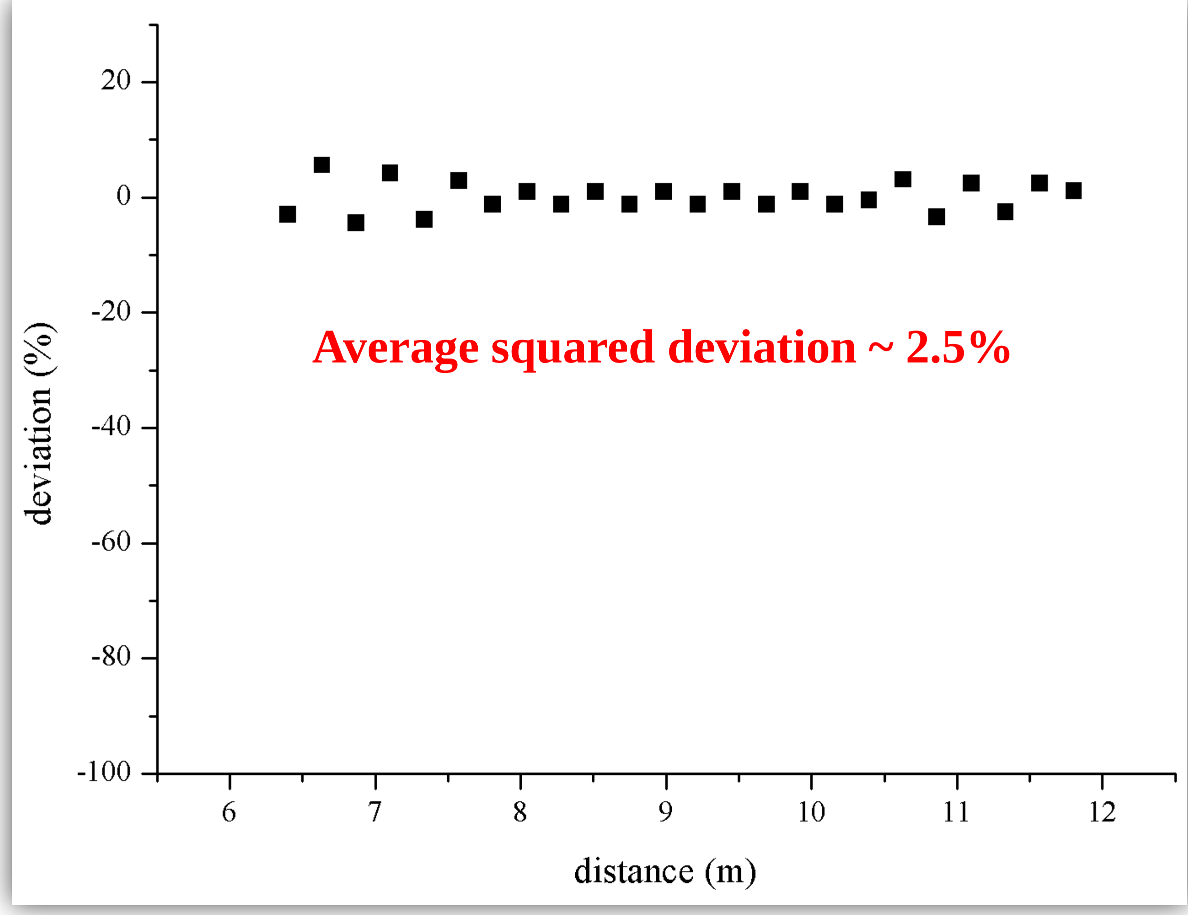


We use only 8 internal rows, the first and tenth are protective.

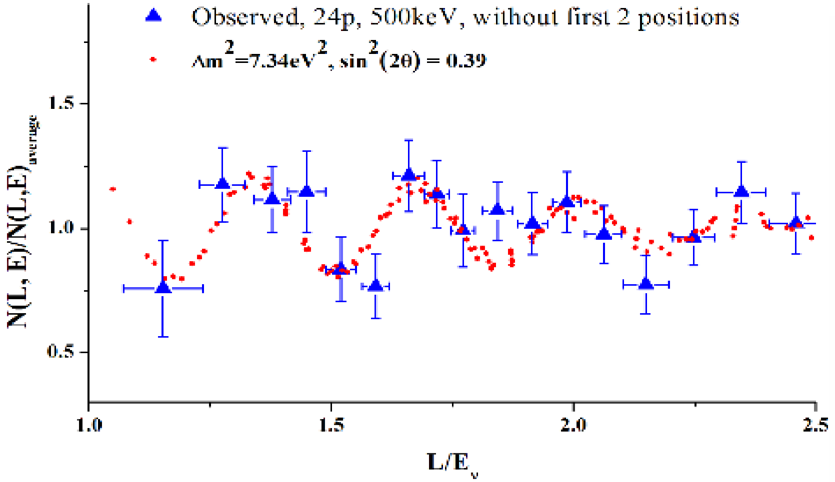
Averaging of detector rows efficiencies due to movements (above estimation)

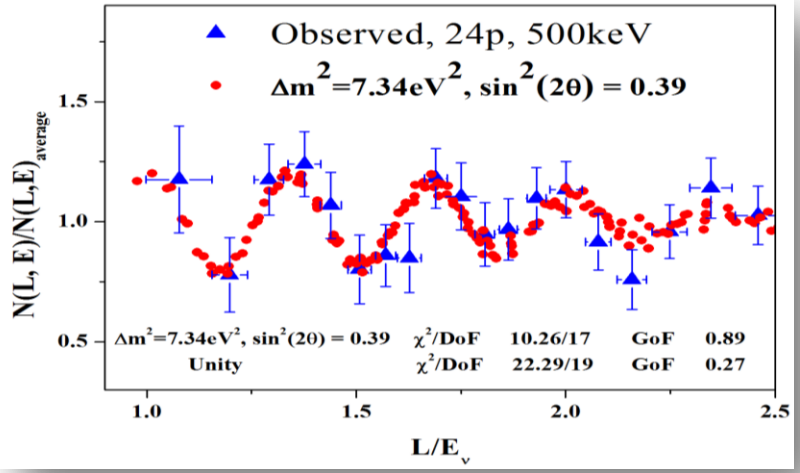
L(m)	Numbers of detector row				
6.4025	2				
6.6375	3				
6.8725	4	2			
7.1075	5	3			
7.3425	6	2	4		
7.5775	7	3	5		
7.8125	8	4	6	2	
8.0475	9	5	7	3	
8.2825	6	2	8	4	
8.5175	7	3	9	5	
8.7525	8	4	6	2	
8.9875	9	5	7	3	
9.2225	6	2	8	4	
9.4575	7	3	9	5	
9.6925	8	4	6	2	
9.9275	9	5	7	3	
10.1625	6	2	8	4	
10.3975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

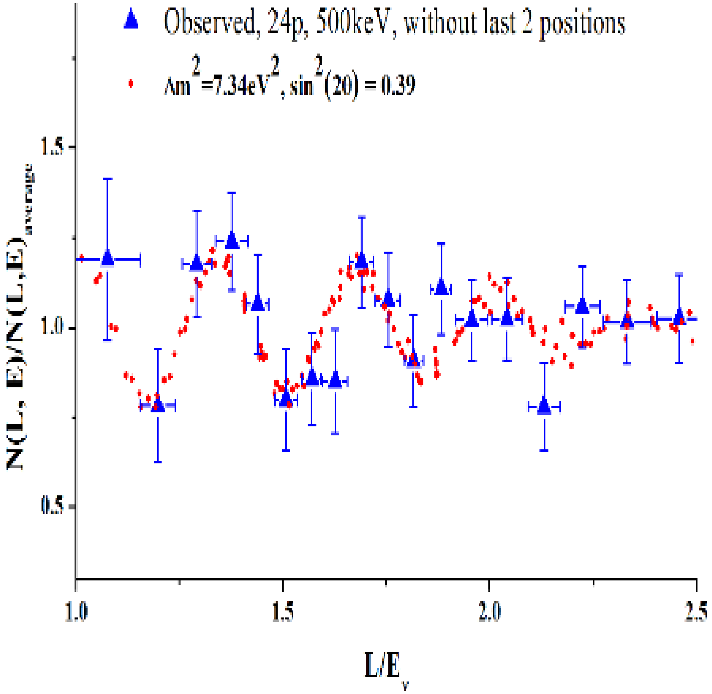
Average efficiency at various distances

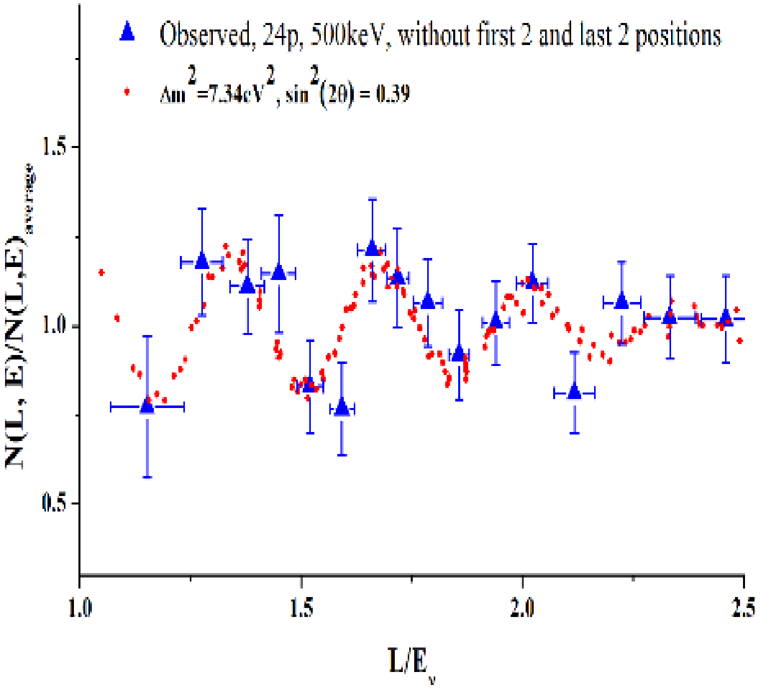


Test of stability of the effect by means of removal of extreme positions





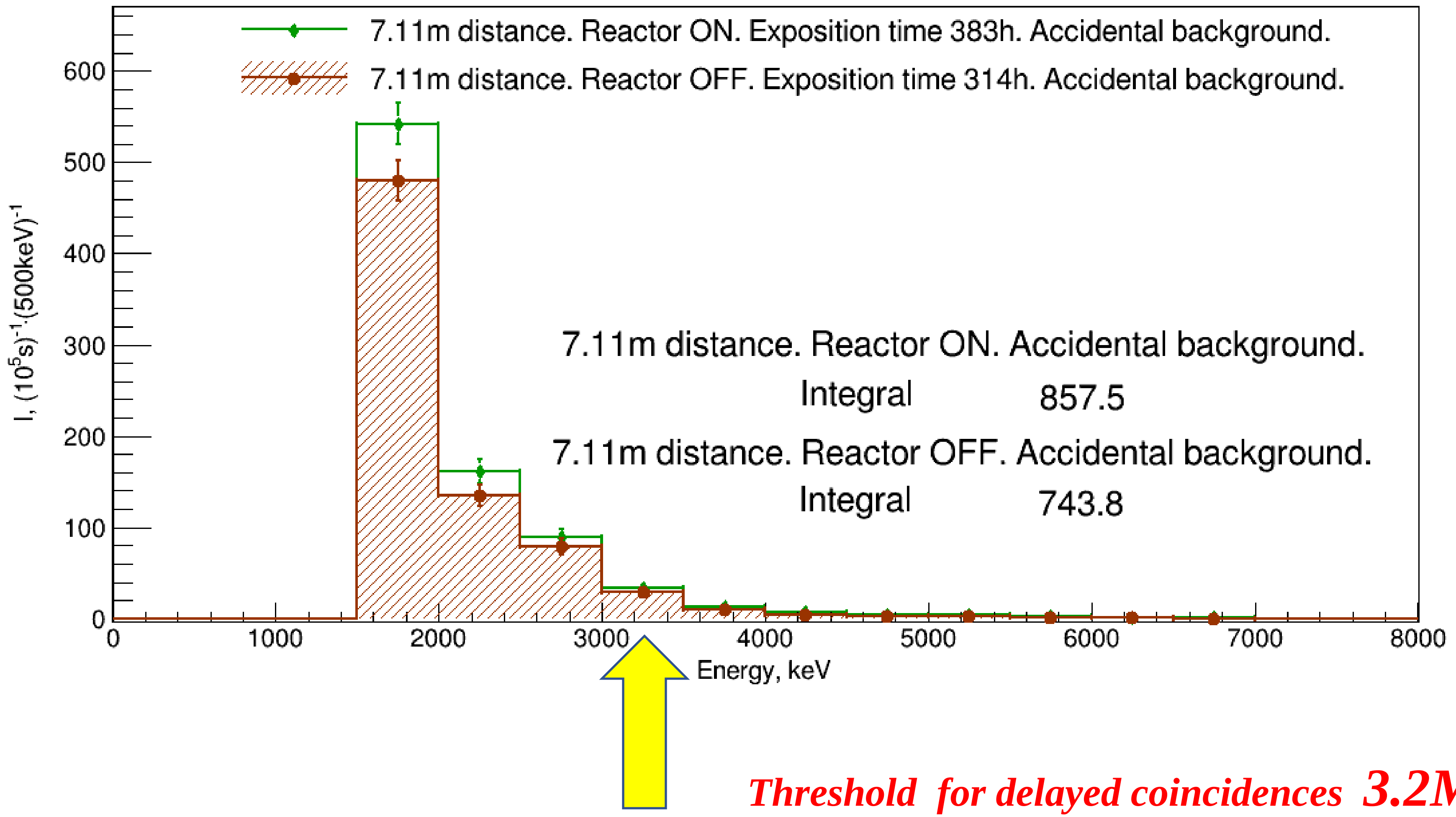




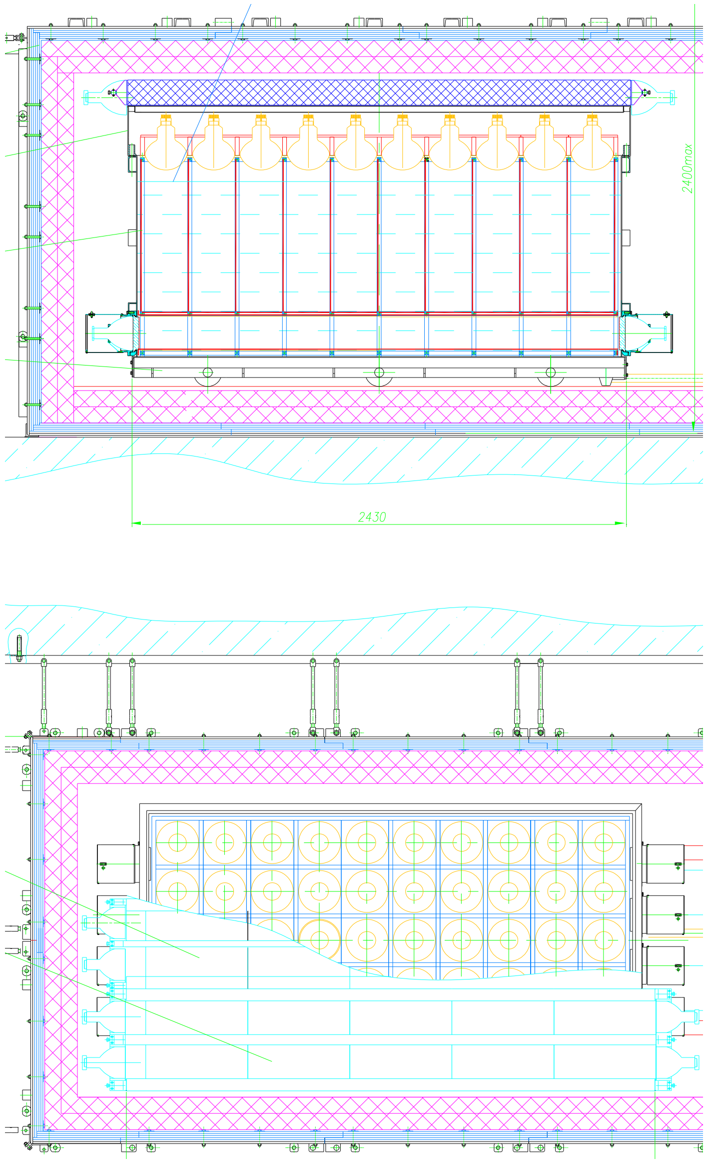
Conclusion

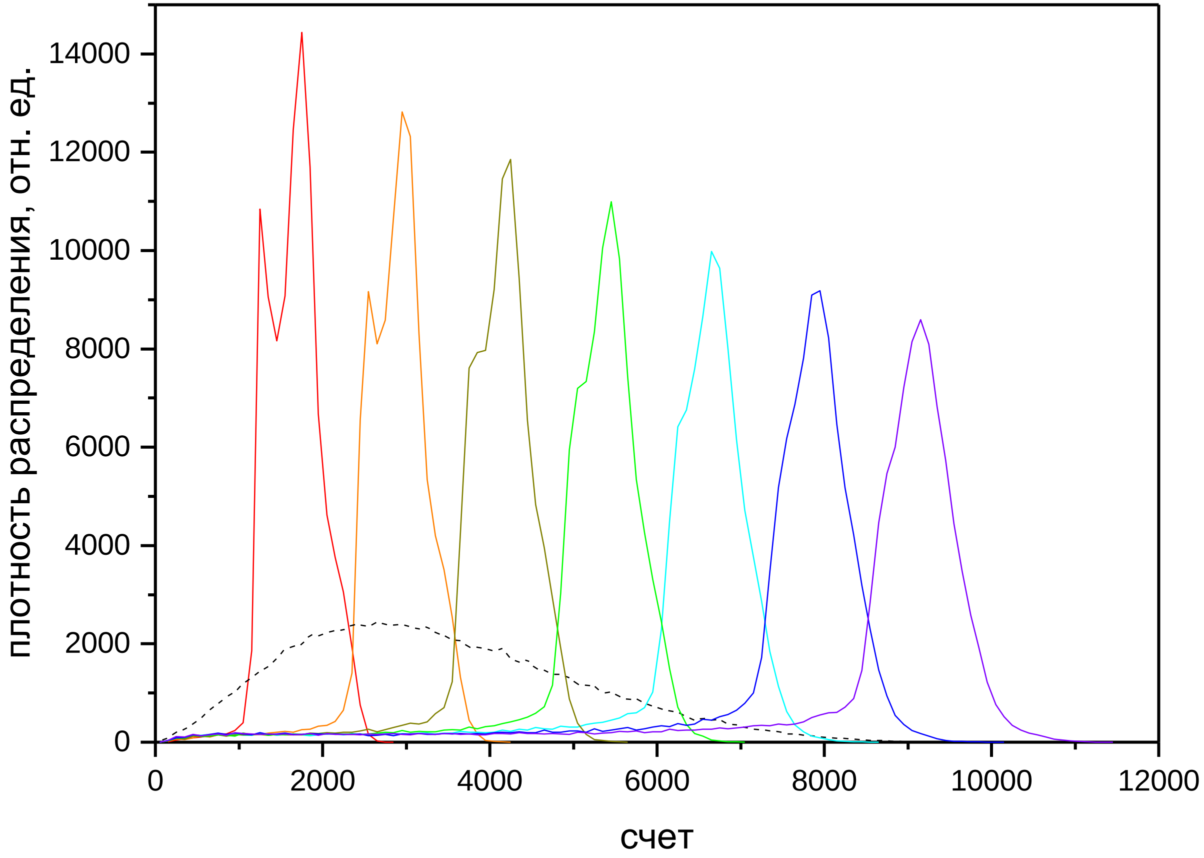
There is no reason to consider that the effect can be caused by structure of the detector. The possibility of averaging of efficiency of various sections by placing them at the same distance is the advantage of our experiment.

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

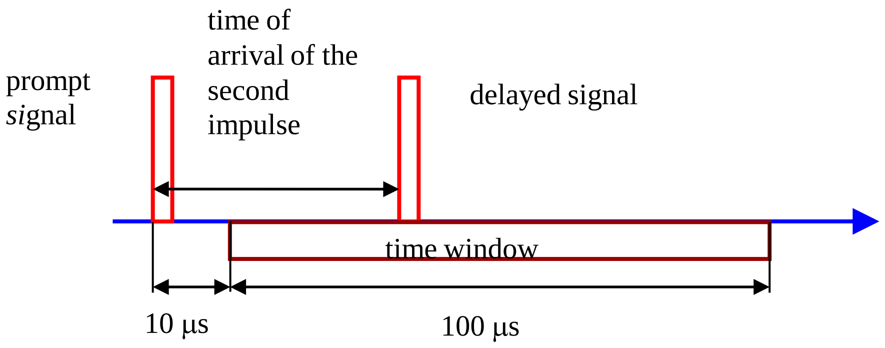


Threshold for delayed coincidences ***3.2MeV***


2400max
2430


плотность распределения, отн. ед.
14000
12000
10000
8000
6000
4000
2000
0
0
2000
4000
6000
8000
10000
12000
счет

Signal of correlated events



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