The Antineutrino Detector for Belarus NPP

V.V. Gilewsky

on behalf of

Belarus AntiNeutrino Detector International Team (BANDIT)

(I.S. Satsunkevich, M.M.Sobolewsky – JIPNR-Sosny NAS Belarus,

V.M.Redkov – Institute of Physics NAS Belarus

O.M.Boyarkin – Sakharov Institution BSU)

SOSNY JOINT INSTITUTE FOR POWER AND NUCLEAR RESEARCH

Goals of neutrino project

A. Additional (independent) NPP monitoring

- Search for neutrino flux variations [$N\nu$ (t)] and possible reasons of these changes
- Spectral measurements in real time [$N\nu(E\nu)$], (this is not only definition of real fuel composition - Pu-U – which is essential to define the time of reloading)
- Can we organize some kind of reactor tomography [we need 3 detectors or one movable - mobile]?

B. What kind of physics (ν-properties) can we study by neutrino detector? – i.e. pure scientific part

The (anti-)neutrino sources

We want to start experimental research in particle physics

- Belarus do not have deep lake (as Baikal)
  or sea (as Mediterranean)
  or even tunnel under the mountain (as Grand-Sasso)
- But Belarus is building NPP – free source of anti-neutrino

$P_{thermal}$=3600 MW [$P_{electrical}$=1200 MW], Q =201.7 MeV, n[fission/s]= $1.04*10^{20}$ and taking n_ν ~ 6 [ν/decay]

- Nν=$6.24*10^{20}$ [antineutrino/second]

The neutrino flux: Φ_ν=N_ν /4*π*r^2

- Φ_ν(10 m)=$5*10^{17}$ [ν s^{-1} m^{-2}]= $5*10^{13}$ [ν $s^{-1}cm^{-2}$]
- Φ_ν(25 m)=$8*10^{16}$ [ν s^{-1} m^{-2}]= $8*10^{12}$ [ν $s^{-1}cm^{-2}$]
- The flux becomes equal to Sun flux at 320m from reactor
- *Neutrino investigation is real goal – and it starts experimental HEP-physics in Belarus*

Detecting reaction – IBD or X?

The most often ν detected in invers beta-decay(IBD):

- $\sim\nu_e + p \rightarrow e^+ + n$ (threshold 1.8 MeV)

neutrino interacts with (quasi) free protons from hydrogen-reach media (fiducial volume) – scintillator.

Photo-multipliers register an annihilation photon pair, and latter (10-100 μs) a signal of neutron capture (Gd-doped or ^{3}He)

– These two signals ensure good signal/noise ratio .

May be exists some more interesting reaction?

Possible detecting reactions

	σ_{tot} in 10^{-44} cm^2/fission	Reaction Threshold (MeV)
$\bar{\nu} + p \rightarrow n + e^+$	60	1.804
$\bar{\nu} + d \rightarrow n + n + e^+$ $\bar{\nu} + d \rightarrow n + p + \bar{\nu}$	1.2 1.9	4.0 2.3
$\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$	0.4 @ 1 MeV	Experimentally possible value (construction) and Signal/background ?
	40 @ 10 MeV	
$\bar{\nu} + e^- \rightarrow \bar{u} + d$	1.7 @ 1 MeV 168 @ 10 MeV	

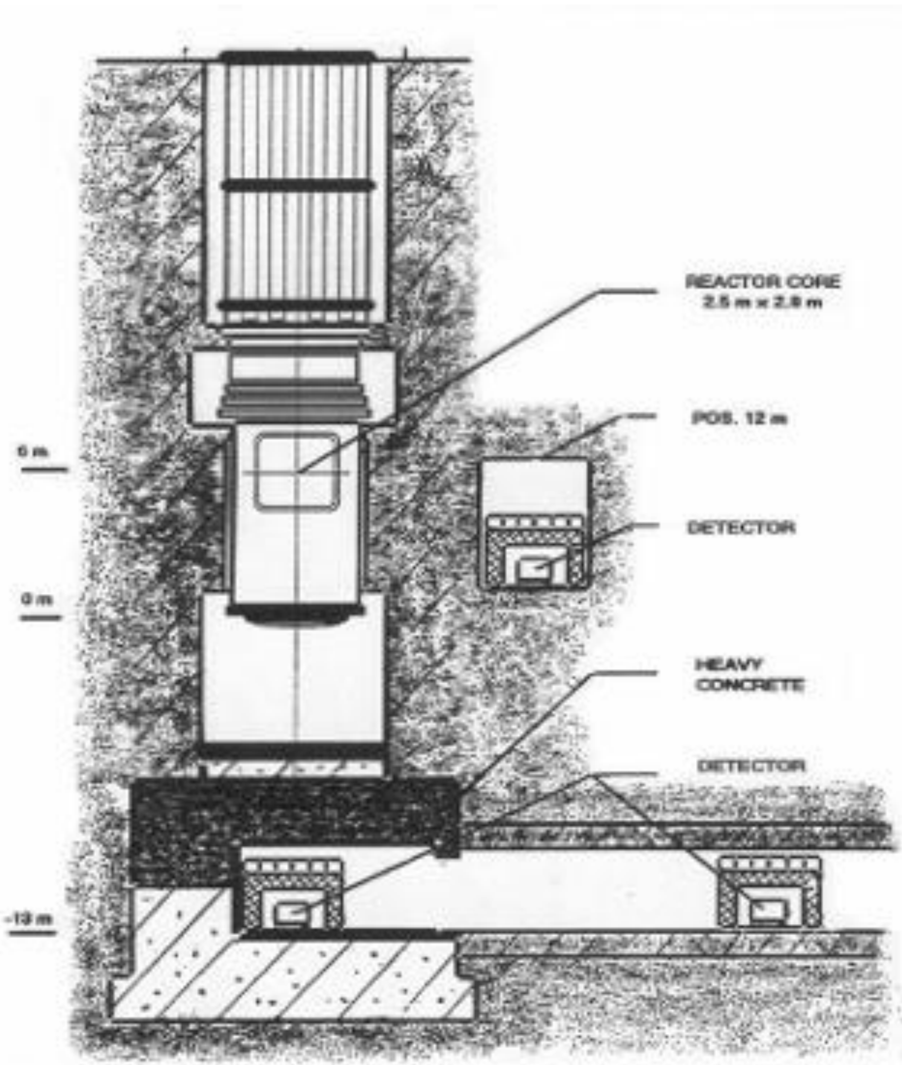
Reactor Large experiments

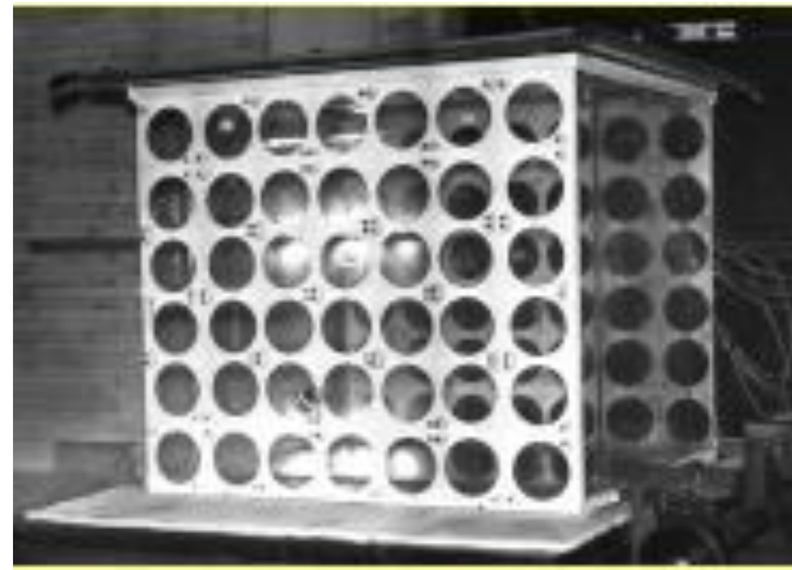
Abbr. Name	Full name	Type	Induced reaction	Detector	Threshold energy	Location	Operation
Daya Bay	Daya Bay Reactor Neutrino Experiment	ν_e	$\sim\nu_e + p \rightarrow e^+ + n$	Gd-doped LAB (LOS)	1.8 MeV	Daya Bay, China	2011–
Double Chooz	Double Chooz Reactor Neutrino Experiment	ν_e	$\sim\nu_e + p \rightarrow e^+ + n$	Gd-doped LAB (LOS)	1.8 MeV	Chooz, France	2011–
KamLAND	Kamioka Liquid Scintillator Antineutrino Detector	ν_e	$\sim\nu_e + p \rightarrow e^+ + n$	Gd-doped LAB (LOS)	1.8 MeV	Kamioka, Japan	2002–
RENO	Reactor Experiment for Neutrino Oscillation	ν_e	$\sim\nu_e + p \rightarrow e^+ + n$	Gd-doped LAB (LOS)	1.8 MeV	South Korea	2011–

Small Reactor experiments

	Name	W (MW), fuel	H (mwe)	L (m)	Type	Days On-Off	Coun t/day	signa l/bkg
1	Nucifer	70		7	Gd-LOS	145-106	280	0.25
2	NEOS	3000, LEU	~8	24	Gd-LOS	180-30	2000	2.3
3	STEREO	58, 235U	~15	10	Gd-LOS			
4	Neutrino-4	90	~10	6-11	Gd-LOS			
5	iDREAM	3000, LEU			Gd-LOS			
6	PANDA	3420, LEU		35.9	Plastic	30-34	~22	
7	DANSS	3000, LEU	~50	11	Gd+plastic		8000	
8	Vidarr	1600		60	Gd+plastic	210-5	0.2	
9	mTC	20		5	B-PS			
10	NuLAT	20, 235U		4.7	6Li-plastic			
11	PROSPECT	85, 235U		~7-12	6Li-plastic			
12	SOLiD	72, 235U	~10	5.7	6LiZnS-plastic			
13	CHANDLER	72, 235U	~10	5.4	6LiZnS-plastic			

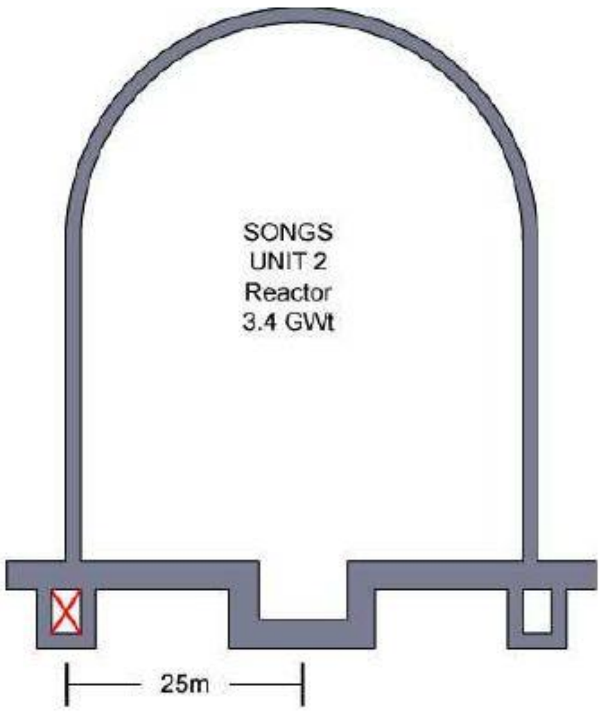
One of the first m^3 neutrino detector (RONS) worked 25 years ago at Rovno NPP - RONS (1986-1990)





Liquid scintillator (~1 m^3)
in special laboratory

SONGS =Near detector – 25 m Lawrence Livermore National Laboratory at SanOnofre NPP.



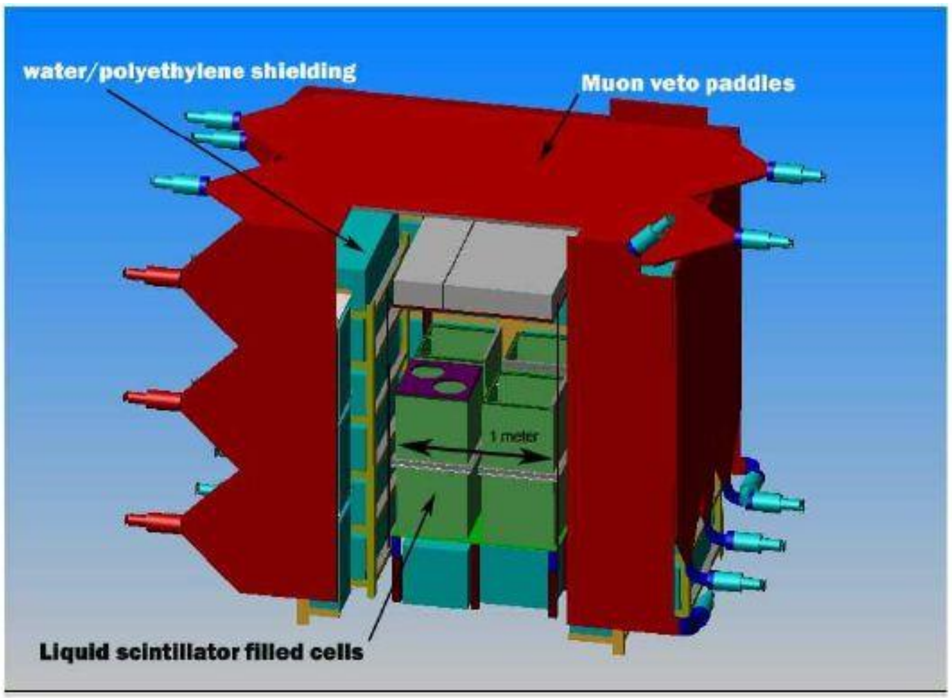


Figure 1. The SONGS detector (right) located in the tendon gallery (left)

Demonstration of sensitivity – fuel reload

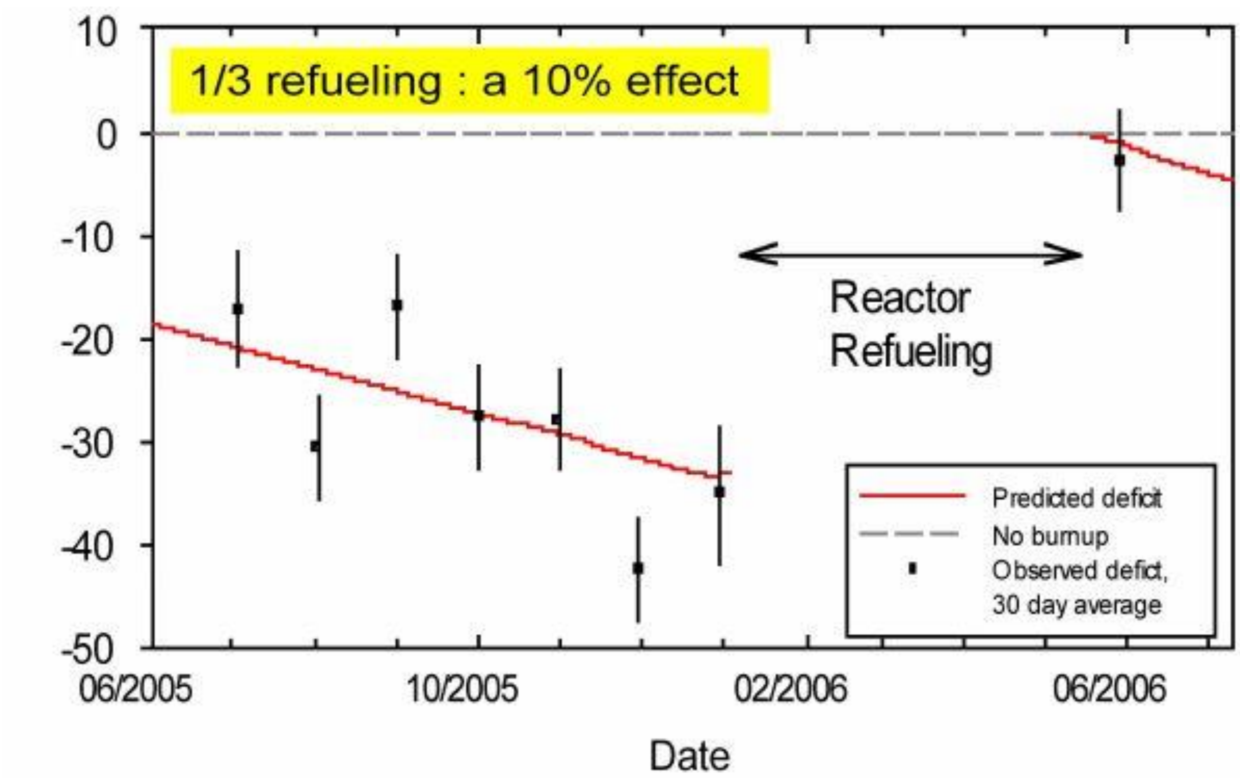


Figure 2. The impact of the refueling is clearly seen on the antineutrino record

France project NUCIFER – compact detector for IAEA (3m x 3m x2.5 m)

- Cylinder from stainless steel: height=1.7 m, diameter=1.2 м, filled with 0.85 m^3 scintillator (Gd-enriched).
- 16 PMT from top thought 25 cm acryl window (calibrated by laser LED signal)

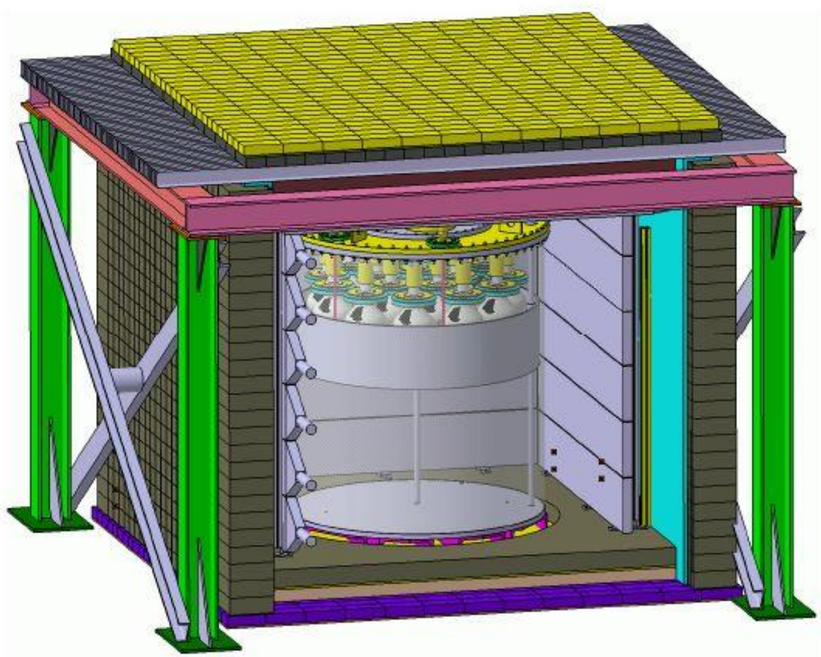


Figure 1. The Nucifer detector.

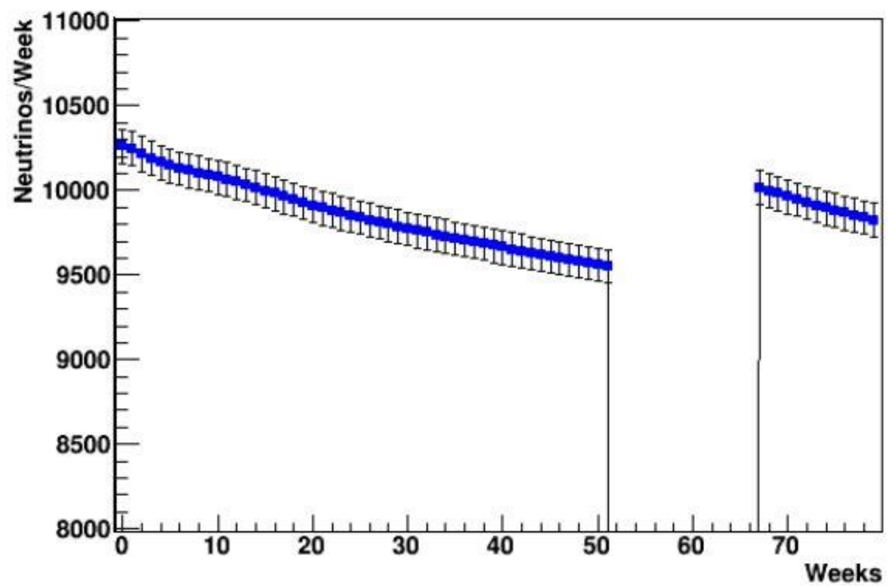


Figure 2. Weekly neutrino rate detected during one cycle by Nucifer installed 25 m away from a 2.9 GWth PWR.

SNIF
(Secrete Neutrino Interaction Finder)

- Detector in large tanker. Moved in desired (suspicious) regions.
- Target –
- 10^{34} protons

(~100 K tones water or

scintillator)

- $100 M

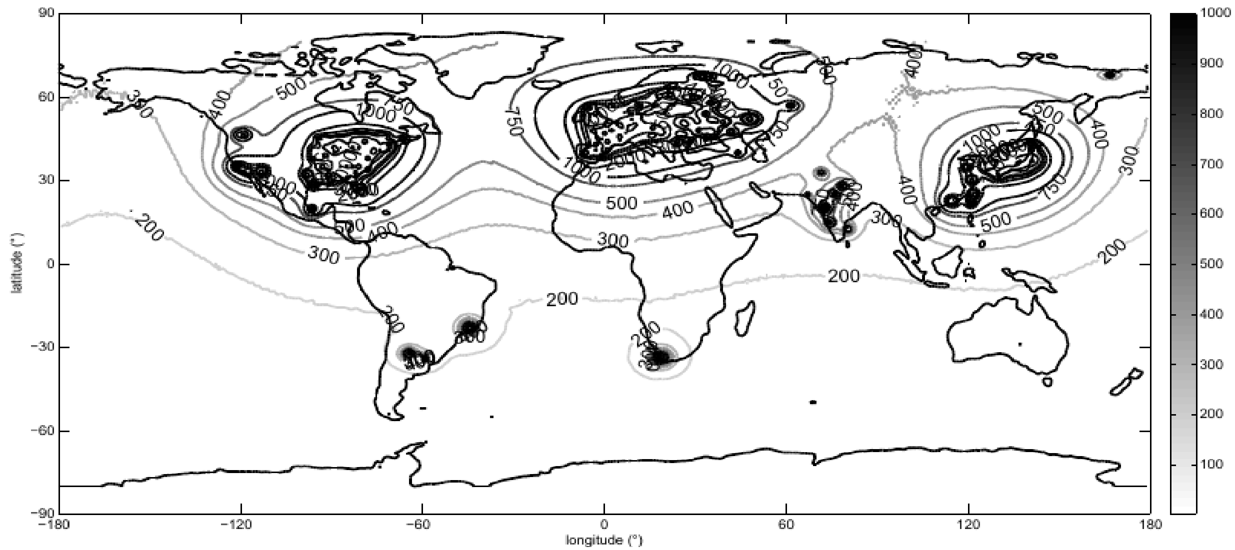
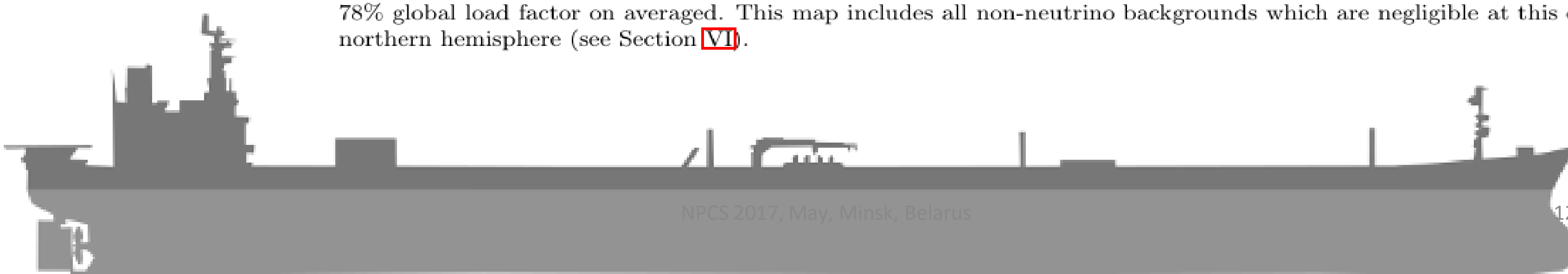


FIG. 2. Maps illustrating the number of neutrino events that would be detected in a 10^{34} free protons detector ($E_{\mathrm{vis}} > 2.6$ MeV, 4,000 m operating depth) after half a year of data taking. 201 nuclear power stations have been included, accounting for a 78% global load factor on averaged. This map includes all non-neutrino backgrounds which are negligible at this depth in the northern hemisphere (see Section VI).



Typical reactor building with **WWER-1000**

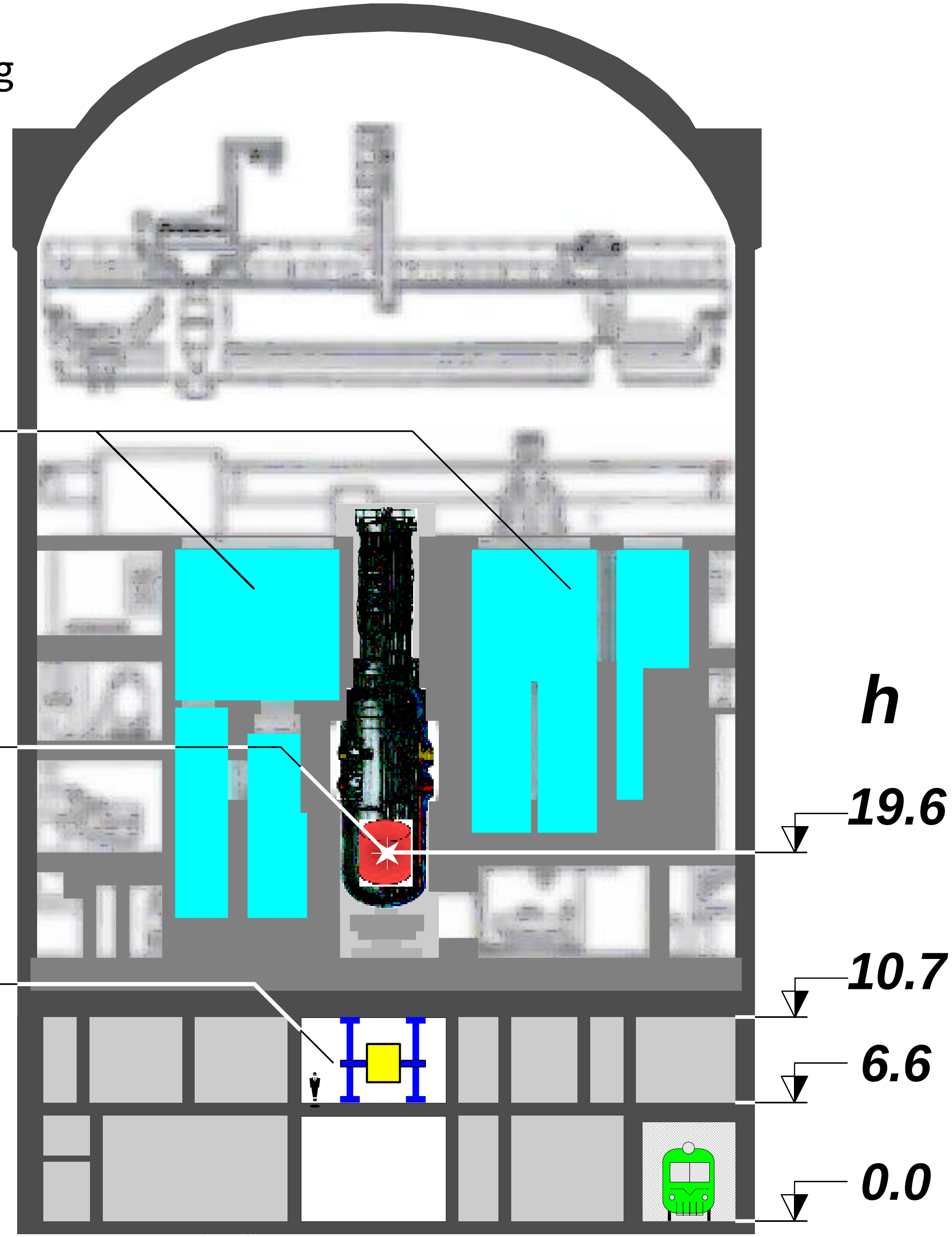
Reservoirs with technological liquids (cooling pond, boric acid, etc.)

Core:
h =3.50 ∅ = 3.12

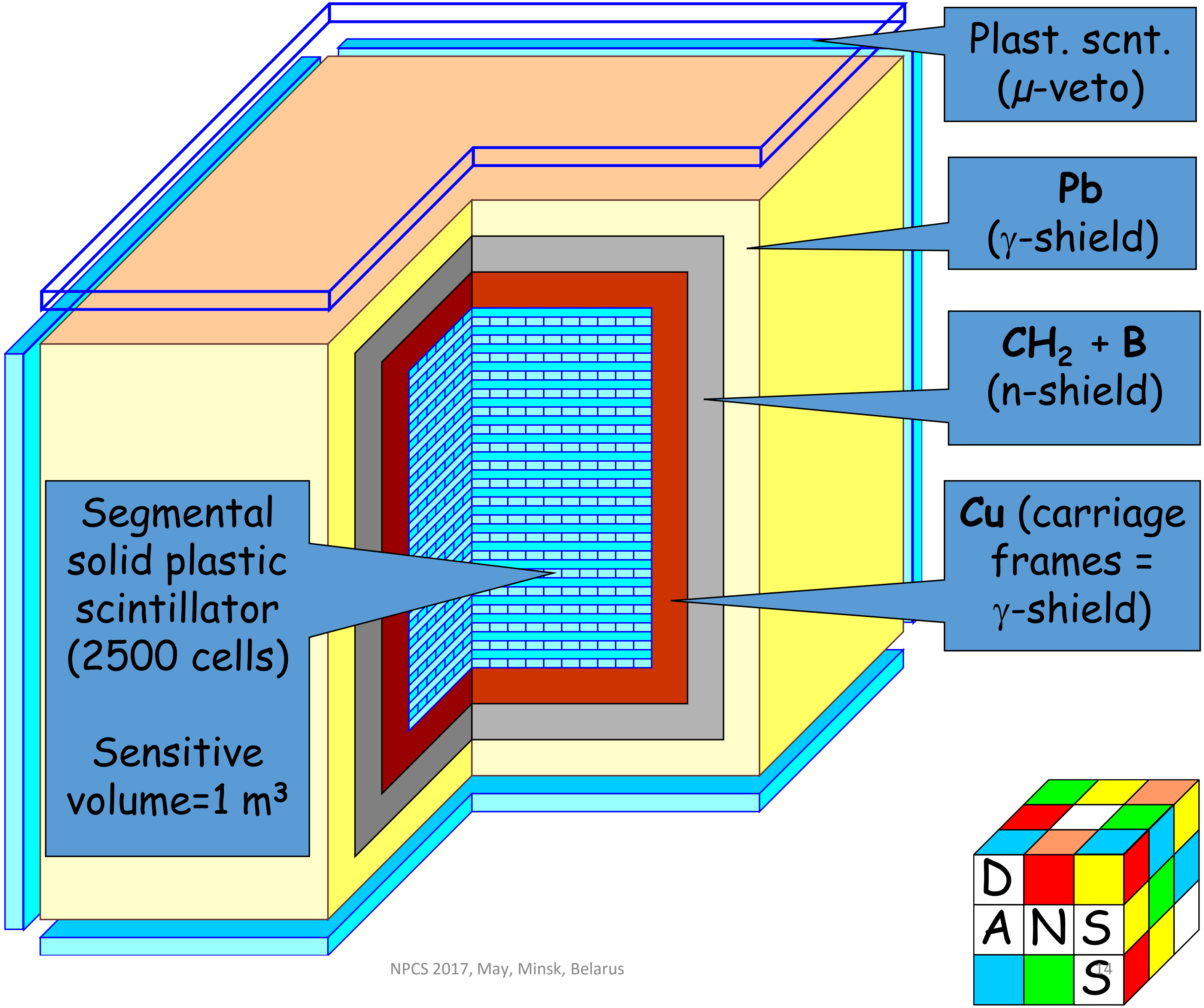
DANSS on a movable platform with a lifting gear.

ν flux ≈ 5 × 10^{13} ν / cm^2 / s

Overburden ≈ 50 m w. e.

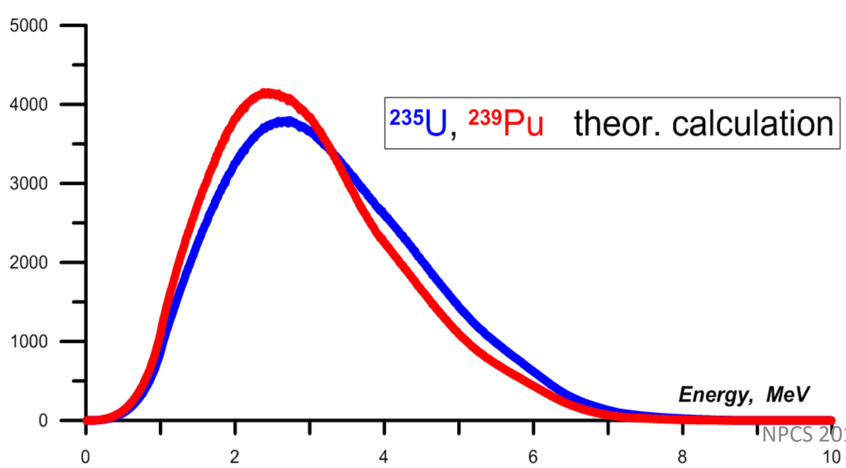


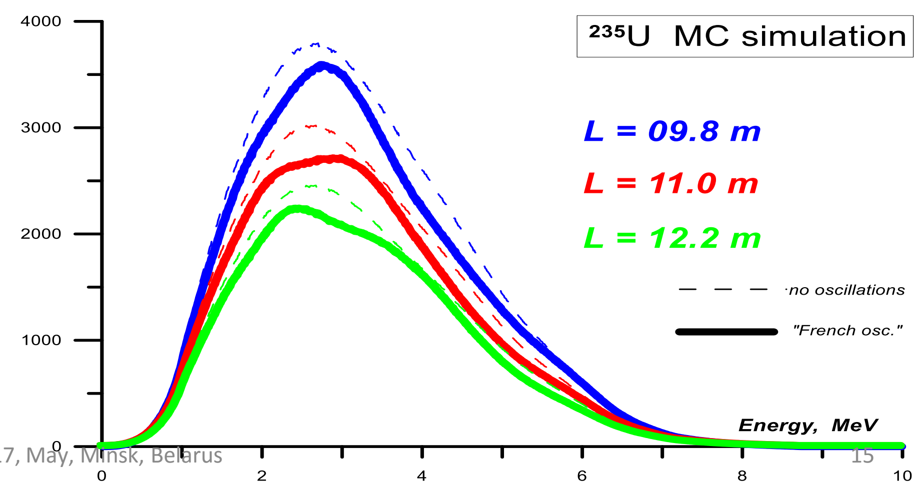
Forbidden to use dangerous materials (LS) nearby the reactor


Plast. scnt. (μ-veto)
Pb (γ-shield)
CH2 + B (n-shield)
Cu (carriage frames = γ-shield)
Segmental solid plastic scintillator (2500 cells)
Sensitive volume=1 m³
D A N S S

Expected parameters:

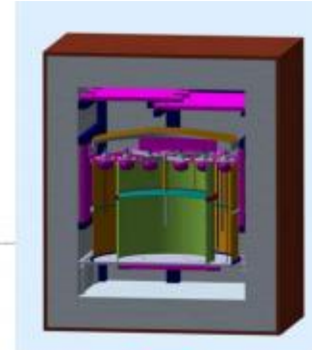
- Sensitive volume : 1 m^3 =100×100×100 cm
- Scintillator: Polystyrene based (~7.7 $\%_{wt}$ of H)
- Structure: (25 X + 25 Y) intercrossing modules =2500 strips
  1 module 20×20×100 cm = 50 parallel strips
- Mass with (CHB+Cu+Pb)-shield: 16-18 tonnes
- Site: reactor unit#4 of Kalinin NPP (standard industrial WWER-1000, Ø3.12 x h3.50 m, 3000 MW_{th})
- Reactor–Detector distance : **9.8–12.2 m** *(variable on-line)*
- Count rate: (**10 000 IBD** + **50 BG**) /day @11 m
- Energy resolution @ Eν =4 MeV: 25% (FWHM)



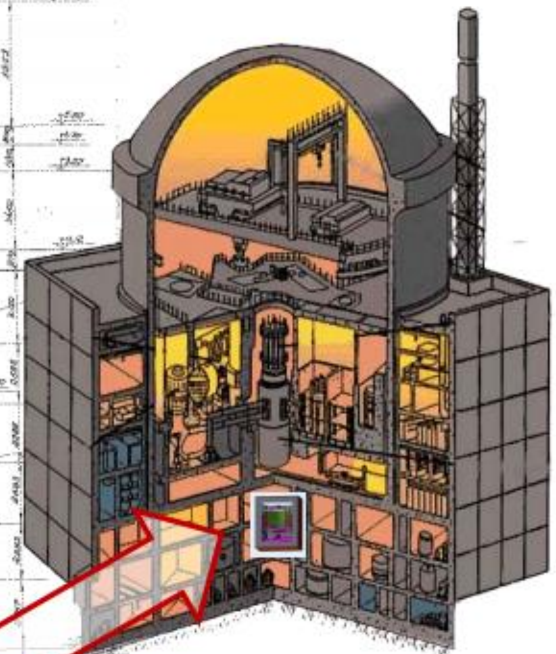


iDREAM roadmap

~ 0 m Kurchatov Institute
Test Laboratory
Physical startup
2014



~ -30 m SINP MSU
Underground Lab
Background tests
2015



WWR-1000 NPP

Demonstration
experiment
(2015-2016)

WHERE ??

iDream

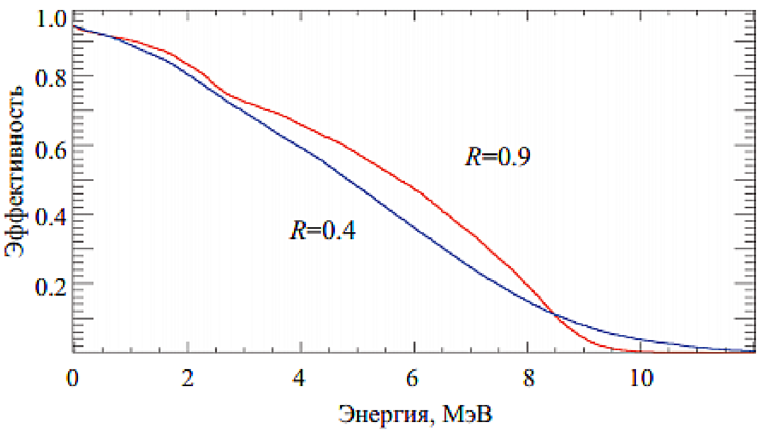


Рис. 4. Зависимость эффективности регистрации детектором как целым нейтронов реакции обратного бета-распада в потоке реакторных антинейтрино

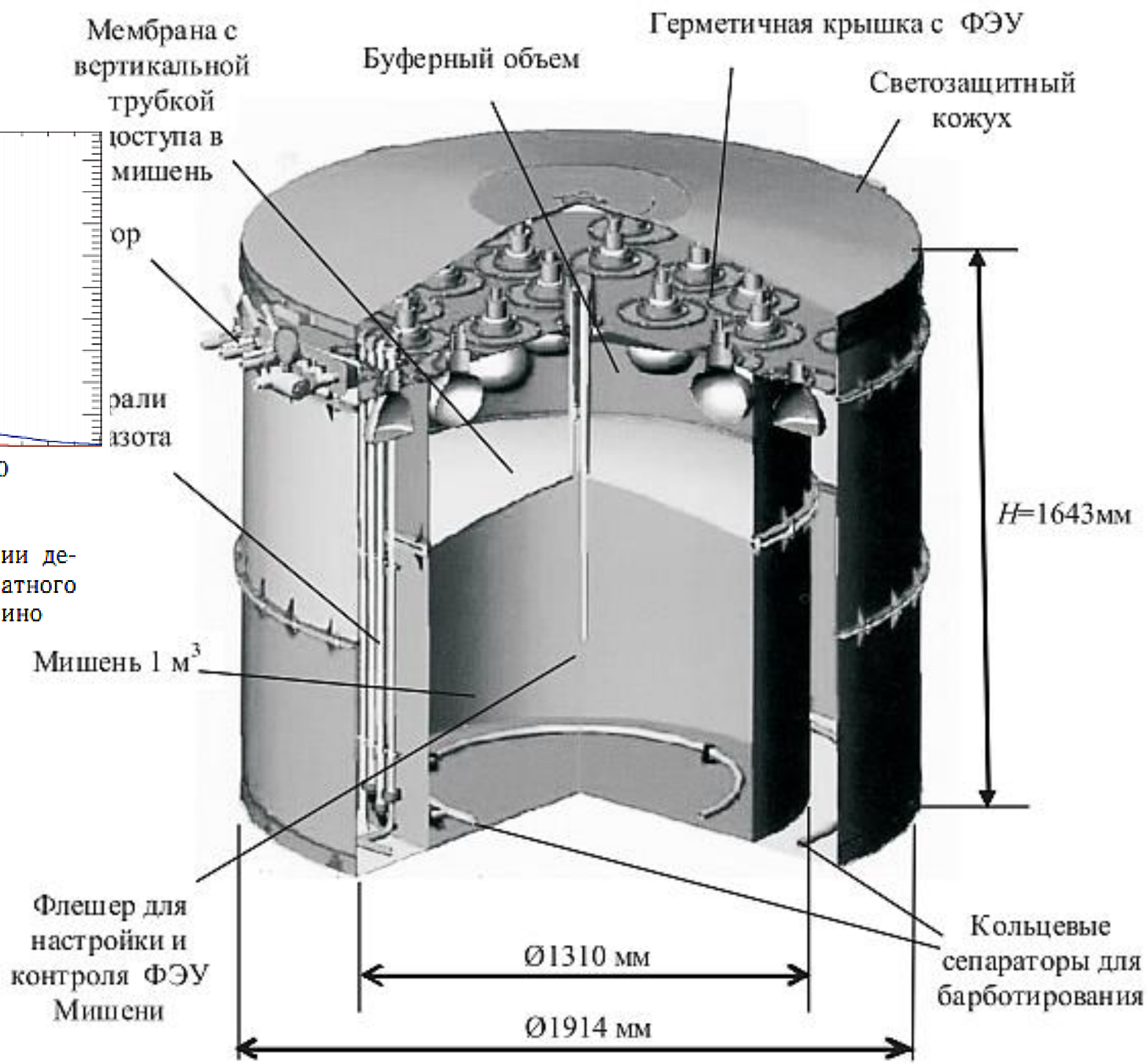


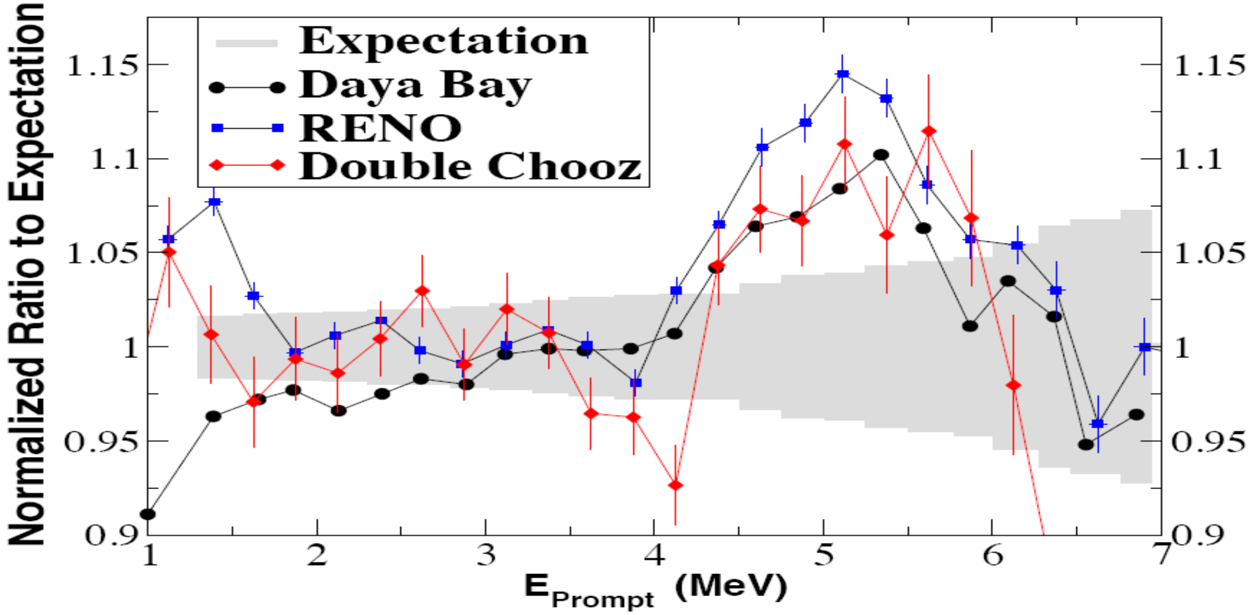
Рис. 1. Конструкция детектора iDREAM

Directions of investigations

- A – Production and spectra of reactor antineutrinos.
- B – How spectra connected with fuel composition (U/Pu ratio).
- C – Description of neutrino field (Dirac-Majorana-Weyl-Pauli and their interconnection), possible types of interactions and links between oscillation and description. Mass matrix and different parameterization of mixing matrix.
- D – Models beyond SM including massive neutrino and proposed variants of explanation for mass splitting of leptons.

Discrepancies of experimental data and theoretical predictions

All three recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations –the 'Bump'

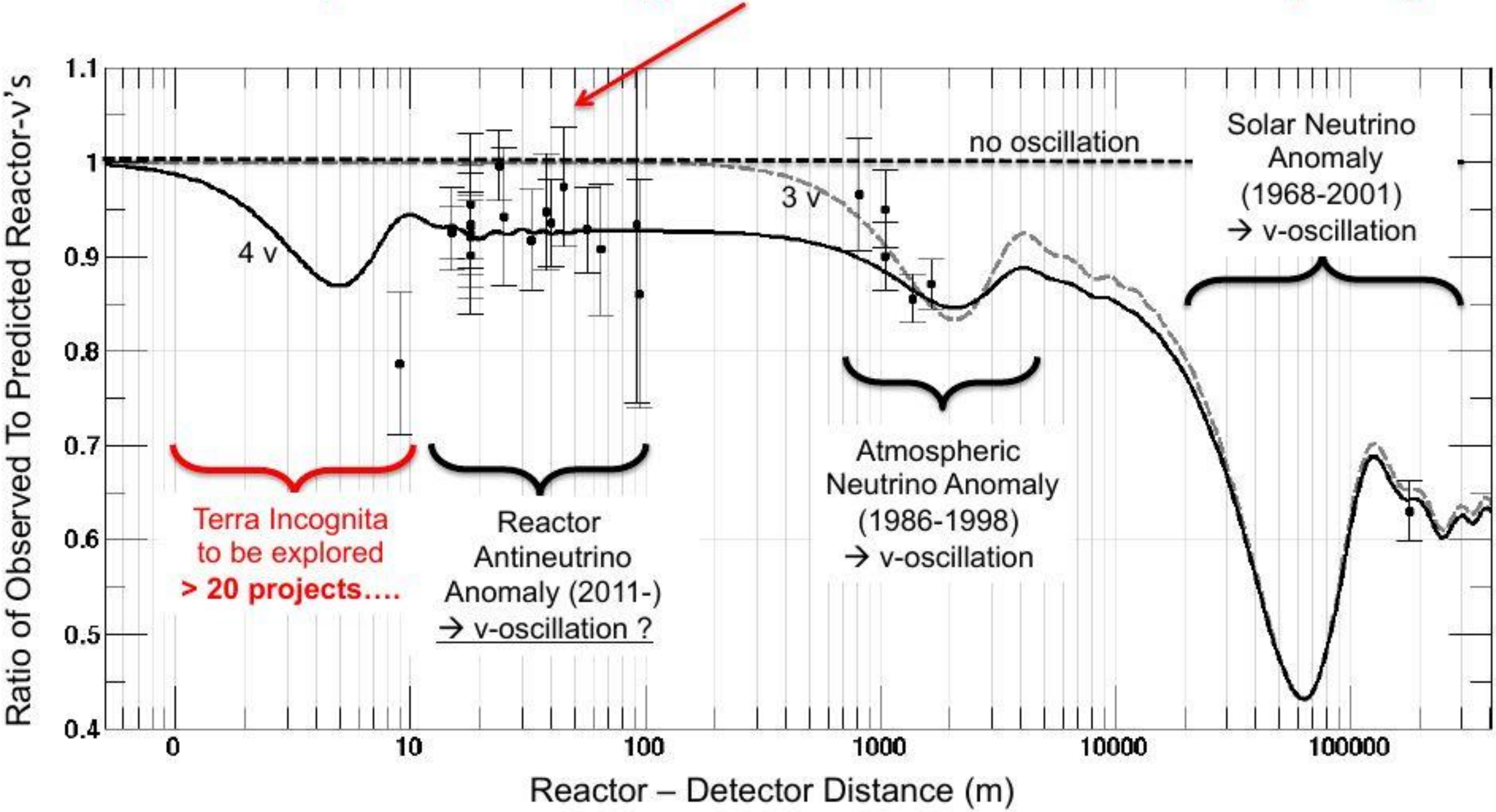


- **The current expectations are Huber (^{235}U,^{239,241}Pu) and Mueller (^{238}U)**
- **RENO observed the largest bump**
- **Double-Chooz used Huber and Haag (^{238}U) for expected flux**

P. Huber, Phys. Rev. C 84, 024617 (2011); Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011); N. Haag, Phys. Rev. Lett. 112, 122501 (2014).

Reactor antineutrino anomaly

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



Beta-decay according to Fermi

- In analogy with electrodynamics the decay probability may be described by ordinary formula

$$dP_{if} = \frac{G_F^2}{2\pi^3}|M_{if}^N|^2 p_\nu^2 dp_\nu p_e^2 dp_e,$$

- If decay is allowed we have only phase factor

$$\frac{dP_{if}}{dE_\nu} = \frac{G_F^2}{2\pi^3}|M_{if}^N|^2 E_\nu^2 (Q_\beta - E_\nu)\sqrt{(Q_\beta - E_\nu)^2 - m_e^2},$$

- For electrons we have to take into account interaction with nuclear field (Fermi count atom as Hydrogenous-like)

$$\frac{dP_{if}}{dE_e} = K \times F(Z, E_e)(Q_\beta - E_e)^2 E_e \sqrt{E_e^2 - m_e^2},$$

$$\frac{dP_{if}}{dp_e} = K \times F(Z, E_e)(Q_\beta - E_e)^2 p_e^2,$$

$$K = \frac{G_F^2}{2\pi^3}|M_{if}^N|^2.$$

- Where F(Z, Ee) is Fermi function

Fermi function

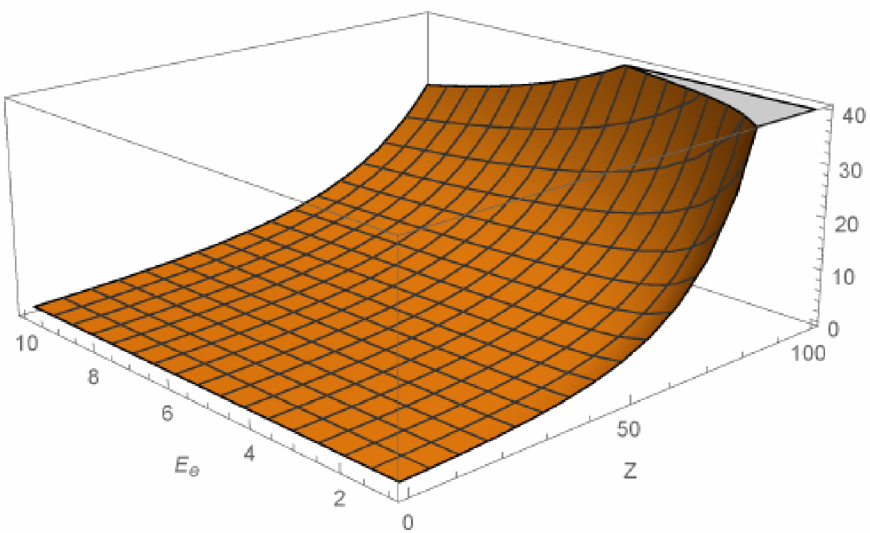
- Has analytical and several approximations

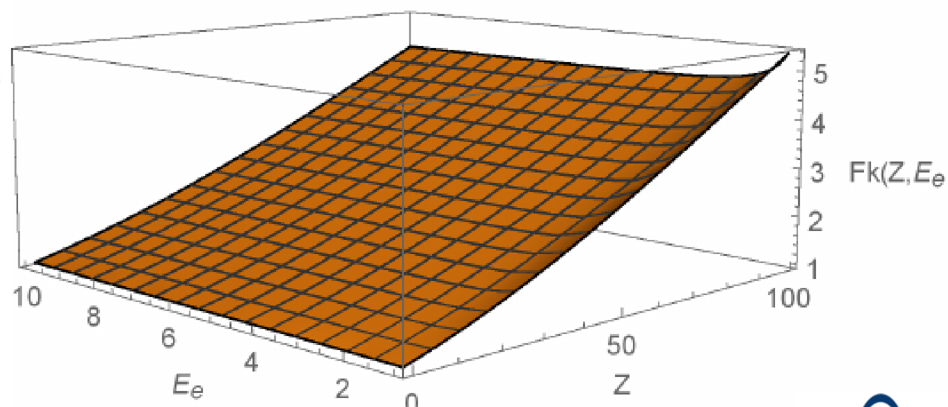
$$F(Z,E_e) = 2(1+d)(2p_eR)^{2(d-1)} e^{\pi\lambda} \frac{|\Gamma(d+i\lambda)|^2}{|\Gamma(2d+1)|^2},$$

- Nonrelativistic (Curie) and Bethe

$$F_K(Z,E_e) = \frac{2\pi\lambda}{1-e^{-2\pi\lambda}}, \quad F_B(Z,E_e) = F_K(Z,E_e)p_e^{2d-2}(\lambda^2+1/4)^{d-1}$$

- Graphics





I. Summation method – Vogel, Mueller

- Vogel et al – directly uses strange formulas

$$N(E_{\bar{\nu}}) = \sum_n Y_n(Z, A, t) \sum_i b_{n,i}(E_0^i) P(E_{\bar{\nu}}, E_0^i, Z).$$

$$P(E_{\bar{\nu}}, E_0^i, Z) = k E_{\bar{\nu}}^2 (E_0 - E_{\bar{\nu}})^2 G(E_0 - E_{\bar{\nu},Z}), \quad G(E_\beta - E_{\bar{\nu},Z}) = P_\beta / E_\beta F(E_\beta, Z$$

- A Mueller et al – more accurately write down the procedure

$$S_{\mathrm{tot}}(E) = \sum_{k={}^{235}\mathrm{U},{}^{238}\mathrm{U},{}^{239}\mathrm{Pu},{}^{241}\mathrm{Pu}} \alpha_k S_k(E), \quad S_k(E) = \sum_{f=1}^{N_f} \mathcal{A}_f(t) S_f(E),$$

$$S_f(E) = \sum_{b=1}^{N_b} \mathrm{BR}_f^b \; S_f^b(Z_f, A_f, E_{0f}^b, E),$$

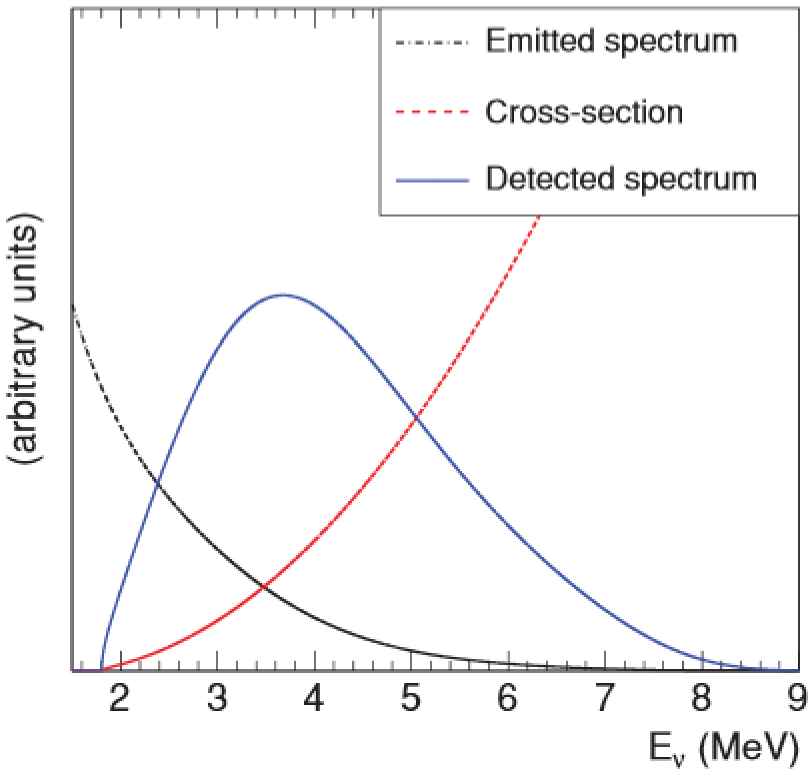
$$S_f^b = \underbrace{K_f^b}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_f, A_f, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E_{0f}^b)^2}_{\text{Phase space}} \times \underbrace{C_f^b(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta_f^b(Z_f, A_f, E)\right)}_{\text{Correction}}.$$

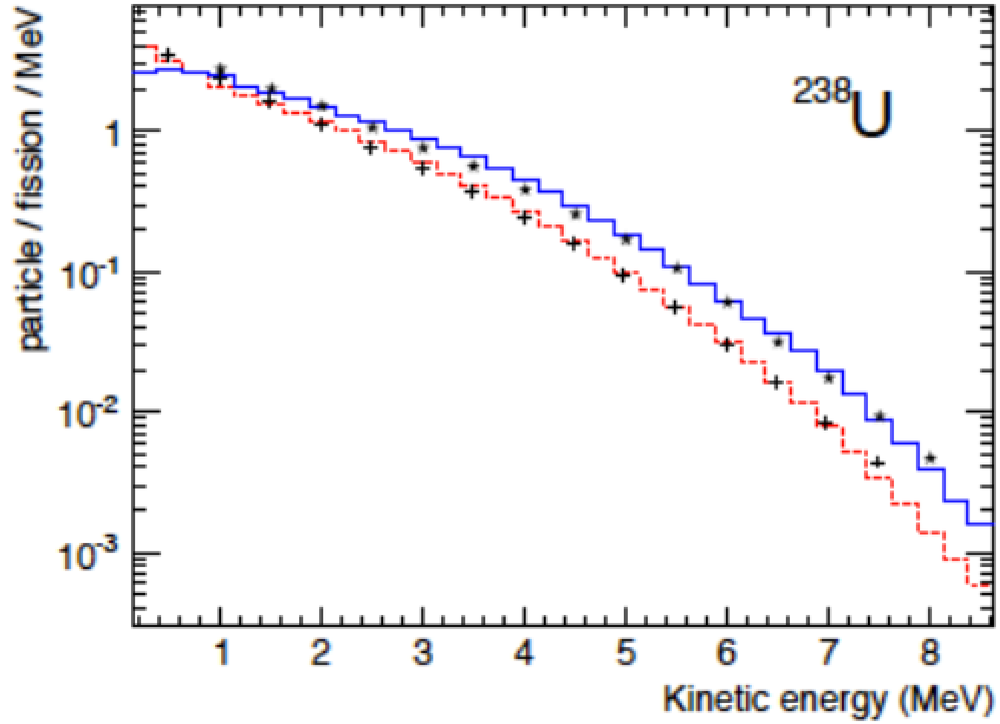
$$\delta_f^b(Z_f, A_f, E) = \delta_{\mathrm{QED}}(E) + A_C(Z_f, A_f) E + A_W E.$$

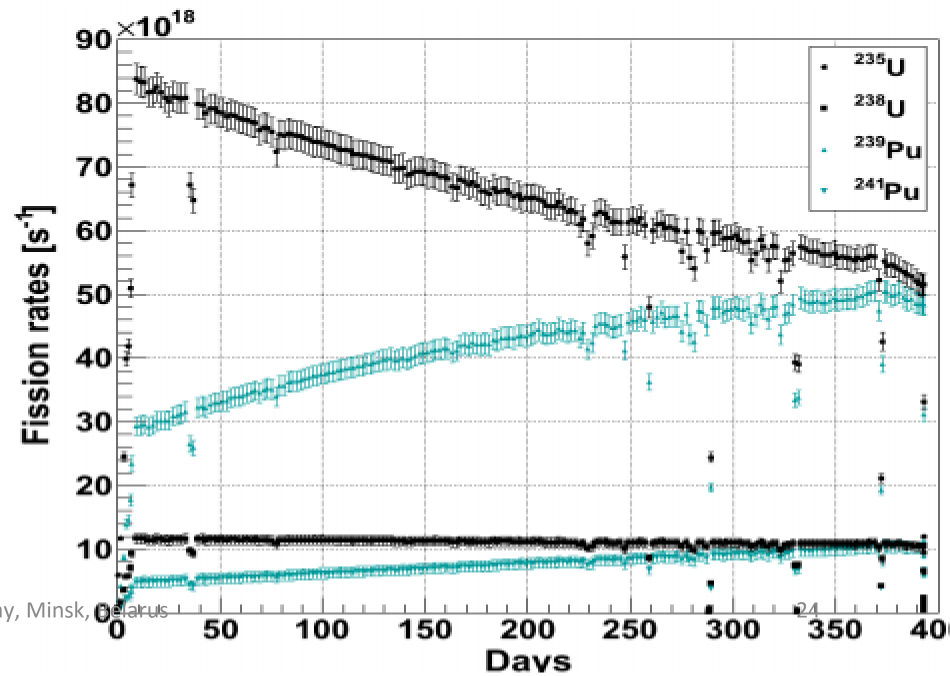
Calculation results

- Spectrum without maximum !

TH. A. MUELLER *et al.*







Our calculations -1

- Individual allowed decay has the form

$$D_\nu(Q_i, E_\nu) = K E_\nu^2 (Q_i - E_\nu)\sqrt{(Q_i - E_\nu)^2 - m_e^2},$$

- Zero generation is 4 fissioning isotops

$$\frac{dN_1}{dt} = Y_{(Z_1,A_1)}^{(Z_0,A_0)} \frac{dN_0}{dt} = Y_{(Z_1,A_1)}^{(Z_0,A_0)} \frac{W_{th}}{Q_0^{fis}} = v_1,$$

- Further decay equations are

$$\frac{dN_1}{dt} = -\lambda_1 N_1 + v_1, \qquad v_1 = const,$$

$$\frac{dN_2}{dt} = -\lambda_2 N_2 + B_2^1 \frac{dN_1}{dt} = -\lambda_2 N_2 + B_2^1 \lambda_1 N_1,$$

$$\dots$$

$$\frac{dN_i}{dt} = -\lambda_i N_i + B_i^{i-1} \frac{dN_{i-1}}{dt} = -\lambda_i N_i + B_i^{i-1} \lambda_{i-1} N_{i-1},$$

$$\dots$$

$$\frac{dN_n}{dt} = B_n^{n-1} \frac{dN_{n-1}}{dt} = B_n^{n-1} \lambda_{n-1} N_{n-1},$$

Our calculations -2

- Up to 5 decays in chain with activities

$$A_1(t) = \kappa_1 \left(1 - e^{-\lambda_1 t}\right),$$

$$A_2(t) = \kappa_2 \left(1 + \frac{\lambda_1}{\lambda_{21}} e^{-\lambda_2 t} - \frac{\lambda_2}{\lambda_{21}} e^{-\lambda_1 t}\right),$$

$$A_3(t) = \kappa_3 \left(1 - \frac{\lambda_1\lambda_2}{\lambda_{32}\lambda_{31}} e^{-\lambda_3 t} + \frac{\lambda_1\lambda_3}{\lambda_{21}\lambda_{32}} e^{-\lambda_2 t} - \frac{\lambda_2\lambda_3}{\lambda_{21}\lambda_{31}} e^{-\lambda_1 t}\right),$$

$$A_4(t) = \kappa_4 \left(1 + \frac{\lambda_1\lambda_2\lambda_3}{\lambda_{41}\lambda_{42}\lambda_{43}} e^{-\lambda_3 t} - \frac{\lambda_1\lambda_2\lambda_4}{\lambda_{43}\lambda_{32}\lambda_{31}} e^{-\lambda_3 t} + \frac{\lambda_1\lambda_3\lambda_4}{\lambda_{42}\lambda_{32}\lambda_{21}} e^{-\lambda_2 t} - \frac{\lambda_2\lambda_3\lambda_4}{\lambda_{41}\lambda_{31}\lambda_{21}} e^{-\lambda_1 t}\right),$$

$$\kappa_1 = v_1, \quad \kappa_2 = B_2^1 v_1, \quad \kappa_3 = B_3^2 B_2^1 v_1, \quad \kappa_4 = B_4^3 B_3^2 B_2^1 v_1, \quad \left(v_1 = Y_{(Z_1,A_1)}^{(Z_0,A_0)} \frac{W_{th}}{Q_0^{fis}}\right).$$

- Spectra and N are calculated according to

$$\frac{dn_0}{dE_{\bar\nu}} = \left(\frac{W_{th}}{Q_0^{fis}}\right) \sum_{(Z_{1i},A_{1i})} Y_{(Z_0,A_0)}^{(Z_{1i},A_{1i})} \left[A_1^{(0)}(t) D_\nu(Q_{1i}, E_\nu) + B_2^1(i) A_2^{(0)}(t) D_\nu(Q_{2i}, E_\nu) + \right.$$

$$\left. + B_3^2(i) B_2^1(i) A_3^{(0)}(t) D_\nu(Q_{3i}, E_\nu) + B_4^3(i) B_3^2(i) B_2^1(i) A_4^{(0)}(t) D_\nu(Q_{4i}, E_\nu)\right]$$

Our calculations -3

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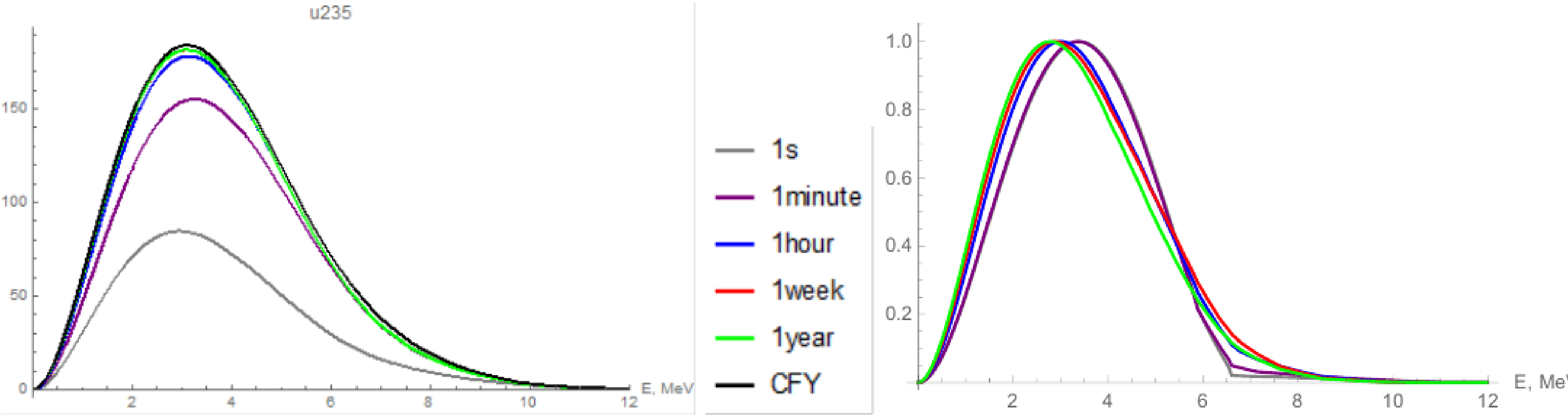
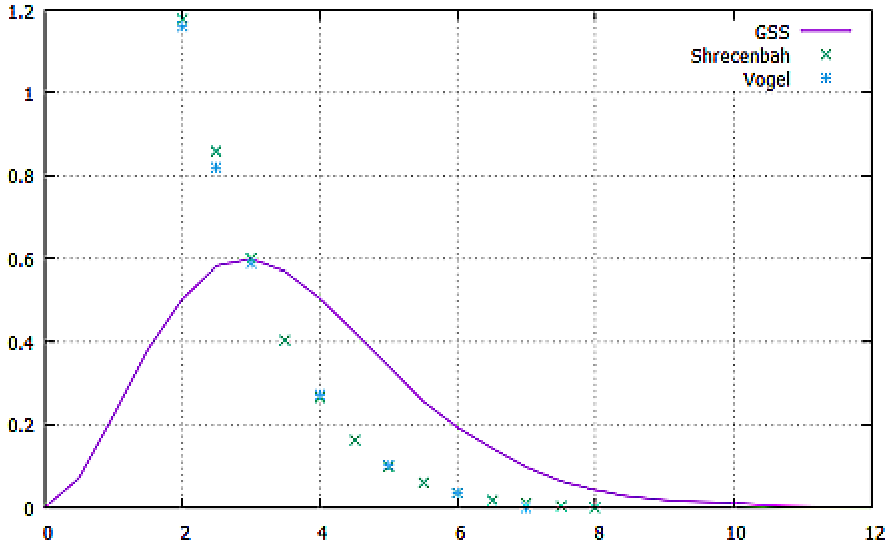
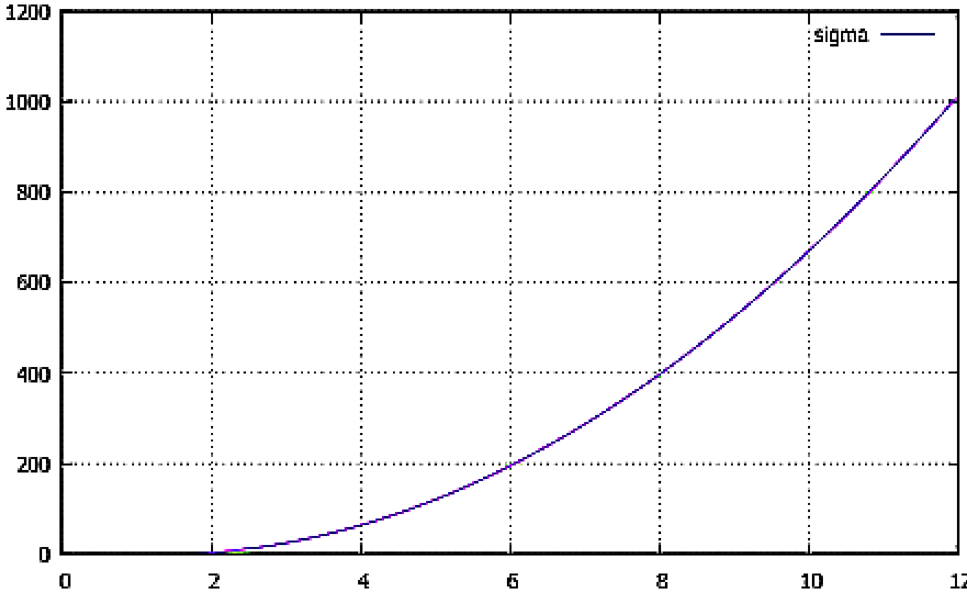


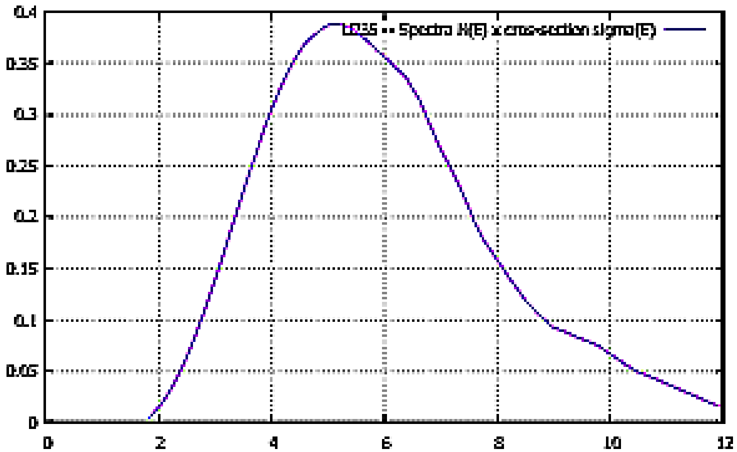
Рис. 2: Спектры антинейтрино при разных временах от начала работы реактора на ^{235}U Справа нормализованные графики для смещения максимума

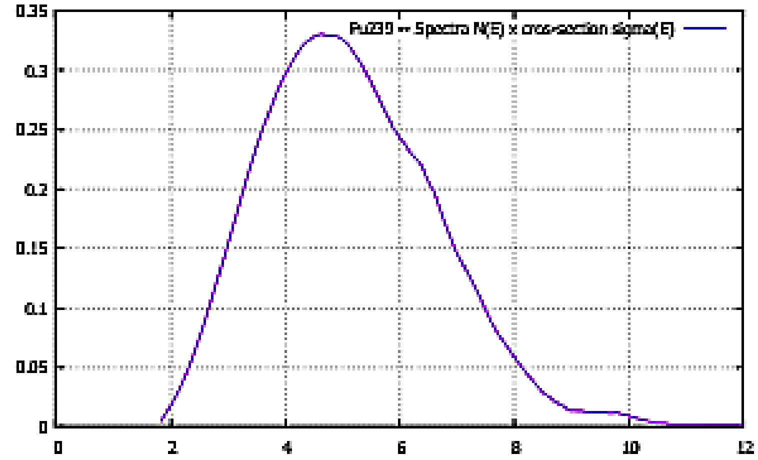
Our calculations -4

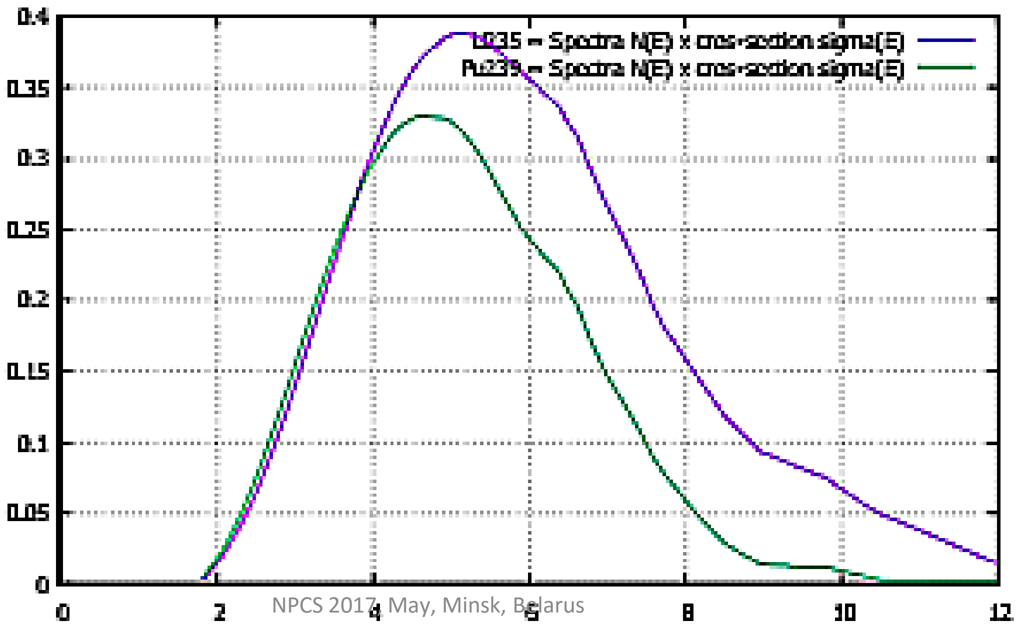




Our calculations -5







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Thank for Your attention