# *Program of fundamental interactions research with neutrons and neutinos at reactor PIK*

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**ISINN-23 Dubna, Russia, May 25 – 29, 2015**

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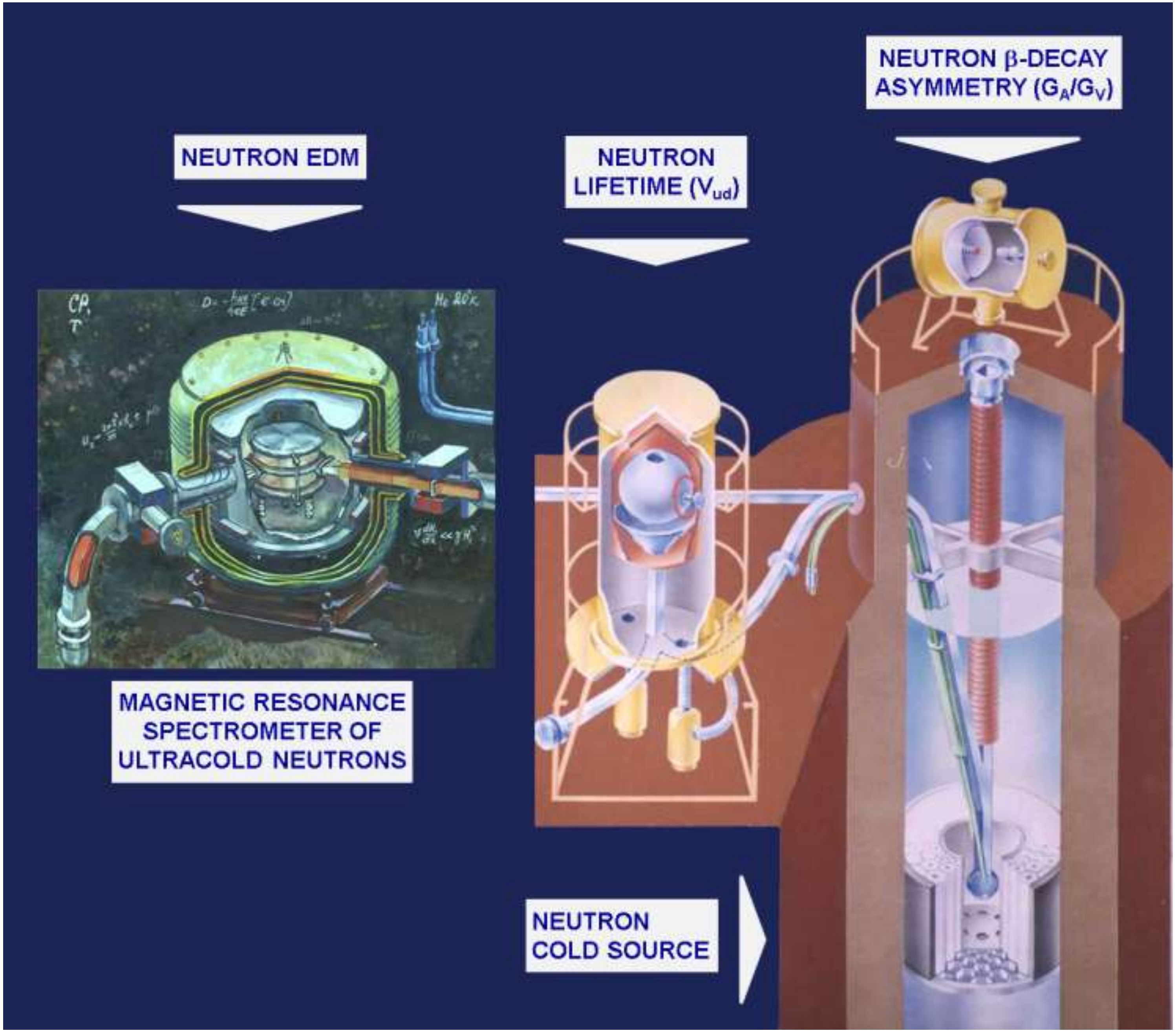
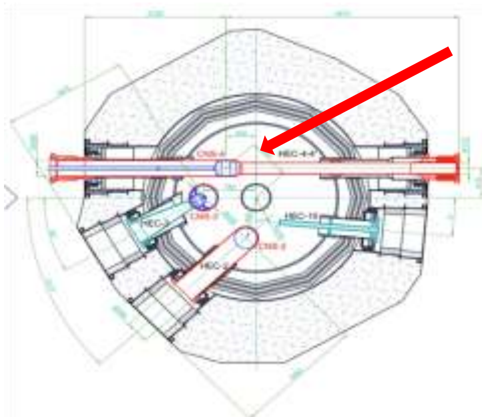
*Preparation for fundamental interactions research at PIK reactor was started at WWR-M reactor*

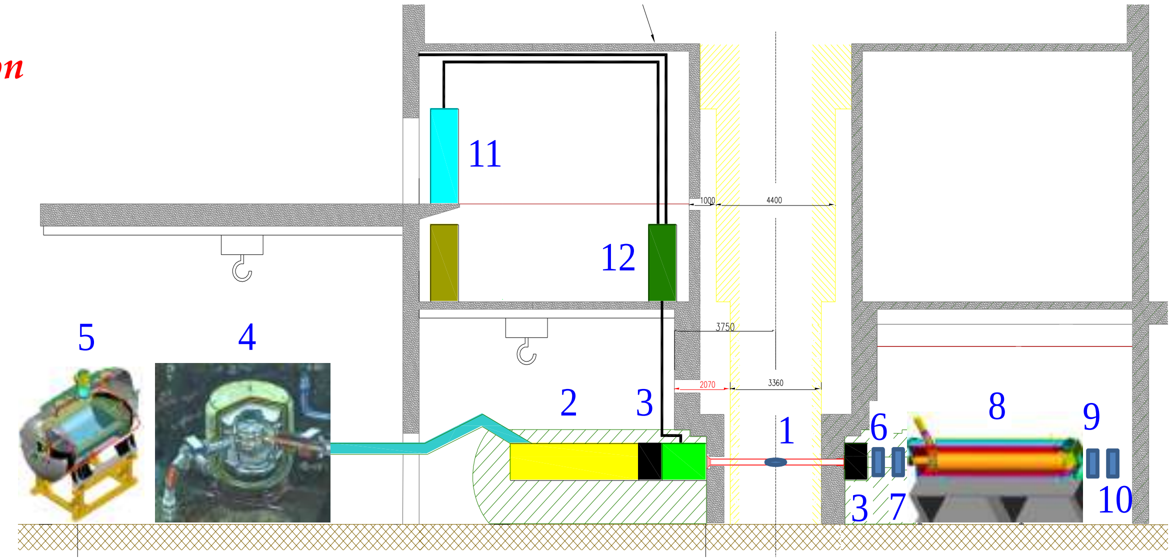


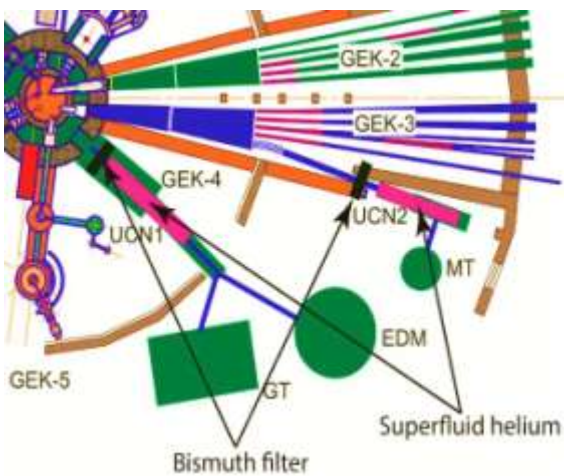
## *The general scheme of a complex of experimental installations for carrying out research of fundamental interactions at GEK 4-4′ channel*



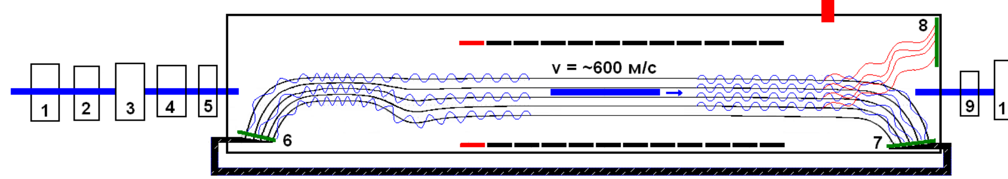
*Cold Neutron Source*

*UCN complex*

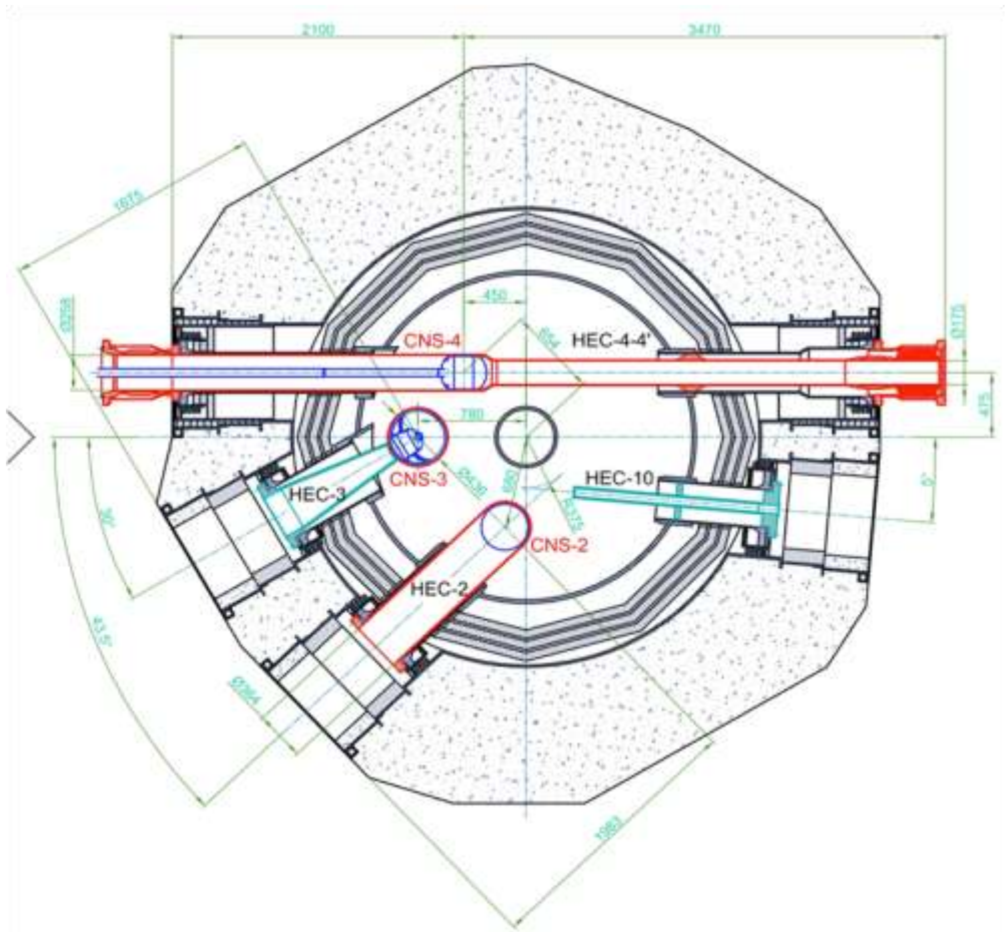


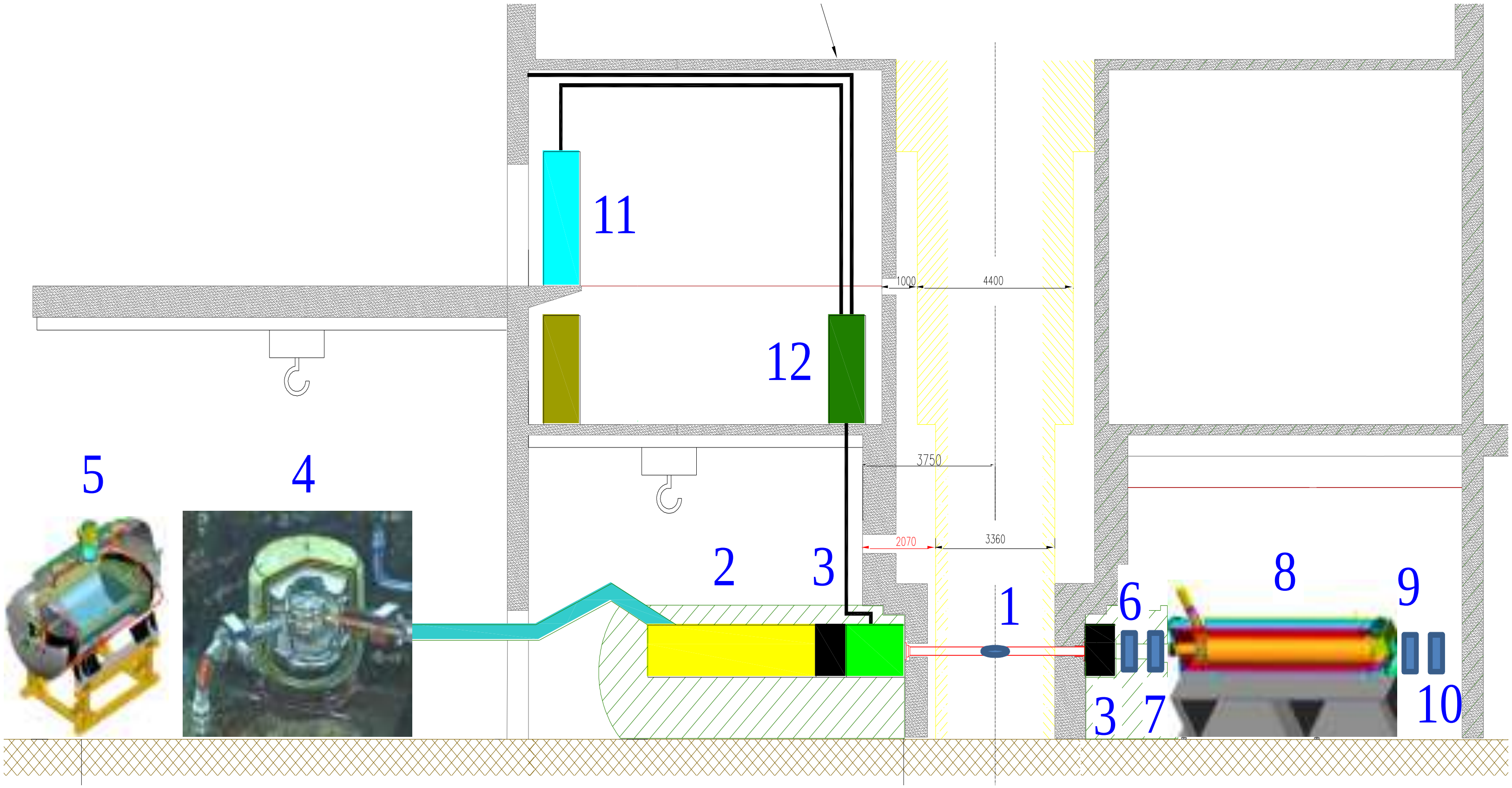

*Beam of polarized cold neutrons*



## Scheme of placement of horizontal channels of PIK reactor. In the channel GEK-4-4' the source of cold neutrons is located.



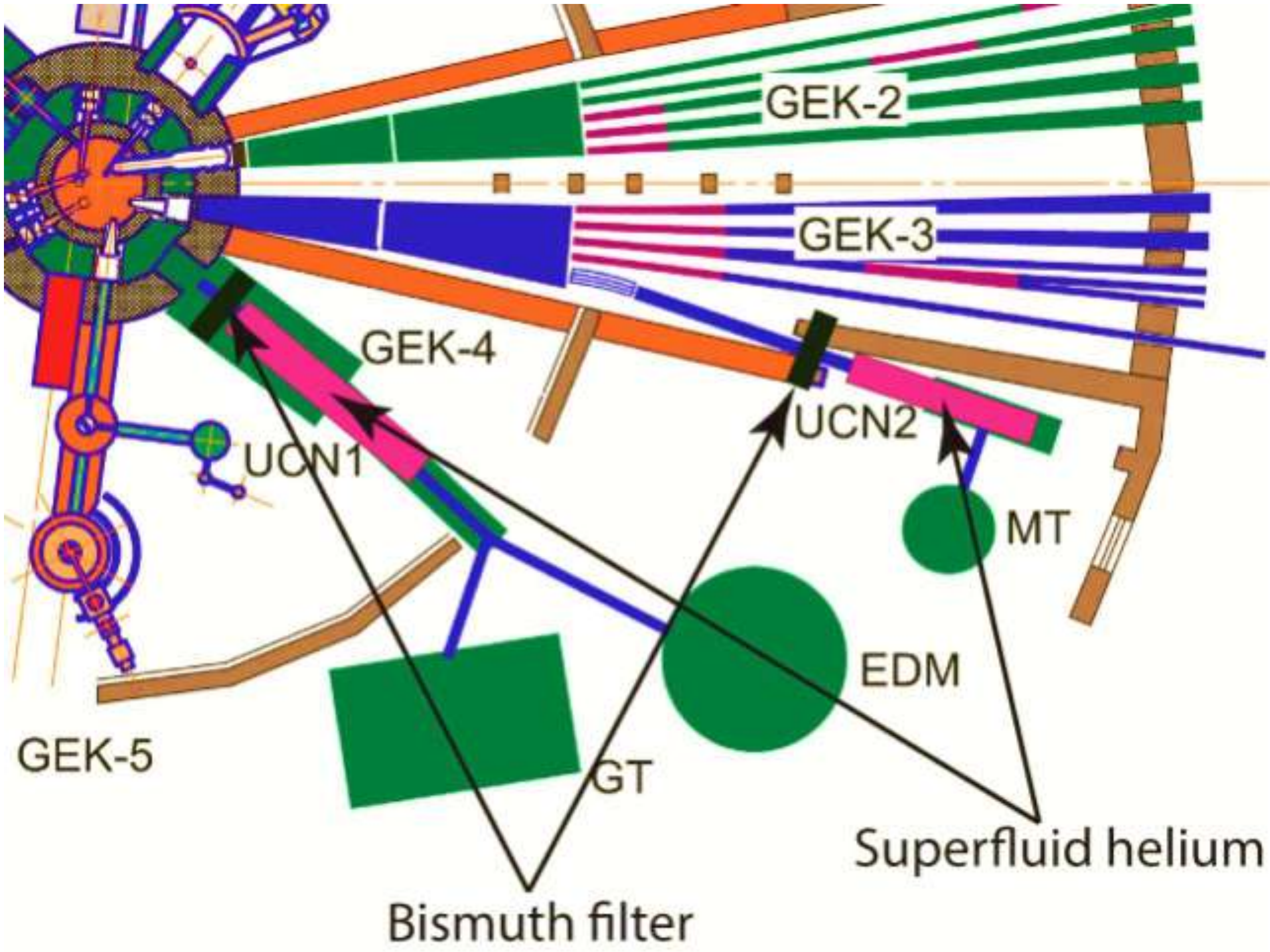
# *The general scheme of a complex of experimental installations for carrying out research of fundamental interactions at PIK reactor*




A vertical outlay of the channel GEK-4-4'**:** 1 – a source of cold neutrons, 2 – UCN source on superfluid He is located on the output beam of cold neutrons, 3 – uncooling bismuth filters comprising valve devices of channels, 4 – EDM spectrometer, 5 – a gravitational trap for measuring a neutron lifetime, 6 – a chopper of cold neutrons beam, 7 – a polarizer of neutron beam on polarized $^3$He, 8 – an installation for measuring asymmetry of a neutron decay with a superconducting solenoid, 9 – a polarization analyzer, 10 – a detector, 11 – He refrigeration unit for a cold neutron source, 12 – a liquid deuterium capacitor for a cold neutron source.

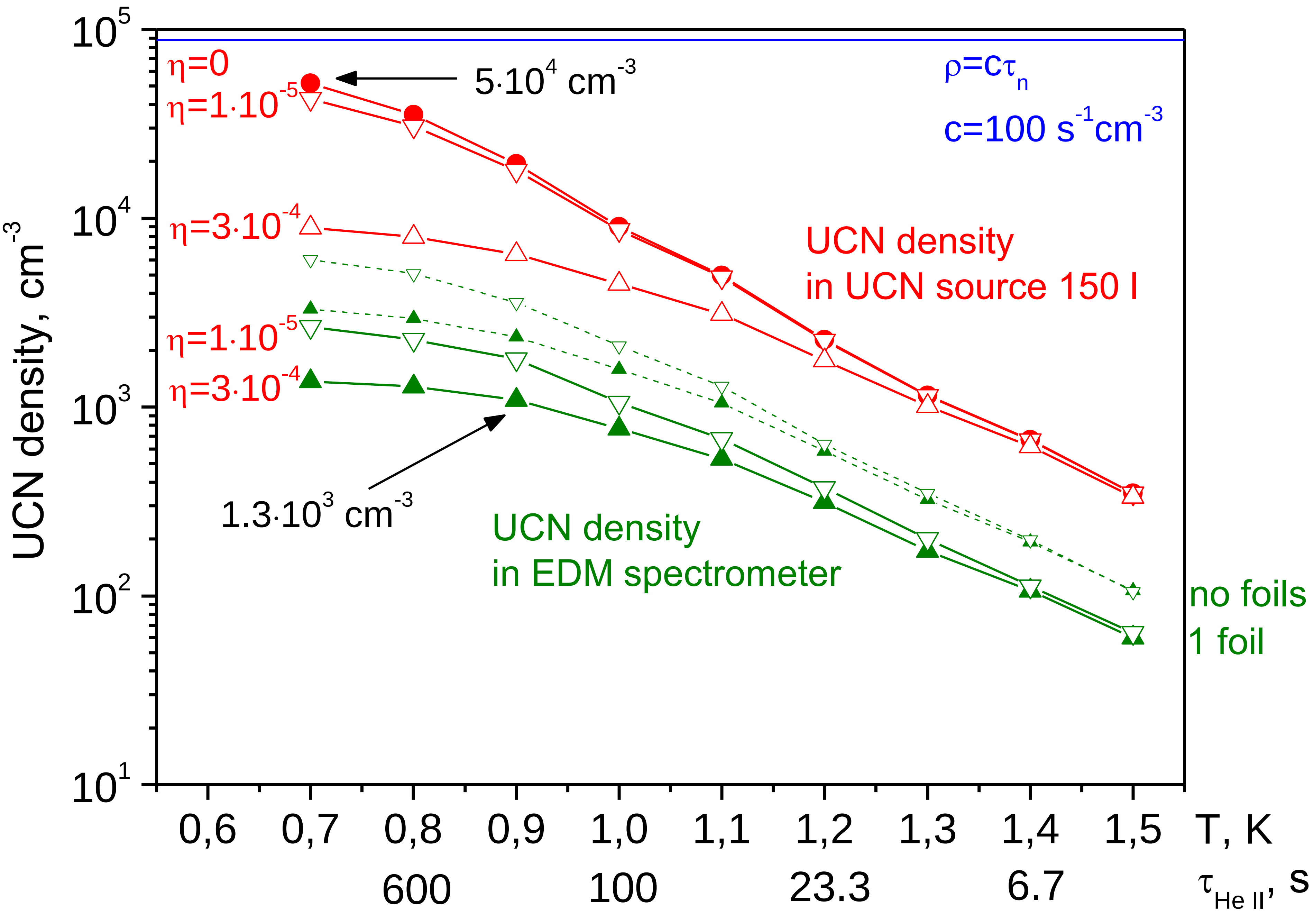
## *UCN complex*

## *The general scheme of a complex of experimental installations for carrying out research of fundamental interactions with UCN at PIK reactor*

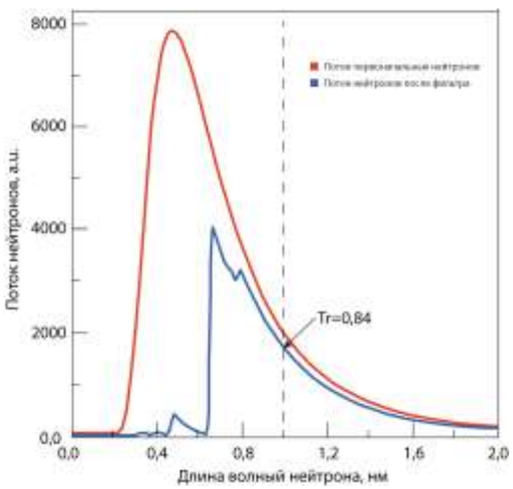


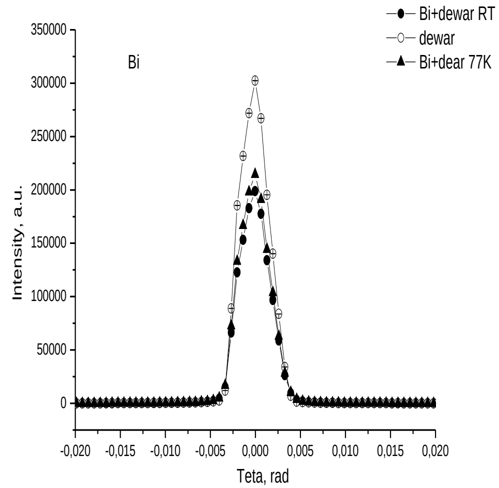

A layout of UCN source with superfluid He and experimental installations on channels GEK-3 and GEK-4 of the reactor PIC: UCN1 – UCN source on channel GEK-4, UCN2 – UCN source on channel GEK-3, EDM – installation for measuring a neutron EDM, GT – installation for measuring a neutron lifetime with UCN gravitational trap, MT – an installation for measuring a neutron lifetime with UCN magnetic trap.

# MC calculation of UCN density in UCN source and EDM spectrometer



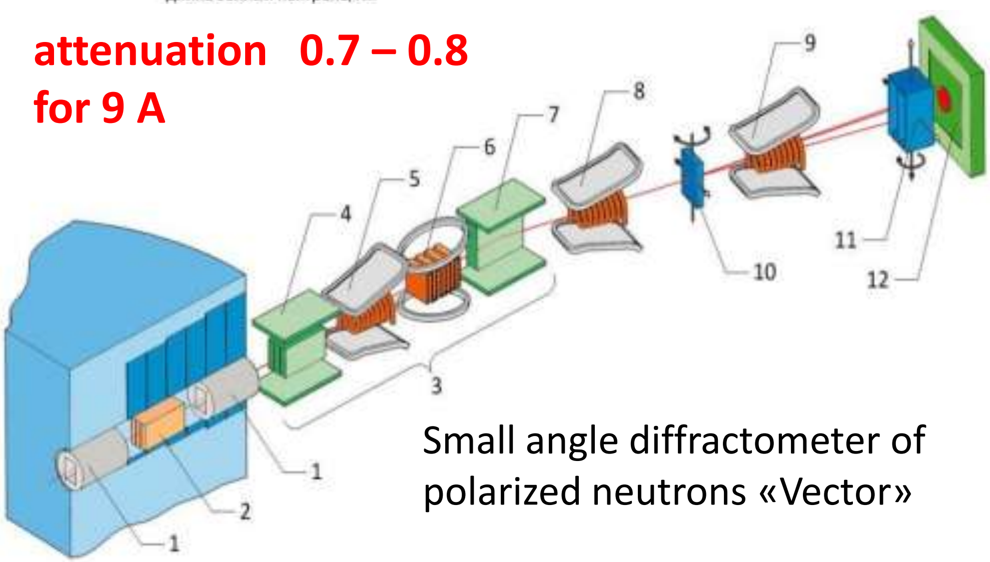
# *Use of the polycrystalline bismuthic filter for UCN source with superfluid helium*




**No small angle scattering**

**attenuation 0.7 – 0.8**
**for 9 A**




Small angle diffractometer of polarized neutrons «Vector»

**Heat load in UCN source with filter and without filter ( )**

| | | Chamber | He |
|---|---|---|---|
| m, g | | 8730 | 22040 |
| ΔE, W | n + γ | **0.14 (3.6)** | **0.26 (11.3)** |
| | β | **0.12 (0.95)** | - |
| Sum, W | | **0.26 (4.55)** | **0.26 (11.3)** |
| Total, W | | **0.52** (15.85) attenuation 30 times | |

Bi filter 10 cm:
- factor of 9 Å neutrons flux reduction is 0.7-0.8,
- factor of heat load suppression is 30.

# *Cryogenic complex at WWR-M reactor*

Hall of the cryogenic equipment


Helium refrigerator and liquefier

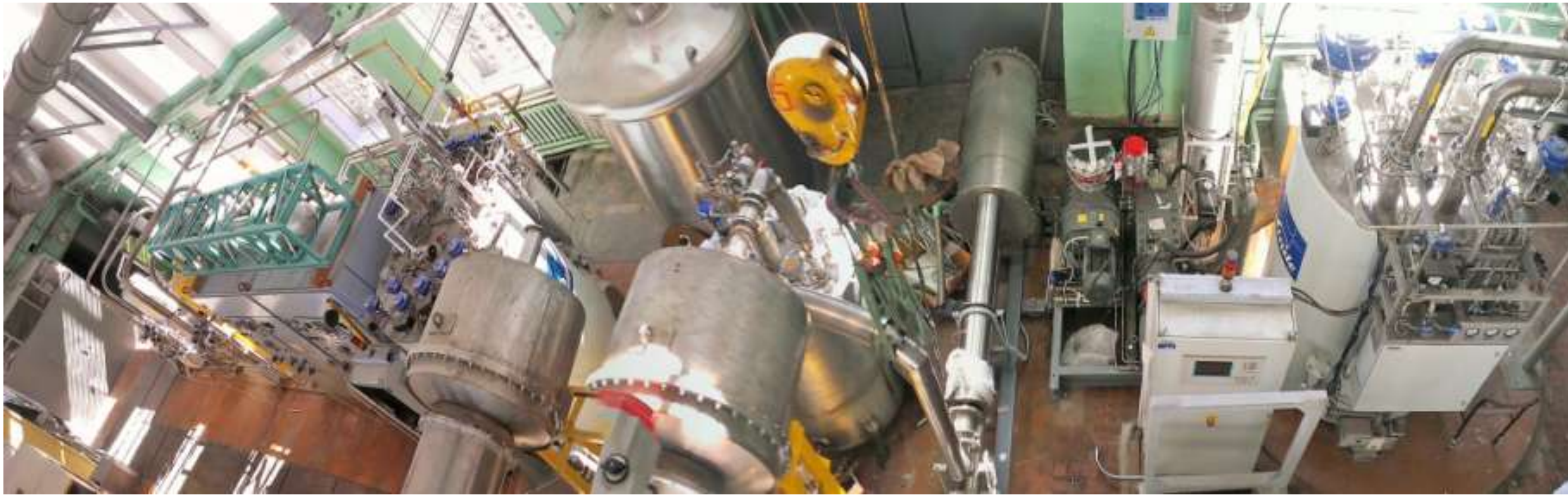
Vacuum equipment

Cryostat

Compressors

Receivers, cryogenic building

# The full-scale technological model of UCN source with superfluid helium is mounted



## The full-scale technological model of UCN source with superfluid helium is mounted

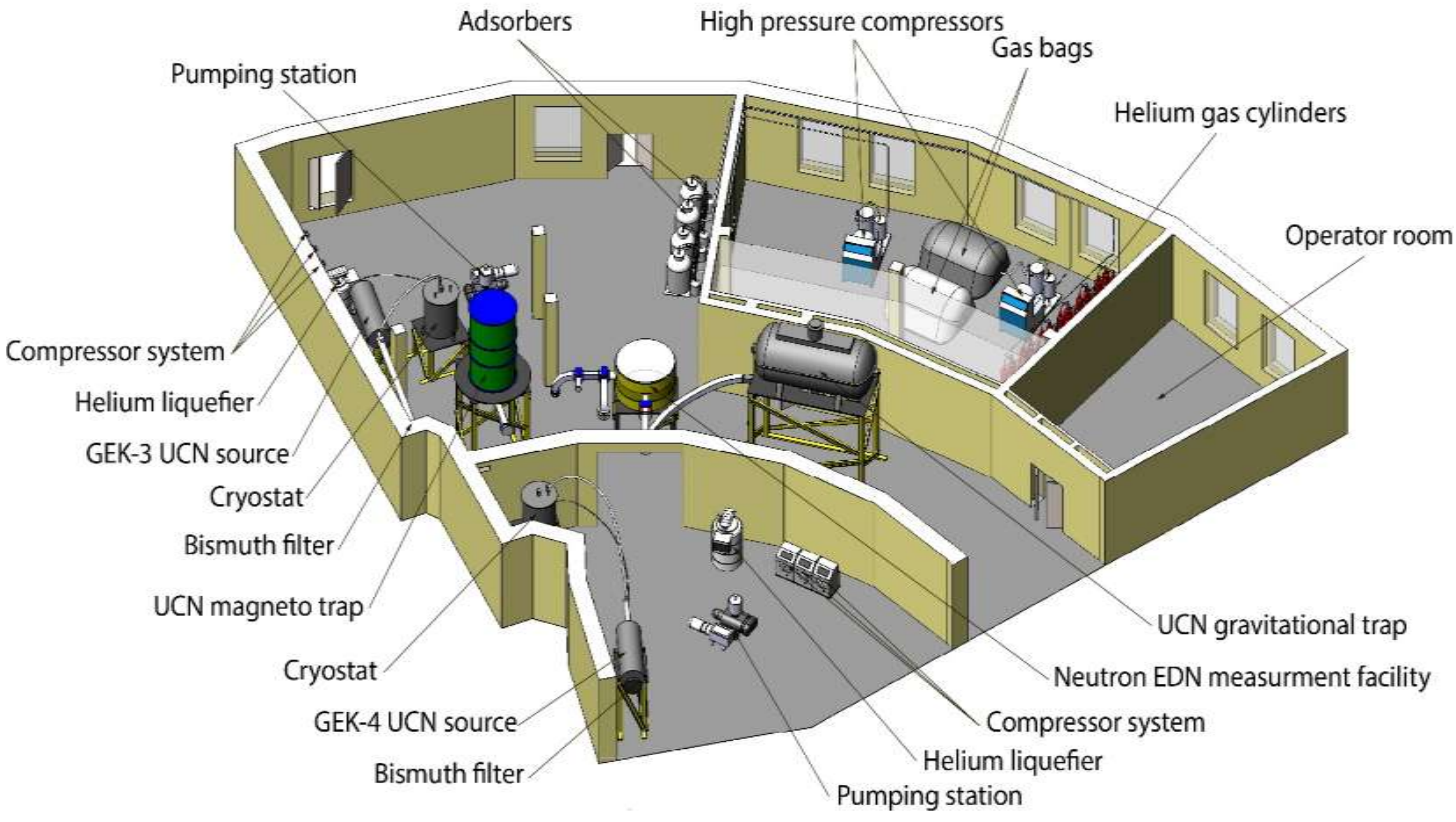

Liquefier

Cryostat

Refrigerator

# *General view of scientific station of UCN source at PIK reactor*

Due to application of polycrystalline bismuth filter, it has become possible to solve the problem of reducing a heat load towards superfluid He up to the level of 0.5 W. In this connection, a project for a technological complex has been elaborated to remove heat load of 1 W at temperature 1 K from superfluid He for UCN source at PIK reactor.



# *Neutron EDM*

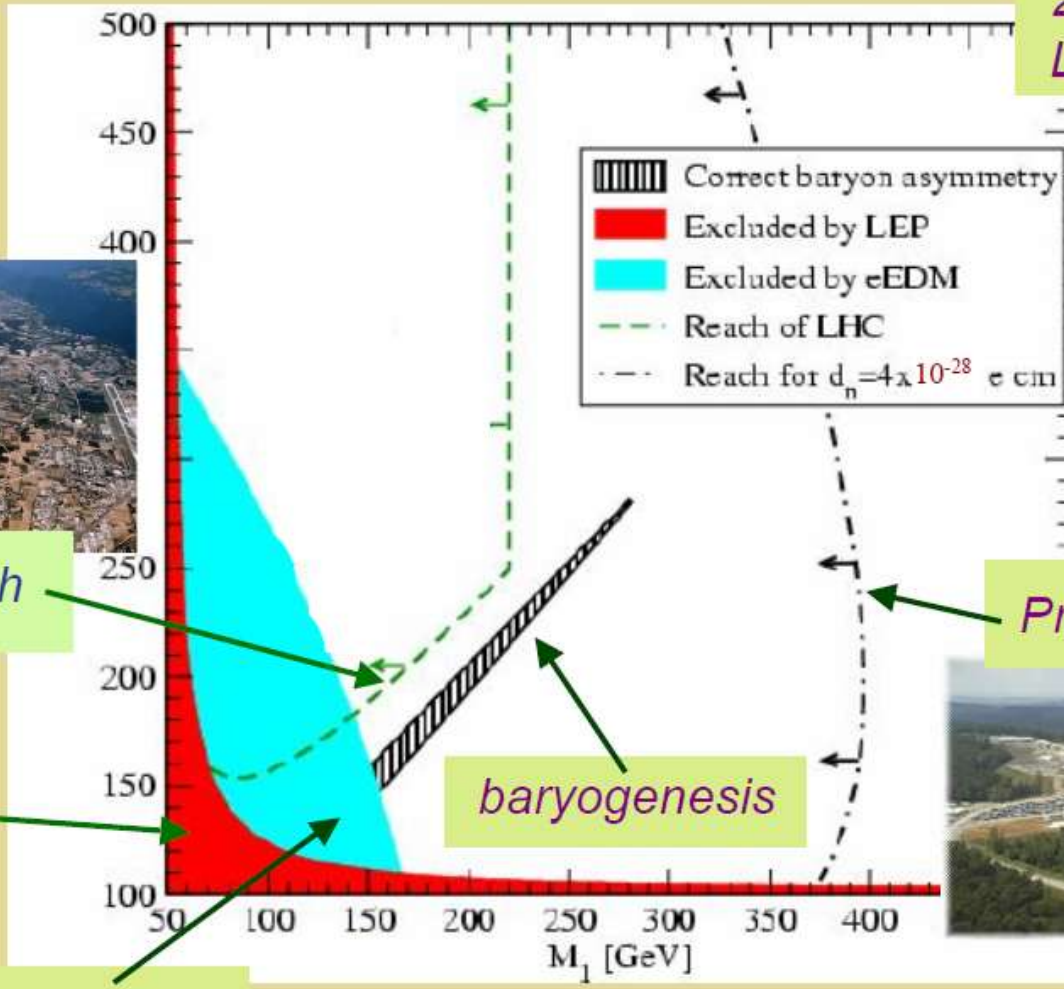
# *Search for neutron EDM*

One of the most significant problems in physics is the time invariance violation primarily concerned with the origin of the Universe.
Experiments on search for neutron electric dipole moment, other than zero, are regarded as a time invariance violation test, while an ultracold neutron method provides a very high estimation accuracy.

In 1967 A.D. Saharov, for the first time, claimed that for interpretation of baryon asymmetry of the Universe, it was necessary to assume that there was an interaction, firstly, non conserving a baryon number and, secondly, violating *CP*-invariance.

# MSSM Baryogenesis: EDMs & LHC

2007 NSAC LRP Update




*Gatchina PNPI*

**OAK RIDGE**

Cirigliano, Li, Profumo, R-M

# *Search for neutron EDM*

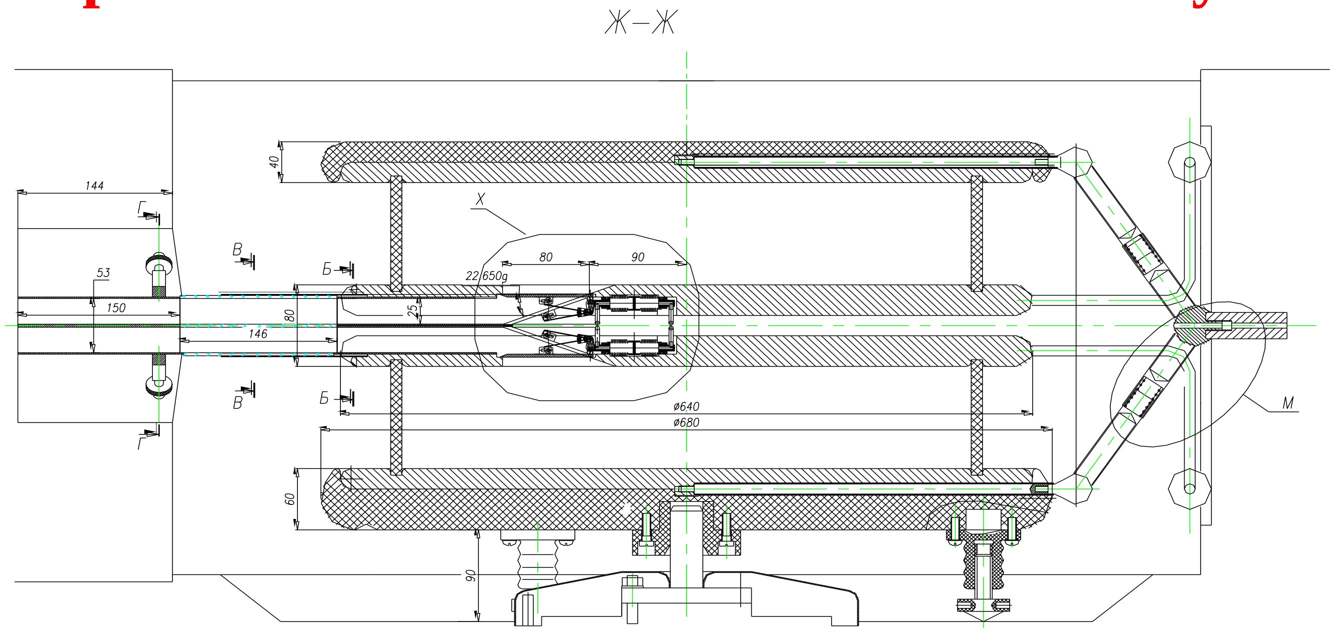
 

*PNPI NRC KI setup for neutron EDM measurement at ILL*

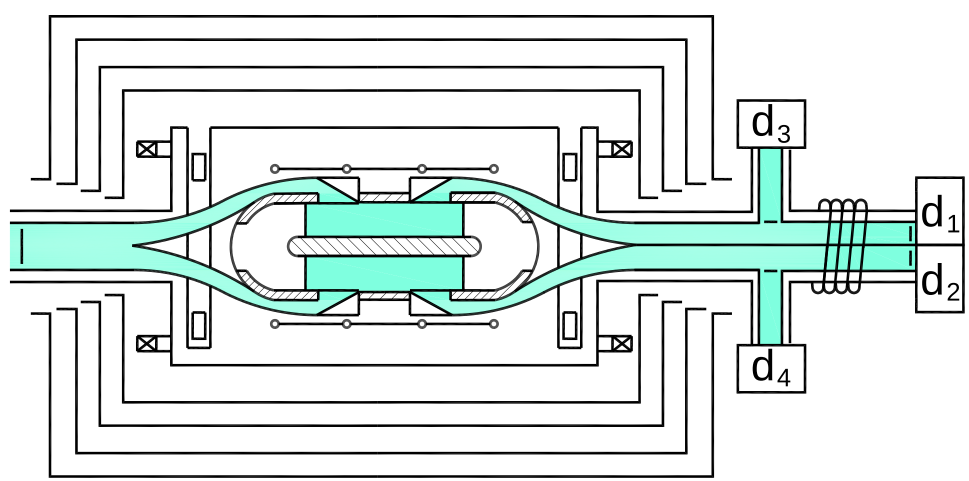
*OUR current result* $/nEDM/ \leq 5.5 \cdot 10^{-26} e \cdot cm$ **90% CL**

# New scheme of UCN trap in EDM spectrometer

# Expected factor UCN transmission intensity is about 2 - 3 times




New scheme

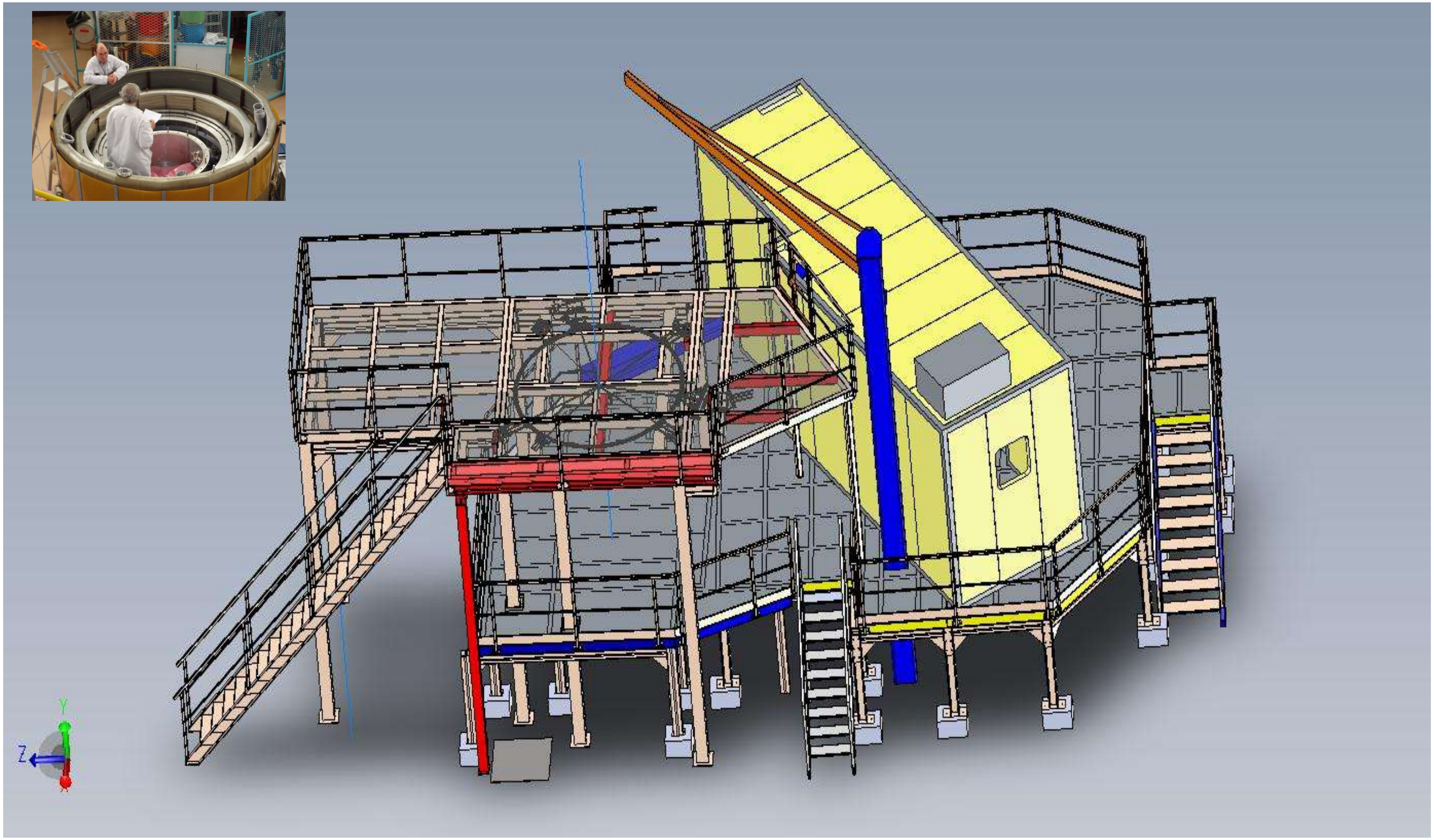



Old scheme

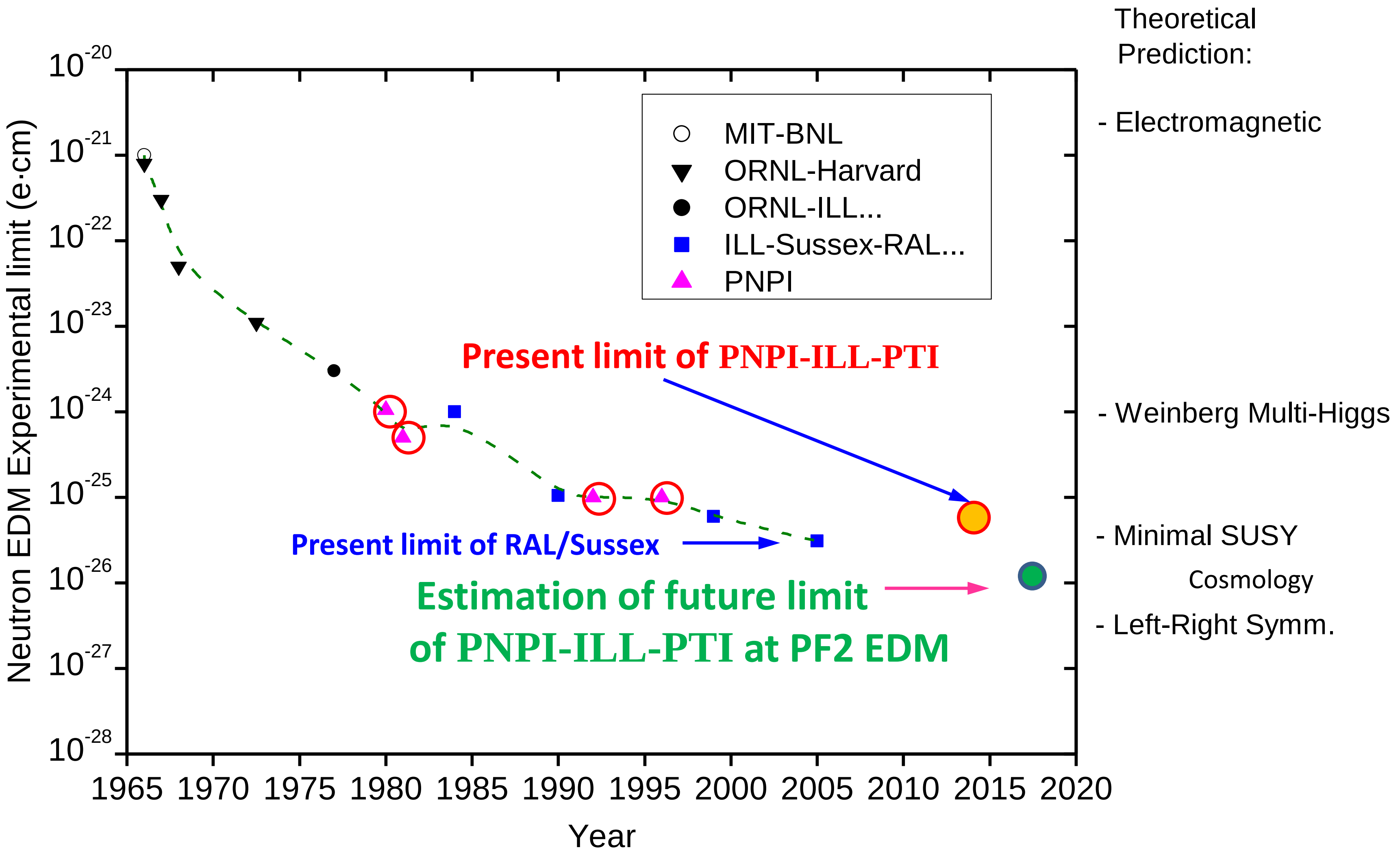
*Assembling of new scheme of EDM spectrometer*

*April – May 2015*

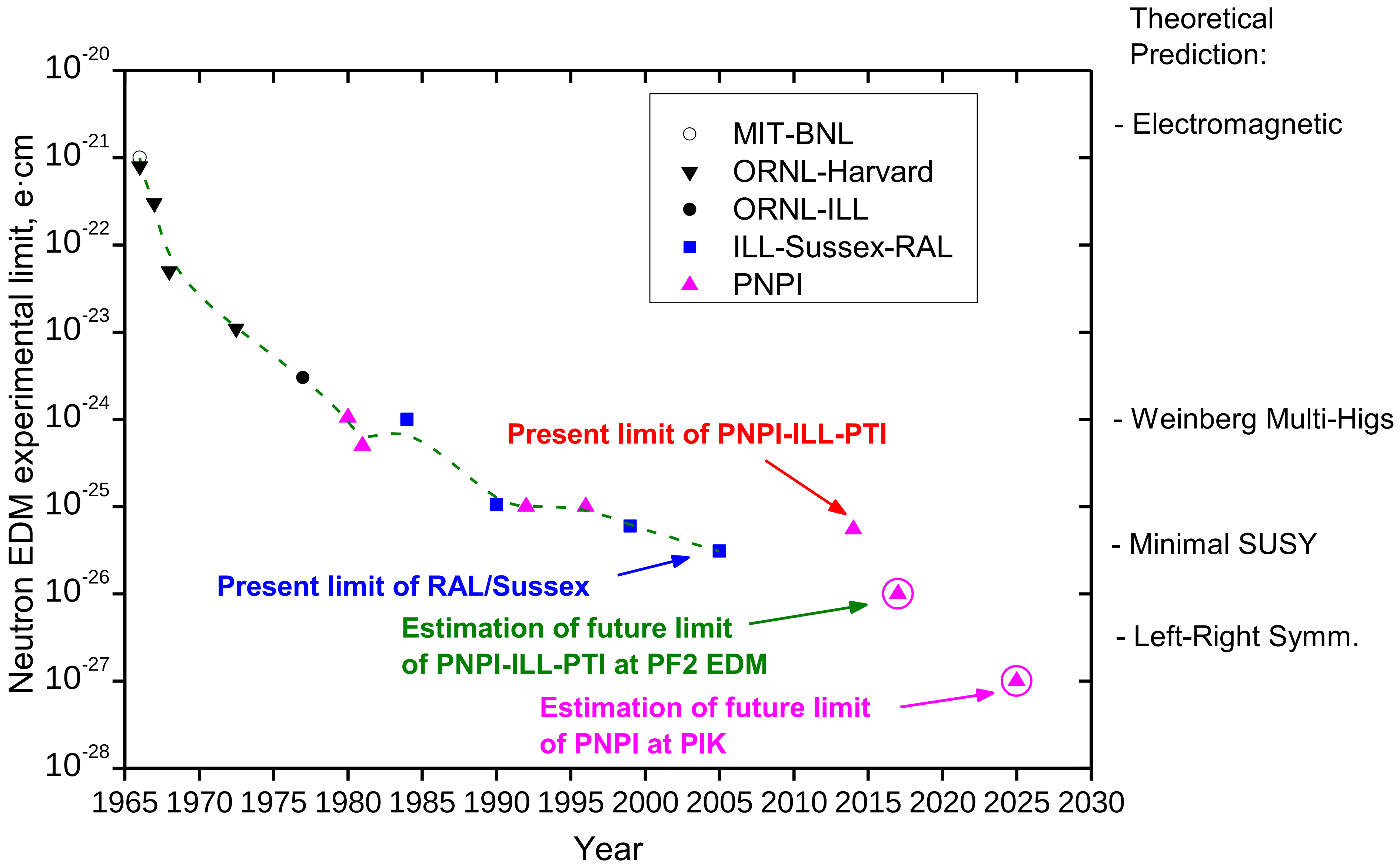
## *Preparation of measurement of neutron EDM with the modified installation on more intensive position for the purpose of increase in accuracy by 2-3 times*



# History of nEDM measurements. Results and prospects of PNPI-ILL-PTI collaboration



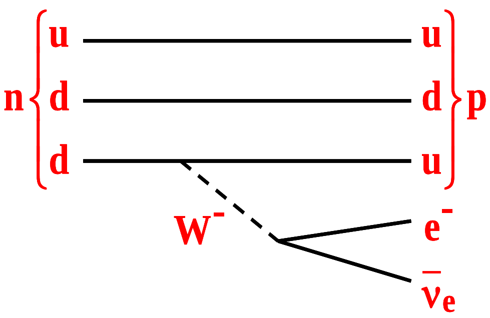
# *History of measurement of neutron EDM and plans of increase in accuracy at ILL and at PIK reactor*

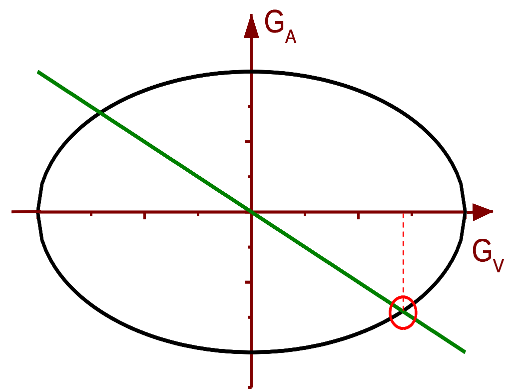


# *Neutron β-decay*

# *Matrix element $V_{ud}$ determination from neutron β-decay*

**Neutron lifetime measurement by method of UCN storage in material and magnetic traps.**
**β-decay asymmetries measurement ( A – electron, B – neutrino).**




$$ft(1+\Delta_R)(1+\delta_R) = \frac{k}{|V_{ud}|^2 G_F^2 (1+3\lambda^2)}$$

~1.5 %   ~2.4 %

CKM mixing matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\lambda = \frac{G_A}{G_V} \qquad A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

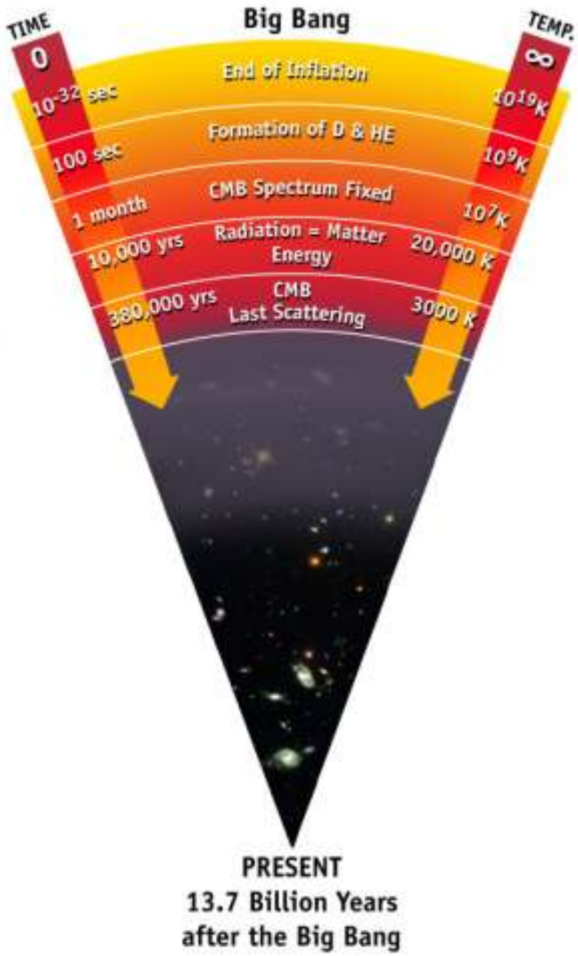
$$G_V = G_F \cdot V_{ud}$$

$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9\ \text{s}}{\tau_n (1+3\lambda^2)}$$

W.Marciano
A.Sirlin
PRL 96, 032002 (2006)

# Neutron decay and cosmology

G. J. Mathews, T. Kajino, T. Shima, Phys. Rev. D 71, 021302(R) (2005)




$$(f\tau_n)^{-1} = \frac{G_F^2}{2\pi^3}\left(1+3g_A^2\right)m_e^5$$

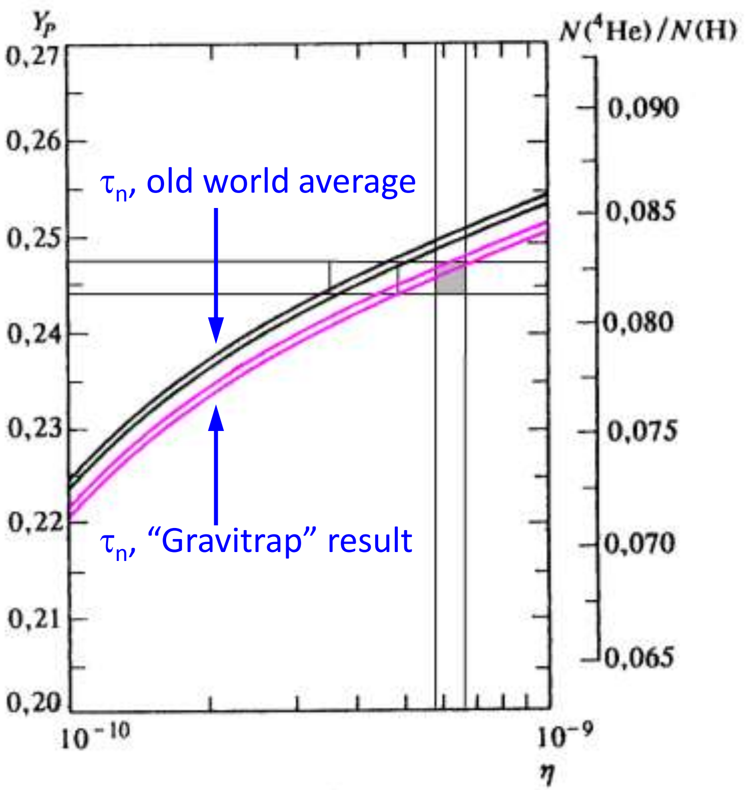
$$\Gamma = (7/60)\pi(1 + 3g_A^2)G_F^2 T^5$$

$$H \approx [(8/3)\pi G\rho_\gamma]^{1/2}$$

$$\rho_\gamma = (\pi^2/30)g_* T^4$$

$$T_f \approx 1 \text{ MeV}$$

$$n/p = \exp\{-\Delta m/T_f\}$$




$$Y_p \approx 2n/(n + p) = 2(n/p)/(n/p + 1)$$

$$\Delta\tau_n = 1\% \quad \rightarrow \quad \Delta Y = 0.75\% \ (\pm 0.61\%)$$

$$\Delta\tau_n = 1\% \quad \rightarrow \quad \Delta\eta = 17\% \ (\pm 3.3\%)$$

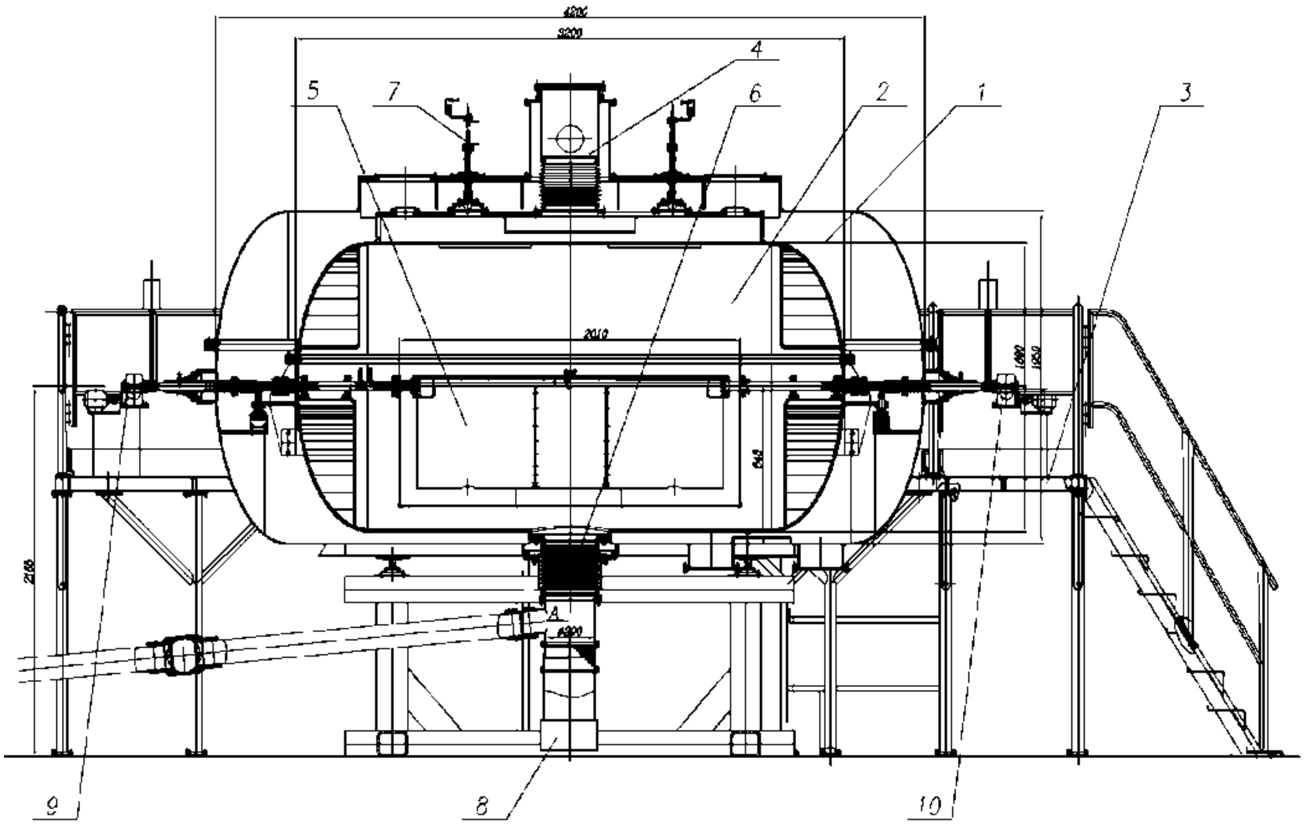
**New $\tau_n$=(878.5±0.8) s confirms $n_b/n_\gamma$ from CMB.**

# *Gravitrap experiment*

A.Serebrov et al. , Phys Lett B 605, (2005) 72-78 : **878.5 ± 0.8 s**

***2002-2004 (PNPI-JINR-ILL), ILL reactor, Grenoble***

# *Scheme of Big Gravitational Trap*




1 – external vacuum vessel; 2 – internal vacuum vessel; 3 – platform for service; 4 – gear for pumping out internal vessel; 5 – trap with insert in low position; 6 – neutron guide system; 7 – system of coating of trap and insert; 8 – detector; 9 – mechanism for turning trap; 10 – mechanism for turning insert

# Installation of Big Gravitrap on ILL reactor (August 2014)

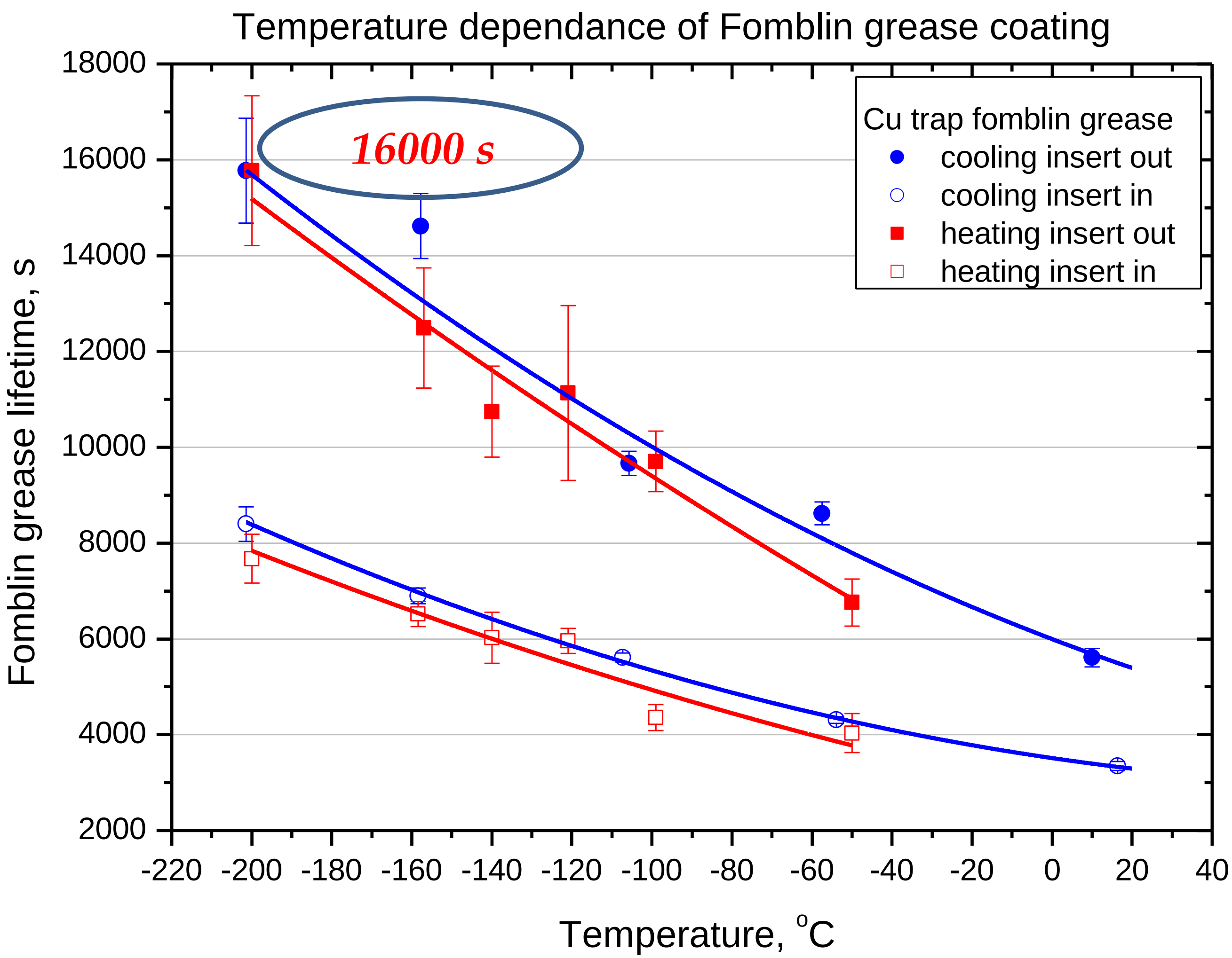
# Completion of installation of big gravitational trap

# Cleaning of  Cu  Trap  and

coating  by Fomblin grease

# Cu Trap coated by Fomblin grease

*Storage time in the trap with Fomblin grease coating*
*(storage time is 16000 s at liquid nitrogen temperature or loss probability is 5% of neutron decay probability)*

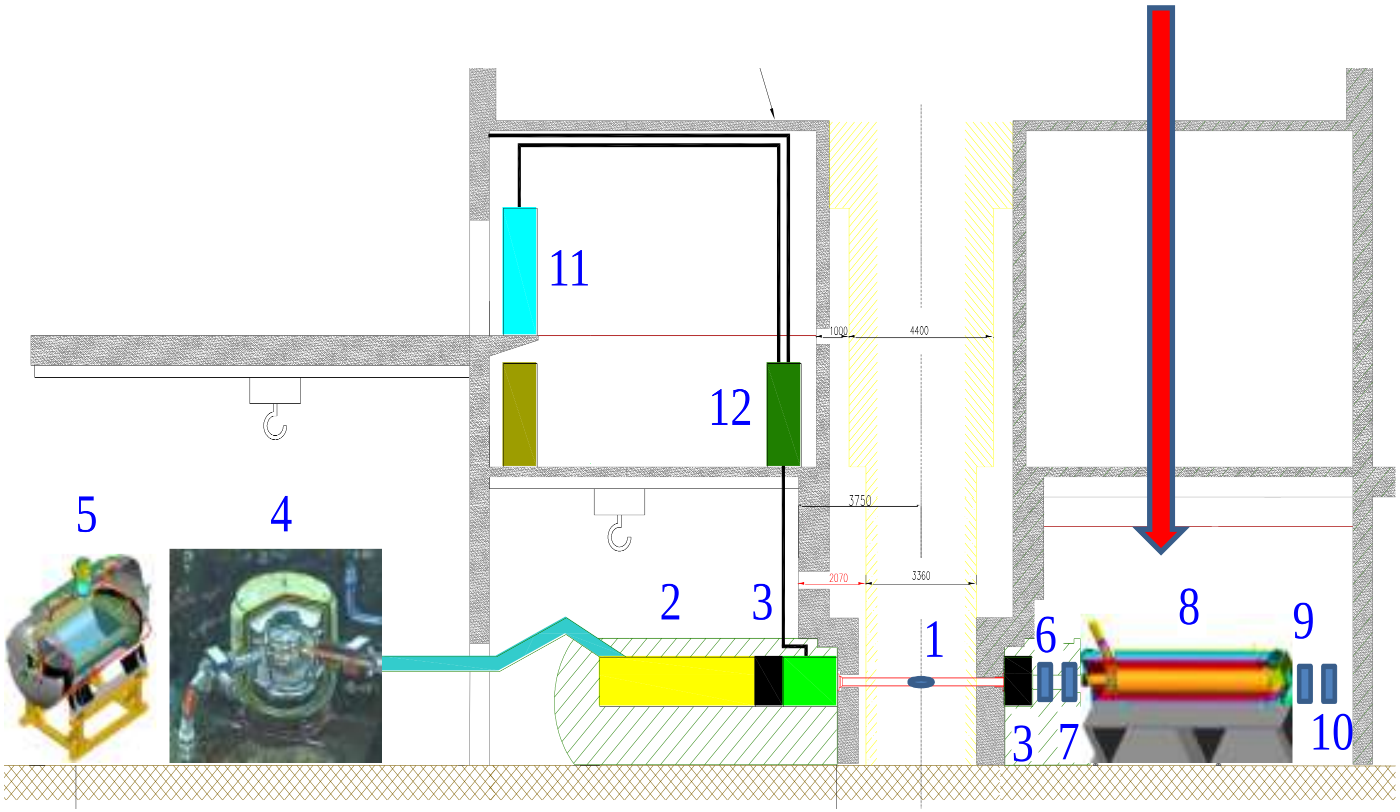


## *Neutron lifetime measurement by method of UCN storage in magnetic trap (V.F.Ezhov talk)*

The first stage of measurements of neutron lifetime with use of prototype magnetic trap (left); the vacuum camera with model of a magnetic trap inside (right)

## *Research of neutron β-decay at GEK-4´ beam of cold neutrons at PIK reactor*

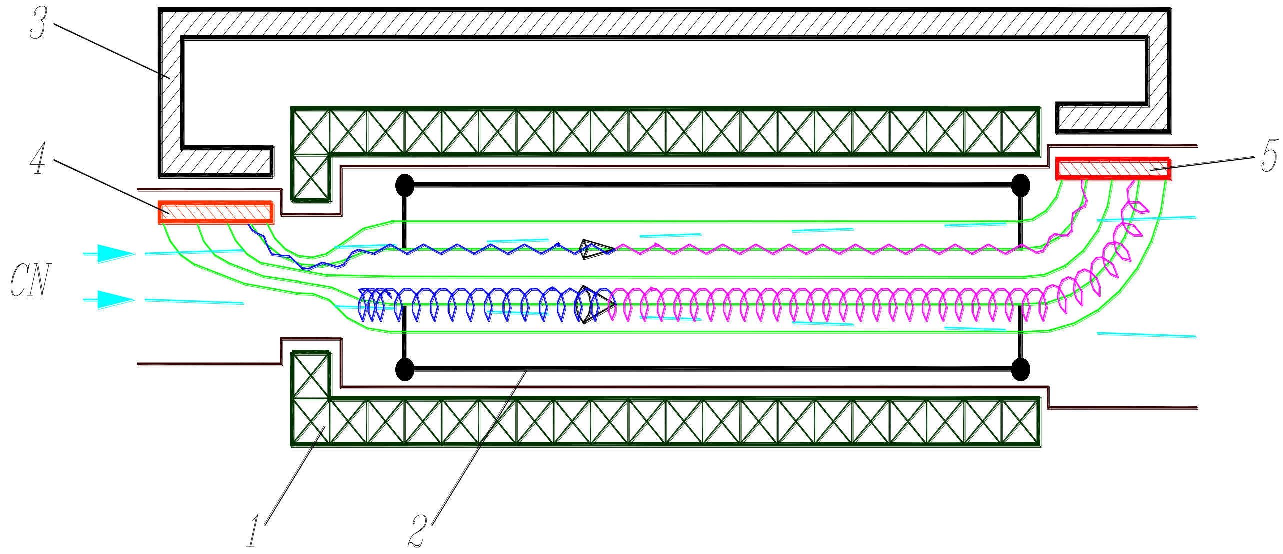
## *Complex research of neutron β-decay at GEK-4′ beam of cold neutrons at PIK reactor*




6 – chopper of cold neutrons beam, 7 – polarizer of neutron beam on polarized $^3$He, 8 – installation for measuring asymmetry of a neutron decay with a superconducting solenoid, 9 – polarization analyzer, 10 – detector

# *Scheme of experiment with superconducting solenoid*

## *Solenoid with a magnetic mirror*




An experimental scheme for measuring an electron asymmetry of a neutron decay. The neutron beam is polarized with He-3 polarized cells, it passes through a flipper and after a collimator gets into the field of decay, restricted by an electrode. All the protons are pulled out of the neutron field of decay by an electric field and get onto the detector (5). Electrons move onto the detector (4). 1 – a superconducting solenoid with a magnetic mirror, 2 – a cylindrical electrode, 3 – a metal yoke, 4 – an electron detector, 5 – a proton detector.

In decay region $B_Z \approx 0.35\ \mathrm{T}$ @ 1 кА

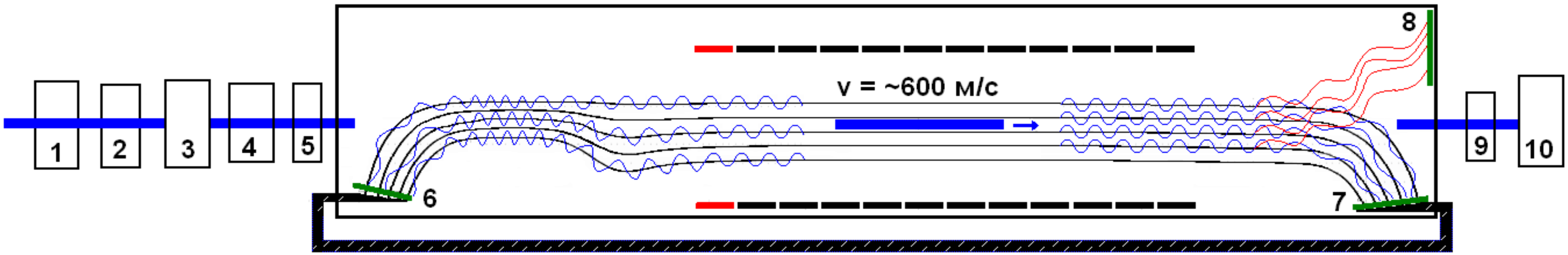
In magnetic mirror region $B_Z \approx 0.8\ \mathrm{T}$ @ 1 кА

*Creation of setup for measurement of neutron decay asymmetries.*
*(Superconducting solenoid, cryostat of superconducting solenoid.)*

Filling of liquid helium in the cryostat is made

# *Asymmetries measurement in neutron β-decay. Scheme of the experiment*

Neutrons velocity ≈ 600 m/s

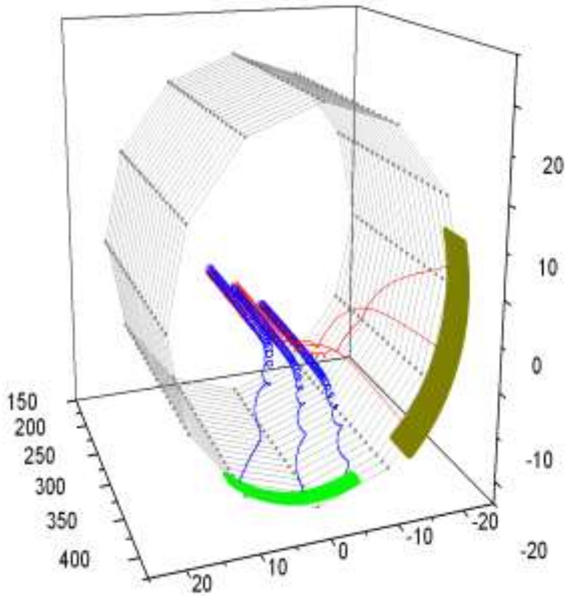


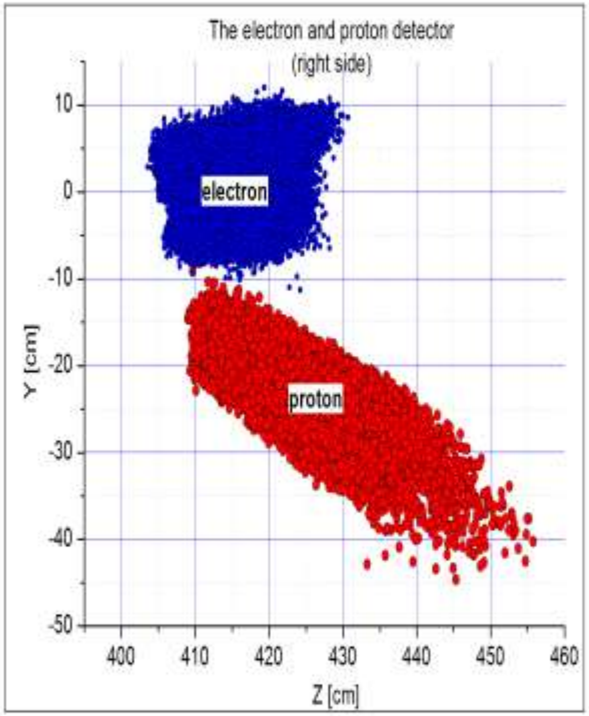

Effective length of decay region ≈ 2 m

1 – a velocity selector, 2 - $^3$He polarizer, 3 – a beam chopper, 4 – a spin-flipper, 5 – a thin neutron detector, 6 – an electron detector, 7 – an electron detector, 8 – a proton detector, 9 – a neutron detector, 10 – a beam polarization analyzer

Count is kept on the electron detector (6). The proton detector (8) is used in regime of delayed coincidences. The electron detector (7) is used in mode of anticoincidence. Detectors of neutrons (5) and (9) are used for control of bunch speed.

# *A scheme of division of electrons and protons in crossed electric and magnetic fields*

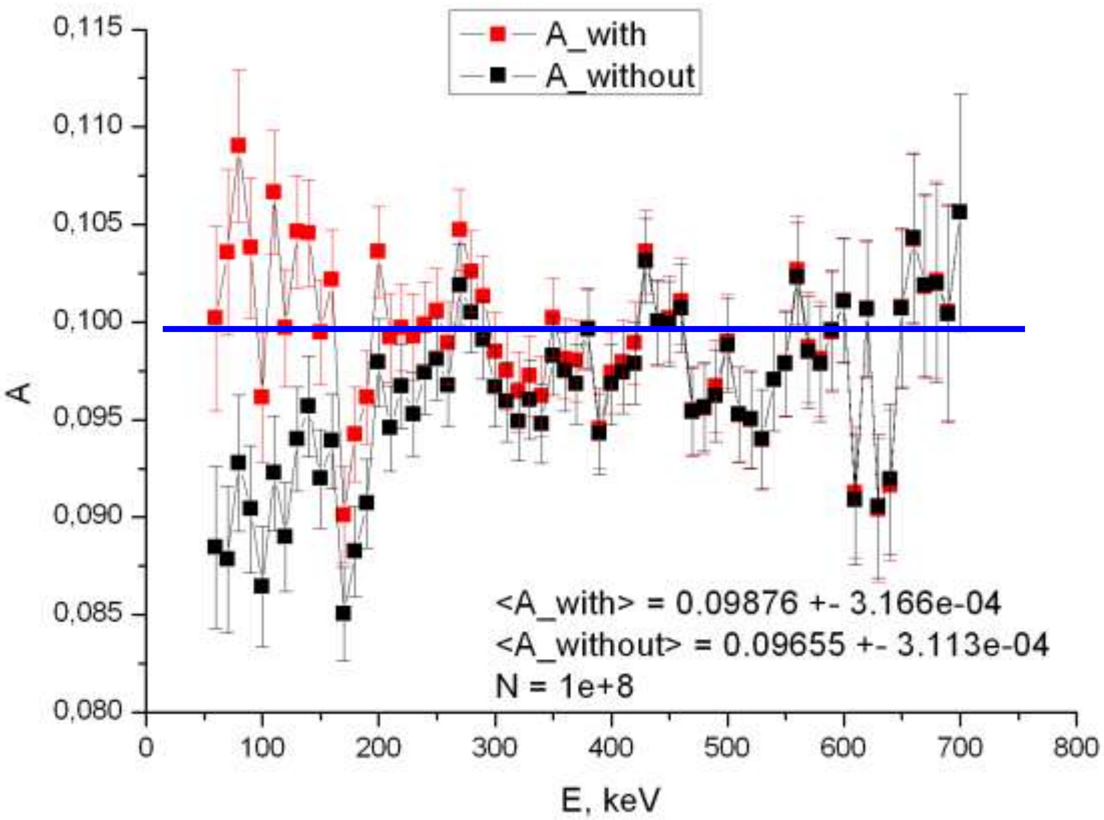


# *Electron-spin asymmetry A measurement. Simulation of the experiment.*

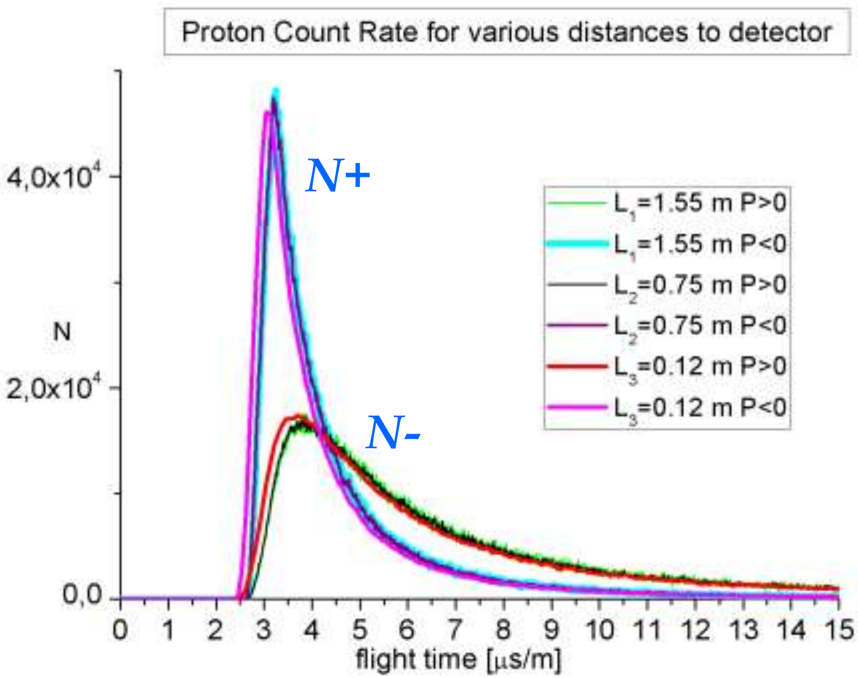
$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \times \left[ P \times \left\langle \frac{\upsilon}{c} \times \cos \vartheta \right\rangle \right]^{-1}$$

Dependence of coefficient A on electron energy taking into account a “dead” layer on detector (reflection from the detector without signal)

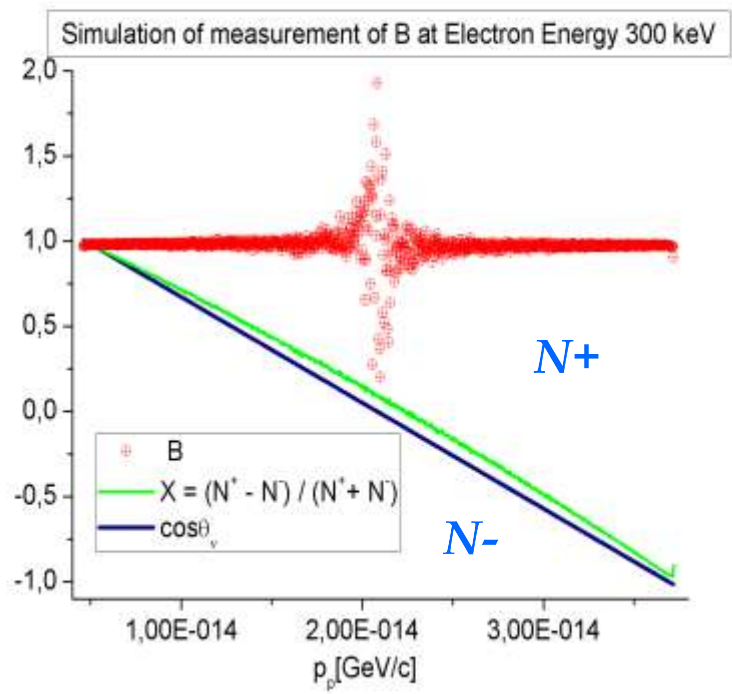


# Neutrino asymmetry B measurement

## Normalized time-of-flight proton spectrum




## Calculation of neutrino asymmetry B




$$X_{ik} = \frac{\left(N_{ik}^{+} - N_{ik}^{-}\right)}{\left(N_{ik}^{+} + N_{ik}^{-}\right)}$$

$$(PB)_{ik} = \frac{X_{ik}\left[1 + a\left(\upsilon_i / c\right)\left(\cos\vartheta_{ev}\right)_{ik}\right] - PA\left(\upsilon_i / c\right)\left(\cos\vartheta_{\sigma e}\right)_{ik}}{\left(\cos\vartheta_{\sigma\nu}\right)_{ik}}$$

## *Search for reactor antineutrino oscillations at short distances*

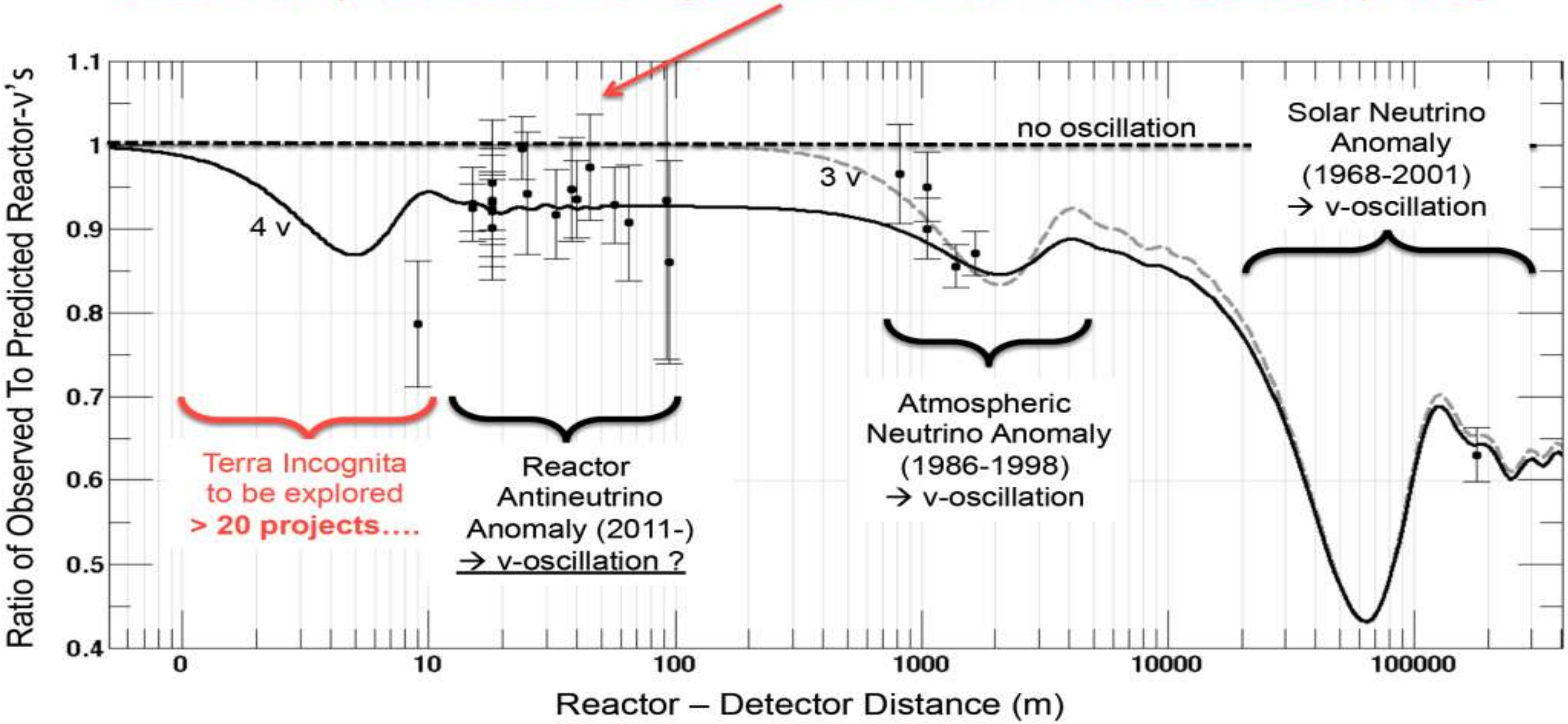
**sterile neutrino**

*G. Mention et al., Phys. Rev. D83, 073006, 2011*

# The reactor antineutrino anomaly and sterile neutrino

## The Reactor Anomaly

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




CEA DSM Irfu T. Lasserre

# Prototype of antineutrino detector at WWR-M reactor

Liquid scintillator BC-525(Gd)

Detector with active shielding 4π

Filling by liquid scitillator
400 liters

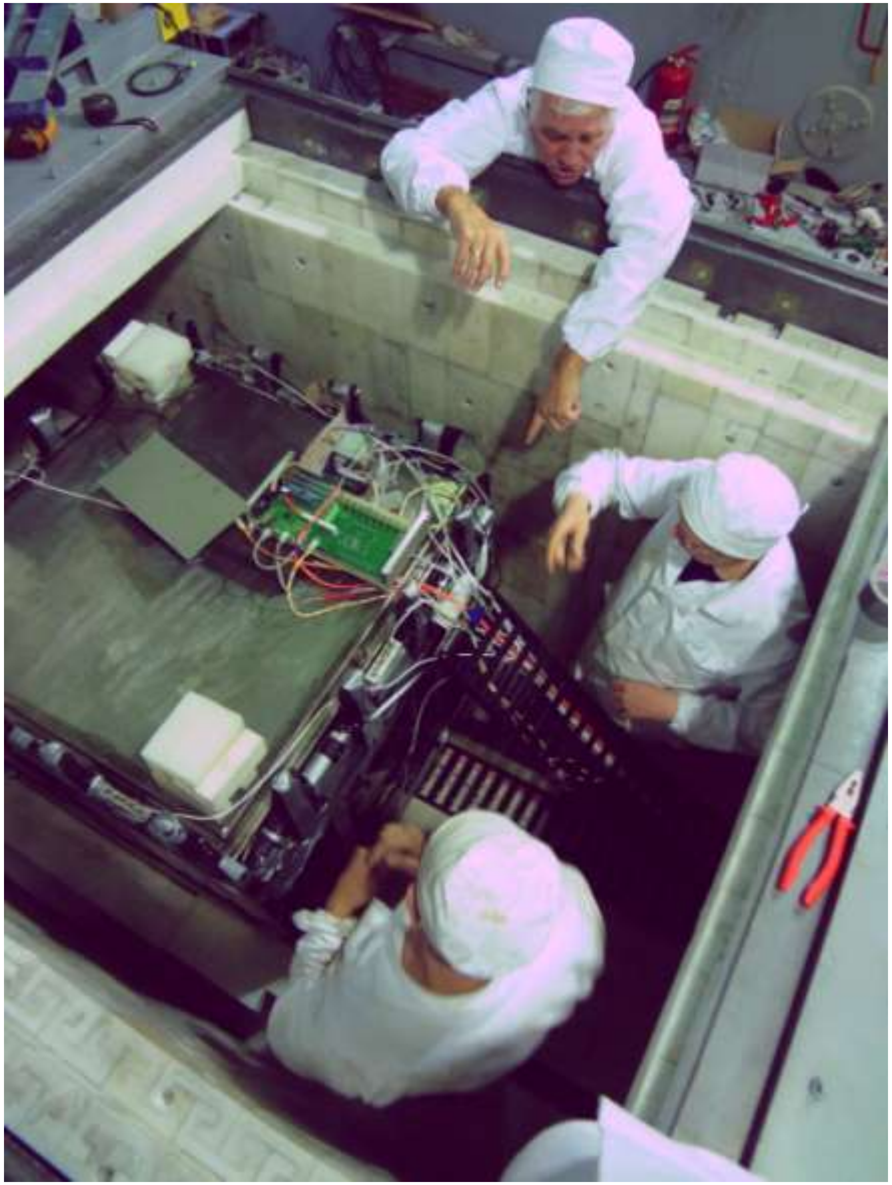
installation of model inside of
passive shielding

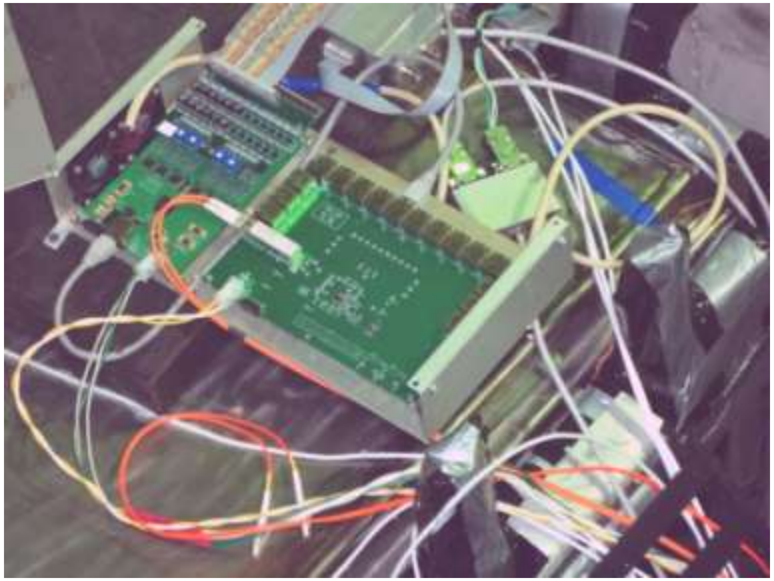
# *Neutrino channel outside and inside*

*Passive shielding of 60 tons*

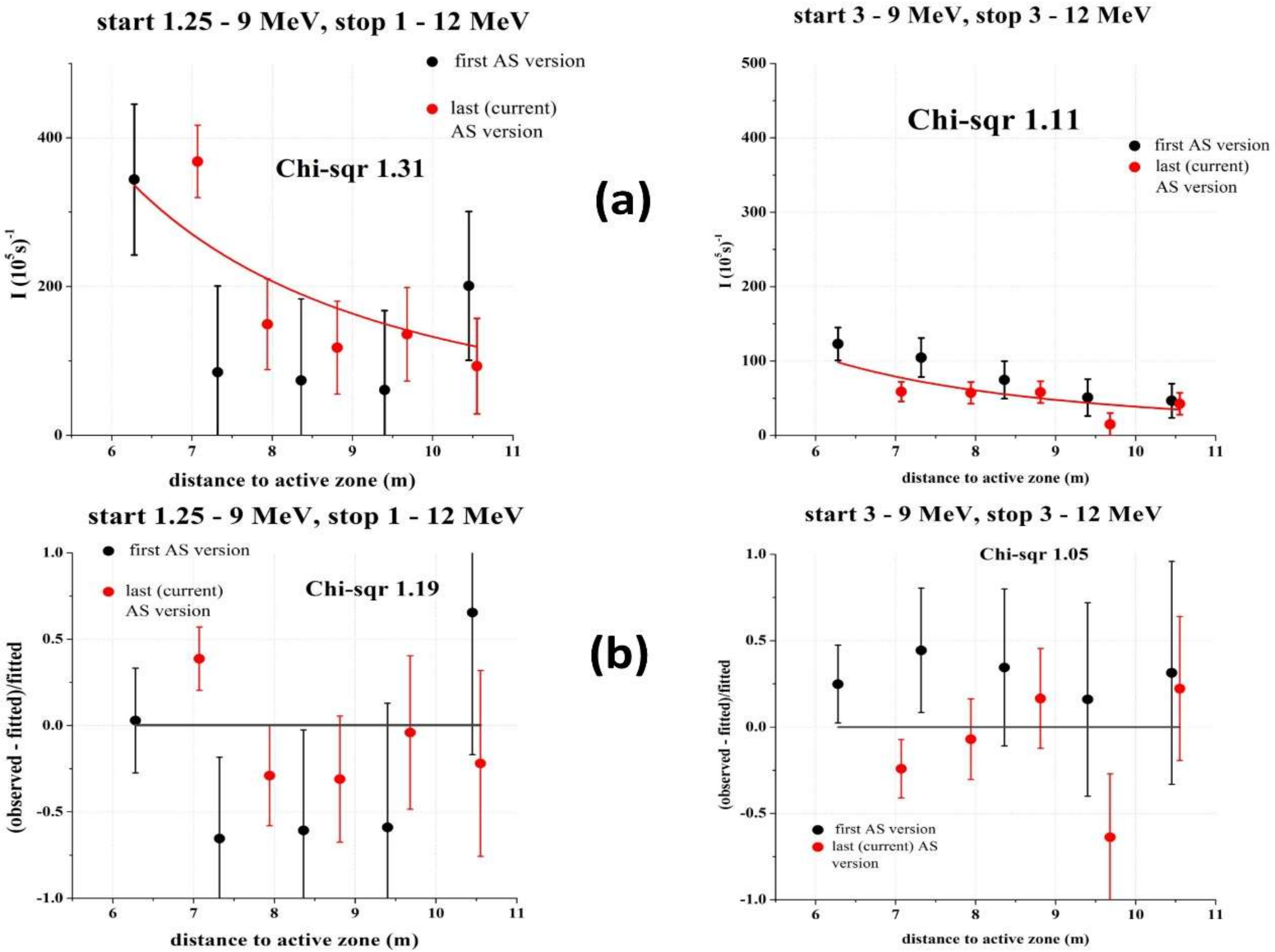
*Range of measurements for the reactor antineutrino flux is 6 – 12 meters from the active reactor core*

# *Assembling of electronics for prototype of NEUTRINO-4 detector*





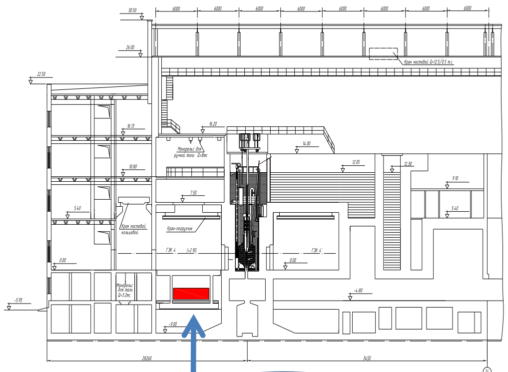
# *First measurements of 1/$R^2$ dependence at the short distances with prototype of NEUTRINO-4 detector*

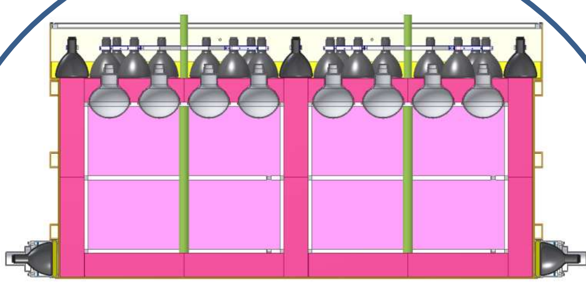


# NEUTRINO-4 experiment for sterile neutrino search at SM-3 reactor and development of installation of neutrino monitoring for PIK reactor

*PNPI NRC KI (Gatchina), NRC KI (Moscow), RIAR(Dimitrovgrad)*

## PIK reactor



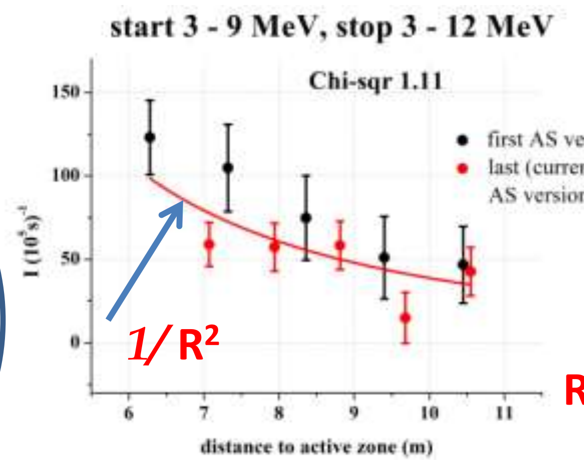


*Active shielding and liquid scintillator detector* ***3 m³***
*+ PMT 64 pcs.*

## SM-3 reactor

*Neutrino laboratory is created at SM-3 reactor to search for sterile neutrino. Region of measurements of reactor antineutrino flux is 6-12 m from reactor core.*

*Passive shielding 60 t*



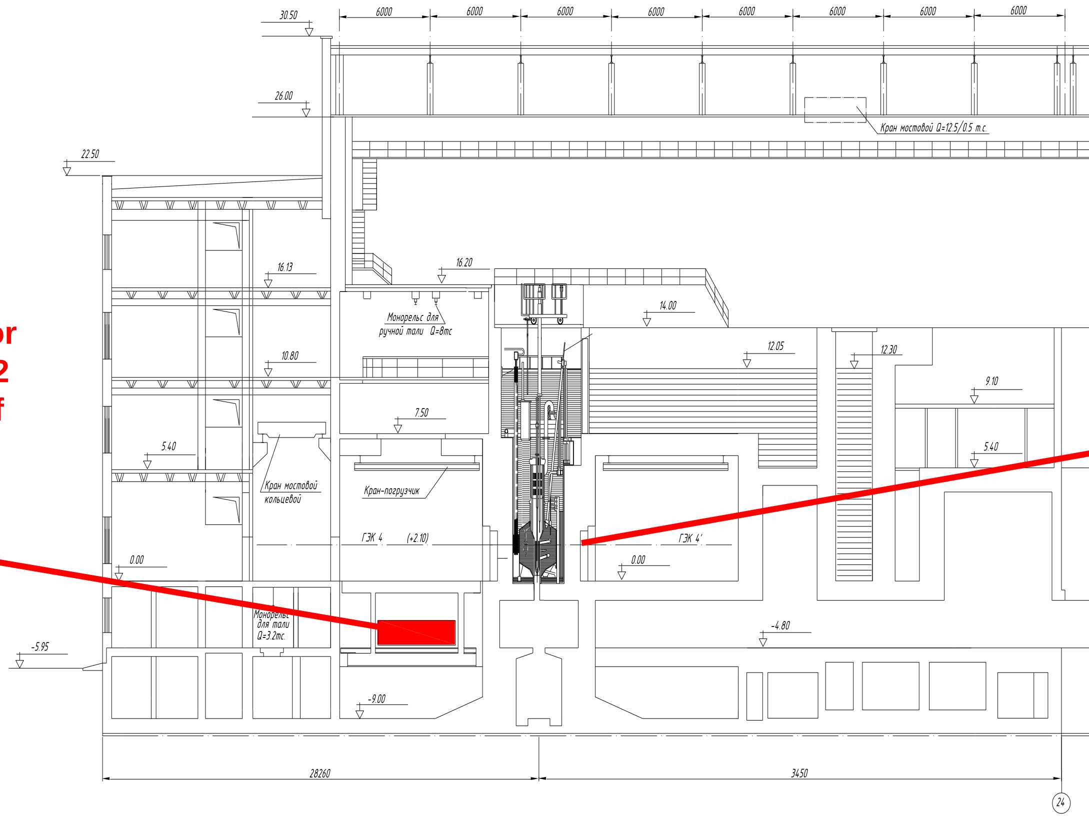

*First 1/R² dependence measurements at short distances with model of neutrino detector*

*Neutrino channel outside and inside view*

*Serebrov (PNPI, Gatchina, Russia)*

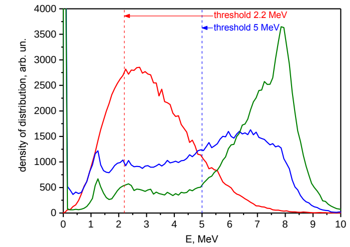
# Scheme of location of antineutrino detector at PIK reactor

**2 – antineutrino detector movement area is 8 – 12 meters from the core of PIK reactor**




**1 – active zone of PIK reactor**

# Production of the full-scale NEUTRINO-4 detector



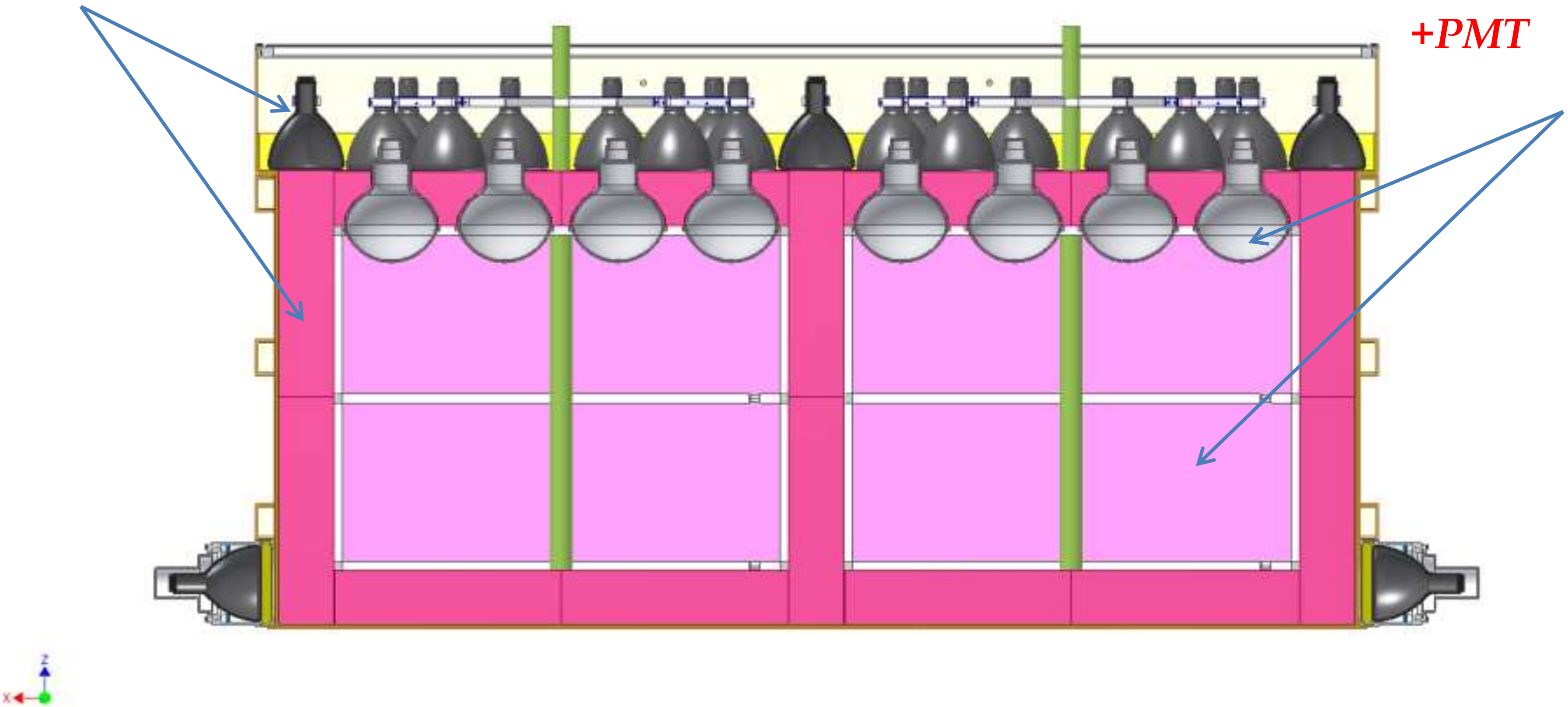

Sensitivity increasing is one order of magnitude with respect to model

**1.3 m³**

*Active shielding from liquid scintillator + PMT*

**1.6 m³**

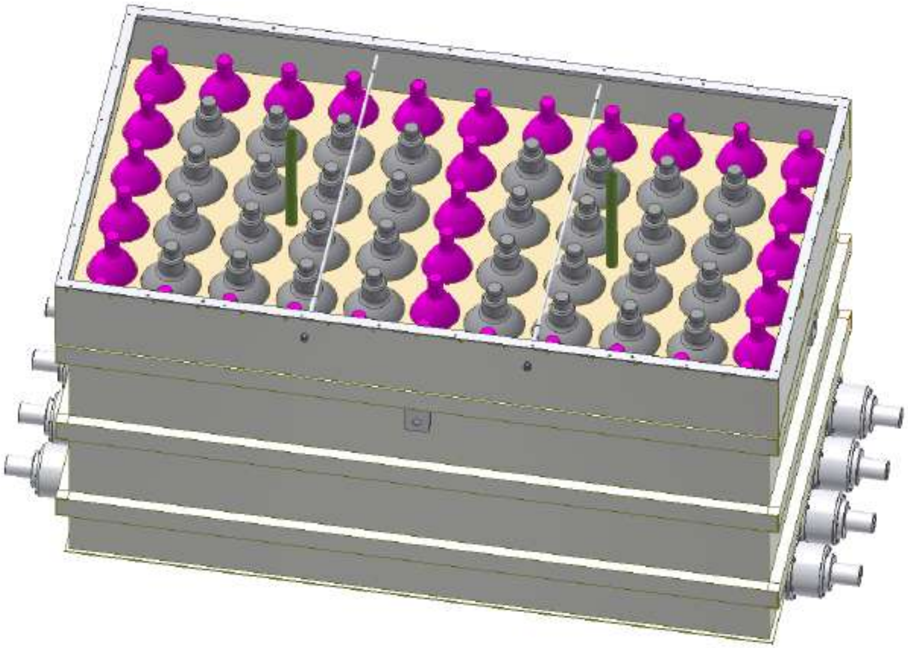
*Liquid scintillator with Gd +PMT*

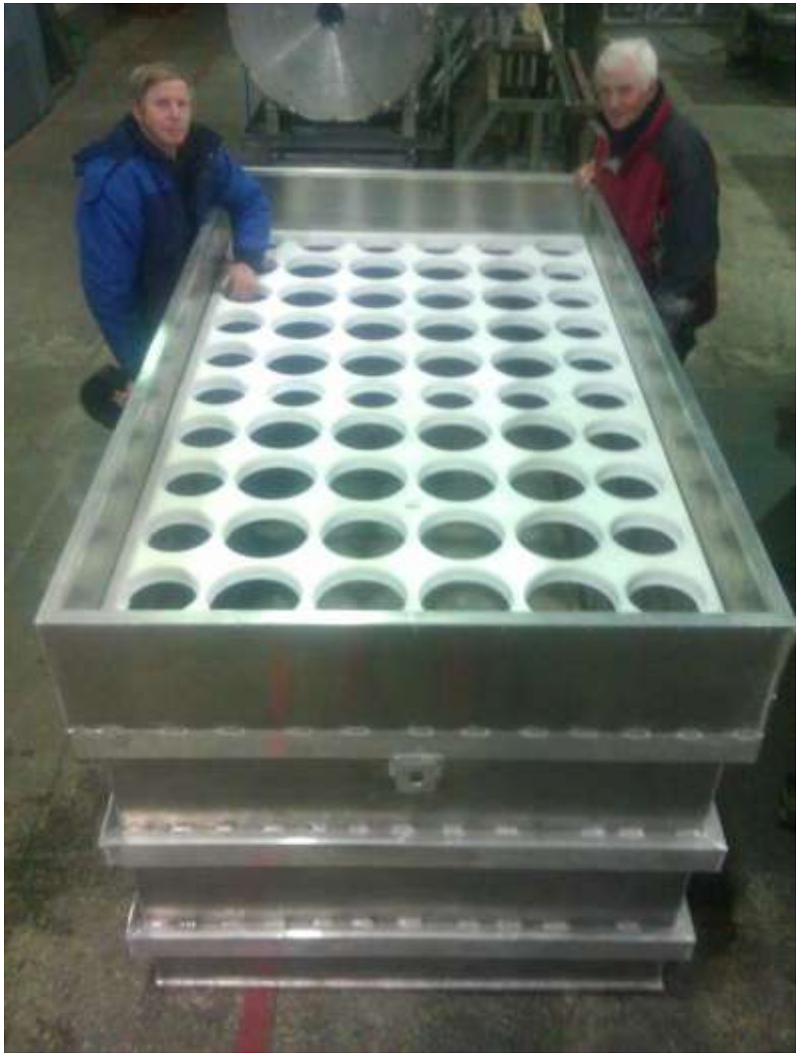



*Serebrov (PNPI, Gatchina, Russia)*

*Designing and production of the full-scale detector NEUTRINO-4*

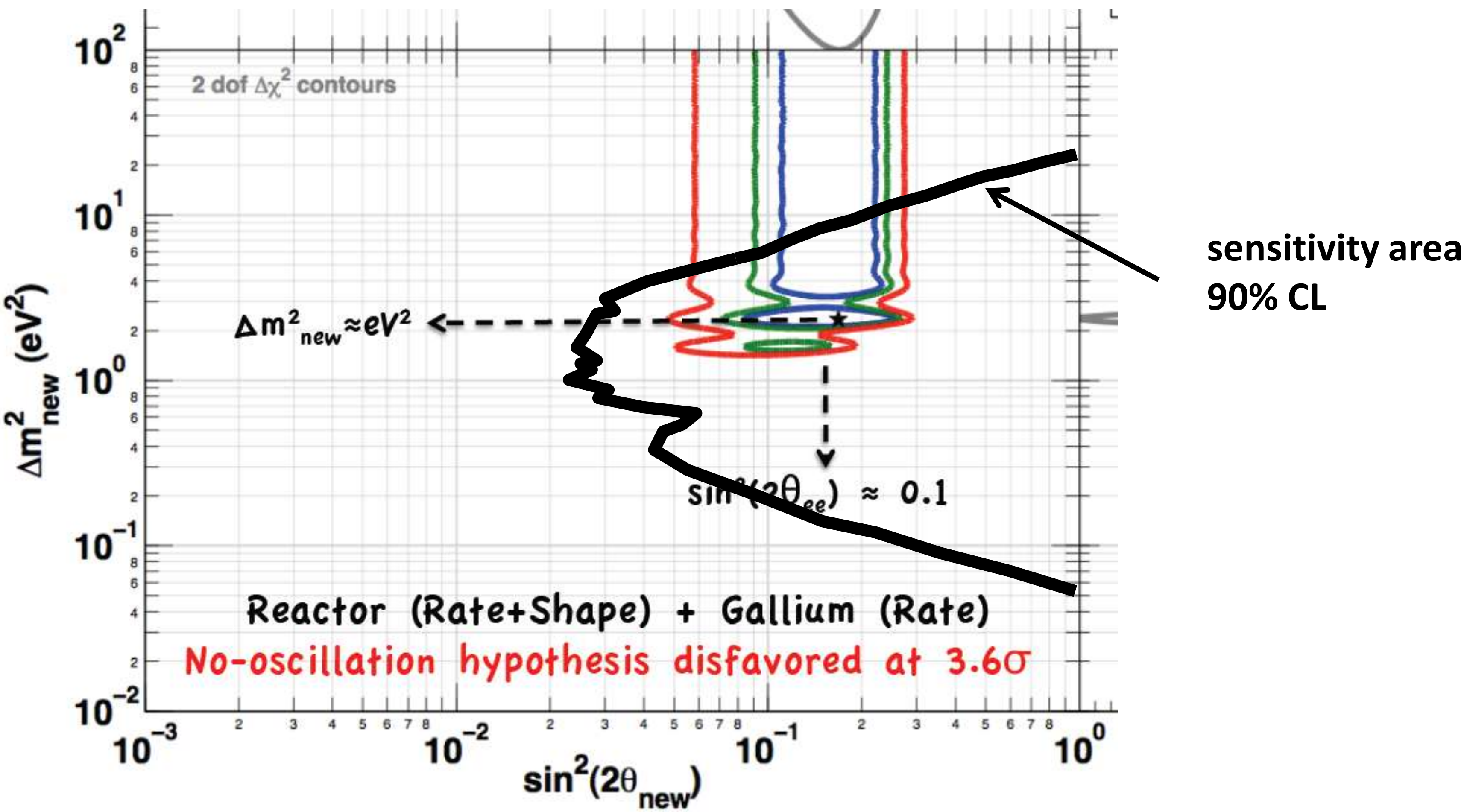
*3 м³ of liquid scintillator, 74 PMT*





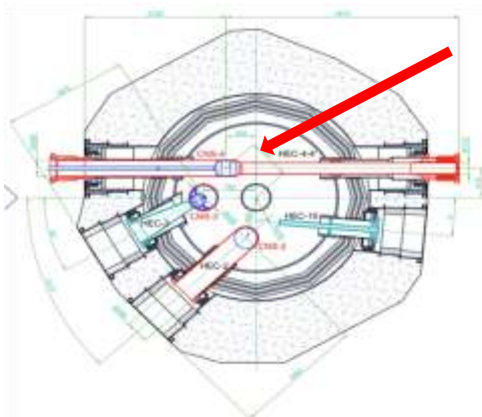
*We obtained 3 м³ of liquid scintillater from China*

# *Possible area of sensitivity of NEUTRINO-4 experiment*



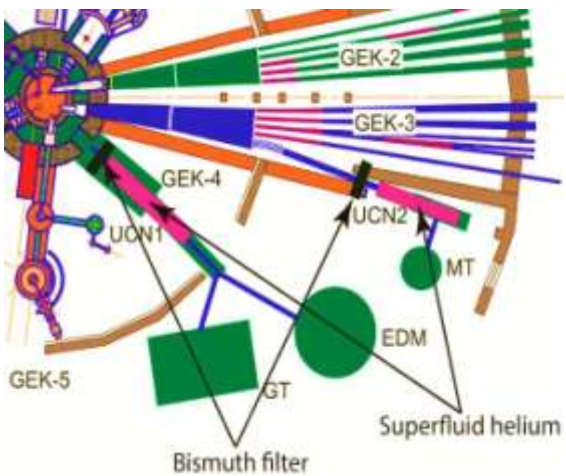
# CONCLUSION

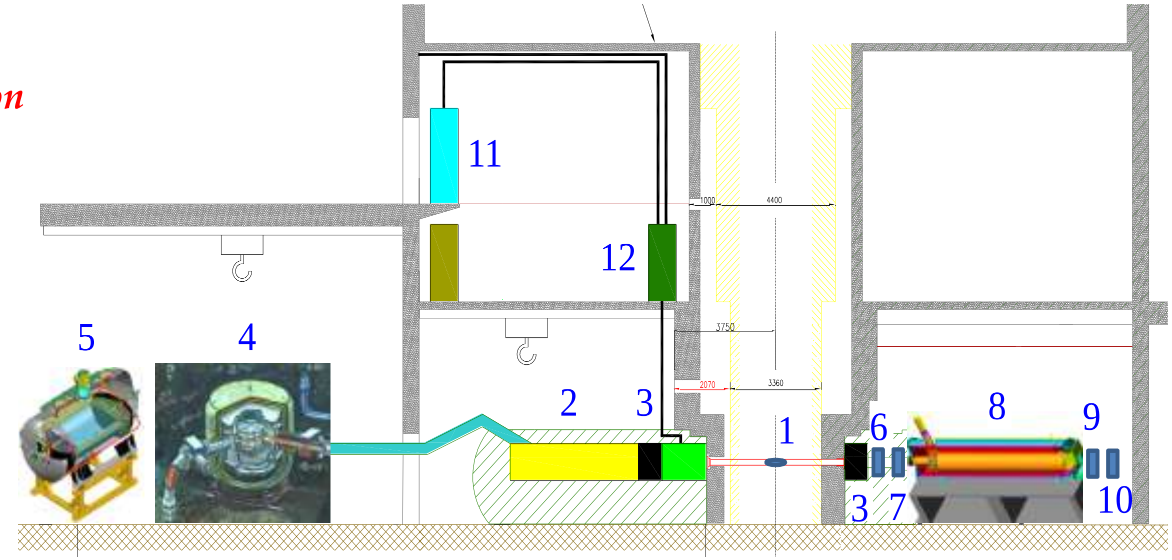
## *Neutron EDM*  *Neutron β-decay*  *NEUTRINO -4*



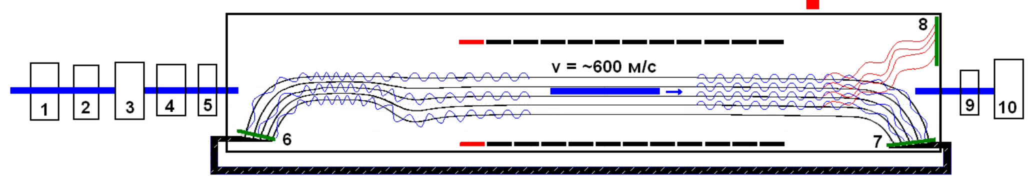
*Cold Neutron Source*

*UCN complex*

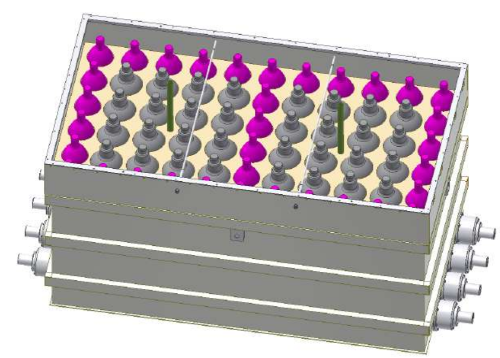



*Beam of polarized cold neutrons*




*NEUTRINO -4*



***THANK YOU FOR ATTENTION***