Investigation of neutrino properties with the low-background germanium spectrometer GEMMA-III

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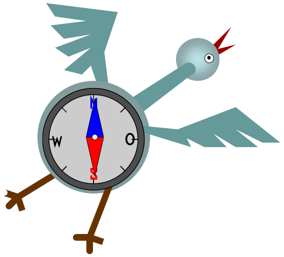
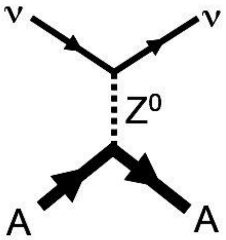
Motivation

Measurement of the neutrino properties is a very important task for a particle physics, astrophysics and cosmology. Being one of the most abundant particle in the Universe its detection is very challenging due to a very weak interaction with matter.

GEMMA-III is a continuation of predecessor projects GEMMA-II and νGEN. It aims to investigate neutrino properties:

- Search for **Magnetic Moment of Neutrino (MMN)** (expected sensitivity ~ 9 10^{-12} μ_B)
- Investigate **Coherent Elastic Neutrino Nuclear Scattering (CENNS)** :
  - Sterile neutrino
  - Non-standard neutrino interactions
  - Reactor monitoring





Magnetic moment of neutrino

Minimally-extended Standard Model
(μ_B – Bohr magneton)

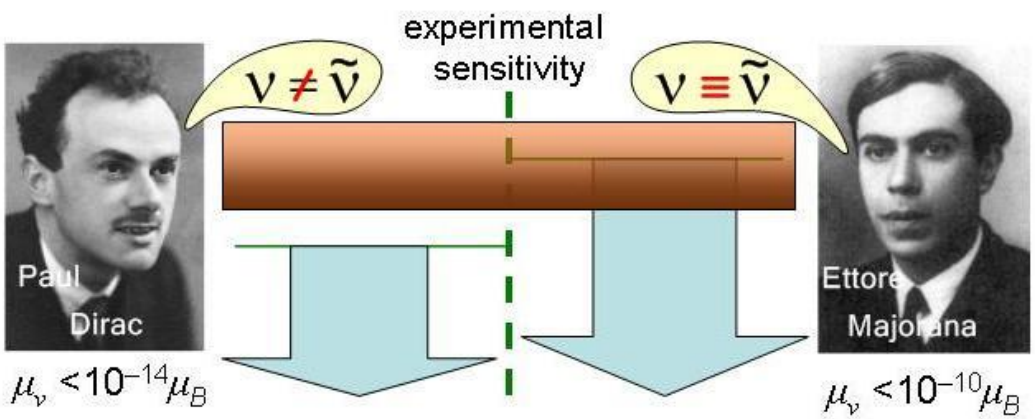
$\mu_\nu \sim 10^{-19}\,\mu_B \times (m_\nu\,/\,1\text{eV})$

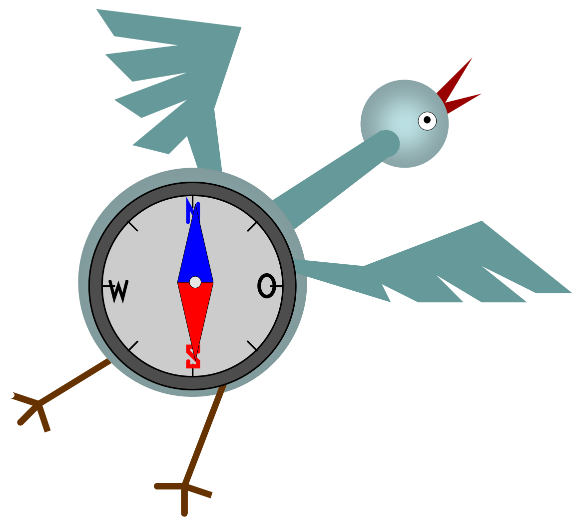
Different SM extensions predicts:

Majorana neutrino: $\mu_\nu = (10^{-11} \div 10^{-12})\,\mu_B$

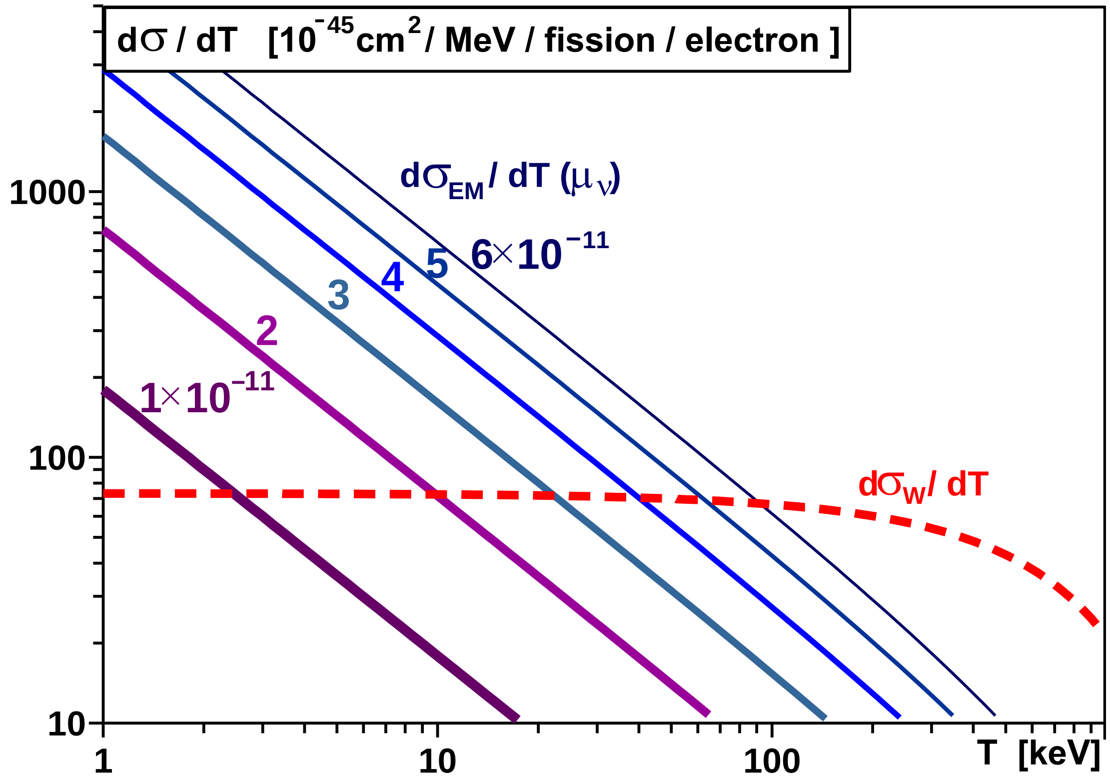
Dirak neutrino: $\mu_\nu < 10^{-14}\,\mu_B$

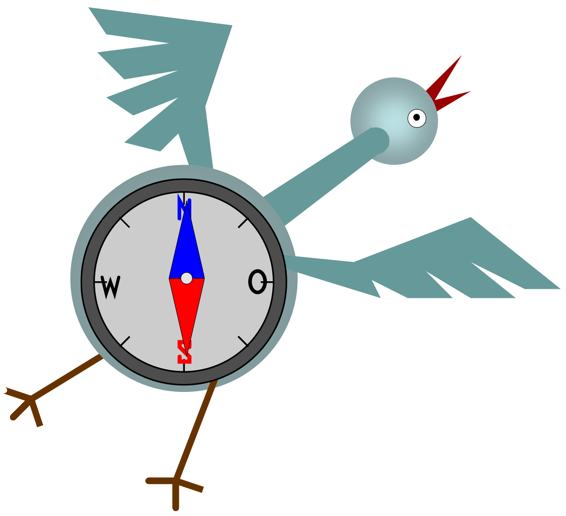
Observation of MMN would be a new physics beyond the Standard Model





Magnetic moment of ν





Cross-section (EM) for anti(neutrino) scattering on electrons:

$$\frac{d\sigma_{EM}}{dT} = \pi r_0^2 \left(\frac{\mu_\nu}{\mu_B}\right)\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

$\pi r_0^2 = 2.495 \cdot 10^{-25} cm^2$,

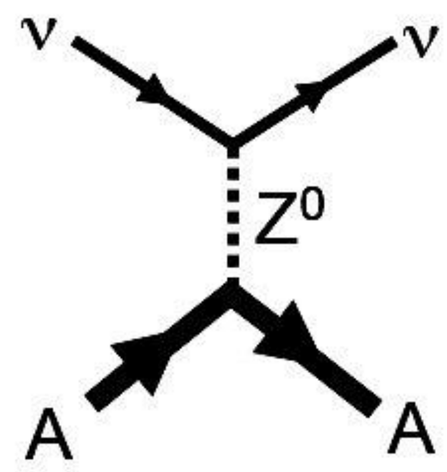
E_ν – neutrino energy

$$\mu_B = \frac{e\hbar}{2m_e}$$

The best terrestrial limit on MMN was set in **GEMMA-I** experiment: μ_ν < 2.9·10-11 μ_B

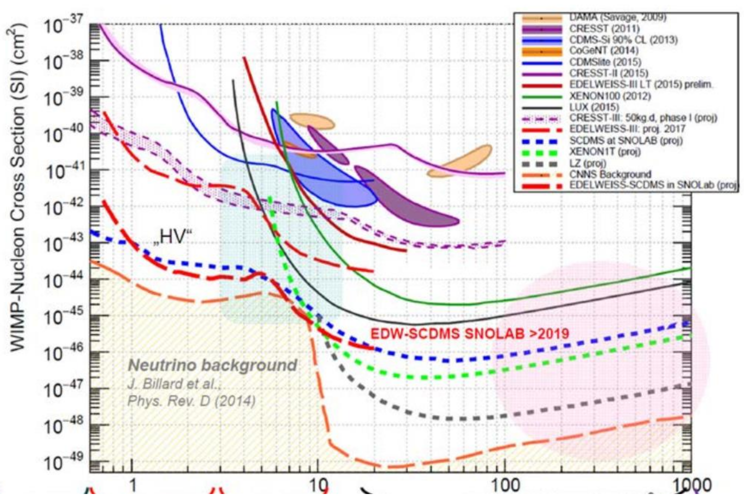
CENNS

Coherent elastic neutrino-nucleus scattering – allowed process in Standard Model it was never observed for reactor neutrinos.

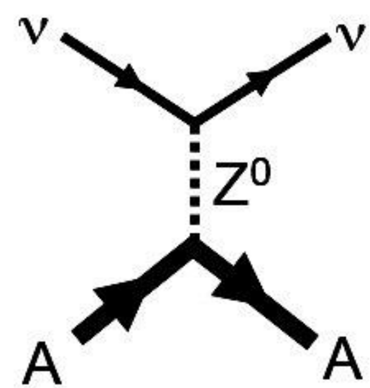


It is important for:

- Astrophysics and cosmology. Irreducible background for dark matter experiments.
- Good tool for searches of non-standard neutrino interactions.
- Can be used for sterile neutrino searches.
- Reactor monitoring.

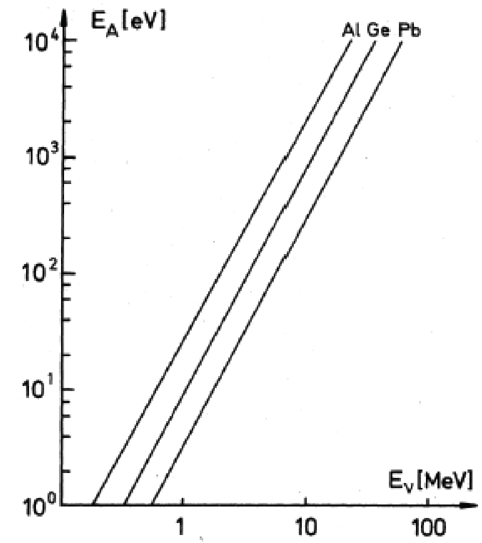


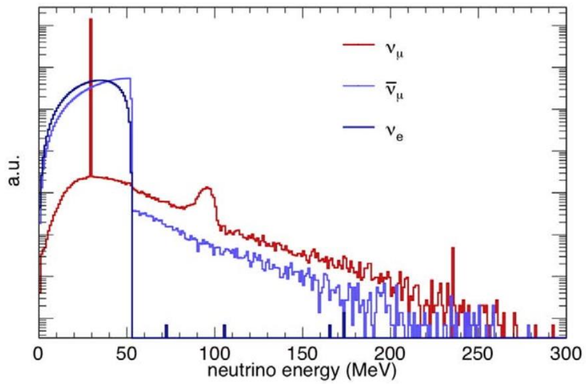
CENNS



$$\frac{d\sigma}{d\Omega} \simeq \frac{G_F^2}{16\pi^2} E_\nu^2 \ (1 + cos\theta) N^2 F^2(Q^2)$$

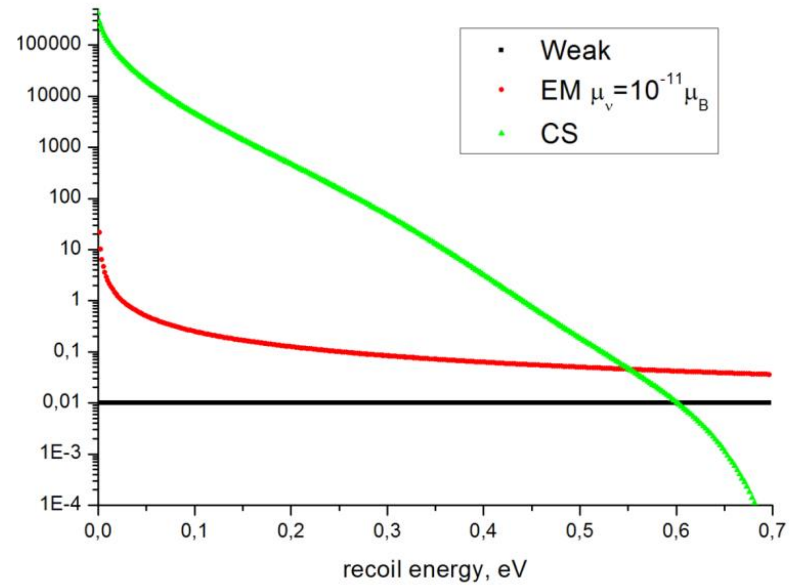
- E_ν < 50 MeV (full coherency ~ 30 MeV)
- Cross-section is being proportional to the number of nuclear target neutrons squared.
- Several orders of magnitude higher than "usual" cross-section of neutrino.
- Energy of recoils is very low (usually less than few keV).
- Moreover often only part of its energy can be detected (for Ge detector ~ 20%)
- Recently COHERENT experiment claims to detect CENNS, however with a rather high energy ν from accelerator, close to its coherency limit. We are going to check this result.





Neutrino detection

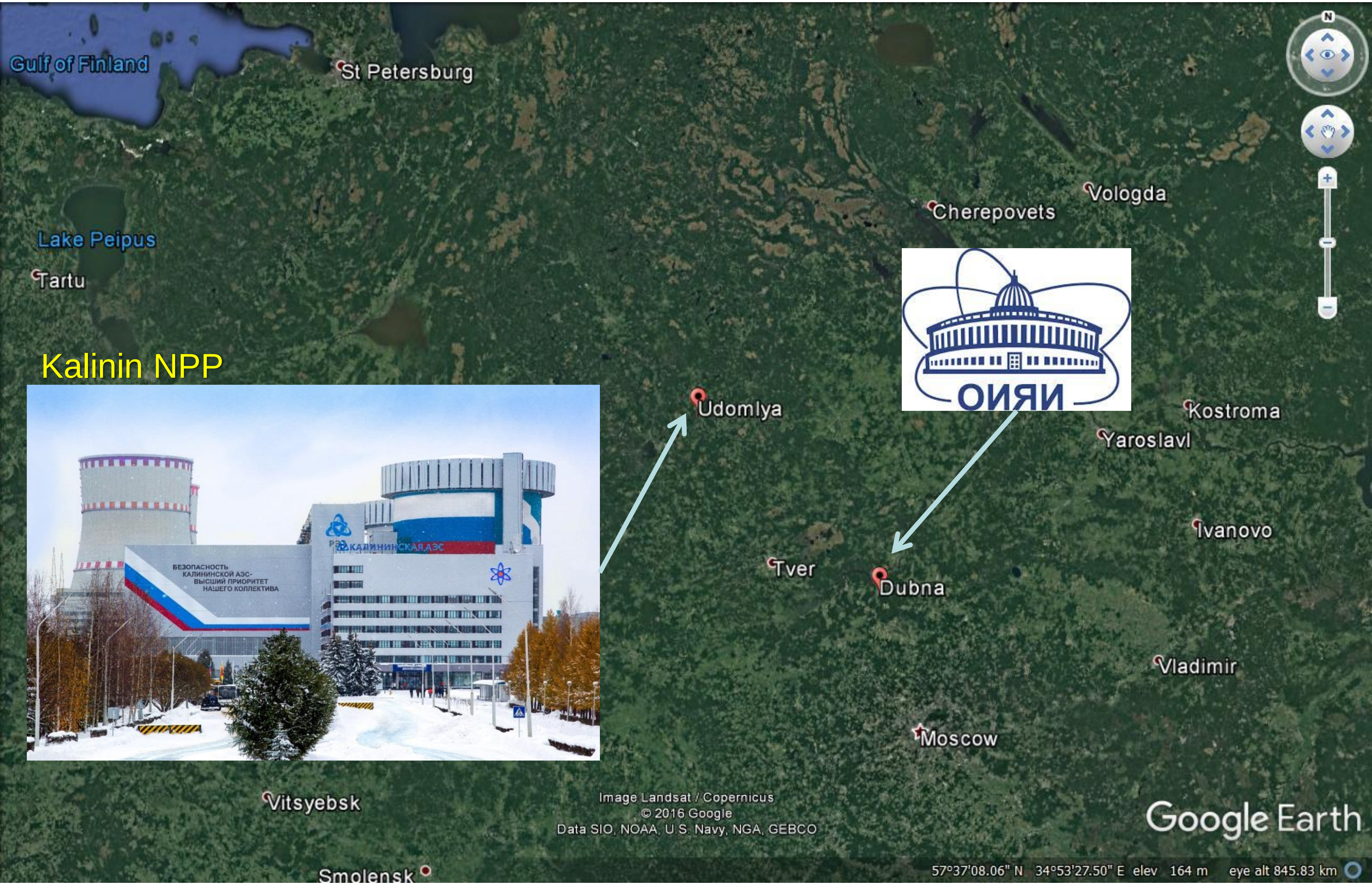
- Neutrino scattering give continuous spectra at low energies.
- Hard to distinguish from a background or noise
- Small number of events



To detect CENNS or MMN we need:

- Powerful source of neutrinos
- Detector with a very low threshold and good resolution
- Low background
- Clear separation of background events from the signal
- Good efficiency and big detector mass

KNPP


Gulf of Finland
St Petersburg
Lake Peipus
Tartu
Cherepovets
Vologda
Kalinin NPP
БЕЗОПАСНОСТЬ
КАЛИНИНСКОЙ АЭС-
ВЫСШИЙ ПРИОРИТЕТ
НАШЕГО КОЛЛЕКТИВА
КАЛИНИНСКАЯ АЭС
Udomlya
ОИЯИ
Kostroma
Yaroslavl
Ivanovo
Tver
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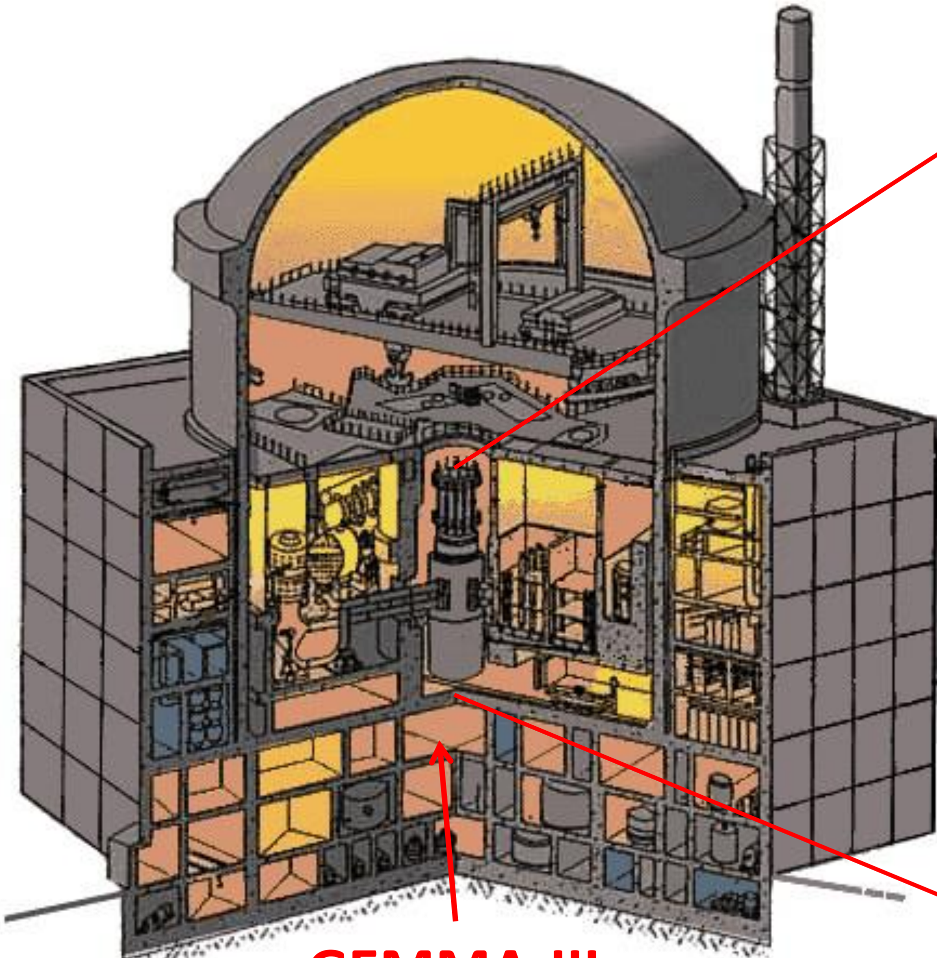
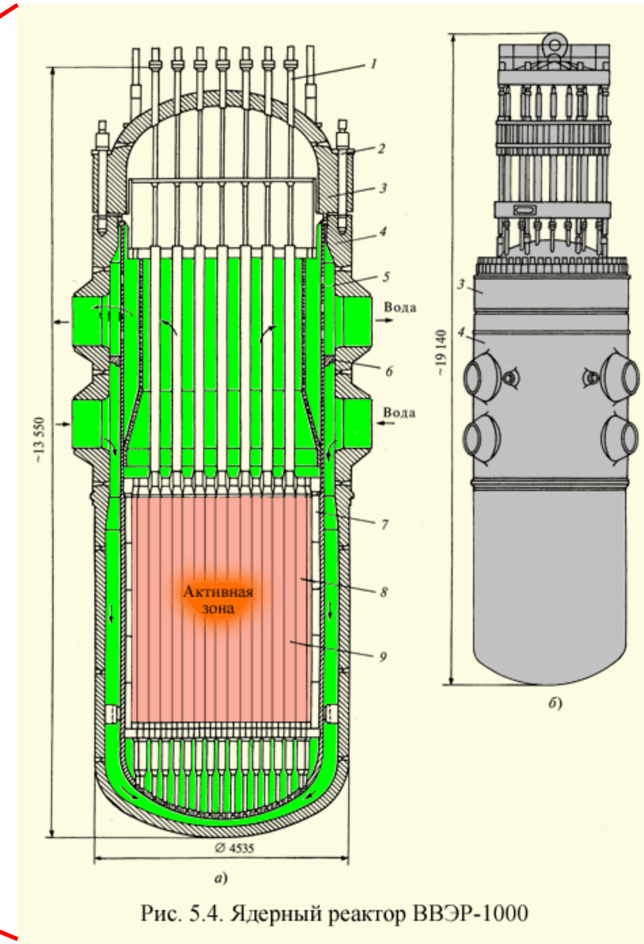
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google Earth
57°37'08.06" N 34°53'27.50" E elev 164 m eye alt 845.83 km

Neutrino source





Experimental setup is located only at **~ 10 m** from **3 GW** reactor's core. The available neutrino flux is **> $5\cdot10^{13}$ ν/(s·cm^{2})** – the highest in the field. Experimental setup is located under the reactor -> ~50 m w.e. (good shielding against cosmic radiation)

GEMMA project

GEMMA-I (done)
1.5 kg HPGe,
threshold ~ 3 keV
14 m from reactor
bkg ~ 2.5 cts/(keV kg day)

- Long and successful history of collaboration with KNPP
- (The best limit $\mu_\nu < 2.9 \cdot 10^{-11}$ μ_B was obtained in GEMMA-I)

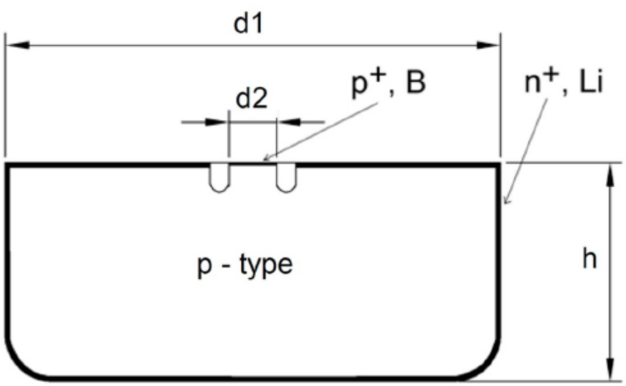
GEMMA-II (frozen)
2x3 kg HPGe (ITEP),
threshold ~ 1.5 keV
10 m from reactor
bkg < 1 cts/(keV kg day)

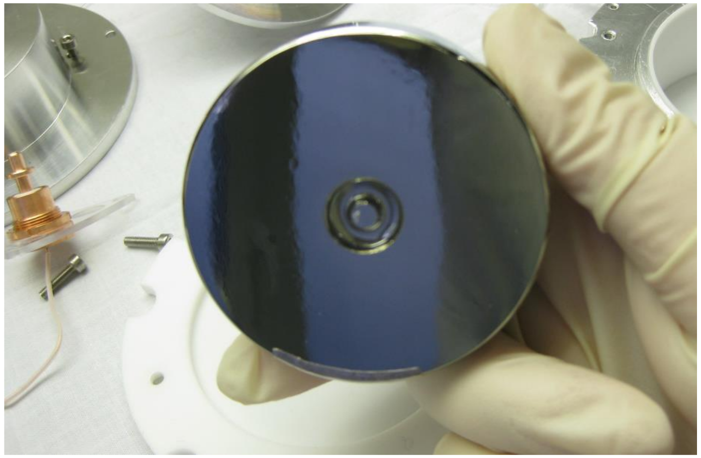
νGEN (under the constraction)
~ 4x0.4 kg HPGe,
threshold ~ 350 eV
10 m from reactor
bkg ~ 1 cts/(keV kg day) at LSM

GEMMA-III (preparation)
4 HPGe (5.5 kg total)
threshold < 200 eV
10 m from reactor
background < 1 cts/(keV kg day)

Detectors νGEN

Low-threshold HPGe detectors were developed in a collaboration JINR with BSI (Riga, Latvia). More than 50 samples were tested at LSM underground laboratory (Modane). Sources of higher background in GEMMA-II were found.

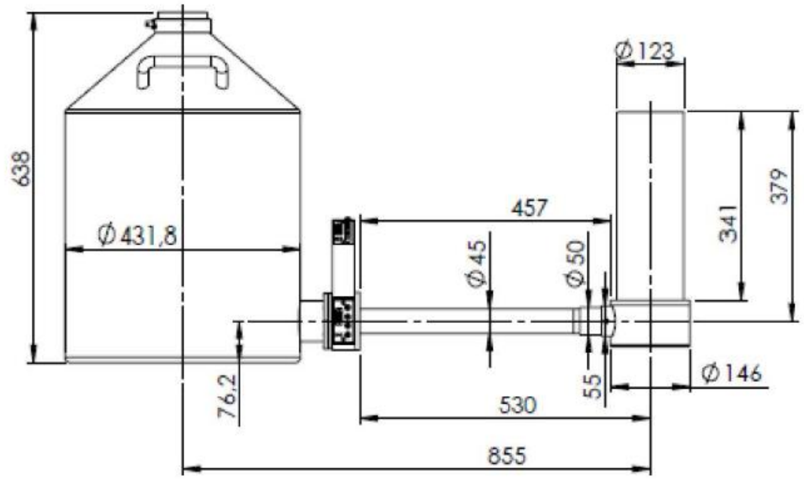


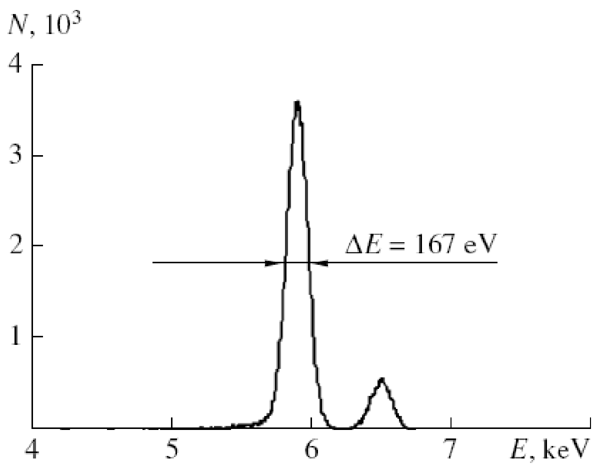


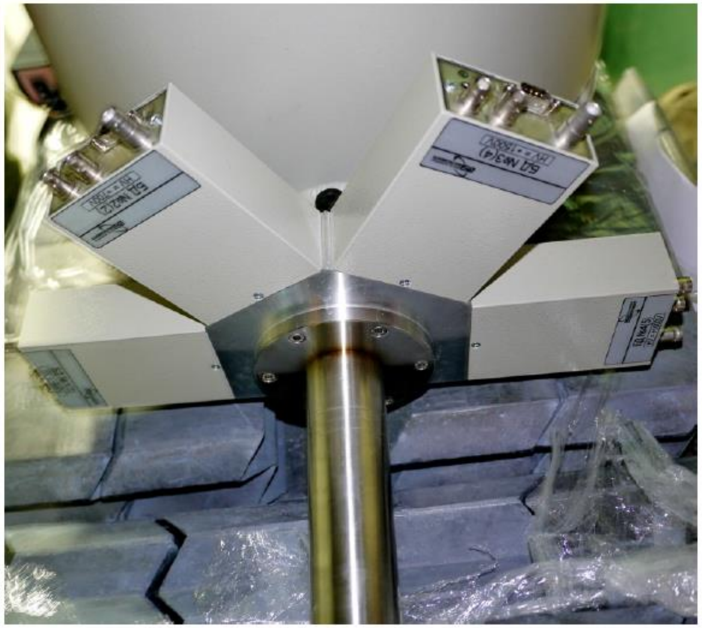
Mass ~ 400 g

νGEN spectrometer

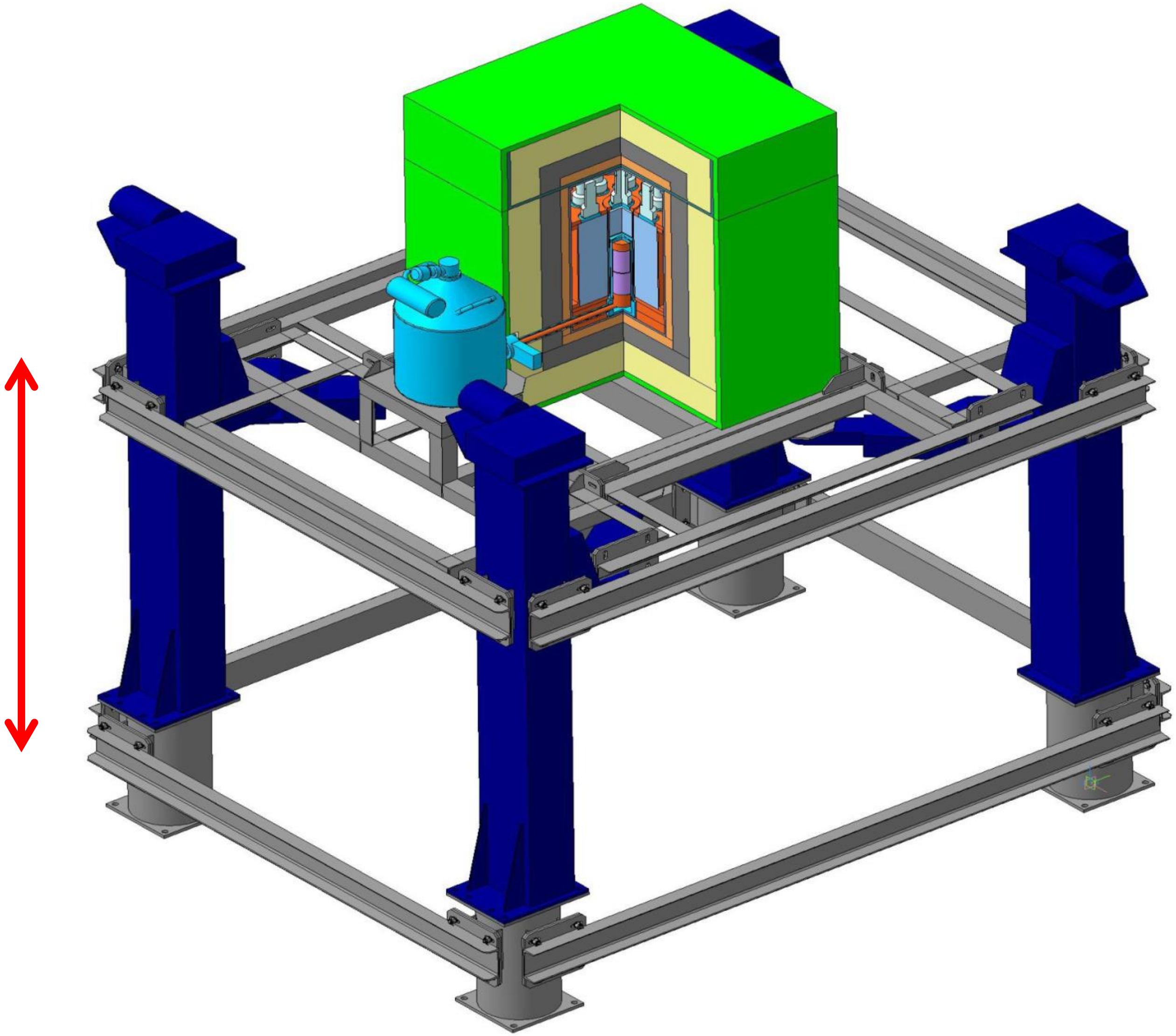
- Detectors resolution ~ 170 eV (FWHM)
- Threshold ~ 350 eV – enough for CENSS detection
- Keeping such parameters with a background level of about 1 cts/(keV kg day) would allow to detect of ~ 10 events from CENNS per day (background level is ~ 1 cts/day)







Lifting mechanism



For signal determination we will use:

- Data during reactor OFF/ON.
- Lifting mechanism changes distance from the reactor core (~ 10 – 12.5 m).
- Allows to decrease significantly systematic uncertainties in a background determination.

Measurements at LSM

The radiopurity and the performance of the detectors were tested at deep underground laboratory LSM (Modane). For the energy region from 100 to 600 keV the background index was found to be 0.66 ± 0.03 cpd/(kg·keV). For the region from 20 to 100 keV it is 1.11 ± 0.07 cpd/(kg·keV) without PSD.

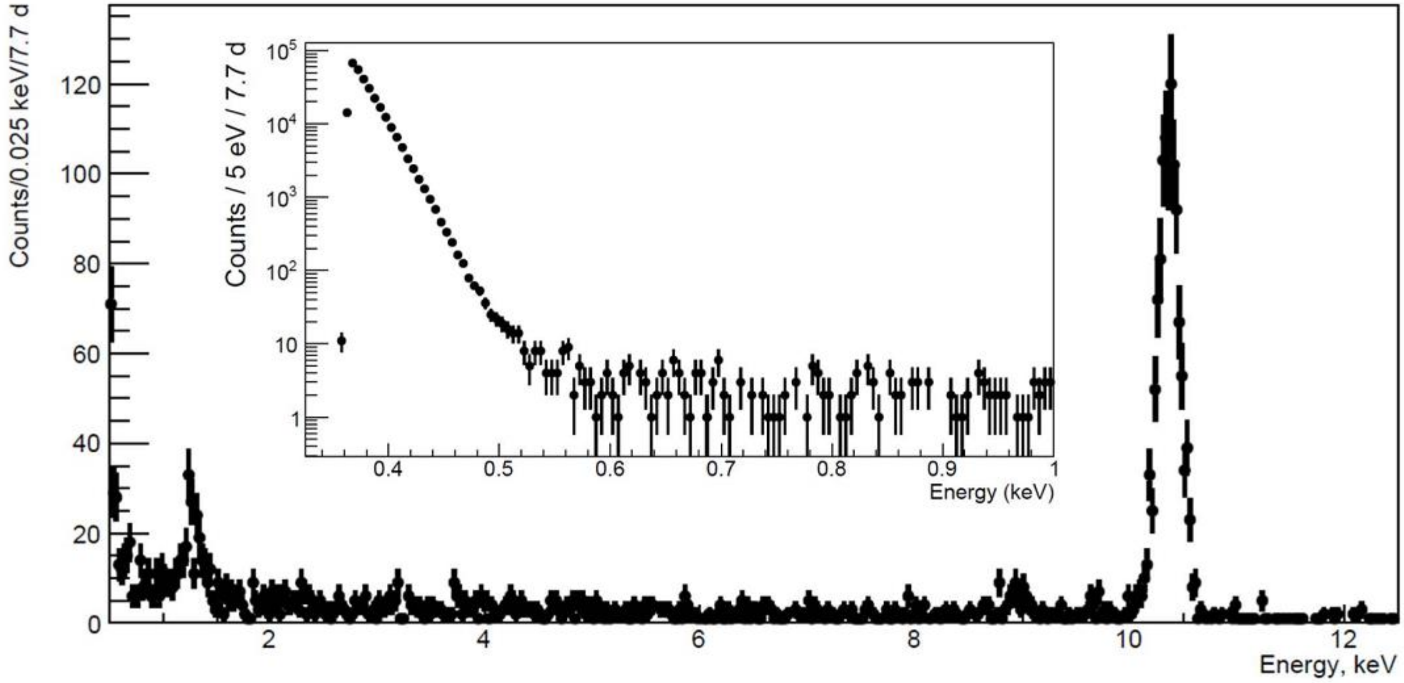
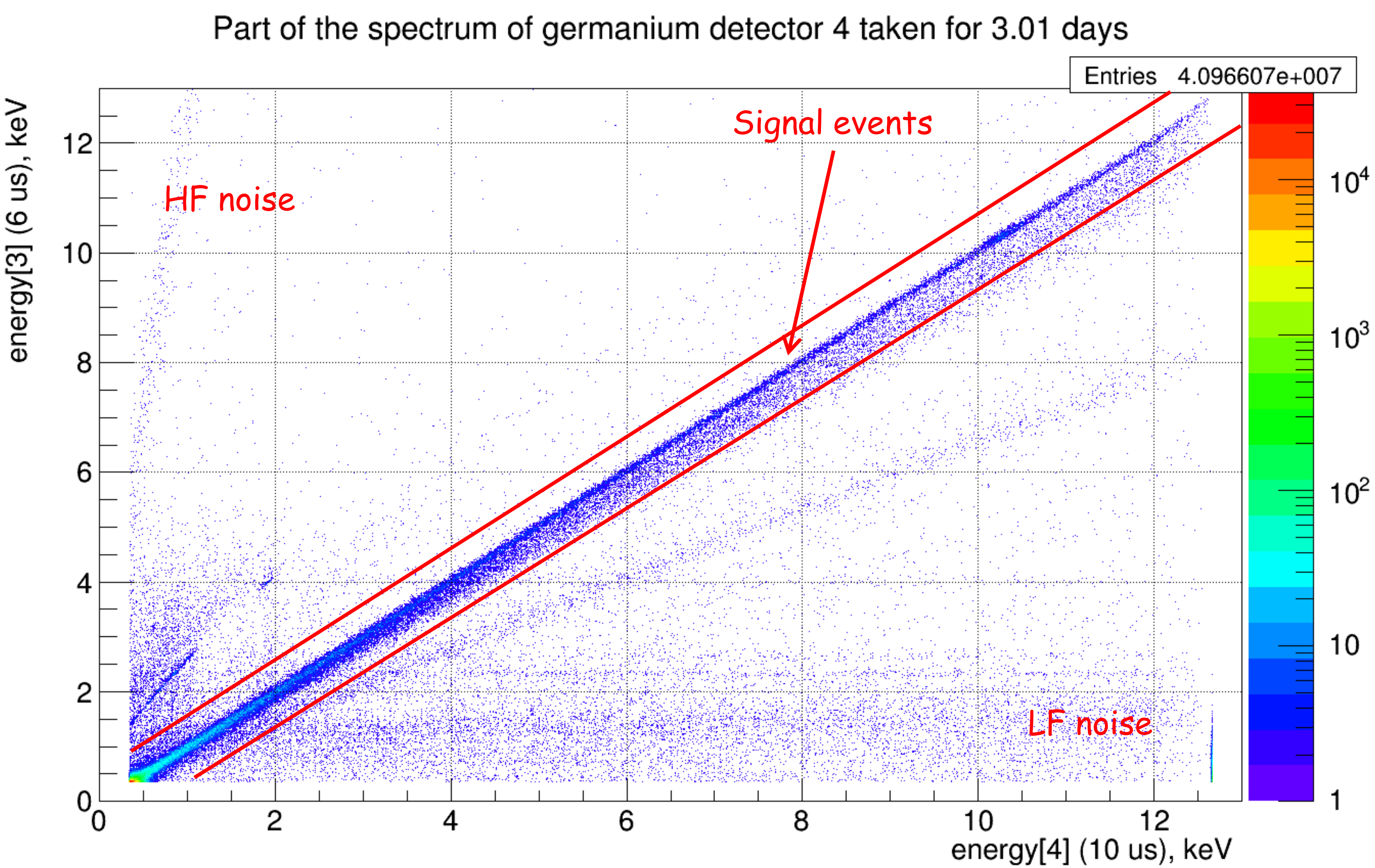


Figure 5. The low energy spectrum for detector N4. The energy scale was calibrated with clearly detected 1.3 keV and 10.37 keV cosmogenic lines. The low energy part of the spectrum is shown as the insert with the logarithmic scale.

V.Belov et. al, 2015 JINST 10 P12011

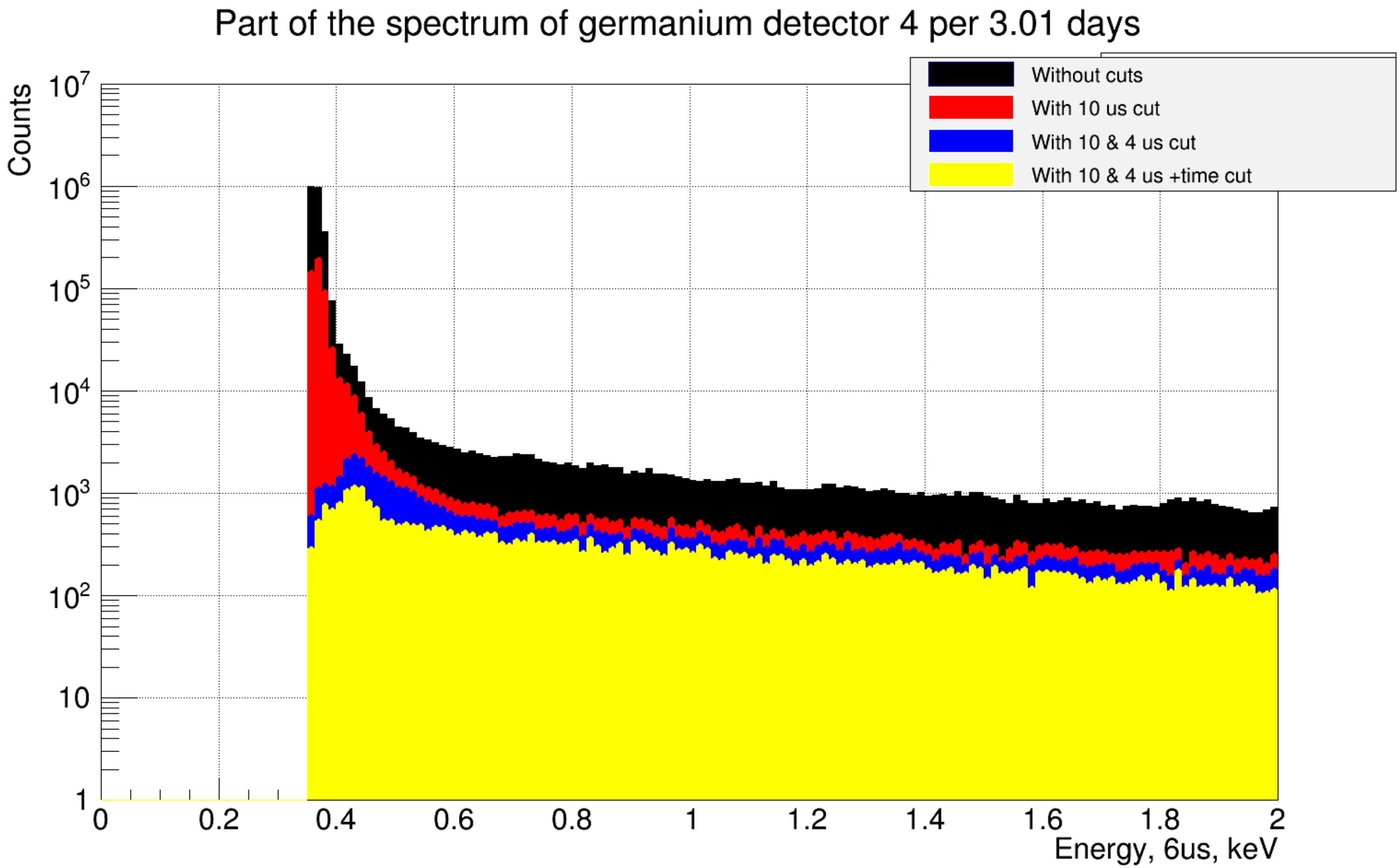
Measurements at JINR

After radiopurity tests at LSM , detectors were moved to JINR (Dubna). A new acquisition system has been installed. Signal from germanium detector currently we are taking with help of real time ADC using different shaping times of amplifiers.



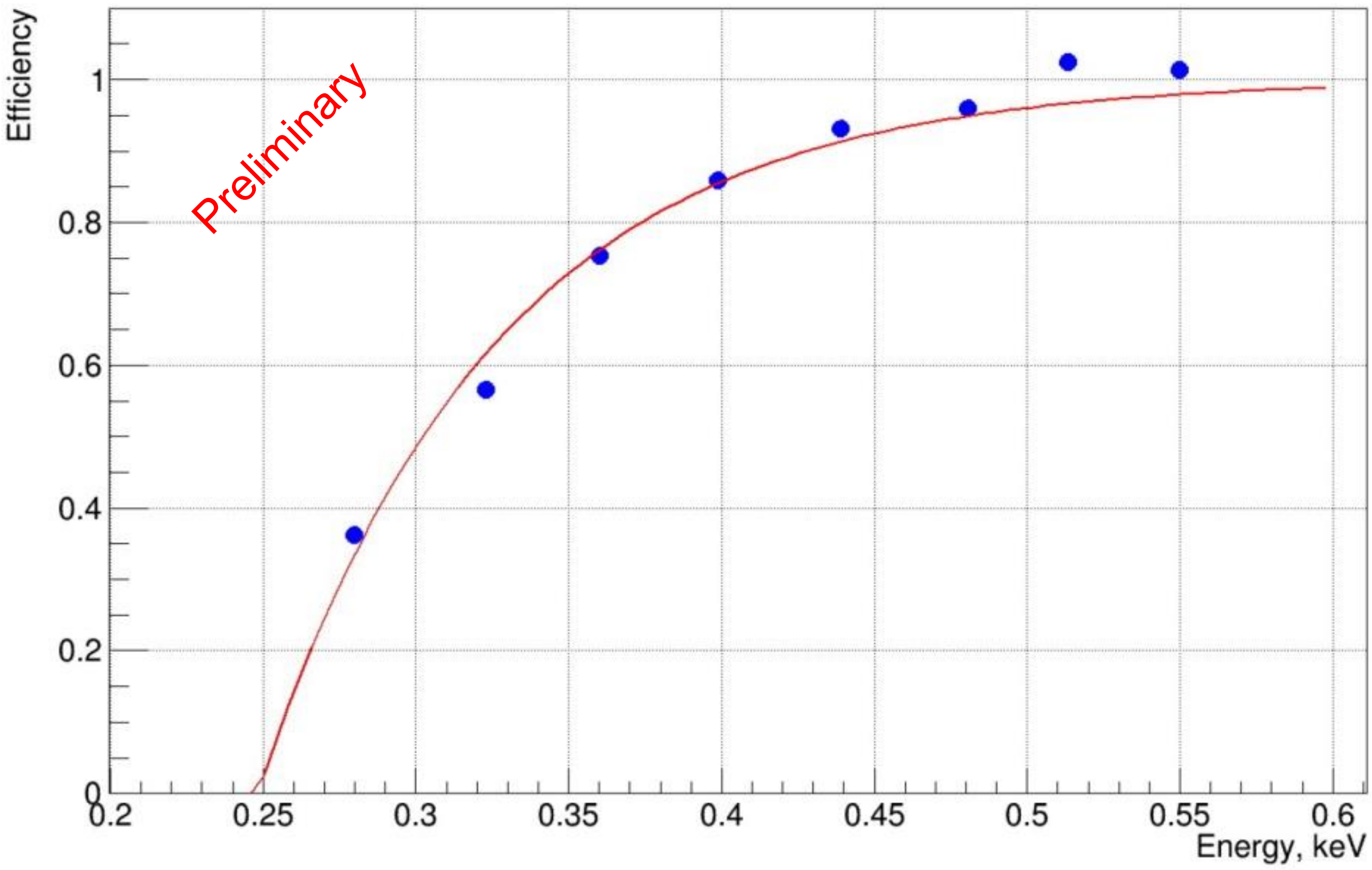
Measurements at JINR

Using difference in energy reconstruction by different filters it is possible to suppress high and low frequency noises. In addition to such cut we suppress periodical noise as well.

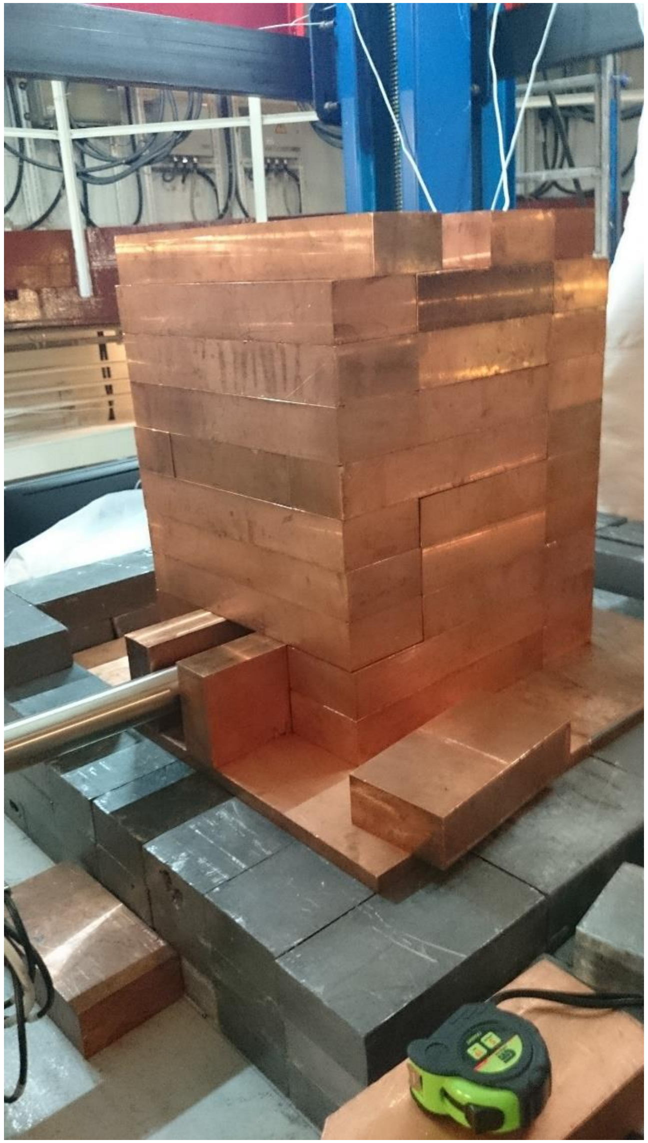


Detection efficiency

Detection efficiency was tested with pulse generator. It was demonstrated at the energies > 350 eV detection efficiency is more than ~ 70%. That is sufficient for CENSS detection.



Installation at KNPP



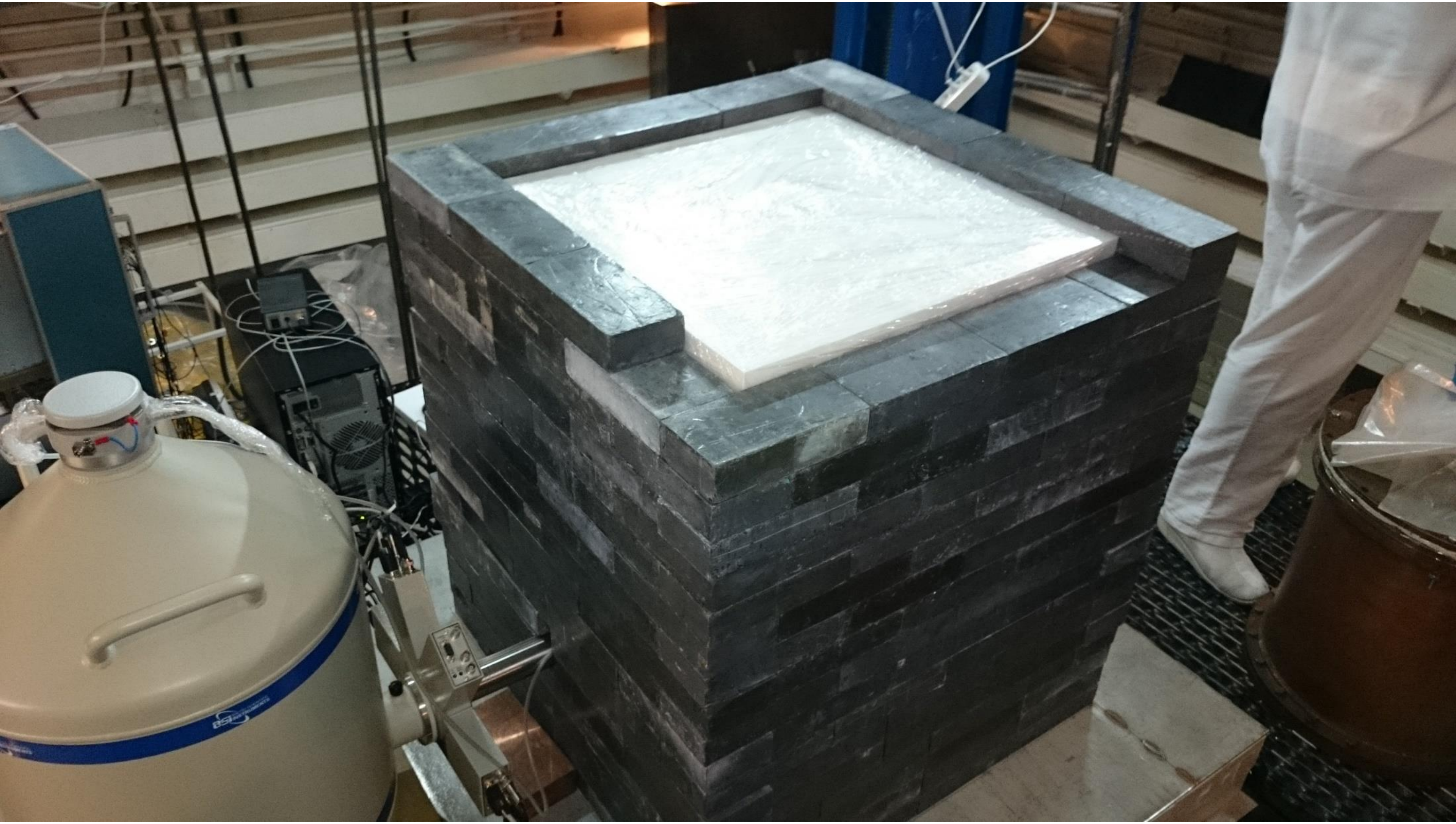
Passive shielding:
- 10 cm copper
- 8 cm borated polyethylene (3%)
- 10 cm lead
- 8 cm borated polyethylene

+ muon veto (5 cm)

Installation at KNPP

To decrease radon background internal parts are being vented with N2.

Installation at KNPP



Installation at KNPP

First measurements with νGEN spectrometer showed that copper shielding from GEMMA-I has contamination of ^{137}Cs much higher than we expected. We performed several iterations of cleaning it, but they were not enough efficient. Therefore we bought new ultra clean copper, it will be installed instead of current one. It radiopurity was tested at LSM (October 2017).

Preparation of μ-veto

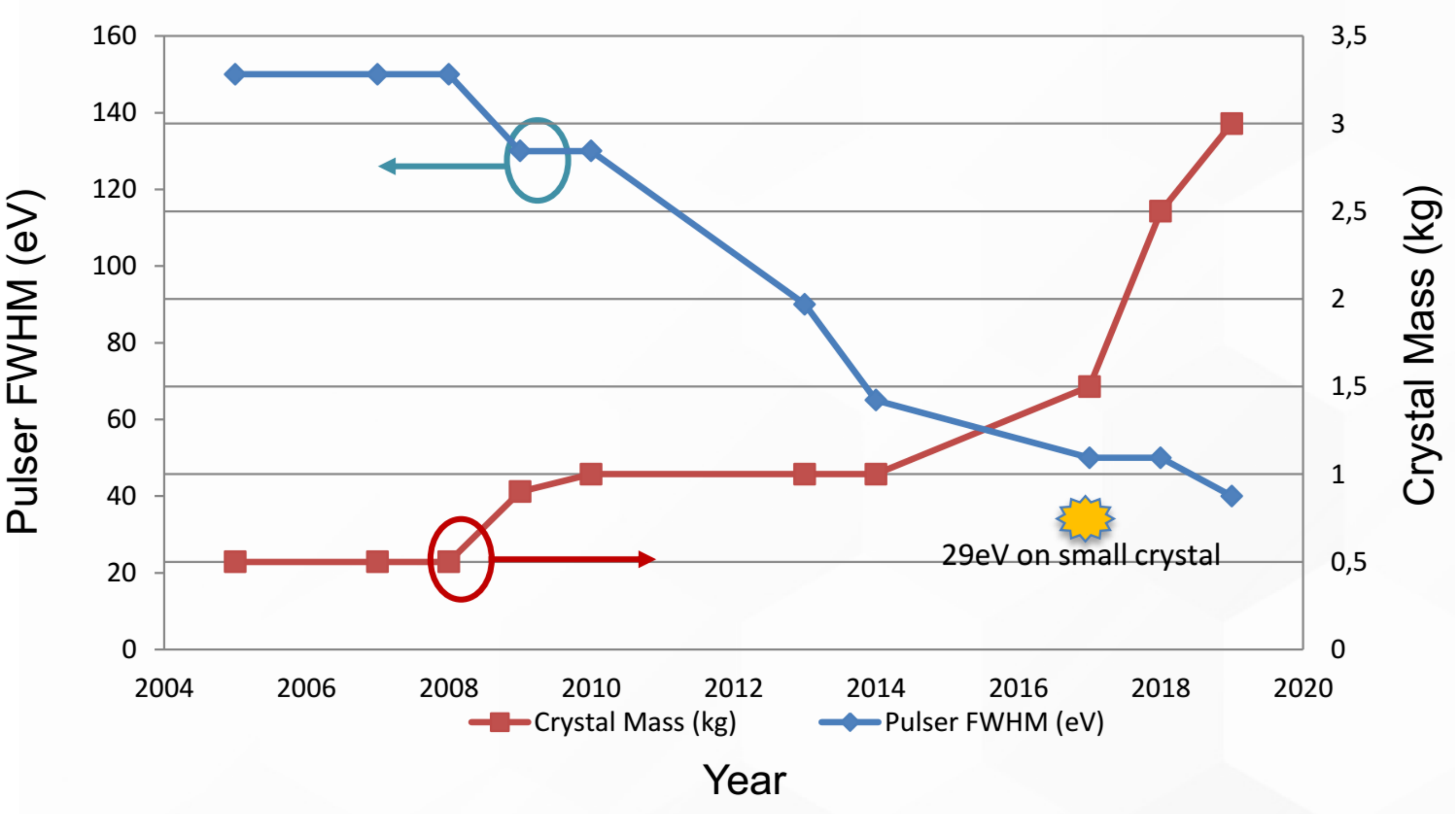
Scintillation plates (5 cm thickness) for muon veto were produced and tested at DLNP, JINR.

Plans for νGEN

- Install new shielding together with muon veto
- Check background level in the final configuration
- In case of higher background we could used internal active defense from NaI.
- Detect CENNS
- Upgrade experimental setup using newly produced CANBERRA detectors (they have much better energy resolution and threshold - GEMMA-III setup).

Detectors for GEMMA-III

Last years technologies for the detector production went to the new level. CANBERRA can produce detector with a mass > 1 kg which can reach resolution of better 80 eV (FWHM), than is allows to reach threshold ~ 200 eV.



Plans for GEMMA-III

- In the beginning of 2018 new CANBERRA detector has to be produced. Dimension of the first detector 62x62 mm. Mass ~ 1 kg, resolution ~ 80 eV (FWHM).
- After successful tests at LSM -> swap νGEN spectrometer.
- In total we are planning to use four detectors with a total mass of ~ 5.5 kg. Start measurements: end 2018 – beginning 2019.
- Planned sensitivity to MMN ~ $9 \cdot 10^{-12}\ \mu_B$ after several years of measurements.
- Expected number of events from CENNS ~ 190 per day will allow to investigate non-standard neutrino interactions, sterile neutrinos,…

Back up

Задействованный персонал

Name	Category	Responsibilities	Full Time Equivalent (FTE)
V. Brudanin	Head of department	Administrative work, project management	0.2
V. Belov	Junior researcher	Muon veto, MC	0.2
V. Egorov	Head of sector	Management, constructions, data analysis	0.3
M. Fomina	Junior researcher	Muon veto, MC	0.3
A. Lubashevskiy	Senior Researcher	Data analysis, MC, commissioning and administrative work	0.5
D. Medvedev	Reseacher	Data analysis, MC	1.0
D. Ponomarev	Engineer	Constructions, detectors building, testing. Experiment running.	1.0
M. Shirchenko	Reseacher	Experiment running. Data analysis	0.3
V.Sandukovsky	Head of sector	Detector configuration, constructions	0.5
S. Rozov	Engineer	Detector building, testing, calibration, running.	0.5
I. Rozova	Engineer	Data analysis, constructions	1.0
I. Zhitnikov	Junior researcher	Experiment running, data analysis	0.2
E. Yakushev	Head of sector	Building, commissioning, running, data analysis	0.3
D. Zinatulina	Reseacher	Muon veto, MC	0.2
Total FTE (Engineers): 2.5, Total FTE (Scientific staff): 3.9, Total FTE: 6.4			

План-график для проекта GEMMA-III

Наименование узлов и систем установки, ресурсов, источников финансирования			Стоимость узлов (тыс.$). установки. Потребности в ресурсах	Предложения Лабораторий по распределению финансирования и ресурсов		
				1 год.	2 год.	3 год
Основные узлы и оборудование	1.Криогенное оборудования для детекторов. (Криостаты)		70.0	70.0		
	2. Материалы для калибровок и пассивной защиты.		30.0	25.0	10.0	5.0
	3. Электроника NIM		50.0	40.0	10.0	
	4. Электороника VME		55.0	35.0	20.0	
	Итого		**215.0**	**170.0**	**40.0**	**5.0**
Необходимые ресурсы	Нормо-часы	ООЭП ЛЯП	600	200	200	200
Источники финансирования	Бюджет	Затраты из бюджета	215.0	170.0	40.0	5.0
	Внебюджетные средства	Вклады коллаборантов. Средства по грантам. Вклады спонсоров Средства по договорам. Другие источники и т.д.	45.0	20.0	15.0	10.0

Прямые затраты по проекту

№	Наименование статей затрат	Полная стоимость	1 год	2 год	3 год
1.	Компьютерная связь	6.0 тыс. $	2.0	2.0	2.0
2	ООЭП ЛЯП	600 нормо/час	200	200	200
3.	Материалы	40.0 тыс. $	25.0	10.0	5.0
4.	Оборудование	175.0 тыс. $	145.0	30.0	
5.	Оплата НИР, выполняемых по договорам	6.0 тыс. $	2.0	2.0	2.0
6.	Командировочные расходы, в т.ч.	60.0 тыс. $	20.0	20.0	20.0
	а) в страны нерублевой зоны		5.0	5.0	
	б) в города стран рублевой зоны		15.0	15.0	20.0
	Итого по прямым расходам:	**287.0 тыс.$**	**194.0**	**64.0**	**29.0**

Investigation of neutrino properties with
the low-background germanium spectrometer GEMMA-III

GEMMA-III

CODE OF THEME 03-2-1100-2010/2018

V.V.Belov, V.B.Brudanin, V.G.Egorov, M.V.Fomina, A.V.Lubashevskiy, D.V.Medvedev, D.V.Ponomarev, M.V.Shirchenko, S.V.Rozov, I.E.Rozova, I.V.Zhitnikov, E.A.Yakushev, D.R.Zinatulina

Laboratory of Nuclear Problems, JINR

NAMES OF PROJECT LEADERS: V.B.Brudanin

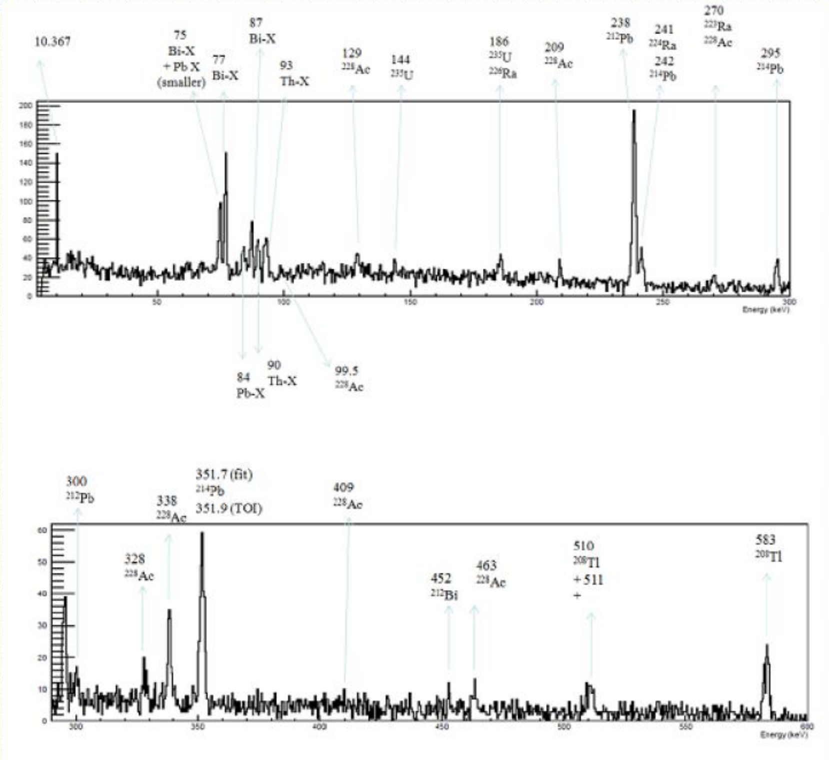
NAME OF PROJECT DEPUTY LEADERS: A.V.Lubashevskiy, E.A.Yakushev

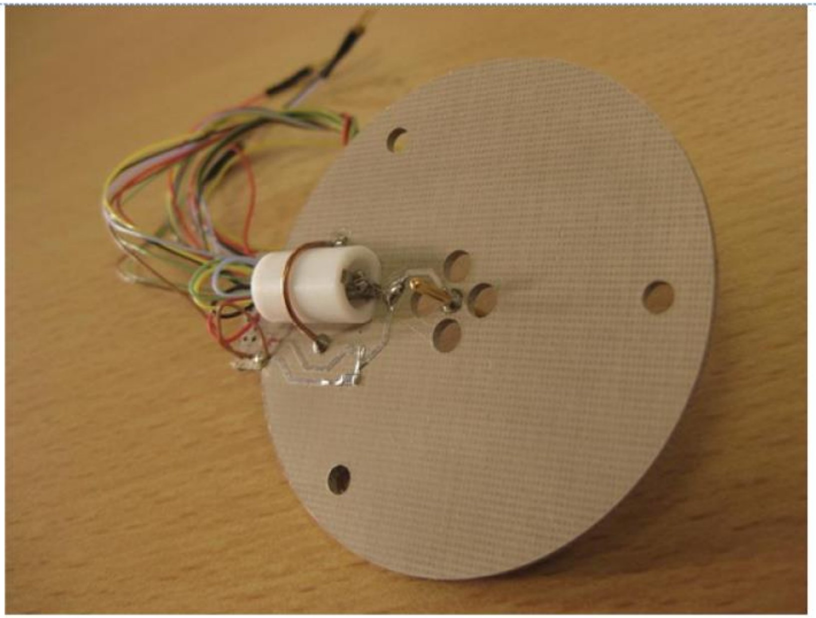
DATE OF SUBMISSION OF PROPOSAL OF PROJECT TO SOD _________

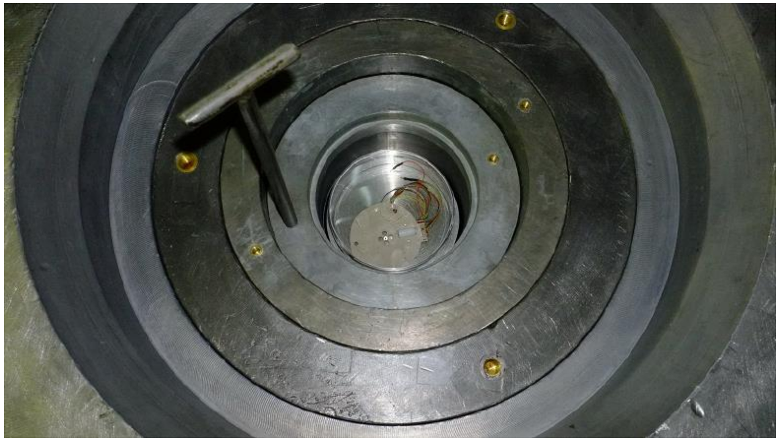
DATE OF THE LABORATORY STC _________ DOCUMENT NUMBER _________

STARTING DATE OF PROJECT __January 2019_______(FOR EXTENSION OF PROJECT — DATE OF ITS FIRST APPROVAL) _07.02.2014________

GEMMA-II

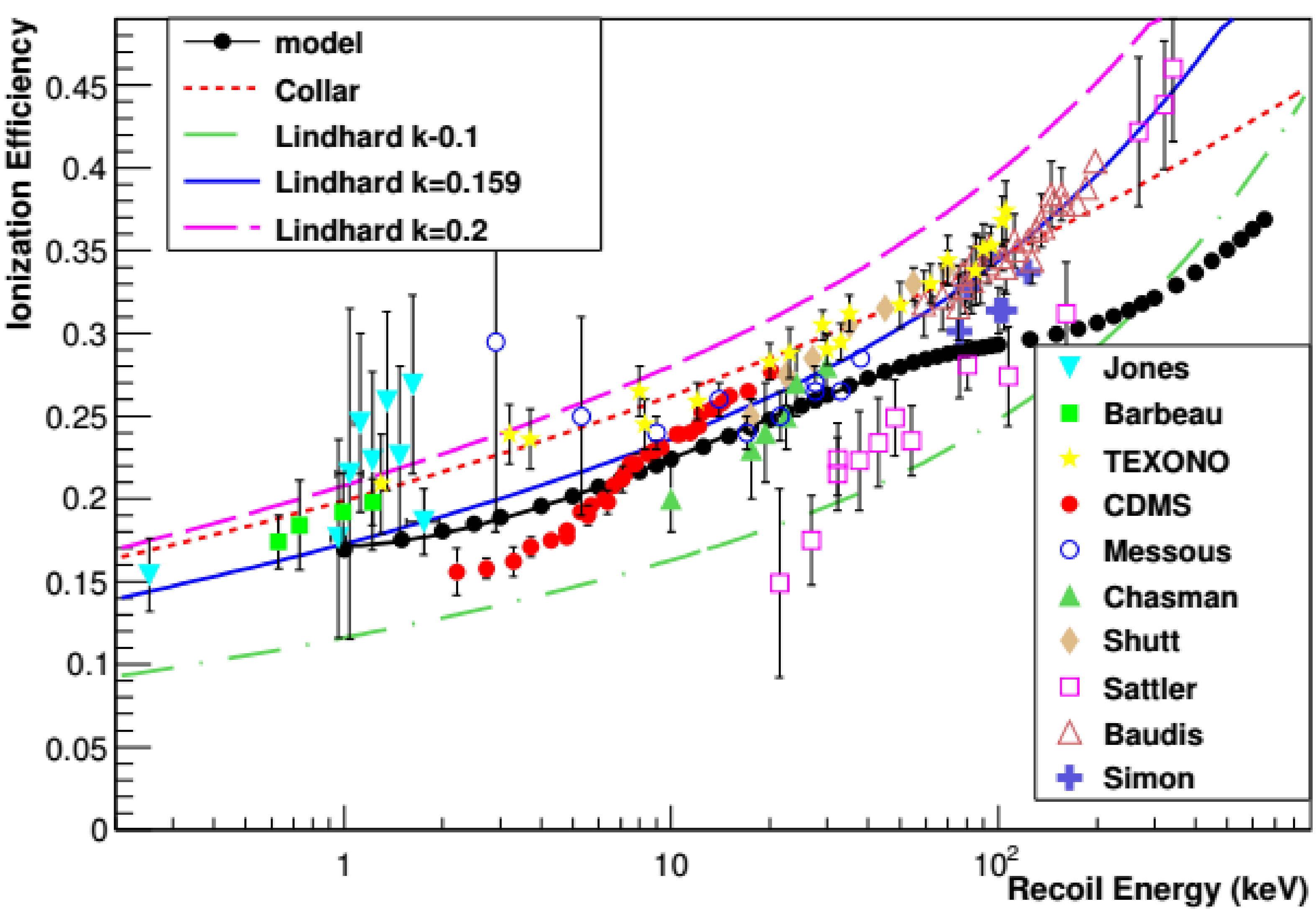






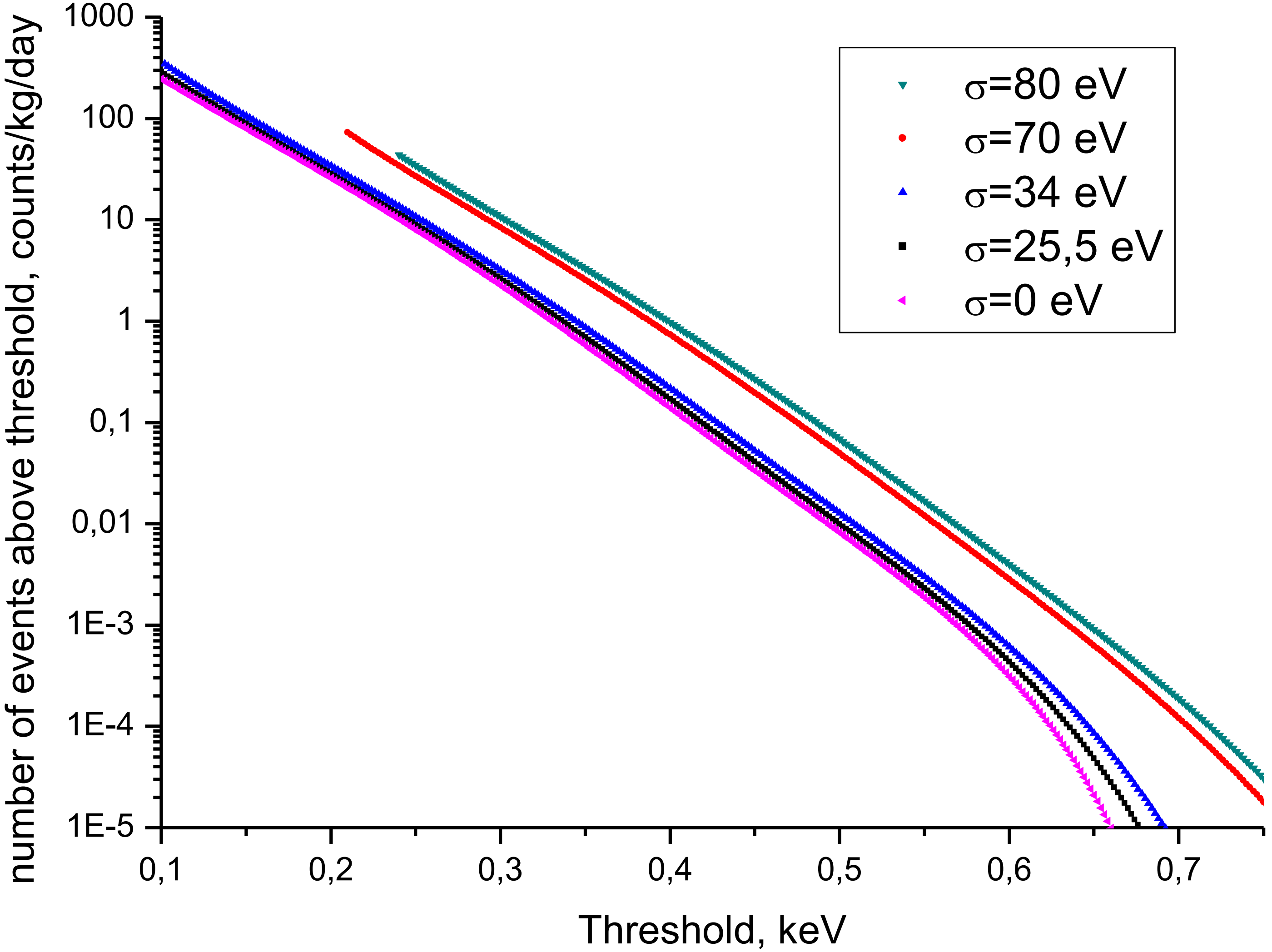
Main problem is background (level is ~100 times higher of desired value)

Quenching



D.Barker, D.M.Mei, Astropart.Phys. 38 (2012) 1-6

Expected number of events



Sensitivity

$$\mu_\nu \propto \frac{1}{\sqrt{N_\nu}} \left(\frac{B}{mt} \right)^{\frac{1}{4}}$$

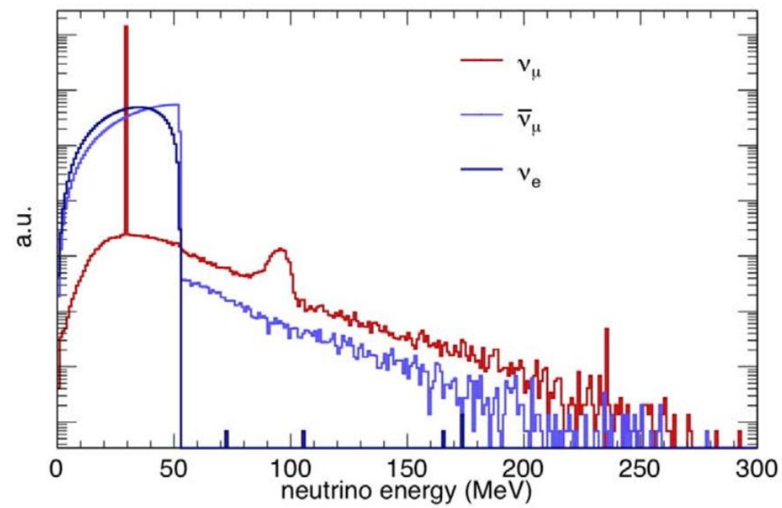
N_ν : number of signal events expected
B : background level in the ROI
m : target (=detector) mass
t : measurement time

$$N_\nu \sim \varphi_\nu (\sim Power / r^2)$$
$$\sim (T_{max} - T_{min} / T_{max} * T_{min})^{1/2}$$

φ_ν ~ 2.7×10^{13} ν / cm^2 / s
t ~ 4 years
B ~ 2.5 keV^{-1} kg^{-1} day^{-1}
m ~ 1.5 kg
T_{th} ~ 2.8 keV

Когерентное рассеяние ν

Поиск когерентного рассеяния нейтрино осуществляется во многих экспериментах: Ricochet, MINER, CONNIE, CONUS, COHERENT, νGEN... В августе этого года коллаборация COHERENT заявила об обнаружении когерентного рассеяния нейтрино, от ускорителя SNS на сцинтилляторах CsI. Результаты получены с достаточно высокоэнергетическими нейтрино с энергиями близкими к границе когерентности.



В проекте GEMMA-III мы планируем проверить результаты эксперимента COHERENT с помощью нейтрино от реактора (E_ν < 10 MeV). При этом отношение сигнал/фон будет значительно выше. Также планируется поиск нестандартных взаимодействий нейтрино.