Status and new results from the νGeN experiment at Kalinin nuclear power plant

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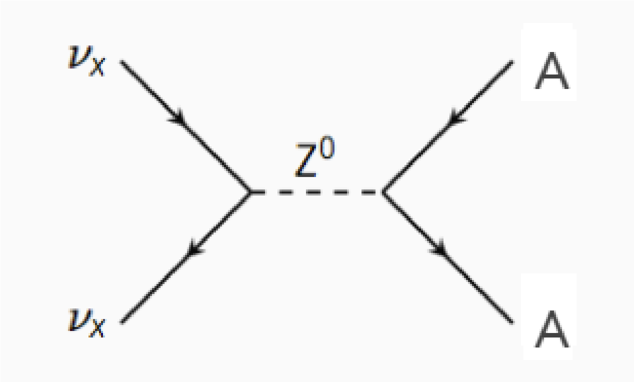
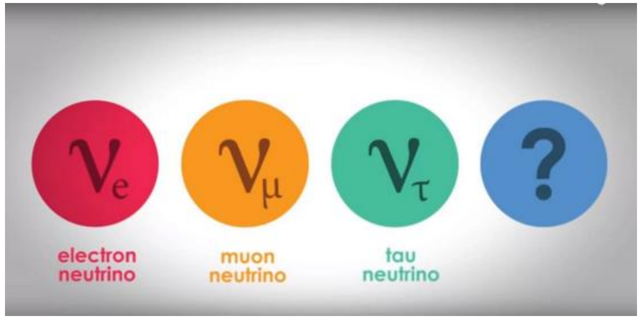
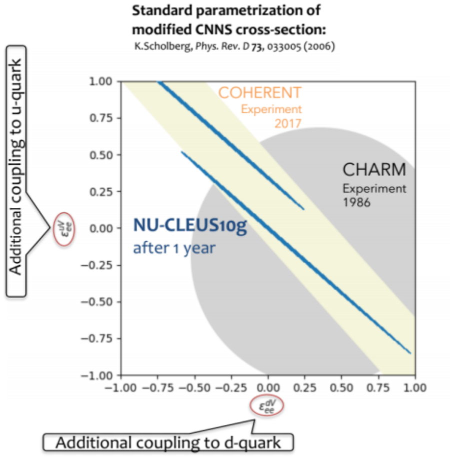
νGeN aims:

νGeN experiment is aimed to study neutrino scattering using antineutrinos from the reactor core of Kalinin Nuclear Power Plant (KNPP) at Udomlya, Russia. Main searches:

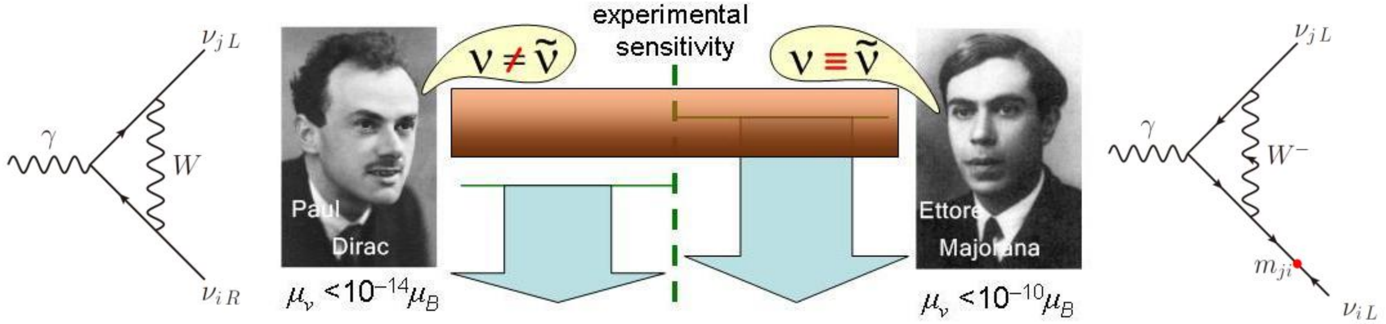
- **Coherent elastic neutrino-nucleus scattering (CEνNS).**
- Non-standard neutrino interactions.
- **Neutrino magnetic moment (NMM).**
- Nuclear physics, sterile neutrino.
- Other rare and exotics processes.
- Applied usage: reactor monitoring.





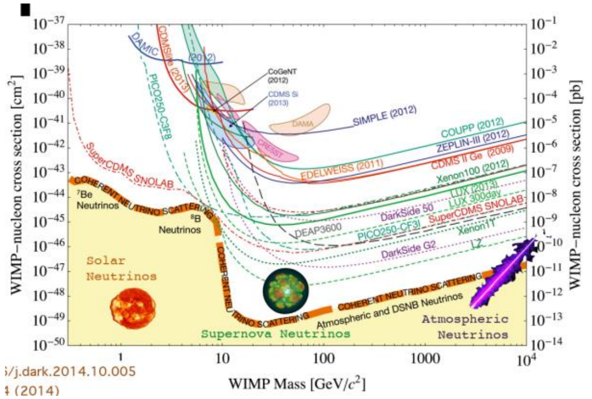


Magnificent CEvNS, Raimund Strauss



1: Magnetic moment diagram for Dirac neutrinos.

Figure 2: Magnetic moment diagram for Majorana neutrinos.



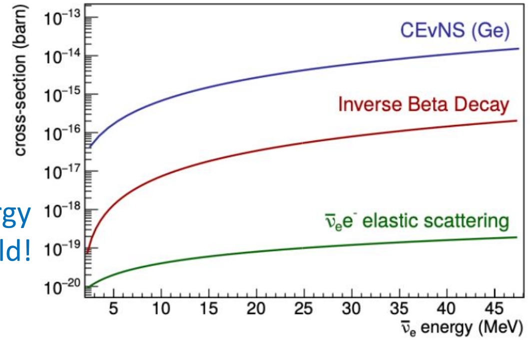
Detection of CEνNS

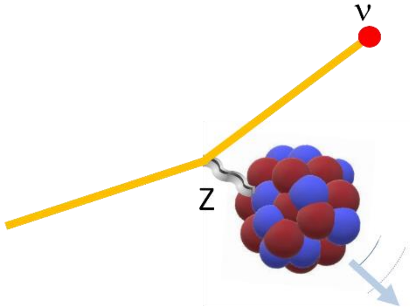
Coherent elastic neutrino-nucleus scattering is the process allowed in the Standard Model. But has not been observed yet for reactor antineutrinos. These observations can help with the search of non-standard neutrino interactions, sterile neutrinos and other investigations.

CEνNS cross section is:

$$\sigma_{tot} \approx \frac{{G_F}^2}{4\pi^2} \cdot N^2 \cdot {E_\nu}^2$$

No energy threshold!





A.Drukier and L.Stodolsky, Phys.Rev.D 30, 2295 (1984)

D. Freedman, Phys.Rev. D 9 1389 (1974)

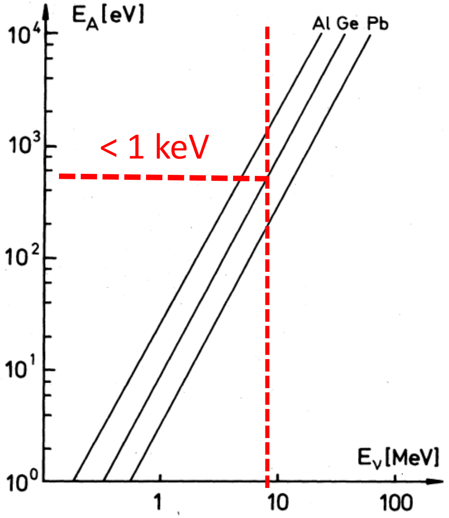


FIG. 2. Average recoil energy for various nuclei as a function of neutrino energy.

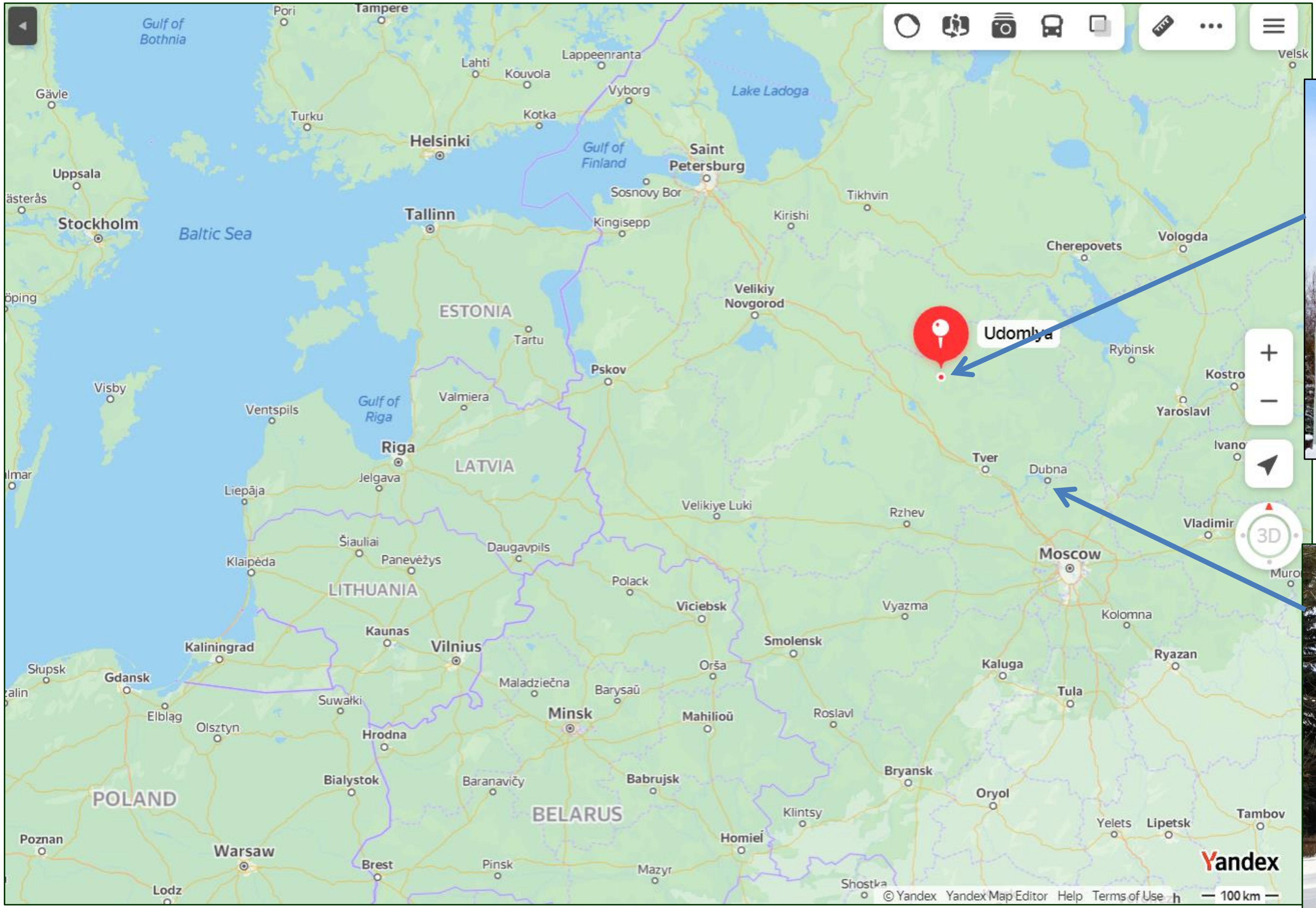
Energy of nuclear recoil from CEνNS is very low:

$$E_A = \frac{2E^2(1 - cos\theta)}{2MA}$$

The detection of this process is very challenging, taking into account that often only part of the energy can be detected due to quenching.

- Powerful neutrino source in full coherency regime < 30 MeV.
- Low threshold and low background detector.
- Effective separation of signals from background.
- Big target mass and good efficiency.
- Stable performance and knowledge of systematical errors.

νGeN reactor site at Udomlya, Russia



Kalinin Nuclear Power Plant (KNPP) 4xWWER – 3.1 GW_{th}

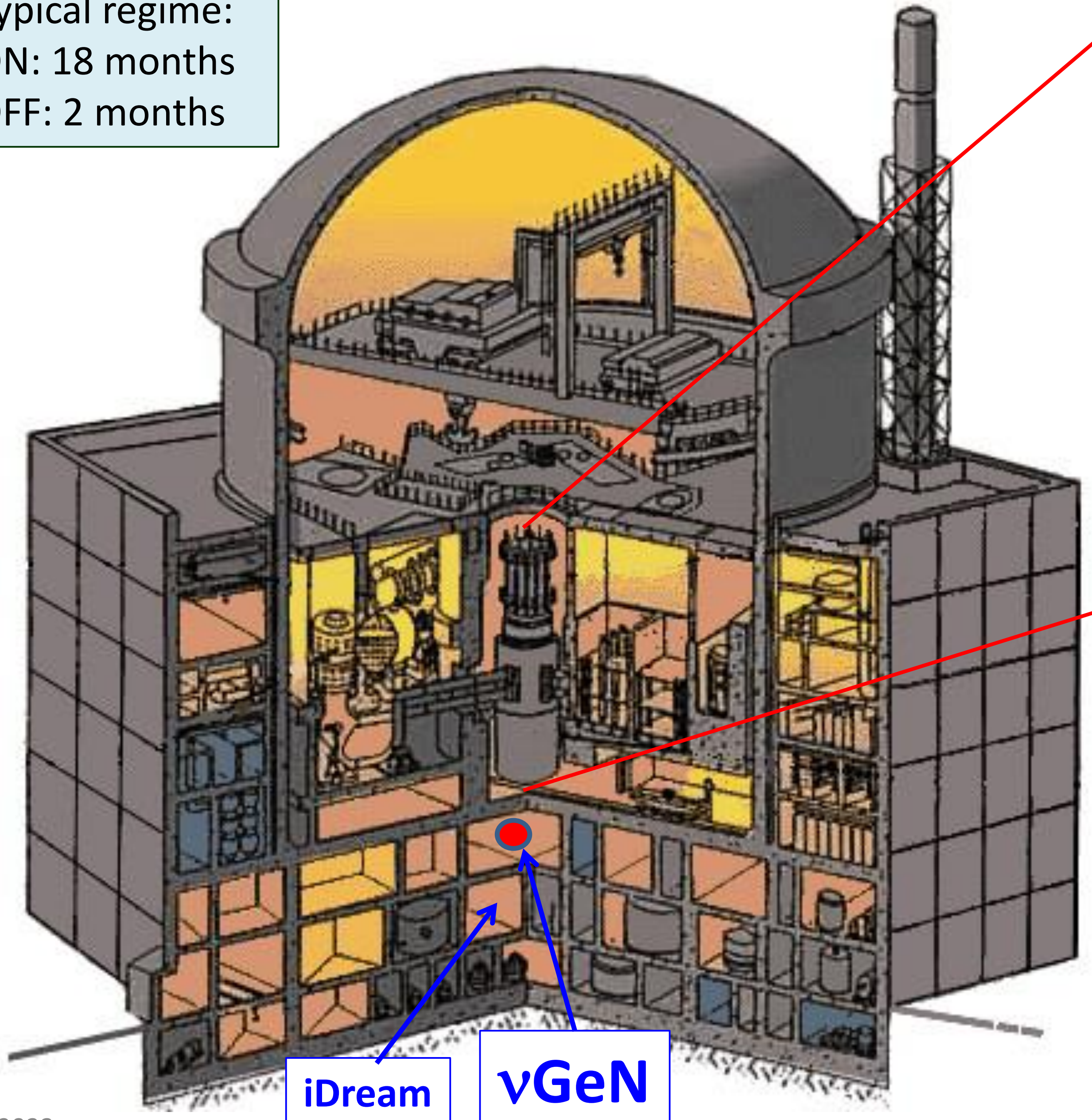
JINR, Dubna, 285 km from KNPP

Comparison of the reactor sites

Experiment	Location	Neutrino flux $\nu/(cm^2\ s)$	Overburden [m w. e.]
νGeN	**KNPP, Russia**	**$\sim(3.6\text{-}4.4)\times10^{13}$**	**~50**
CONUS	Brokdorf, Germany	**2.3×10^{13}**	**10-45**
CONUS+	Leibstadt, Switzerland	**1.45×10^{13}**	**7-8**
TEXONO	Kuo-Sheng NPP, Taiwan	**6.4×10^{12}**	**~30**
RED-100	KNPP, Russia	**1.7×10^{13}**	**>50**
CONNIE	Angra 2, Brazil	**7.8×10^{12}**	**0**
RICOCHET	ILL, France	**2×10^{12}**	**~15**
MINER	Texas A&M, USA	**2×10^{12}**	**~5**
NUCLEUS	Chooz, France	**2×10^{12}**	**~3**
NCC-1701	Dresden-II, USA	**4.8×10^{13}**	**-**
NEON	Hanbit 6, Korea	**7.1×10^{12}**	**~8**
SBS	Laguna Verde, Mexico	**3×10^{12}?**	**?**

Reactor unit #3 @ KNPP

Typical regime:
ON: 18 months
OFF: 2 months



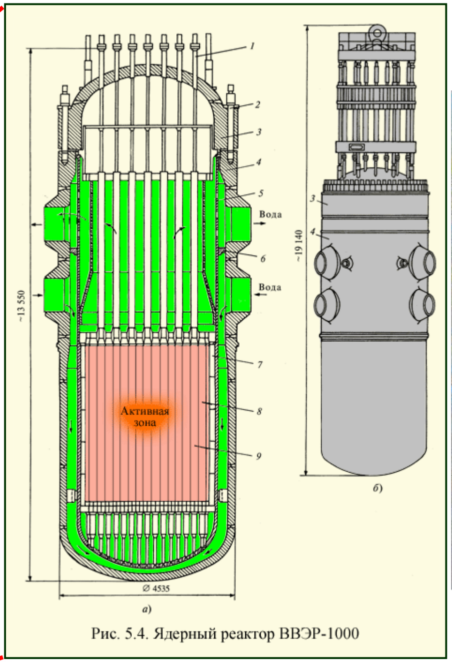


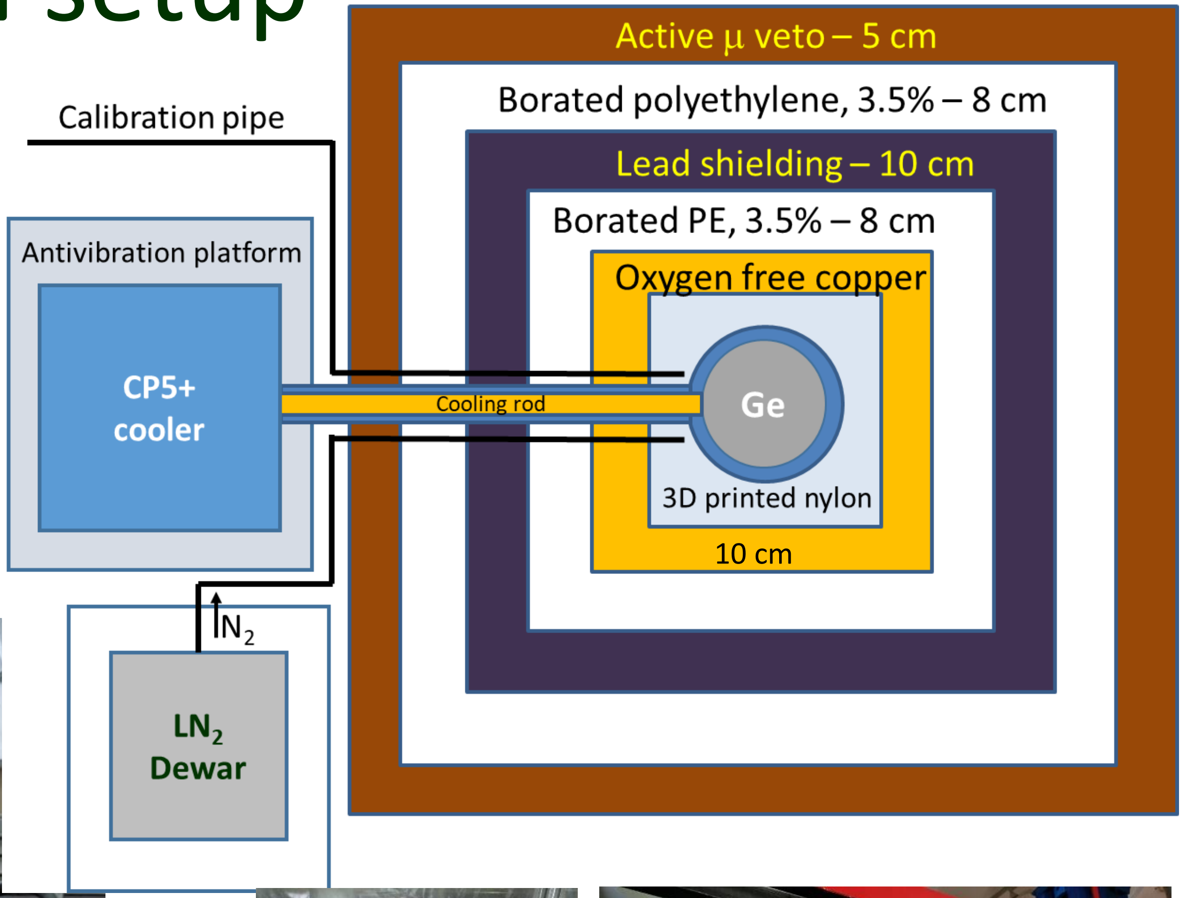
Рис. 5.4. Ядерный реактор ВВЭР-1000

KNPP #3

- Spectrometer **νGeN** is located under the reactor unit #3 (3.1 GW_{th} – thermal power)
- Distance to the center of the reactor core is about 11 m, this gives **> $4{\cdot}10^{13}$ ν/(sec·cm^2)**
- Overburden ~ **50 m w.e.** – good shielding against cosmic radiation due to reactor's surrounding
- Good support from KNPP administration

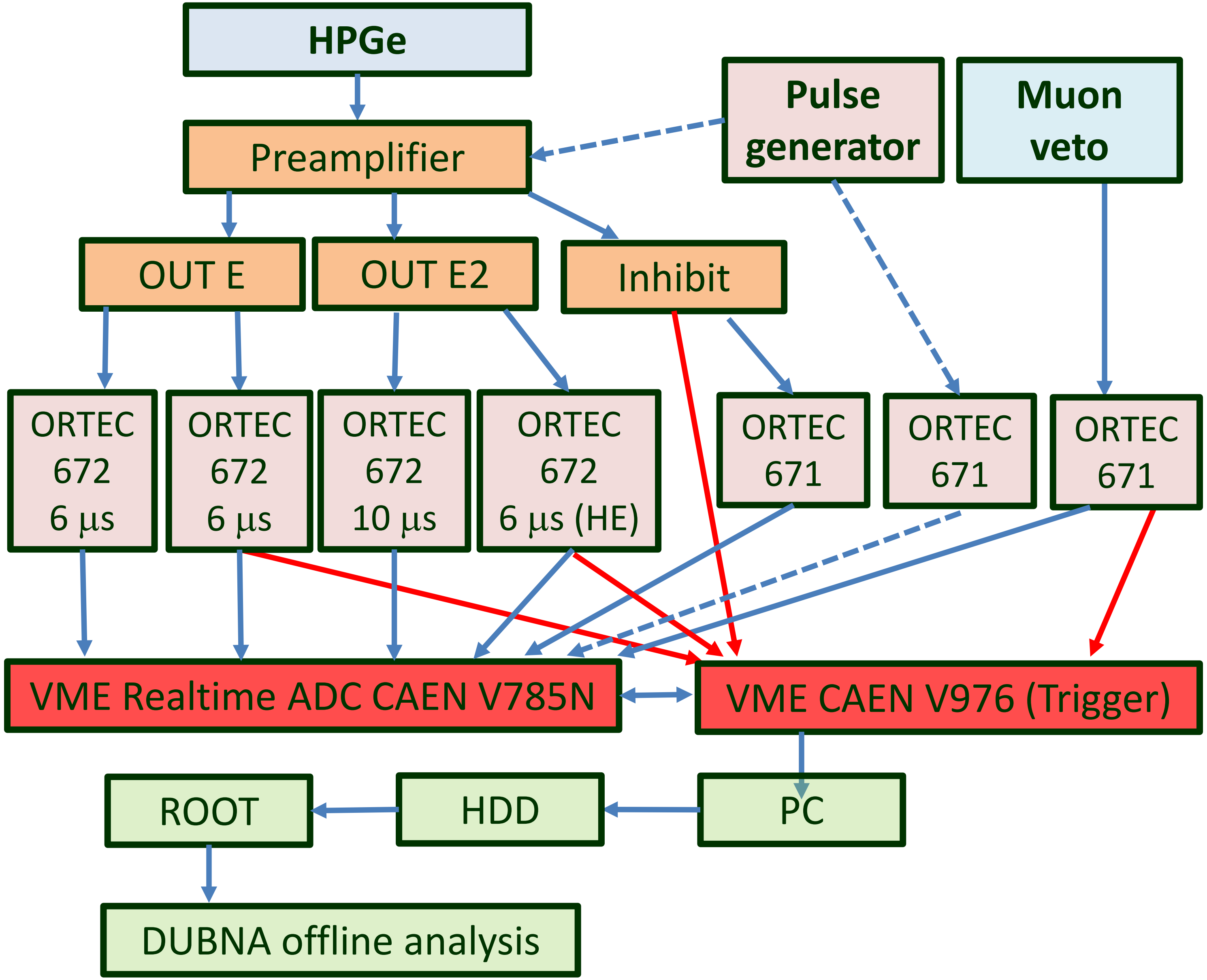
The νGeN setup

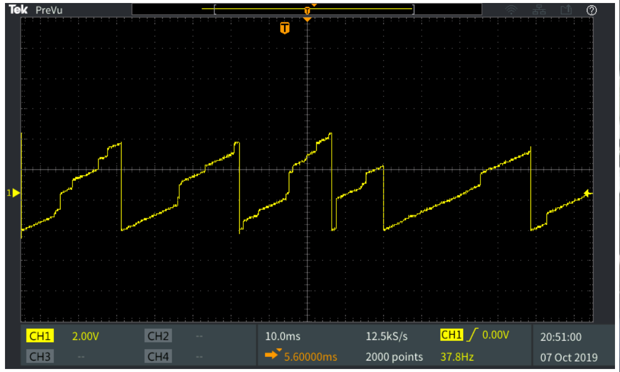
- To detect signals from neutrino scattering we use a specially low-threshold, low-background HPGe detector.
- Detector with a mass of 1.4 kg and e-cooling is used for the detection at KNPP.
- The passive and active shielding protects detector from external radiation.
- A setup is installed on a lifting mechanism allows to change distance to the reactor's core from 11 - 12.5 m.



Phys. Rev. D 106, L051101, (2022)

Electronics and DAQ

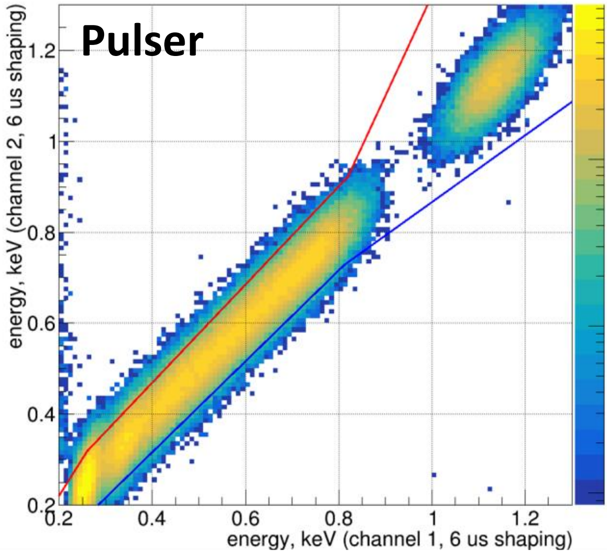


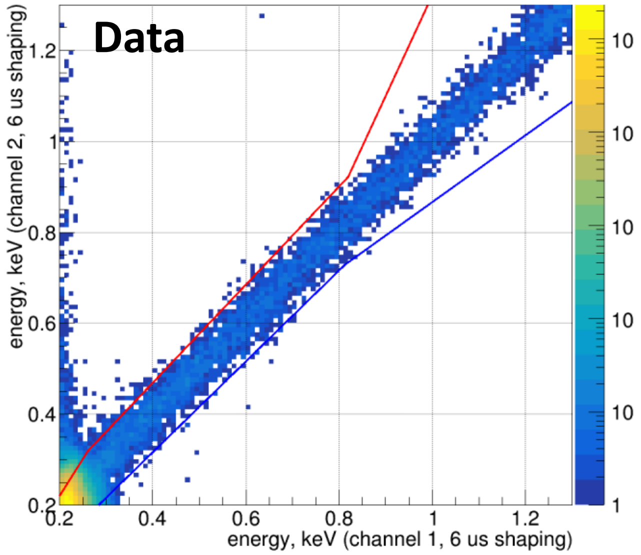


- Reset preamplifier
- DAQ organize with real-time ADC system based on CAEN electronics.
- Shaping amplifiers / no WFs so far
- Noise suppression by comparison signals OUT E to E2 with the same shaping time, comparison of signal with different shaping times τ_{sh} (6 µs and 10 µs)
- Event selection with «inhibit» removing reset signal
- Anticoincidence with muon veto

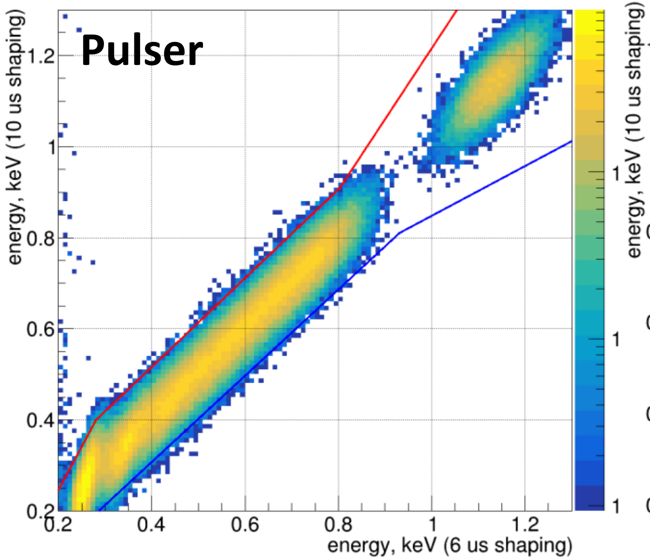
Noise cuts

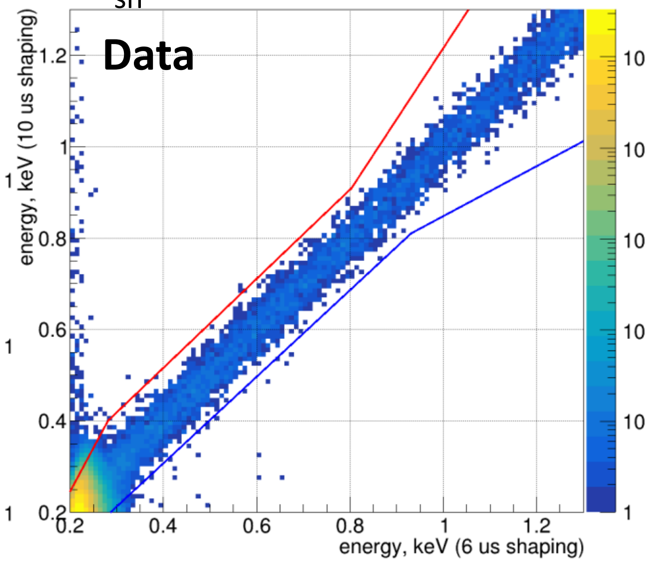
Comparison of two channels with the same τ_{sh}



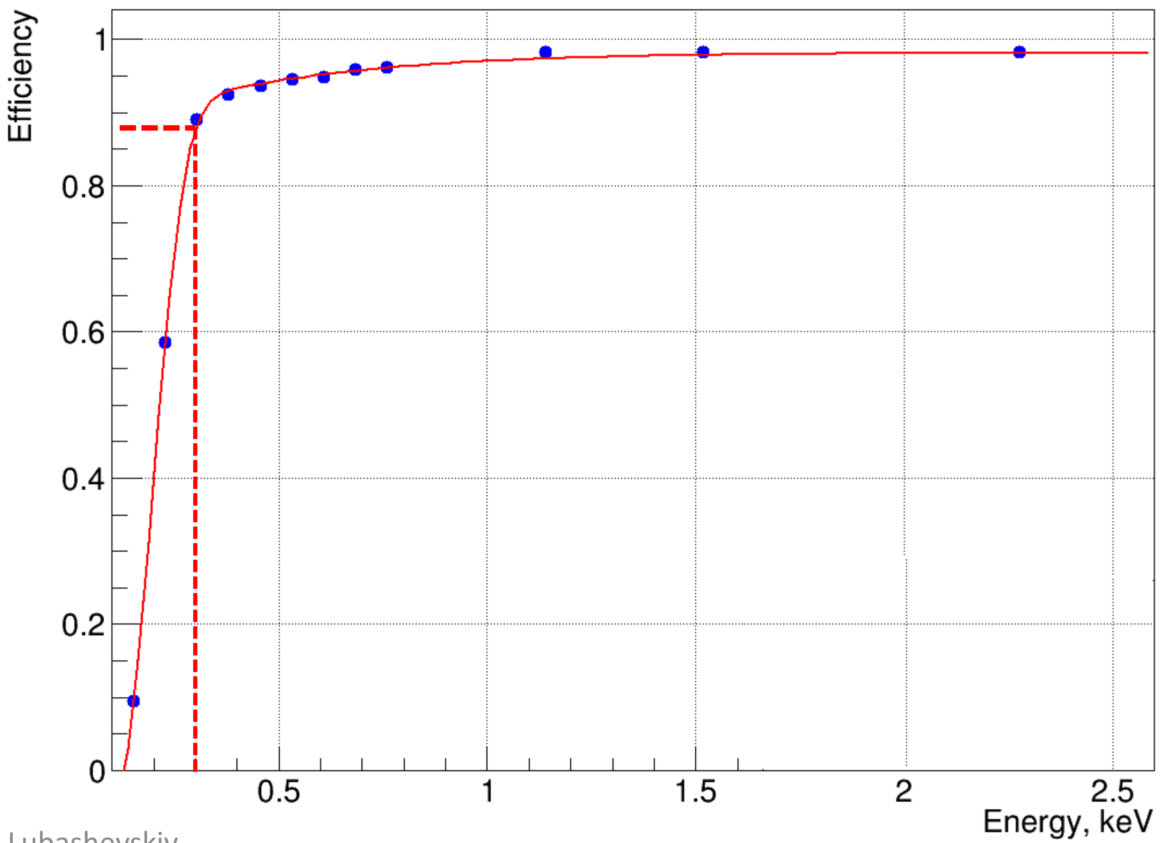


Comparison with different with τ_{sh}



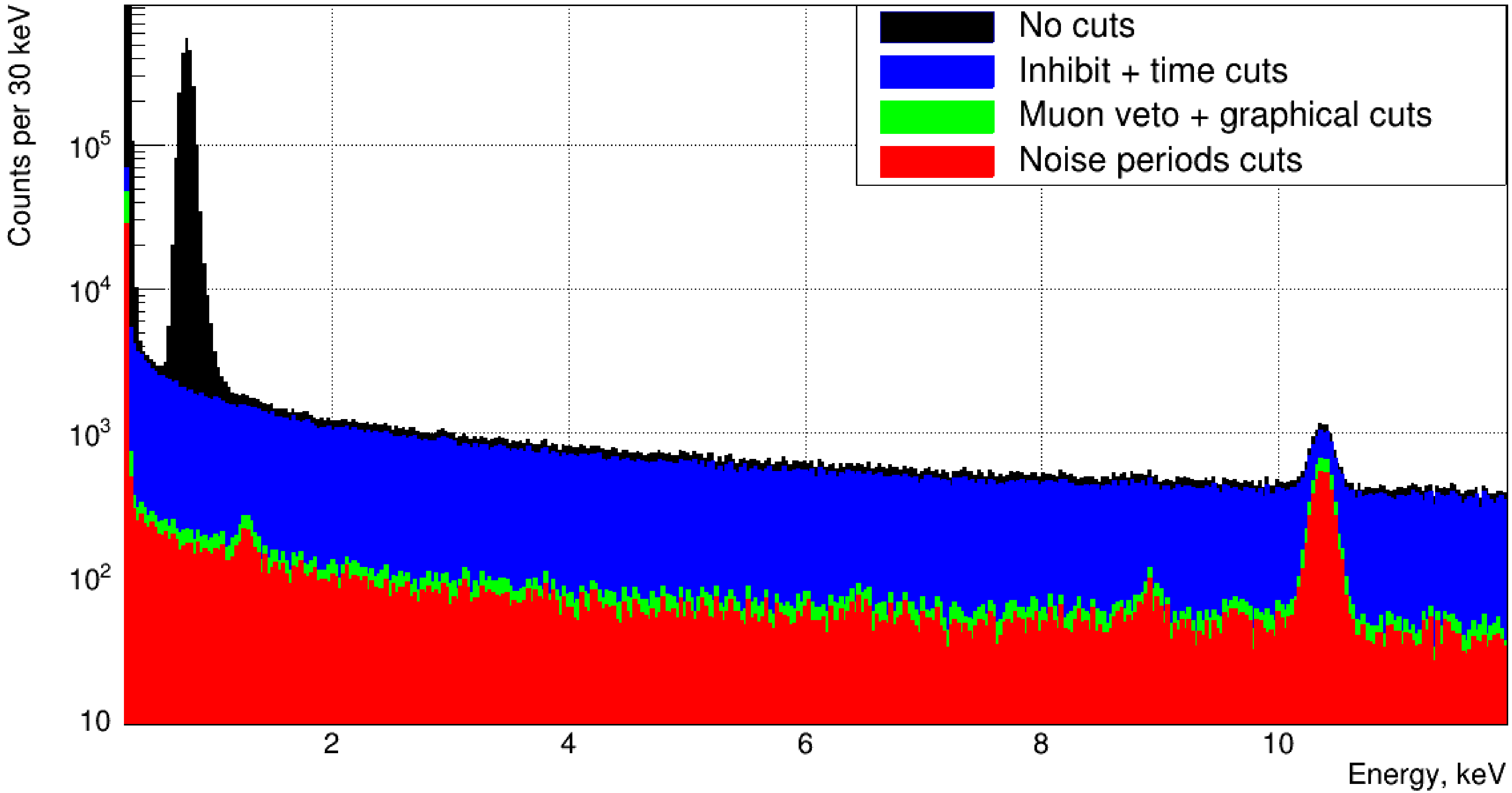


- Comparison of different signal reconstructions are used to suppress the noise.
- Efficiency of trigger + graphical cuts:
  - ~ 40% for 0.2 keV
  - ~ 85% for 0.3 keV



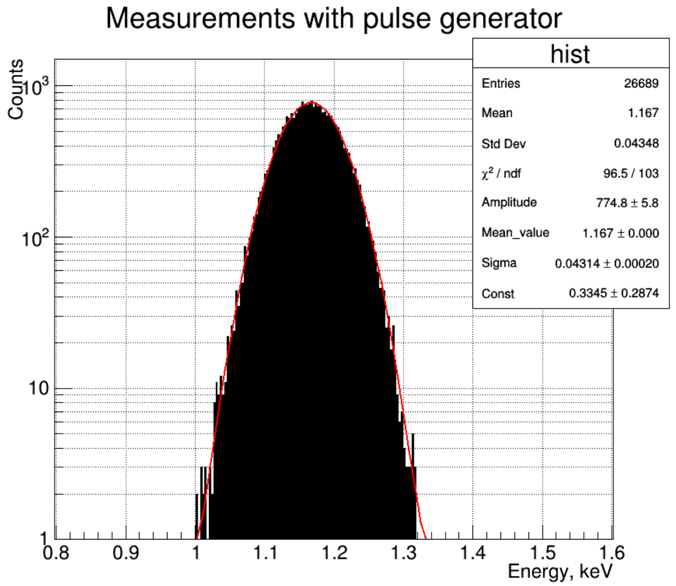
Muon veto & time cuts

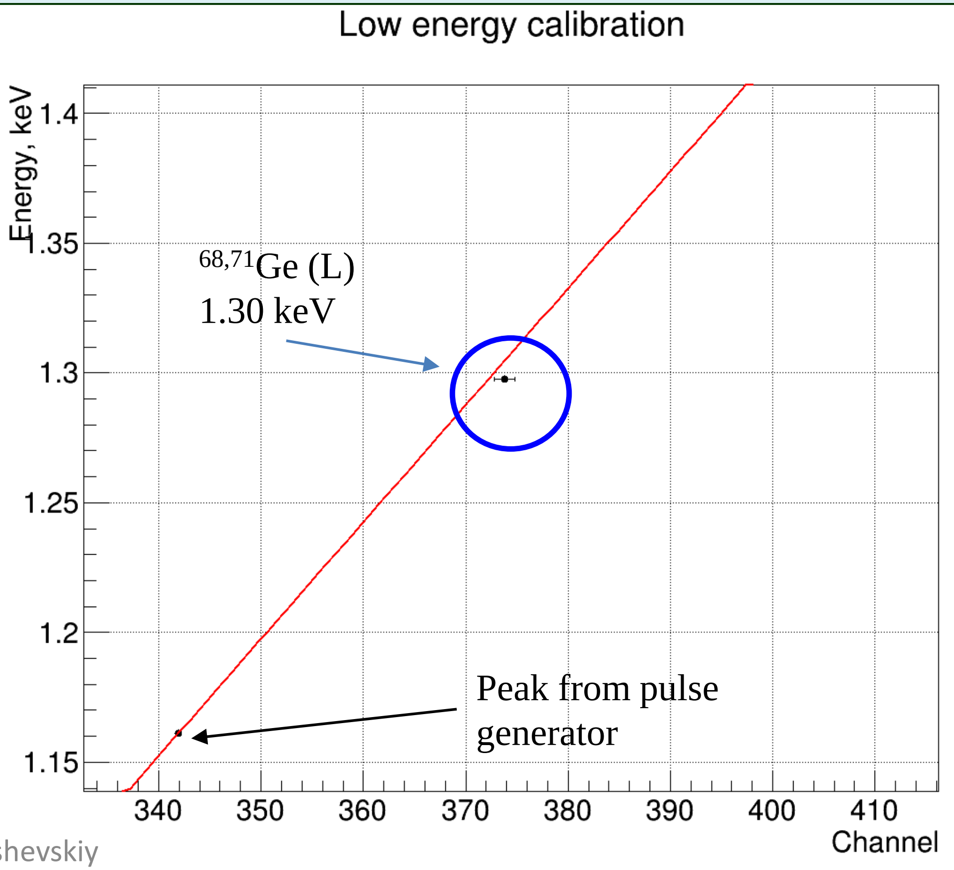
- Time cuts allow to suppress signals generated by reset of the preamplifier.
- Anticoincidence with muon veto allow to suppress background connected with muons.
- These cuts introduce additional 9-10% dead time (calculated).

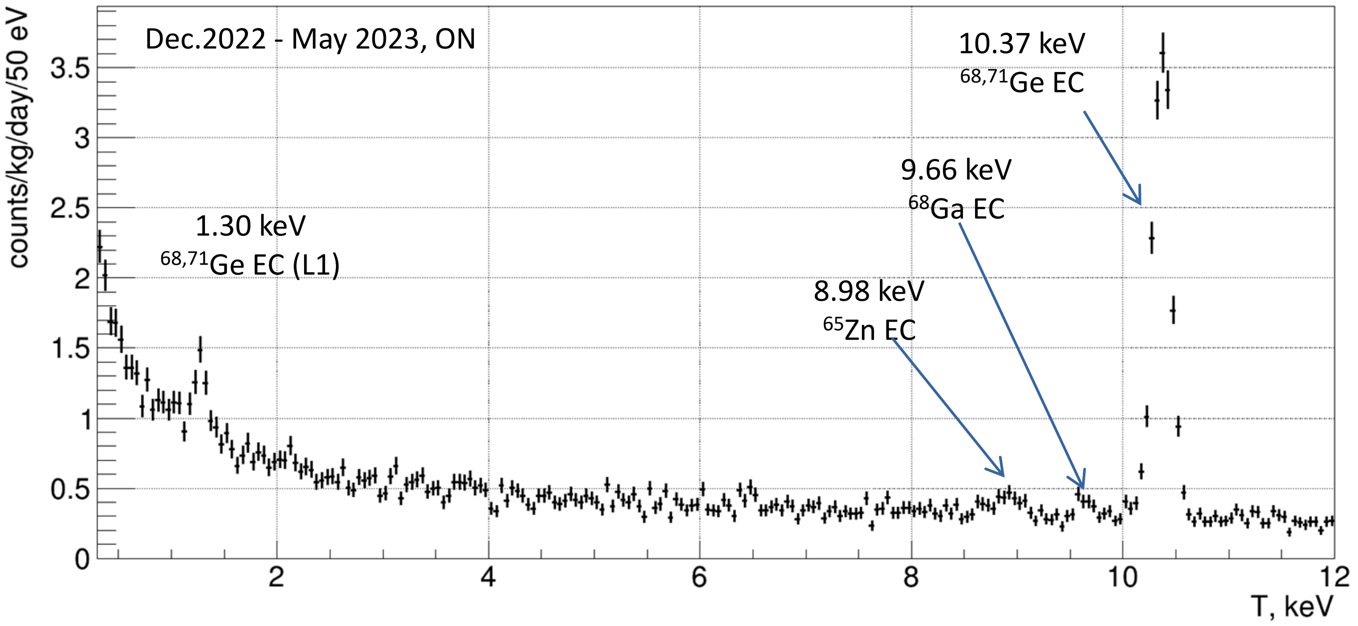


Calibration at low energies

- Energy calibration at low energy is performed by means of 10.37 keV cosmogenic line and pulse generator.
- Calibration check with 1.3 keV line
- Data taking shows very good stability of peak position during all measurement time.
- Energy resolution of 1.4 kg detector at KNPP is 101.6(5) eV (FWHM).

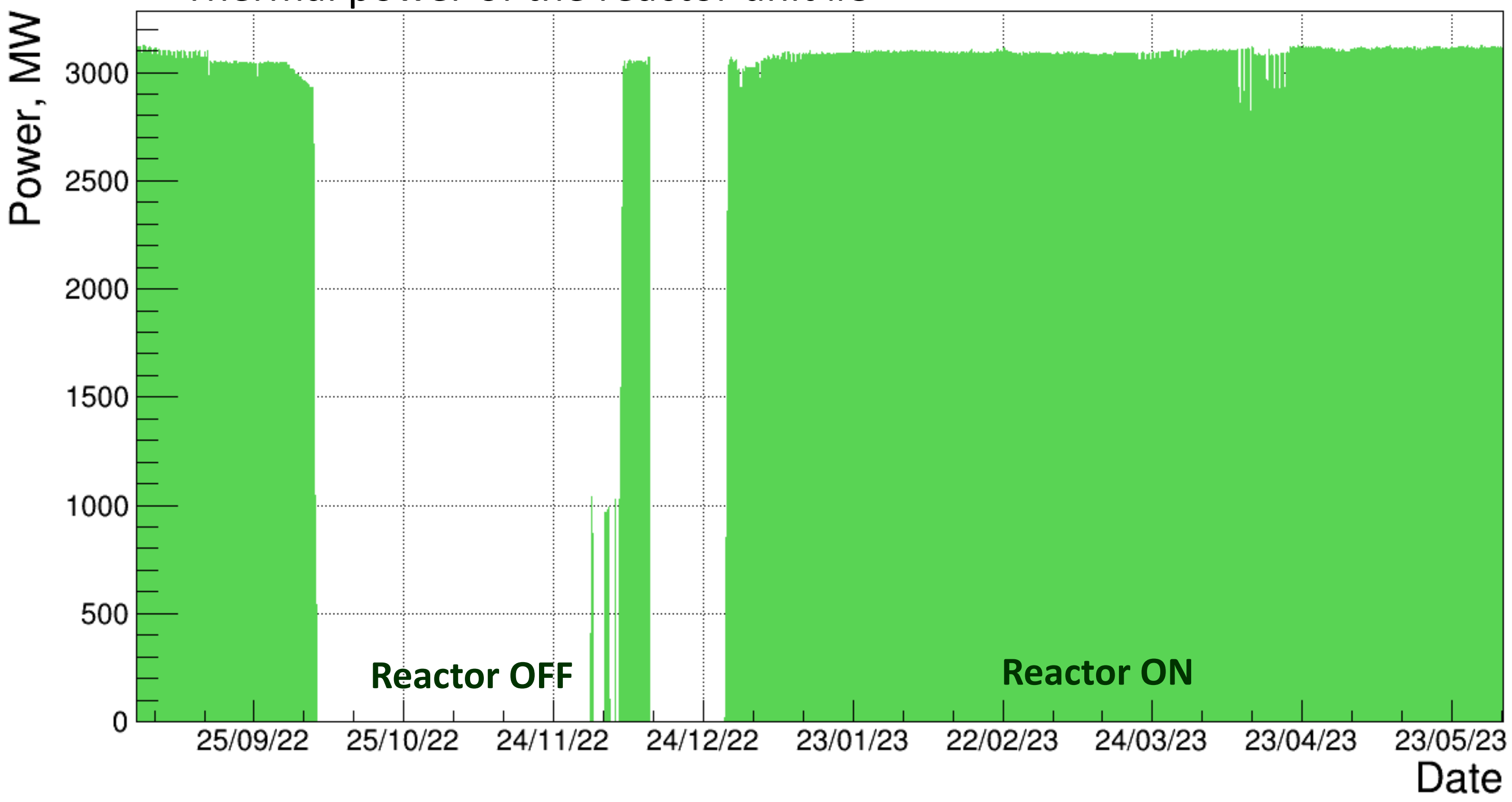




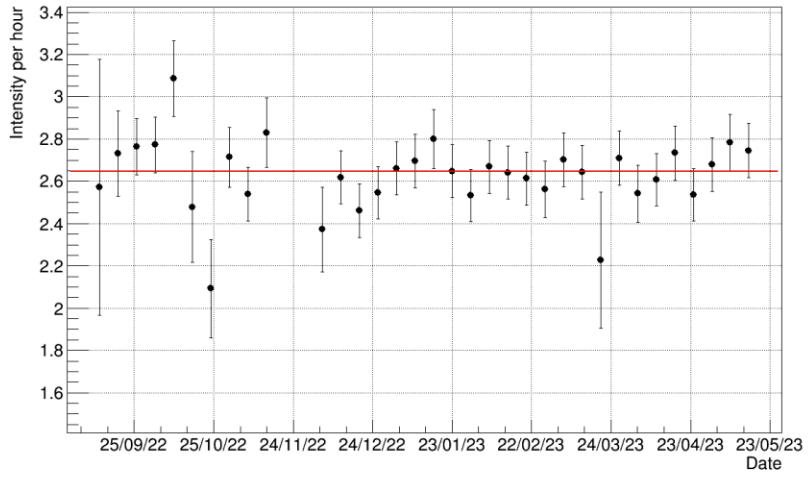


Data taking

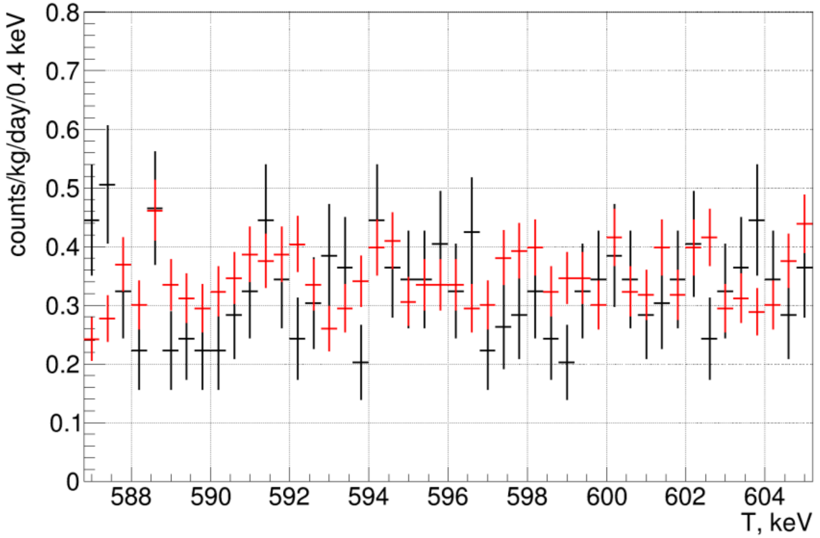
Thermal power of the reactor unit #3



Stability, count rate 2-8 keV



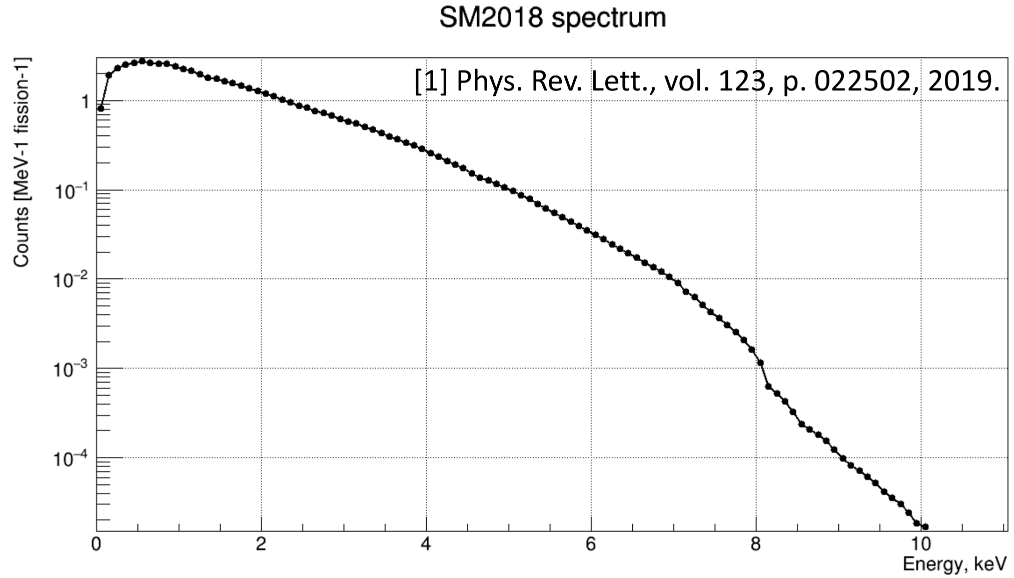
No evidence for fast neutrons scattering in the data

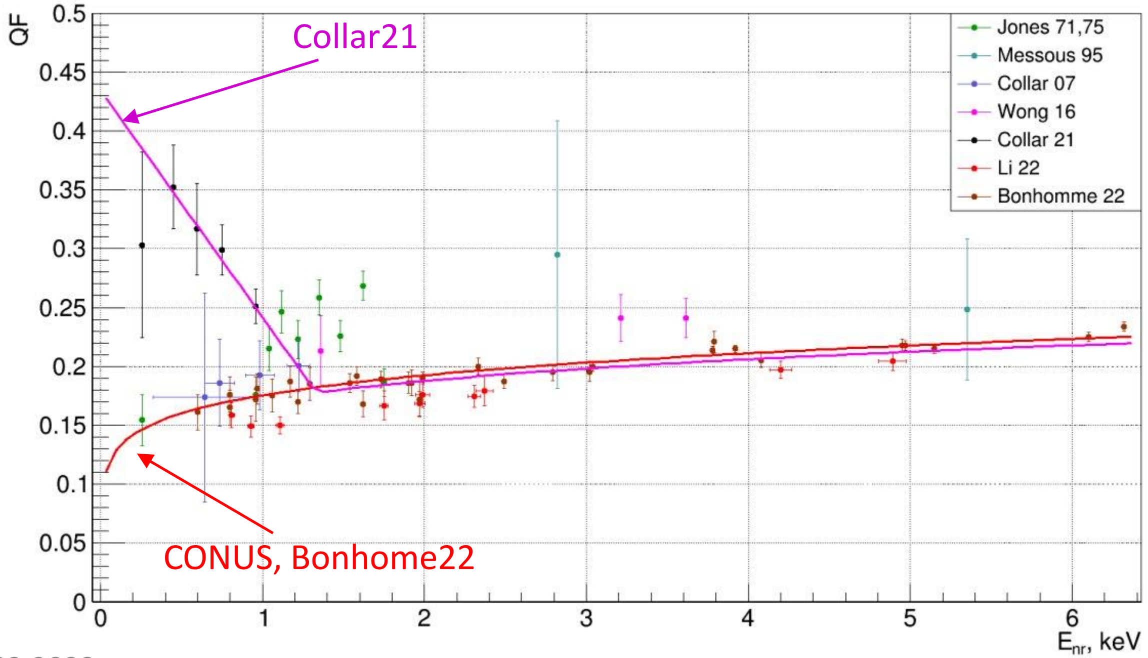


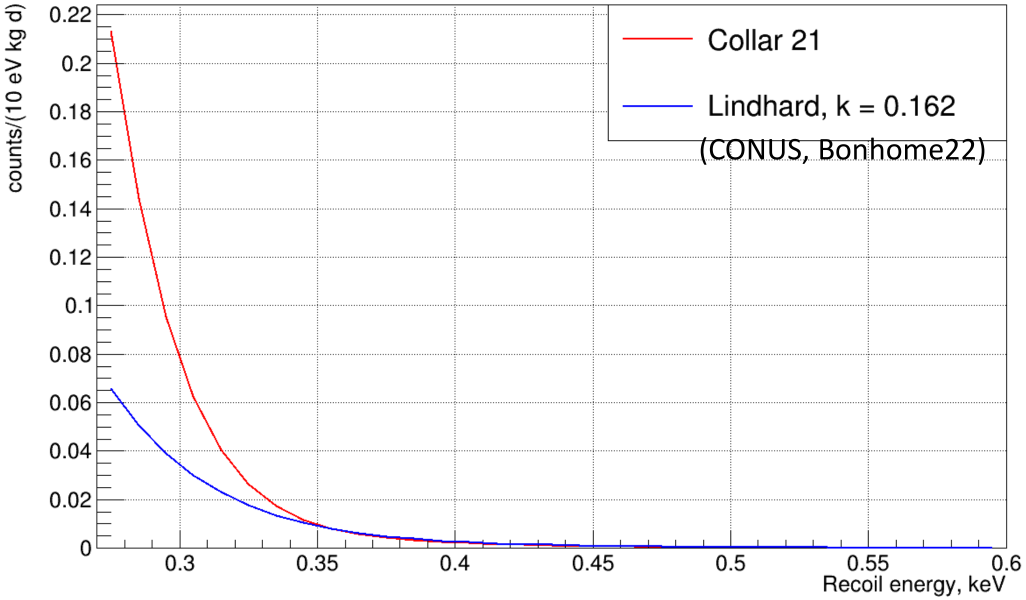
- Collected October 2022 — May 2023 at 11.1 m from the center of the reactor core
- Background conditions were stable
- Selected statistics: **OFF - 38 days**, **ON - 137 days**

CEνNS signal calculation

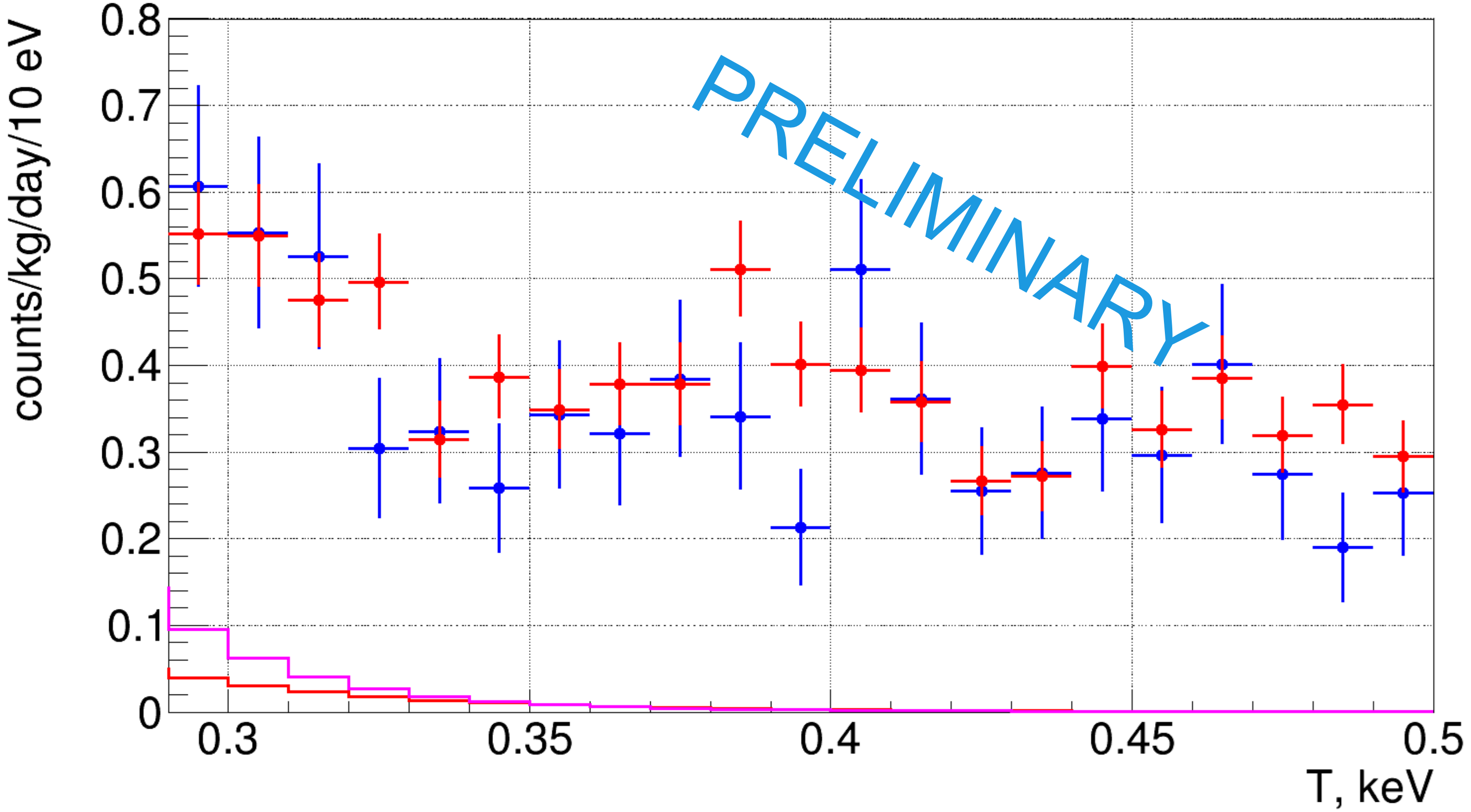
- Neutrino spectrum is calculated with SM2018 model [1] up to 11 MeV taking into account fission fractions of isotopes and average thermal power of the reactor – 3.081 GW.
- The expected CEνNS spectrum was calculated for all germanium isotopes, taking into account detector's performance.
- Two cases for quenching (ionization part of the energy deposited) were considered for analysis.







Data comparison and sensitivity



No significant difference in background level during reactor ON and OFF regimes is observed.

OFF (blue): 38 days

ON (red): 137 days

CEvNS predictions:

CONUS QF — red line

Collar21 QF — magenta line

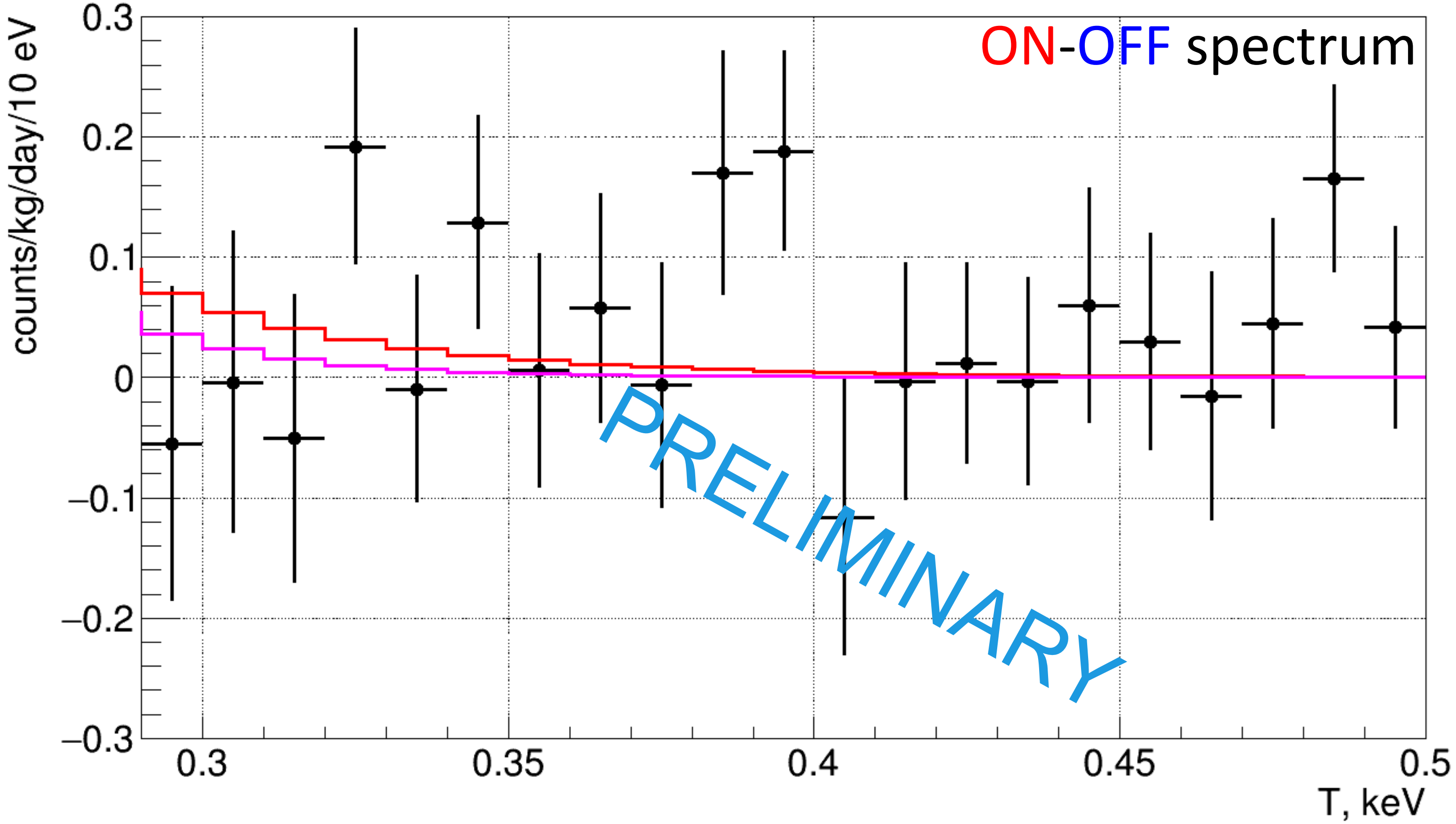
Analysis ROI: 0.29-0.4 keV

0.29 keV — stability considerations

0.40 keV — provides <1% loss of the sensitivity

QF	Prediction, ev./kg/day	Sensitivity, ×SM	68% expectation for a 90% C.L. limit, ×SM
CONUS	0.159	4.1	2.3-6.0
Collar21	0.278	2.6	1.6-3.6

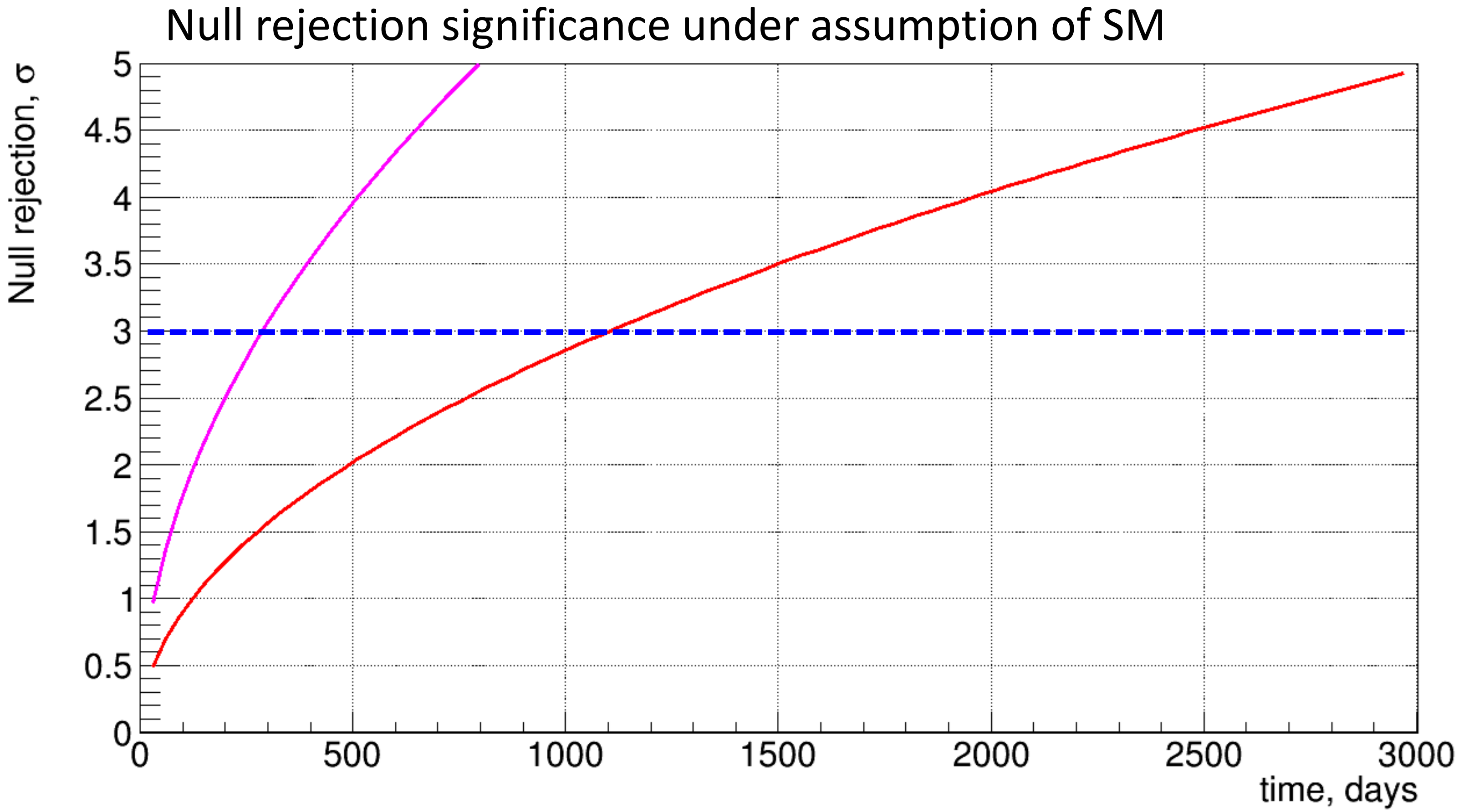
Fit and results



Analysis of the data allowed to set up the upper limit on the CEvNS rate depending on the quenching factor.
Best fits:
CONUS QF — red line
Collar21 QF — magenta line

QF	Prediction, ev./kg/day	Sensitivity, ×SM	68% expectation for a 90% C.L. limit, ×SM	Best fit, ×SM	**90% C.L. limit**
CONUS	0.159	4.1	2.3-6.0	1.80	**5.0**
Collar21	0.278	2.6	1.6-3.6	0.38	**2.0**

Sensitivity exploration



Given the measured BG rate and currently achieved threshold we can extrapolate the sensitivity studies.
Two scenarios:

1. Direct ON - OFF: time = OFF, ON = 11×OFF

3σ at ~ 300/1100 days OFF depending on QF - unrealistic for a current energy threshold

2. ON - BG model (no syst.): time = ON

3σ at ~ 1/3 years, **5σ** at 2.5 / 8 years

Need to:
1. Deconvolve the BG → full BG model: studies and simulations ongoing
2. Improve energy threshold → noise reduction, improve energy resolution
3. Reduce background → modifications and upgrades of the setup

Upgrade and improvements

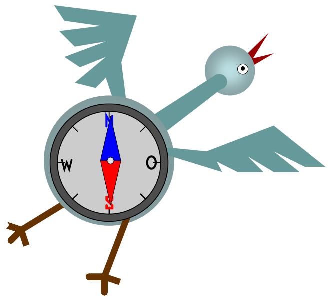
Plans to improve noise level and reduce background:

- 1. «Compton veto around the detector» — set of NaI crystals to suppress multiple scattering events
- 2. Modifications of the cryocooler to reduce its power consumption and noise
- 3. DAQ tests for a better discrimination of noise and surface events
- 4. Improve radon protection.

Sensitivity studies to NMM

The best limit at reactors is set by GEMMA experiment — $\mu_\nu < 2.9\cdot10^{-11}\ \mu_B$ (90% C.L.)

Experiment	Mass, kg	ν flux, $cm^{-2}s^{-1}$	E_{th}, keV_{ee}	Reference
GEMMA	1.5	$2.7\cdot10^{13}$	2.8	Adv.High Energy Phys. 2012
νGeN	**1.4**	**$4.4\cdot10^{13}$**	**0.2-0.3**	**Phys.Rev.D 106 (2022)**
COνUS	3.7	$2.3\cdot10^{13}$	0.2-0.3	Eur.Phys.J.C 82 (2022)
Dresden-II	2.9	$4.8\cdot10^{13}$	0.2-0.3	JHEP 05 037 (2022)

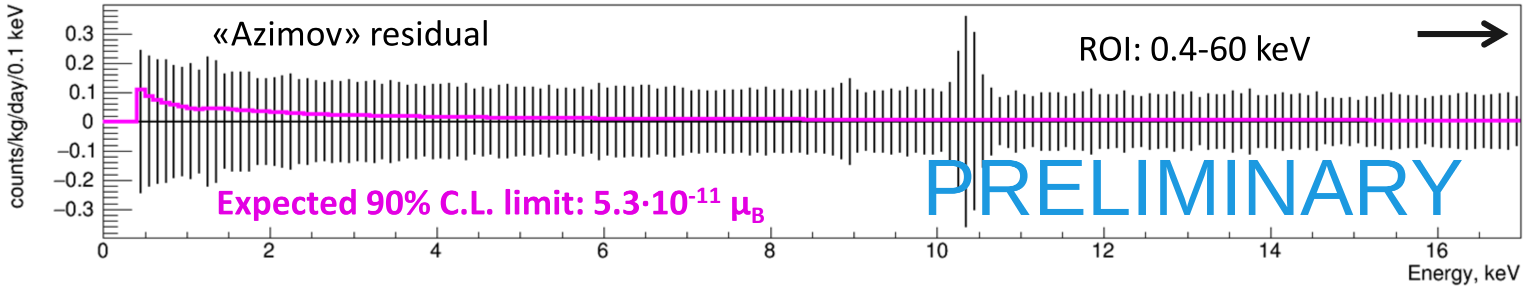


Other results, like:
XenonNT dark matter experiment (solar ν) — $\mu_{\nu e} < 0.64\cdot10^{-11}\ \mu_B$ (90% C.L.)
Astrophysical considerations — $\mu_\nu < 3.0\cdot10^{-12}\ \mu_B$ (90% C.L.)
cannot be directly compared, also the results are model dependent

Physical review letters 129.16 (2022): 161805.

Astrophys. Journal, 365 559 (1990)

Sensitivity studies: OFF – **69.2 d** (same dataset, loose cuts), ON (est.) – **140.2 d**



Analysis is sensitive to stability and BG systematics due to large ROI and statistics

For 900 days ON + BG model
Median exp. limit: ~ **$2.5\cdot10^{-11}\ \mu_B$**
68% in **$[1.8,3.3]\cdot10^{-11}\ \mu_B$**

Currently more than **1200 days** of data has been taken. Analysis is ongoing.

Conclusion

- Measurements with the νGeN spectrometer at Kalinin Nuclear Power Plant are ongoing successfully.
- We set the 90% C.L. limit on the CEvNS rate: 5.0/2.0
- The lab tests of the modifications to reduce background and improve the threshold are in the process.
- More than 1600 kgd of data has been accumulated so far. Data analysis and simulations for all available statistics are ongoing.
- New results with more statistics are expected soon.

νGeN collaboration

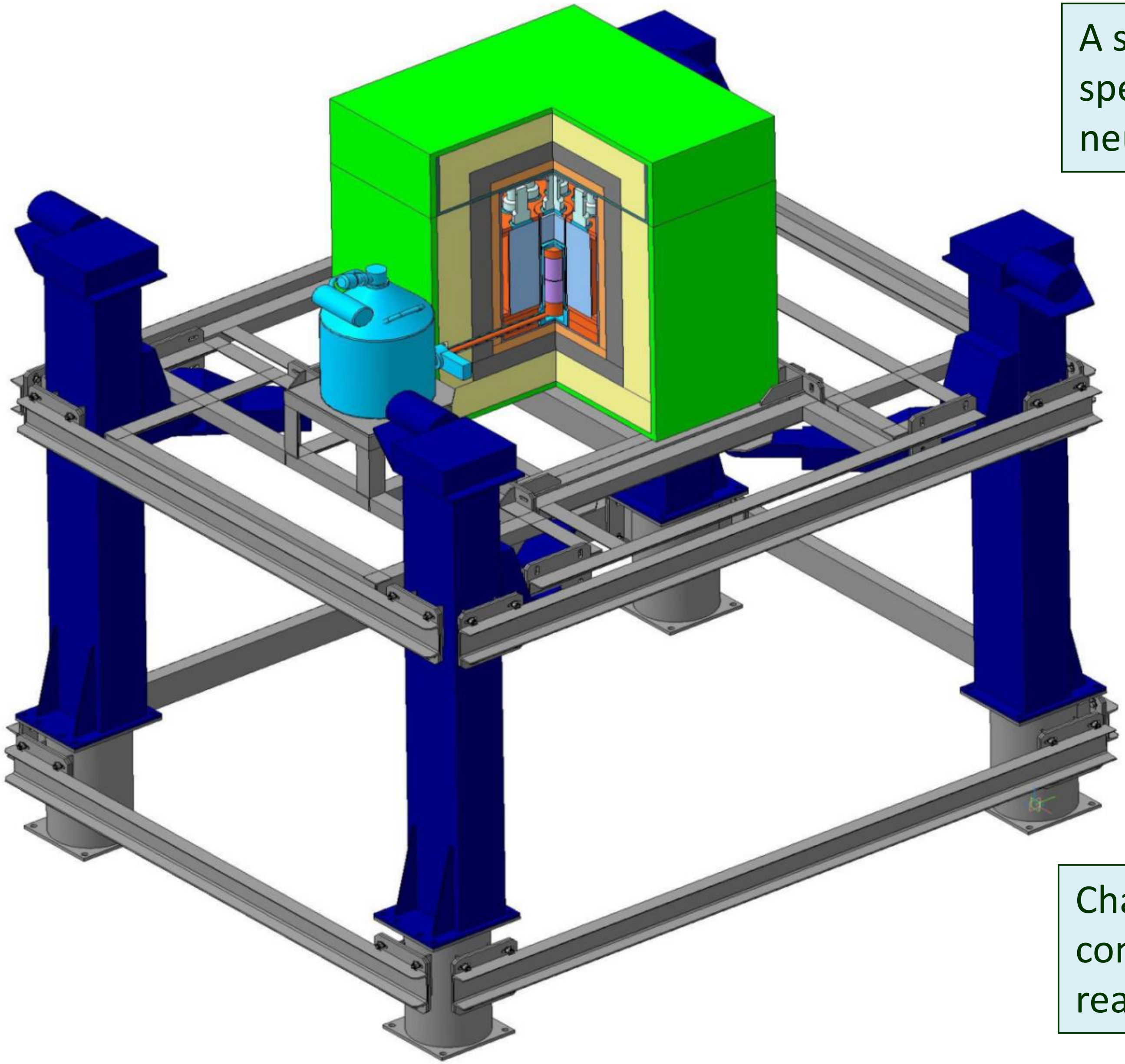
- Joint Institute for Nuclear Research, Dubna, Russia
- Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- Institute of Experimental and Applied Physics, Czech Technical University in Prague

Thank you!

Спасибо!

Backup slides

νGeN @ KNPP – lifting mechanism



A special lifting mechanism has been installed to move the spectrometer towards the reactor core to change the neutrino flux through the detector.

11.09 m – top position (current)

12.14 m – first position

~12.5 m – lower position

Distances to the center of reactor core:

Changes of the ν flux help to suppress systematic errors connected with changes of the background while the reactor ON/OFF

Control of experimental conditions

- The stable measurement conditions are very important, because instabilities can change amplification and noise level.
- Cosmogenic activation products slowly decay in time and have to be taken into account during analysis.

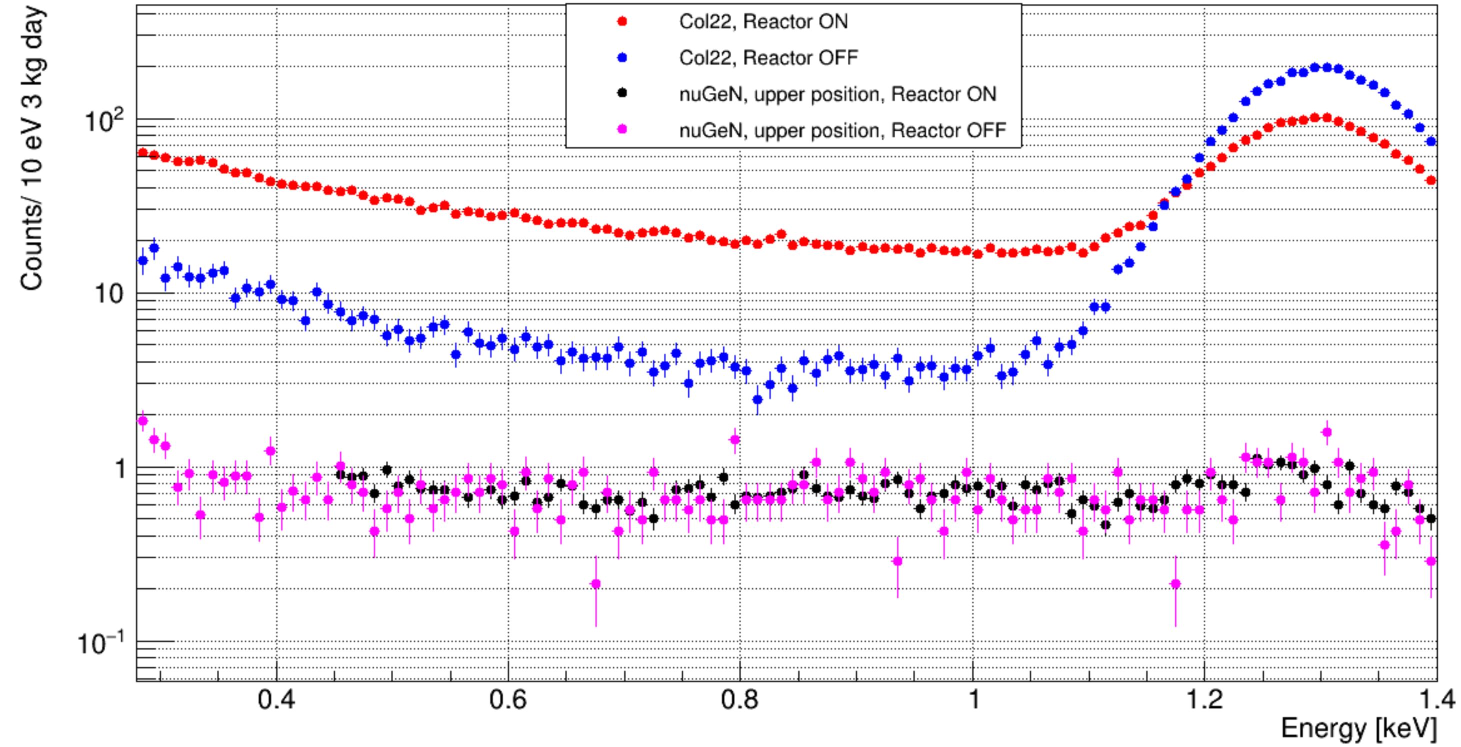
✓ Air temperature condition in the experimental hall is stabilized by three air-conditioners.

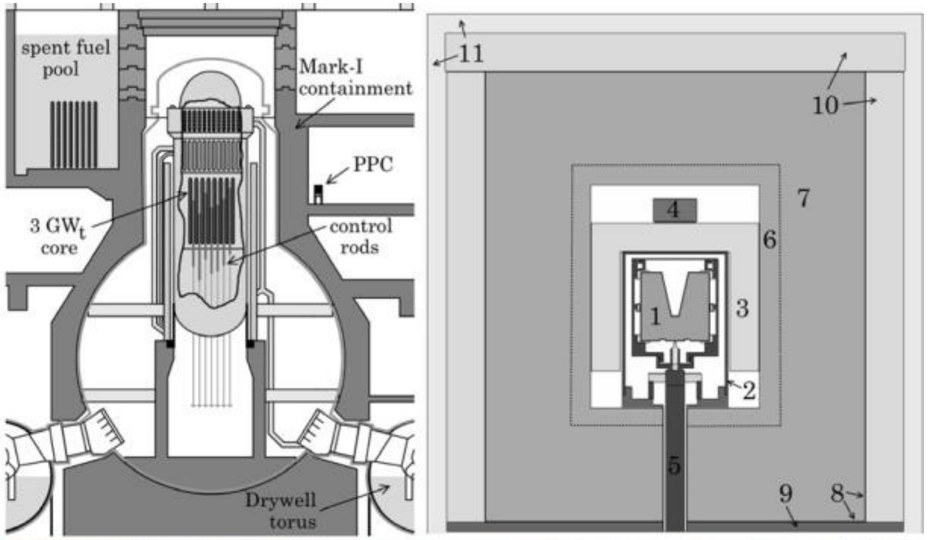
✓ Temperature and humidity are constantly monitored by two sensors.

✓ Neutron background outside shielding (fast and thermal) is measured by special low background He3 counter and NAIL detector.

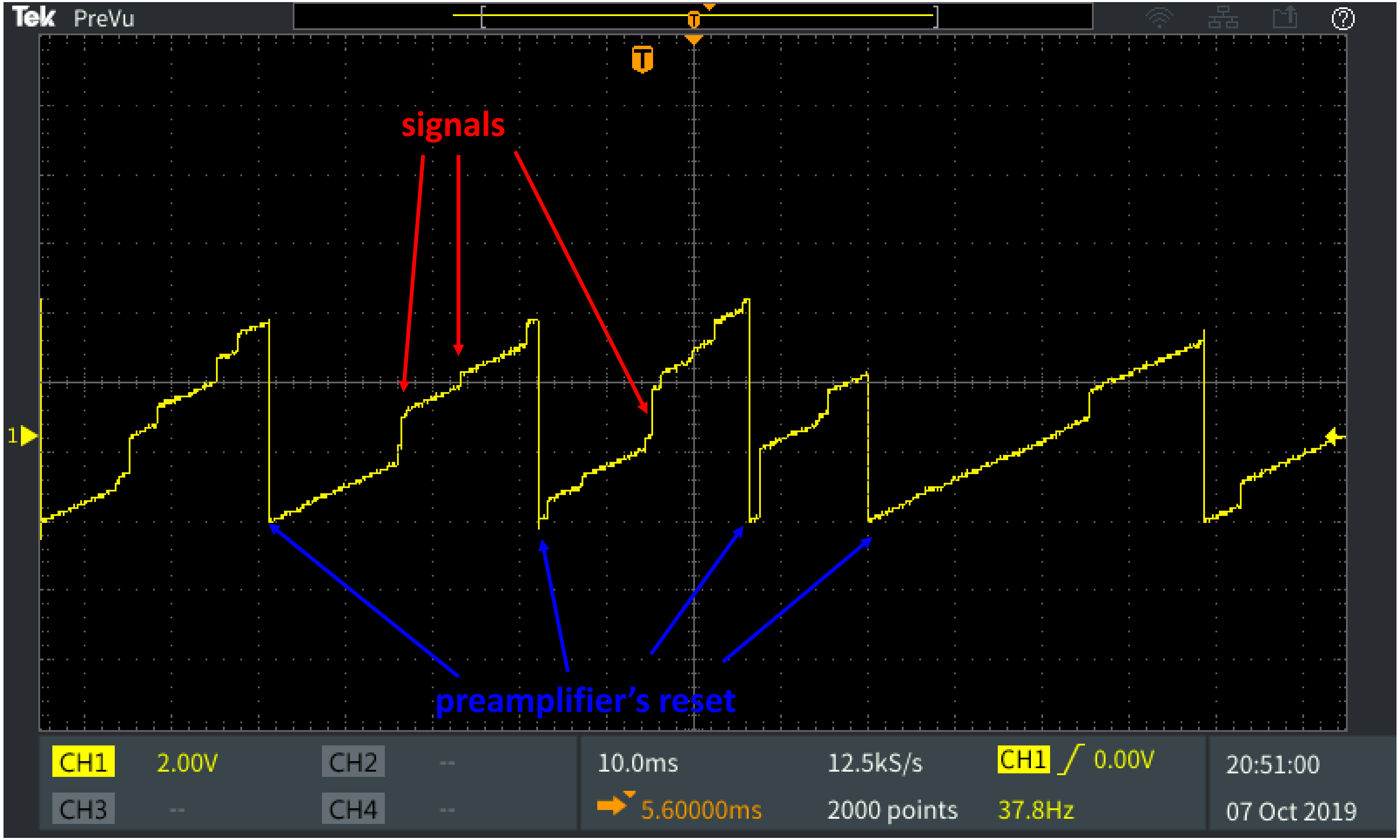
J. Colaresi, J. I. Collar,* T. W. Hossbach , C. M. Lewis , and K. M. Yocum, «Measurement of Coherent Elastic Neutrino-Nucleus Scattering from Reactor Antineutrinos», PHYSICAL REVIEW LETTERS 129, 211802 (2022)

- Claimed about strong preference ($p<1.2\cdot10^{-3}$) for the presence of CEνNS.
- Similar to nuGeN antineutrino flux from reactor (4.8 10^{13} ν/cm2/sec)
- Sideway location gives almost no overburden (cosmogenic background).
- Almost no shielding against fast neutrons.
- Different shielding during reactor ON and OFF
- Big difference in background levels during reactor ON and OFF
- Moderate energy resolution > 160 eV (FWHM) (in nuGeN – 101.6(5) eV)





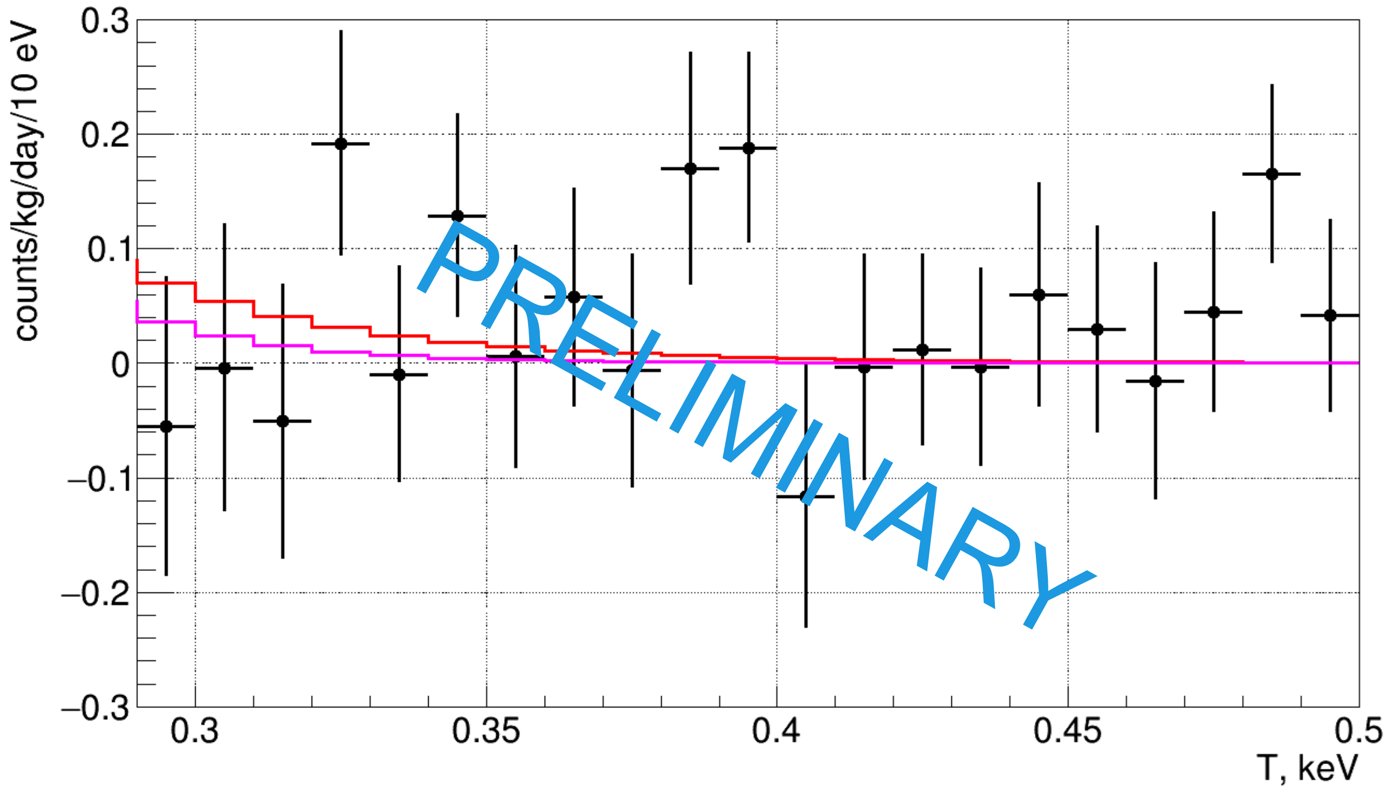
Signals from detector

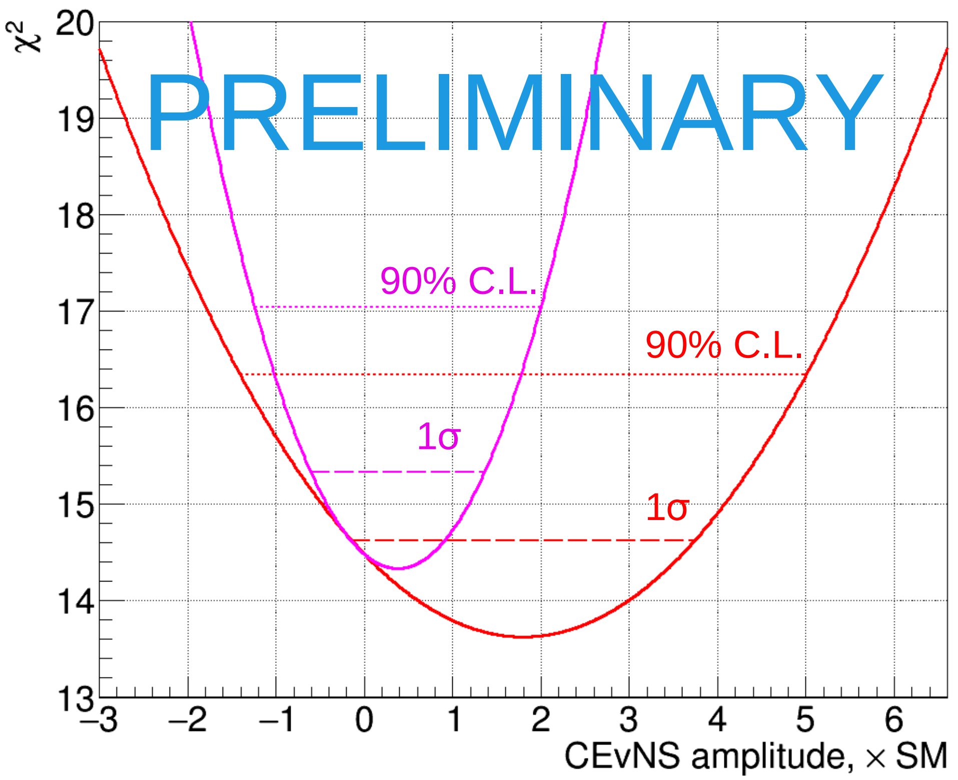


- Detectors are equipped with reset preamplifier.
- There is a special inhibit signal that indicates the time when the reset happens.
- The signals are shaped with amplifiers and processed with a real-time ADC.

Fit and results

Best fits and χ^2 profiles: CONUS QF(red line), Dresden QF (magenta line)





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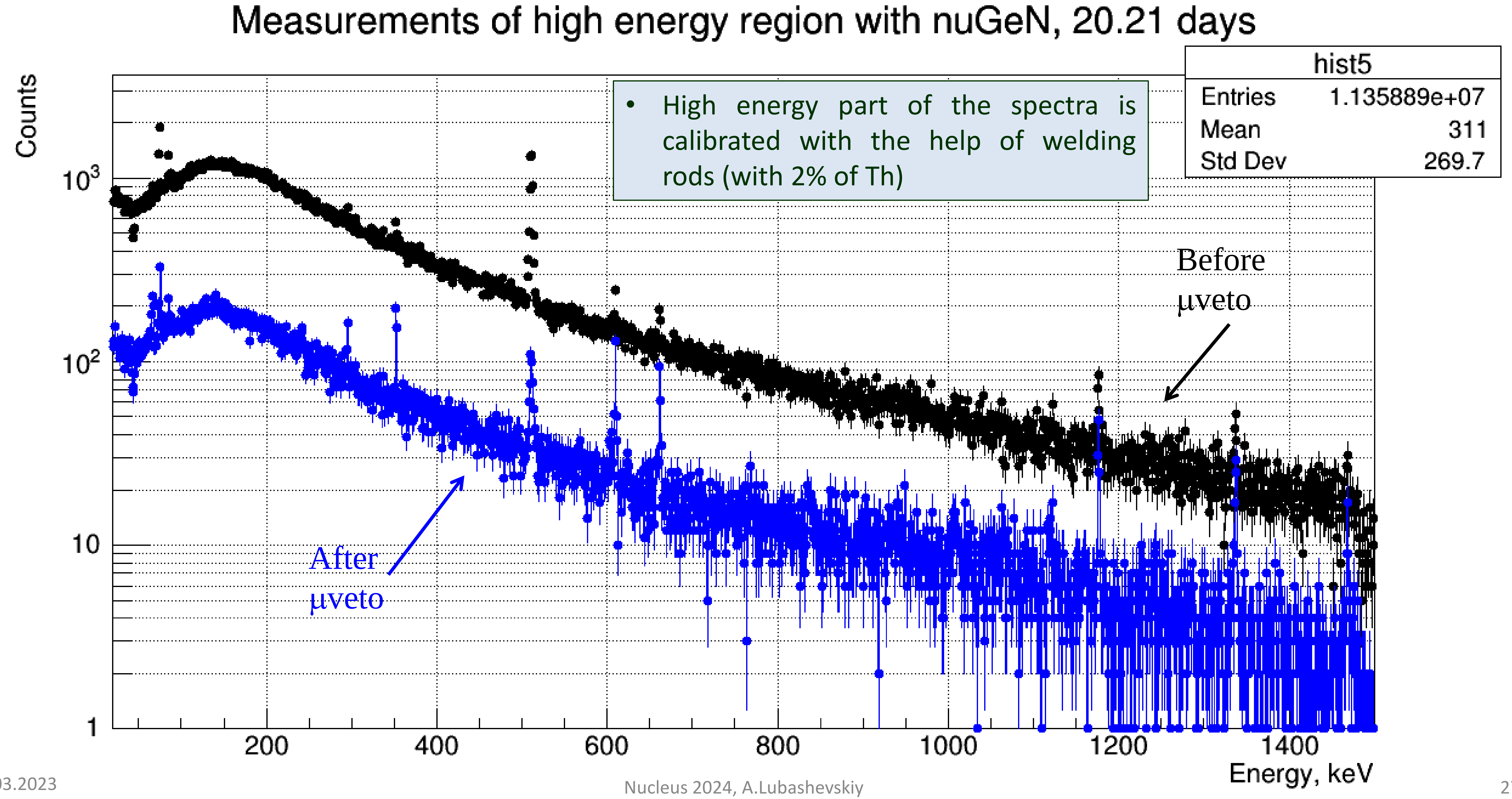
Dresden	0.278	2.6	1.6-3.6	0.38	2.0

High energy part of the spectrum



- High energy part of the spectra is calibrated with the help of welding rods (with 2% of Th)