Development of nuclear power plant reactor monitoring by the neutrino method using the iDREAM detector.

On behalf of iDREAM collaboration
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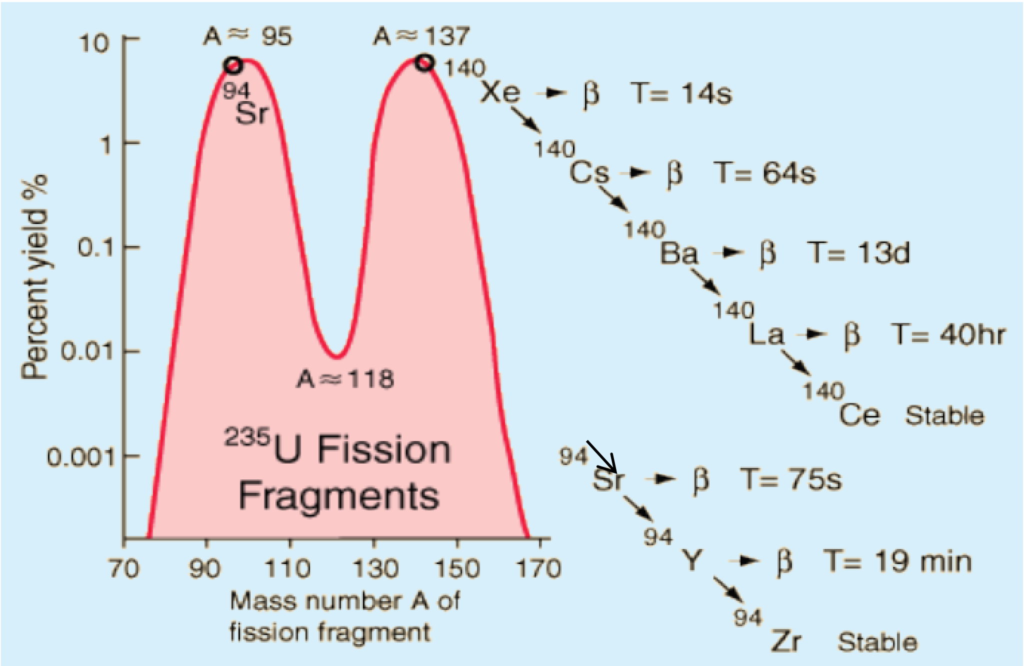
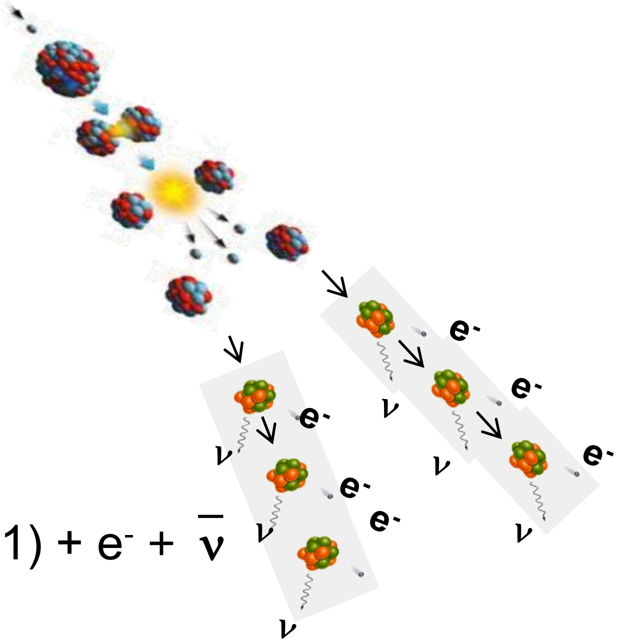
Nuclear reactor is a powerful source of reactor e⁻ antineutrinos

Fission isotopes have different fission product distributions.

$$n + {}^{235}U(Z=92, N=143) \rightarrow A_1(Z_1, N_1) + A_2(Z_2, N_2) + 2\,n$$



Unstable fission products are a source of antineutrinos. Reactors produce electron antineutrinos via the β -decay of neutron rich fission daughter products



$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}$$

Fission isotopes have different fission product distributions.

The density of the antineutrino flux, measured remotely during the operation of the reactor, is directly proportional to the number of fissions, i.e. nuclear fuel burnup rate or nuclear reactor thermal power

Summary of detection channels for reactor antineutrinos.

Channel	Name	Cross Section (10^{-44} cm^2)	Threshold (MeV)
$\bar{\nu}_e + p \to e^+ + n$	inverse beta decay (IBD)	63	1.8
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	ν-electron elastic scattering (νES)	$0.4 \cdot Z$	—
$\bar{\nu}_e + A \to \bar{\nu}_e + A$	coherent elastic ν-nucleus scattering (CEνNS)	$9.2 \cdot N^2$	—
$\bar{\nu}_e + d \to n + n + e^+$	ν-deuteron charged current (CC) scattering	1.1	4.0
$\bar{\nu}_e + d \to n + p + \bar{\nu}_e$	ν-deuteron neutral current (NC) scattering	3.1	2.2

https://arxiv.org/pdf/2310.13070

The cross section is integrated over the reactor antineutrino energy distribution assuming the typical fission fractions from the four main isotopes.

For the νES and the CEνNS reaction, Z and N are the total number of protons and neutrons in the target nucleus, respectively.

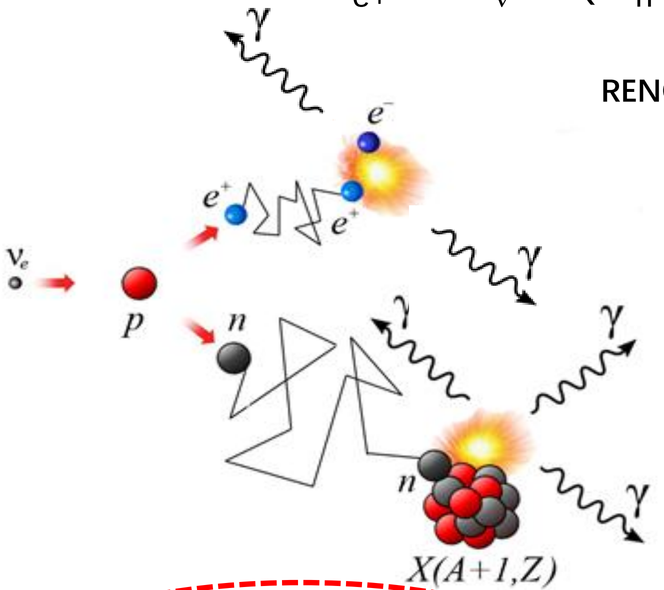
Inverse beta decay (IBD) is a magic reaction to catch reactor antineutrino

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

$$dN_{e+}(E_{e+})/dE_{e+} = dN_{\nu}(E_{\nu})/dE_{\nu} \times N_p \times (4\pi L^2)^{-1} \times \sigma(E_{\nu}) \times \delta_{REC}$$

$$E_{e+} = E_{\nu} - (M_n - M_p) - m_e = E_{\nu} - 1.804\ \text{MeV}$$

$\sigma \sim 10^{-43}$ см^2
very small !!



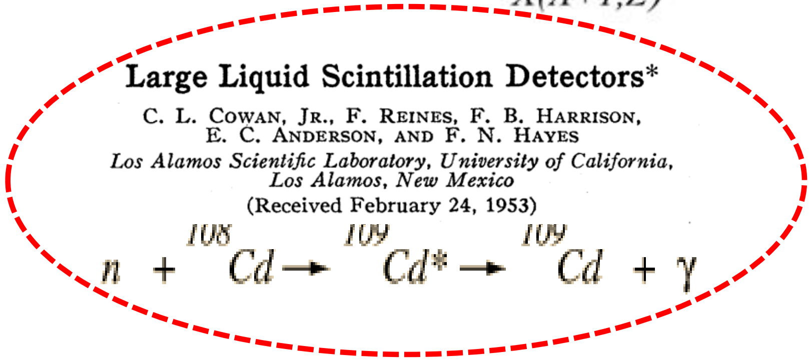
RENO, NEOS, Neutrino-4, STEREO, PANDA, DANSS, iDREAM
Rovno, Nuzifer, DayaBay, JUNO/TAO, WATCHMAN

1 – «Prompt event» – annihilation $e^+ + e^- \rightarrow 2\gamma$
Visible energy under the condition of neglecting the recoil of the neutron $E_{pt} = E_{\nu e} + Q + 2m_e$

2 – «Delayed event» – neutron capture followed by γ- emission $n + (A,Z) \rightarrow (A+1,Z) + \gamma$

Organic liquid/plastic scintillators - most popular target material for IBD detection

- **high H (p) concentration**
- **possible doping by Cd/Gd/^{6}Li/^{10}B**
- **well developed technology**



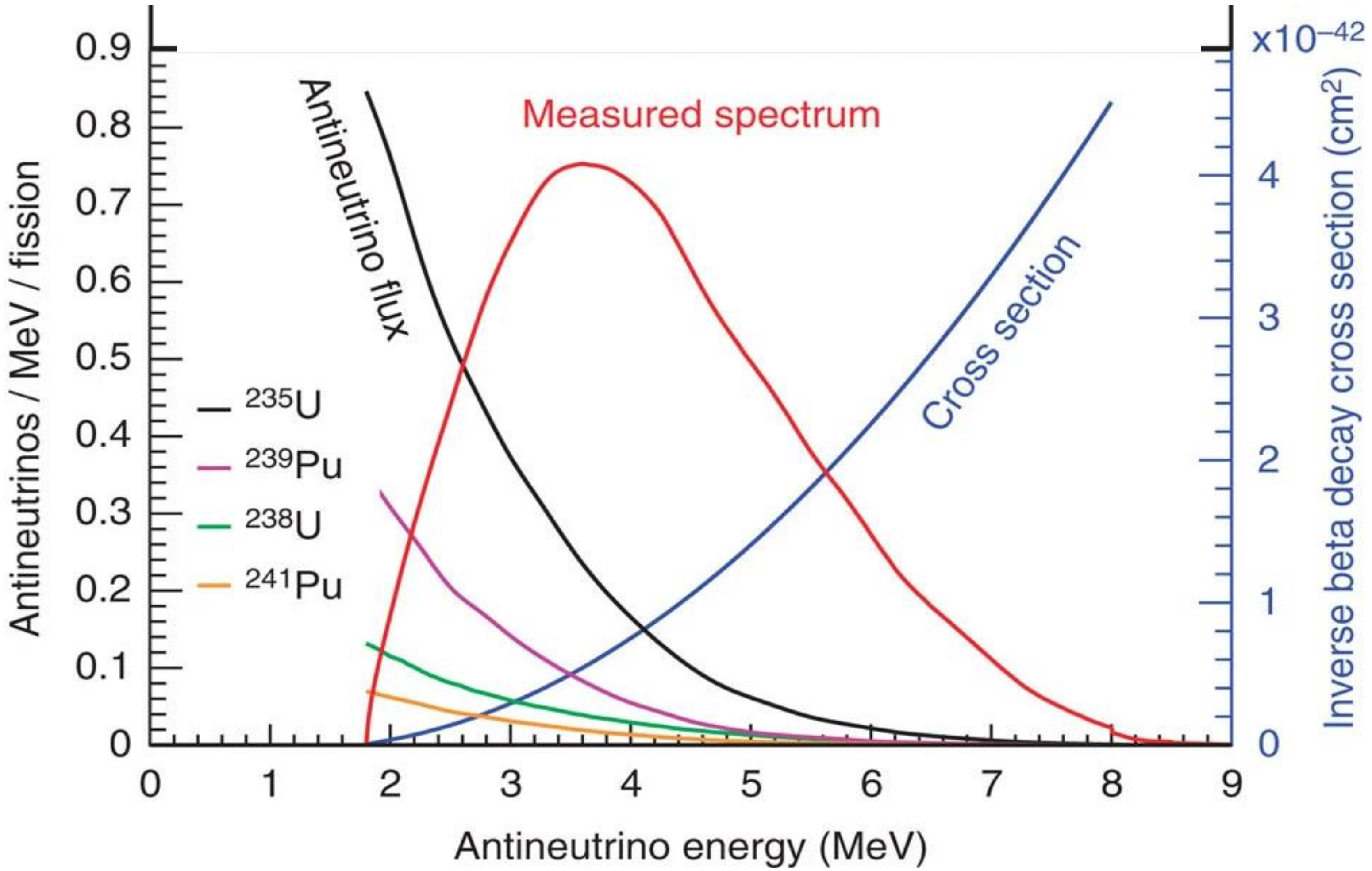
Large Liquid Scintillation Detectors*

C. L. Cowan, Jr., F. Reines, F. B. Harrison, E. C. Anderson, and F. N. Hayes
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received February 24, 1953)

$$n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$$

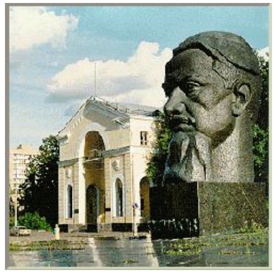
The detection methodology of reactor neutrinos has remained unchanged over the past ~70 years.

Reactor antineutrino detection using the inverse beta decay (IBD) reaction



P. Vogel, L. Wen, C. Zhang, Neutrino Oscillation Studies with Reactors, Nature Commun. 6 (2015) 6935. arXiv: 1503.01059, doi:10.1038/ncomms7935.

The advent of applied antineutrino physics



温故而知新 "By reviewing the old, one learns the new" Source: Confucius's *Analects*.

1974-1977 Calculation and measurement of spectra from ^{235}U & ^{239}Pu & ^{238}U & ^{241}Pu
It was shown that the number of antineutrinos per ^{239}Pu fission is less than in ^{235}U fission.
A.Borovoi, Yu.Dobrynin, V.Kopeikin. Nucl. Phys. (Rus.), 1977, 25, 264

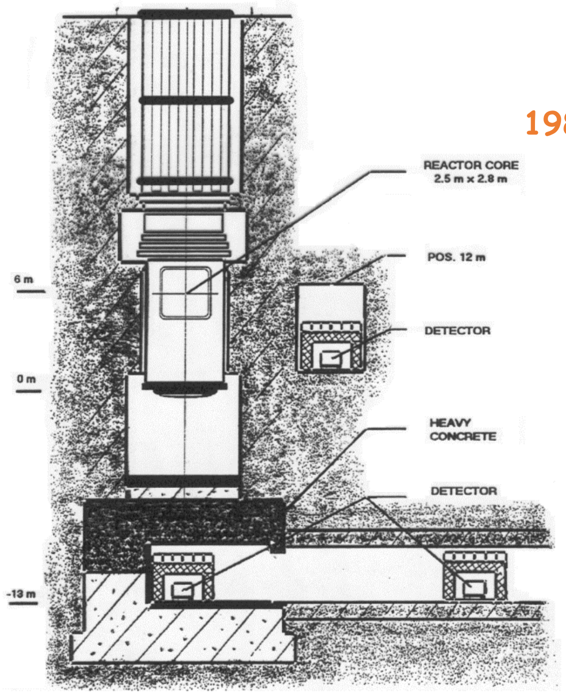
The following ideas where expressed by L.A. Mikaelyan during the *"Neutrino-77":*

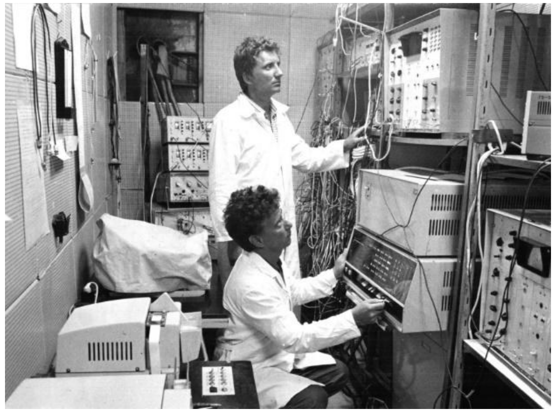
- antineutrino event count rate enables remote monitoring of the reactor output power due to the direct relationship between *N(antineutrino) ~ N(fissions),*
- the shape of the antineutrino spectra can be a source of additional information about the isotopic composition of the reactor core

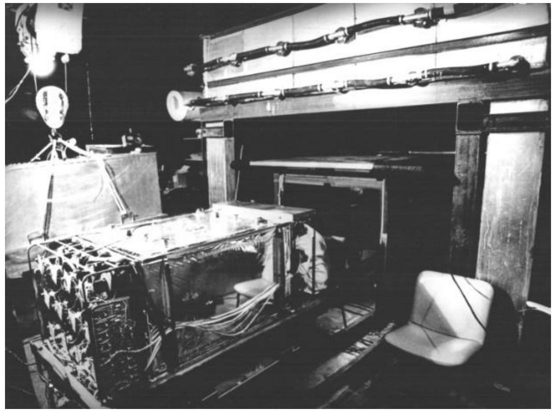
1978-1982 Several types of detectors for reactor antineutrino research from reactors have been developed (KIAE)

1982 A neutrino laboratory was created at the Rovno NPP

1983-1994 The feasibility study of the method was confirmed in experiments at the Rovno NPP (USSR) and, later, at the NPP in Bugey (France) (KIAE/IN2P3).







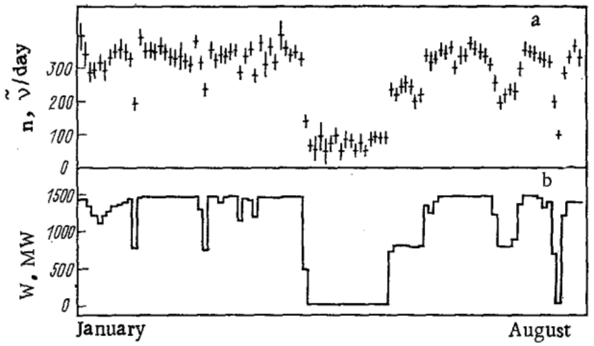


Fig. 2. Neutron instrumentation readings for January-August 1986 (a) and average daily reactor power based on data from thermal measurements (b).

Korovkin et al. 1988

The iDREAM is not just a detector, it is a comprehensive project based on more than 40 years experience in neutrino counting with the following aims:

«孔子曰：述而不作，信而好古» "Confucius said: "I transmit rather than create; I believe in and love the ancients."

- to ensure the safest possible development of nuclear energy in Russia
  - to implement complementary methods for nuclear reactors monitoring, including in abnormal and emergency situations

$W_{NPP} \sim \sum_i f_i(t)\, e_i(t)$ - The reactor power according to the **standard methods for VVER-1000 reactor** (fission products energy release)

$N_\nu \sim \sum_i f_i(t) \langle\sigma\rangle(t)$ - the **number of antineutrinos emitted from an active zone** of the reactor measured by antineutrino detector

The iDREAM is not just a detector, it is a comprehensive project based on more than 40 years experience in neutrino counting with the following aims:

«孔子曰：述而不作，信而好古» "Confucius said: "I transmit rather than create; I believe in and love the ancients."

- to ensure the safest possible development of nuclear energy in Russia
    - to implement complementary methods for nuclear reactors monitoring, including in abnormal and emergency situations

- to investigate a possibility to use the neutrino method for IAEA safeguards on the floating nuclear power units and other modular reactors
    - Operation of the floating nuclear power plant does not involve handling fresh and irradiated fuel, since the reactor is pressed at the manufacturing plant and is returned to the manufacturing plant after 8-10 years of operation

- to develop and test new methods, instruments, materials and technical solutions for neutrino detectors with focus on local Russian technologies

Fundamental publications of our teachers (in Russian) :

1. L. Mikaelyan, Neutrino laboratory in the atomic plant (fundamental and applied researches), in Proceedings of the International conference “Neutrino-77”, Vol. 2, Nauka, Moscow **(1978),** pp. 383-385.
2. 2. A.A. Borovoy, L.A. Mikaelyan, Possibilities of practical application of neutrinos, Atomic Energy 44, issue 6, 508-510 **(1978).**

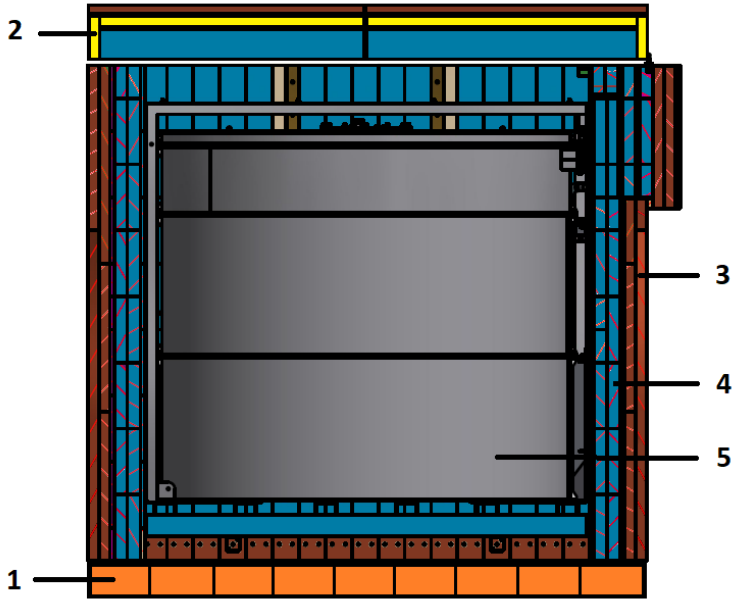
Reactor antineutrino physics at Kalinin NPP (KNPP)

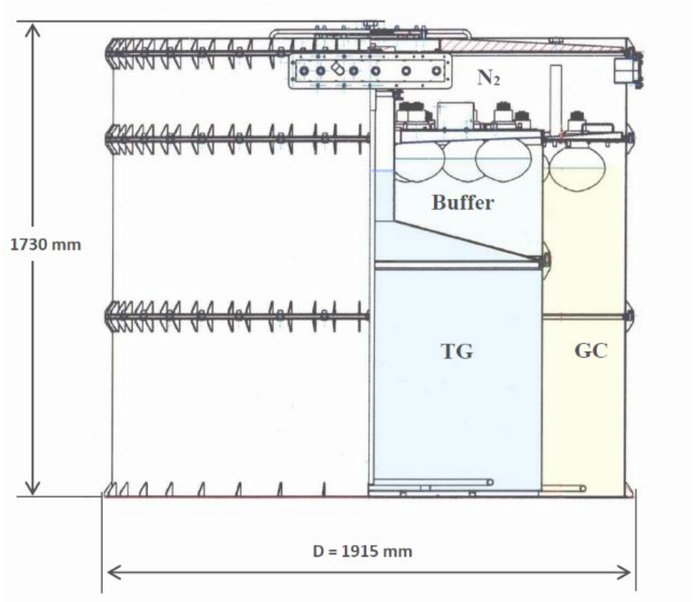
KNPP is located in the north of the Tver region, near the city of Udomlya and on the shore of the lake. It consists of four VVER-1000 reactors with a total capacity of 4 GW.

Kalinin NPP is a branch of the JSC Rosenergoatom Concern.

iDREAM

Detector design and laboratory location

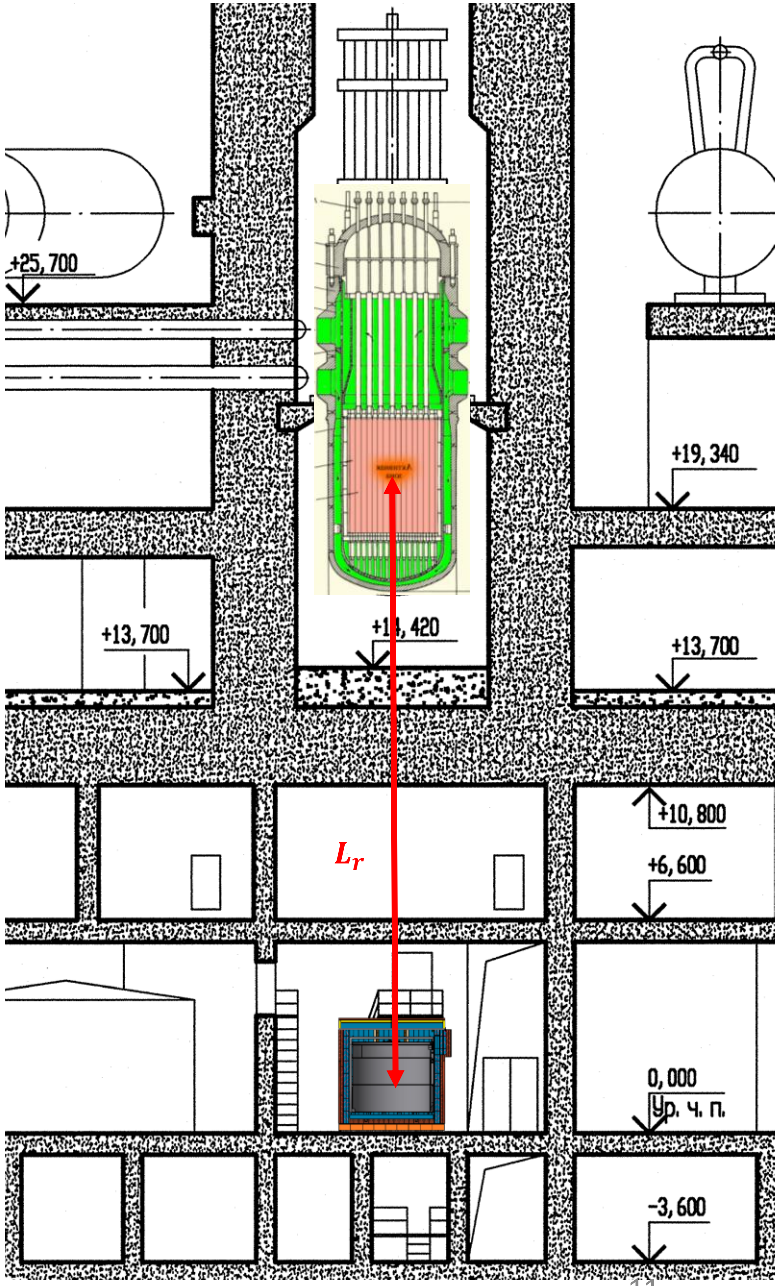




SHIELDING
1 (orange) – cast iron (14 см)
2 (yellow) – lead (5 см)
3 (brown) – pure polyethylene (10 cm)
4 (blue) – borated polyethylene (16 см)
5 – detector body

3 GWt “VVER-1000 (B-320)”
(KNPP 3d power unit, Russia)
$L_r = 19.5 \pm 0.1\ m$
(the Geodetic measurements was done with the uncertainty $\leq 0.5\%$*)*
active zone h=3.55 m d=3.12 m

DETECTOR
- Buffer – pure LAB, 0.5 m^3
- γ-catcher (GC) – LOS w/o Gd, 1.8 m^3
- Target (TG) – Gd-LOS (1 g/l) , 1 m^3
- 16 R5912 PMT in TG, 12 PMT in GC
- Two μ –plates above detector



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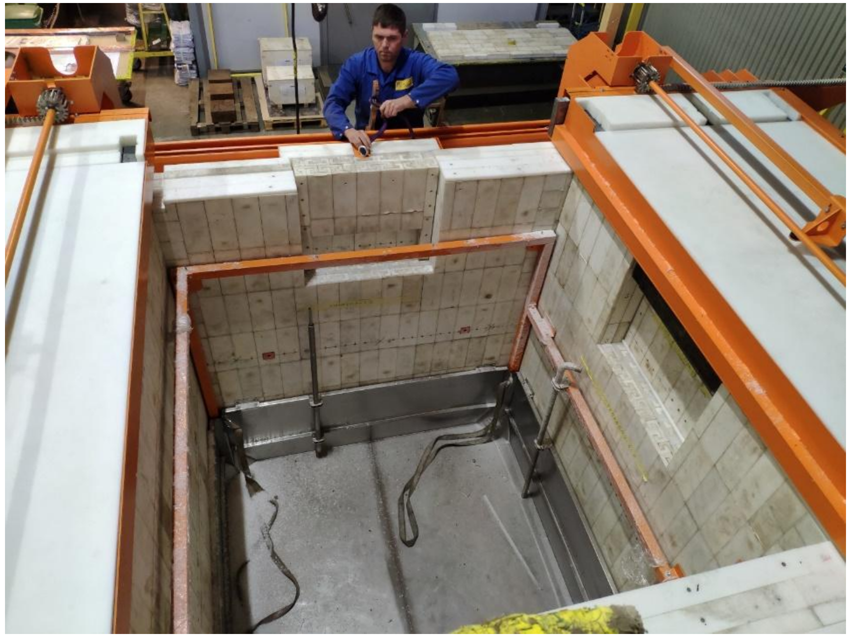
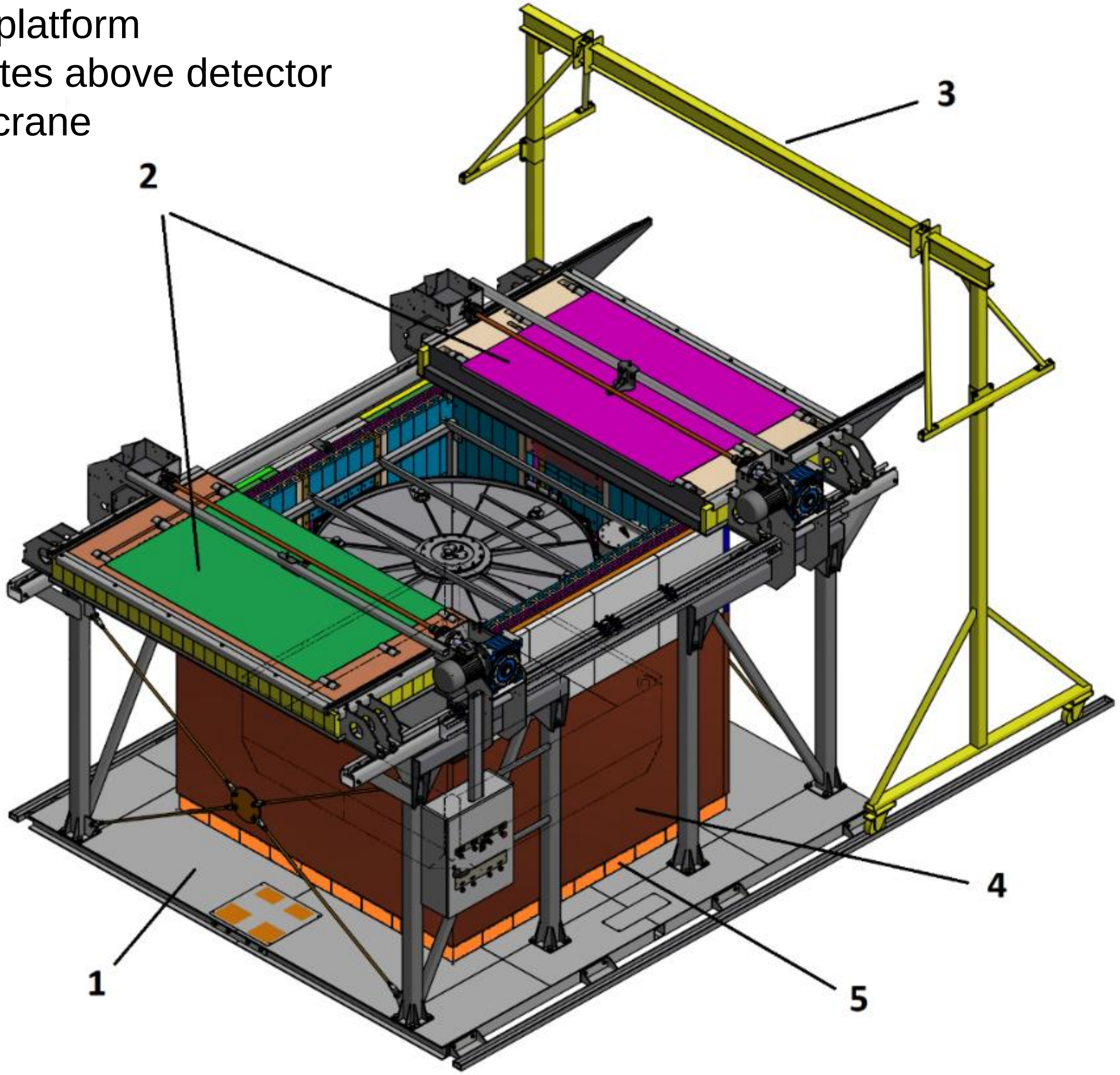
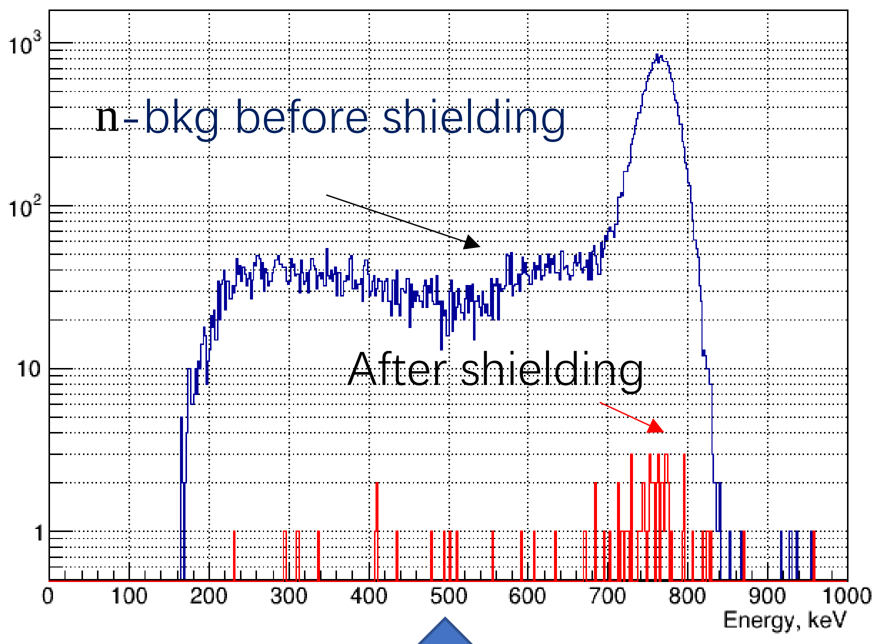
Shielding is critical !

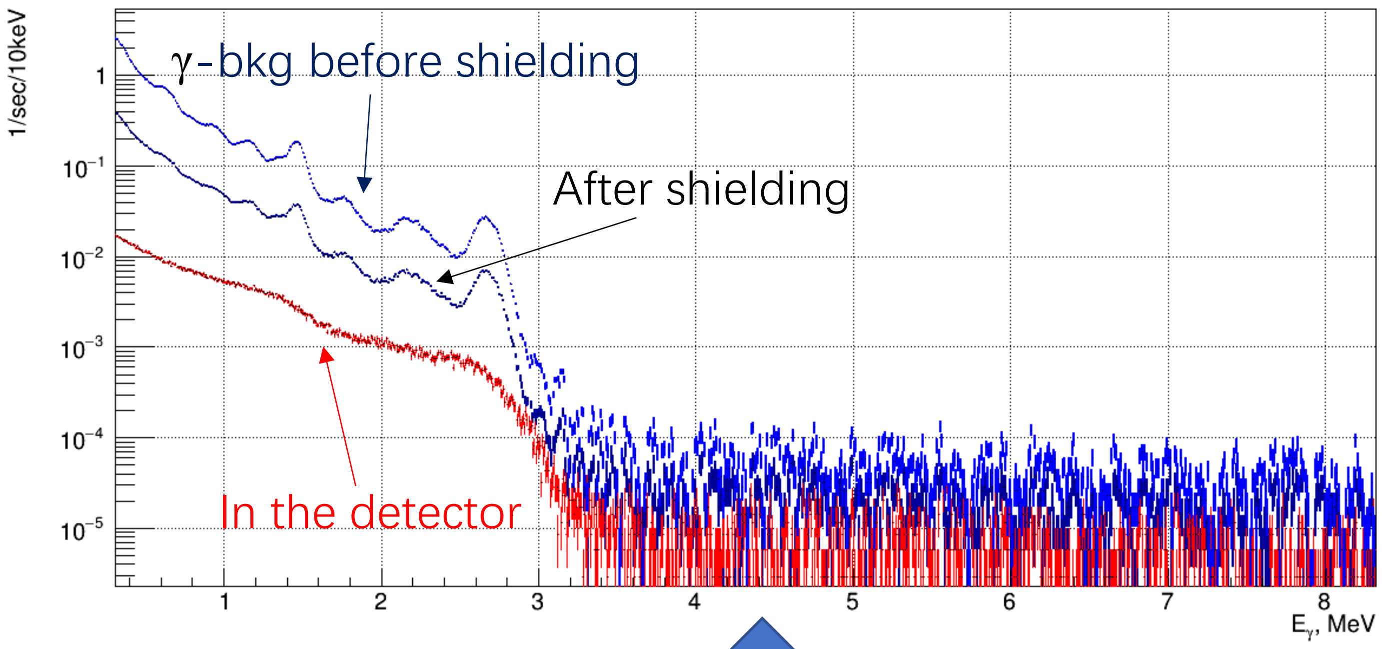


1 – unloading platform
2 – two μ –plates above detector
3 – assembly crane
4 – PE plates
5 – cast iron



Shielding is critical !





$n + {}^3He \rightarrow {}^3H + p + 764$ кэВ.

- Measurements using an array of 3He counters with a moderator.
- Neutron suppression factor is >100.

- Gamma background in the sub-reactor room measured by a detector based on NaI(Tl) d=h=90 mm.
- Suppression of the gamma-quantum flux by 3÷8 times, depending on the energy.
- N.B.: The iDREAM detector additionally suppresses the external γ-bkg due to the presence of a 30 cm gamma-catcher (along the perimeter) and a 40 cm buffer (on top).

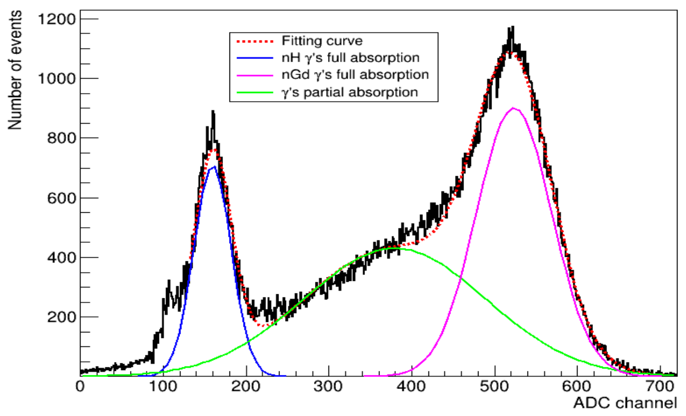
Gd-Liquid Organic Scintillator

$$\frac{N_{Gd}}{N_H} = \frac{\sigma_{Gd}}{\sigma_H} \times \frac{\rho_{Gd}}{\rho_H}$$

$$R_{Gd-H} = N'_{Gd}/(N'_H + N'_{Gd})$$

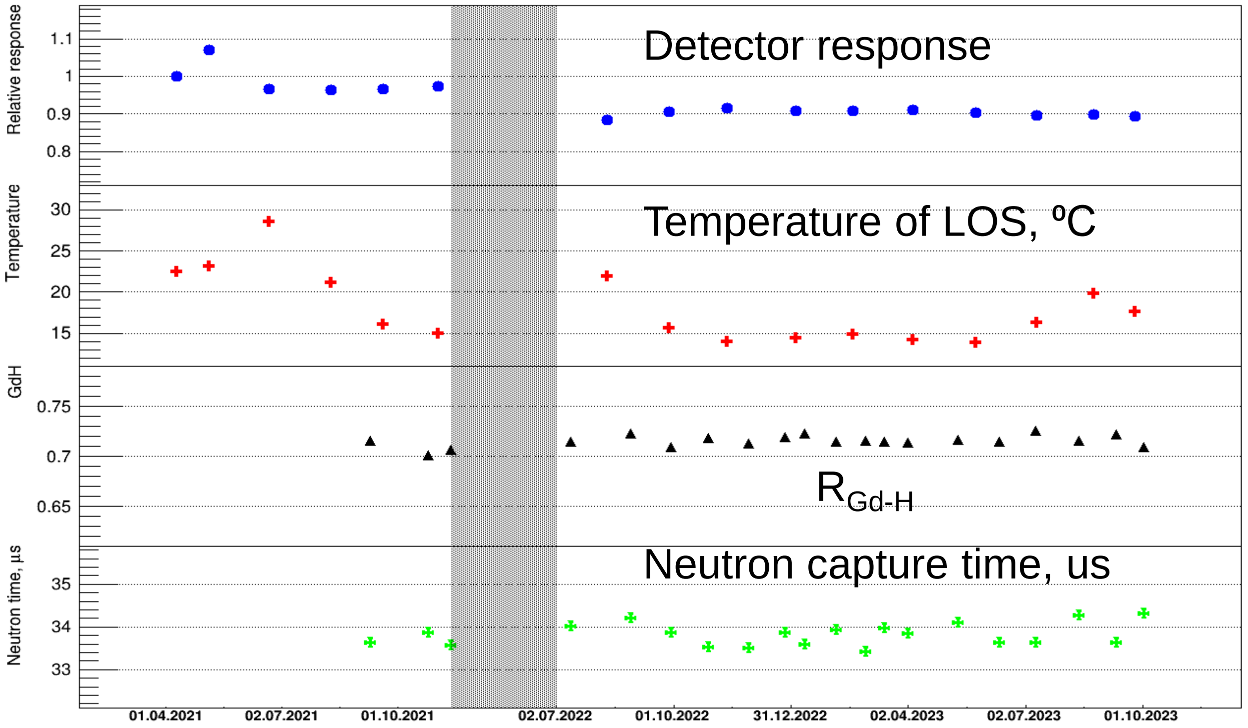
N'_{Gd} и N'_H - integrals in the peaks of total absorption of γ-quanta from neutron captures by gadolinium and hydrogen

Charge spectrum of neutron captures from the ^{252}Cf source at the center of the detector:



- LAB + PPO + bis-MSB + Gd (0.1%), 1.1 m^3 in total, $Gd(TMHA)_3$
- Gd-LOS – original recipe of Kurchatov Insitute
- Over 2.5 years of use, no degradation of the optical and chemical properties of Gd-LOS was observed, provided that the temperature of the LOS was stable, < 20 ºC, and there was no contact with the atmosphere.
- R_{Gd-H} is stable within ±2.4% (±3σ)
- τ - neutron capture time is stable within ±2% (±3σ)
- Rate of the detector response decreasing : ~3%/y

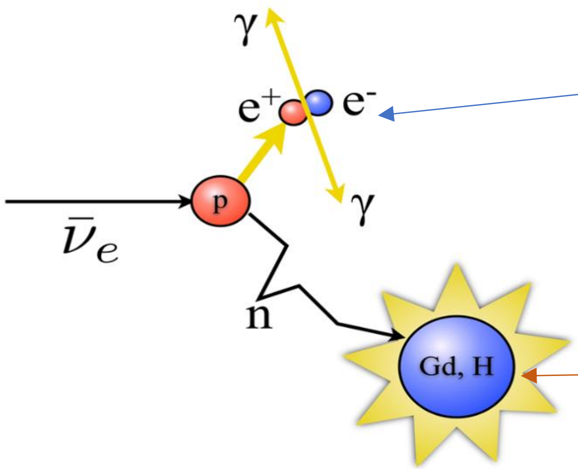
The Gd-containing liquid scintillator is stable for > 2.5 years of observations, provided that the temperature is maintained at a level below 20 ºC and there is no contact with the atmosphere



A. Abramov et al., Technical Physics Letters, 2023, Vol. 49, No. 8

IBD detection and selection criteria, delayed coincidence technique

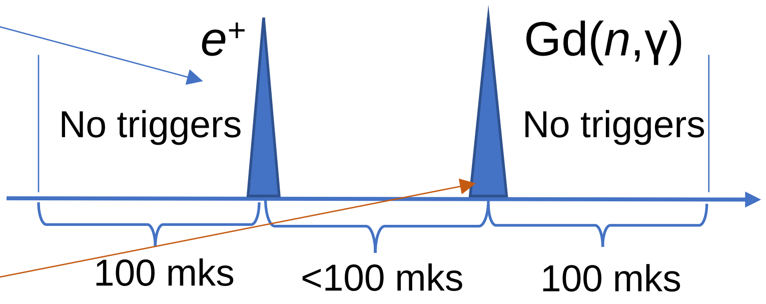
:



Prompt event- positron

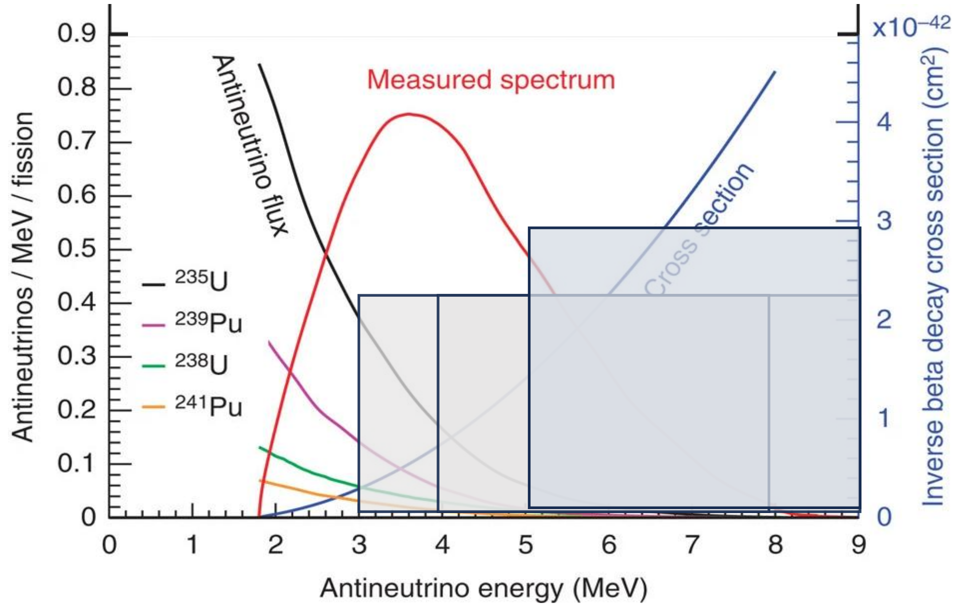
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Delayed event - neutron

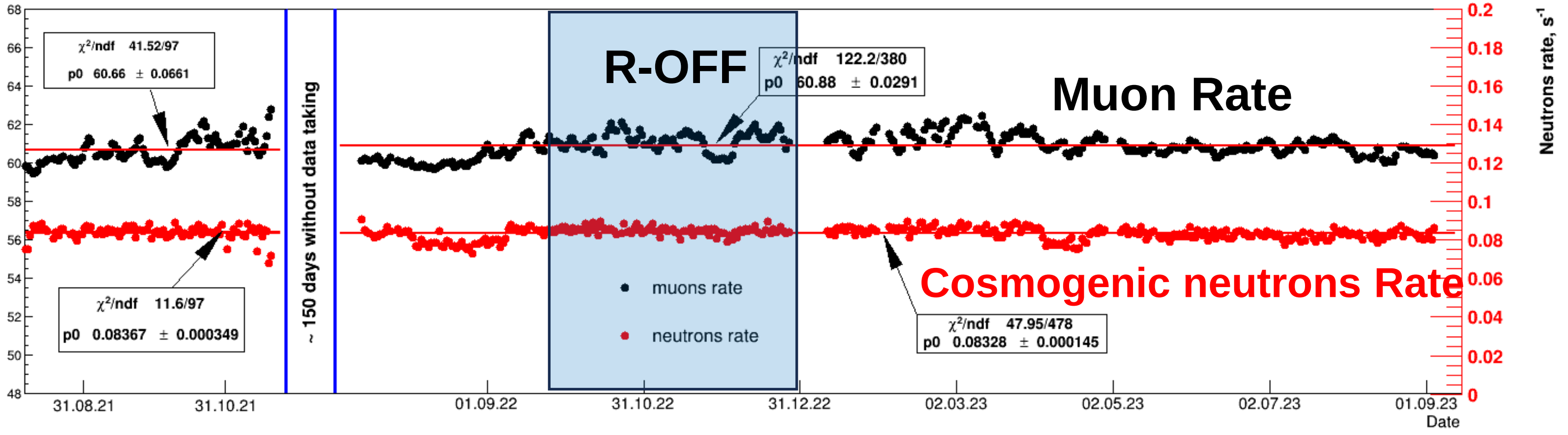


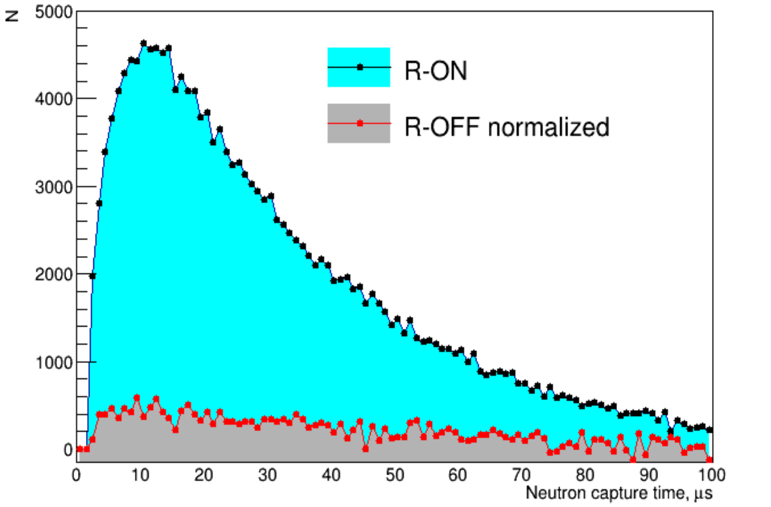
Selection criteria:

- $E_{prompt} > 3$ MeV or $\in [4;8]$ MeV
- $E_{delayed} \in$ [5;10] MeV
- $\Delta T = \ 2 - 100\ \mu s$
- Isolation cut: absence of any trigger within 100 μs before prompt and after the delayed event;



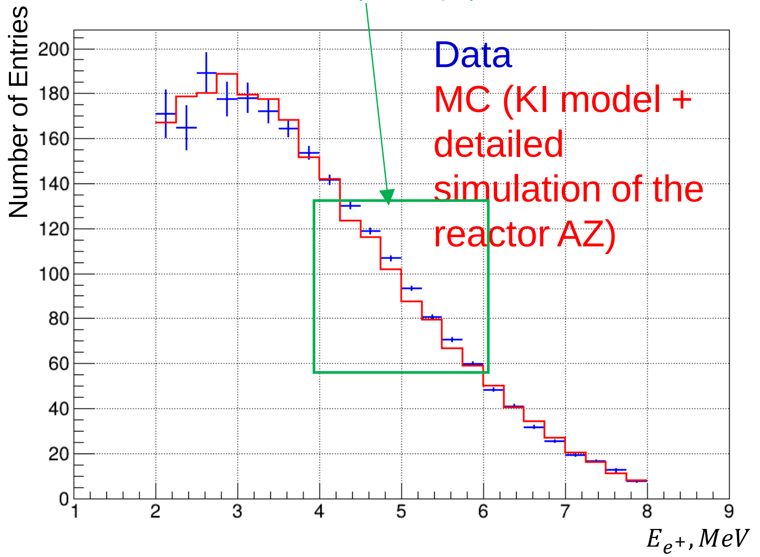
Signal and Background

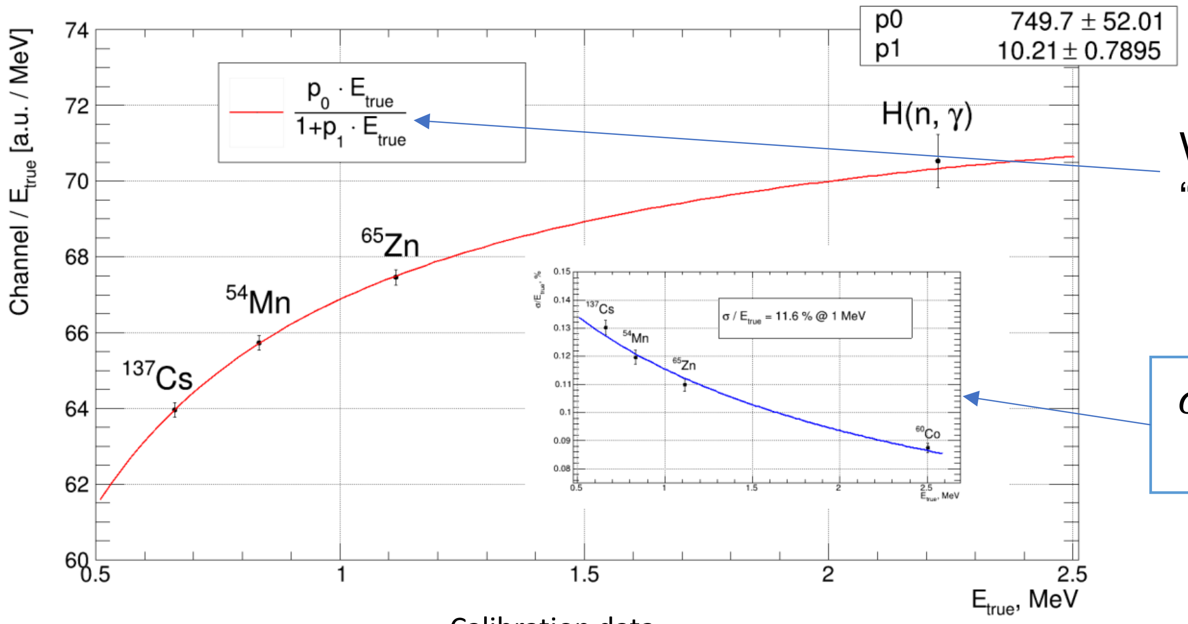




Time spectra of the candidate events selected during R-ON (*1*) and R-OFF(*2*) periods.

There is a trace of the 5MeV spectral distortion ("Bump")





Calibration data

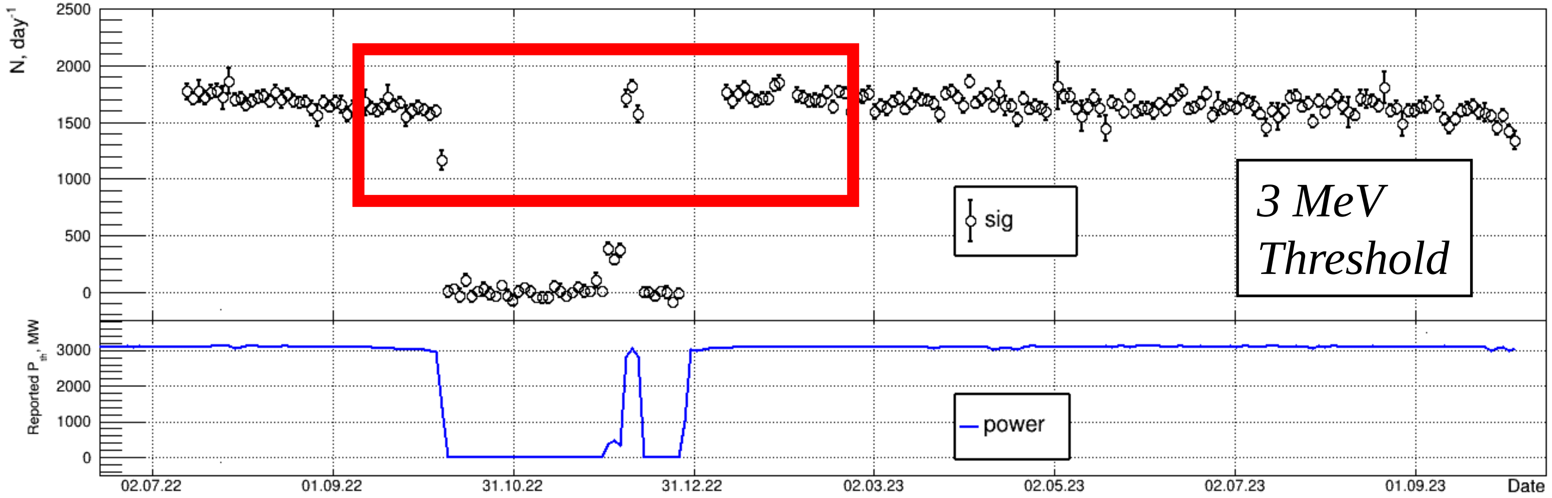
Well-described with "Birks" function

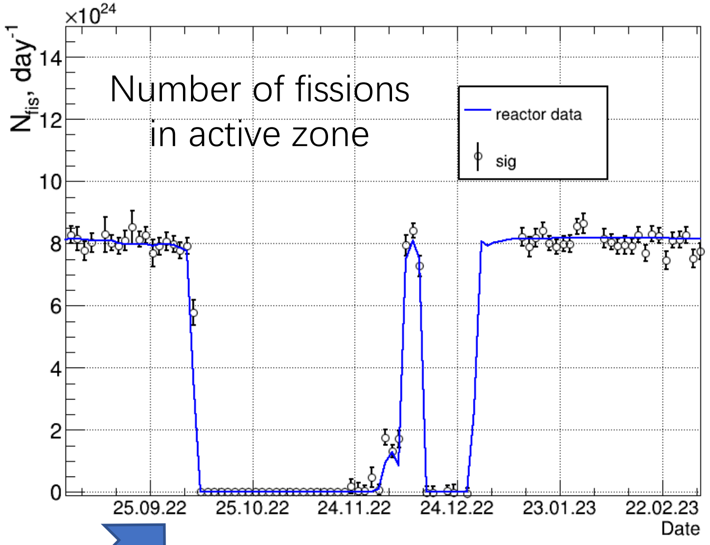
$$\sigma/E_{true} = 12\% \text{ at } 1\ MeV$$

The Gd-doped scintillator is stable during three years. A successful experience.

Signal and Background

- T_{live}(R-ON) = 217 d, T_{live}(R-OFF) = 41 d
- E_{prompt} > 3 МэВ, 5 MeV < $E_{delayed}$ < 10 МэВ
  - Advantages of a high threshold: correction for the nonequilibrium component in the antineutrino spectrum (Kopeikin, V.I., Skorokhvatov, M.D. Phys. Atom. Nuclei 80, 266-274 (2017)) and the contribution from spent nuclear fuel from the spent fuel pool in total <1%
  - The units No. 2 (1.2%) and No. 4 (1.6%) contribution to the antineutrino flux is taken into account according to their power data





$$N_\nu \sim \sum_i f_i(t) \langle \sigma \rangle (t)$$

Reactor energy production measurements

For practical applications, the time t during which the neutrino detector is capable of measuring the energy production W is of interest. In fact, we recalculate the number of IBD events with corrections for the difference in the spectra of antineutrinos from different isotopes

$$W(t) = \int_{t_1}^{t} P_{th}(t')dt',$$

$$N_\nu = \gamma(1+k)P_{th},$$

$$\gamma = \frac{\epsilon N_p}{4\pi R^2} \cdot \frac{\sigma_5}{E_5},$$

$$1+k = \frac{1+\sum_i \alpha_i(\sigma_i/\sigma_5 - 1)}{1+\sum_i \alpha_i(E_i/E_5 - 1)},$$

Klimov Yu.V., Kopeikin V.I., Mikaelyan L.A. et al. // Atomic Energy. 76, N 2. 130 (1994)

- $\mathbf{P_{th}}$ – thermal power of the reactor
- $\mathbf{N_\nu}$ – number of IBD events
- $\boldsymbol{\epsilon}$ – detector efficiency
- $\mathbf{N_p}$ – number of H-atoms in the target
- **R** – distance from the target center of the active zone center
- $\boldsymbol{\sigma_i}$ —cross section of the IBD for one fission of the i-th isotope weighted with the antineutrino spectrum (according to the Kurchatov spectral model (KM)) [1]
- $\mathbf{E_i}$— thermal energy of fission of the i-th isotope[2]
- $\boldsymbol{\alpha_i}$ — fraction of fission of the i-th isotope (according to KNPP data)
- i = 5, 8, 9, 1 means values corresponding to ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu

[1] Kopeikin V., Skorokhvatov M., Titov O. // Phys. Rev.D. 104. L071301 (2021)
[2] Kopeikin V.I., Popov D.V., Skorokhvatov M.D. // Phys. Atom. Nuclei. 87. 389 (2024)

Reactor energy production measurements

The number of IBD events is equal to:

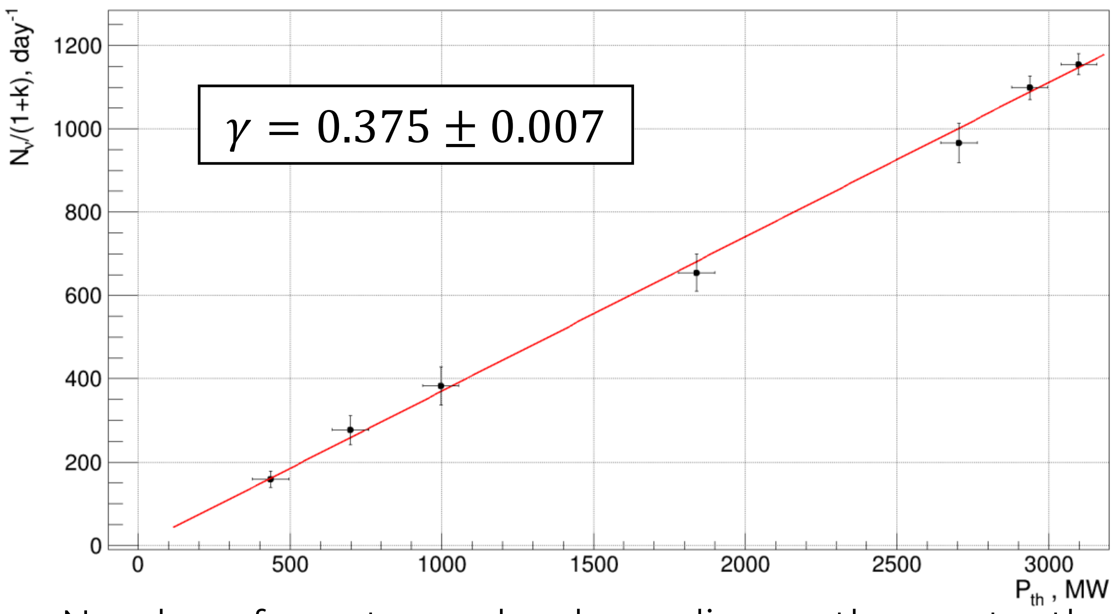
$$N_\nu = \gamma(1+k)P_{th}$$

$\gamma = \frac{\epsilon N_p}{4\pi R^2}\frac{\sigma_5}{E_5}$ - a detector dependent parameter from the experiment

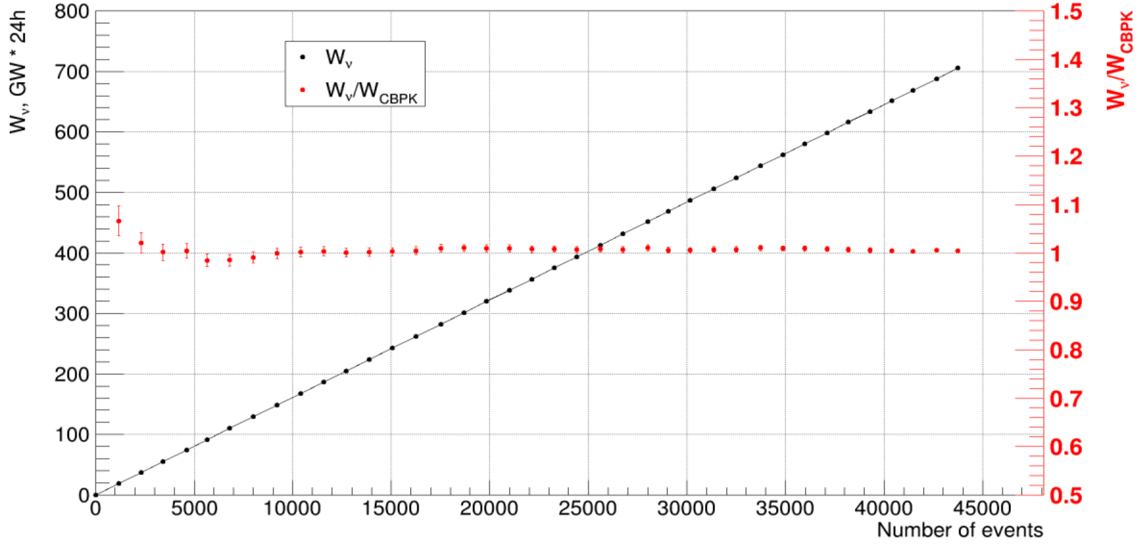
$1+k = \frac{1+\sum_i \alpha_i(\sigma_i/\sigma_5 - 1)}{1+\sum_i \alpha_i(E_i/E_5 - 1)}$ - a reactor dependent parameter calculate via KM

$$\frac{N_\nu}{1+k} = \gamma P_t$$

$N_\nu = 224 \pm 20 \frac{\overline{\nu}_e}{4h.}$ for 103% of nominal power



Number of events per day depending on the reactor thermal power



Energy production by the antineutrino method $\mathbf{W_\nu}$ depending on the number of registered events (black) and its relation to energy production $\mathbf{W_{CBPK}}$ according to the data of the KNPP (red)

Relative method:

- Operational power data and fission fractions estimates have been provided by the NPP;
- The detector properties parameter γ determined by the calibrations with known operational power.

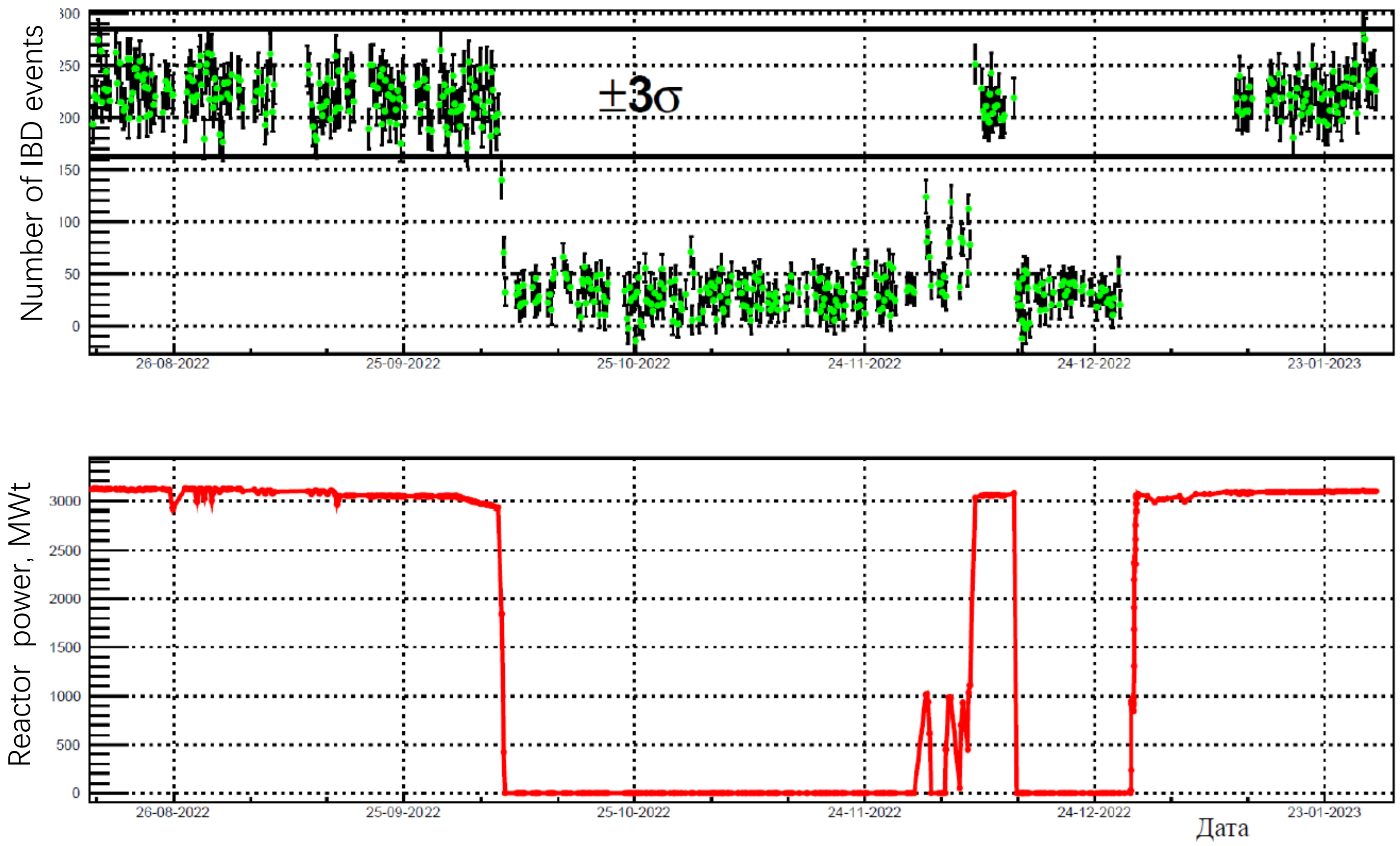
Power output: $W_{th} = \int P_{th}(t)dt$;

If N_ν ~ 10000, $W_{\text{СВРК}}$ agrees with W_ν within less than 1%.

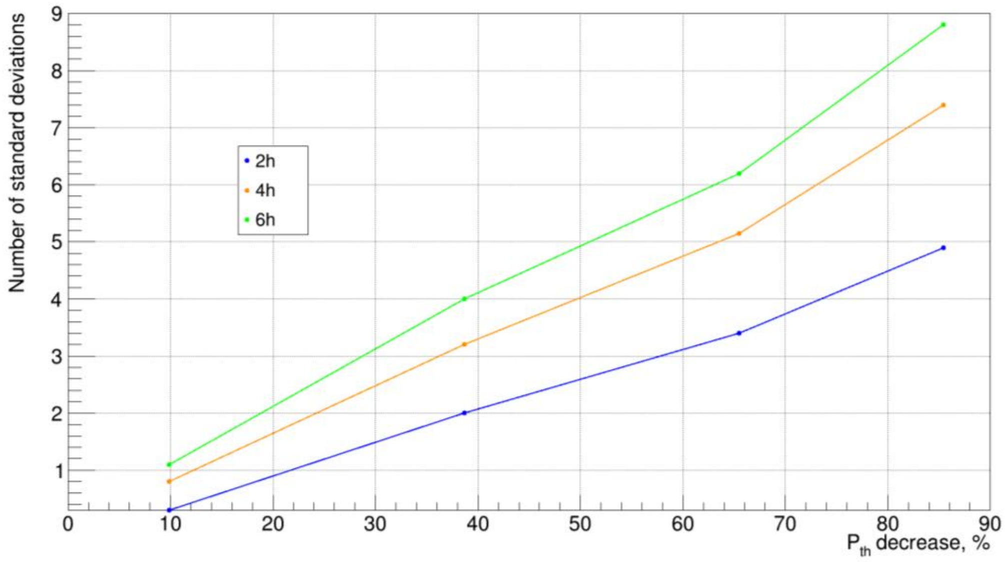
VMU. Series 3. PHYSICS. ASTRONOMY. 80(2), 2520202 (2025)

Sensitivity of iDREAM to reactor power changes

$$\sigma = 20\,\frac{\overline{\nu}_e}{4h.}$$



Top: Number of detected antineutrinos in iDREAM detector for 4-hour data collection intervals.
Bottom: Thermal power of the reactor according to the reports of KNPP

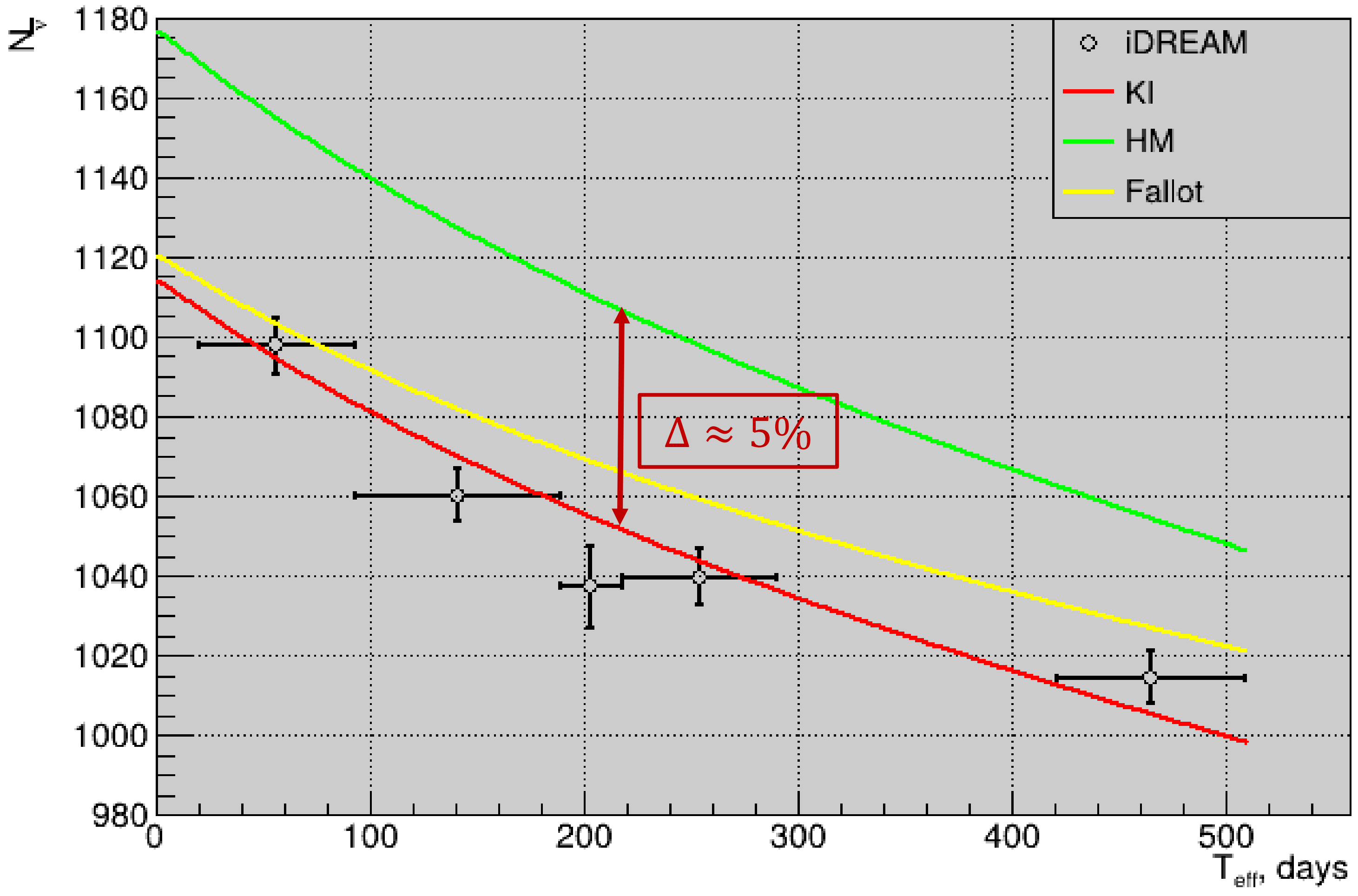


The iDREAM sensitivity for the operational power decrease

- The relative power measurement method is used.
- **N$_\nu$** = 224 ± 20 event/ 4 h (1344 ± 120 event /d)
- The 50% power decrease can be registered within 2 (4) hours with 2.6 (4)σ stat. significance;
- The 10% power decrease can be registered within 6 hours with 1.1 σ stat. significance.

Abramov, A.V. et al., Moscow Univ. Phys. Bull. ***80*, 255–261 (2025).**

The $\overline{\nu}_e$ rate evolution during the campaign.



Abramov, A.V. et al., Moscow Univ. Phys. Bull. **80, 255–261 (2025).**

- The $\overline{\nu}_e$ rate decrease over the full cycle is ~10%. Energy range [4; 8] MeV
- Δ is due to the normalization of ^{235}U spectrum;
- Seems like that KI model represents the data better.

KI – Kurchatov institute model[1]
HM – Huber-Muller model[2]
Fallot – Estienne-Fallot model[3]

References:
[1] V. Kopeikin, M. Skorokhvatov, and O. Titov, Phys. Rev. D 104, L071301 (2021).
[2]T. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, et al., Phys. Rev. C 83, 054615 (2011). P. Huber, Phys. Rev. C 84, 024617 (2011)
[3] M. Estienne, M. Fallot, A. Algora, J. Briz-Monago, V. M. Bui, S. Cormon, W. Gelletly, L. Giot, V. Guadilla, D. Jordan, et al., Phys. Rev. Lett. 123, 022502 (2019).

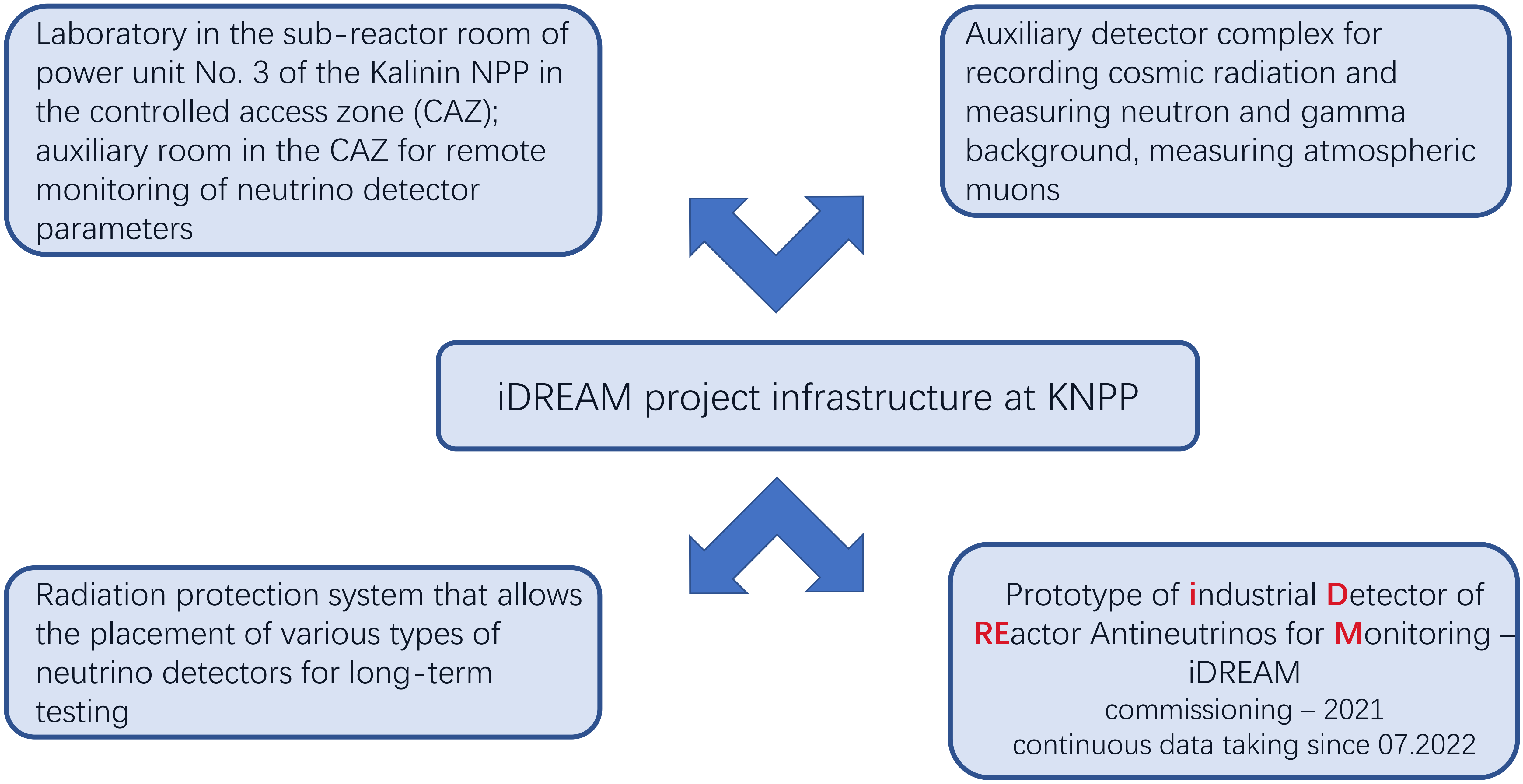
Conclusion:

- A laboratory has been created for research in the antineutrino flow from VVER-1000 unit No. 3 of the Kalinin NPP. The iDREAM detector is being tested in the antineutrino flux of the industrial reactor
- The Gd-containing liquid scintillator is stable for > 2.5 years of observations, provided that the temperature is maintained at a level below 20 ºC and there is no contact with the atmosphere
- The daily energy production of the VVER-1000 unit No. 3 was measured based on the iDREAM data.
- The power output measurements was done:

  If $\boldsymbol{N_{\nu}}$ **~ 10000,** $\boldsymbol{W}_{\text{СВРК}}$ **agrees with** $\boldsymbol{W_{\nu}}$ **within less than 1%.**
- The unauthorized reactor shutdowns registering perspectives:

  - 50% power decrease can be registered within 2 (4) hours with 2.6 (4)σ stat. significance;
  - 10% power decrease can be registered within 6 hours with 1.1 σ stat. significance.

Thank you for your attention!


Laboratory in the sub-reactor room of power unit No. 3 of the Kalinin NPP in the controlled access zone (CAZ); auxiliary room in the CAZ for remote monitoring of neutrino detector parameters
Auxiliary detector complex for recording cosmic radiation and measuring neutron and gamma background, measuring atmospheric muons
iDREAM project infrastructure at KNPP
Radiation protection system that allows the placement of various types of neutrino detectors for long-term testing
Prototype of industrial Detector of REactor Antineutrinos for Monitoring – iDREAM
commissioning – 2021
continuous data taking since 07.2022

Nuclear reactor monitoring with neutrino

Reactor Neutrino Detectors for flux and spectrum measurements:

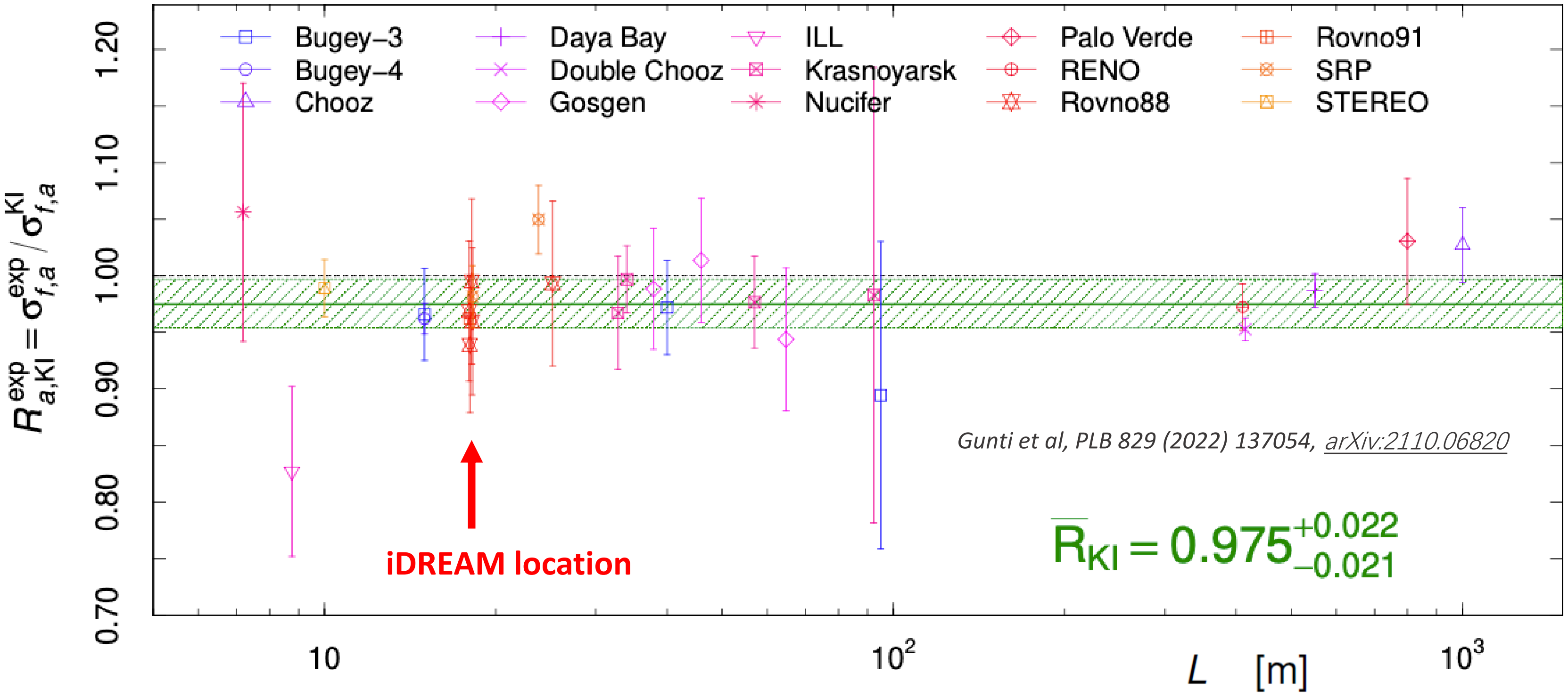
Precision Instruments with percent-level control of detection efficiencies

Energy-scale and response well understood

Total neutrino yield measurements have achieved great precision

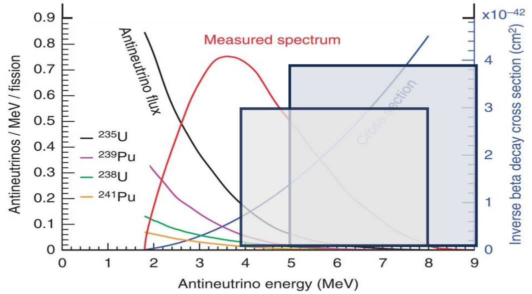
Θ_{13} - DayaBay, DoubleChooz, RENO, JUNO/TAO

SBL – NEOS (-II), STEREO, PROSPECT, Neutrino-IV, DANSS, **iDREAM,** TAO

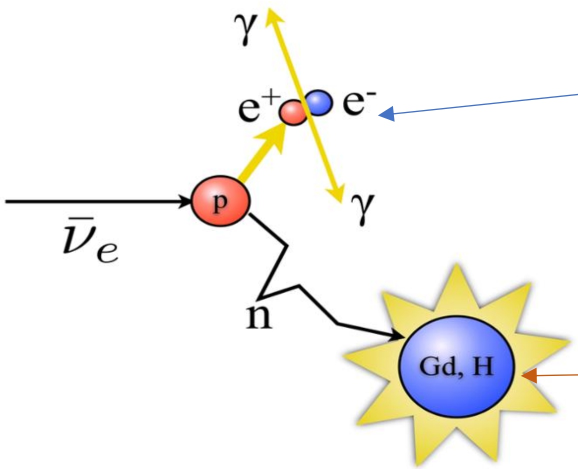


Ratio of measured and expected IBD yields for the reactor experiments as a function of the reactor-detector distance L.
The error bars show the experimental uncertainties.

IBD detection and selection criteria



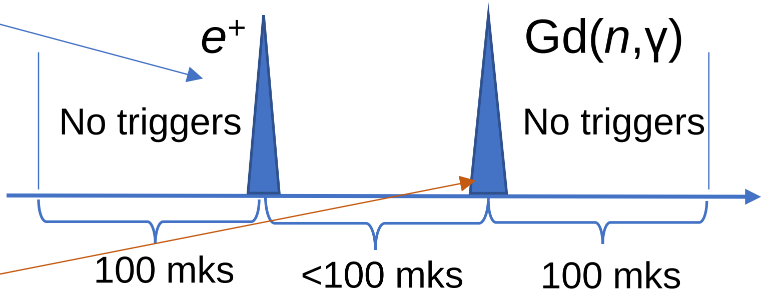
Delayed coincidence technique:



Prompt event- positron

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

Delayed event - neutron



Selection criteria:
- $E_{prompt} \in [4;8]$ MeV
- $E_{delayed} \in$ [5;10] MeV
- $\Delta T = \; 2 - 100 \; \mu s$
- Isolation cut: absence of any trigger within 100 μs before prompt and after the delayed event;

Accidentals approximation(“off-time window” method)

- GAP = 500 μs;
- WINDOW = 100 μs;
- 100 consecutive windows.