The RED-100 results & prospects

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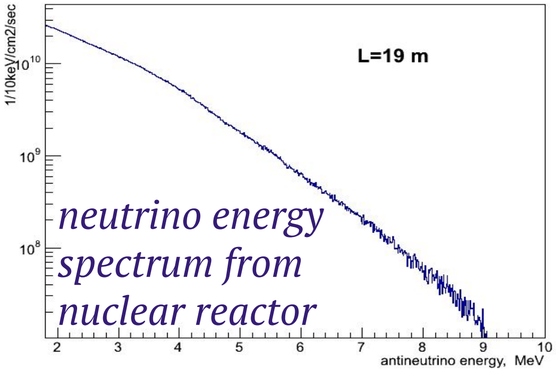
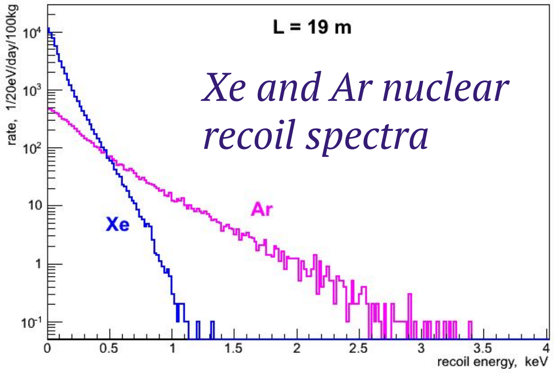
on behalf of RED collaboration

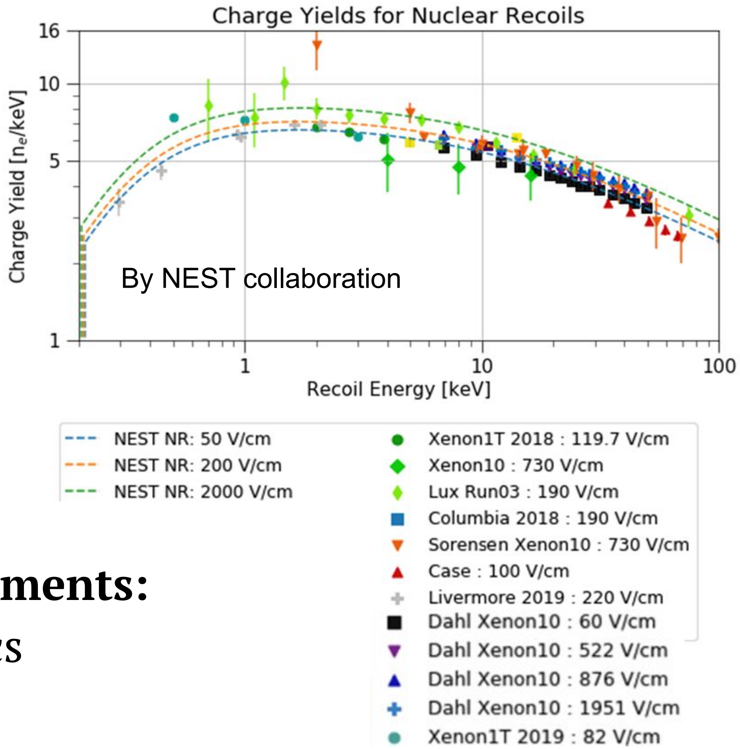
2023
Moscow

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{(N-(1-4\sin^2\theta_W)Z)^2}{4}F^2(Q^2) \propto N^2$$







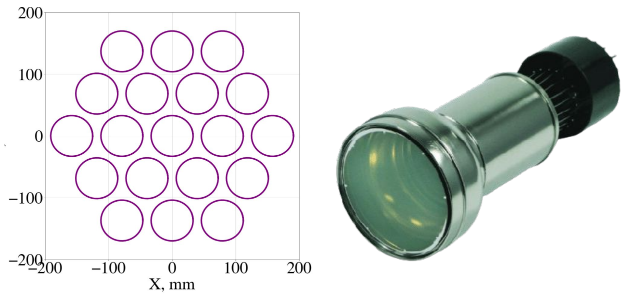
— predicted by Standard Model
— extremely low energy of the recoil nucleus
— only in 2017 it was discovered by COHERENT collaboration

Motivation of experiments:
— fundamental physics (supernova dynamics)
— SM verification
— practical goals (monitoring of nuclear reactors)

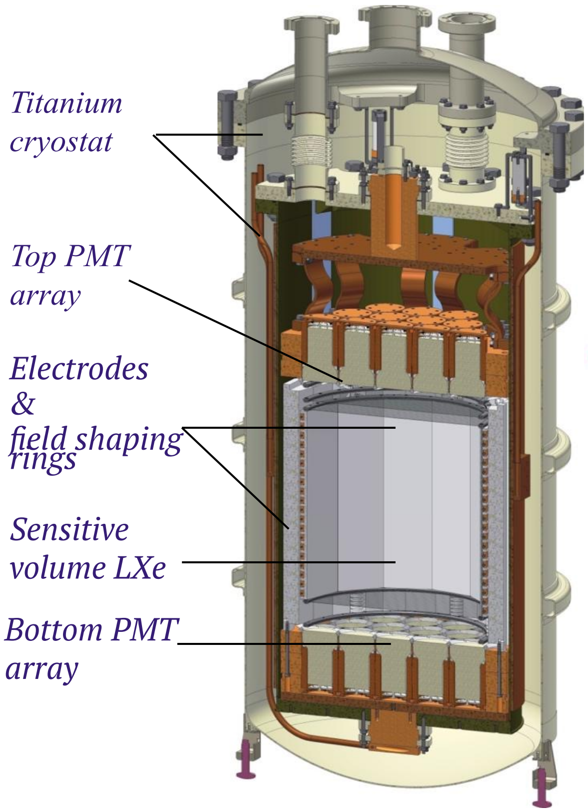
more information — D.Akimov "Worldwide experimental study of CEvNS"

RED-100 experiment

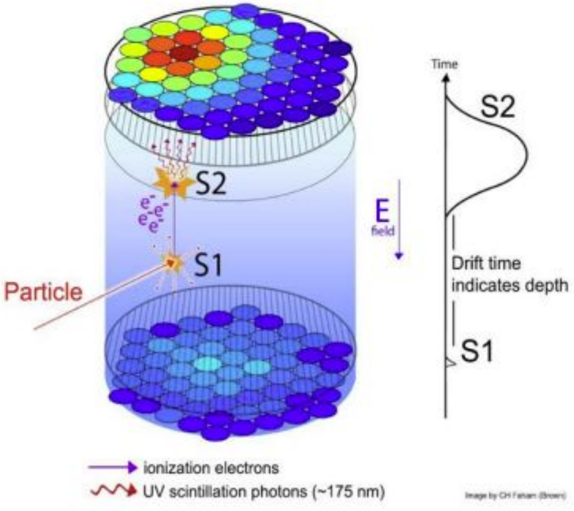
- Two-phase noble gas emission detector
- Contains ~200 kg of LXe (~ 100 kg in FV)
- 26 PMTs Hamamatsu R11410-20 (19 in top PMT array, 7 in bottom PMT array)
- Thermosyphon-based cooling system (LN_2)



Geometry of the PMT matrix (left) and photo of Hamamatsu R11410-20 (right)

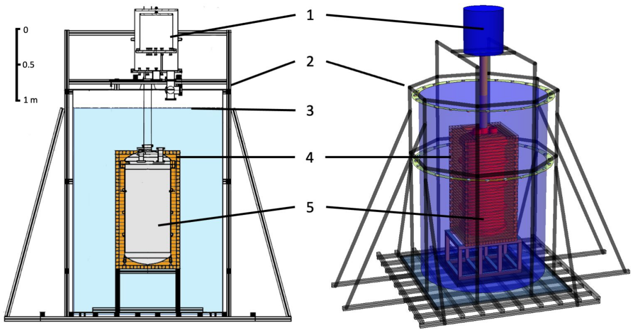


Two-phase emission detector technique



Sensitive to the single ionization electron (SE) signal. CEvNS response is expected to be of several electrons.

RED-100 at Kalinin NPP (Udomlya, Russia)



Design of the RED 100 passive shielding.
1 — LN2 tank, 2 — support frame, 3 — water tank,
4 — Cu shielding, 5 — Ti cryostat of the RED-100

— 19 meters from the reactor core
— reactor core, building&infrastructure works as a passive shielding from cosmic muons
— 70 cm of passive water shielding from neutrons
— 5 cm of copper passive shielding from gamma sources
— Antineutrino flux at place ~ $1.35*10^{13}$ $cm^{-2}s^{-1}$
— 65 m.w.e. in vertical direction

— 2020 RED-100 was shipped to KNPP
— 2021 Deployed and tested
— 2022 (Jan-Feb) Physical run
— reactor OFF and reactor ON periods

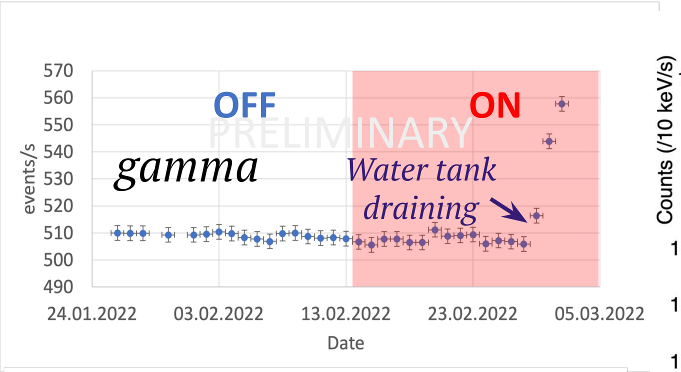
[*Akimov D. Y., et al. JINST 17.11 (2022), T11011*]

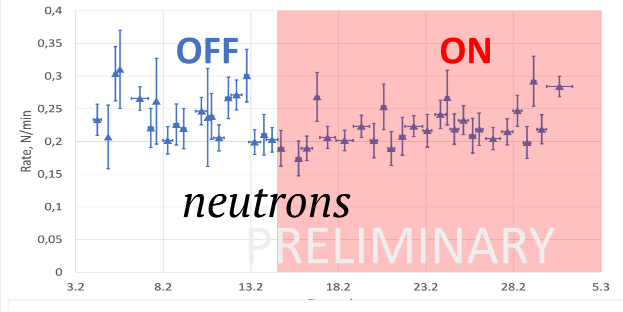
External background

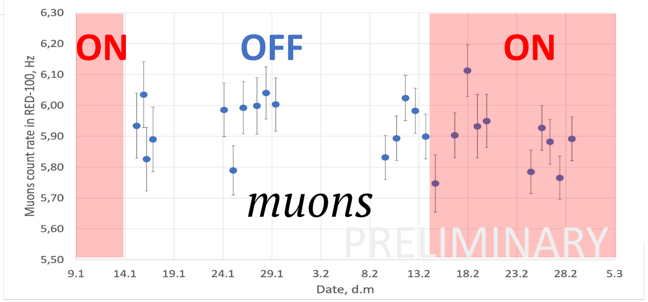
- background was measured with RED-100 itself and with different additional detectors:
  — NaI[Tl] — gamma background
  — Bicron (BC501A liquid scintillator) — neutron background

- muon background was measured using RED-100

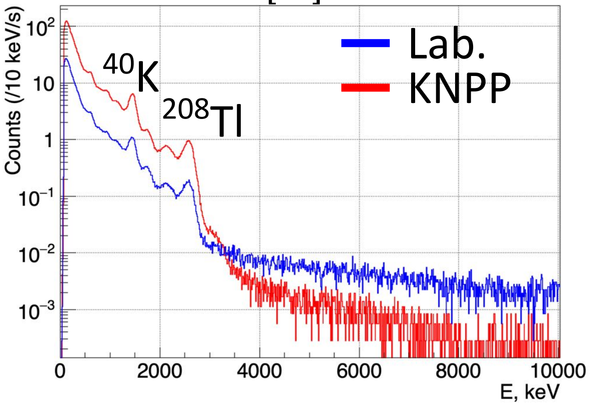
- no significant correlation in external background count rate with reactor operation

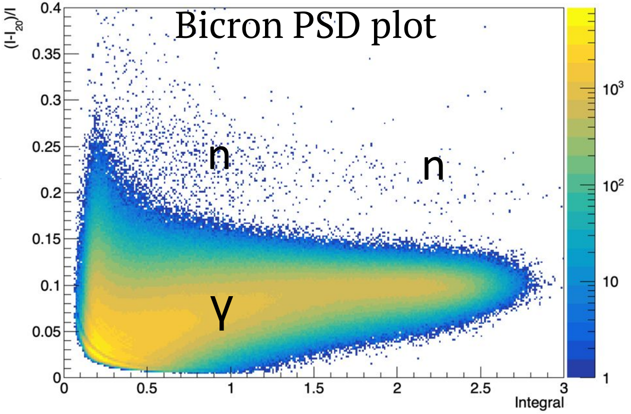






background spectra measured with NaI[Tl]

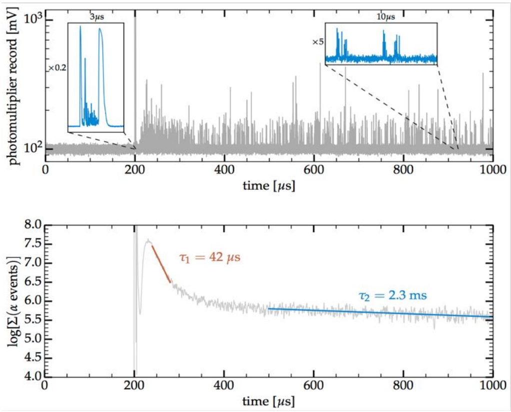




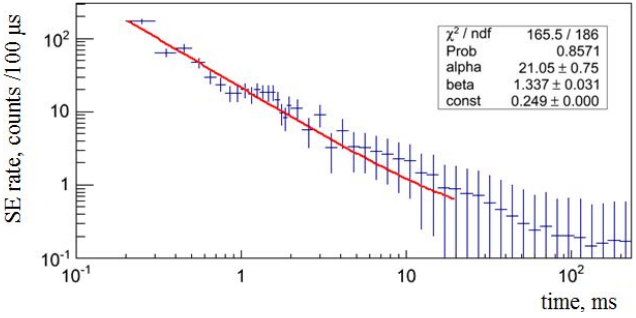
The main background in the ROI

- SE rate increasing after big energy deposition in liquid noble gas detector
- It was observed by several groups
- Electron shutter
  - To block the muon signals
  - To minimize short component of SE background
- Still very high rate (250 kHz in the lab. test)
- Reduction in a factor of ~7-8 at KNPP

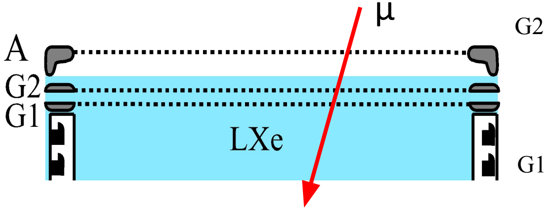
P. Sorensen, K. Kamdin **JINST 13 (2018) no.02, P02032**

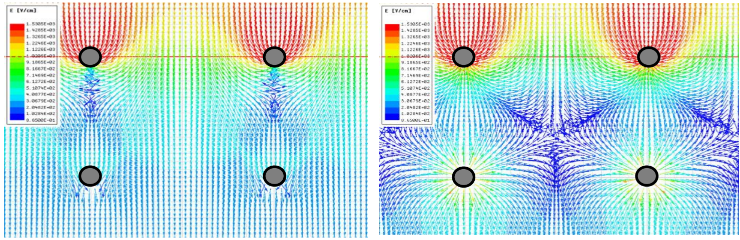


JINST 11 (2016) no.03, C03007



Observed in ZEPLIN-III: **JHEP 1112 (2011) 115, arXiv:1110.3056 [physics.ins-det]**



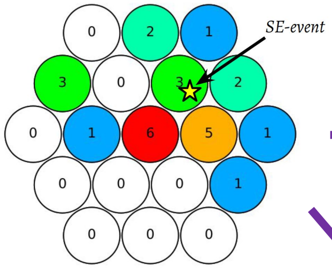


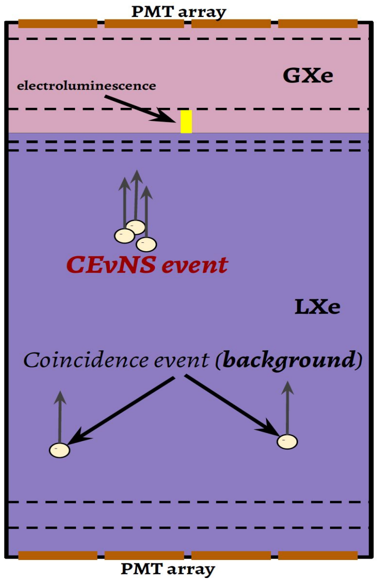
open: $U_{G2} - U_{G1} = 50$ V closed: $U_{G2} - U_{G1} = -250$ V

D.Yu. Akimov et al., Two-phase emission low-background detector (in Russian), Utility model patent RU 184222 U1, 2018

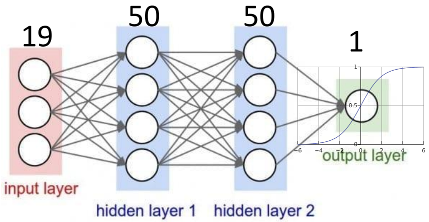
Neural Networks for background rejection

- Significant background part: accidental coincidence of several spontaneous electrons
  - CEvNS events are **point-like** events
  - Background is mostly **NOT point-like**
- Deep learning models to mitigate this kind of background
- For 5-6e events (for simulated test dataset):
  - ~90% bckg suppression
  - ~10% CEvNS suppression
- But in real life things are a little bit more complicated…

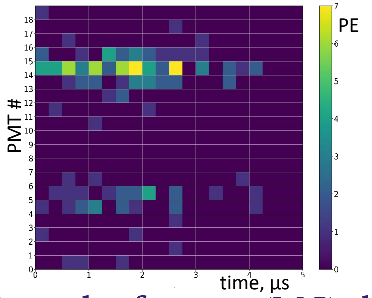




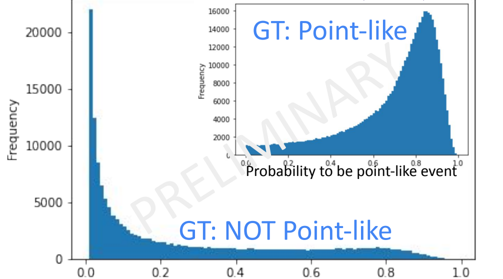
Fully Connected Neural Network (FCNN)



Convolutional Neural Network(CNN)



FCCN results for test (MC) dataset

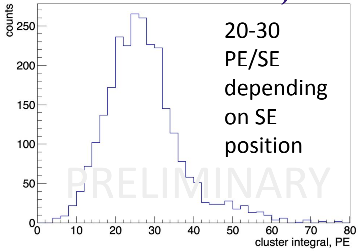


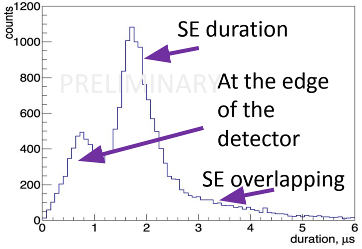
Probability to be point-like event

RED-100 blind analysis

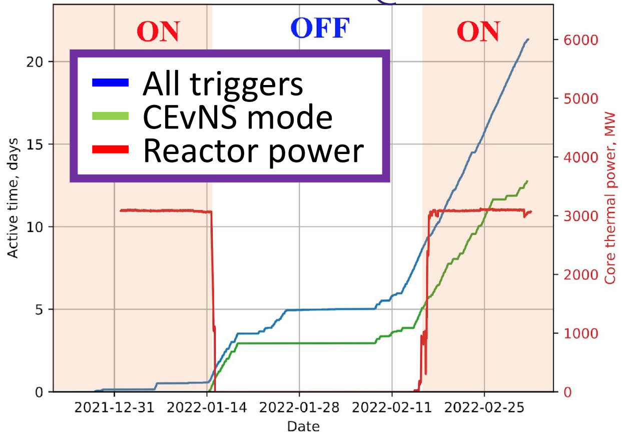
- Reactor ON data is closed until all the data analysis methods are ready
- Analysis is based on Reactor OFF data and calibration data
- Stability checks:
  - *SE count rate*
  - *LY response*
  - *SE duration*
  - *Background rates*
  - *Other parameters*

LY & duration of SE

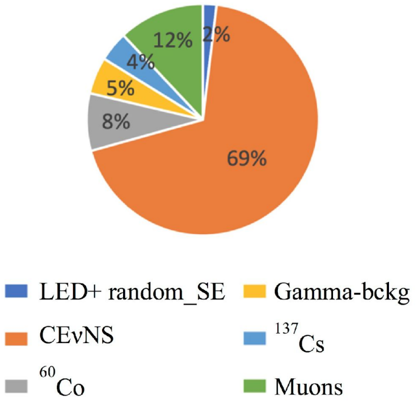




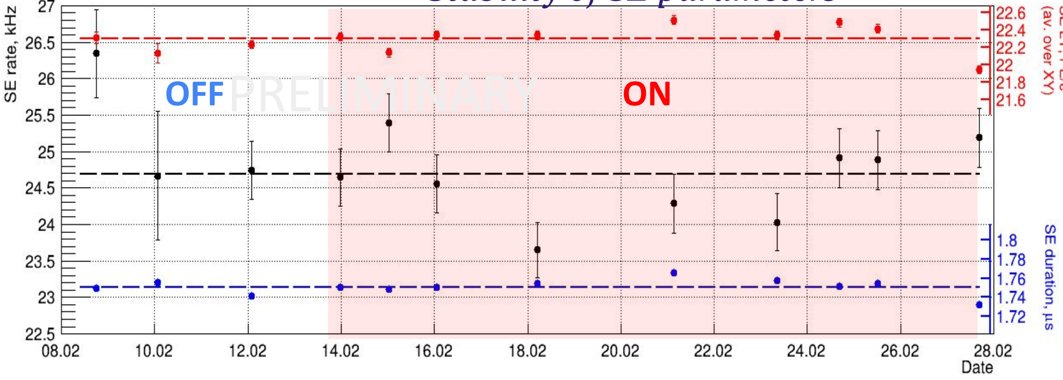
Data collection @ KNPP



Akimov D. Y., et al. JINST 17.11 (2022), T11011



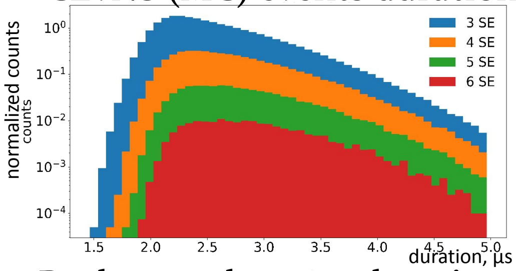
Stability of SE parameters



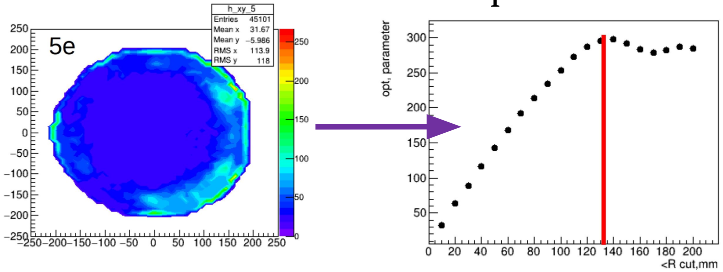
Cuts

- Analysis based on Reactor OFF data in the ROI
- Cuts optimization
  - Quality (number of PEs in pre- and post- traces)
  - Energy (PEs per 5-6e event)
  - Radius
  - Duration
  - Neural Networks
- 3D likelihood fit machinery to calculate sensitivity (energy, radiu duration)

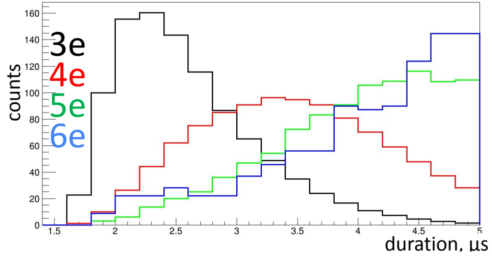
CEvNS (MC) events durations



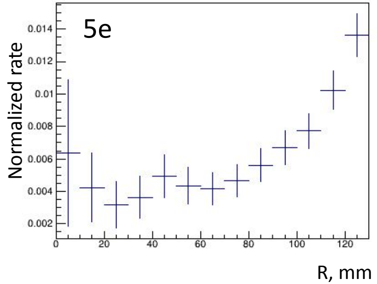
Radius cut optimization

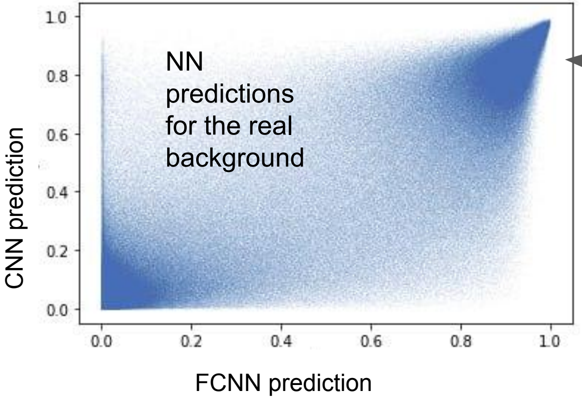


Background events durations

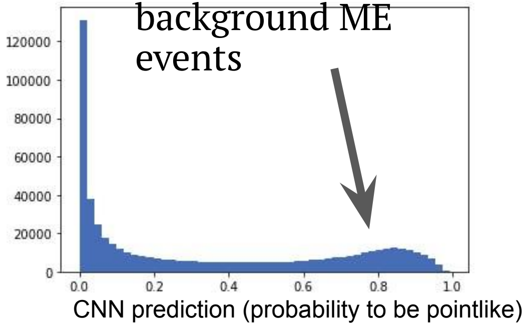


Bckg rate per radius (normalized per rings area)





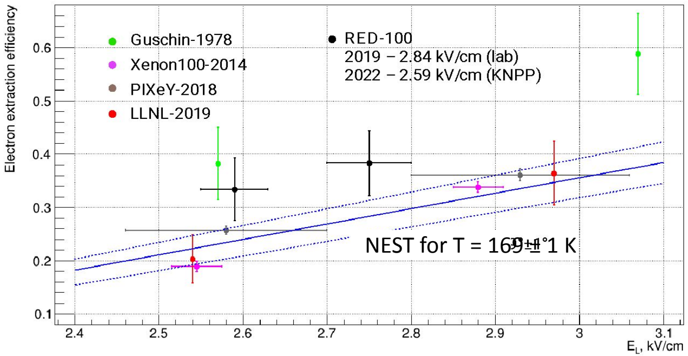
Highly correlated background ME events



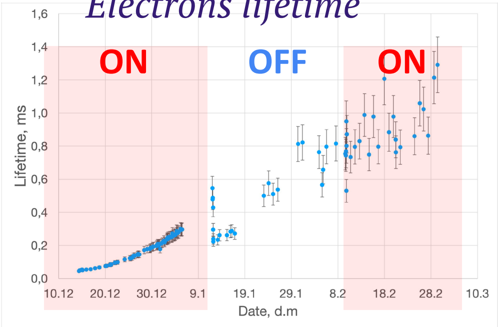
Sensitivity

- The most significant influence on CEvNS response prediction
  - Electron extraction efficiency (absolute measurements based on NEST predicted charge yeild)
  - Electrons lifetime
- GEANT4 + ANTS2 simulations of the CEvNS prediction
- RED-100 sensitivity calculated using 3D likelihood fit method:
  in the region 5-6 SE we can register CEvNS if signal is 50 times greater than SM predictions

Electron extraction efficiency



Electrons lifetime



Background rate and CEvNS prediction /~65 kg LXe / day (Preliminary)

number of e-	5	6
bckg	307	41
cevns	0.4	0.06

*Uncertainties on prediction numbers are under calculation
Current estimation is 30%

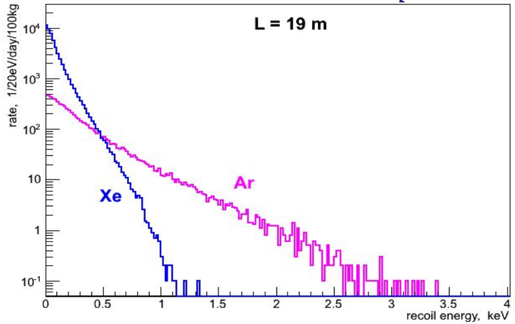
Current status and plans

- RED-100 decommissioned and shipped back to MEPhI for the upgrade
- Data analysis is ongoing

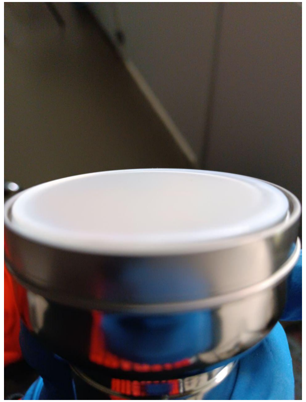
Future of RED-100

- The main idea is to substitute LXe with LAr
- Higher nuclear recoils energies → more electrons per CEvNS event
- Upgrade is ongoing:
    - Light readout system
        - TPB coating
    - Cooling system power increasing

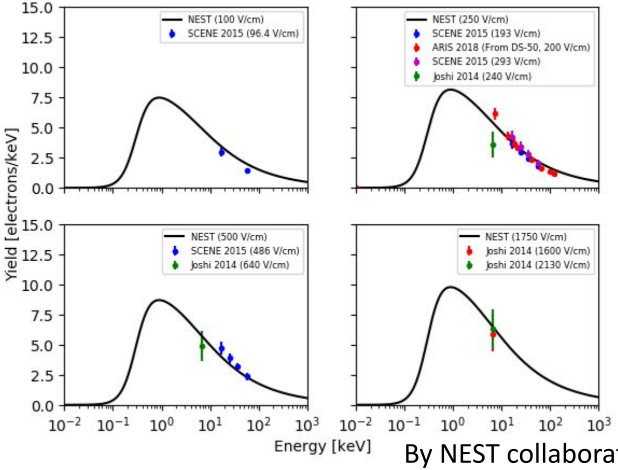
Xe and Ar nuclear recoil spectra



RED-100 PMT coated with TPB



Charge Yields for Nuclear Recoils in LAr



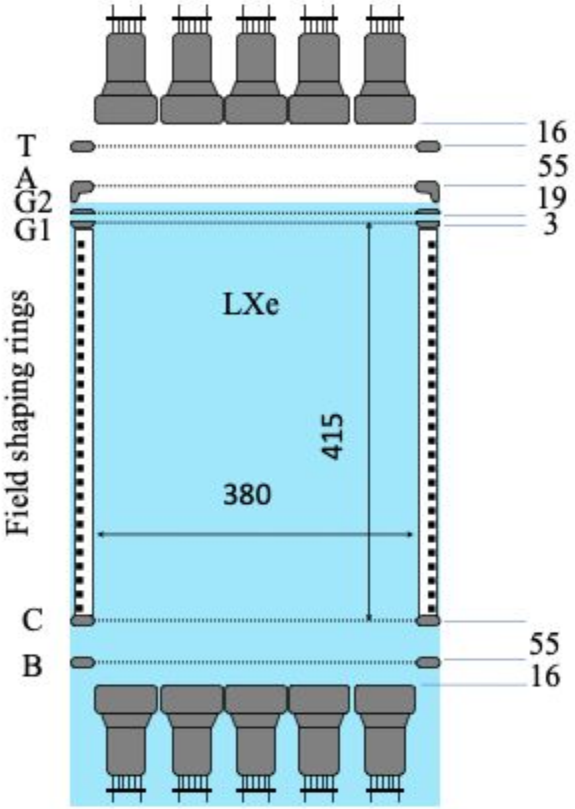
By NEST collaboration

Summary

- RED-100 was successfully deployed and ran at industrial NPP
- Data analysis is in progress
- First results of Reactor ON data analysis are expected soon (presumably, the limit for the CEvNS cross-section)
- Detector was shipped back, upgrade is ongoing
- RED-100 with LAr first tests in this year

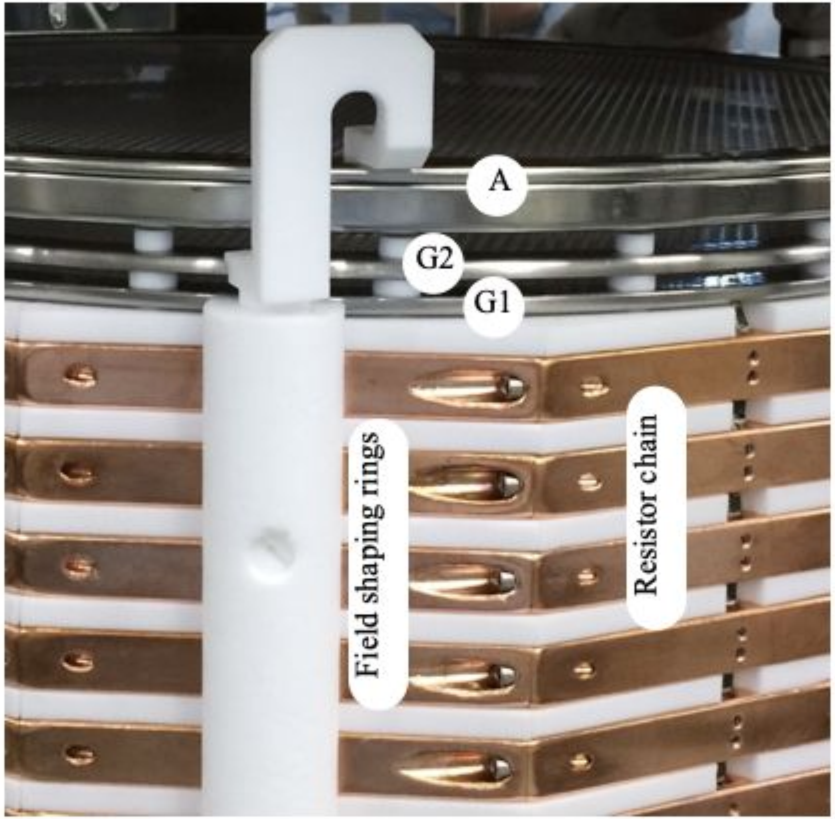
Thank you for your attention!

RED-100: schematic layout of grids and PMTs



Sizes of the drift volume and distances between grids are in mm.

T and B – top and bottom grounded grids,
A – anode grid,
G1 – electron shutter grid,
G2 – extraction grid,
C – cathode grid

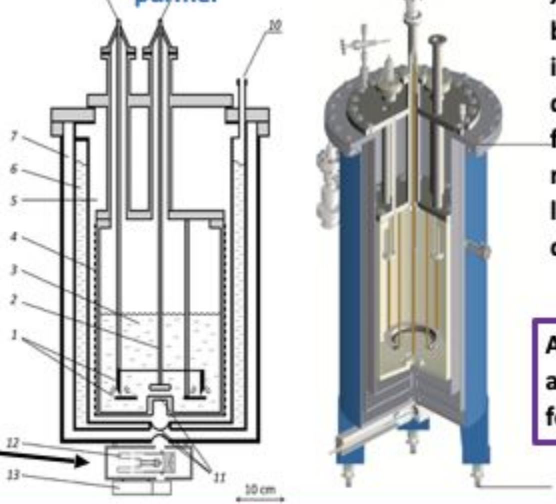


RED-100 performance: LXe purity

- Electronegative impurities catch the ionization electrons
- Purification in two stages
  - 1st: spark discharge technique with “Mojdodyr”
  - 2nd: continues circulation of Xe through RED-100 and SAES
- Electron lifetime of several milliseconds was achieved

“Mojdodyr” spark-discharge purifier

D.Yu. Akimov et al., Instrum. Exp. Tech. 60 (2017) no.6, 782

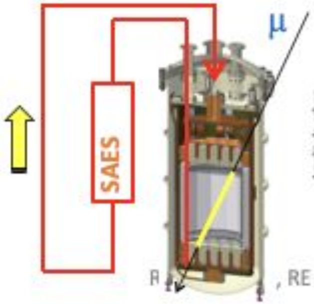


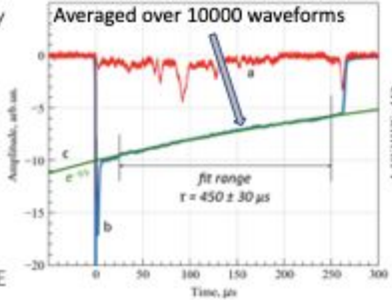
X-ray tube as a source of ionization electrons for e- lifetime measurements

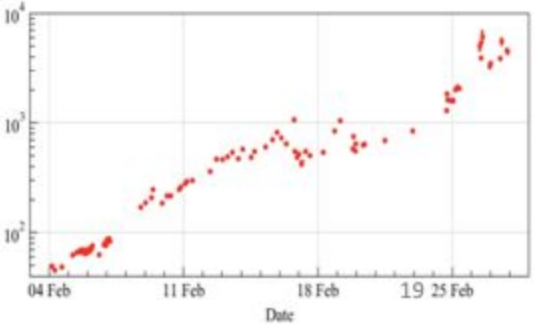
Xenon was contaminated by highly-electronegative impurities presumably due to the use of a special fluorine-containing high-molecular-weight lubricant in gas centrifuges.

After purification, the achieved lifetime ≳ 50 μs for ~200 kg of LXe

Electron lifetime was measured by cosmic muons passed through the detector:

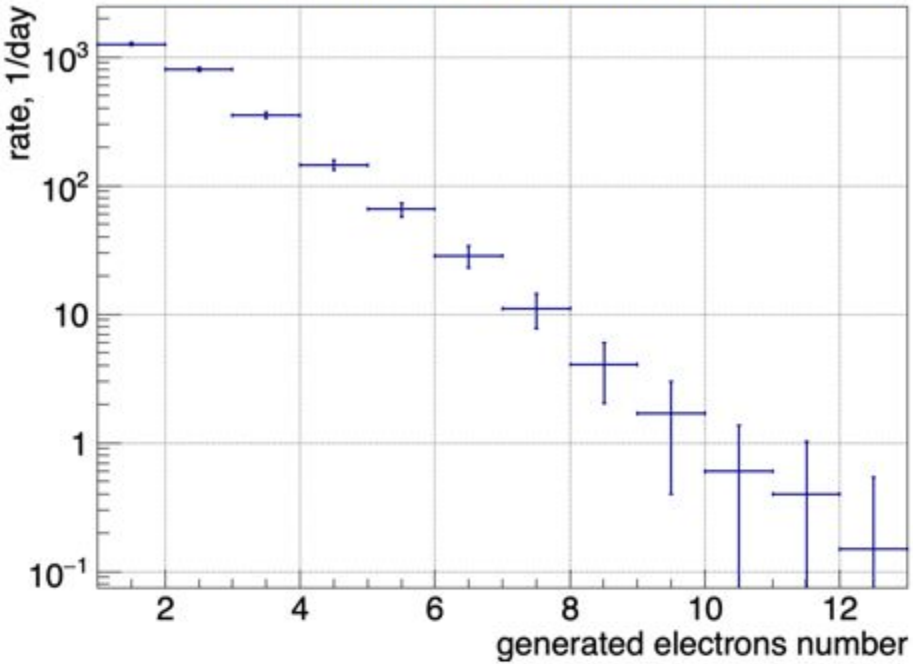




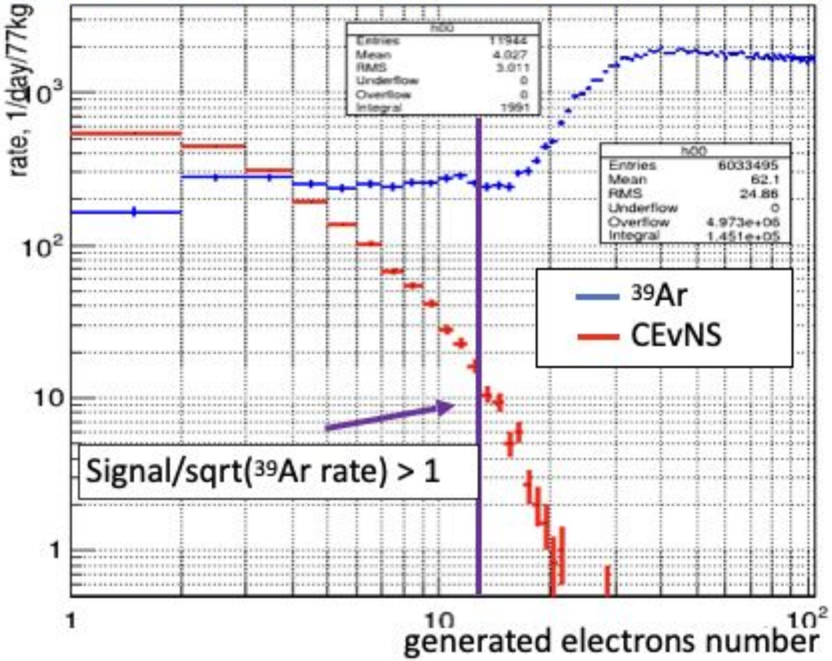


Generated electrons in RED-100

Generated electrons in RED-100 with LXe for CEvNS events

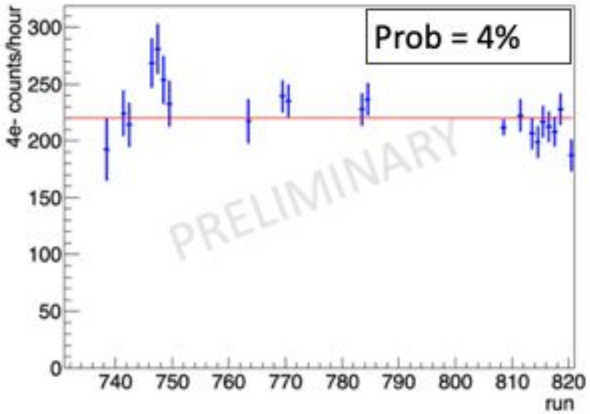


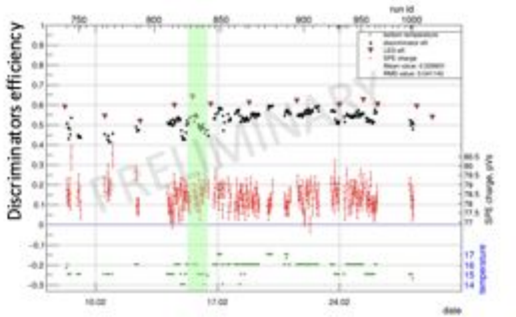
Generated electrons in RED-100 with LAr for CEvNS events and ^{39}Ar

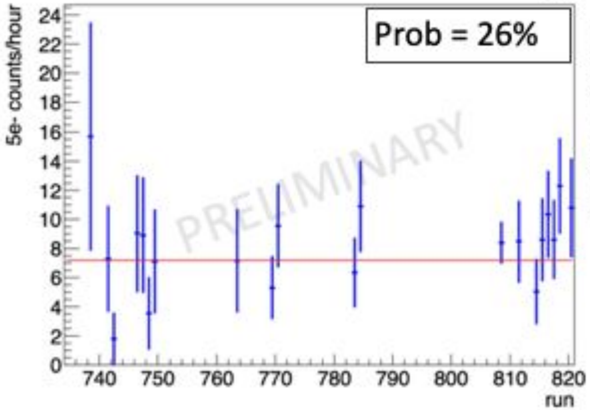


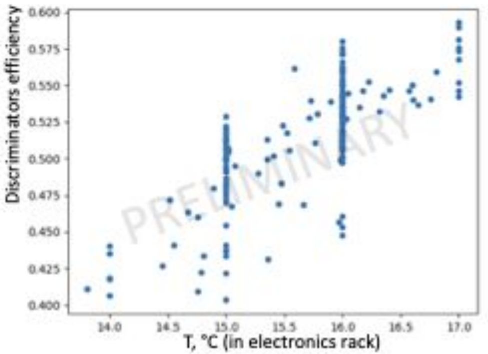
Background stability in ROI

- Count rate normalized on lifetime
- After optimized cuts applied
- Background in the region of 4 electrons per event is not very stable
- Backgrounds in the region 5-6 electrons can be considered as stable
- Possible improvement: check the stability of environmental parameters









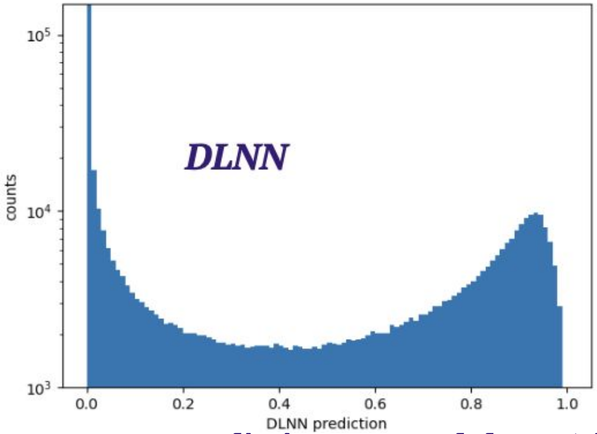
Testing on reactor OFF data

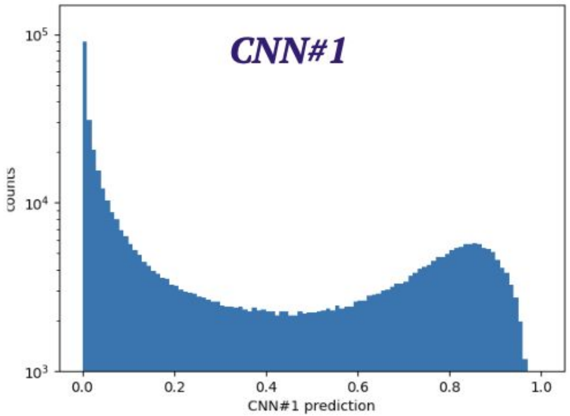
— significant part of real background is pointlike
— now we use optimized on sensitivity 2d cut based on DLNN and CNN#1:

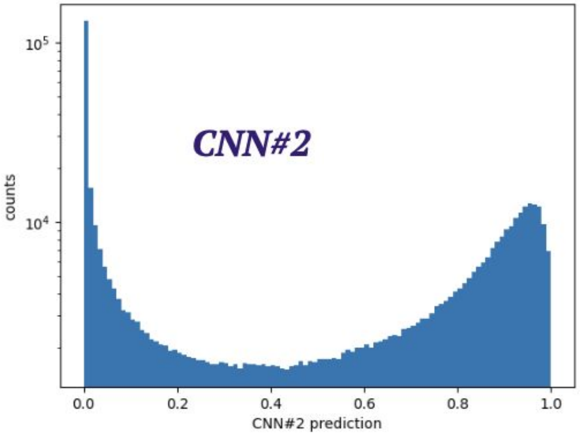
DLNN threshold: 0.6
CNN#1 threshold: 0.2

Background and signal reduction in ROI (r<130mm, duration <5000ns)

	~5SE	~6SE
signal (MC) reduction	11%	6%
bckg reduction	64%	54%

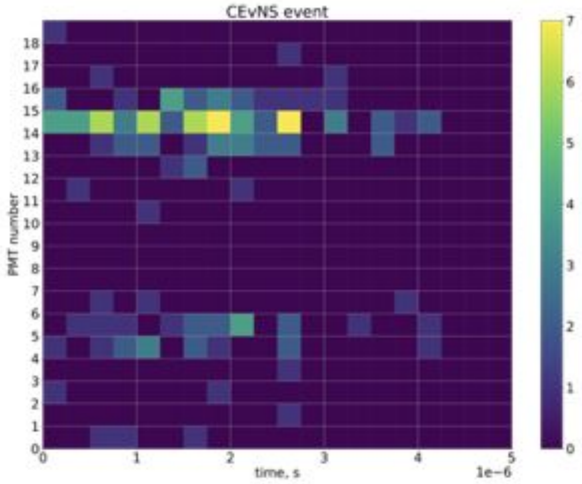


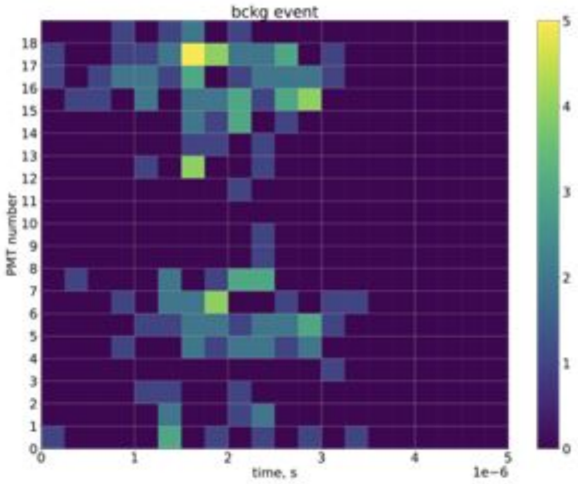


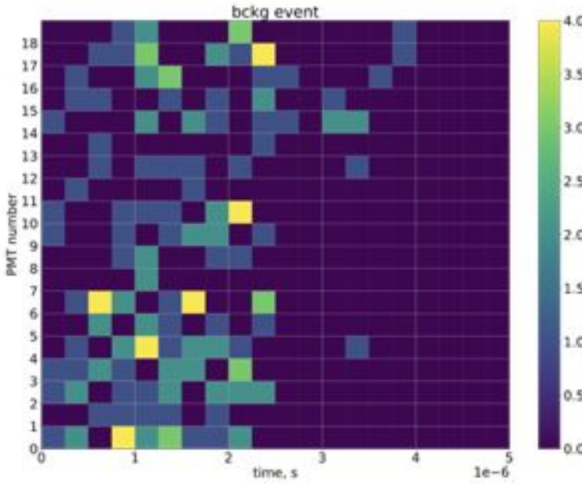


NNs predictions on real data. *A lot of background events with high probability to be pointlike.*

Examples of events for CNN (simulations)

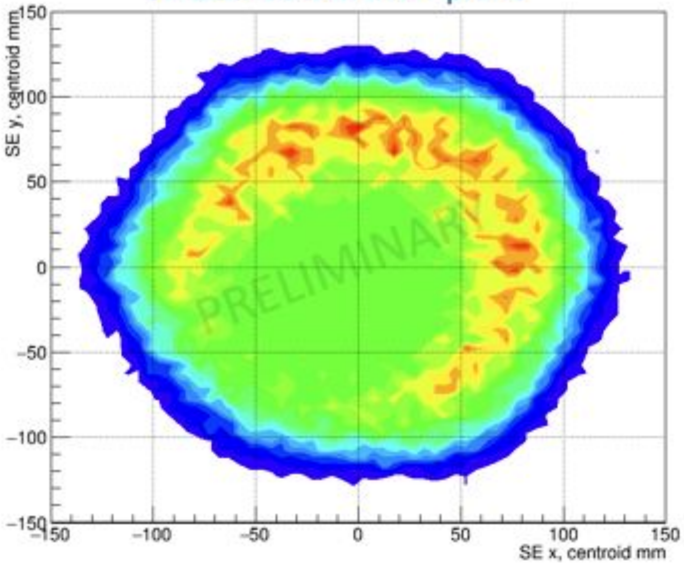




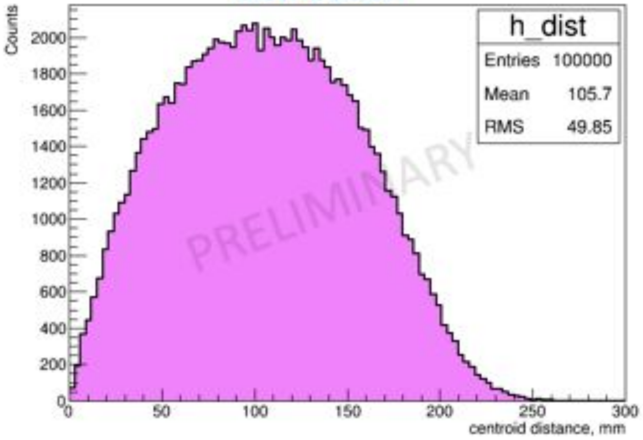


Investigation of spatial correlation between events

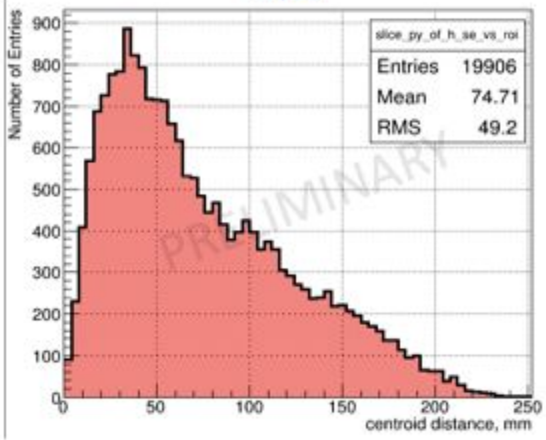
SE distribution in XY plane



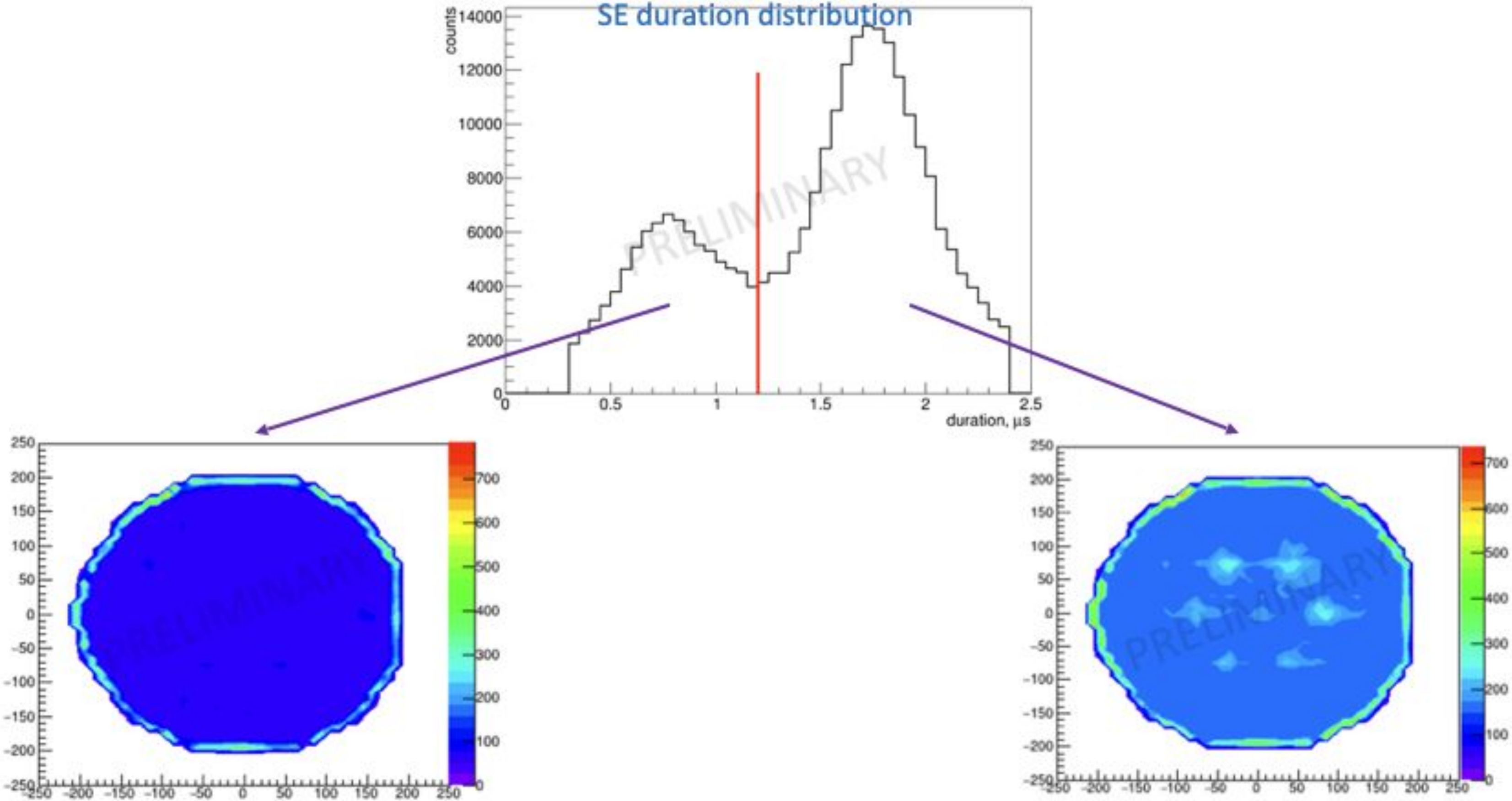
Distance between 2 random SEs from spatial distribution



Distance between 2 consequent SEs from real data



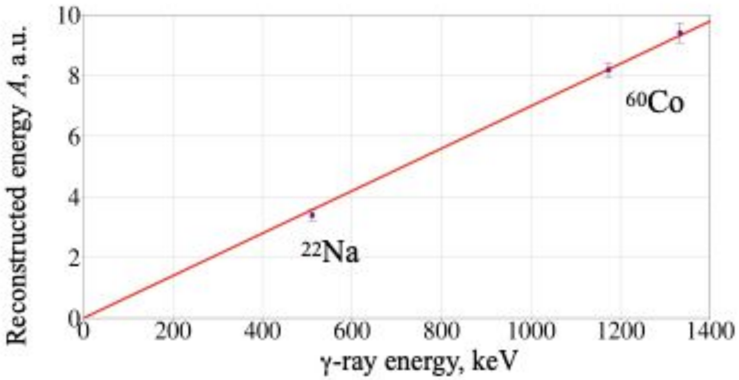
Short SEs


SE duration distribution
counts
14000
12000
10000
8000
6000
4000
2000
0
0.5
1
1.5
2
2.5
duration, µs
PRELIMINARY
PRELIMINARY
PRELIMINARY

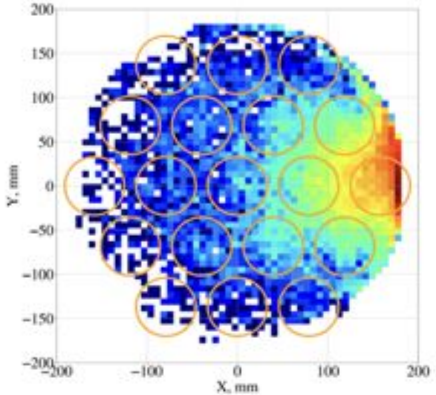
Gamma calibration (Lab. test)

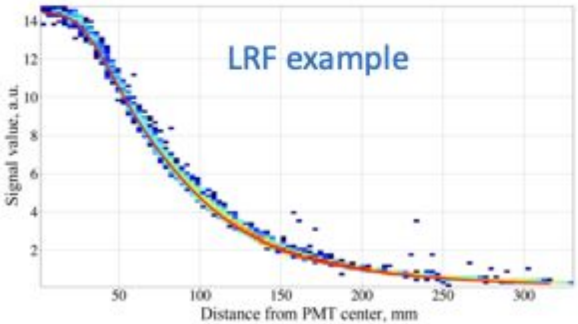
- Gamma calibration was done
- Position reconstruction tested
- LRF obtained for the top PMT plane

Gamma calibration

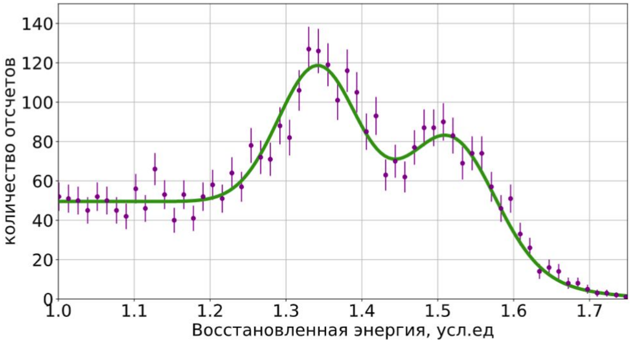


Position reconstruction for ^{22}Na





Измерения с гамма-источниками. Результаты восстановления.

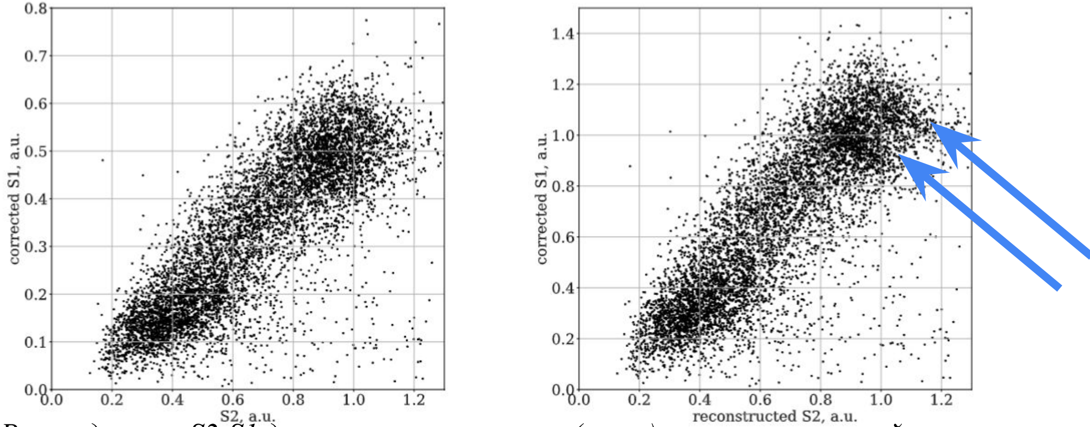


Полученный энергетический спектр источника ^{60}Co (после восстановления) при измерениях на КАЭС, фитированный суммой функции ошибок и двух распределений Гаусса

Энергия, кэВ	Положение пика, кэВ	(σ/E), %	FWHM/E, %
662	688±29	8.4	19.6
1173	1169±27	3.7	8.7
1333	1323±33	3.9	9.2

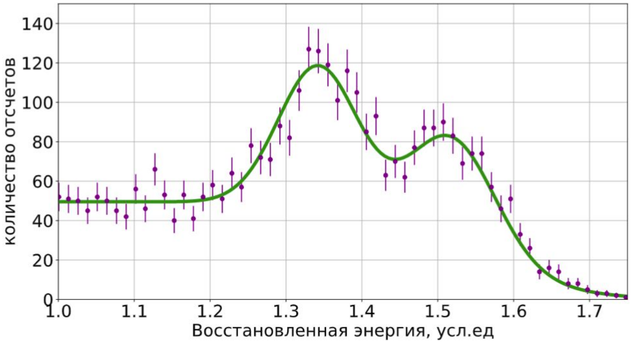
Результаты энергетической калибровки при измерениях на КАЭС

- Присутствует антикорреляция между S1 и S2
- В качестве полной восстановленной энергии используется линейная комбинация S1 и S2
- После восстановления и дополнительного отбора по радиусу (<130мм) представляется возможным выделить пики от источников



Распределение S2-S1 для суммарного сигнала (слева) и восстановленной энергии (справа) при измерениях на КАЭС

Измерения с гамма-источниками. Результаты восстановления.



Полученный энергетический спектр источника ^{60}Co (после восстановления) при измерениях на КАЭС, фитированный суммой функции ошибок и двух распределений Гаусса

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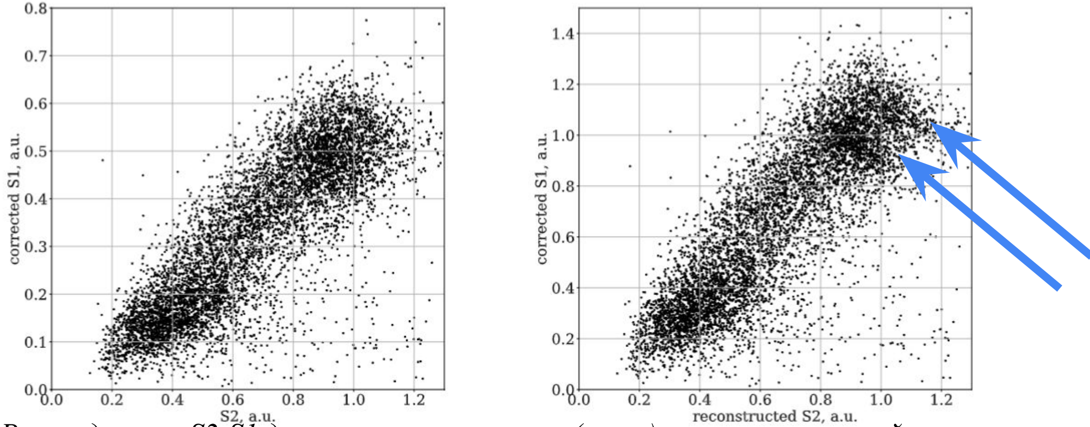

Распределение S2-S1 для суммарного сигнала (слева) и восстановленной энергии (справа) при измерениях на КАЭС