Methods of data processing and analysis in the RED-100 experiment

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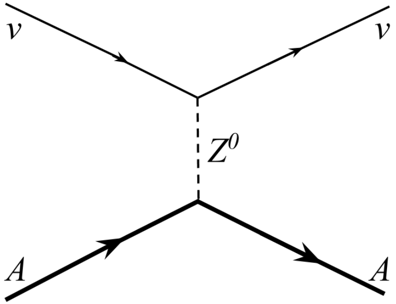
on behalf of RED collaboration

ICPPA 2022
Moscow

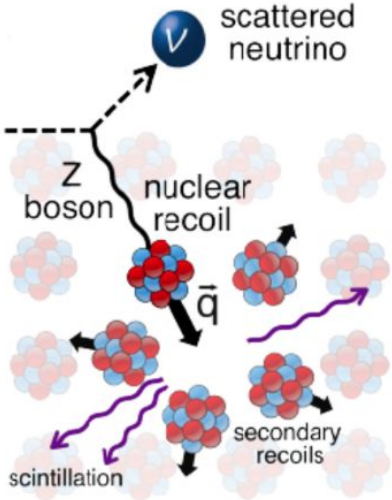
Coherent Elastic Neutrino-Nucleus Scattering



Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) is predicted by Standard Model but it has not been observed experimentally for a long time due to extremely low energy of the recoil nucleus. Only in 2017 it was discovered by COHERENT collaboration

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

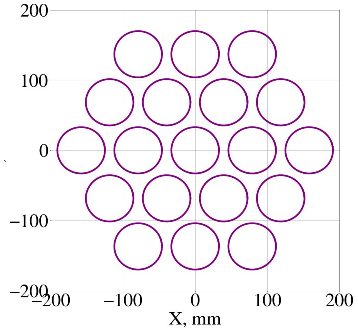
Motivation of experiments:
— fundamental physics (supernova dynamics)
— SM verification
— practical goals (monitoring of nuclear reactors)



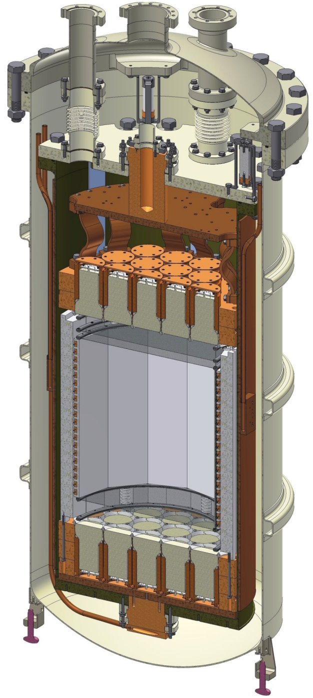
D.Z. Freedman, Phys. Rev. D 9 (1974) 1389
D.Akimov, J. Albert, P. An et.al., Science. — 2017.
Kopeliovich V B, Frankfurt L L JETP Lett. 19 145 (1974); Pis'ma Zh. Eksp. Teor. Fiz. 19 236 (1974)

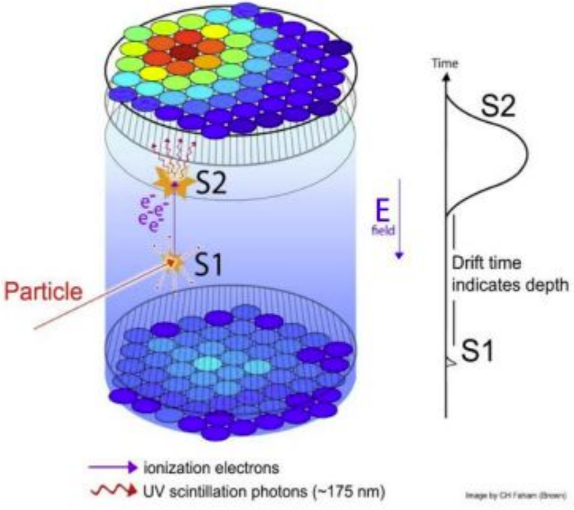
RED-100 detector construction

— designed for study of coherent elastic scattering of reactor electron antineutrinos off xenon atomic nuclei
— two-phase Xe emission detector
— sensitive to single ionization electron (SE)



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

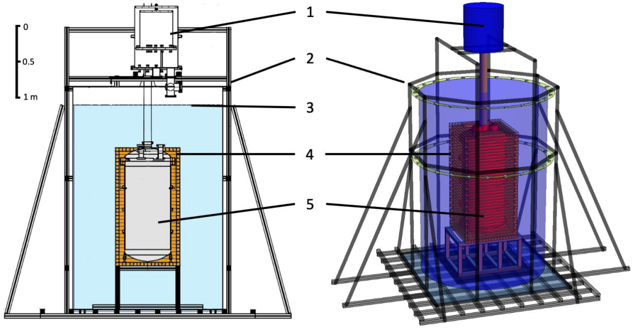




- 2 arrays with 19 PMT Hamamatsu R11410-20
- height of 415 mm and diameter of 368 mm
- ~130 kg of LXe

First ground-level laboratory test of the two-phase xenon emission detector RED-100, Akimov D. et.al., JINST 2020

RED-100 at KNPP



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

RED-100 experiment

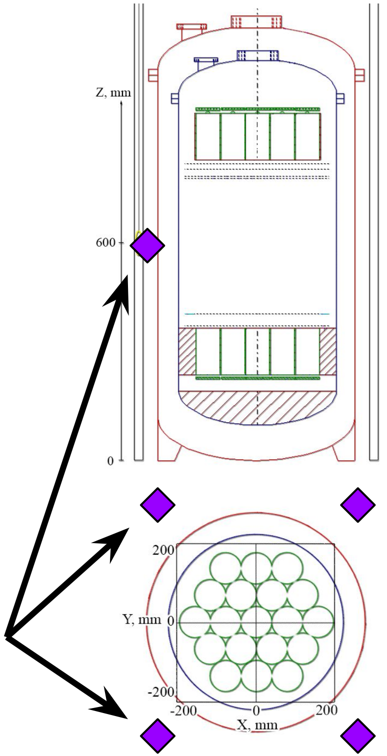
— 19 meters from the reactor core

— reactor and reactor 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

— calibration with ^{60}Co and ^{137}Cs gamma sources



calibration source positions

KNPP WWER-1000 reactor:

— thermal power ~3000MW

— reactor OFF and reactor ON periods

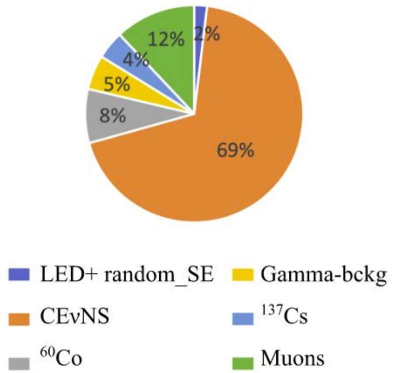
For more information about RED-100 on KNPP see:
Exposition of the RED-100 two-phase emission detector at the Kalinin NPP for the study of coherent elastic neutrino scattering off Xenon nuclei, Bolozdynya A., ICPPA 2022

RED-100 data

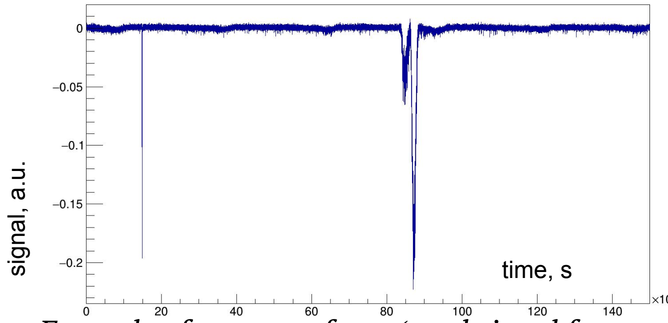
Types of collected data:

1. Muons
— cosmic muons through the detector
— electron lifetime in LXe measurement
2. Gamma sources
— calibration sources ^{60}Co and ^{137}Cs
— energy and spatial calibration
3. Gamma background
— without calibration sources

4. Zero threshold
— trigger from a pulse generator with a frequency of ~2 Hz
— SPE and SE (single electron) signals from spontaneous SE emission events
5. CEνNS-like data
— both reactor ON and reactor OFF periods
— dedicated trigger for several-ionization-electron events (ME)
— veto after muons and gammas
— average livetime ~60%



The percentage of each mode of data taking time from the total active data taking time

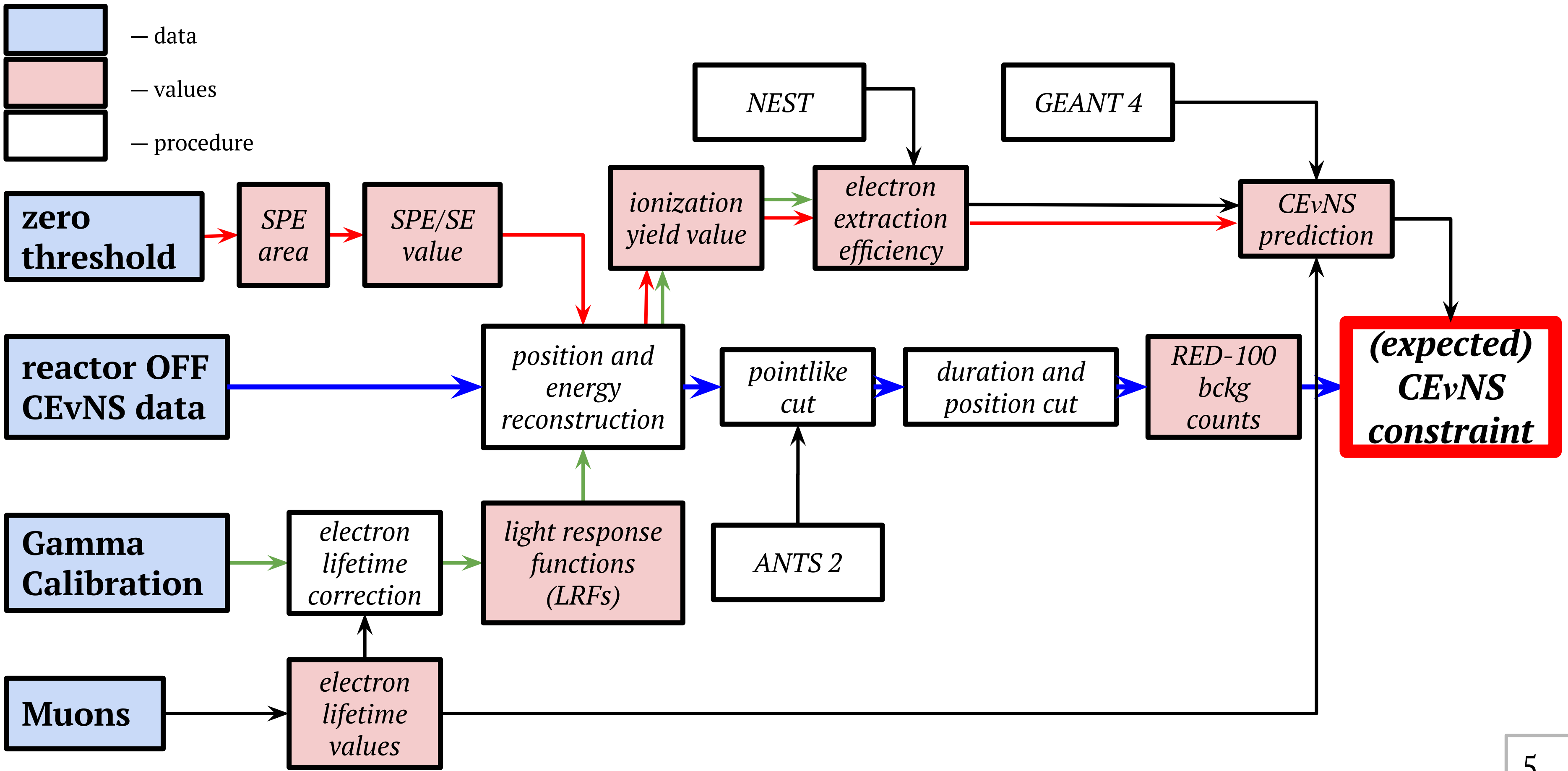


Example of raw waveform (total signal from bottom matrix) of the calibration event.

RED Offline
software for data processing which includes:
— waveform correction
— pulse finding and measuring
— clustering

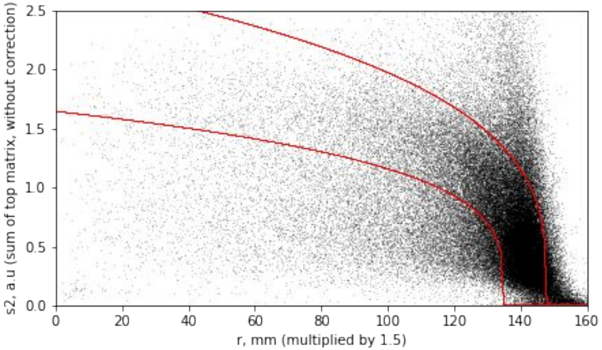
The RED-100 experiment, Akimov D. et.al., JINST 2022, DOI:10.1088/1748-0221/17/11/T11011

Analysis scheme (reactor OFF data)

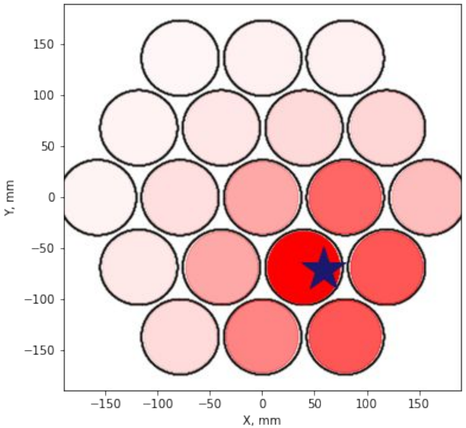


Calibration data analysis

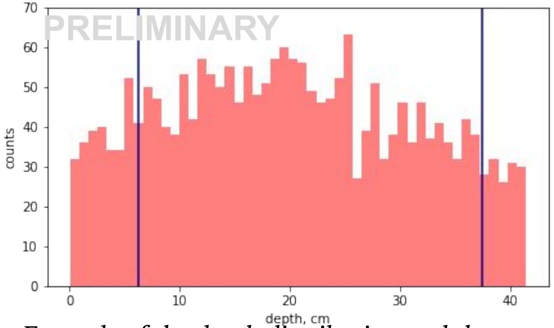
First stage
— waveform to pulses
— s1 and s2 signals were defined as sum of pulses with specific parameters
— electron lifetime correction



Example of the total (from top matrix) s2 pulse area vs r (reconstructed using centroid method) distribution and the cut (red lines)

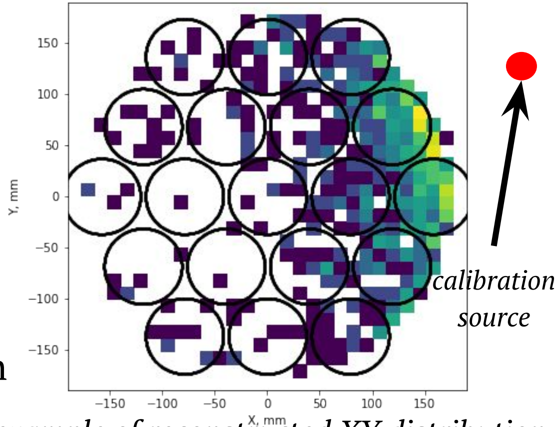


Example of the PMT (top matrix) S2 pulse areas from the calibration event. Blue star denotes the reconstructed position.



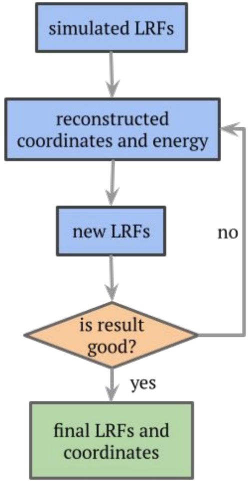
Example of the depth distribution and the cut (blue lines)

Cuts before reconstruction
— single scintillation and single electroluminescence
— on the event depth (reconstructed using drift time)
— energy peak selection (total S2 area with radial dependence, see on the left), where radius was reconstructed using centroid method

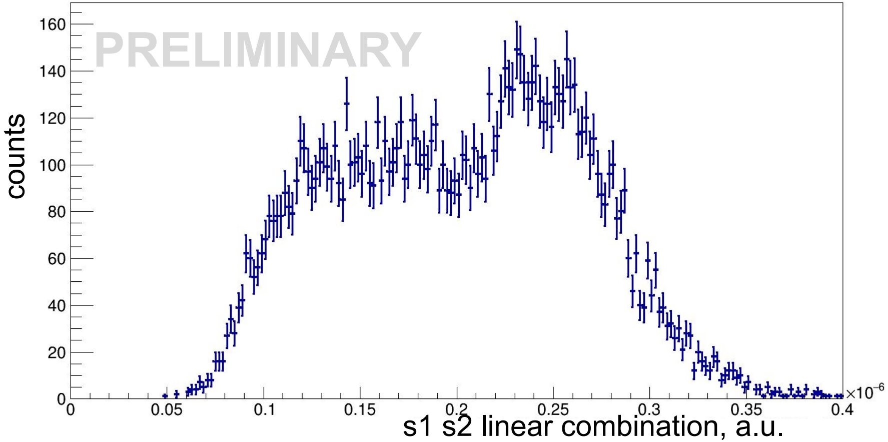


example of reconstructed XY distribution

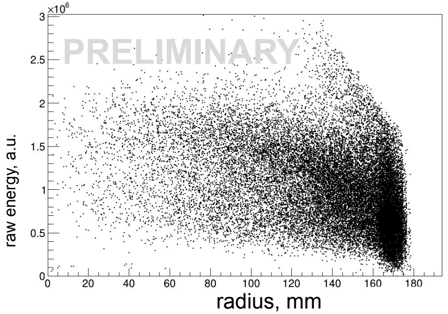
Calibration data analysis



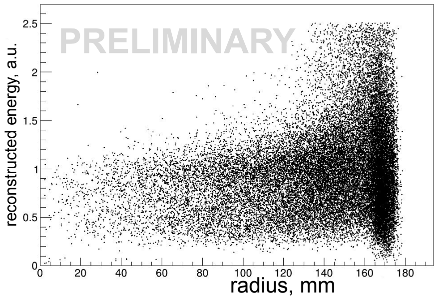
Reconstruction
— ANTS2 package for modelling and reconstruction
— we use light response functions (LRFs), that are the maps of signal vs light emission point for each PMT
— reconstruction algorithm is based on minimization of error between the observed signal distribution among PMTs and that expected from calculation using LRFs
— both s2 energy and coordinates are reconstructed



distribution of s1 s2 (corrected) linear combination for ^{60}Co



raw energy vs. reconstructed radius



reconstructed energy vs reconstructed radius

— energy is a linear combination of s1 and reconstructed s2
— cut on reconstructed radius <140 mm
— energy resolution (σ/mean): ~6% (^{60}Co)

ANTS2 package: Simulation and experimental data processing for Anger camera type detectors / A. Morozov [et al.] // JINST. — 2016.

Electron extraction efficiency (EEE)

$$EEE = k \cdot \frac{137Cs\ peak\ position}{SE\ peak\ position} \cdot \frac{1}{661.7\ keV \cdot charge\ yield\ from\ NEST}$$

— k is a correction coefficient for SPE area = 0.85

— ^{137}Cs and SE peaks positions obtained using corrected S2 (not linear combination):

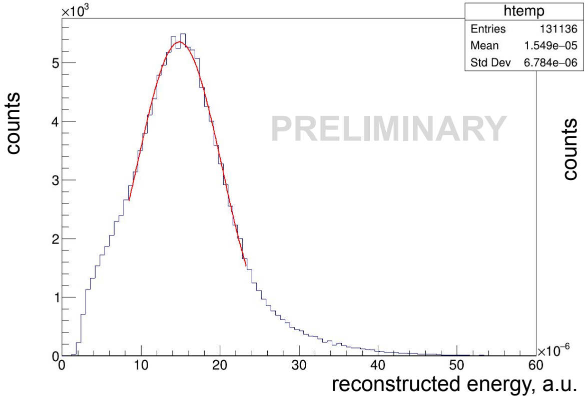
^{137}Cs: 1.58e-1±0.6e-2 a.u.

SE: 1.48e-5±2.6e-8 a.u.

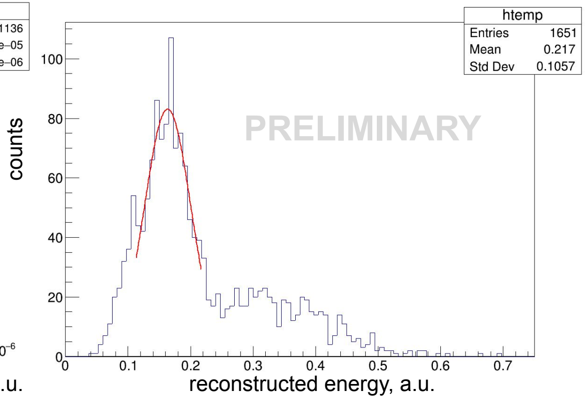
— number of ionization electrons for 661.7 was calculated using NEST (v 2.3.11)

Result

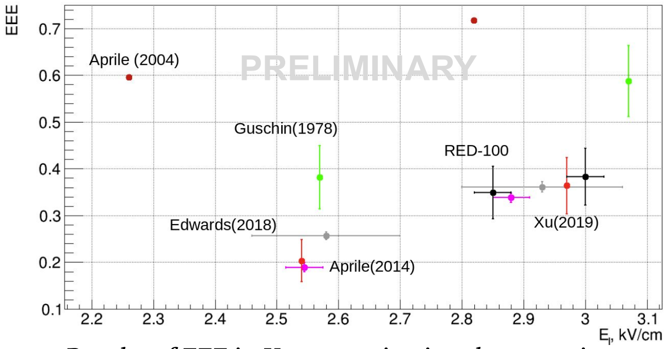
EEE = 34.9±5.9%



Corrected SE S2 distribution and gauss fit



Example of corrected ^{137}Cs S2 distribution and gauss fit



Results of EEE in Xe measuring in other experiments

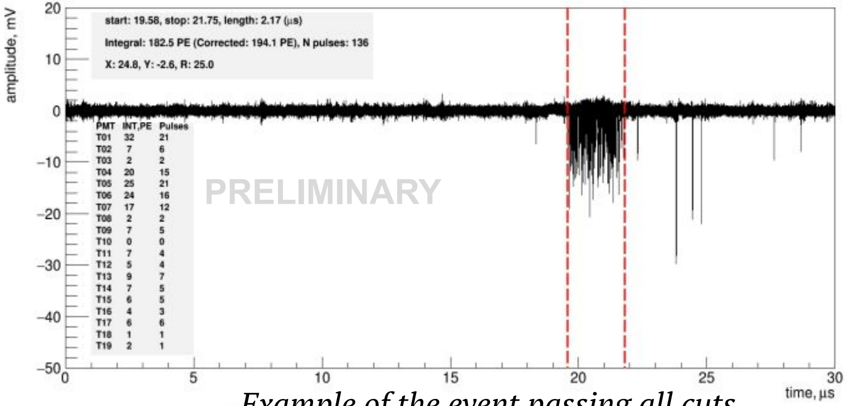
M.Szydagis et al. (NEST collaboration), A Review of NEST Models, and Their Application to Improvement of Particle Identification in Liquid Xenon Experiments, arXiv:2211.10726

SE and ME data processing

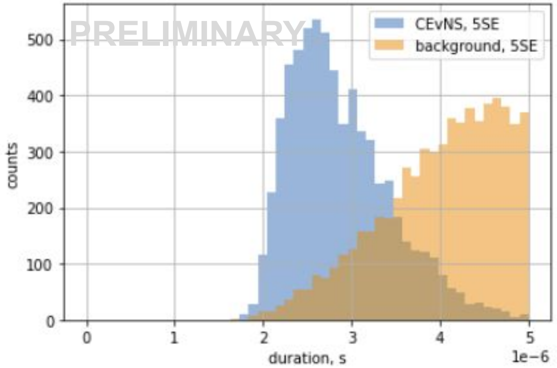
CEvNS events in our case are of a size of several ionization electrons (our region of interest is 3-6) generated at one point.

SE — single electron
ME — multiple electrons (includes SE)

Data analysis:
— electric pickup correction
— SPE detection
— clusterization
— event selection cuts:
    reconstructed radius <130 mm
    duration ~3us (cut optimized using diffusion model)
    energy ~3-6 ionization electrons
    “pointlike” signal shape



Example of the event passing all cuts



Example of the duration distribution for measured background and simulated CEvNS signal for 5 SE (normalized)

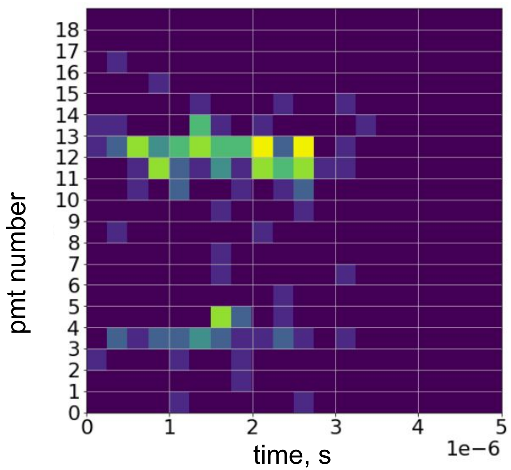
Coincidence background

The important background source in our energy range comes from random overlapping of several independent ME events because of spontaneous emission of electrons.

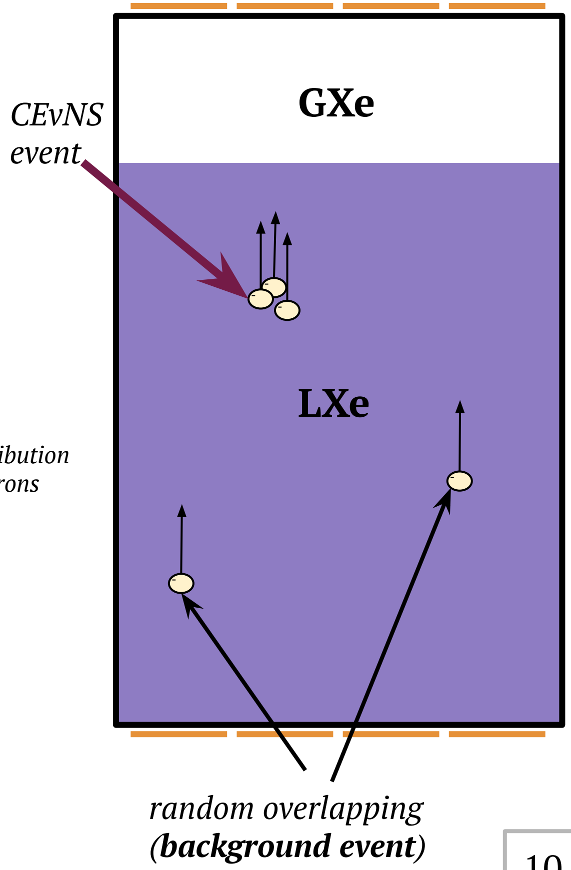
Possible ways of solving this problem:

1. Deep Learning (DL) cut based only on light distribution (NN1)
2. DL cut based both on light and photon time detection distribution (NN2)

These cuts are under development. We train our neural networks with simulated data.



Example of photon time and place of detection distribution of simulated CEvNS event with 6 ionization electrons



NN1 result \ NN2 result	bckg	signal
bckg	**63%**	3%
signal	15%	19%

Percentage of events marked as signal/background after applying neural networks to reactor OFF dataset

Conclusion

— data analysis of the first physical run of the RED-100 experiment at KNPP is in progress

— procedure of position and energy reconstruction was developed using data from calibration gamma sources ^{137}Cs and ^{60}Co

— electron extraction efficiency was calculated using both SE and calibration data

— general methods of ME analysis were developed

— complex methods of background reduction are under development

Thank you for your attention!

backup

Diffusion

For an initial δ-function charge deposit of N electrons centered at position $\vec{x} = (0, 0, 0)$ at time $t = 0$, the charge density, $n(\vec{x}, t)$, at later time t and position $\vec{x}$ can be determined by solving the 3-dimensional diffusion equation [7]:

$$n(\vec{x}, t) = \frac{N}{4\pi D_T t \sqrt{4\pi D_L t}} \exp\left[\frac{-(x^2 + y^2)}{4 D_T t}\right] \times \exp\left[\frac{-(z - v_d t)^2}{4 D_L t}\right] \quad (1)$$

Measurement of the Drift Velocity and Transverse Diffusion of Electrons in Liquid Xenon with the EXO-200 Detector (EXO-200 Collaboration)

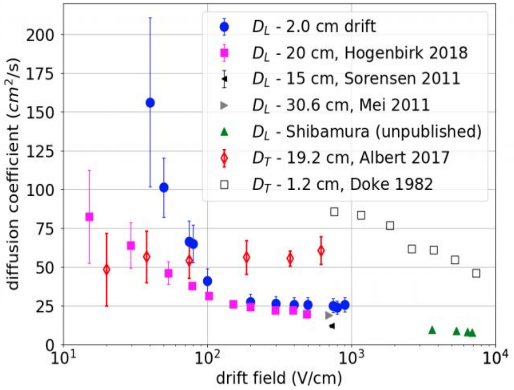
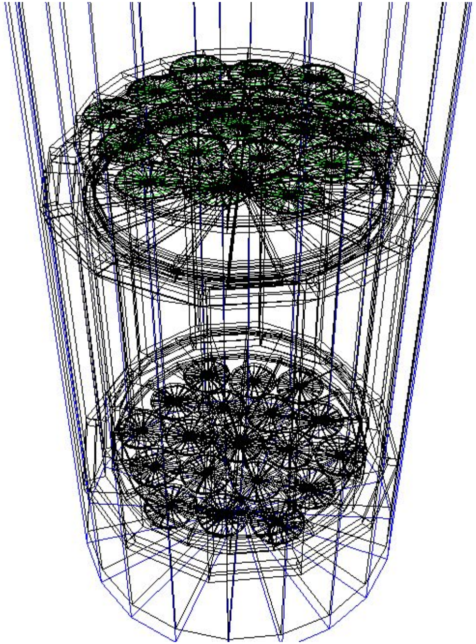


Figure 7: Electron longitudinal diffusion coefficient D_L versus drift field in LXe. Values from this work (blue circles) and measurements from [40] (magenta squares), [37] (black triangle), [38] (gray triangle), and Shibamura (green triangle) [39]. Also shown are the transverse diffusion coefficient D_T from EXO-200 [30] (hollow red diamonds), and [36] (hollow black squares).

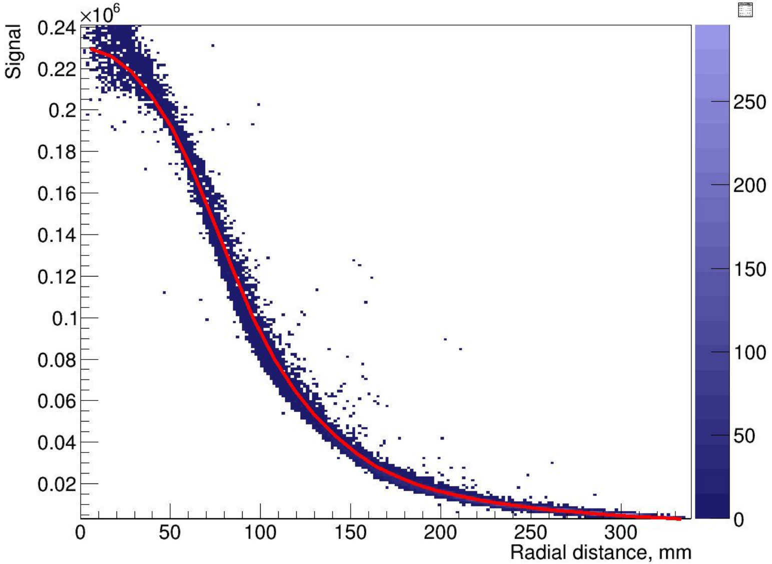
Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode
O. Njoya, T. Tsang, M. Tarka, et.al.

optical model

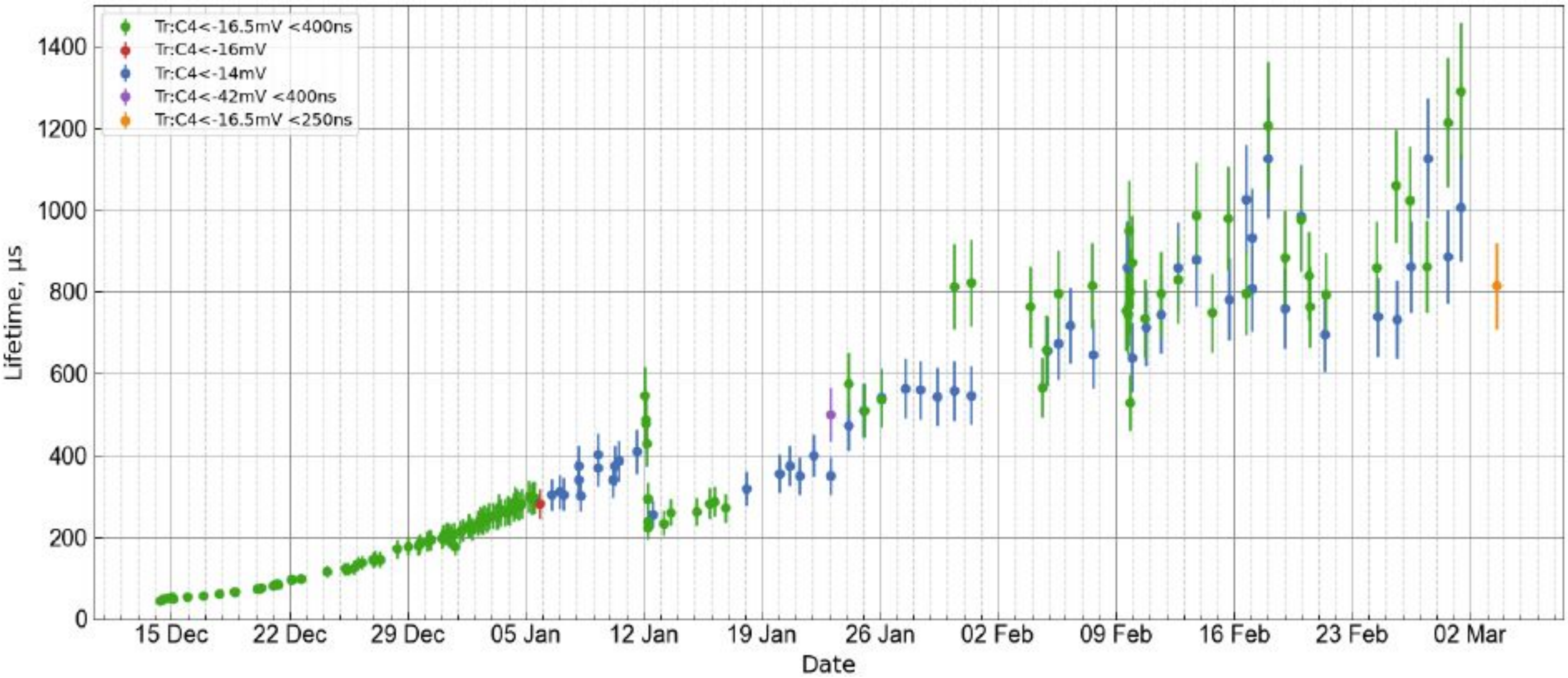


The model of RED-100 in ANTS-2

(ANTS2 package: Simulation and experimental data processing for Anger camera type detectors / A. Morozov [et al.] // Journal of Instrumentation. — 2016. — Apr. — Vol. 11. — P04022–P04022.)

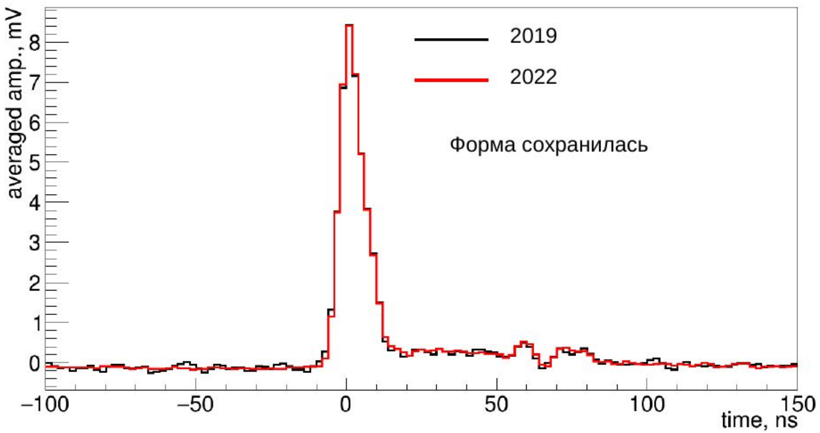


Example of LRF (red line) for PMT T06 (from second ring) scaled on reconstructed energy



Tr:C4<-16.5mV <400ns
Tr:C4<-16mV
Tr:C4<-14mV
Tr:C4<-42mV <400ns
Tr:C4<-16.5mV <250ns
Lifetime, μs
0
200
400
600
800
1000
1200
1400
15 Dec
22 Dec
29 Dec
05 Jan
12 Jan
19 Jan
26 Jan
02 Feb
09 Feb
16 Feb
23 Feb
02 Mar
Date

Эффект формы SPE



В 2022г коэффициент коорректировки:

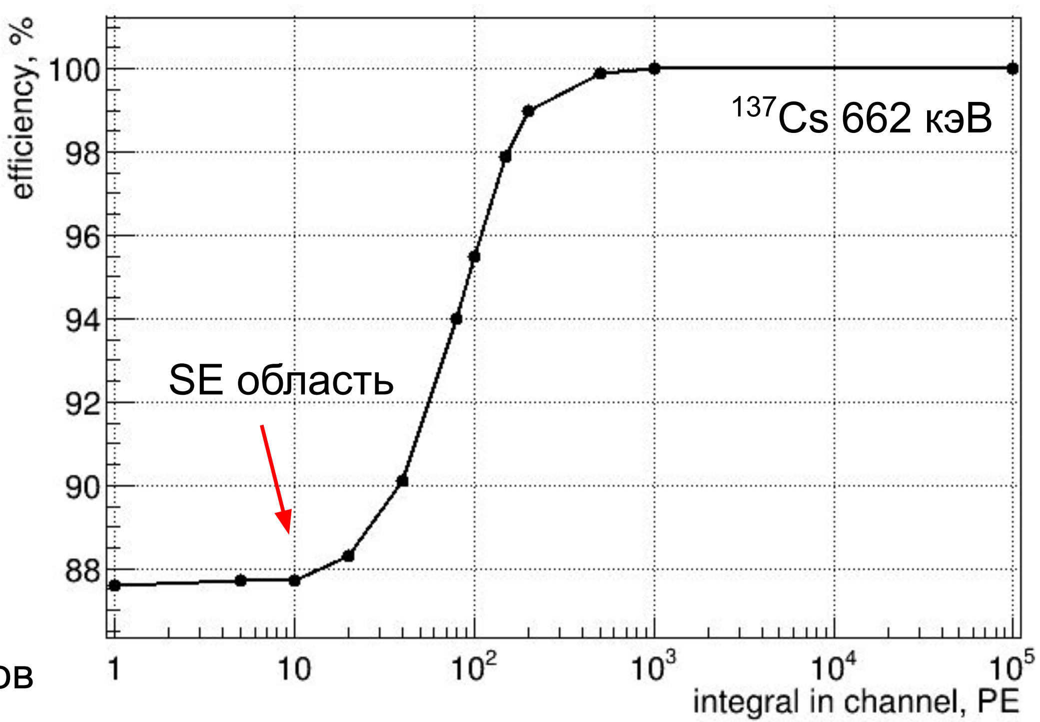
k_{eff} = 0.85±0.03

В 2019г коэффициент коорректировки:

k_{eff} = 0.80±0.04

Разница – изменения REDOffline и порогов

С “боевой” конфигурацией REDOffline 2022 г.



EEE measurements in different experiments

1. E.M.Gouschin et.al., «Electron emission from condensed noble gases», JETP (1978)

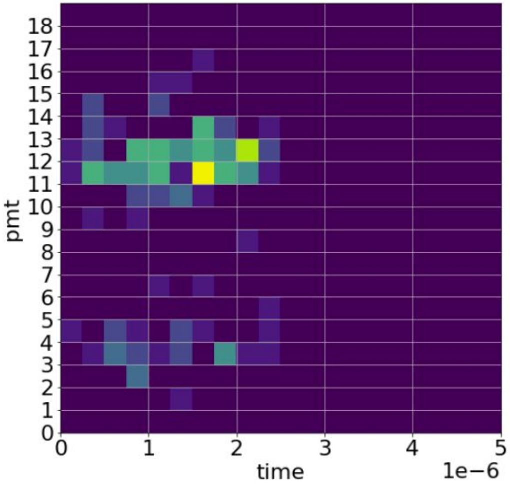
2. E. Aprile et al., “Proportional Light in a Dual-Phase Xenon Chamber”, IEEE TNS 51 (2004)

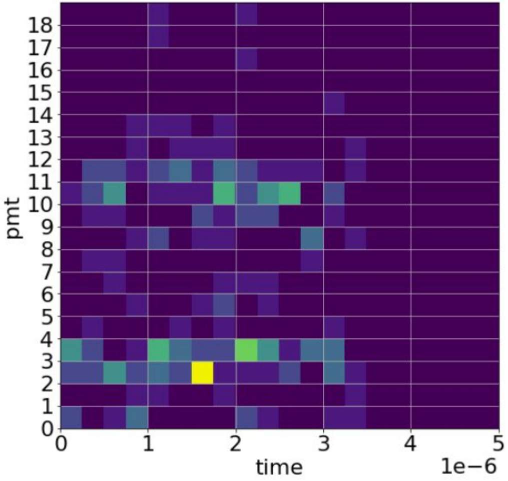
3. E. Aprile et al., “Observation and applications of single-electron charge signals in XENON-100 experiment” (2014)

4. B. Edwards et al., “Extraction efficiency of drifting electrons in a two-phase xenon time projection chamber” (2017)

5. J. Xu et al., «Electron extraction efficiency study for dual-phase xenon dark matter experiments» (2019)

pointlike





bckg