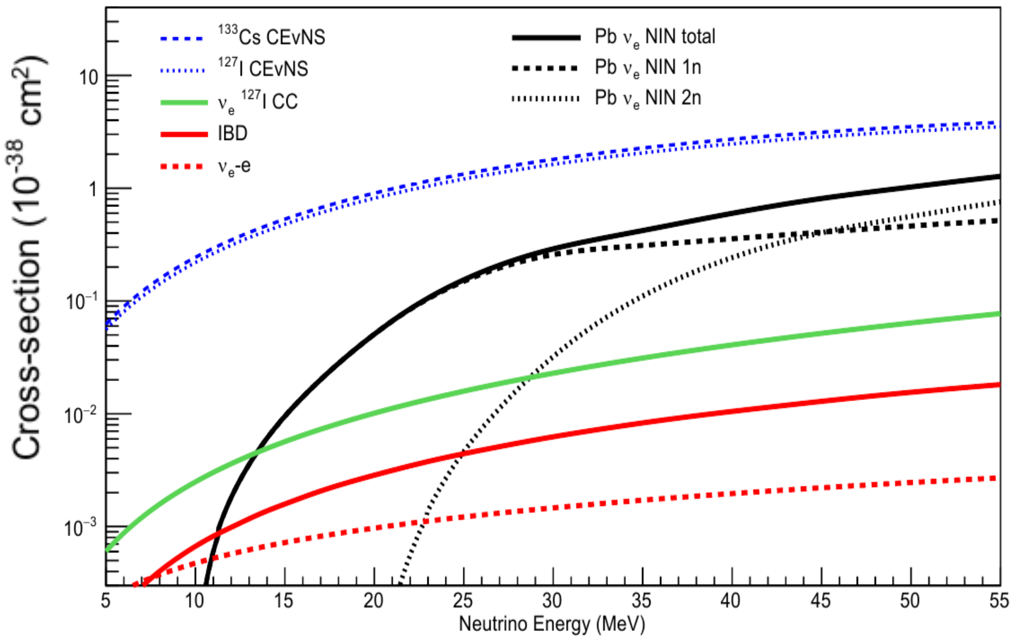
Recent results of the RED-100 experiment

Dmitrii Rudik on behalf of RED-100 collaboration

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

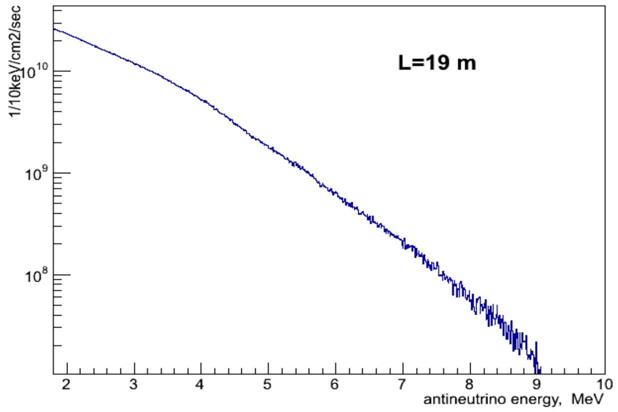
Low recoil energy → difficult to detect

$$\sigma \approx \frac{G_F^2}{4\pi}(N-(1-4\sin^2\theta_W)Z)^2 E_\nu^2 \quad \propto \quad N^2$$

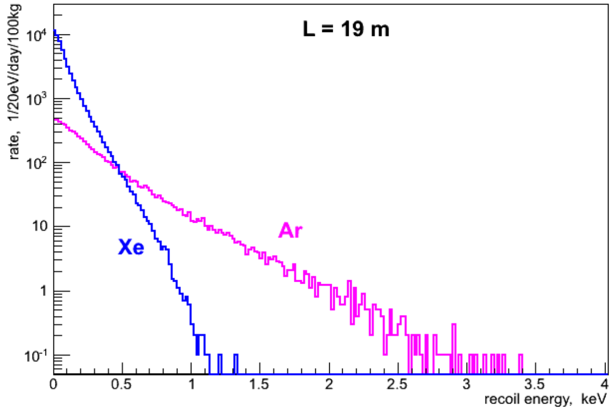


By Kate Scholberg

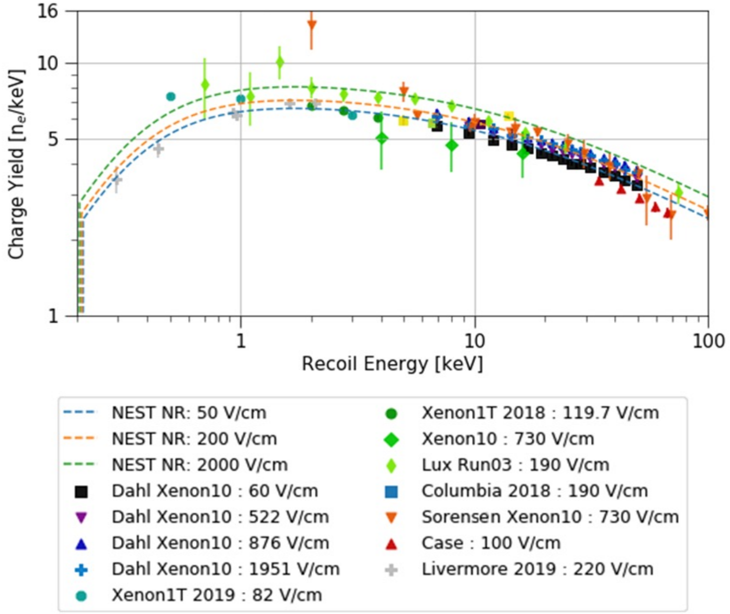
$\tilde{\nu}_e$ energy spectrum from nuclear reactor



Xe and Ar nuclear recoil spectra



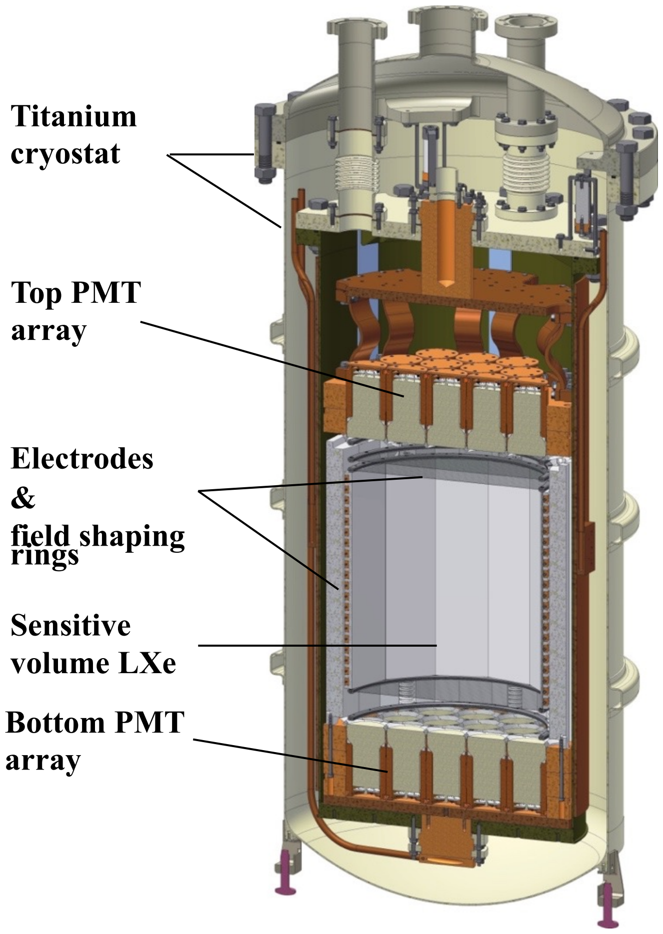
Charge Yields for Nuclear Recoils in LXe

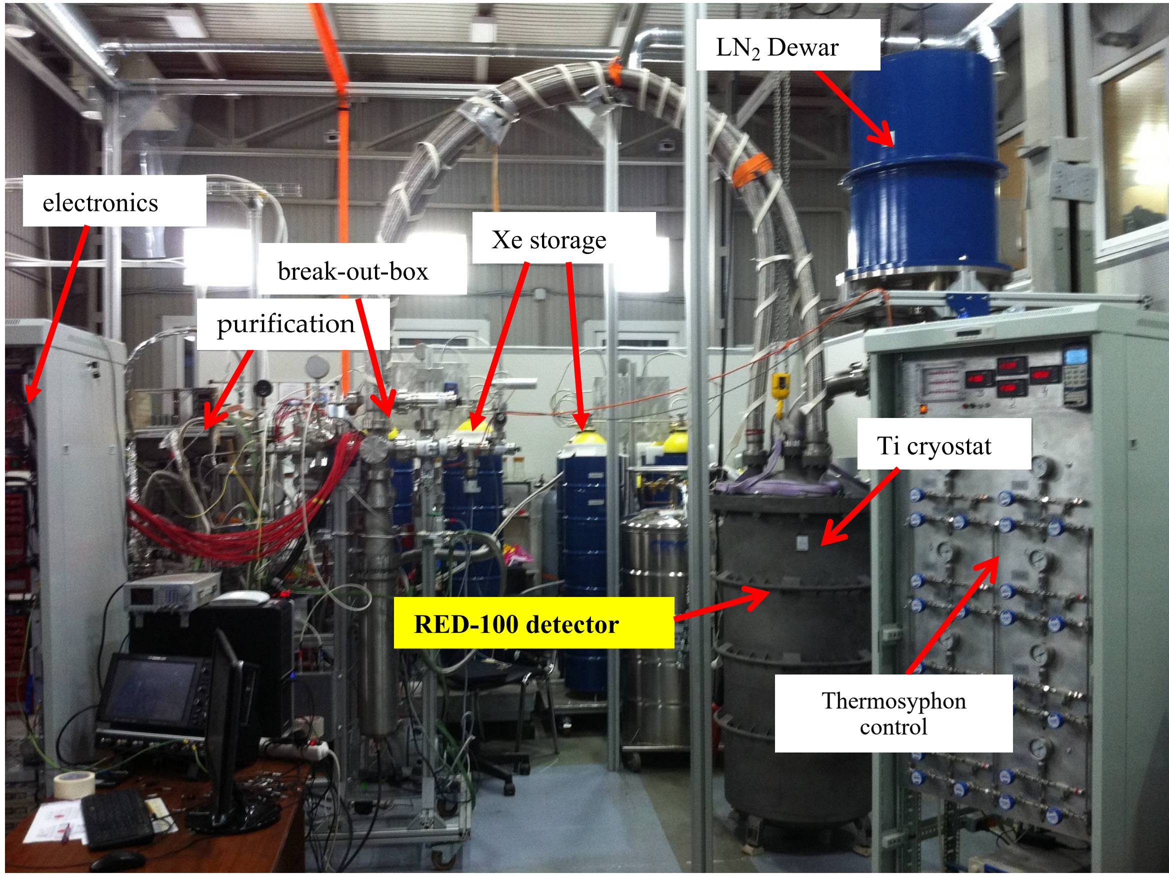


By NEST collaboration

RED-100

- 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)

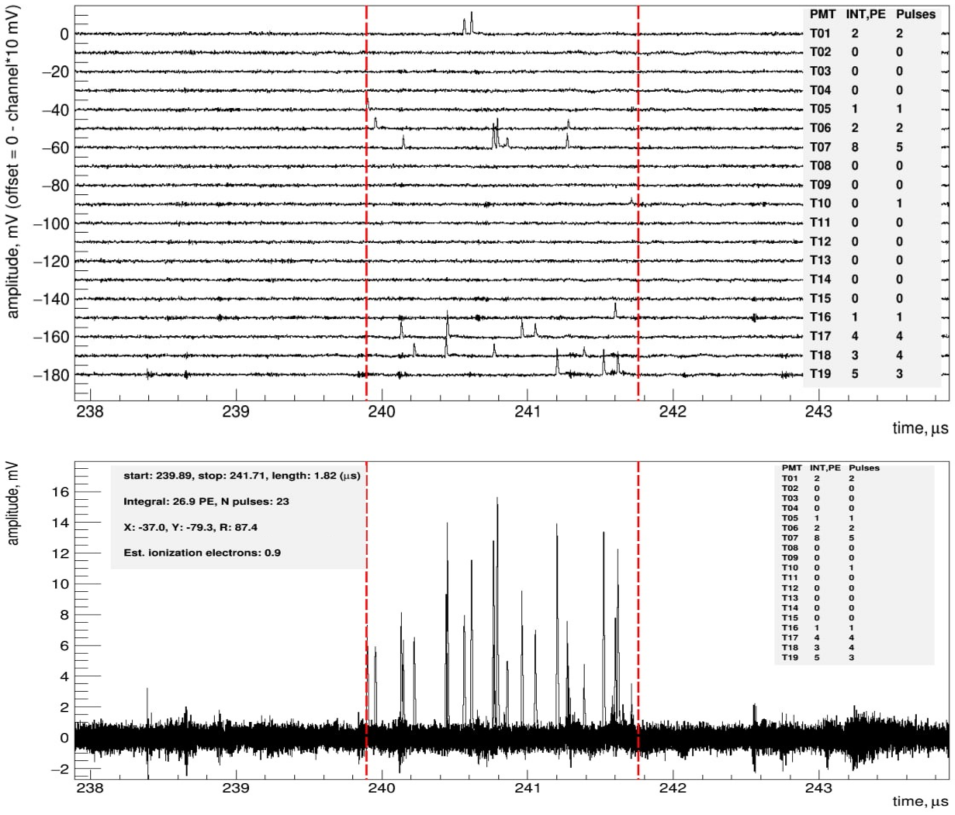


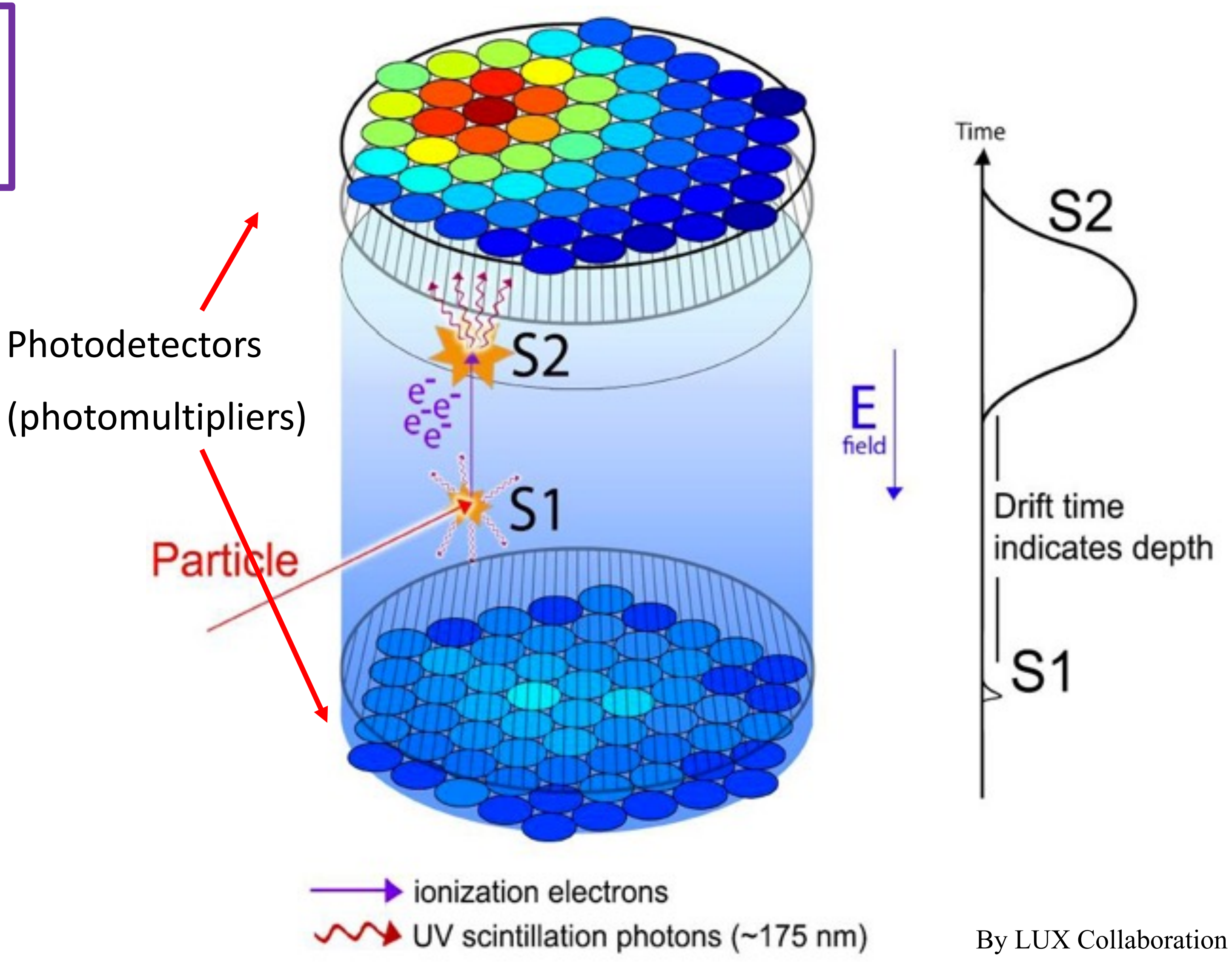


Two-phase emission detector technique

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

Typical single electron (SE) signal in RED-100

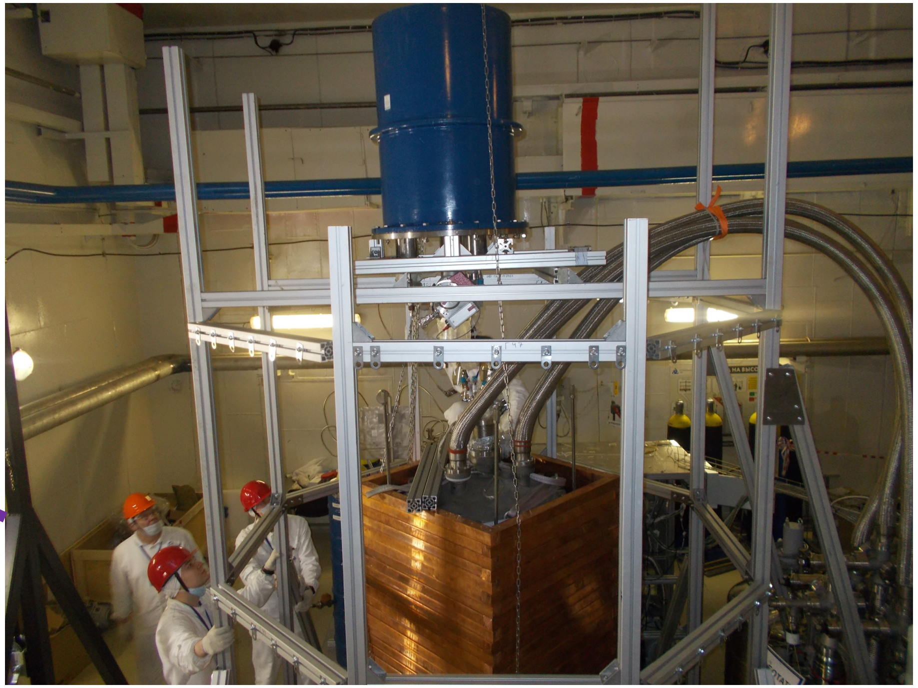




By LUX Collaboration

RED-100 at KNPP

KNPP – Kalinin Nuclear Power Plant



2020 RED-100 was shipped to KNPP

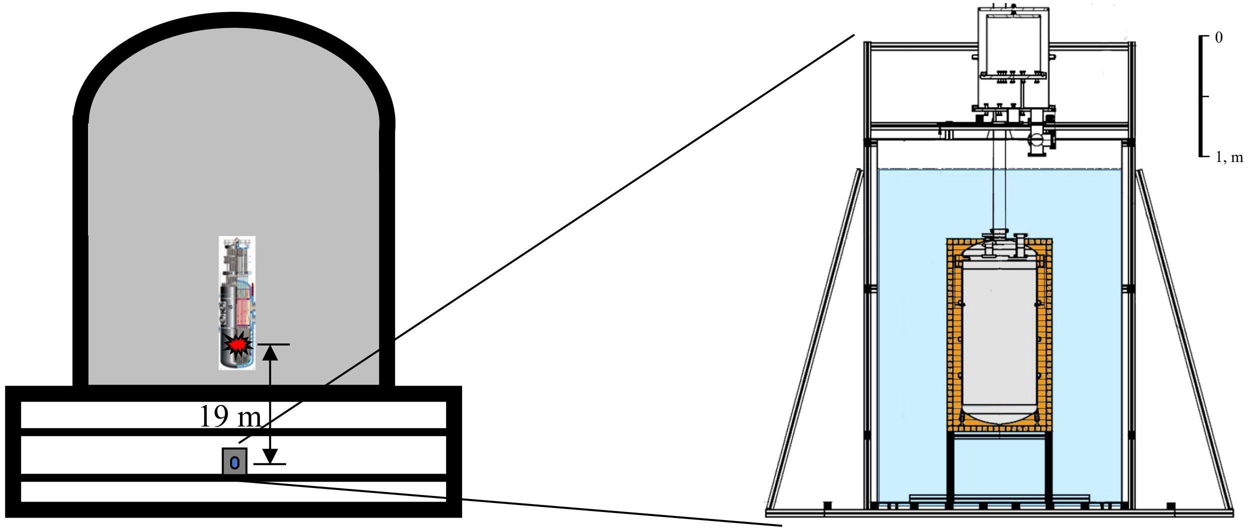
2021 Deployed and tested

2022 (Jan-Feb) Physical run

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

RED-100 at KNPP

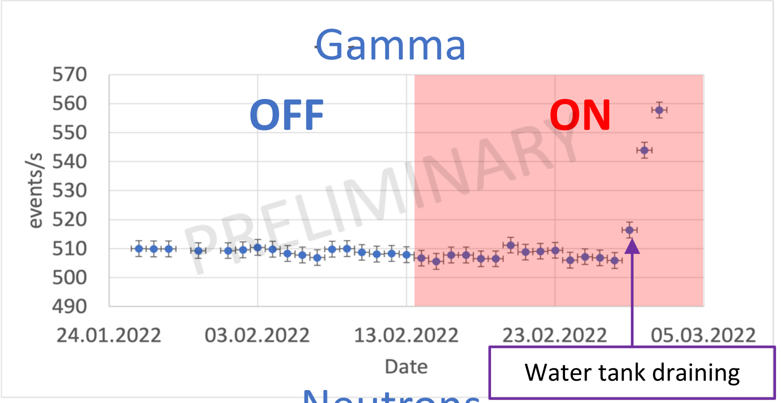
- 19 m from the reactor core of 3000 MW power unit 4
- Antineutrino flux at place ~ $1.35*10^{13}$ $cm^{-2}s^{-1}$
- ~ 65 m.w.e. in vertical direction
- Passive shielding:
    - 5 cm Cu
    - ~ 60 cm H_2O
- First physical run is over

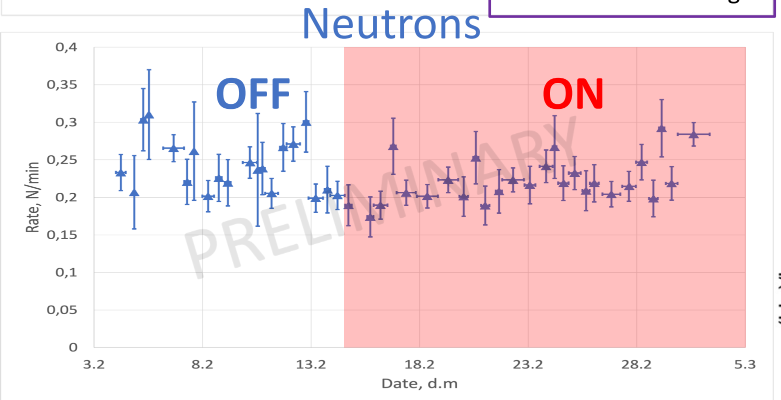


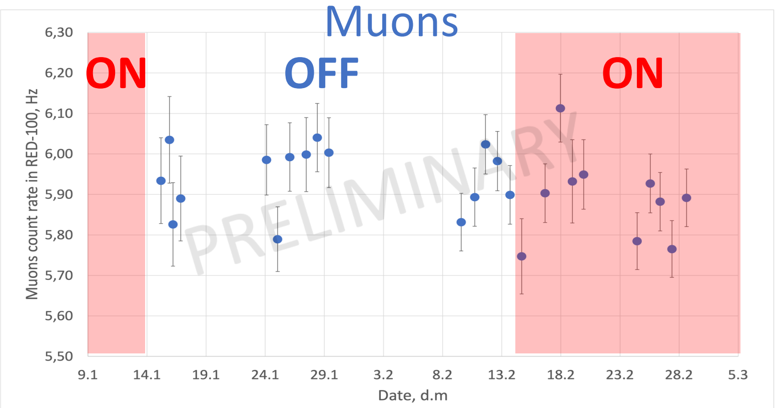
External background

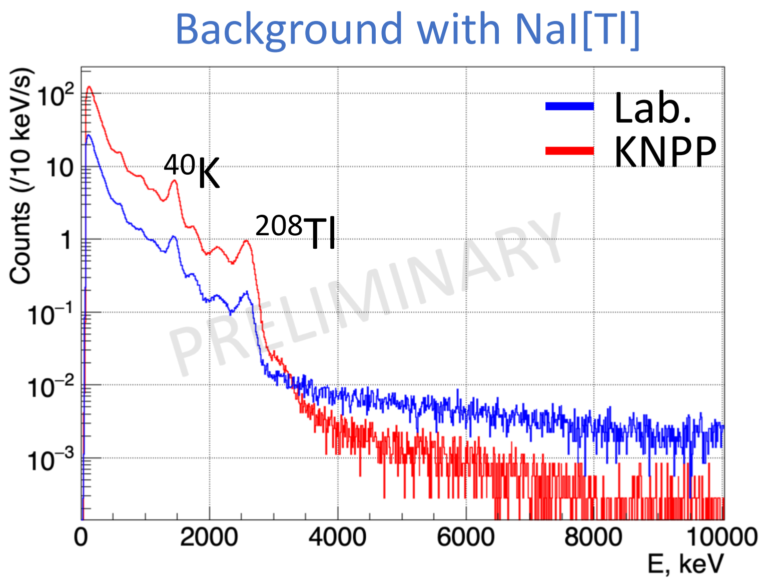
- Background was measured with RED-100 itself and with different additional detectors
- We did not observe any significant correlation in external background count rate with Reactor operation

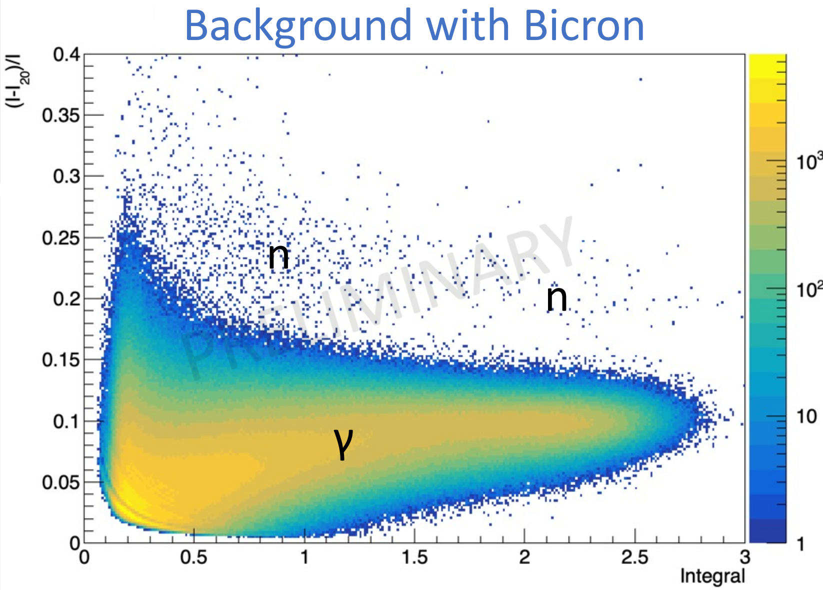
For more details → see the poster "Background study in RED-100 experiment"







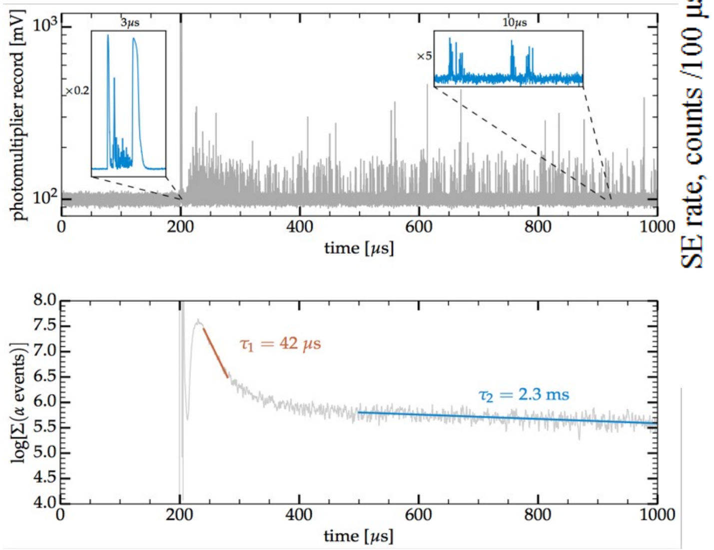




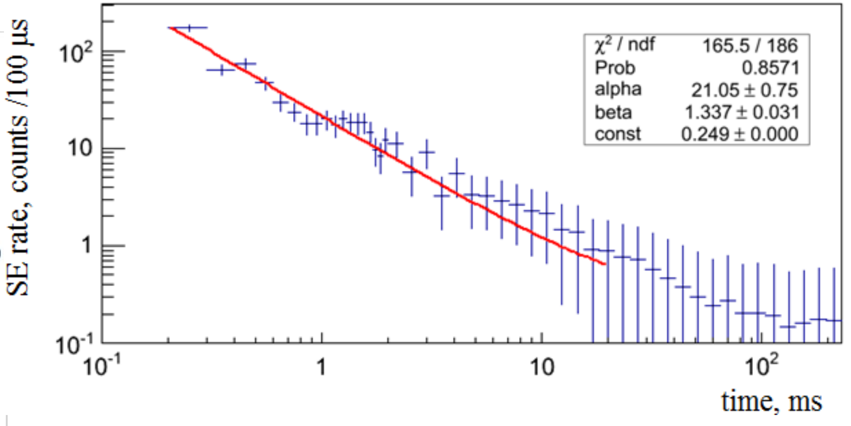
The main background in the ROI

- SE rate increasing after big energy deposition in liquid noble gas detector
- It was observed by several groups
- Electron shutter
  - To block the muons
  - 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

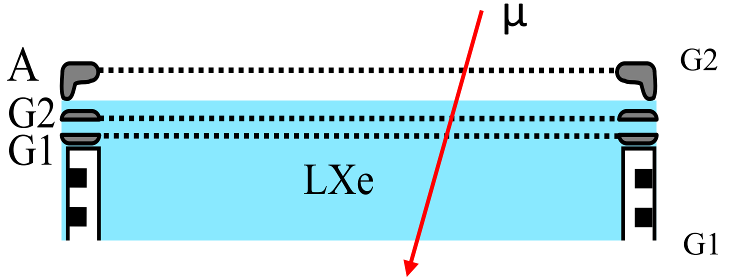


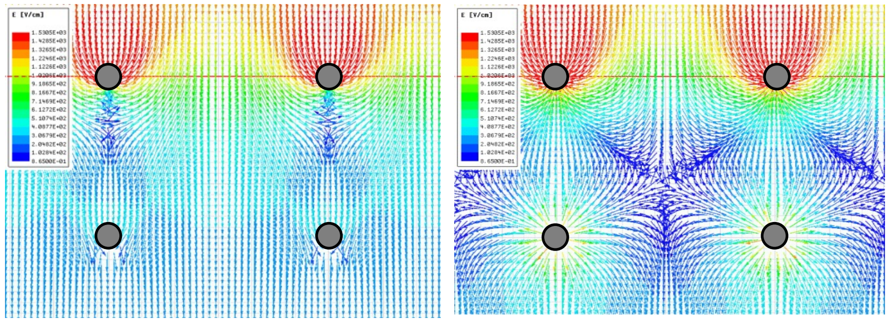
JINST 11 (2016) no.03, C03007



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

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

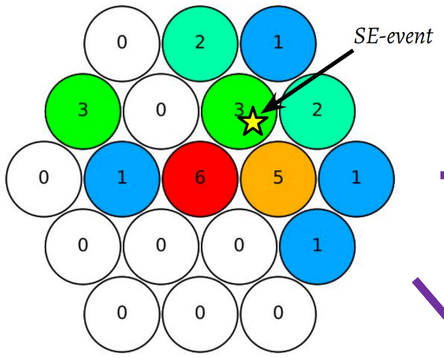


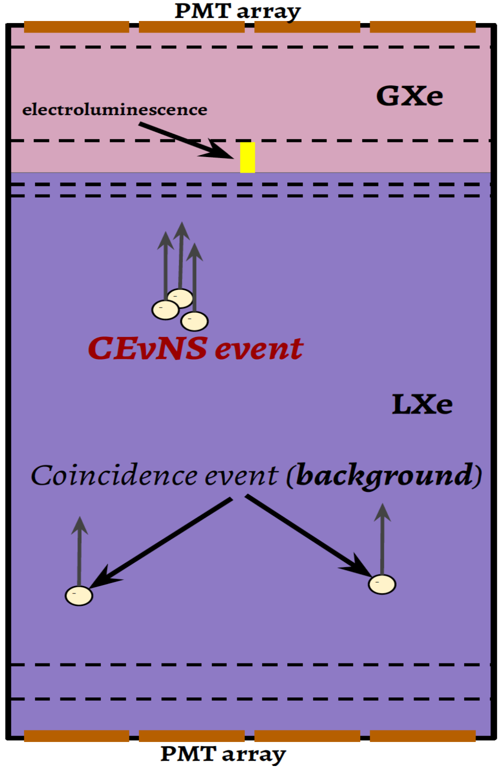


open: $U_{G2} - U_{G1} = 50$ V   closed: $U_{G2} - U_{G1} = -250$ V

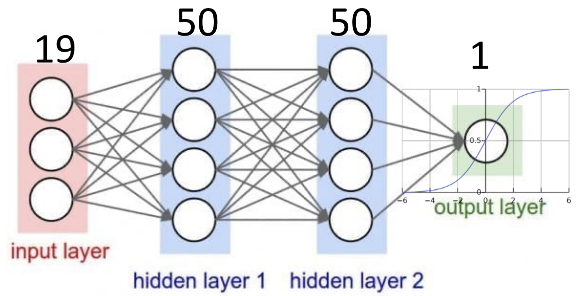
Neural Networks for background rejection

- Main background → 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
- It works! E.g., for 5-6e events (for simulated test dataset):
    - ~90-95% bckg suppression
    - ~2-6% CEvNS suppression
- But in real life things are a little bit more complicated…

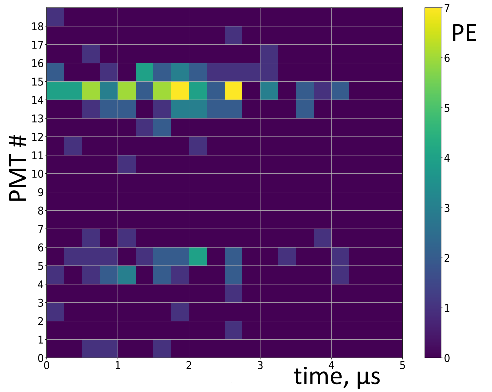




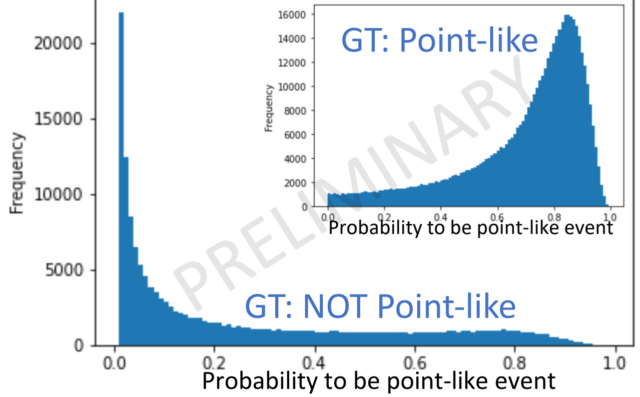
Fully Connected Neural Network (FCNN)



Convolutional Neural Network (CNN)



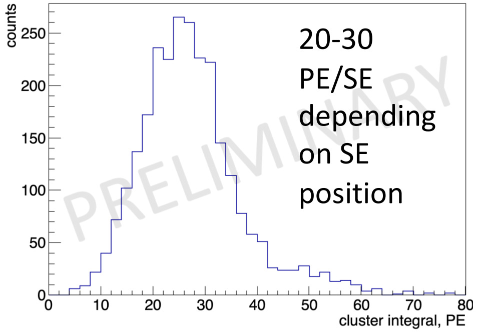
FCCN results for test (MC) dataset

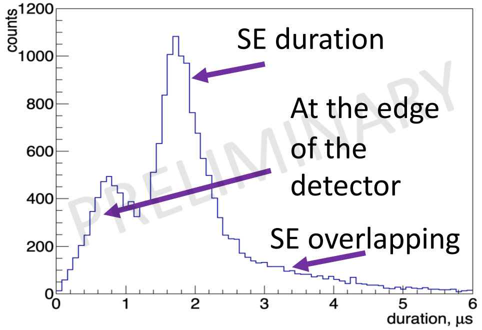


RED-100 blind analysis

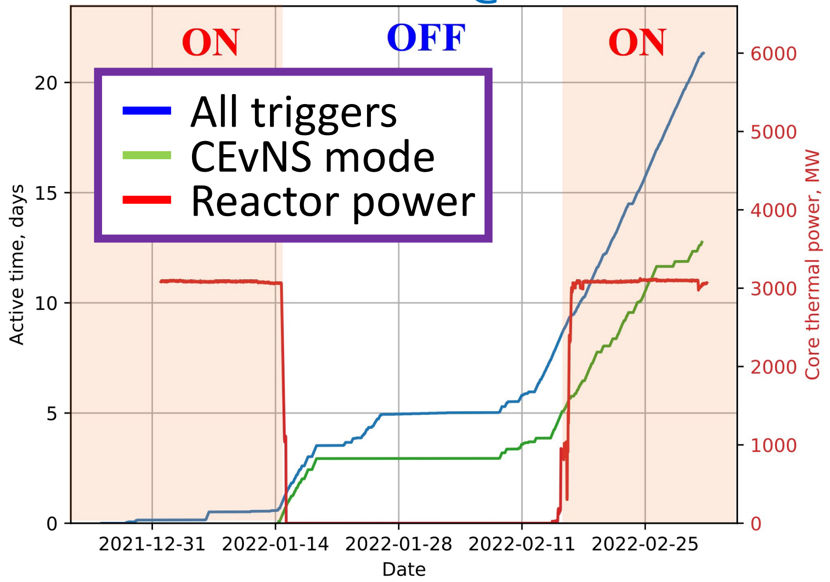
- Reactor ON data is closed until all the data analysis methods are ready
- Analysis Based on Reactor OFF data and calibration data
- Stability checks:
  - SE count rate
  - LY response
  - SE duration
  - Background rates
  - Other parameters

LY & duration of SE

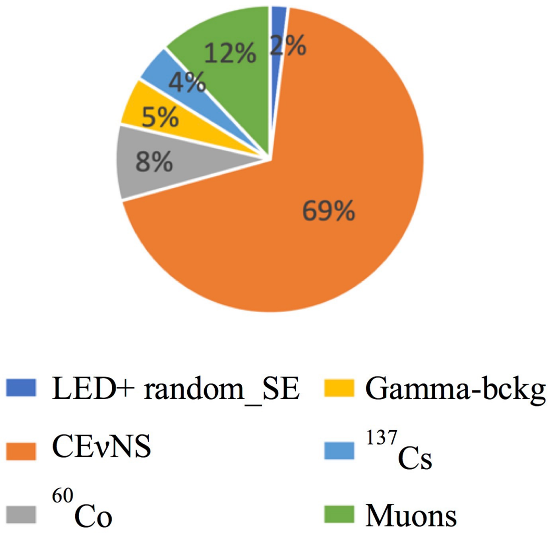




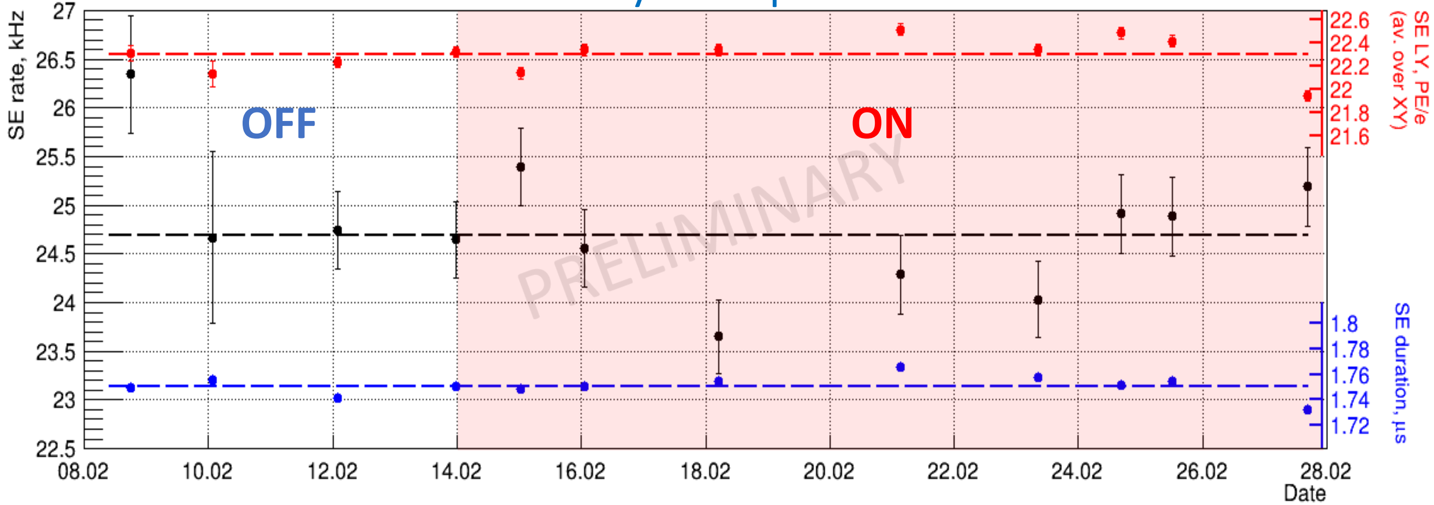
Data collection @ KNPP



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



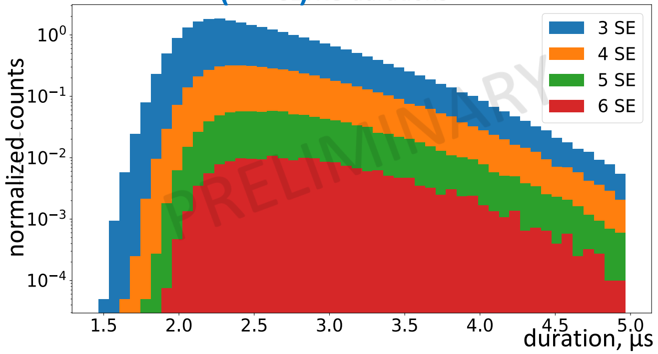
Stability of SE parameters

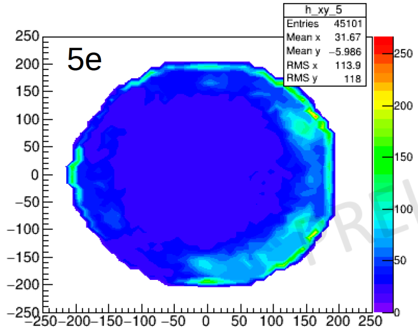


Cuts

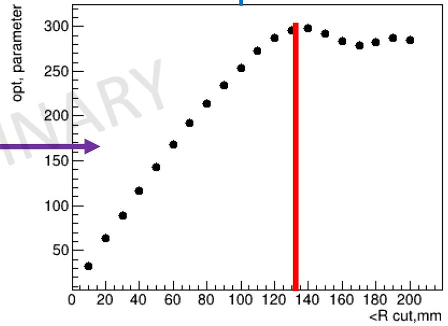
- Analysis based on Reactor OFF data in the ROI
- Cuts optimization
    - Quality (number of PEs in pre- and post- traces)
    - Energy (PEs per 5-6e event)
    - Radius
    - Duration
    - Neural Networks
- 3D likelihood fit machinery (energy, radius, duration)
- Highly correlated background ME events

CEvNS (MC) events durations

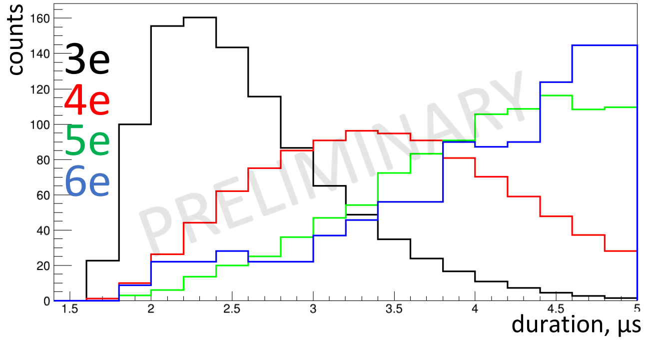




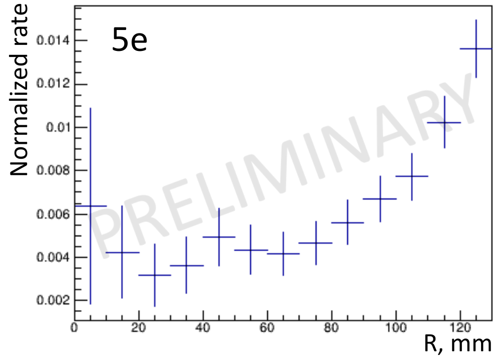
Radius cut optimization



Background events durations



Bckg rate per radius (normalized per rings area)



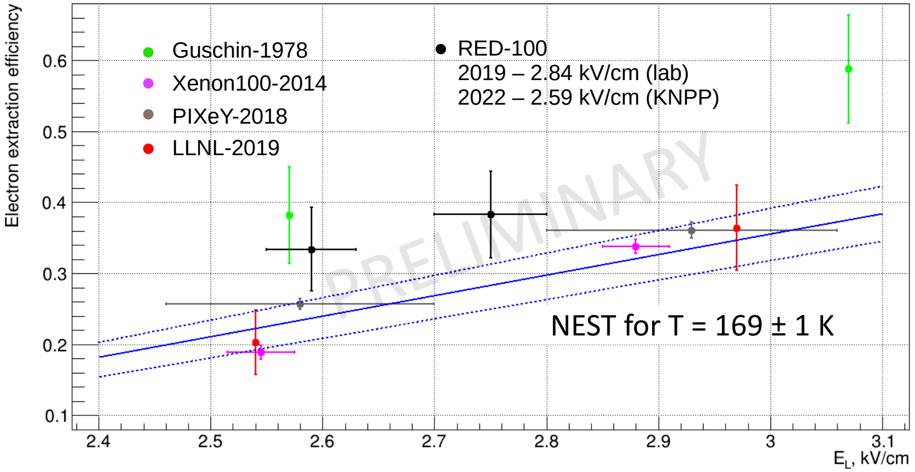
NN efficiency on Reactor OFF data (Preliminary)

FCNN \ CNN	Point-like	Not Point-like
Point-like	17.1%	9.1%
Not Point-like	5.0%	68.7%

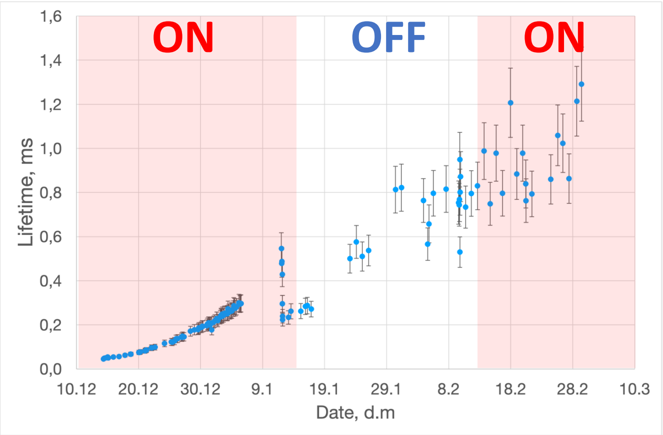
Sensitivity

- 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 in the region 5-6 electrons is ~33 times lower than SM predicted CEvNS rate

Electron extraction efficiency



Electrons lifetime

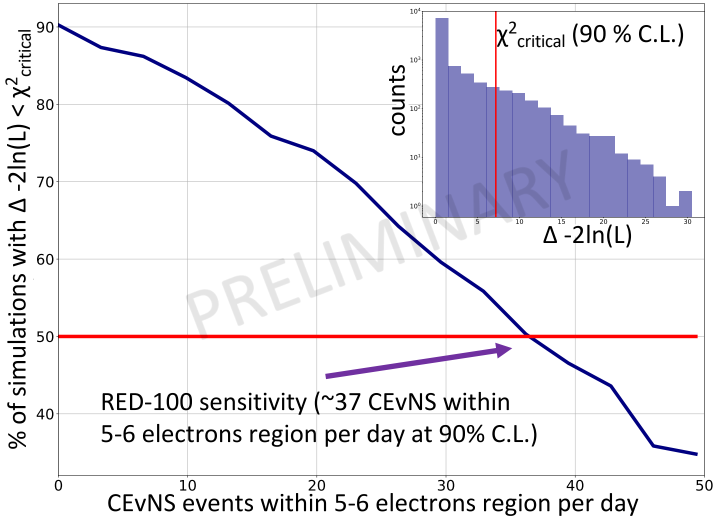


Background rate and CEvNS prediction /~65 kg LXe / day (Preliminary)

Number of e-	4	5	6
background	6375	236	27
CEvNS	3.1*	0.6*	0.1*

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

Sensitivity calculations



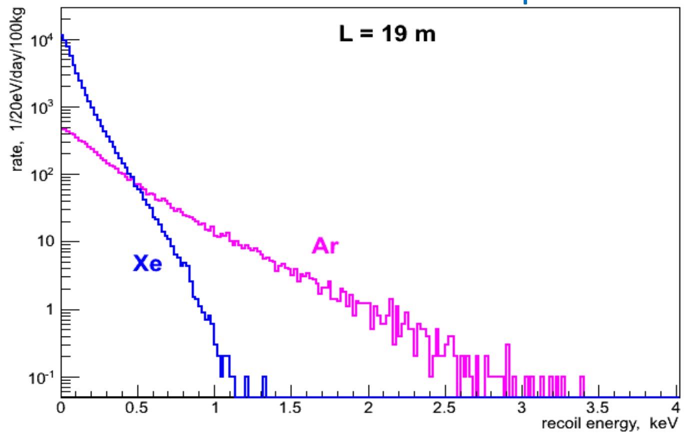
Current status and plans

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

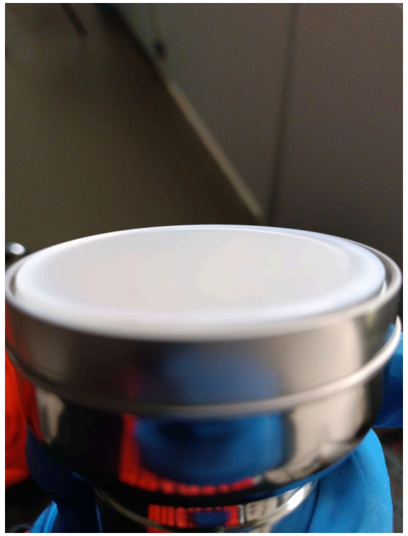
Future of RED-100

- 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

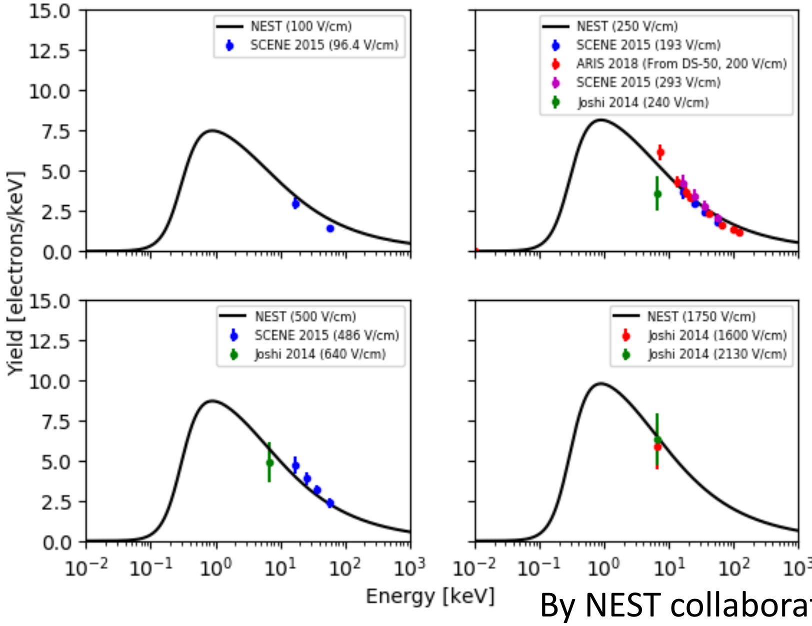
Xe and Ar nuclear recoil spectra



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 this spring (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!

Backup

Noble gas detectors and CEvNS

In Dark Matter search experiments, the progress of setting limits has increased significantly when **liquid noble gas detectors (two-phase)** started operation

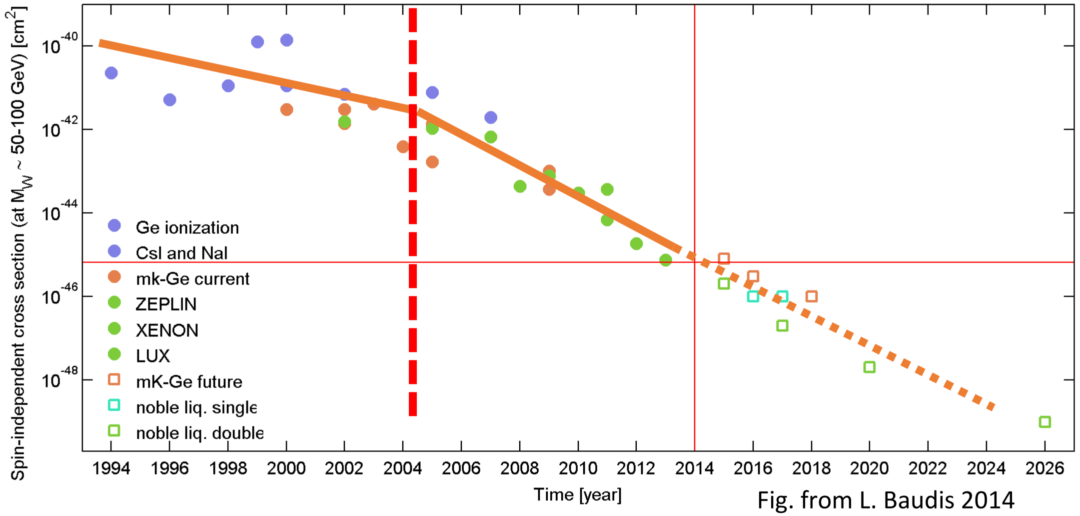
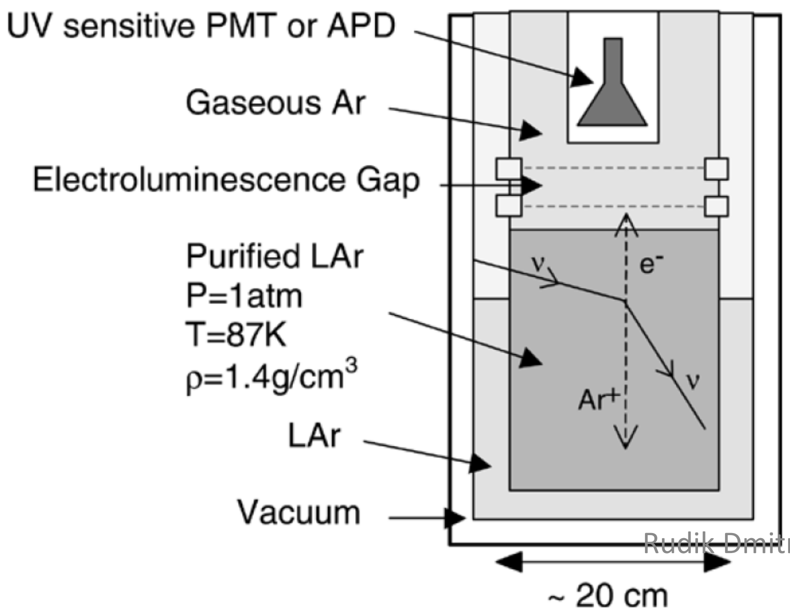


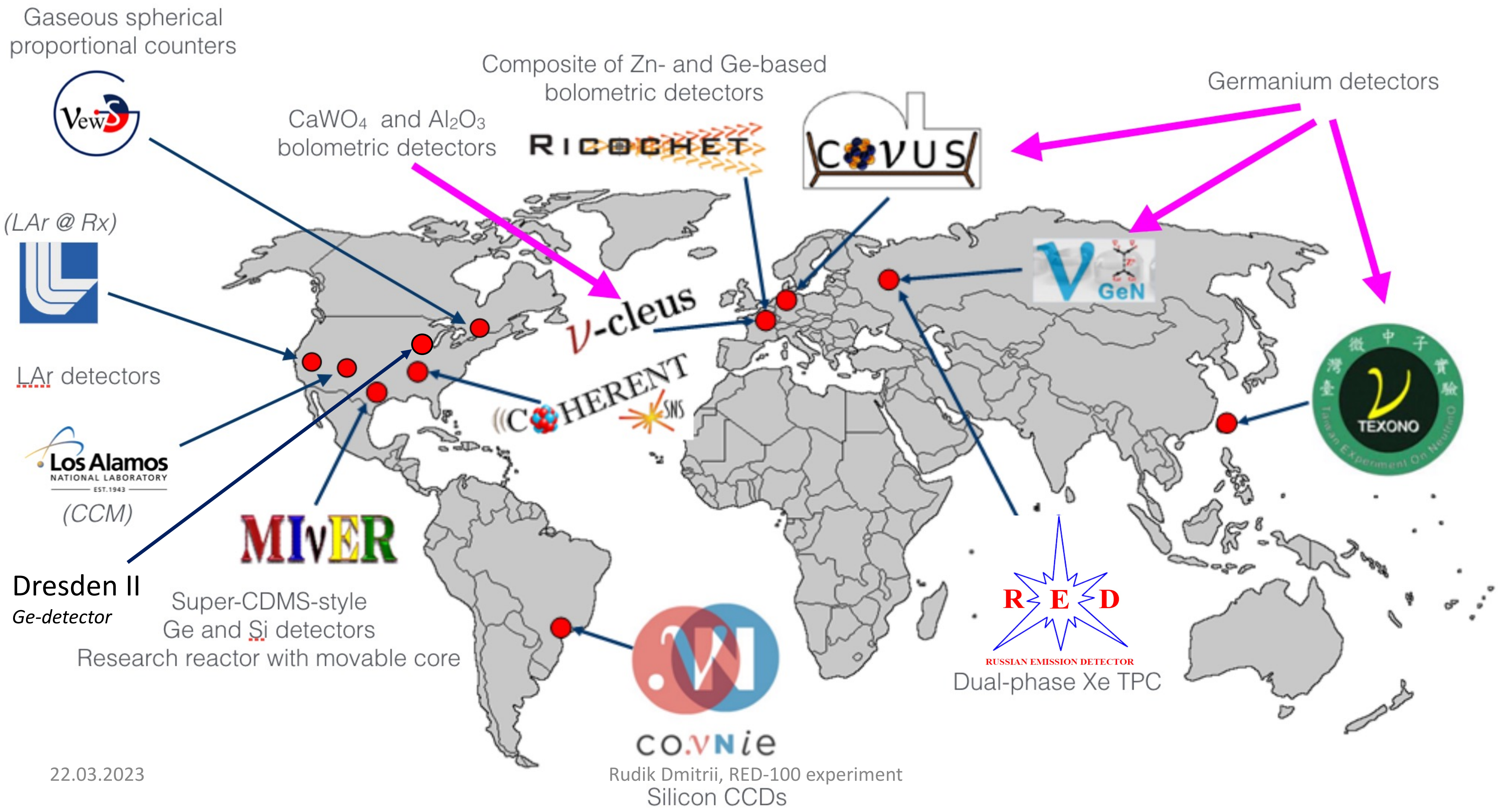
Fig. from L. Baudis 2014

1st proposal (in 2004); LAr detector

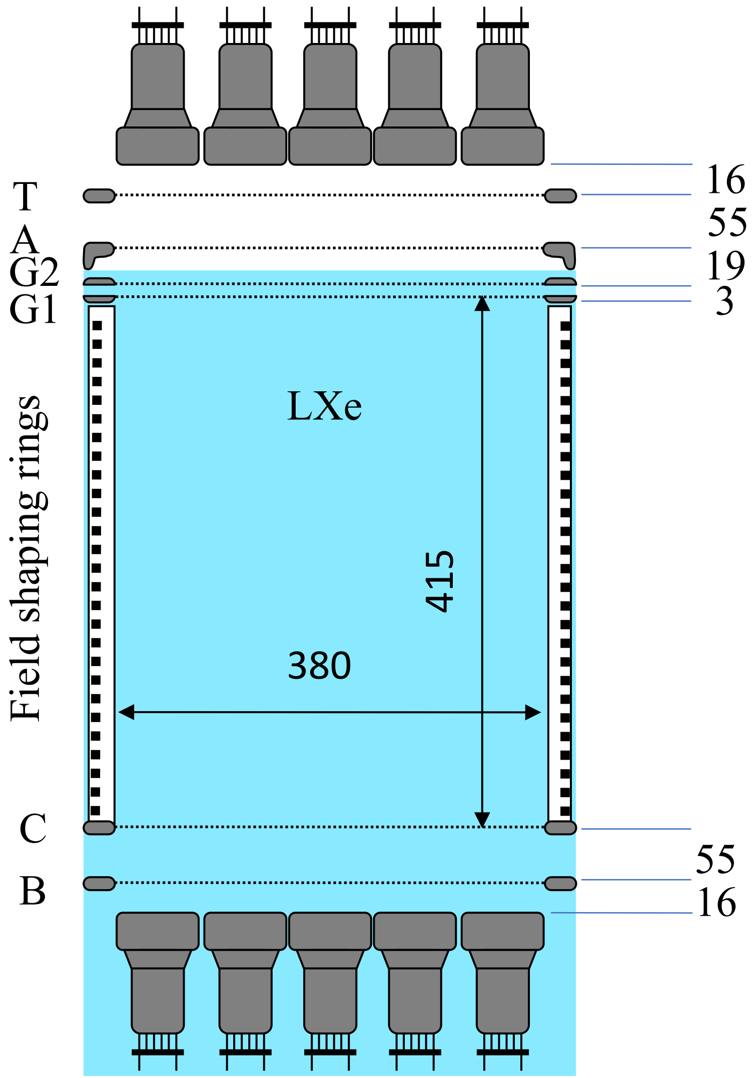


C. Hagmann and A. Bernstein,
Two-Phase Emission Detector for Measuring Coherent Neutrino-Nucleus Scattering
IEEE Trans.Nucl.Sci. 51 (2004) 2151

CEvNS around the World

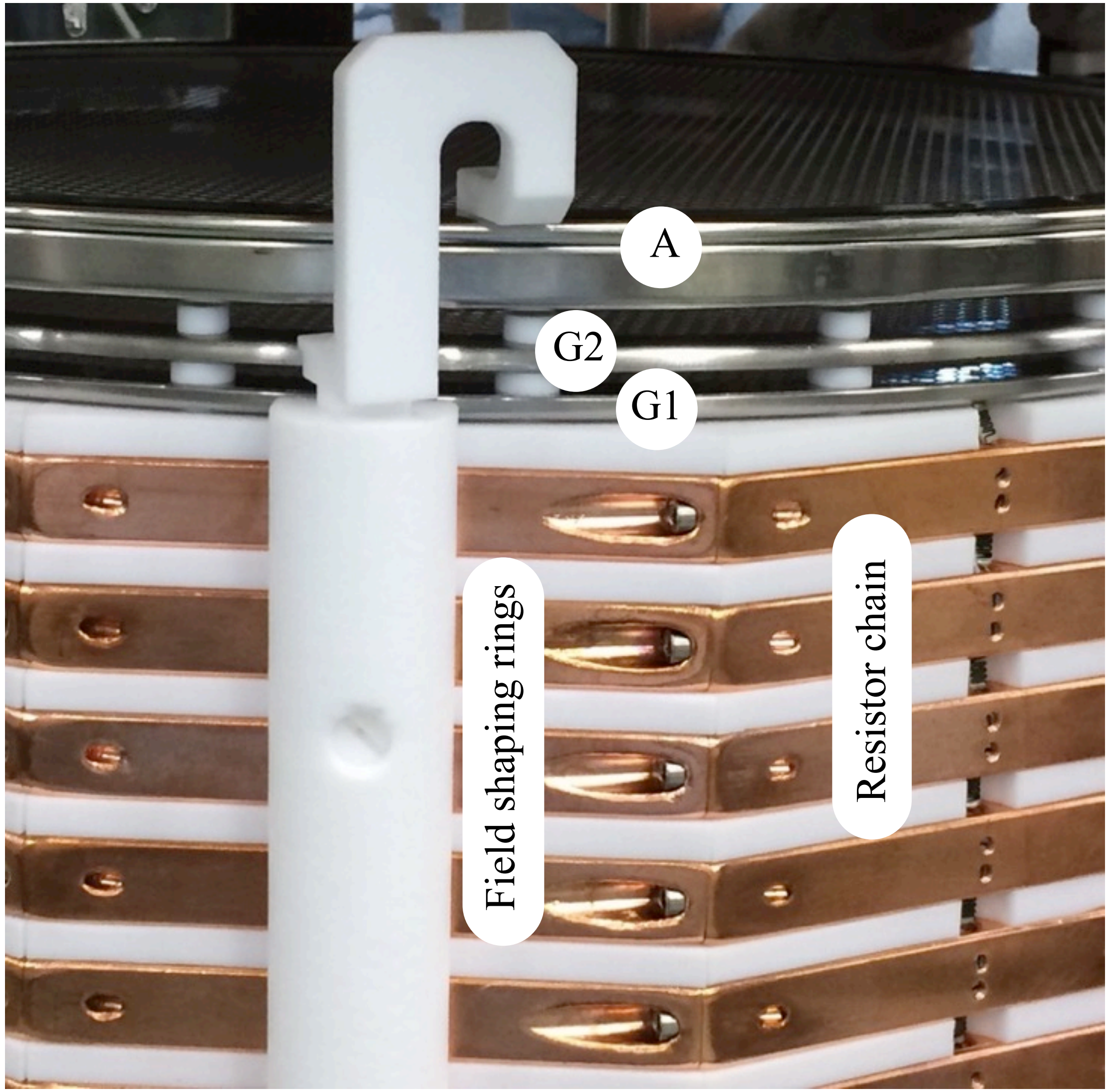


RED-100: schematic layout of grids and PMTs



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

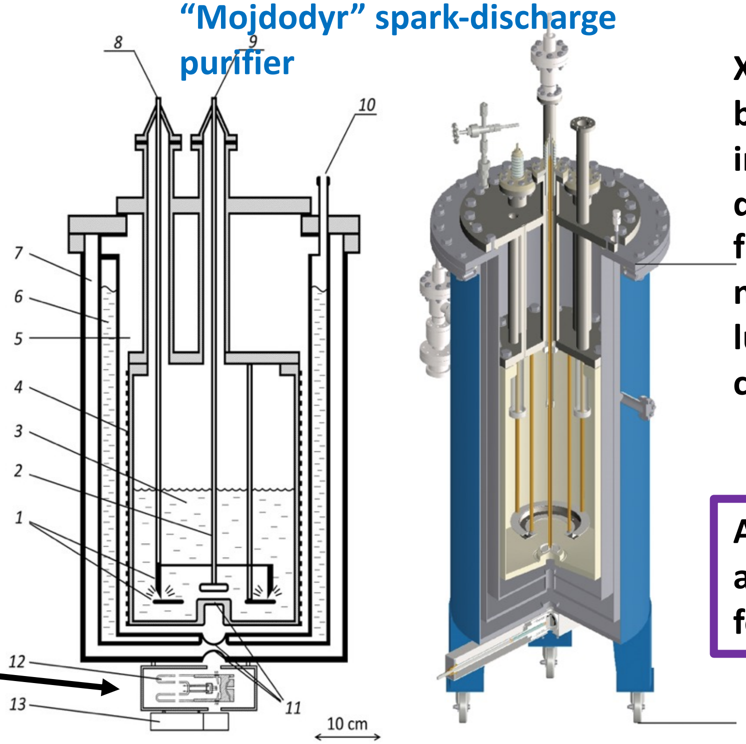


RED-100 performance: LXe purity

- 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

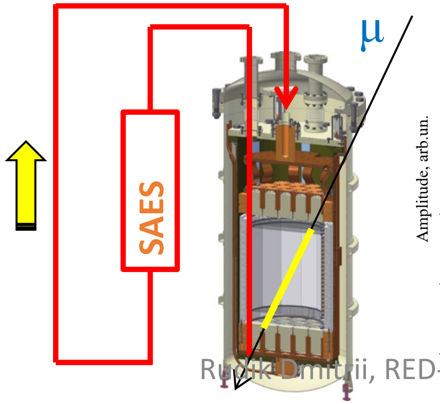


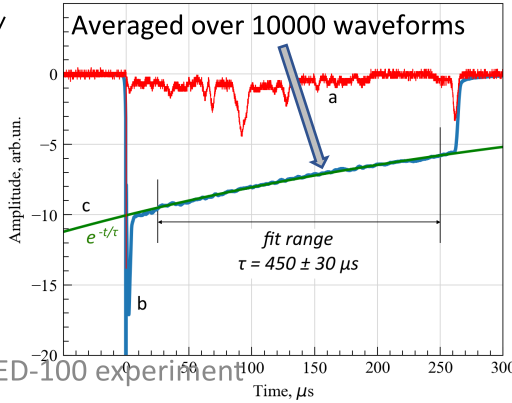
X-ray tube as a source of ionization electrons for e⁻ lifetime measurements

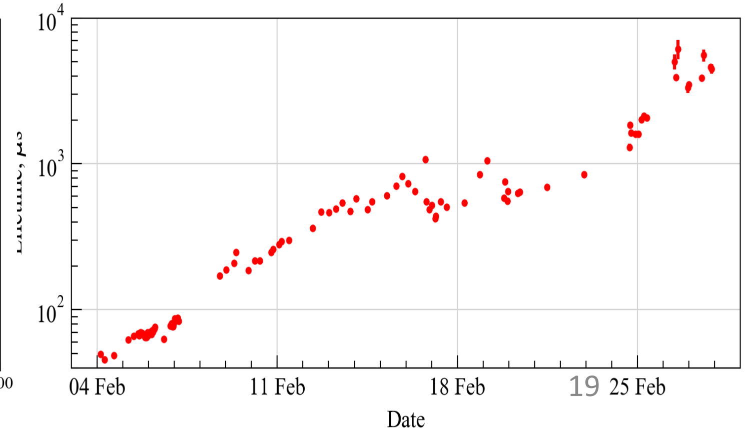
Xenon was contaminated by highly-electronegative impurities presumably due to the use of a special fluorine-containing high-molecular-weight lubricant in gas centrifuges.

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

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

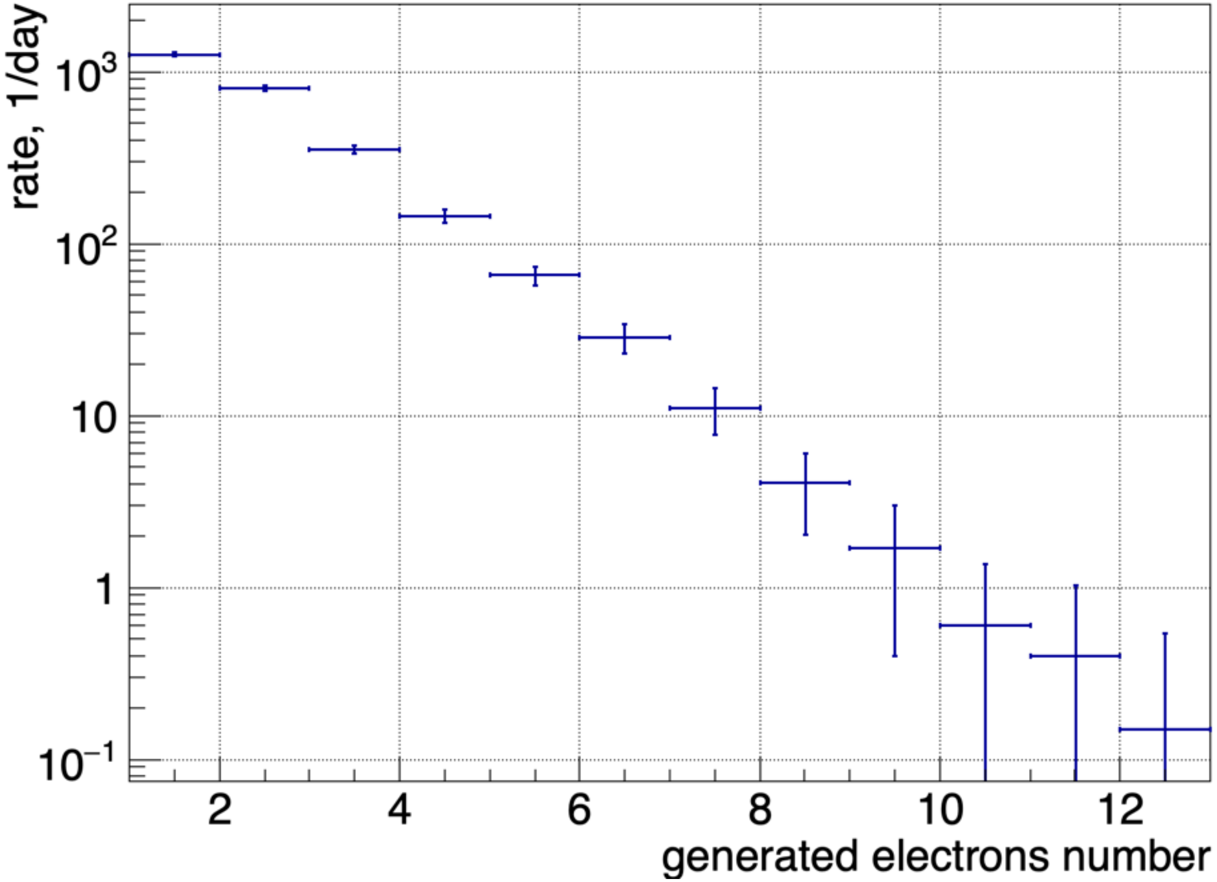




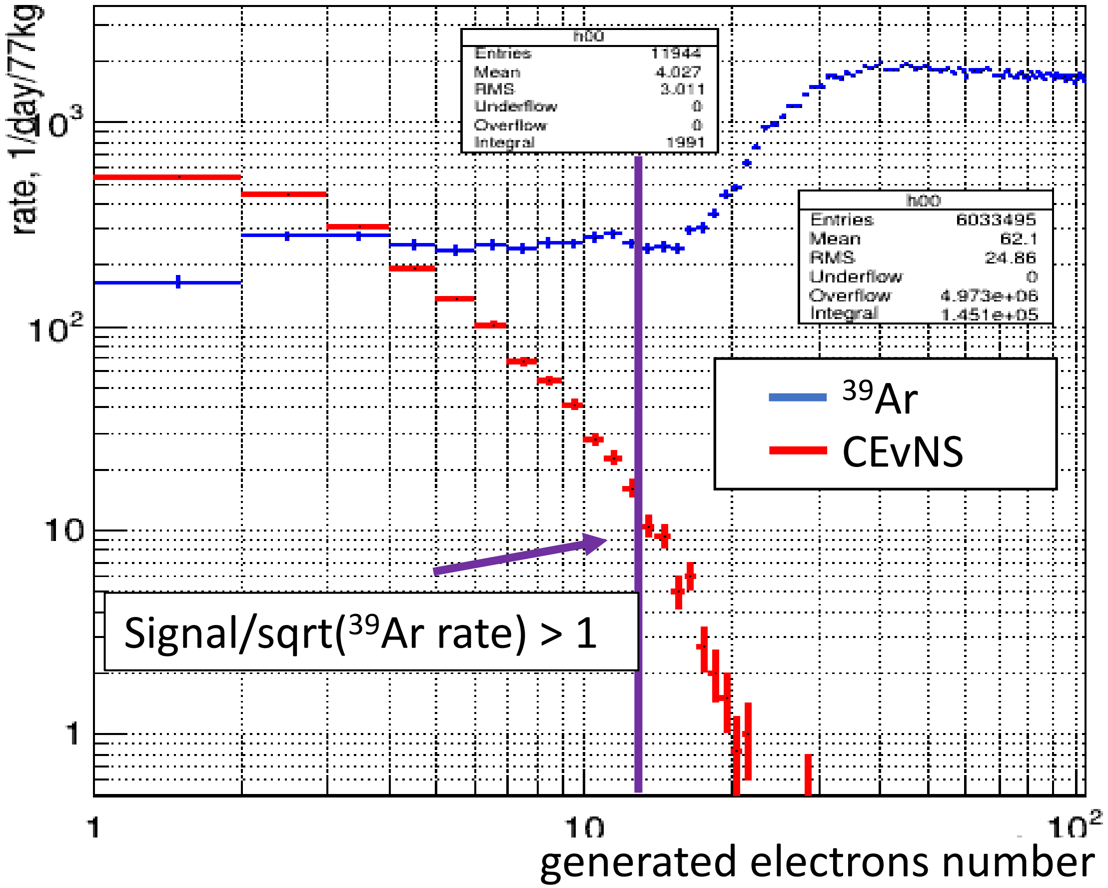


Generated electrons in RED-100

Generated electrons in RED-100 with LXe for CEvNS events

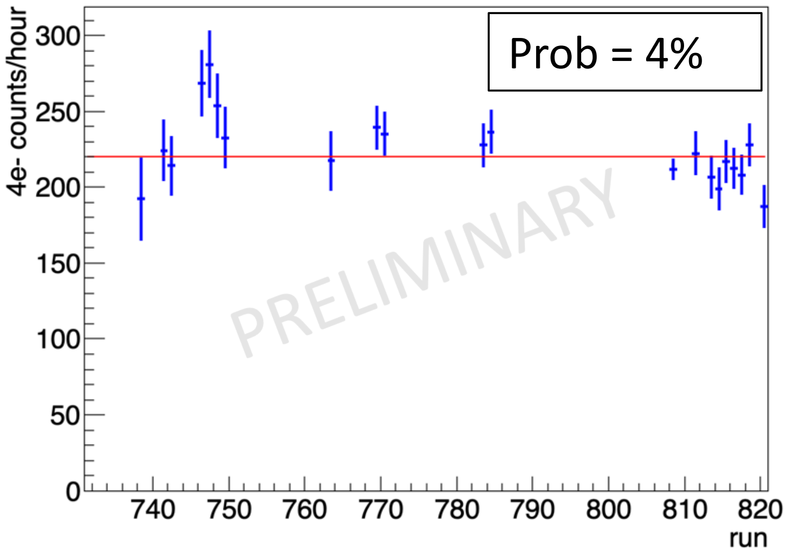


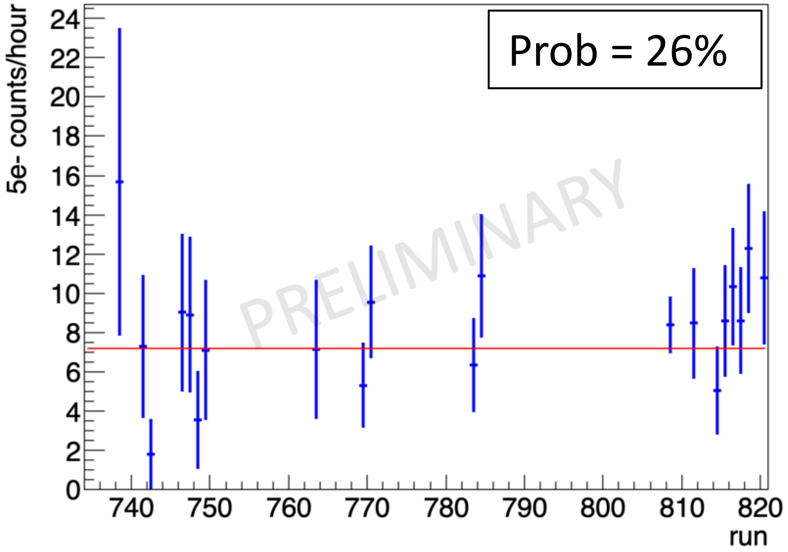
Generated electrons in RED-100 with LAr for CEvNS events and ^{39}Ar

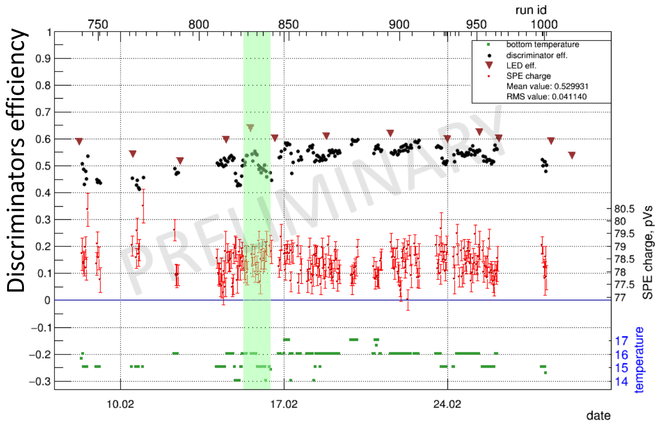


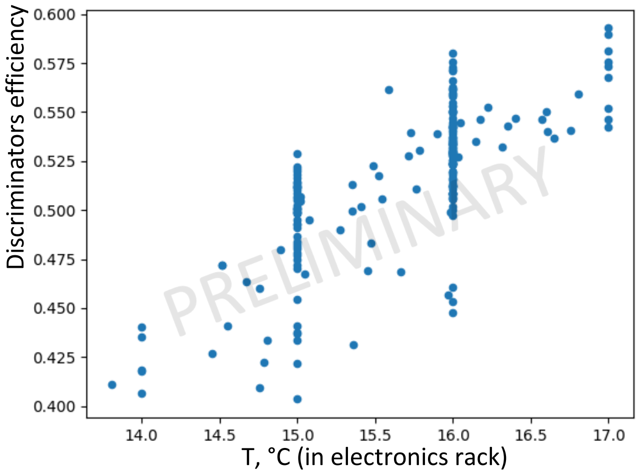
Background stability in ROI

- 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







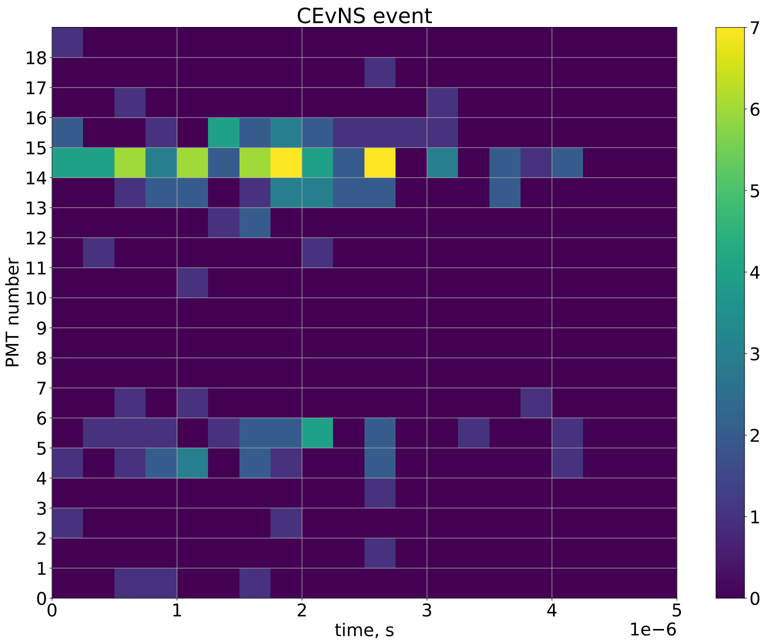


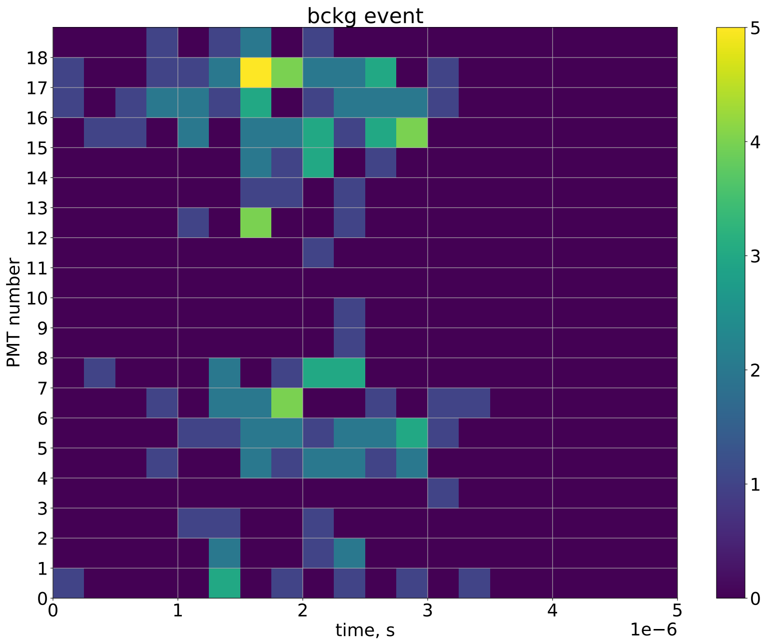
Cuts efficiency (preliminary)

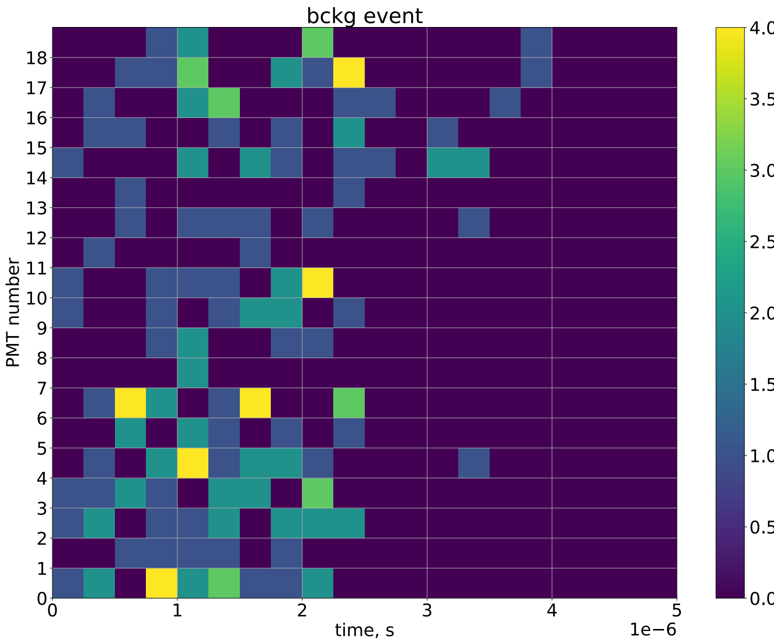
Cut	Meaning	Influence on CEvNS
Quality	All cuts to check the quality of the run/wf: number of PEs before/after trigger, no outliers, signal starts within trigger window, etc.	0.956
Point-like cut	Aggressive cut based on the coincidence of 2 NN results	4/5/6 e 0.89/0.92/0.94
R	Event reconstructed position should be within 130 mm radius	0.5
Duration	Different duration due to the diffusion	4/5/6 e 0.67/0.60/0.80
TOTAL		**4/5/6 e 0.29/0.26/0.36**

Background is suppressed in ~350 times in the region of 5-6 electrons

Examples of events for CNN (simulations)

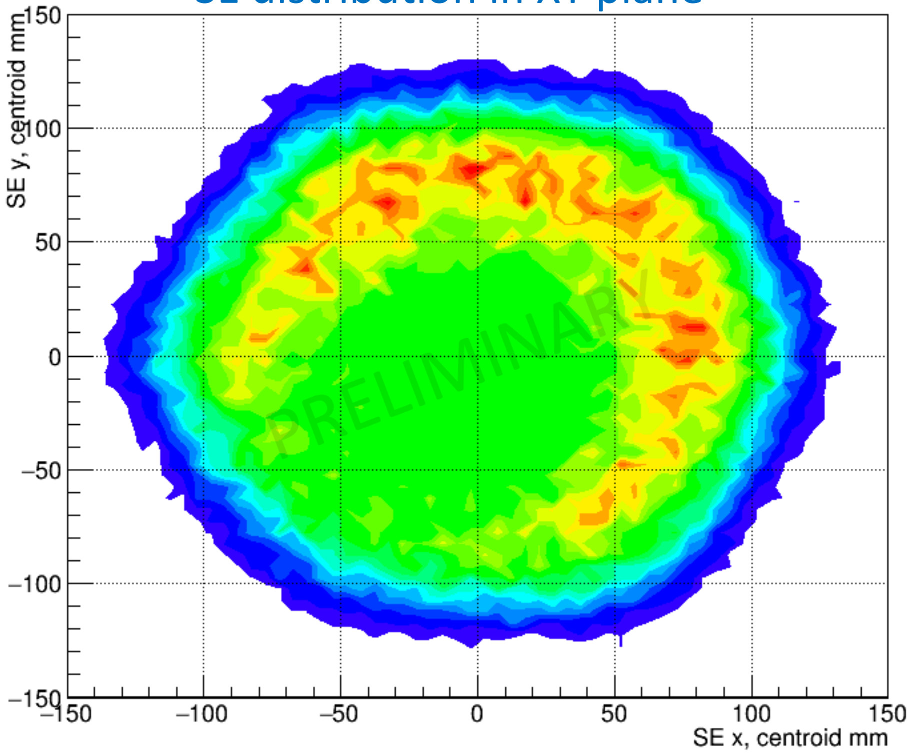




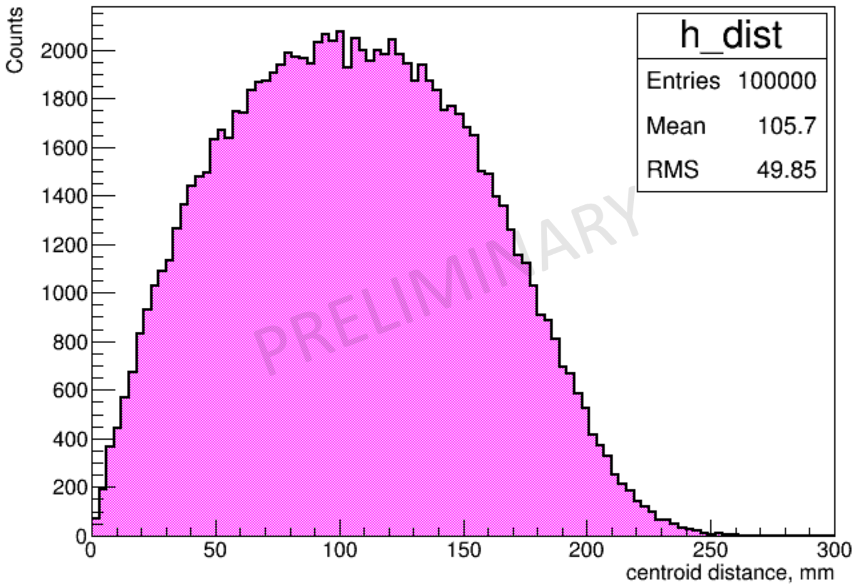


Investigation of spatial correlation between events

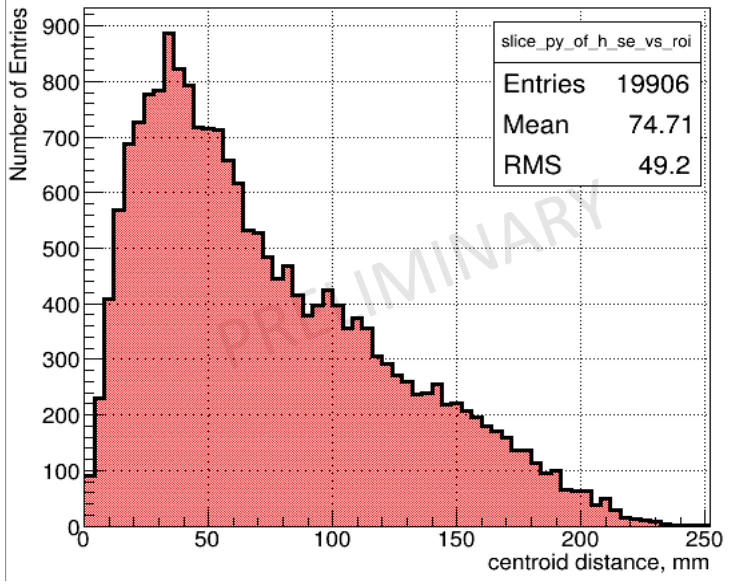
SE distribution in XY plane



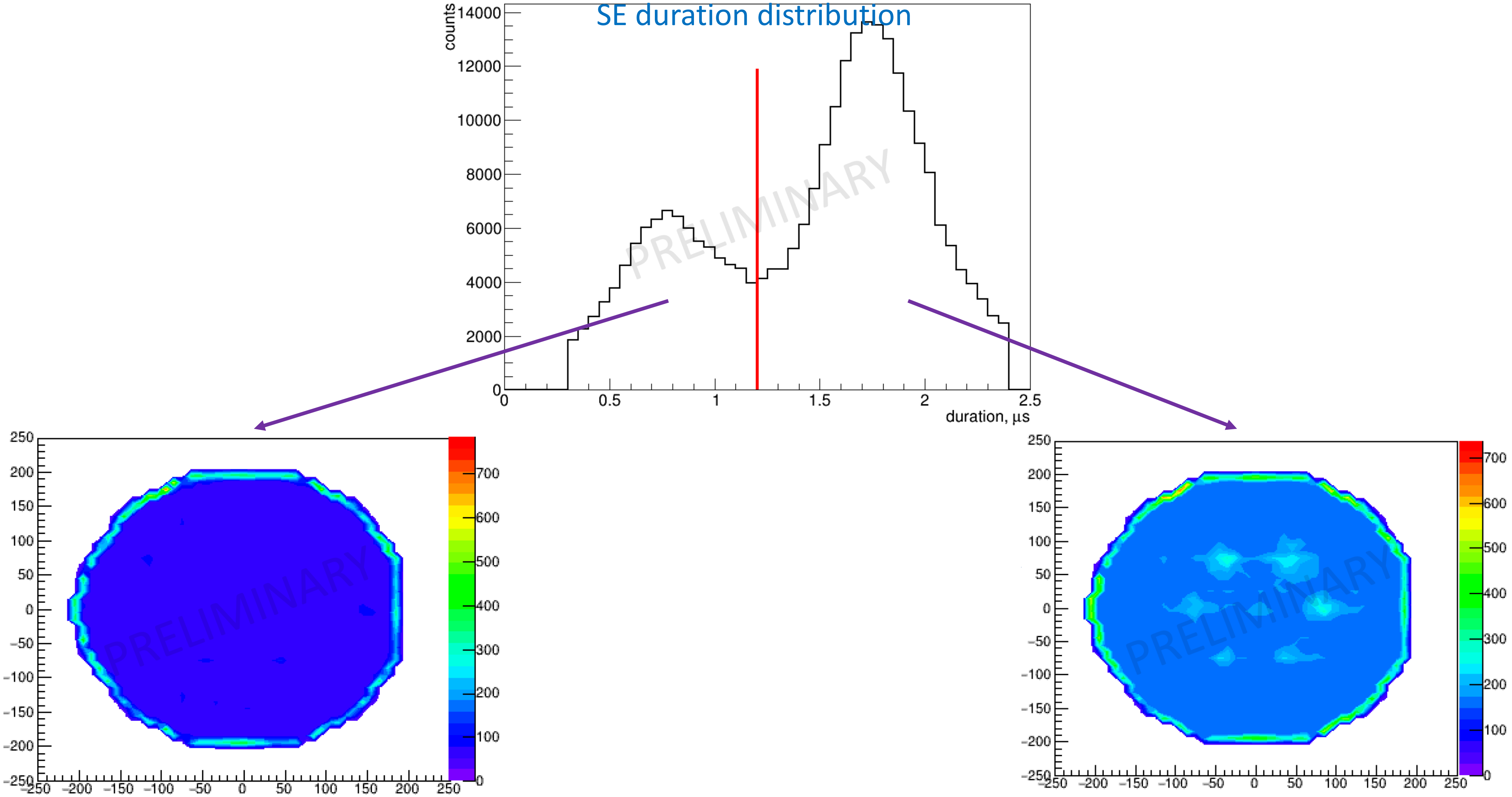
Distance between 2 random SEs from spatial distribution



Distance between 2 consequent SEs from real data



Short SEs

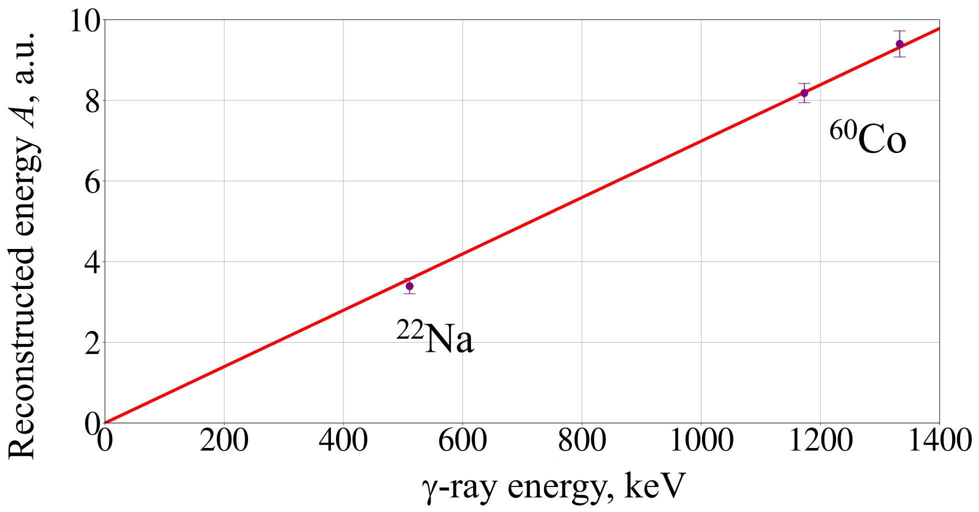


SE duration distribution
counts
duration, μs
PRELIMINARY
PRELIMINARY
PRELIMINARY

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