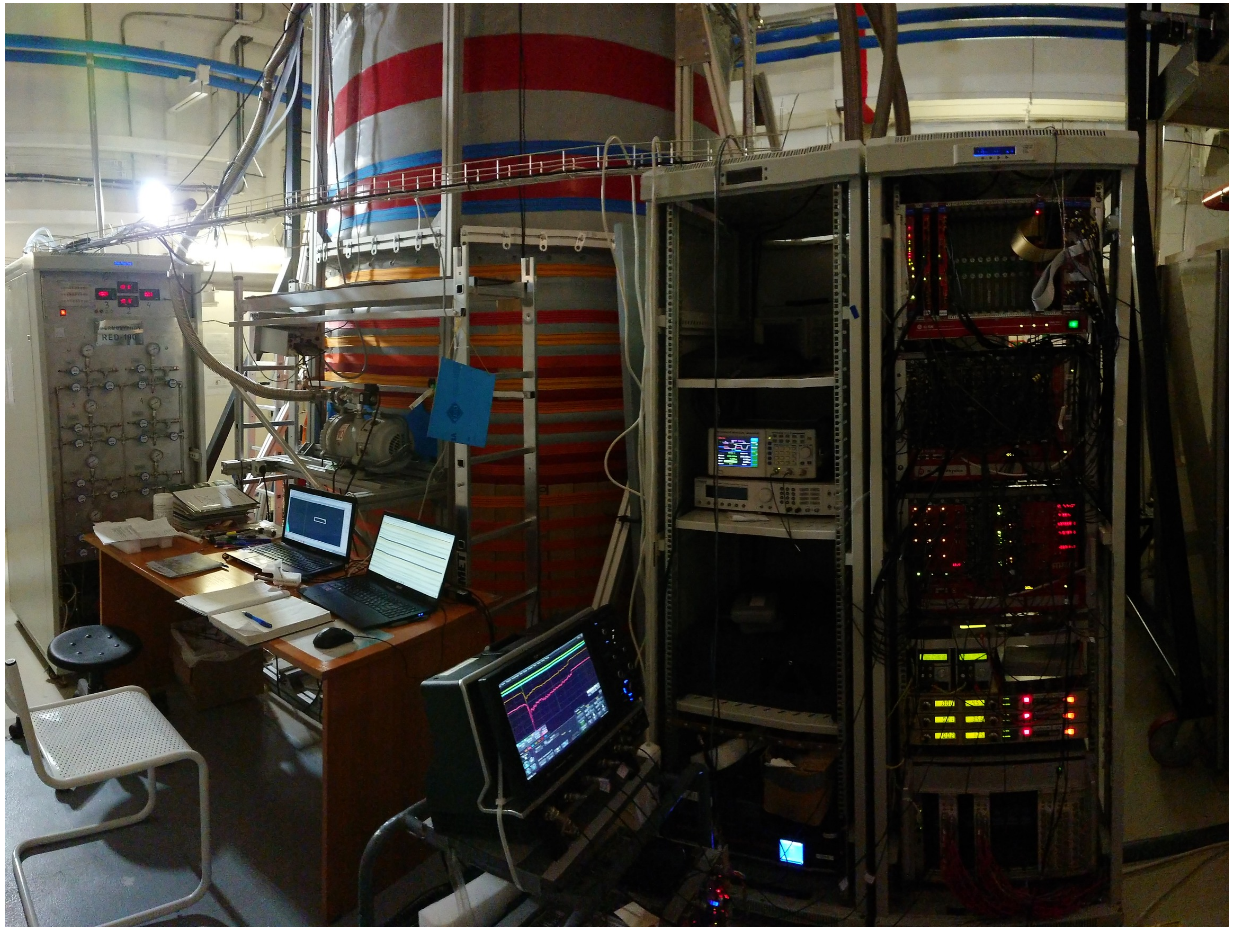
The RED-100 experiment

Dmitrii Rudik on behalf of RED-100 collaboration

NPML 2023

Outline

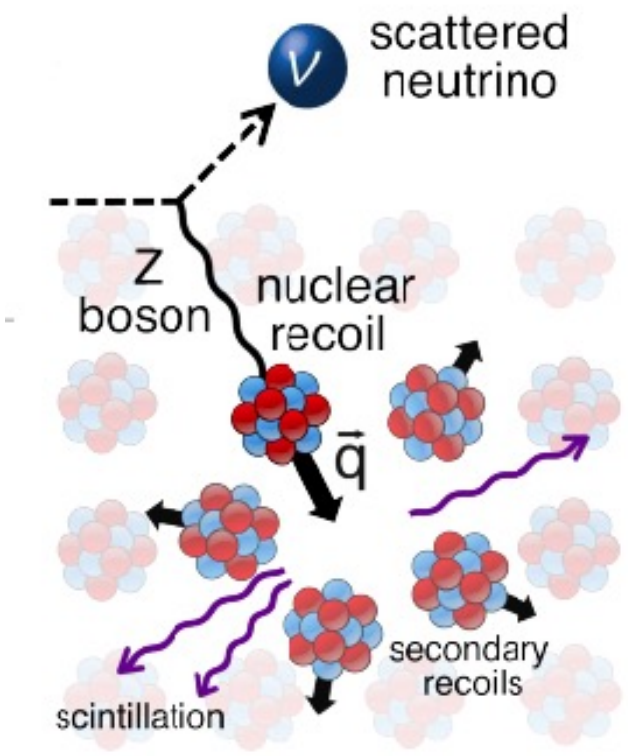
- Coherent Elastic ν-Nucleus Scattering
- Two phase emission detector
- RED-100 at Kalinin NPP
- Data taking and analysis
- Background sources
- Problem which we are trying to solve with ML
- Summary

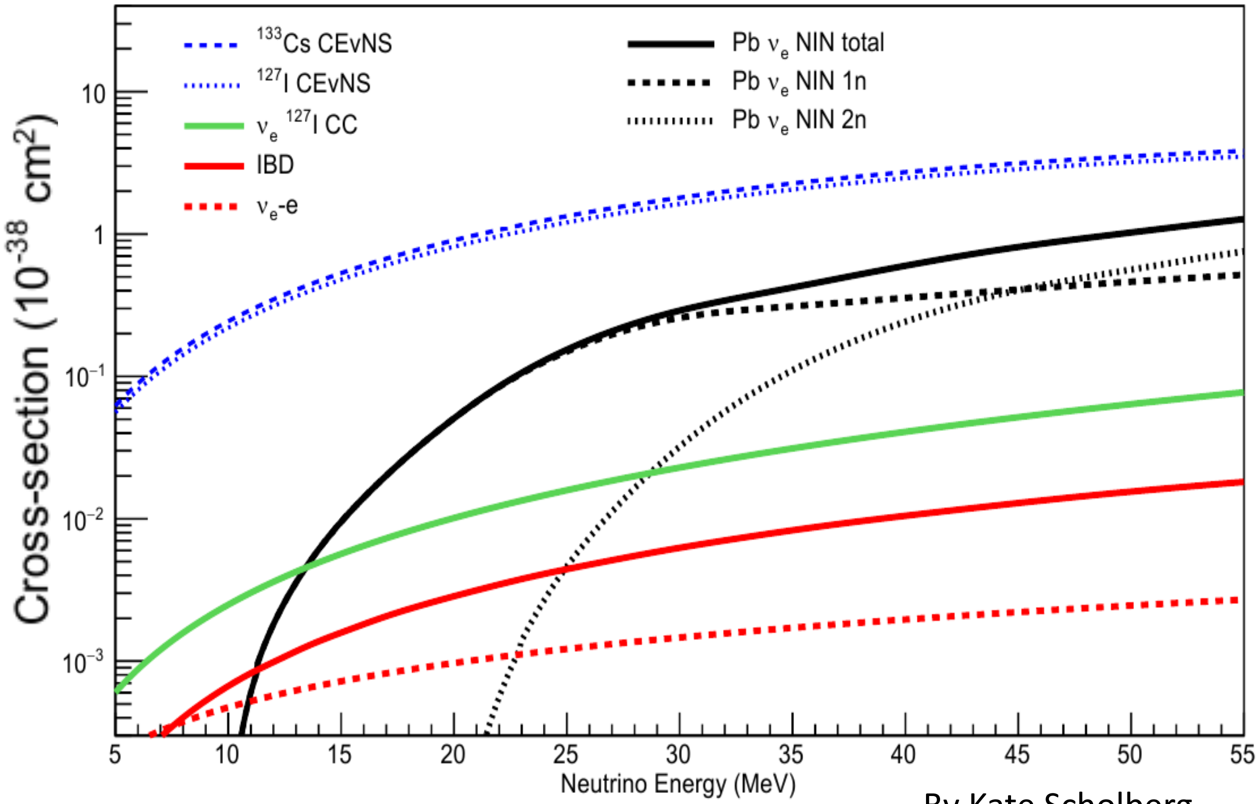


Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

Predicted more than 45 years ago within the Standard Model

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



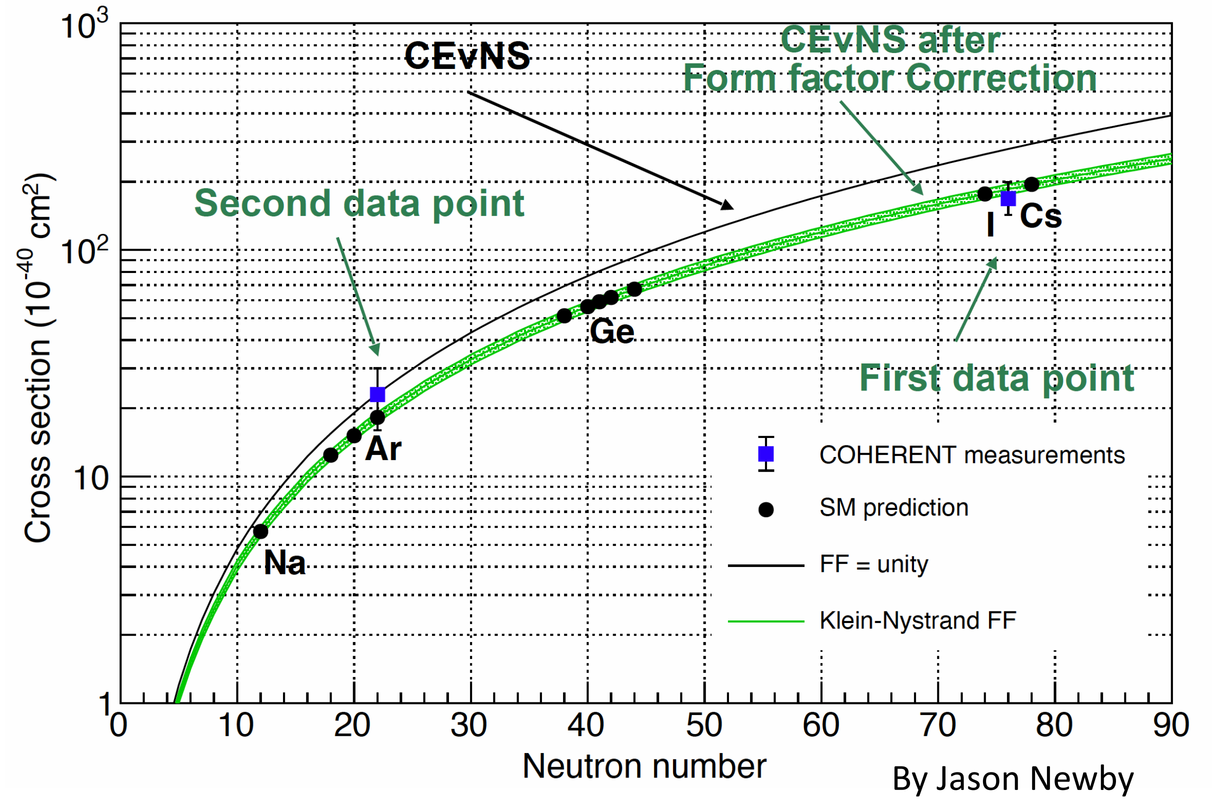


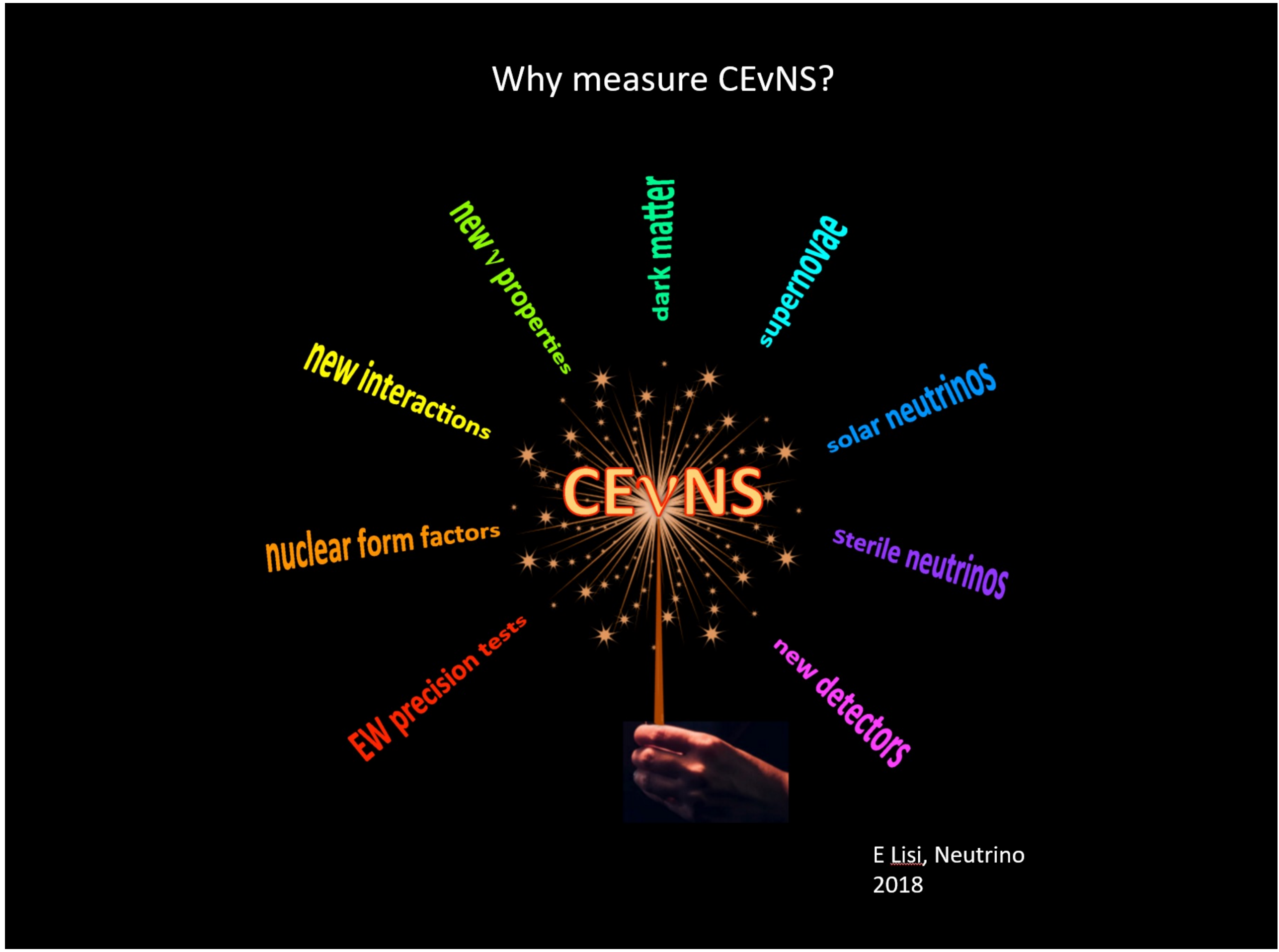
By Kate Scholberg

Low recoil energy → difficult to detect

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

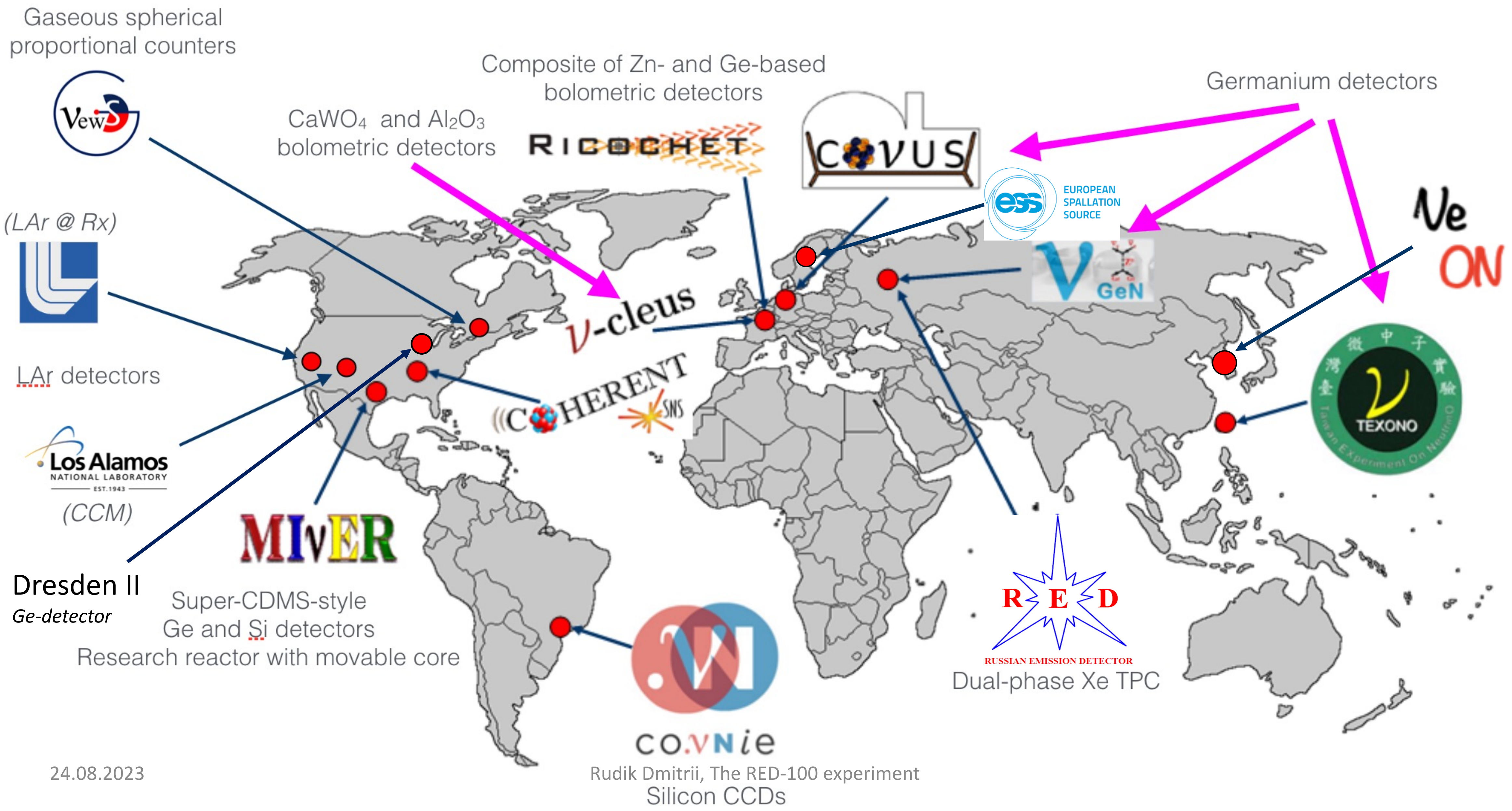
First observations by COHERENT in 2017 and 2021





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

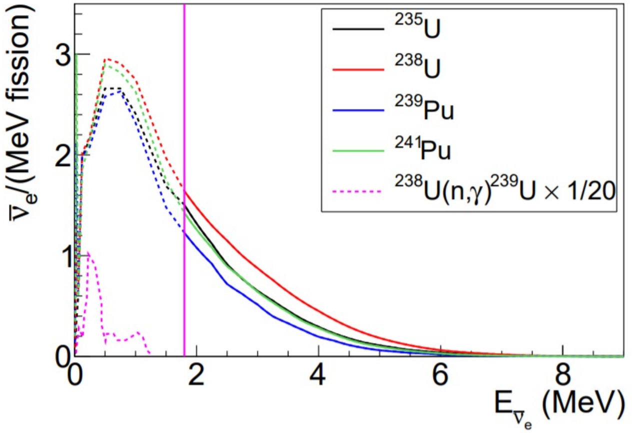
CEvNS around the World

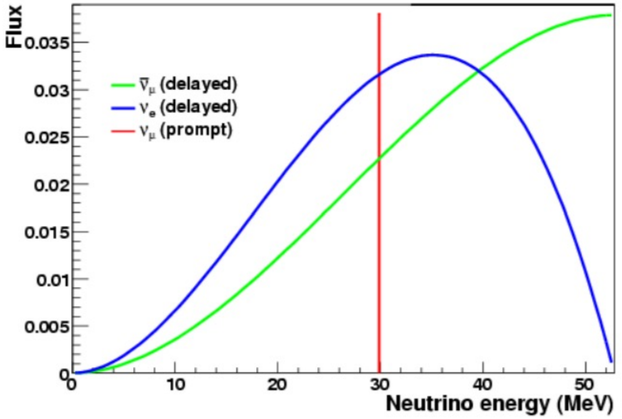


Neutrino sources for CEvNS study

- Reactors
  - Very high flux: $\sim 10^{20}\bar{\nu}_e$ /s
  - Lower recoil energy
  - Reactor off data for the background constraint
- Pion decay-at-rest at accelerators
  - High flux: $\sim 10^{14}\ \nu_\mu/\nu_e/\bar{\nu}_\mu$ / s
  - Higher recoil energy
  - Pulsed beam

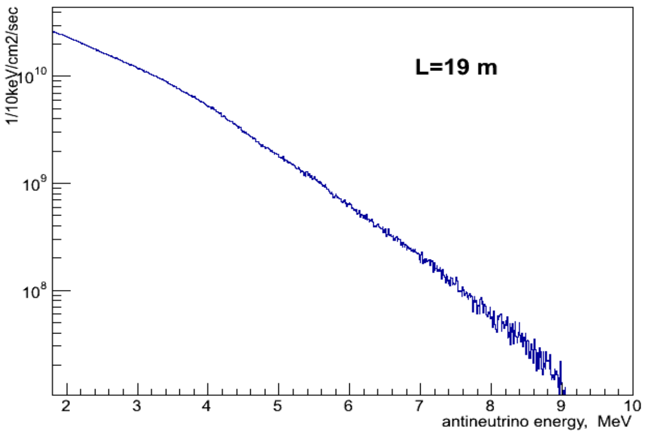
Rept. Phys. Prog. 82 3, 036201 (2019)



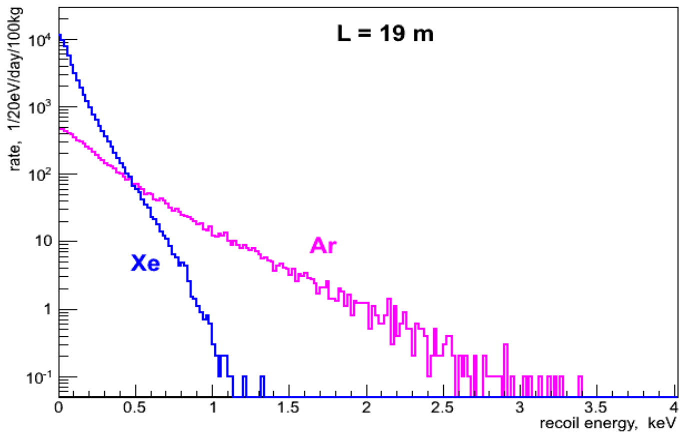


- Reactors antineutrinos produce nuclear recoils with very low recoil spectra

$\widetilde{\nu_e}$ energy spectrum from nuclear reactor

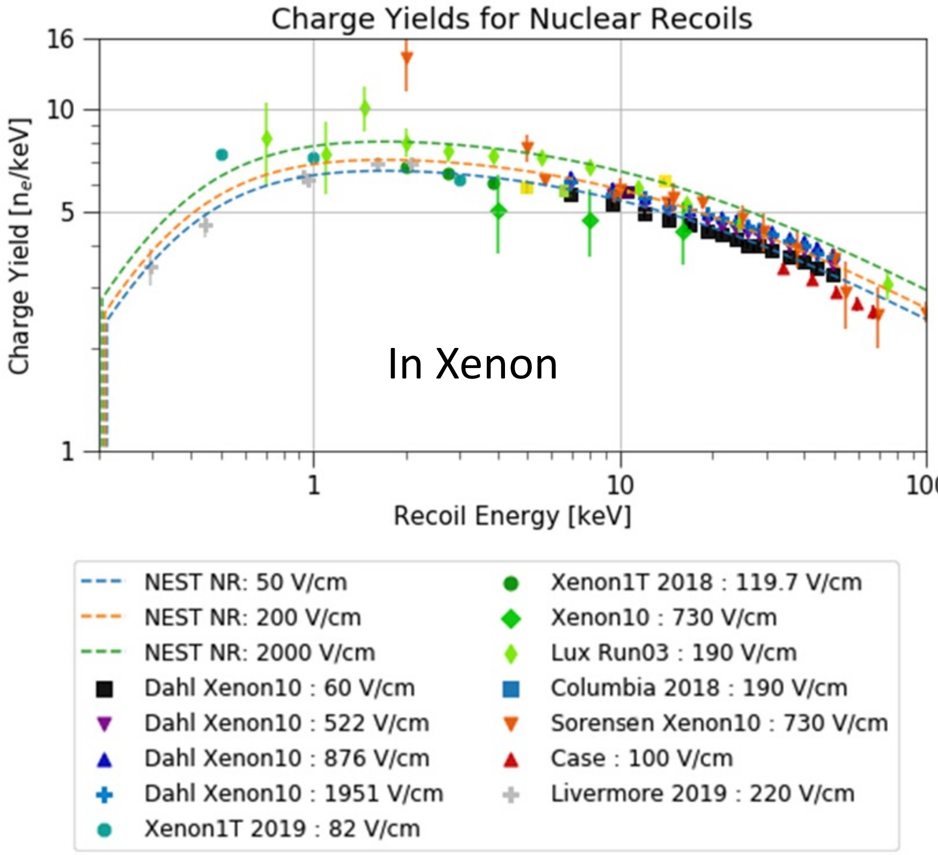


Xe and Ar nuclear recoil spectra



Ionization yield for sub-keV nuclear recoils

- Several ionization electrons in the region of interest
- The detector must be able to detect a signal of a Single Electron (SE)

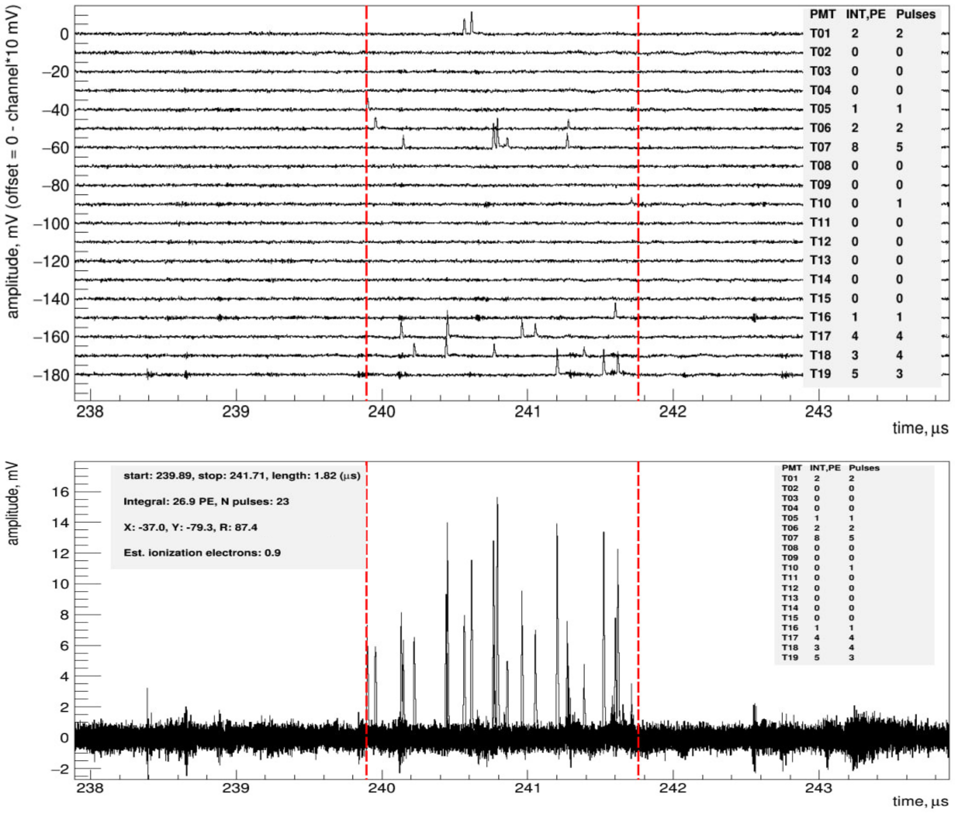


By NEST collaboration

Two-phase emission detector technique

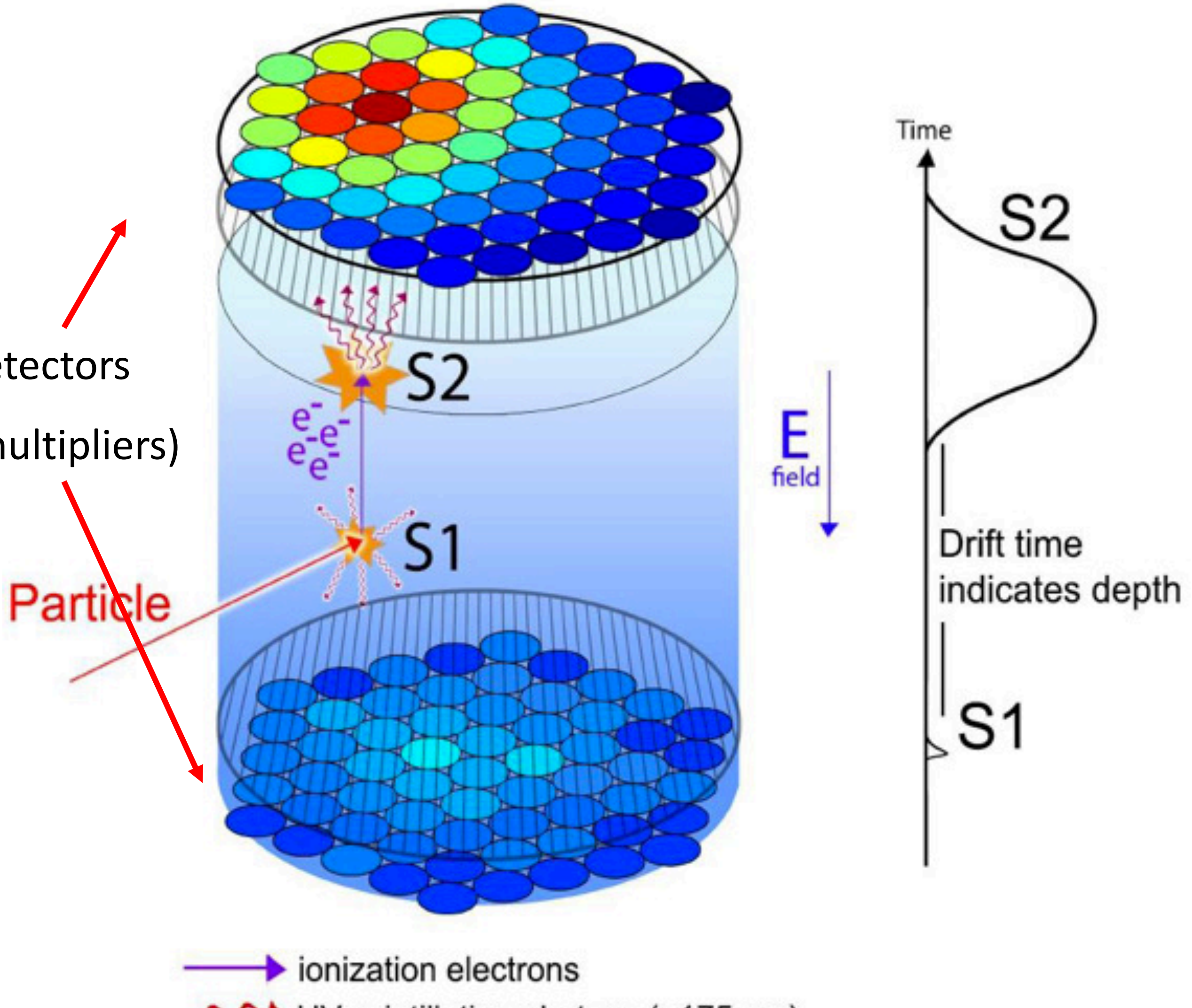
Sensitive to the single ionization electron (SE) signal. CEvNS response is expected to be of several electrons.

Typical single electron (SE) signal in RED-100



Photodetectors

(photomultipliers)



By LUX Collaboration

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

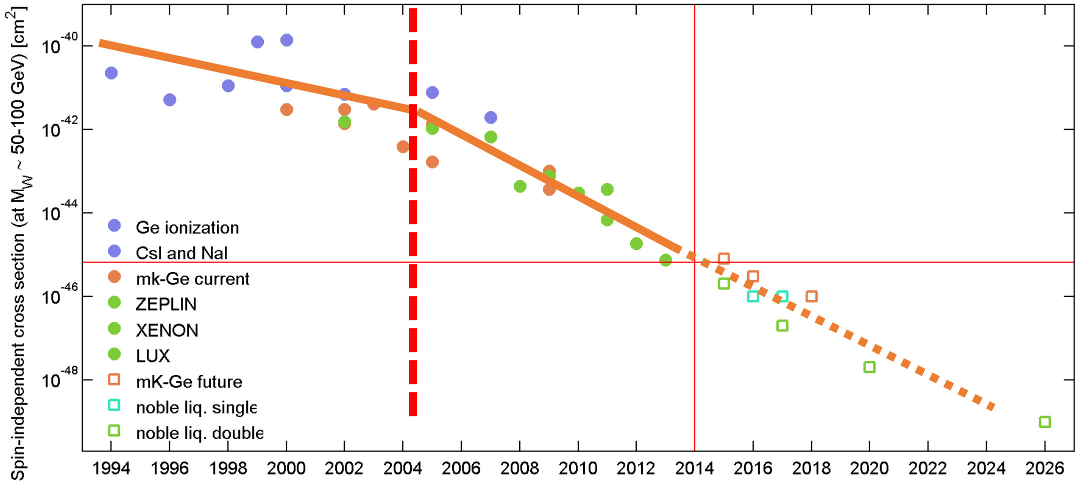
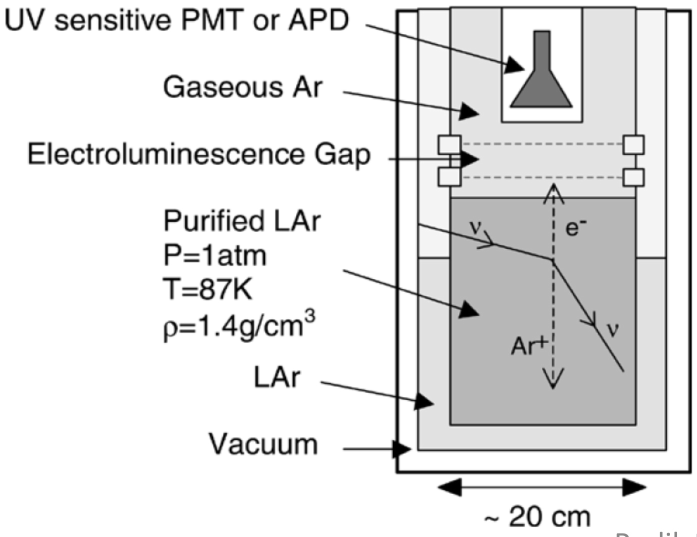


Fig. from L. Baudis 2014

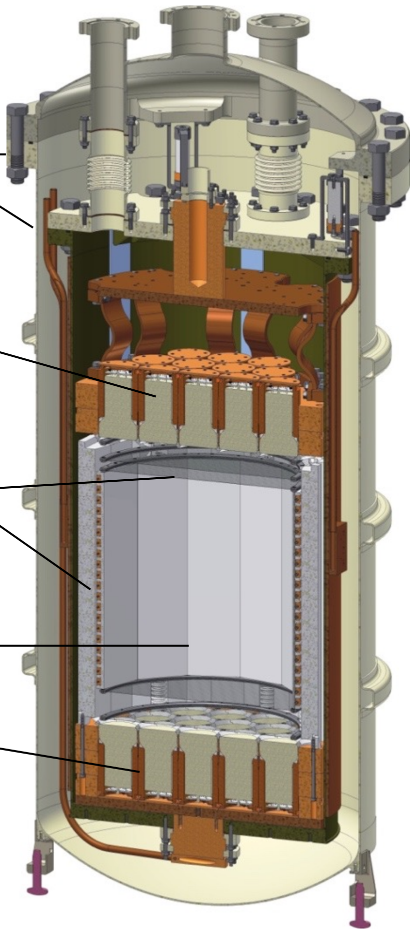
1st proposal (in 2004); LAr detector

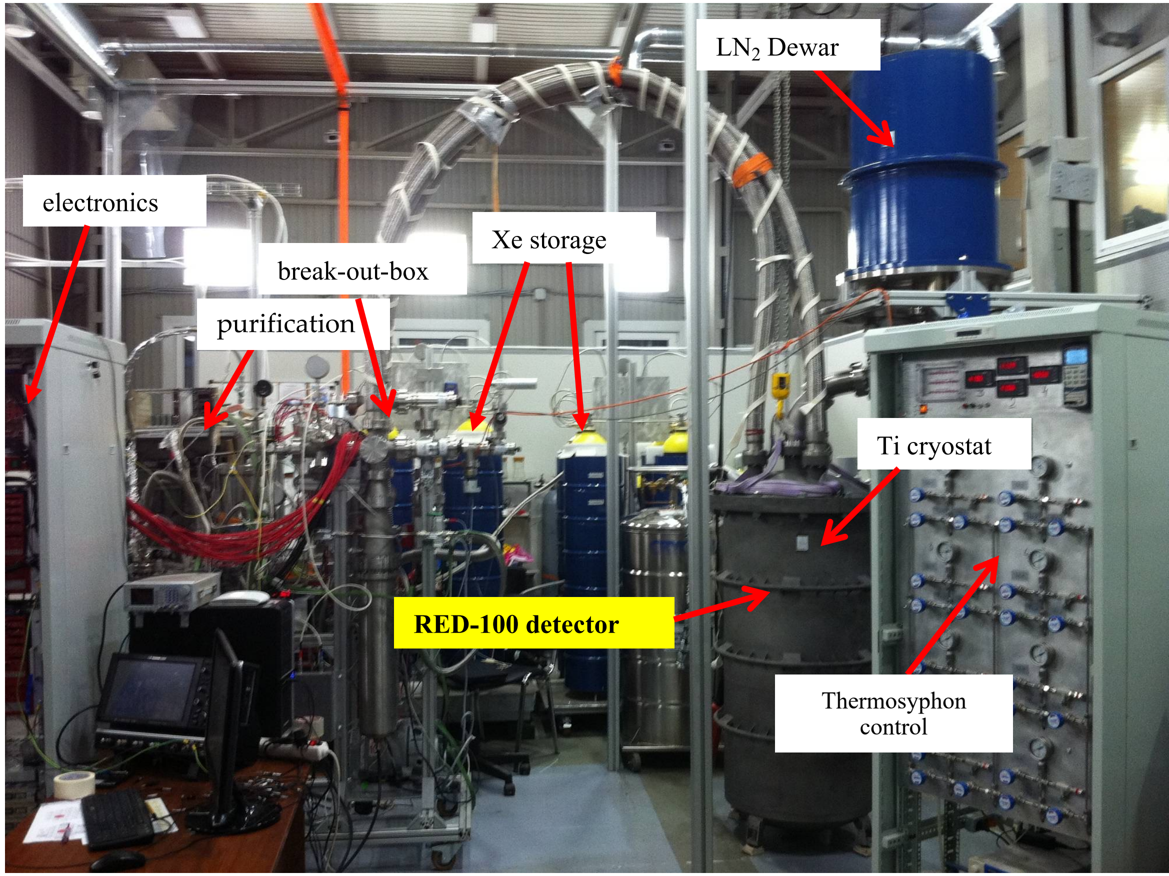


C. Hagmann and A. Bernstein,
Two-Phase Emission Detector for Measuring Coherent Neutrino-Nucleus Scattering
IEEE Trans.Nucl.Sci. 51 (2004) 2151

RED-100

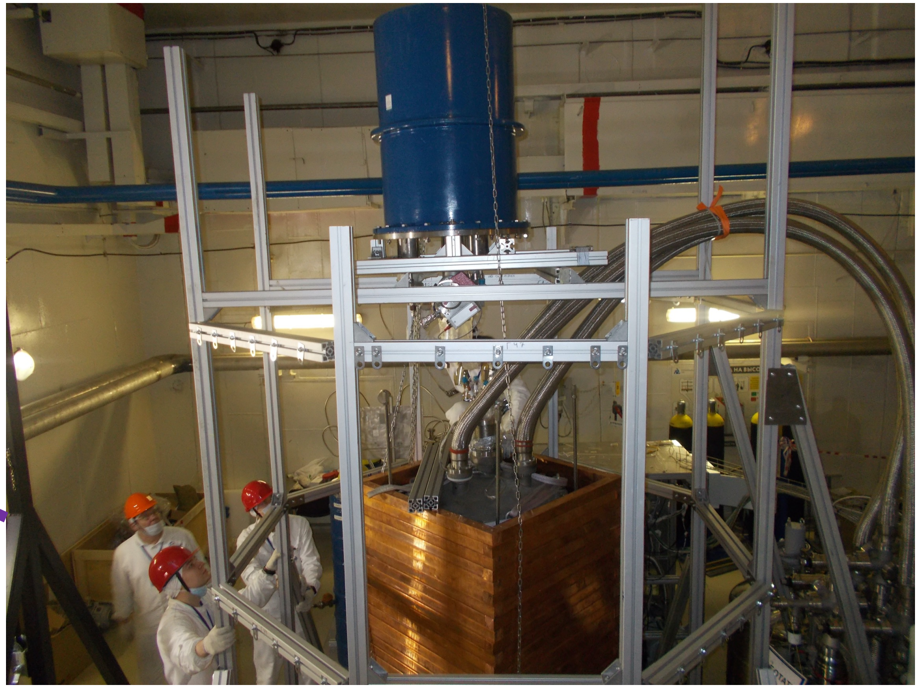
- Two-phase noble gas emission detector
- Contains ~200 kg of LXe (~ 100 kg in FV)
- 26 PMTs Hamamatsu R11410-20 (19 in top PMT array, 7 in bottom PMT array)
- Thermosyphon-based cooling system (LN_2)





RED-100 at KNPP

KNPP – Kalinin Nuclear Power Plant



2020 RED-100 was shipped to KNPP

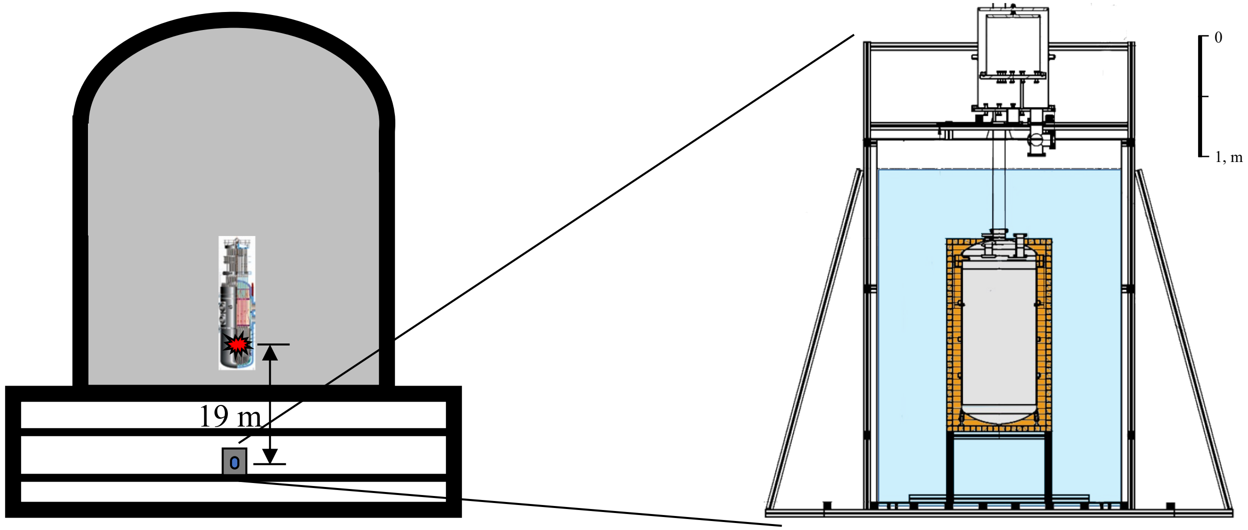
2021 Deployed and tested

2022 (Jan-Feb) Physical run

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

RED-100 at KNPP

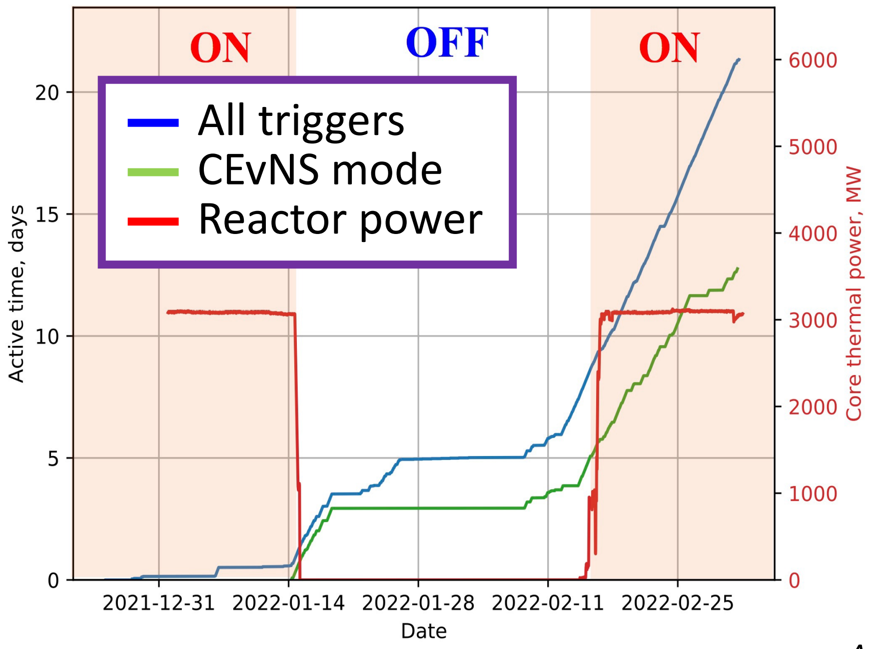
- 19 m from the reactor core of 3000 MW thermal power unit 4
- Antineutrino flux at place ~ $1.35*10^{13}$ $cm^{-2}s^{-1}$
- ~ 65 m.w.e. in vertical direction
- Passive shielding:
  - 5 cm Cu
  - ~ 60 cm H_2O

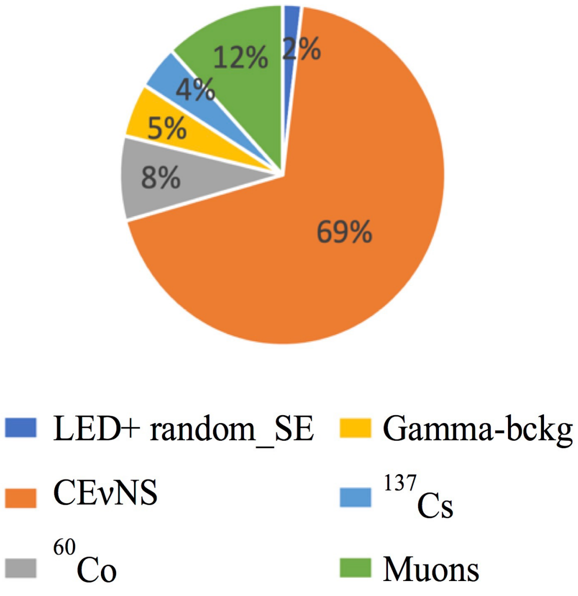


Data collection and analysis

- Blind analysis strategy
- Reactor ON data is closed until all the data analysis methods are ready
- Analysis is based on Reactor OFF data and calibration data

Data collection @ KNPP



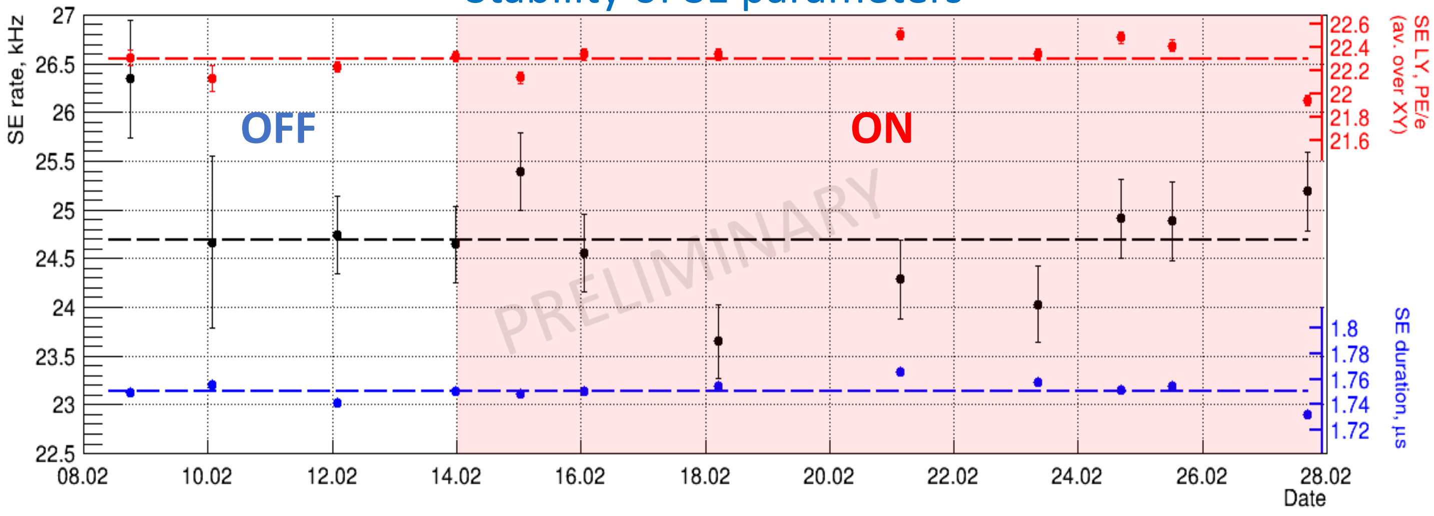


Akimov D. Y., et al. JINST 17.11 (2022), T11011

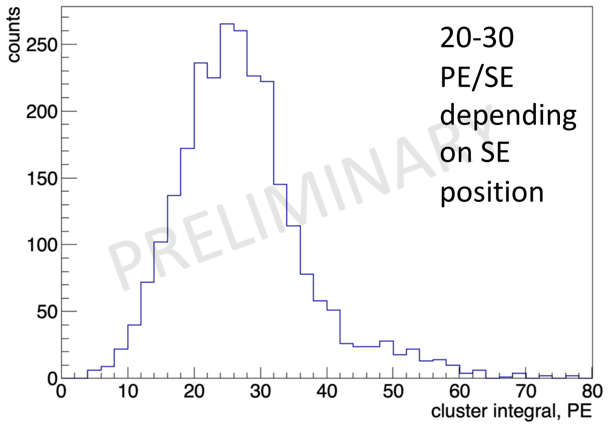
Stability checks

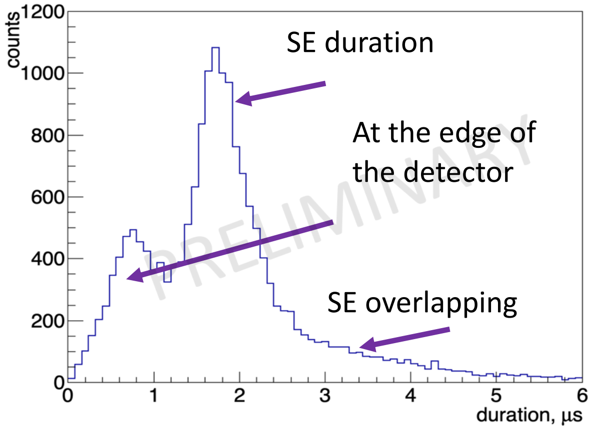
- SE count rate
- Light yield (LY) response
- SE duration
- Background rates
- Other parameters

Stability of SE parameters



LY & duration of SE

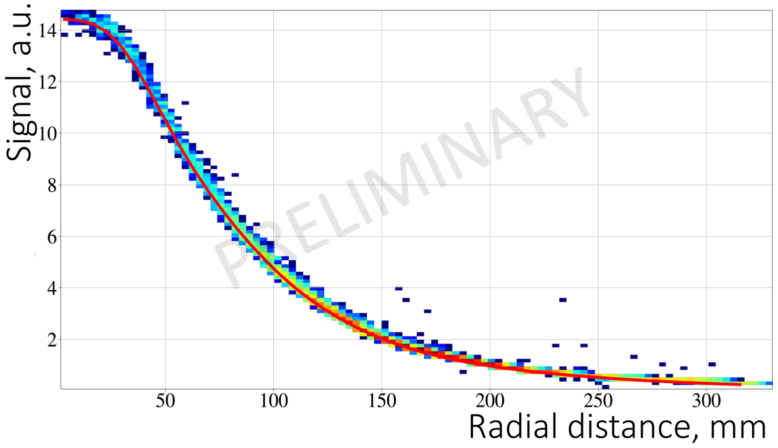




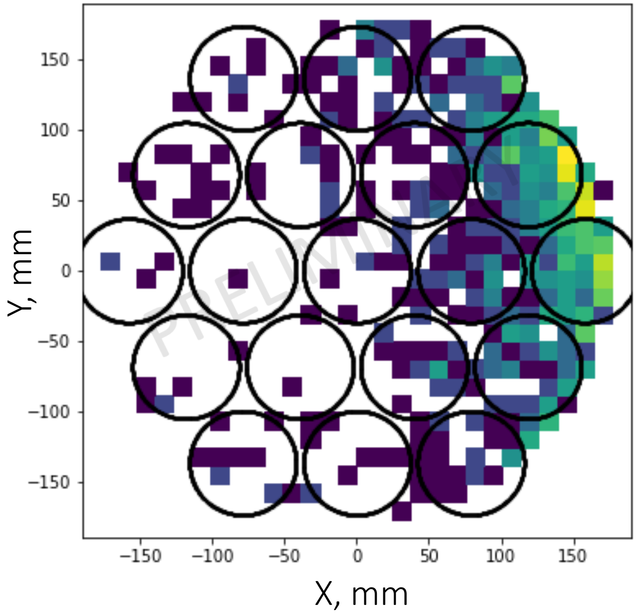
Gamma calibrations

- Gamma calibrations each week
- LY stability check
- Light response functions (LRF)
  - Simultaneous reconstruction of position and energy of the event
  - See the talk of Olga Razuvaeva
- Electron extraction efficiency

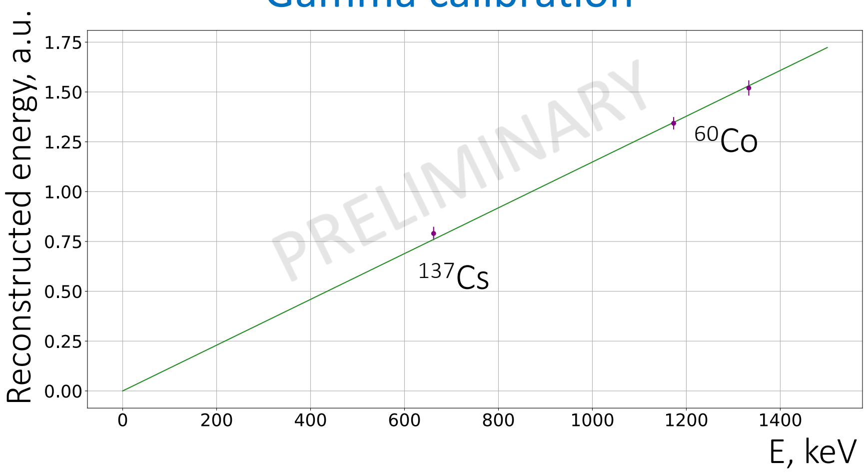
LRF example



Position reconstruction for ^{60}Co



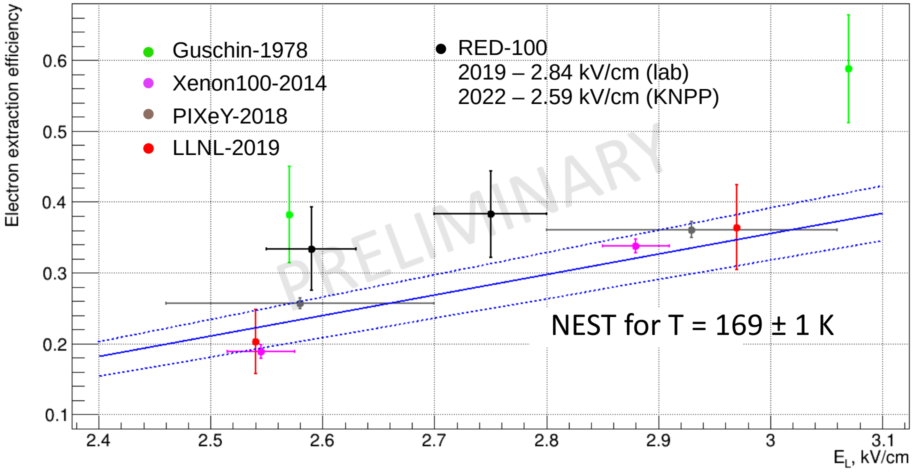
Gamma calibration



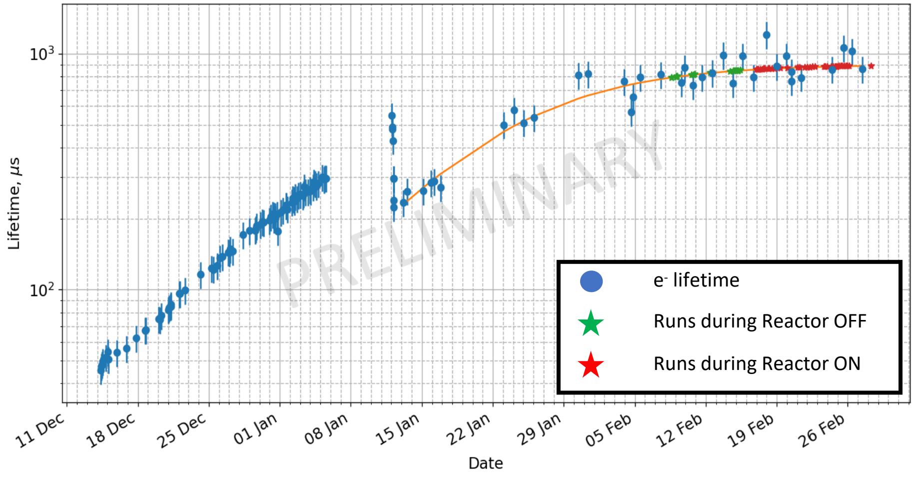
Electrons extraction parameters

- The most significant influence on RED-100 response
- e^- extraction efficiency (absolute measurements based on NEST predicted charge yield)
- e^- lifetime before capture on electronegative impurities
  - compare with total drift time of ~265 μs
- Resulted in reduction of expected CEvNS spectrum to the lower number of electrons in the events
- We are expecting around 1 CEvNS event per day in the region of 5-6 electrons per event

Electron extraction efficiency



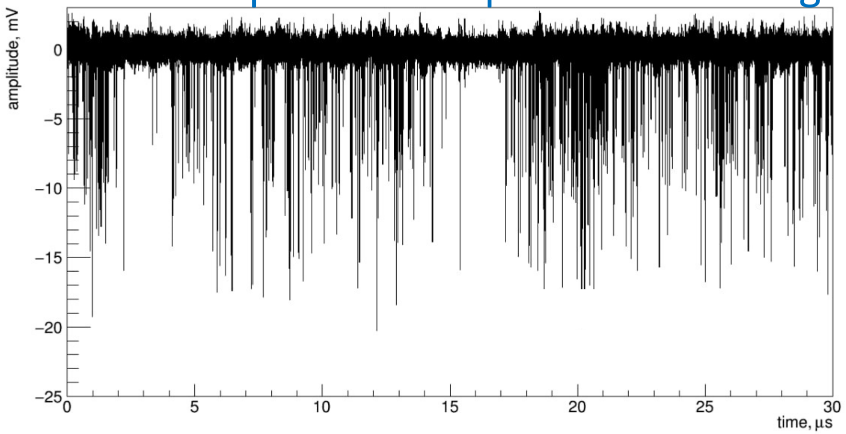
Electron lifetime



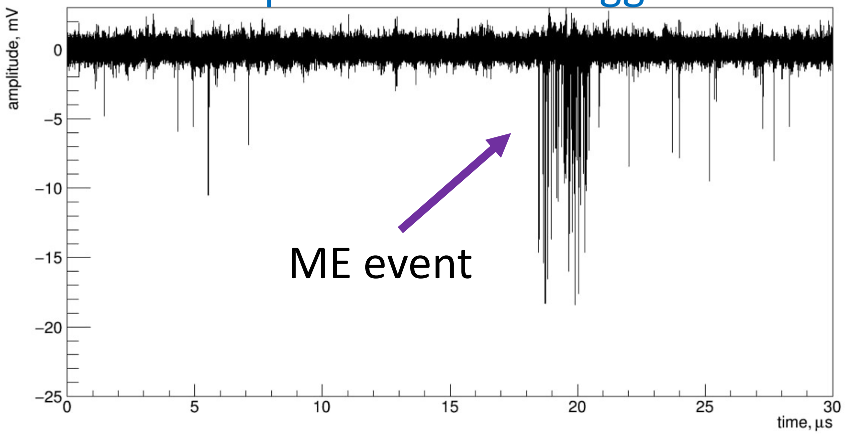
“Smart” trigger

- Huge SE background
- To reduce this background a “smart” trigger was introduced
  - >2 SE within 2 μs (60 PE)
  - <50 PE in pretrace of 50 μs before trigger
- Only 30 μs windows with signals in S2-only mode are recorded
- Order of magnitude benefit for live time

Wf example without pretrace blocking

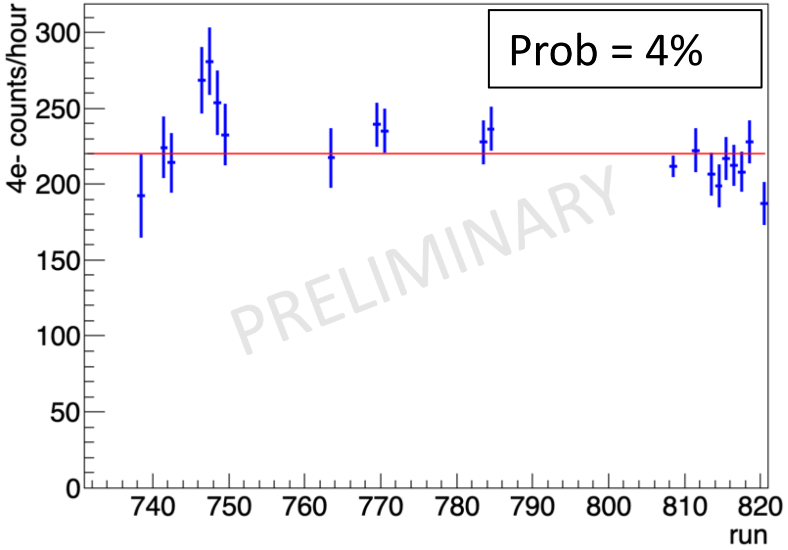


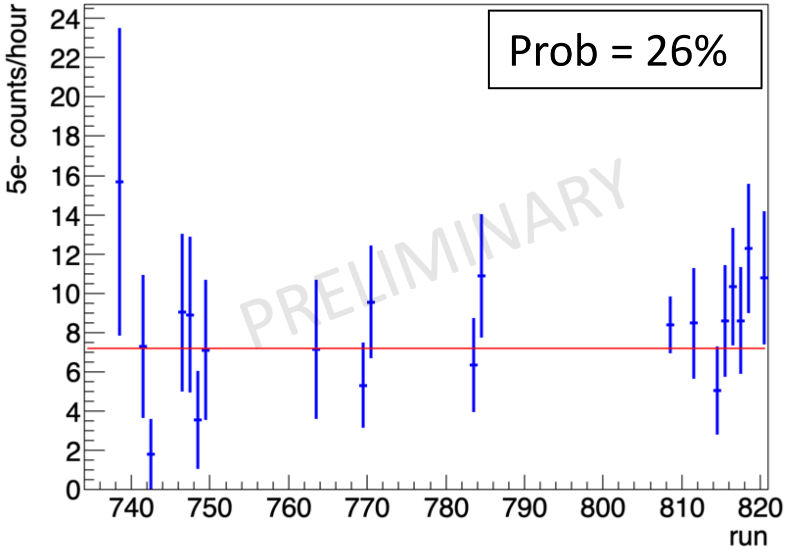
Wf example with smart trigger in use

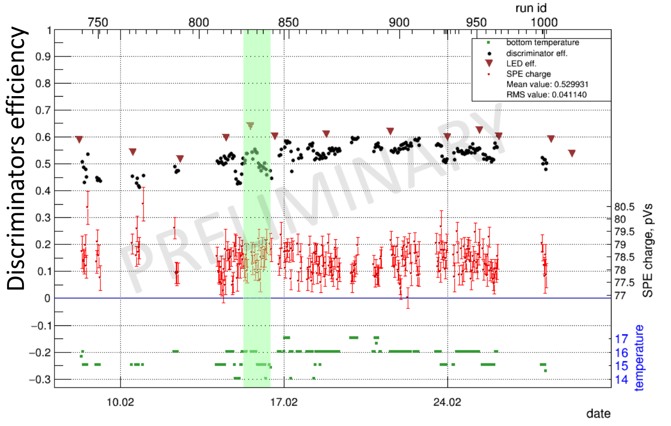


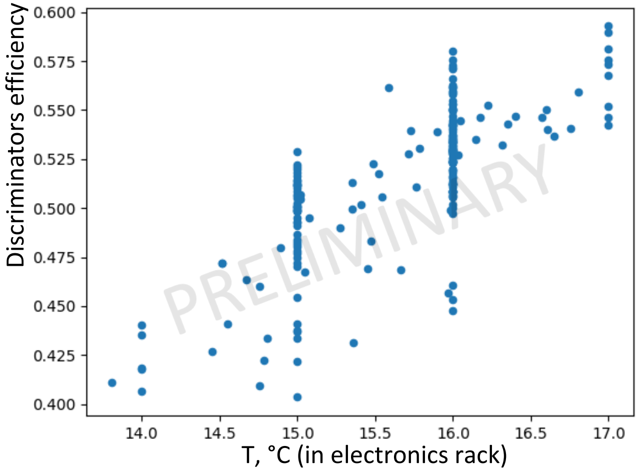
Background stability in ROI (Reactor OFF data)

- 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
- What are the sources of possible background variations with Reactor operation?



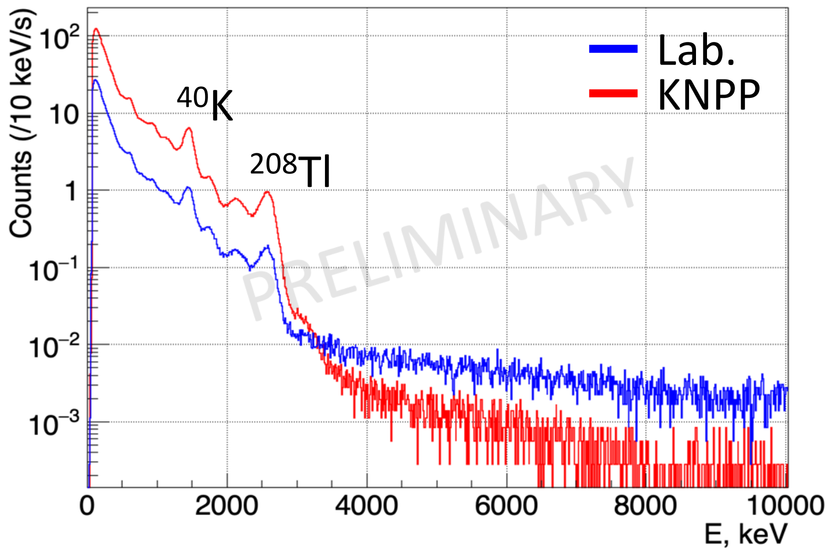


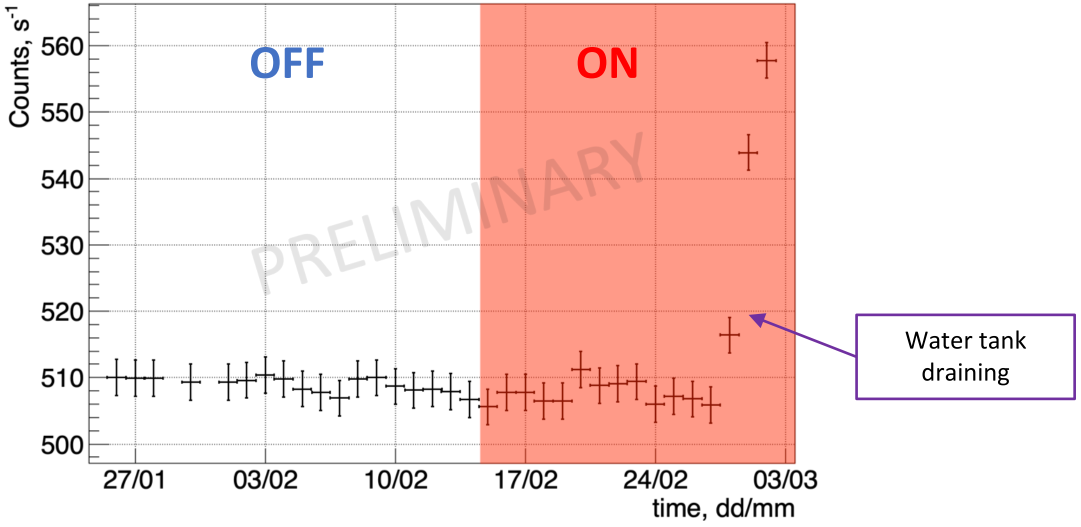




External background: gammas

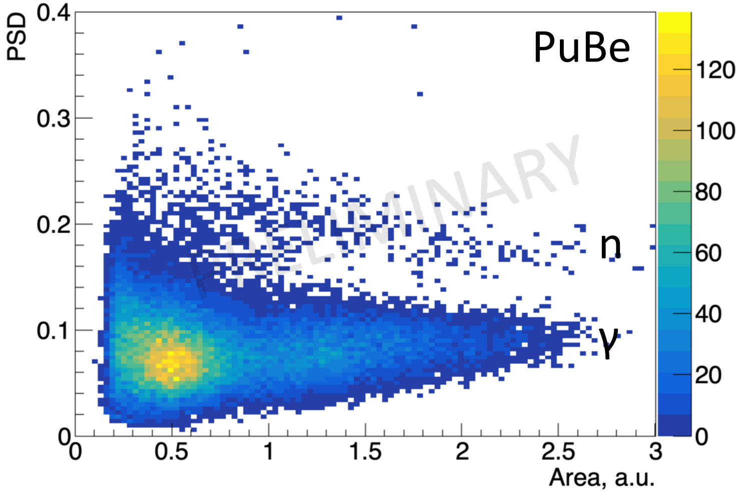
- NaI[Tl] detector
- Count rate is in ~5 times larger than in laboratory due to thick concrete around
- Mainly the same spectrum structure
- No dependence on Reactor operation periods
- Diurnal ^{222}Rn variations in water shielding are bellow (3.2 ± 0.3) Bq/L at 95% C.L.

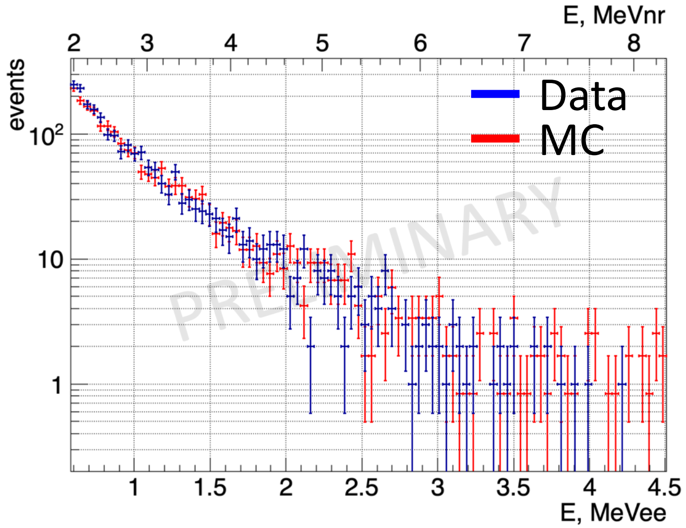


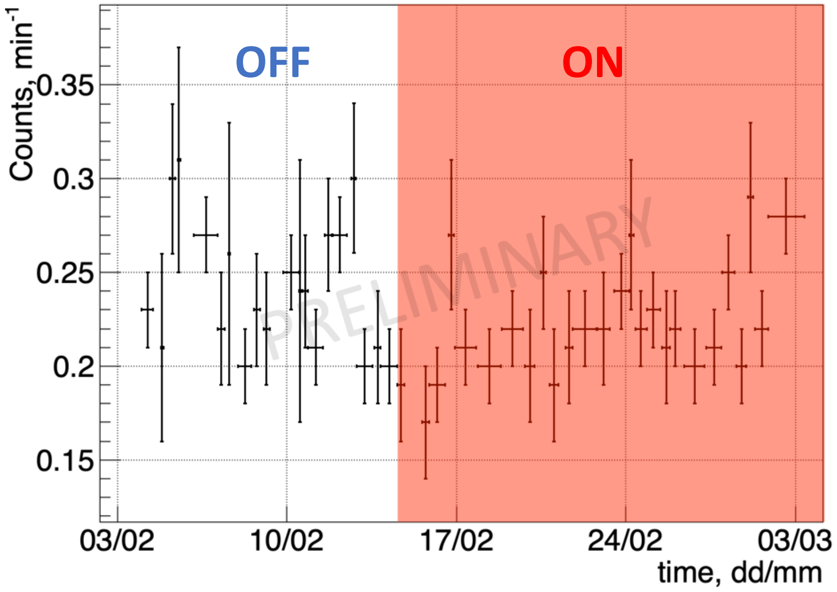


External background: neutrons

- Bicron LS (BC501A) detector
- Pulse shape discrimination
- Spectrum was unfolded
- Neutrons flux upper limit $(24.1 \pm 1.2)*10^{-5}$ N/cm²/s
- No dependence on Reactor operation periods

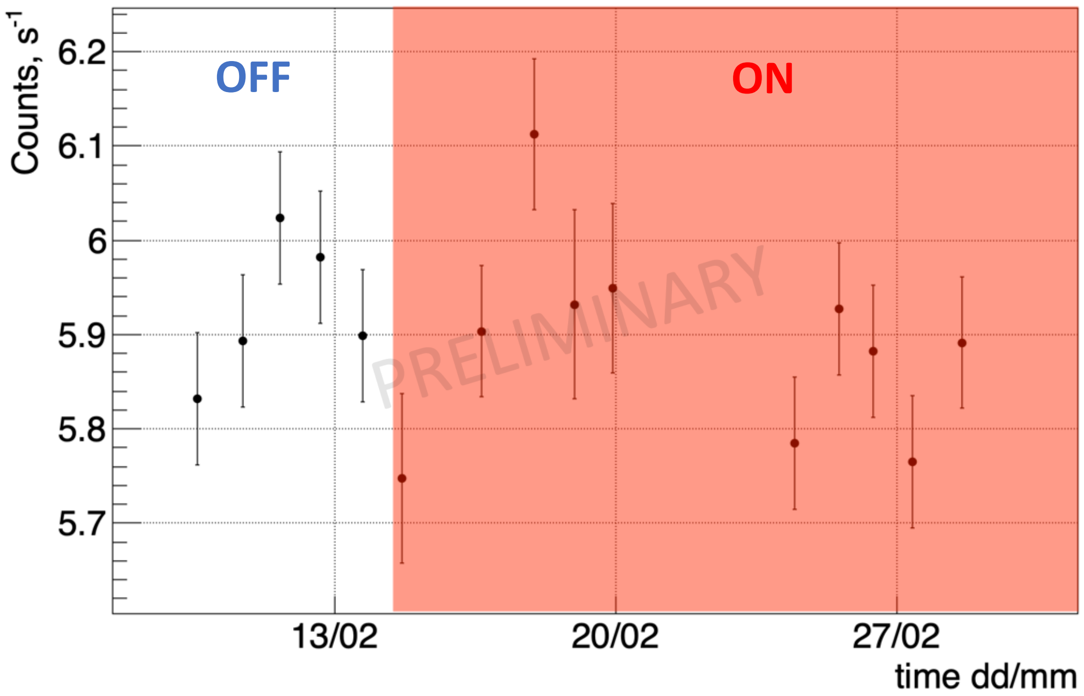






External background: muons

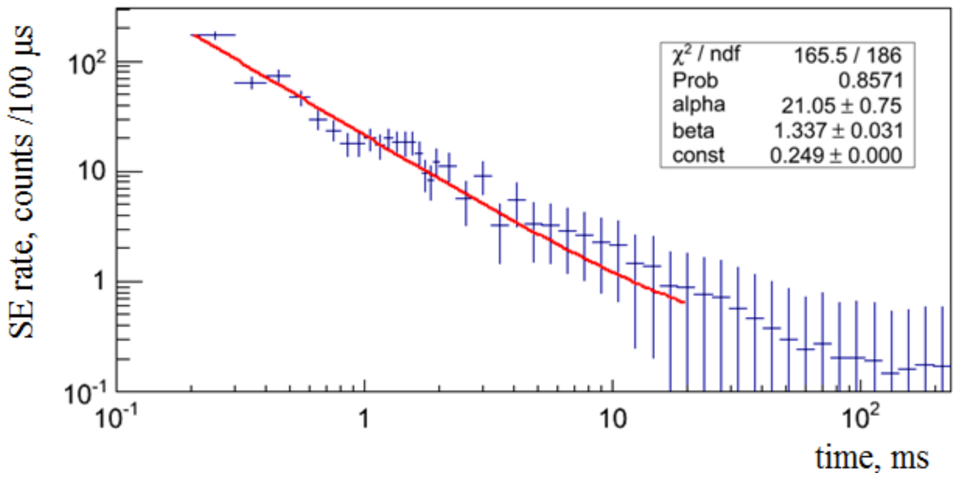
- Muons background was measured with RED-100 itself
- No dependence on Reactor operation periods
- Count rate is reduced in 7-8 times in comparison with the Lab test
- But muons provide a huge energy deposition in the detector



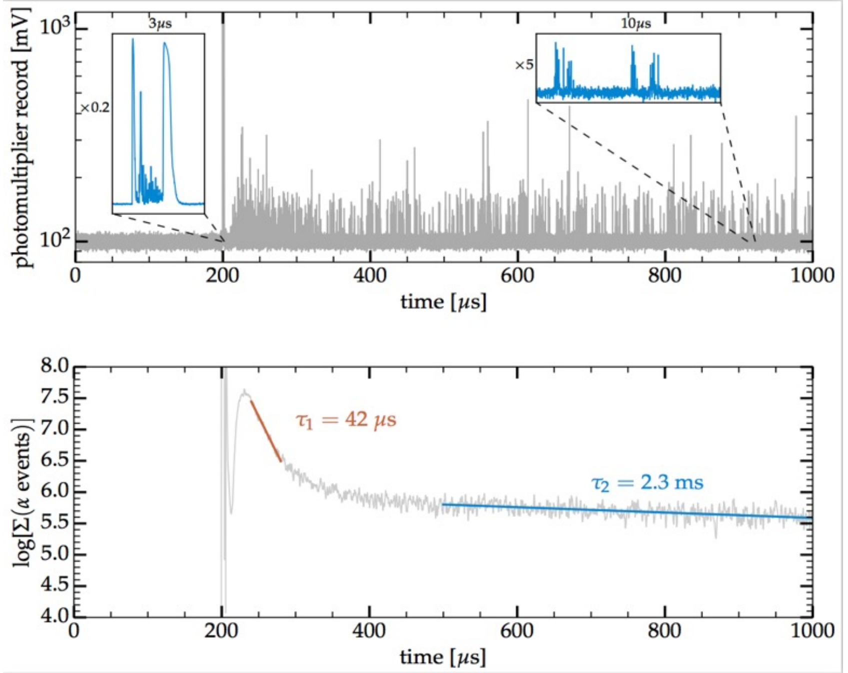
Muons as a source of the SE background

- SE rate increasing after big energy deposition in liquid noble gas detector
- It was observed by several groups
- Very long component of several milliseconds

JINST 11 (2016) no.03, C03007



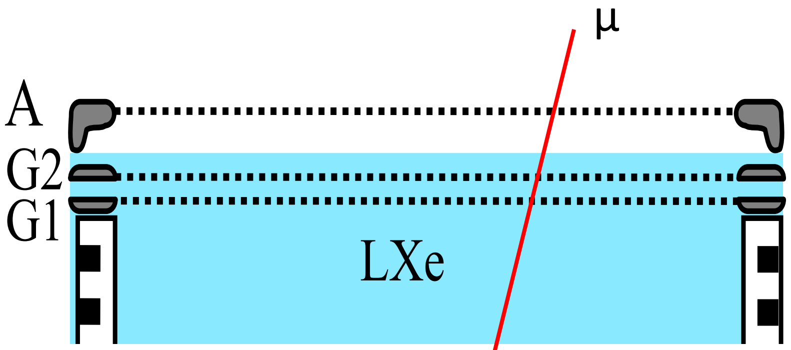
P. Sorensen, K. Kamdin
JINST 13 (2018) no.02, P02032

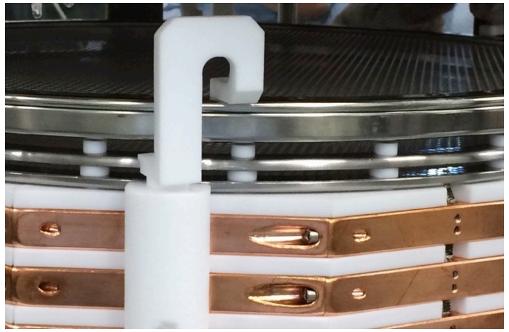


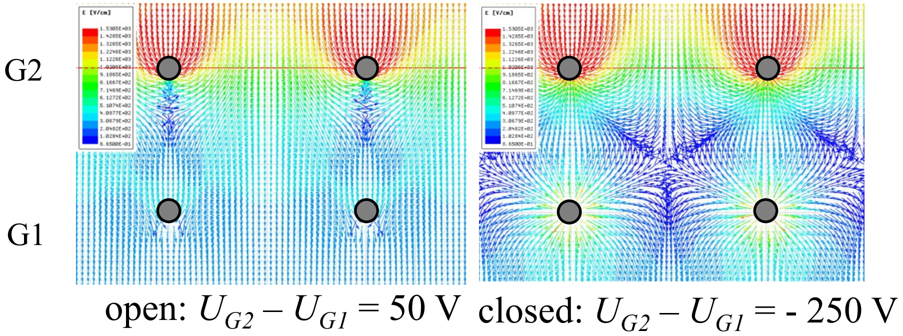
Also, observed in ZEPLIN-III: **JHEP 1112 (2011) 115, arXiv:1110.3056 [physics.ins-det]**

Electron shutter

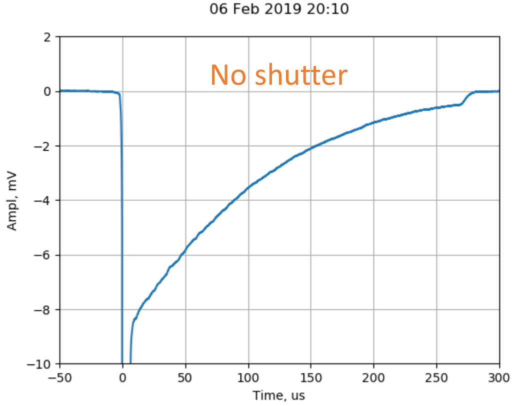
- To block signals induced by muons
- To minimize short component of SE background
- Still very high SE rate (250 kHz in the lab. test)
- Reduction by a factor of ~7-8 at KNPP

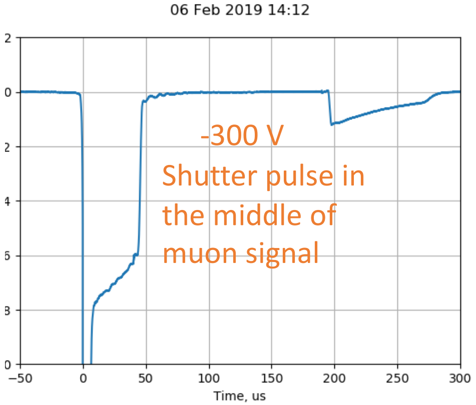






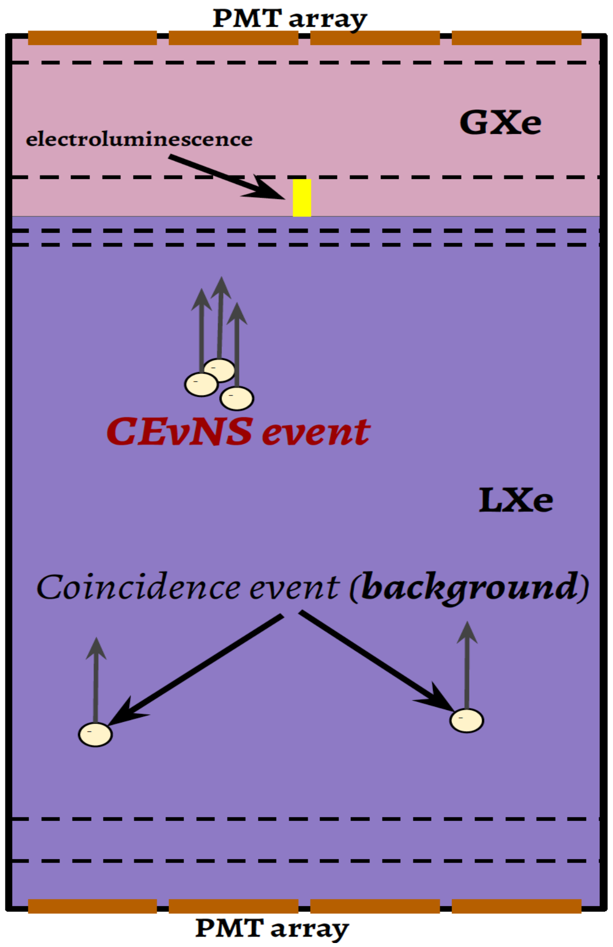
[D.Yu. Akimov et al., Two-phase emission low-background detector (in Russian), Utility model patent RU 184222 U1, 2018]

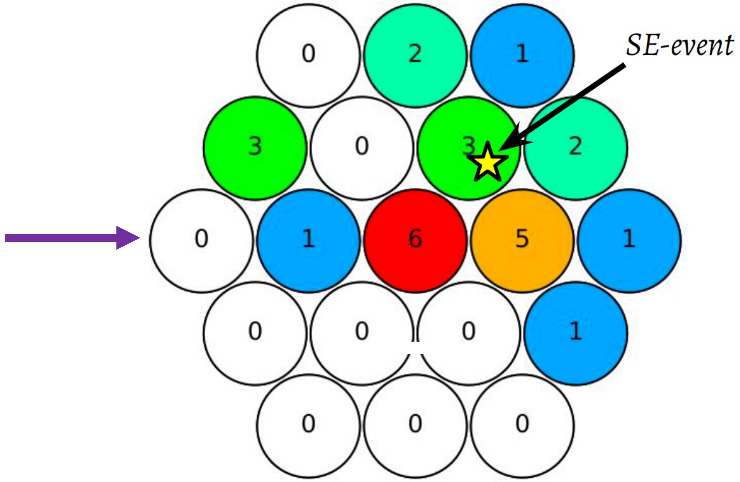




Main background in the ROI

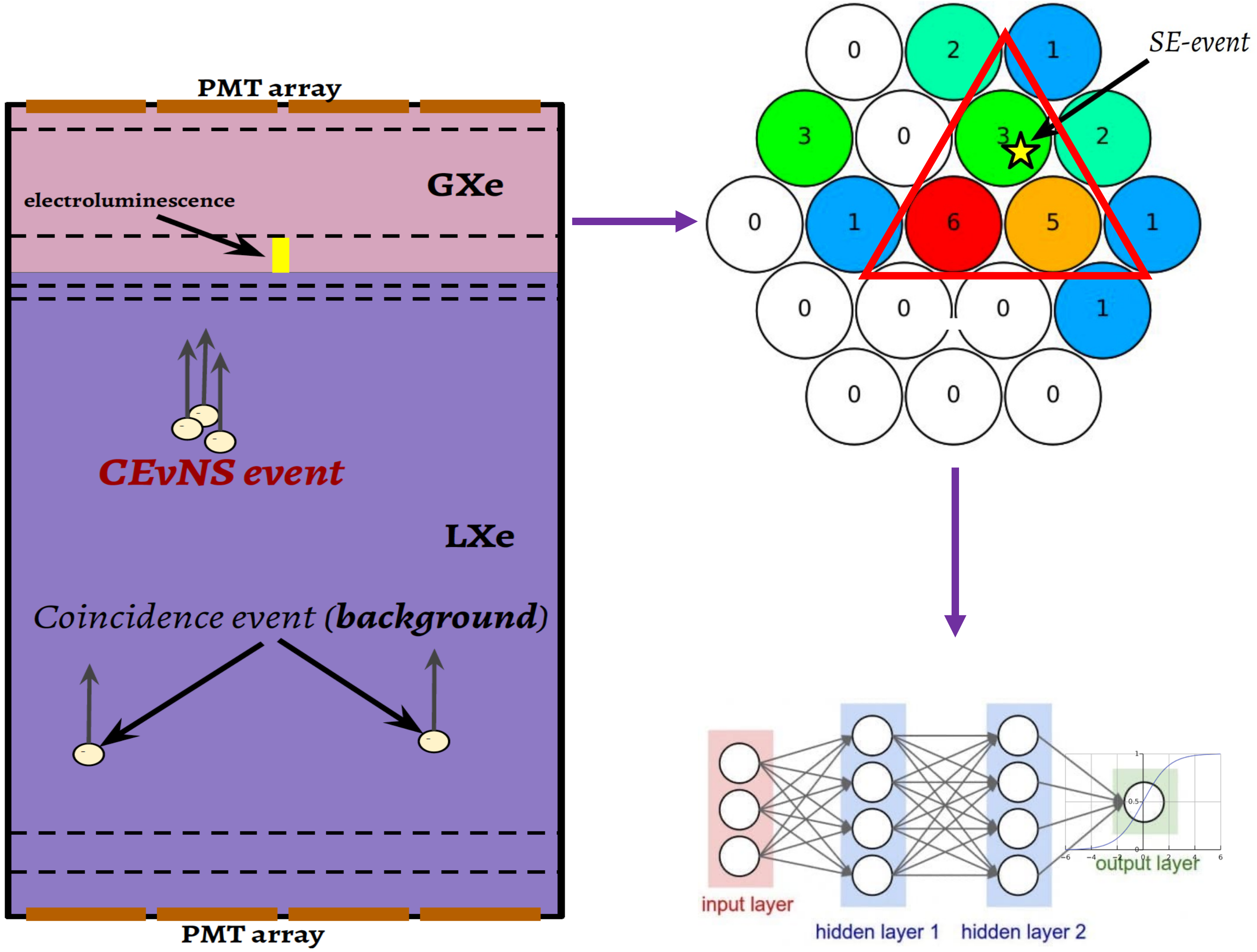
- Main background → accidental coincidence of several spontaneous electrons
  - CEvNS events are **point-like** events
  - Background is mostly **NOT point-like**
- Light distribution across PMT array should by different





Neural Networks for background rejection

- First idea of cut: the relation between amount of light collected by leading 3 neighboring PMTs to the total amount of light in event
- Classical ML approaches were tested with further improvement of the discrimination power
- Finally, deep learning techniques to mitigate this kind of background
- See the talk of Olga Razuvaeva



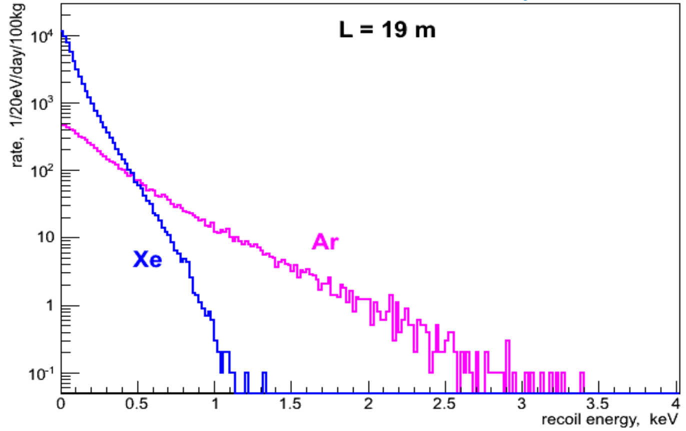
Current status and plans

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

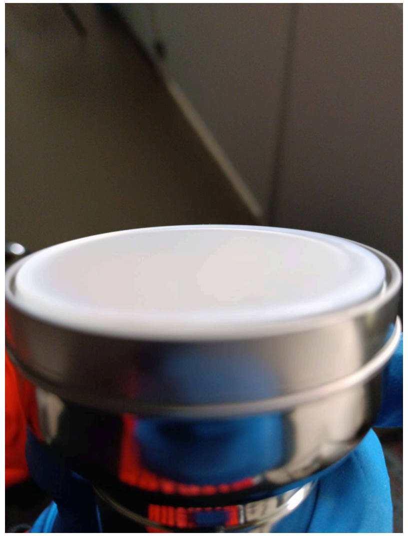
Future of the RED-100

- 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

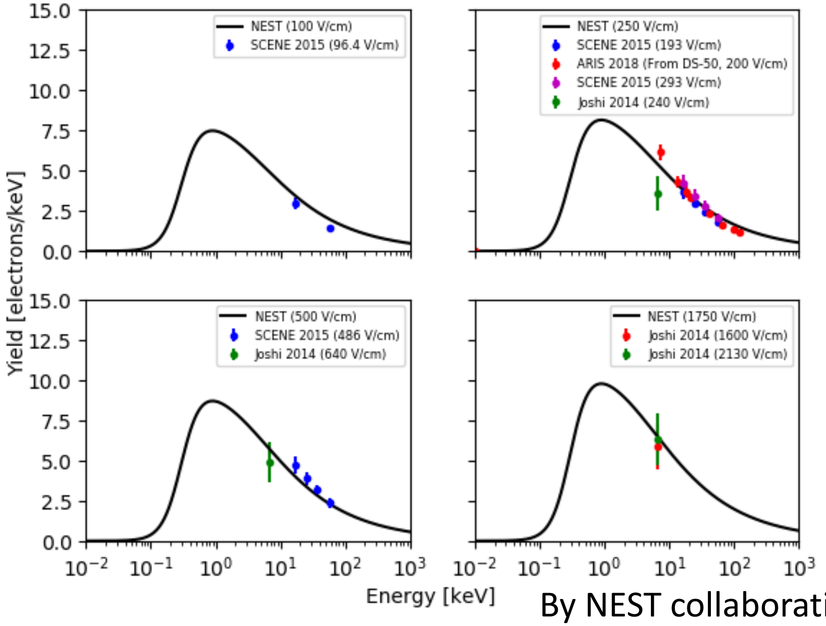
Xe and Ar nuclear recoil spectra



RED-100 PMT coated with TPB



Charge Yields for Nuclear Recoils in LAr



By NEST collaboration

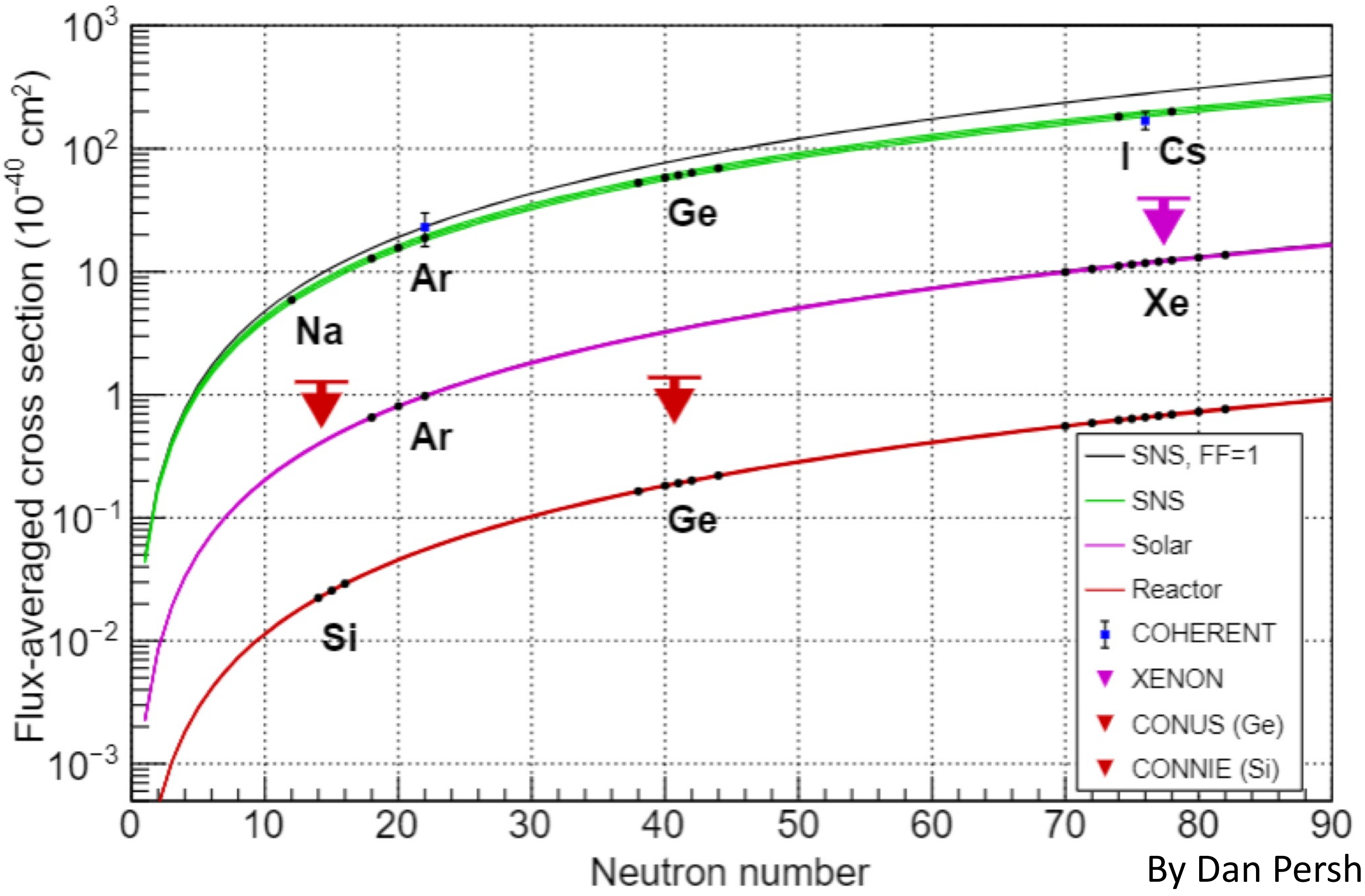
Summary

- RED-100 was successfully deployed and ran at industrial NPP
- Data analysis is in progress
  - ML techniques are used for the specific background rejection
- First results of Reactor ON data analysis are expected soon
- Detector was shipped back, upgrade is ongoing
- RED-100 with LAr first tests in this year

Thank you for your attention!

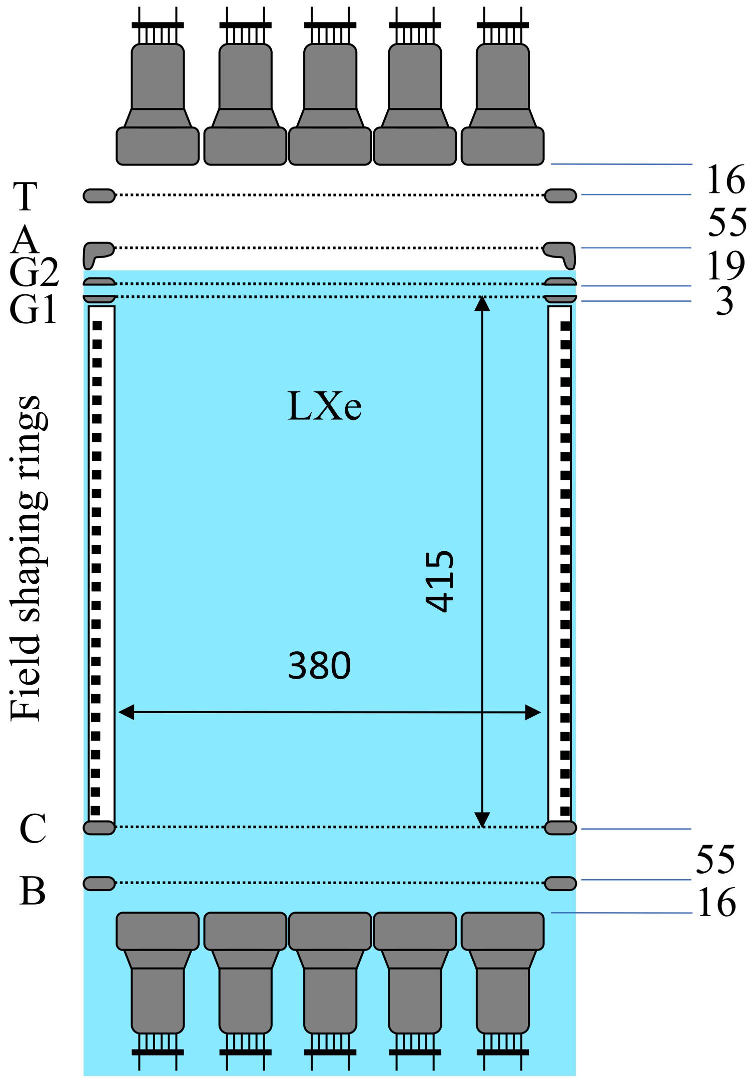
Backup

CEvNS measurements



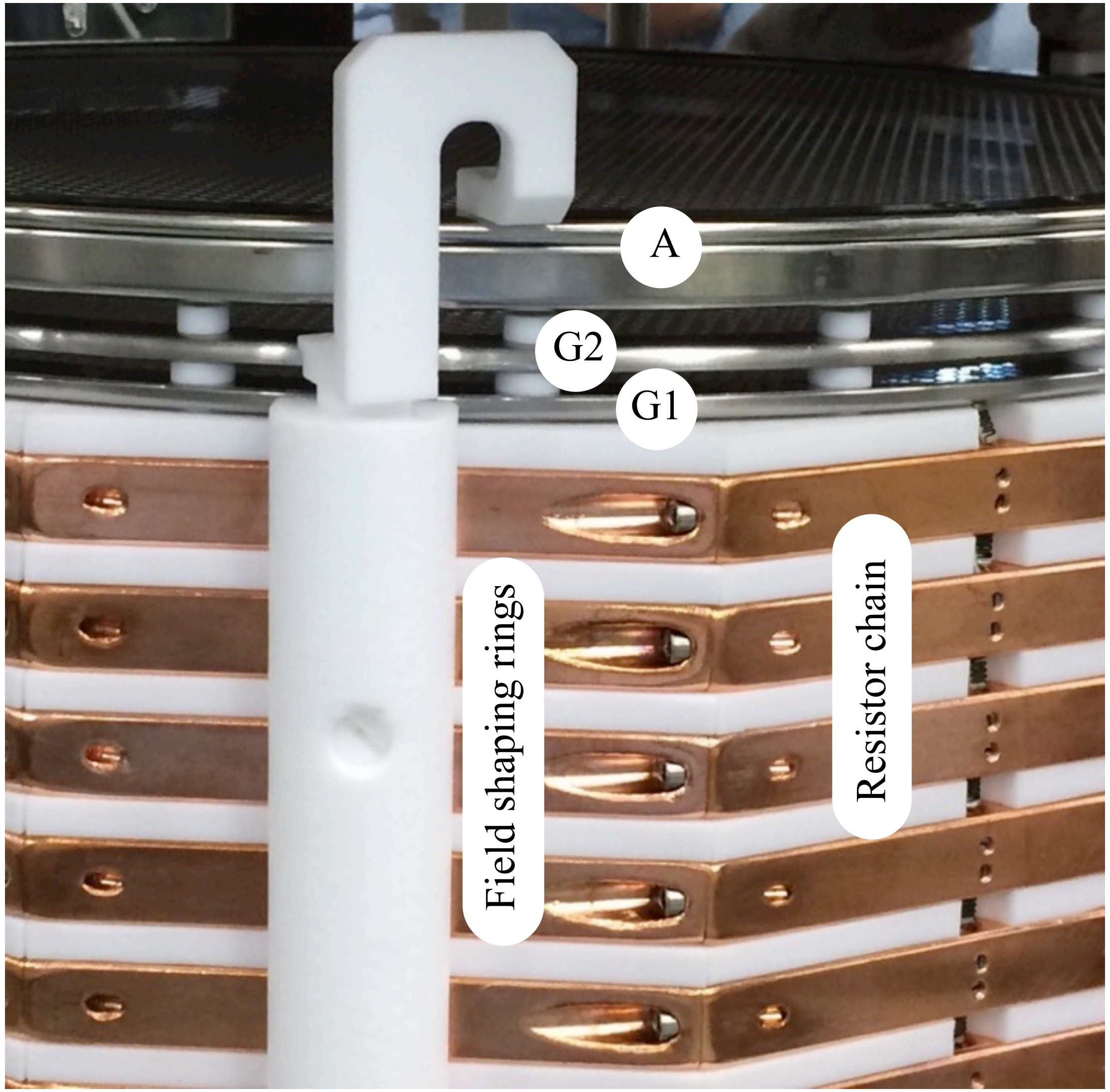
By Dan Pershey

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

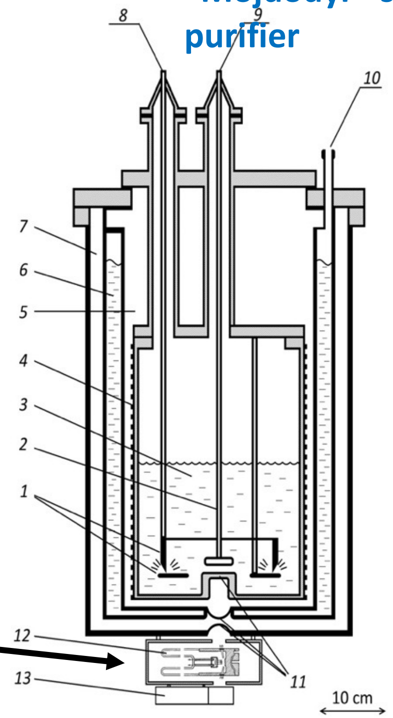


RED-100 performance: LXe purity

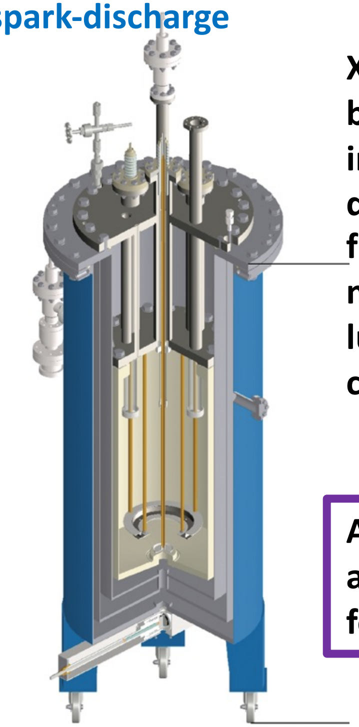
- Electronegative impurities catch the ionization electrons
- Purification in two stages
    - 1st: spark discharge technique with "Mojdodyr"
    - 2nd: continues circulation of Xe through RED-100 and SAES
- Electron lifetime of several milliseconds was achieved

"Mojdodyr" spark-discharge purifier

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



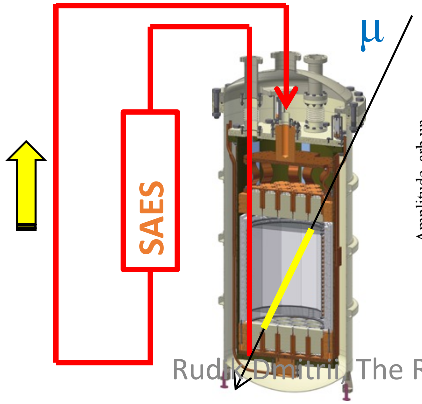
X-ray tube as a source of ionization electrons for e⁻ lifetime measurements

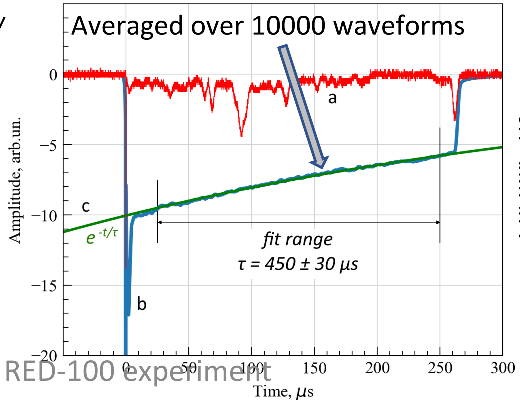


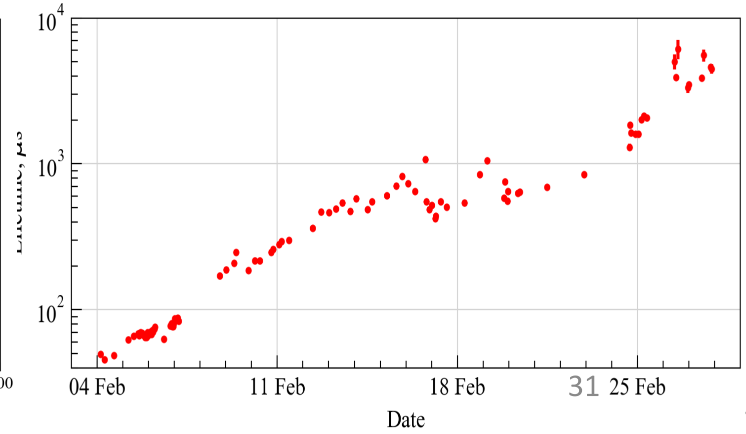
Xenon was contaminated by highly-electronegative impurities presumably due to the use of a special fluorine-containing high-molecular-weight lubricant in gas centrifuges.

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

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

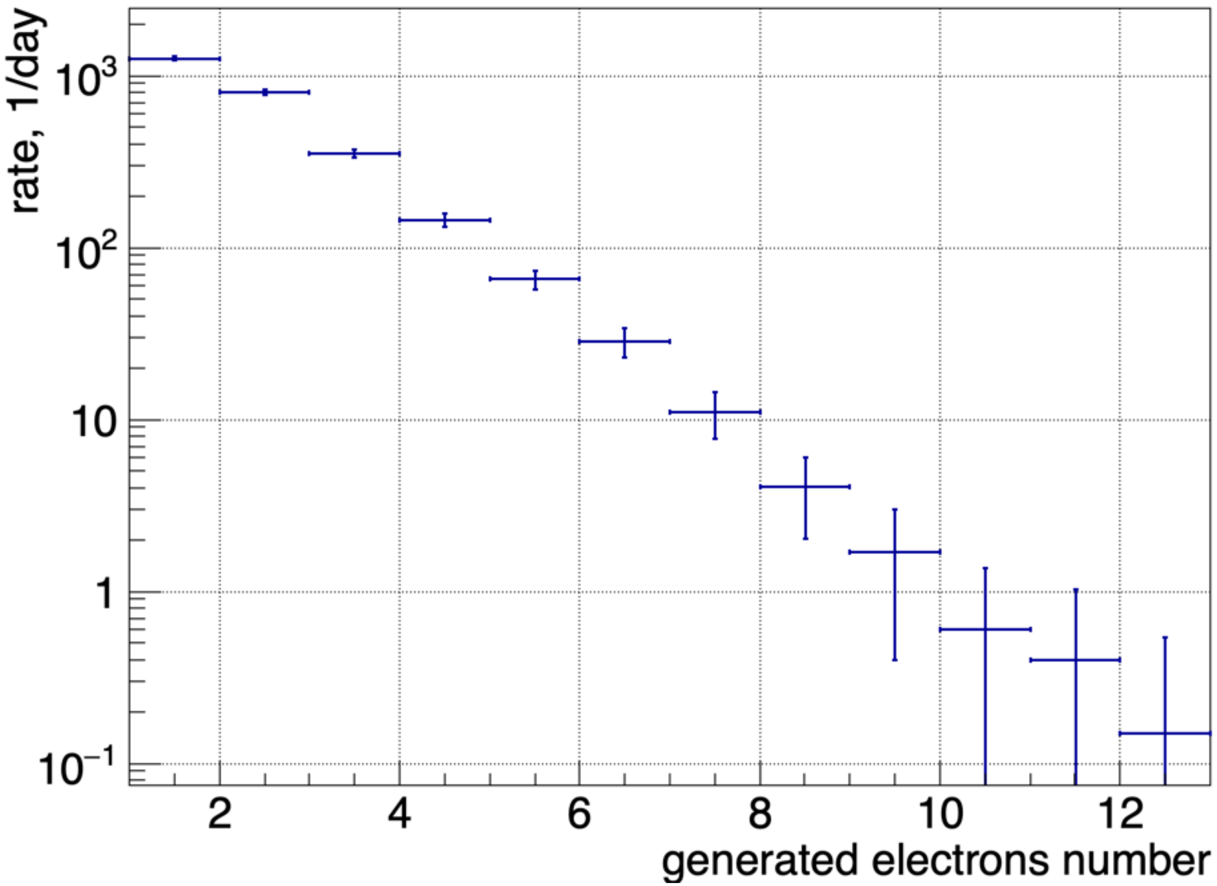




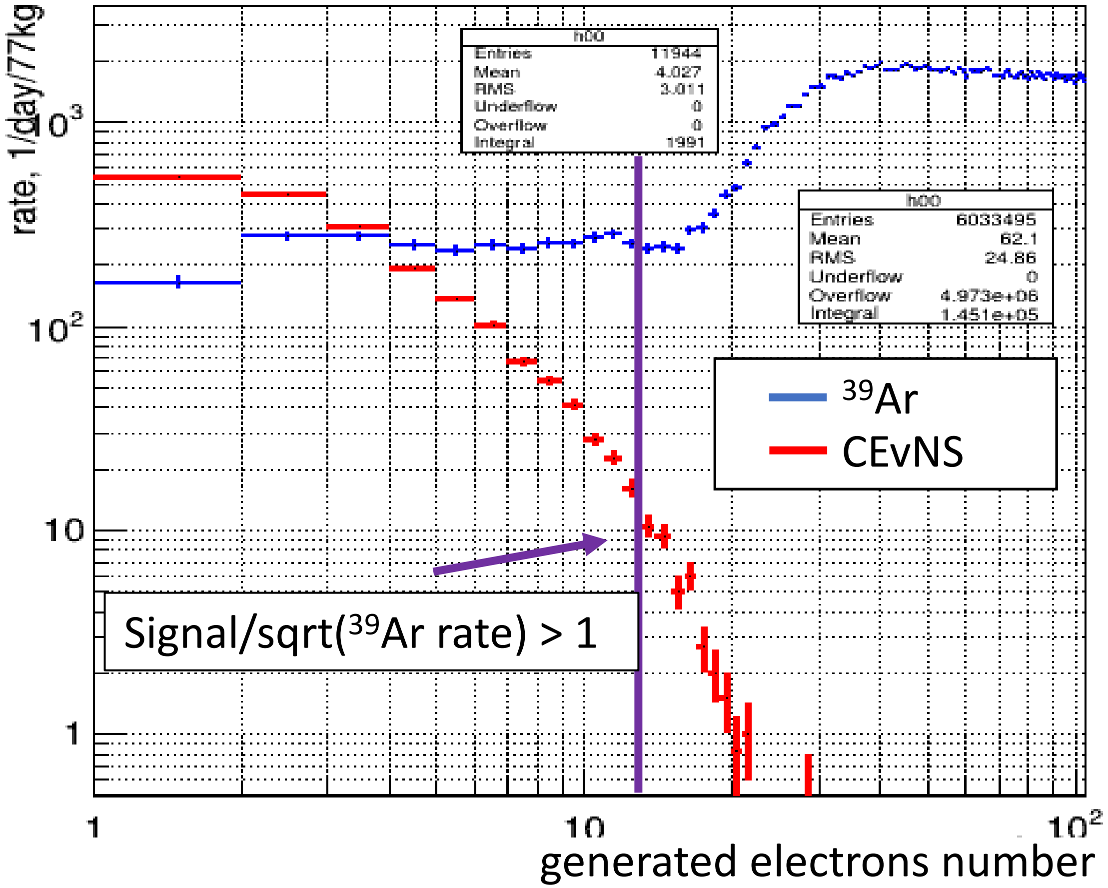


Generated electrons in RED-100

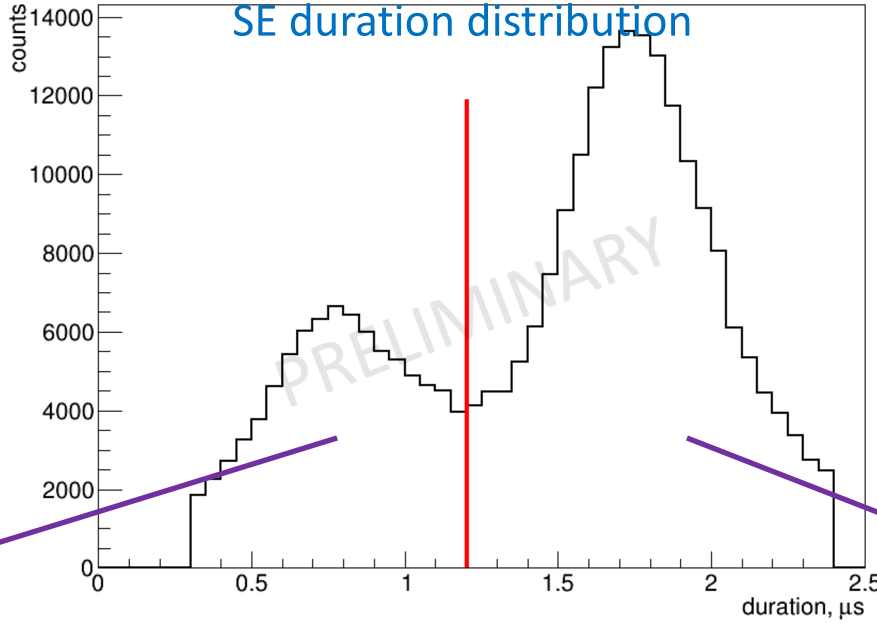
Generated electrons in RED-100 with LXe for CEvNS events

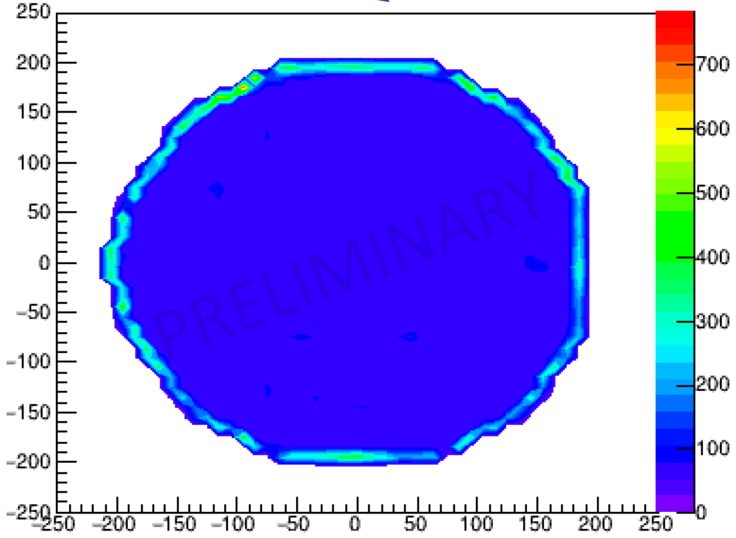


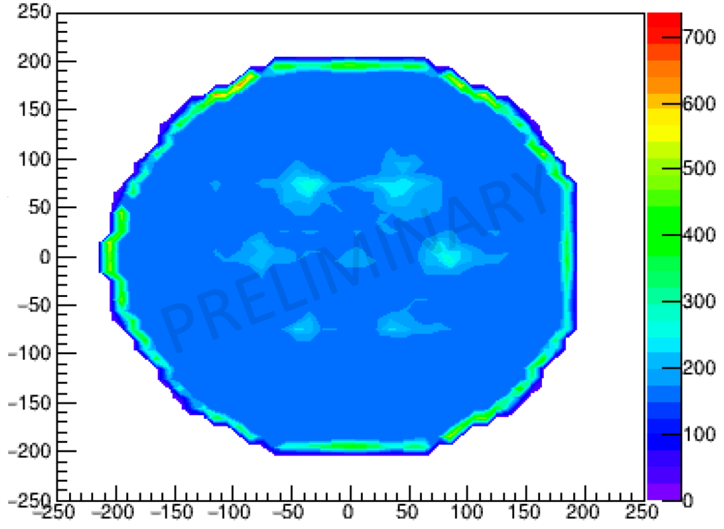
Generated electrons in RED-100 with LAr for CEvNS events and ^{39}Ar



Short SEs


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


250
200
150
100
50
0
−50
−100
−150
−200
−250
−250 −200 −150 −100 −50 0 50 100 150 200 250
700
600
500
400
300
200
100
0
PRELIMINARY


250
200
150
100
50
0
−50
−100
−150
−200
−250
−250 −200 −150 −100 −50 0 50 100 150 200 250
700
600
500
400
300
200
100
0
PRELIMINARY