Status of the RED-100 experiment

Rudik D. G.

NRNU MEPhI

RED

RUSSIAN EMISSION DETECTOR

Magnificent CEvNS 2020

Cyberspace

16-20.11.2020

RED-100 collaboration

RED

RUSSIAN EMISSION DETECTOR

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Our goal is to detect and study CEvNS @ close vicinity of reactor core with RED-100 detector

Supported by

НАУКА И ИННОВАЦИИ РОСАТОМ *

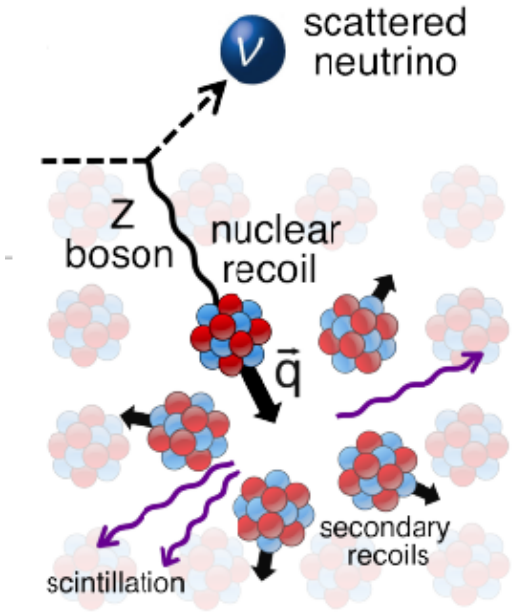
RSF Russian Science Foundation

RFBR RUSSIAN FOUNDATION FOR BASIC RESEARCH

MEPhI

* Science and innovations Rosatom

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

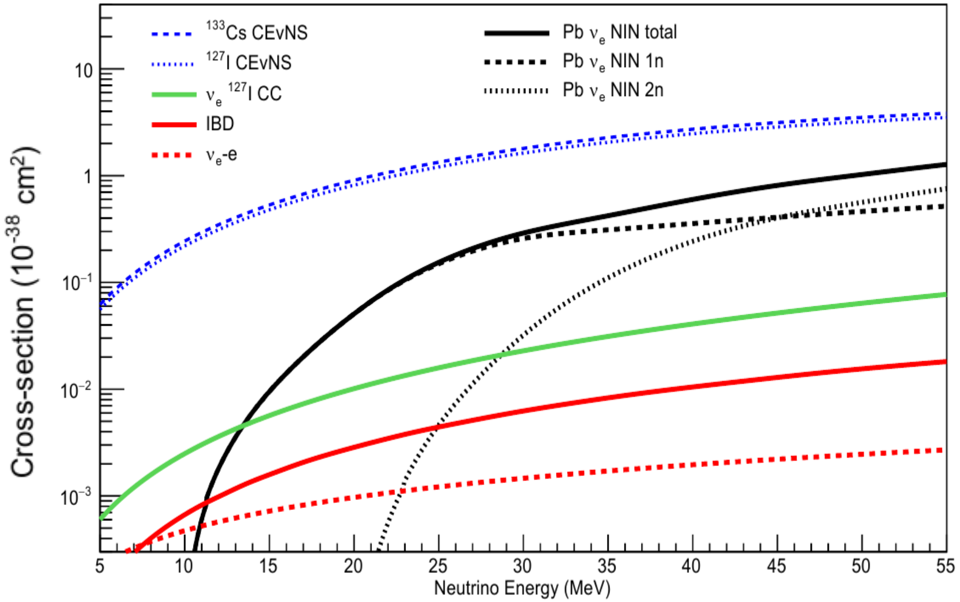


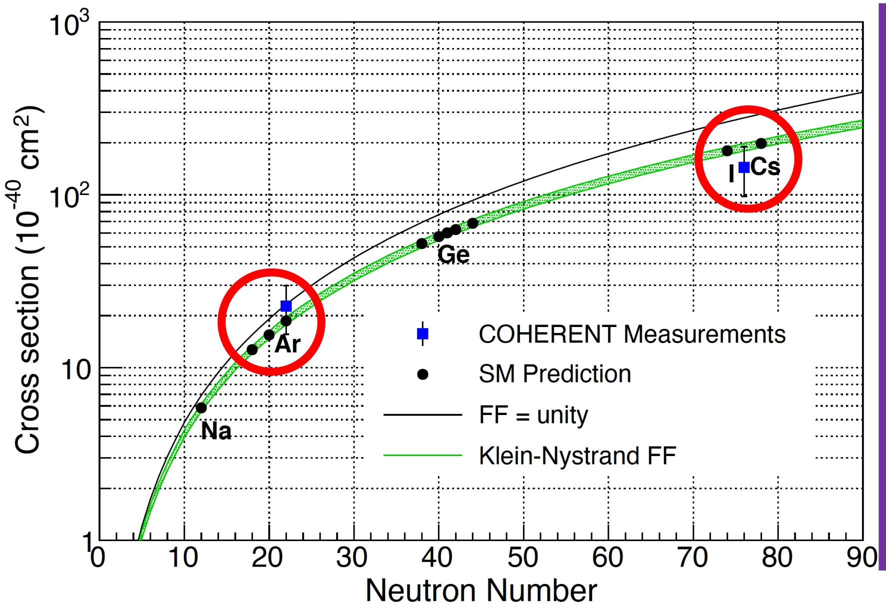
Predicted more than 40 years ago within Standard Model (SM)

- *D.Z. Freedman, Coherent effects of a weak neutral current, Phys. Rev. D 9 (1974) 1389*
- *Kopeliovich V B, Frankfurt L L JETP Lett. 19 145 (1974); Pis'ma Zh. Eksp. Teor. Fiz. 19 236 (1974)*

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

where G – Fermi constant, Z – number of protons, N – number of neutrons, $F(Q^2)$ – nuclear form factor, Q – momentum transfer, k – neutrino energy, θ_w – Weinberg angle



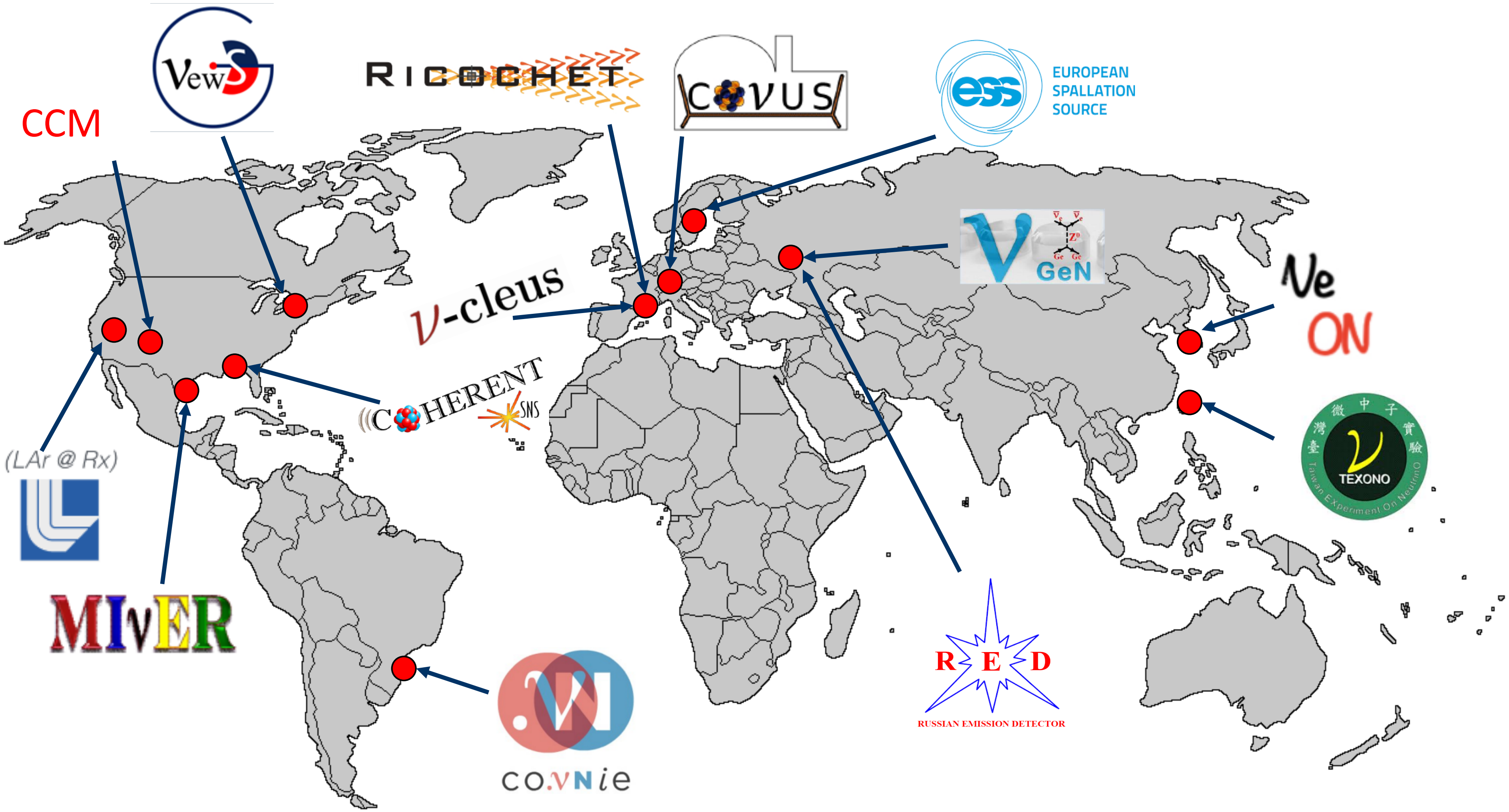


First observations:

Cs & I - Experimental point by COHERENT: **Science** Vol. 357 (2017) 1123

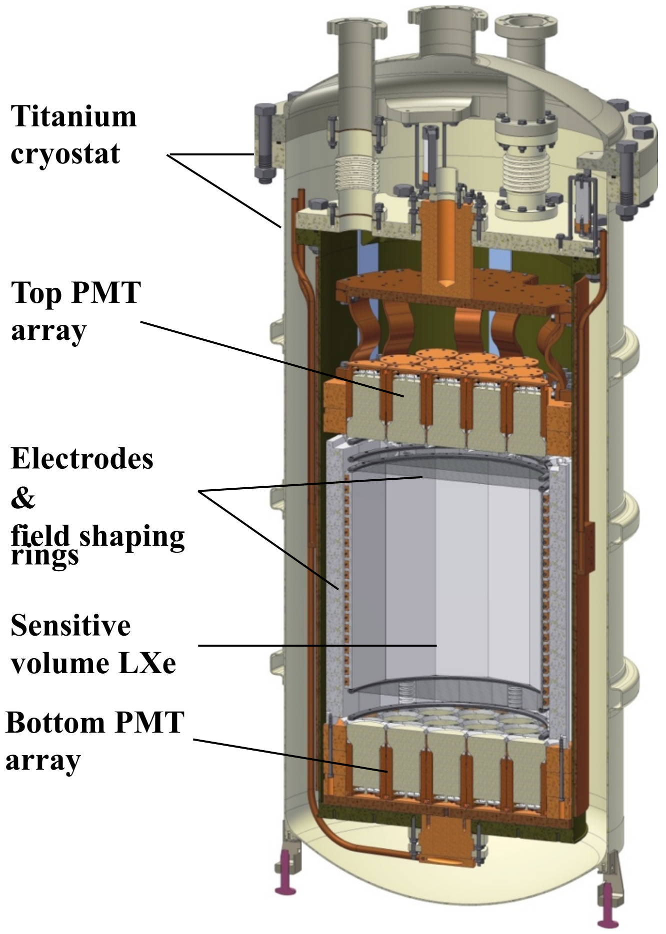
LAr - Experimental point by COHERENT: *arXiv: 2003.10630* (2020)

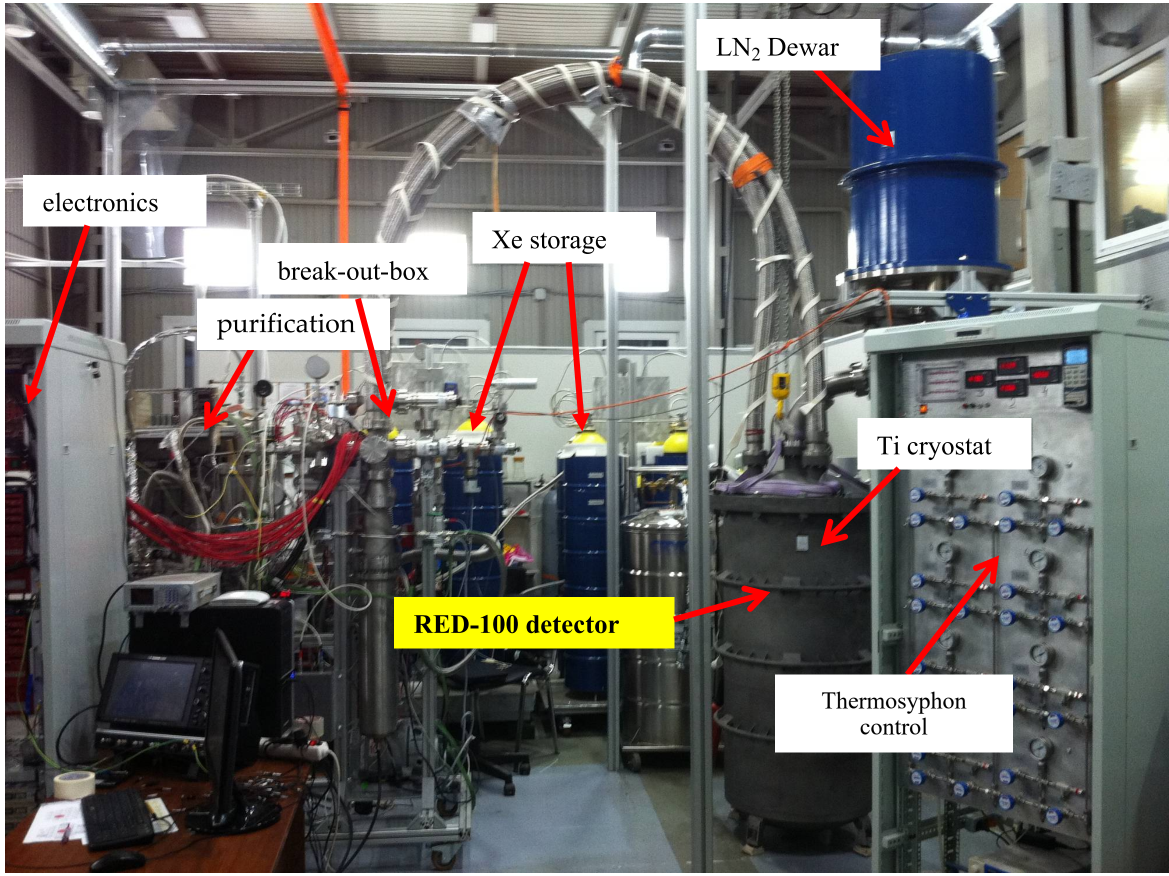
CEvNS around the World



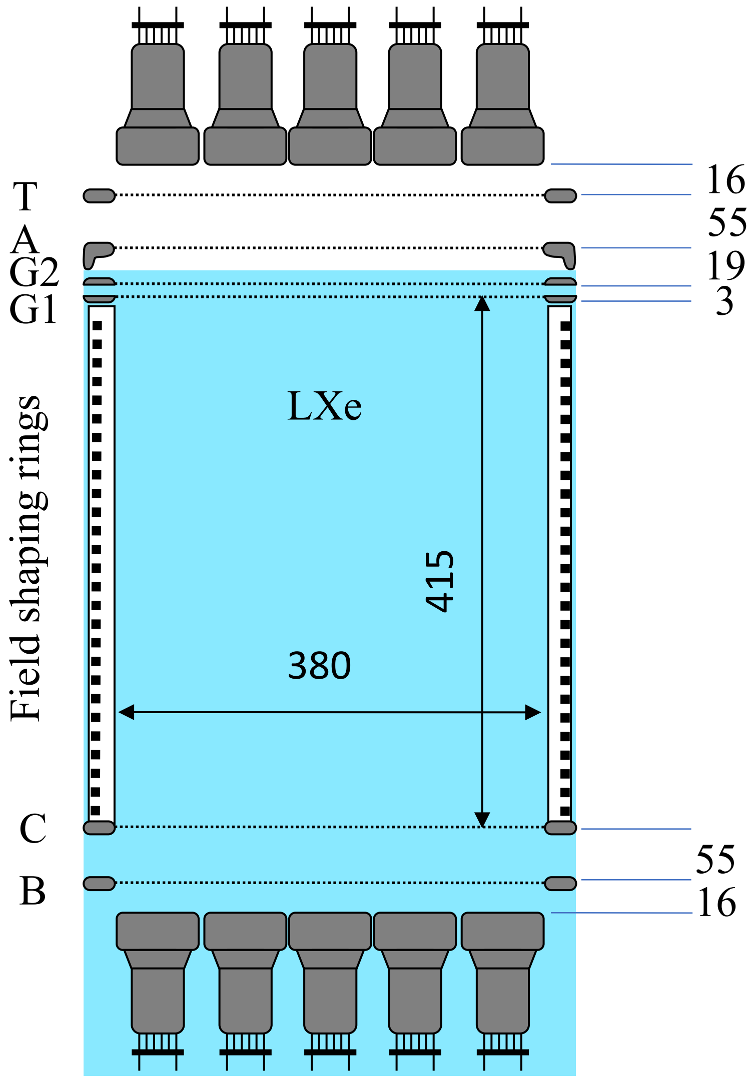
RED-100

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



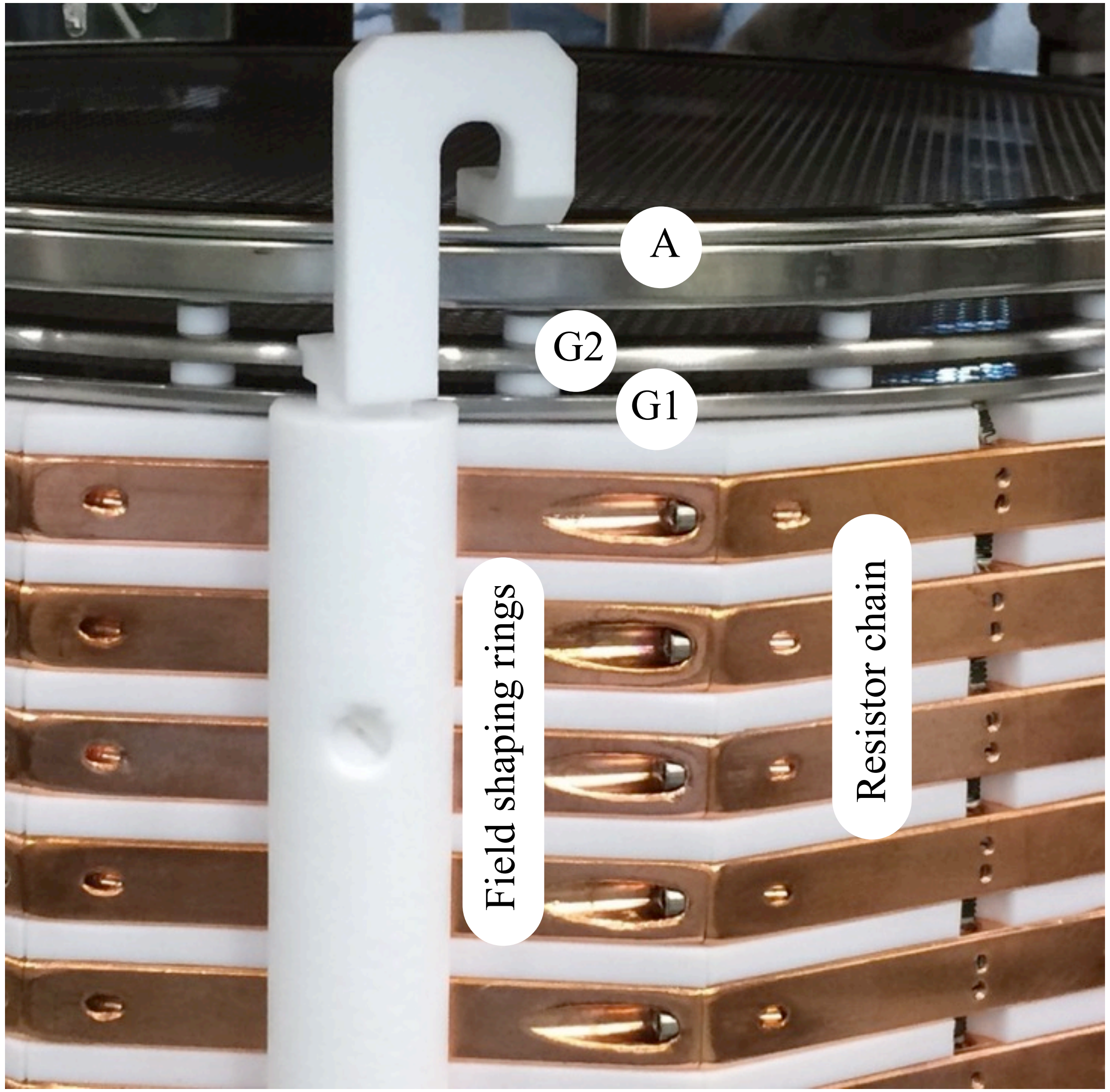


RED-100: schematic layout of grids and PMTs



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



Two-phase emission detector technique

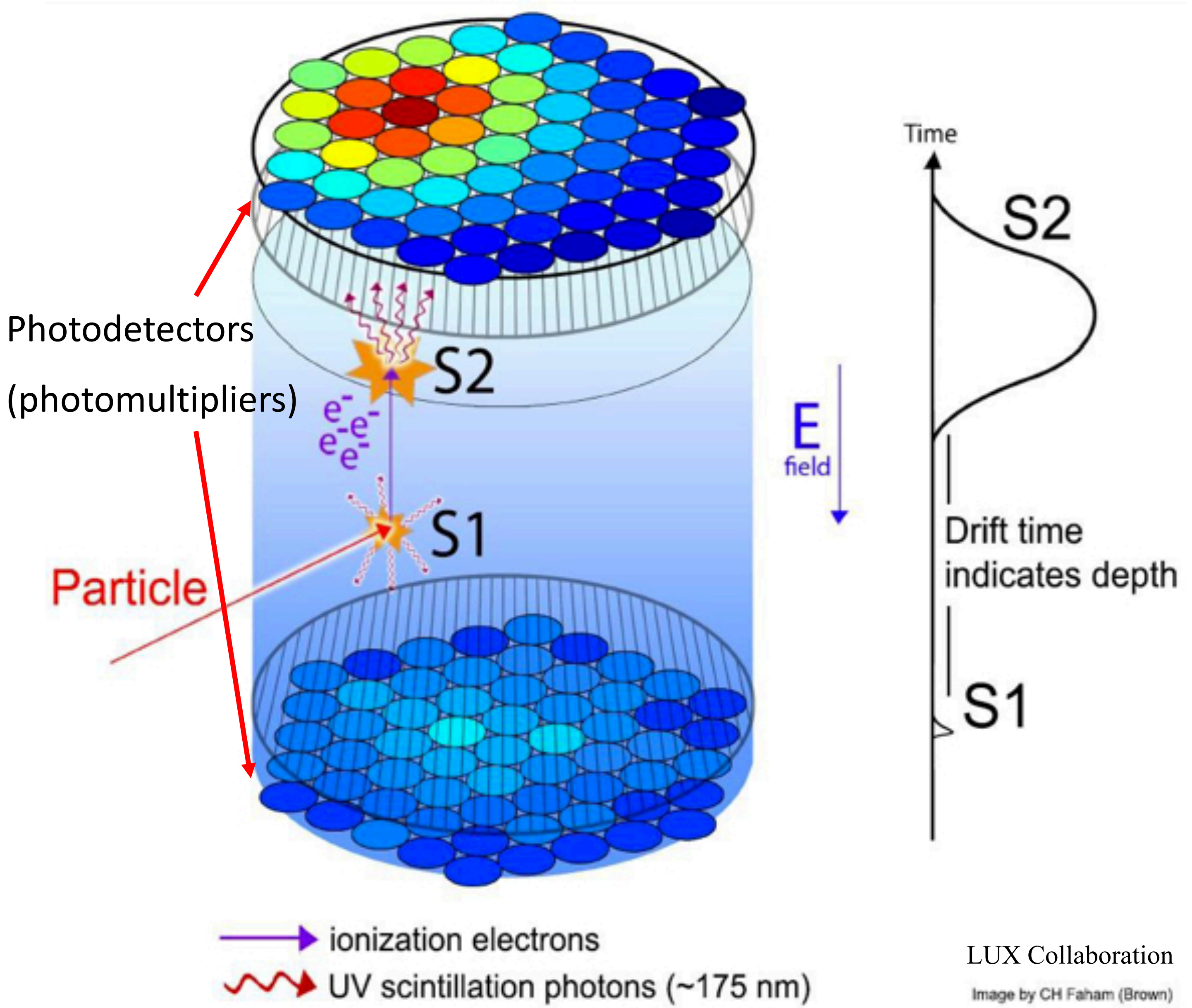
Very suitable for CEvNS study. It combines the advantages of gas detectors: the possibility of proportional or EL amplification, XYZ positioning, and the possibility to have the large mass!

This method was proposed by Russian scientists in MEPhI in 1970:

B.A. Dolgoshein, V.N. Lebedenko, B.U. Rodionov, JETF Letters (in Russian), 1970, v. 11, p. 513

Two-phase emission detector with PMT matrices for rare events study:

Bolozdynya A. I., Egorov O. K., Rodinov B. U., Miroshnichenko V. P. (1995). Emission detectors. IEEE Trans. Nucl. Sci. 42:565-569

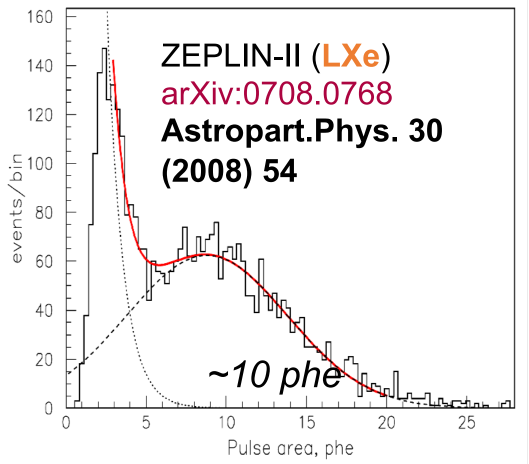


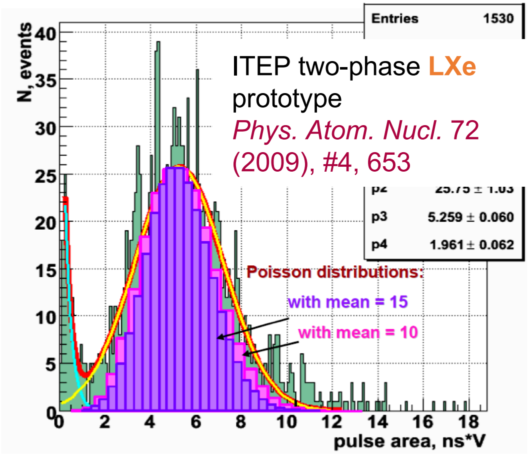
LUX Collaboration

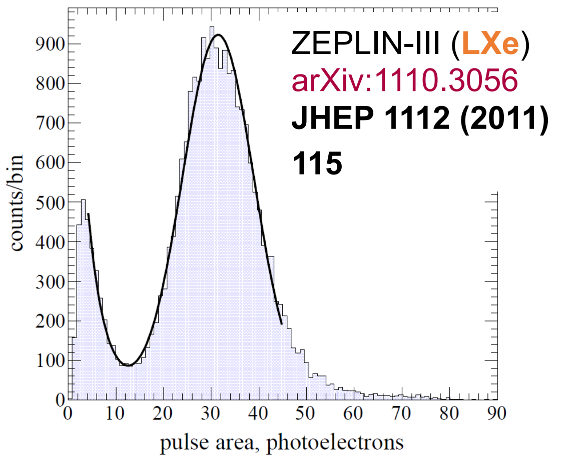
Image by CH Faham (Brown)

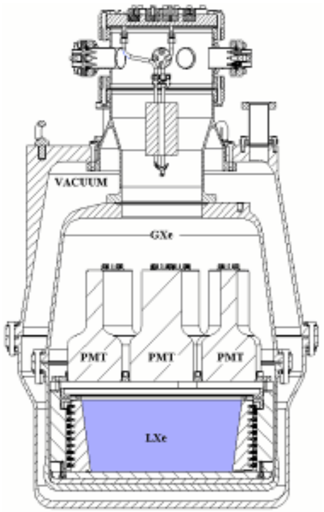
Single Electron (SE) detection

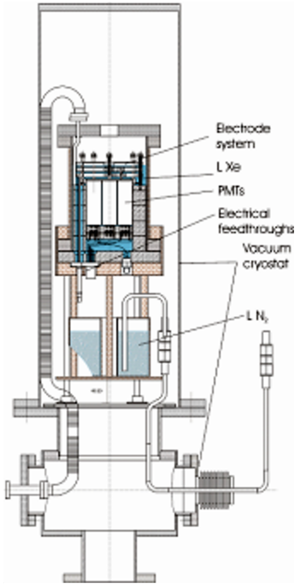
- Capability to detect single ionization electrons (SE) was demonstrated
- Projects for CEvNS with LXe two-phase detectors appeared

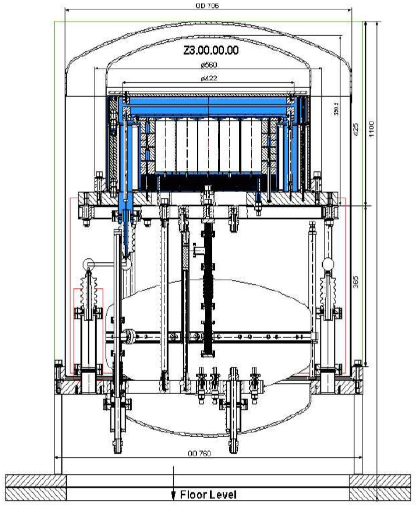












Proposals on CEvNS detection:

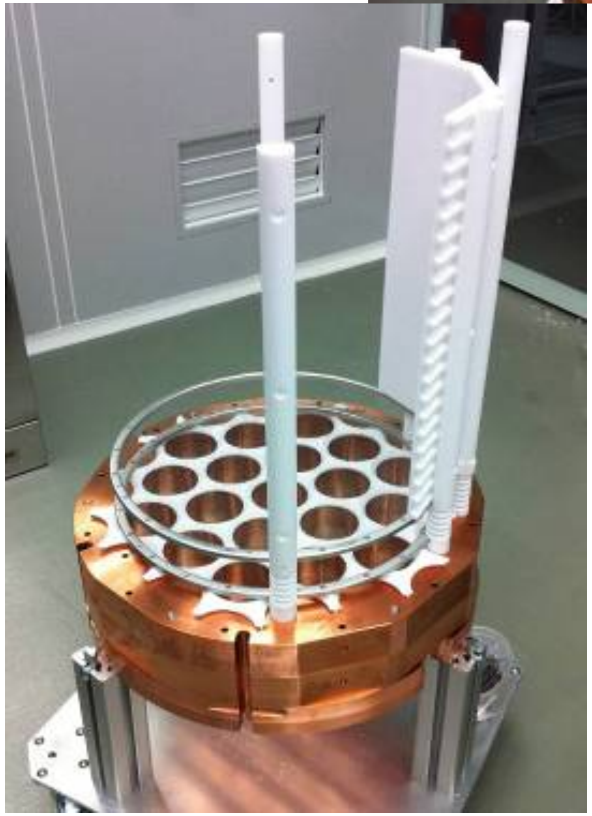
ITEP&INR LXe:
JINST 4 (2009) P06010 [arXiv:0903.4821]

ZEPLIN-III Collaboration LXe:
JHEP 1112 (2011) 115 [arXiv:1110.3056]

RED-100 assembling

- RED-100 was assembled and tested in the MEPhI laboratory

  Akimov D. Yu., et al. JINST 15.02 (2020): P02020.

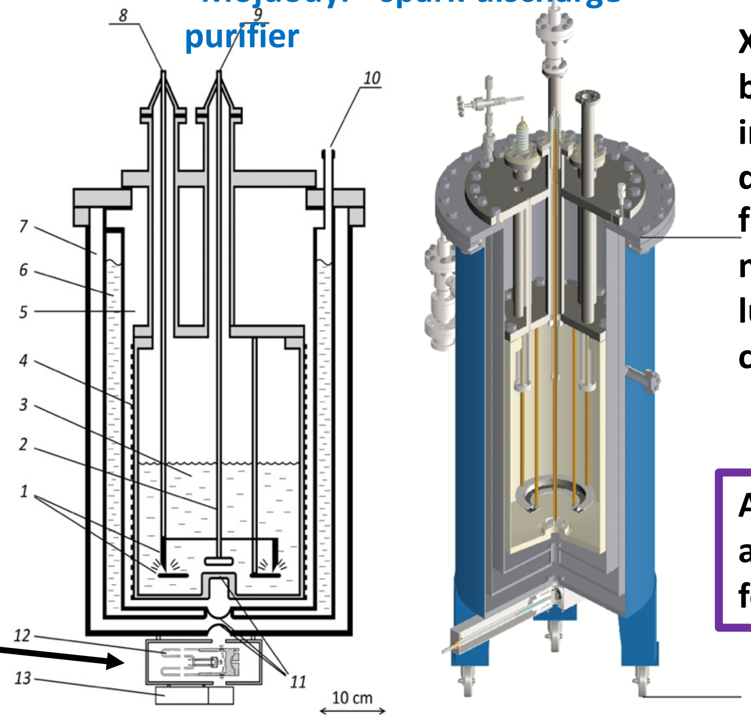


RED-100 performance: LXe purity

- 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

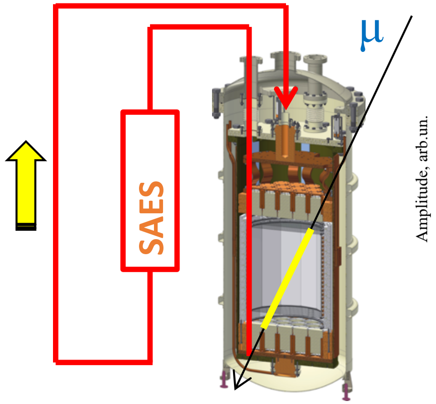


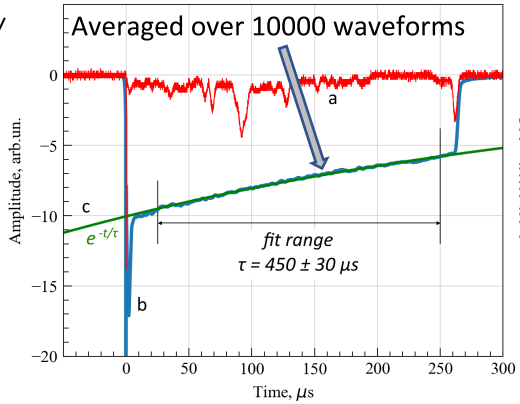
X-ray tube as a source of ionization electrons for e⁻ lifetime measurements

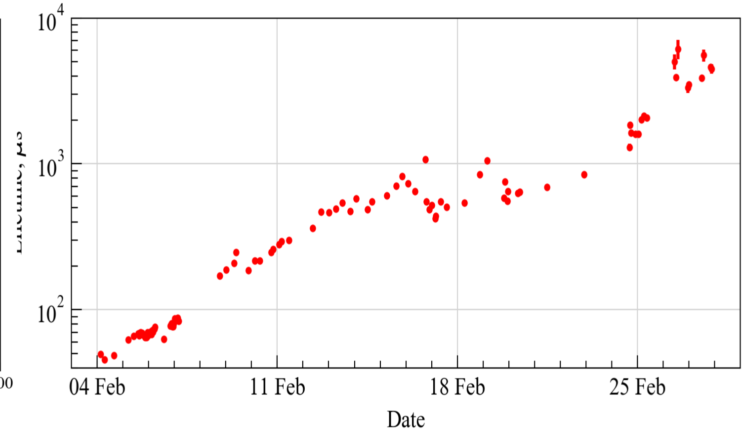
Xenon was contaminated by highly-electronegative impurities presumably due to the use of a special fluorine-containing high-molecular-weight lubricant in gas centrifuges.

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

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

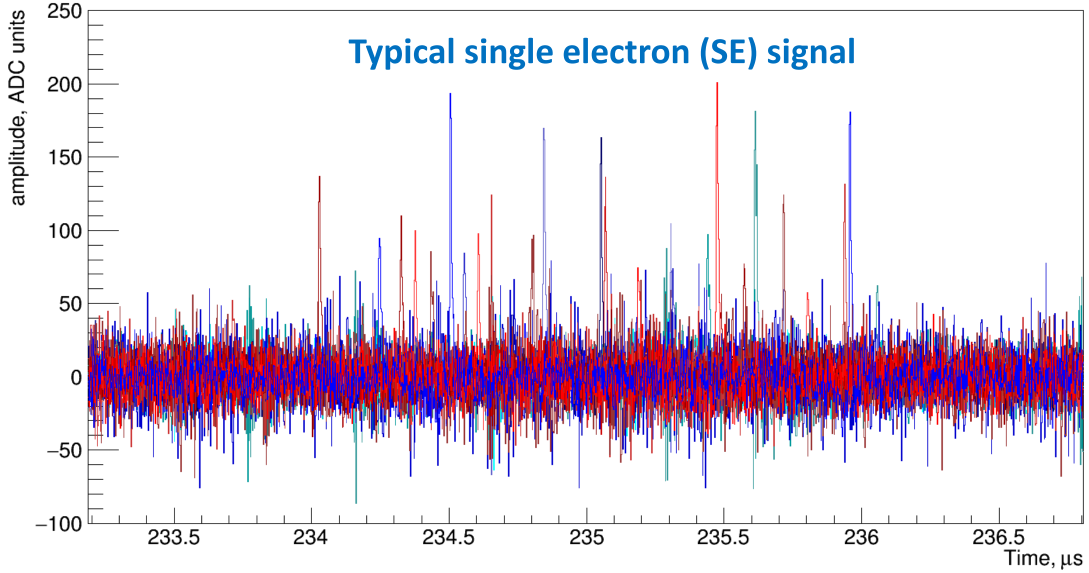




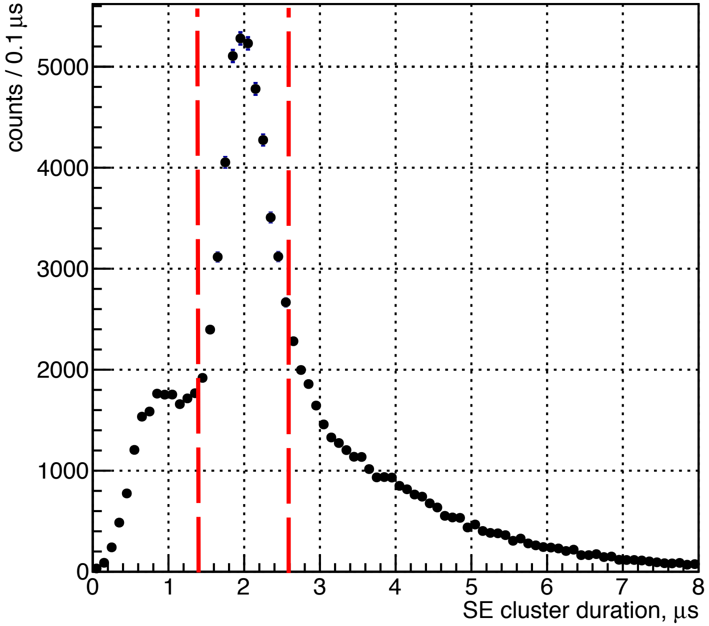


RED-100 performance: SE

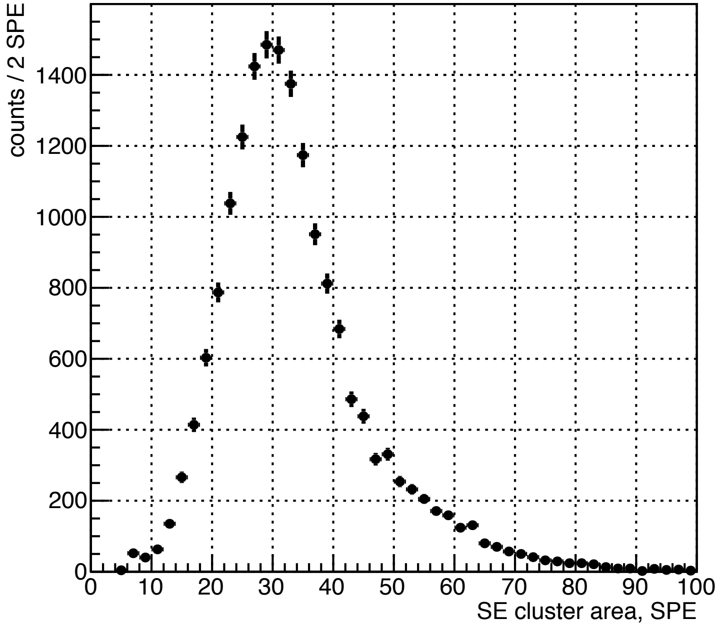
- SE is a cluster of individuals SPEs (single photo electrons)
- Typical duration ~ 2 μs
- ~ 30 SPE/SE for RED-100



Different colors → different PMTs



Distribution of SE duration

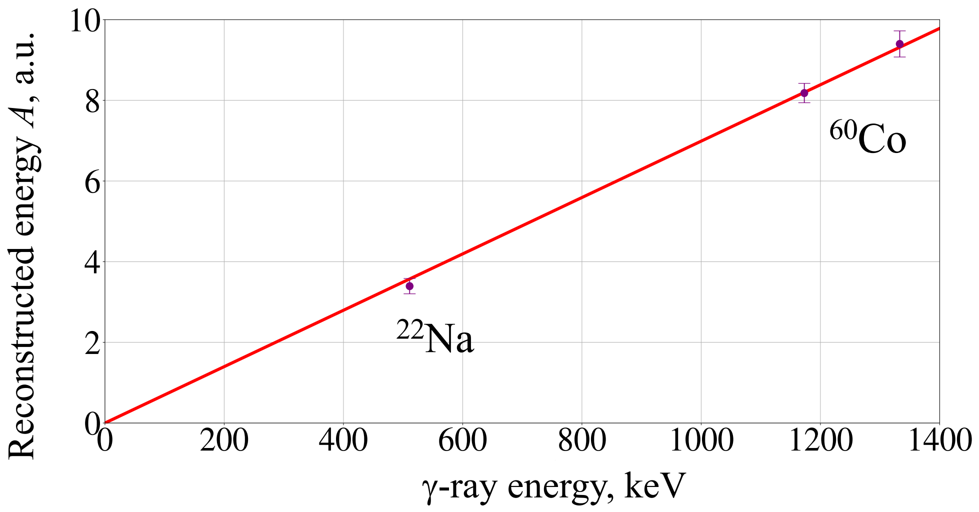


Distribution of SE area

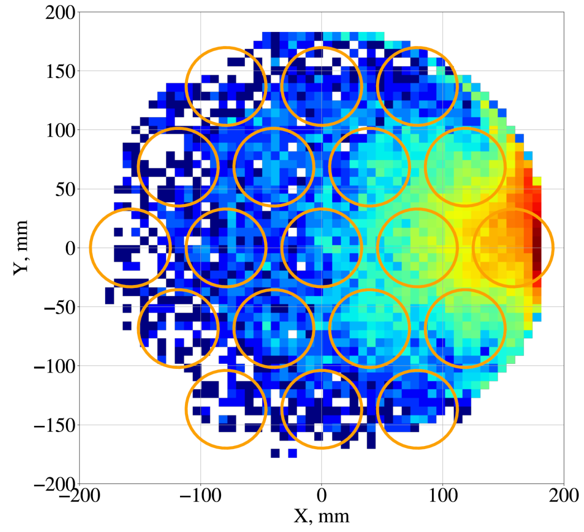
RED-100 performance: gamma calibration

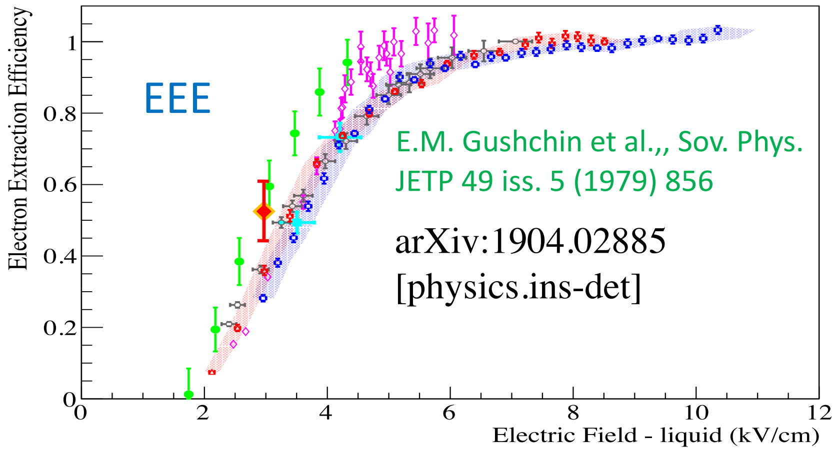
- Gamma calibration was done
- Position reconstruction tested
- LRF obtained for the top PMT plane
- Electron extraction efficiency (EEE)
  - S2-based only
  - N_{SE} = ^{22}Na peak position/SE area
  - N_E – from NEST @ E_{dr} = 0.217 kV/cm
  - N_E^* – corrected for electron lifetime
  - EEE = N_{SE}/N_E^* = 0.54 ± 0.08 @ E_{extr} = 3.0 ± 0.1 kV/cm

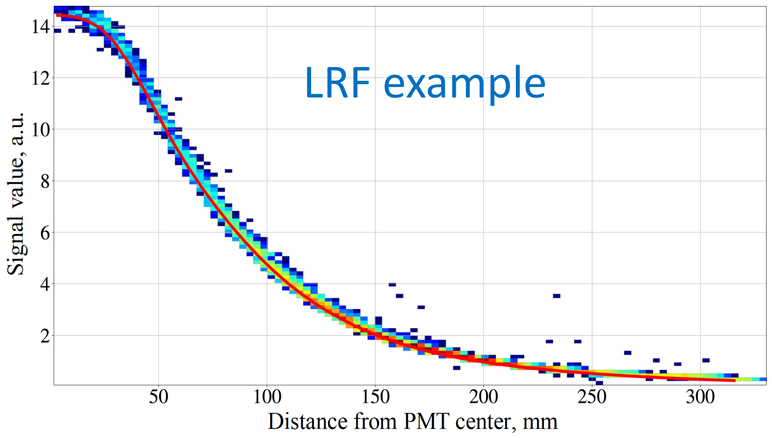
Gamma calibration



Position reconstruction for ^{22}Na



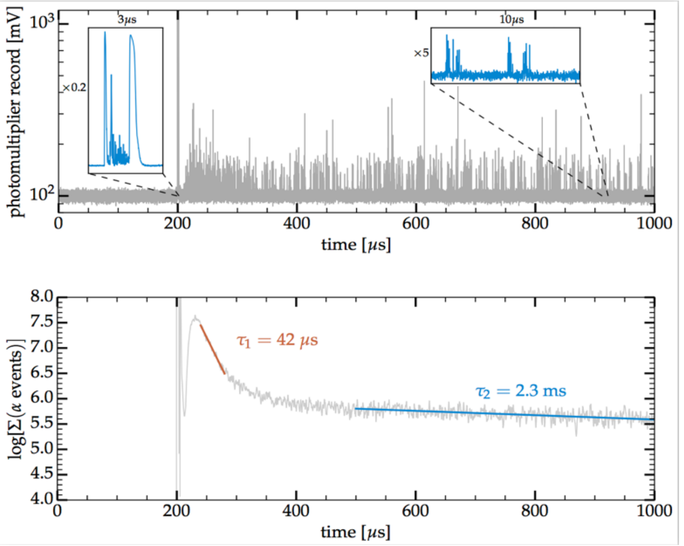




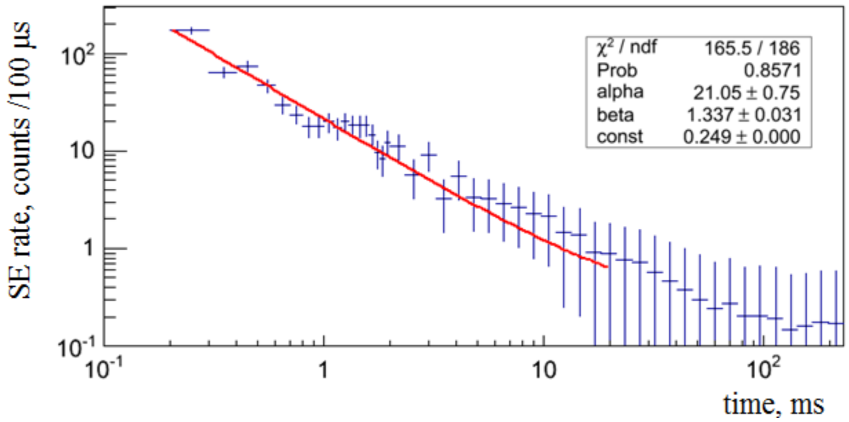
RED-100 performance: “spontaneous” SE

- An increasing of SE rate after energy deposition in liquid noble gas detector was observed by several groups
- Two components:
  1. short, but more intense, caused by emission of the electrons trapped at LXe surface
  2. long, but less intense; unknown mechanism, decreases with time as purity increase; possibly, catching and releasing electrons by impurities (correlation with purity (of LAr) was also observed in DS50)
- Electron shutter in RED-100
  - To minimize 1st component
  - Muon is a trigger
  - SE rate was reduced by factor of about 3
  - Still high SE rate of the second component (250 kHz) in the lab
  - Expecting reduction at the site of KNPP in a factor of about 5

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

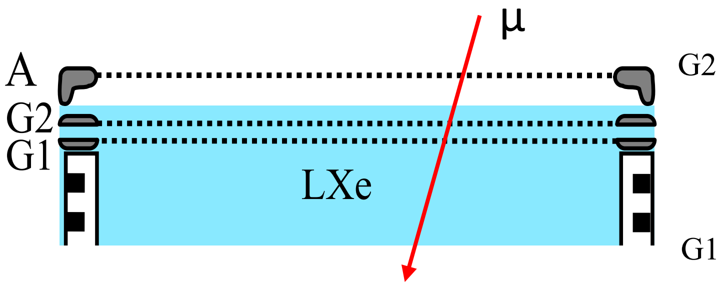


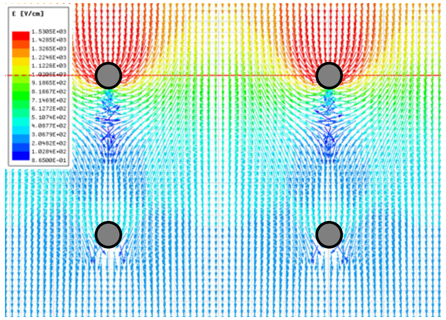
JINST 11 (2016) no.03, C03007



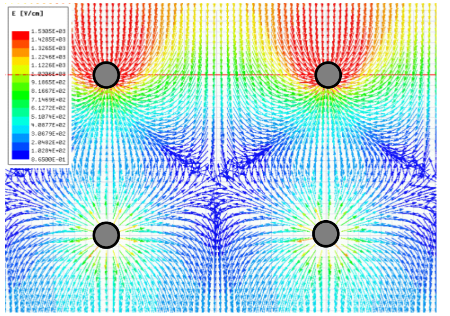
Observed in ZEPLIN-III: **JHEP 1112 (2011) 115, arXiv:1110.3056 [physics.ins-det]**

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





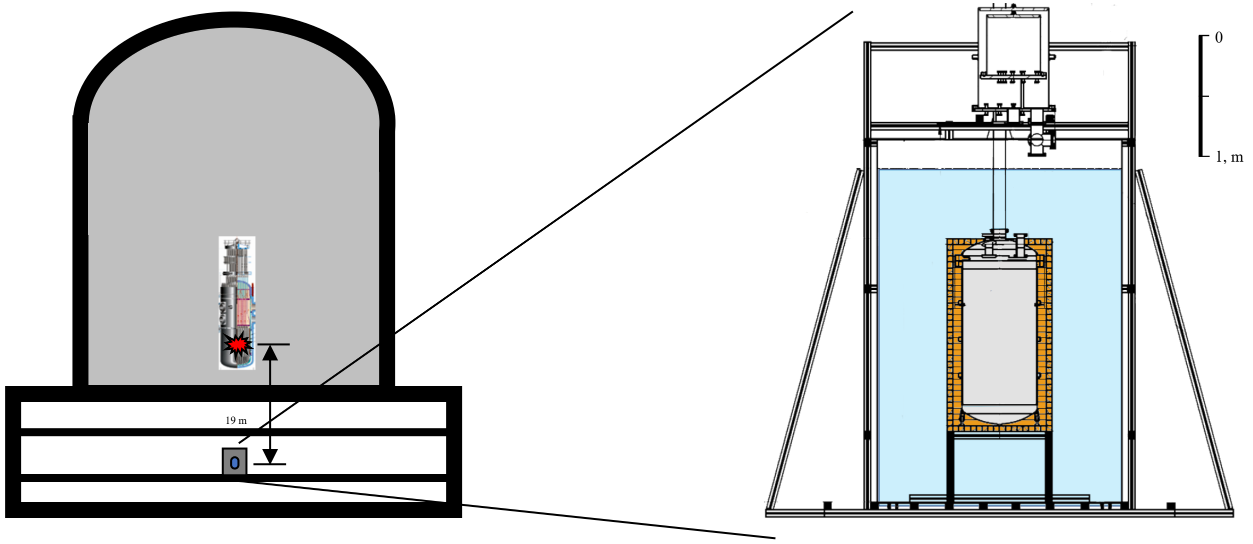
open: $U_{G2} - U_{G1} = 50$ V



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

RED-100 at KNPP

- KNPP – Kalinin Nuclear Power Plant
- 19 m from the reactor core
- Antineutrino flux ~ $1.35*10^{13}$ $cm^{-2}s^{-1}$
- ~ 65 m.w.e. in vertical direction
- Passive shielding:
  - 5 cm Cu
  - ~ 60 cm H_2O



Neutron flux

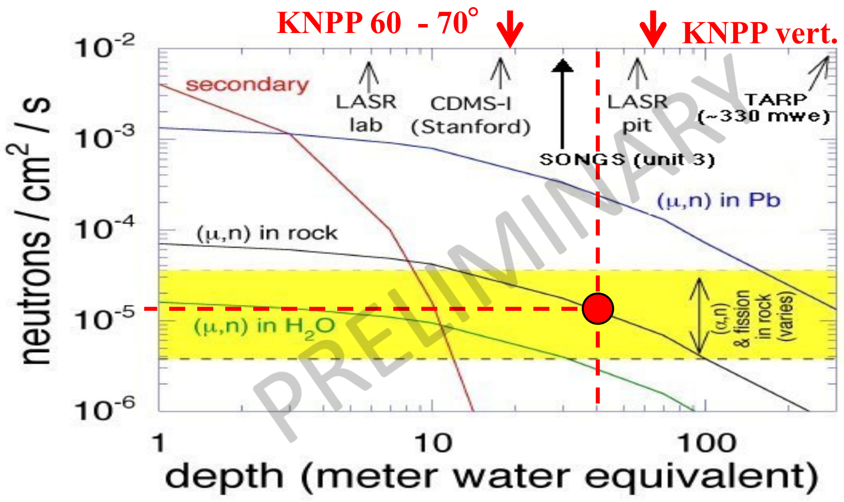
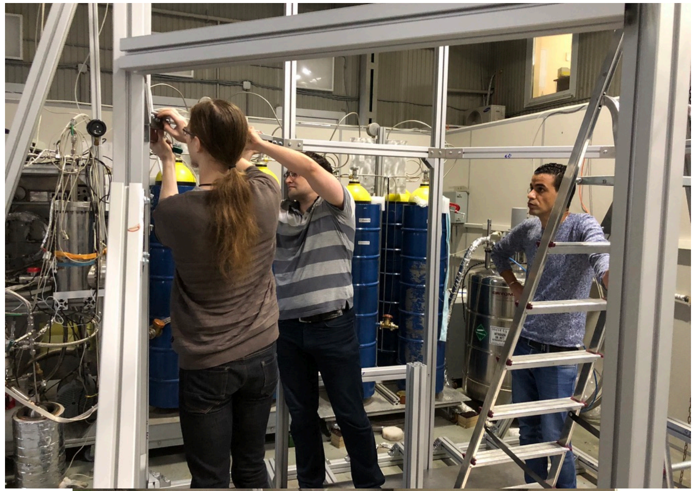
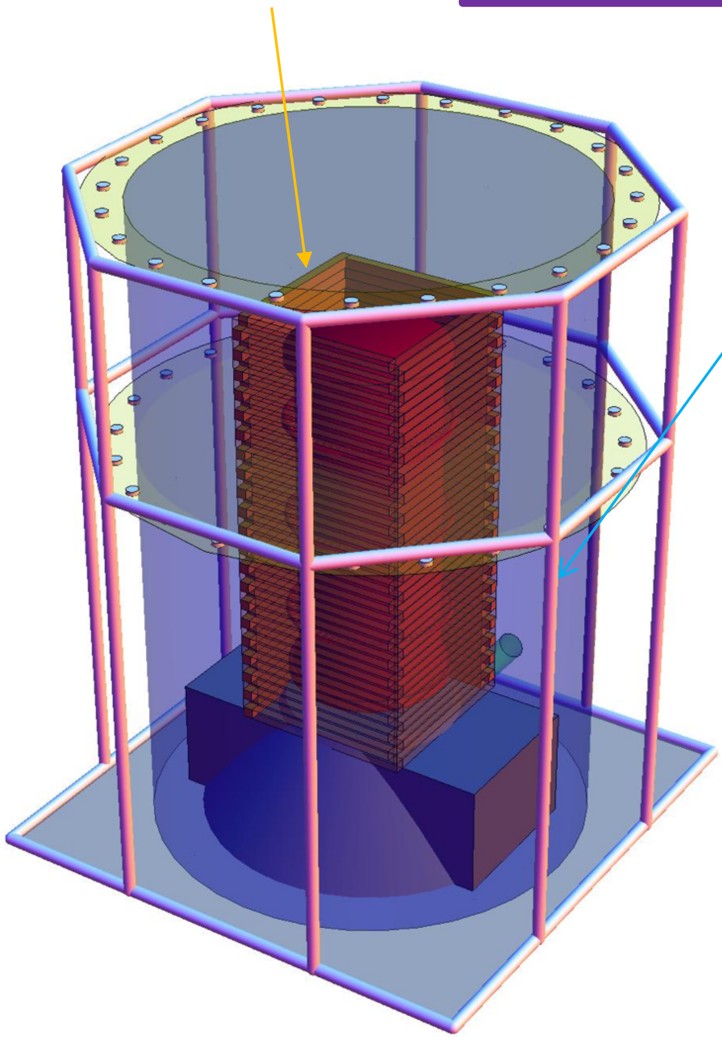


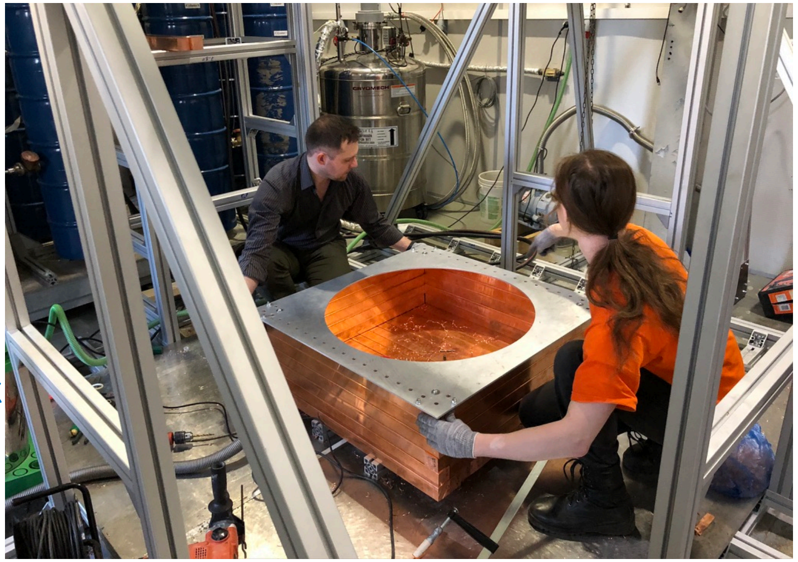
Image by J.I. Collar

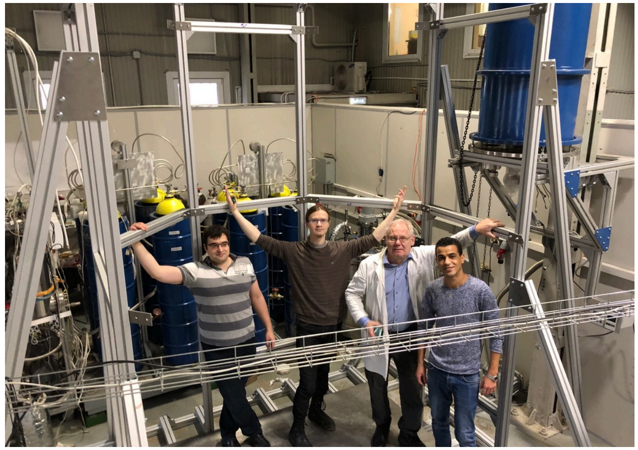
Passive shielding





Assembled and tested in MEPhI

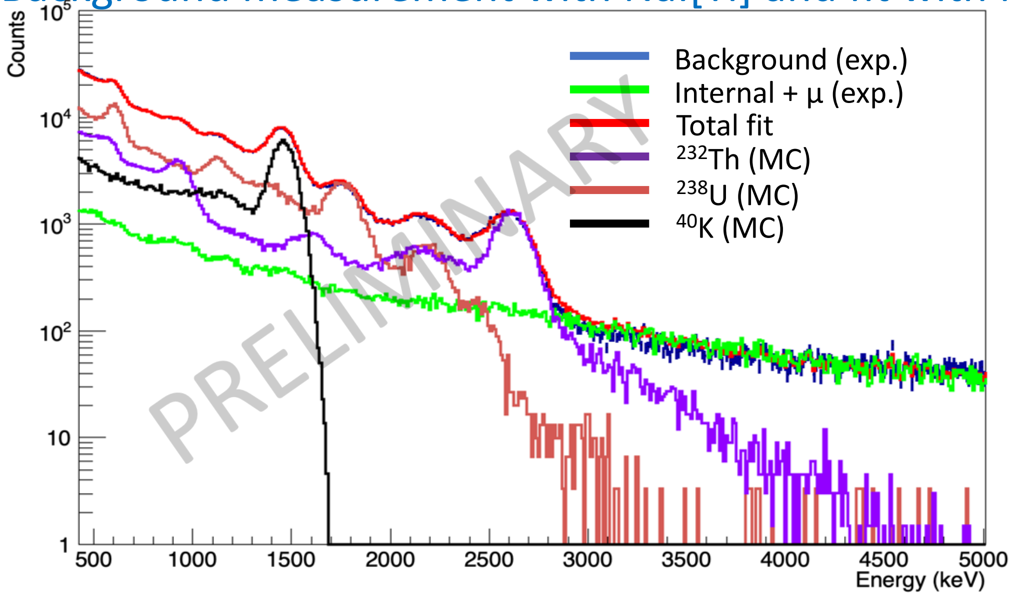




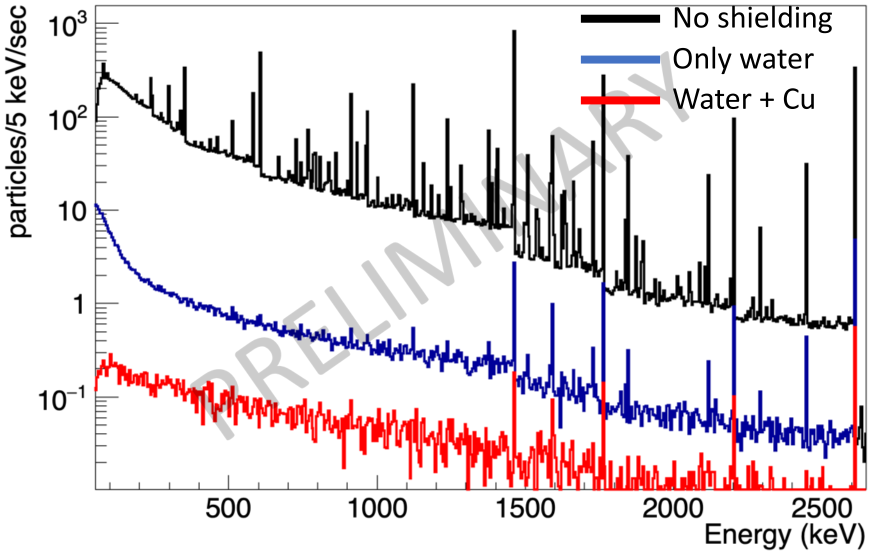
Passive shielding

- Restrictions in space and kg/m^2 at KNPP
- 5 cm Cu and ~ 60 cm water
- Reduction of gamma background in a factor of ~ 700 according to tests and MC
- MC for neutron background reduction is on going
- Paper is submitted

Background measurement with NaI[Tl] and fit with MC



MC background at the external cryostat surface



Estimation of CEvNS count rate at KNPP

- Main background → accidental coincidence of several spontaneous SE (multi-electron event = ME)
- But:
  - CEvNS events are point-like events
  - Background is mostly NOT point-like
- Naive point-like cut was tested, and it works!
- Several ML approaches, CNN and DL networks were tested → further improvement (PRELIMINARY)

ME value in electrons	Estimated ME background at KNPP, events/160kg/day			Expected CEνNS count rate at KNPP, events/160kg/day		
	no cut	Naive point-like	DL point-like	no cut	Naive point-like	DL point-like
2	$5.3 \cdot 10^{7}$	$1.8 \cdot 10^{7}$	$0.8 \cdot 10^{7}$	465	283	317
3	$4.4 \cdot 10^{5}$	$0.9 \cdot 10^{5}$	$1.7 \cdot 10^{4}$	129	79	100
4	$2.7 \cdot 10^{3}$	348	34.2	35.5	21.7	29.3
5	13.7	1.1	0.05	10.6	6.4	9.1
6	$5.7 \cdot 10^{-2}$	$3.0 \cdot 10^{-3}$	$6.3 \cdot 10^{-5}$	1.9	1.2	1.7

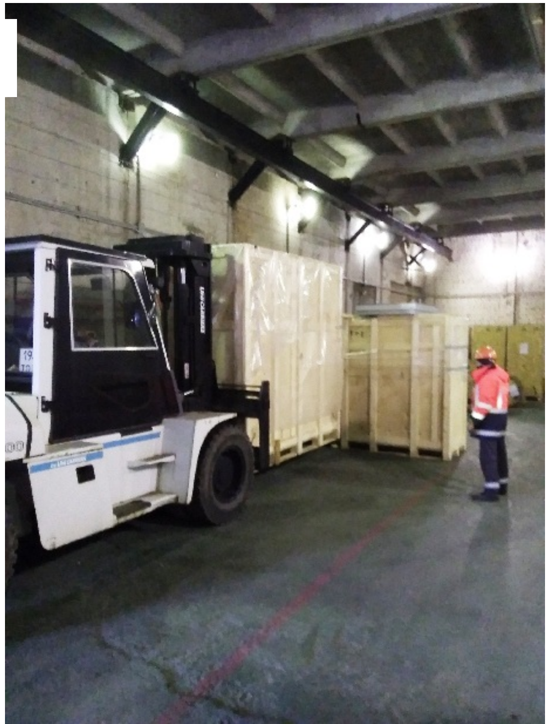
We can detect CEνNS with threshold of ≥ 4 SE

Taken into account:
- Recent data on ionization yield in LXe for NR
- EEE = NSE / N*E = 0.54 ± 0.08
- Factor of 5 reduction of muon rate ⟹ 50 kHz spontaneous SE rate
- Poisson flow of spontaneous SE

Timeline

RED-100 shipment

RED-100 @ KNPP



- Despite COVID-19 situation we are in time!
- 2020
  - October: water tank was tested
  - November: RED-100 is moved to KNPP!
- 2021
  - Winter: deployment; background measurements and analysis
  - Spring: start of data taking
- 2022
  - Data analysis
- Prolongation of experiment (?)

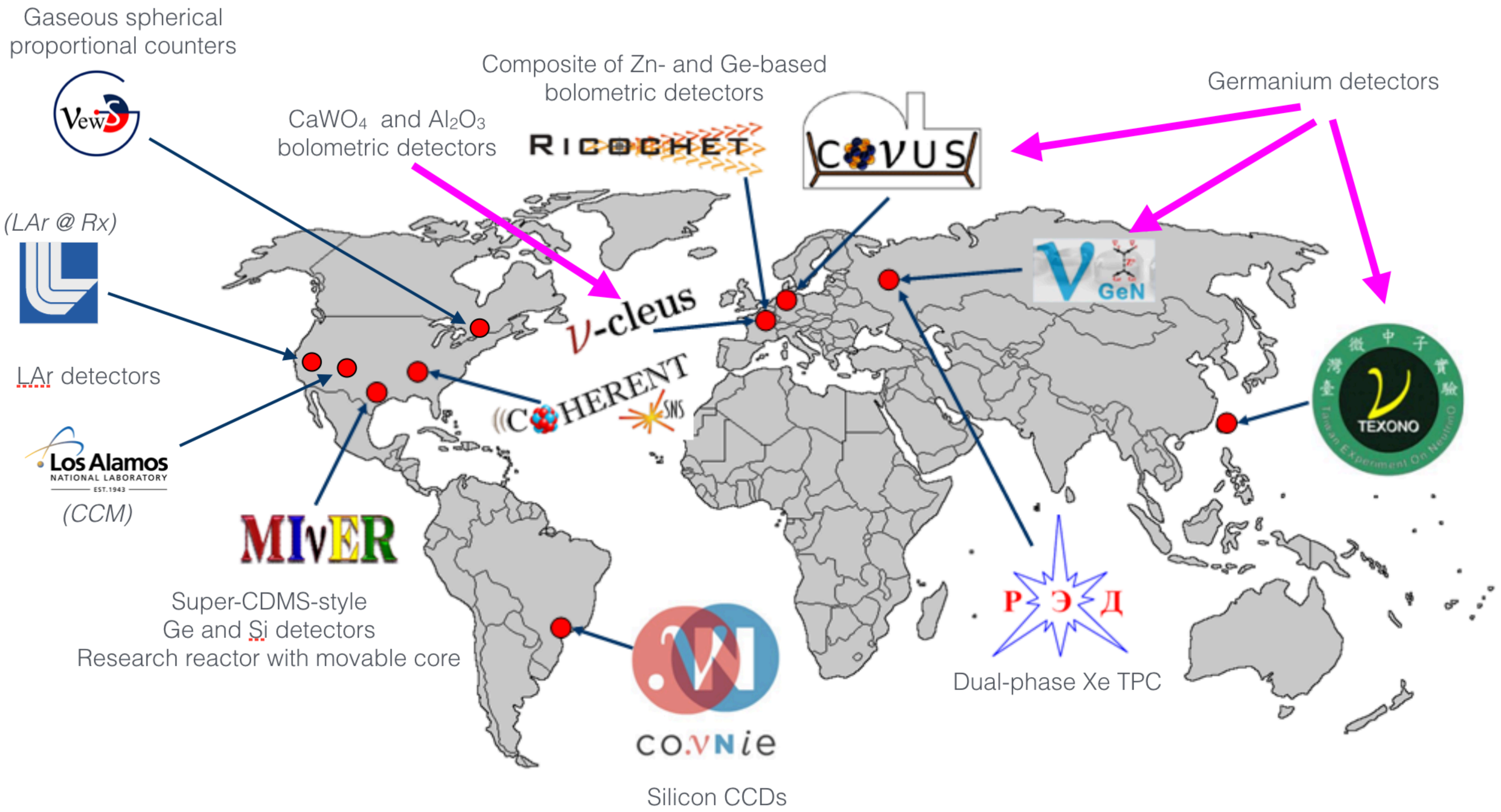
Conclusion

- RED-100 was assembled and tested @ MEPhI
    - Excellent electron lifetime of several milliseconds
    - Electron extraction efficiency = 0.54 ± 0.08 @ 3.0 ± 0.1 kV/cm
    - SE gain is about 30 SPE/SE
    - The electron shutter was tested: the spontaneous SE rate suppressed but still high
- The results of the first lab test are available: Akimov D. Yu., et al. JINST 15.02 (2020): P02020
- Estimations based on our tests show the possibility to detect CEvNS at KNPP with a threshold ≥ 4 SE (progress is ongoing)
- RED-100 already at KNPP!

Thank you for your attention!

Backup

CEvNS around the World



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

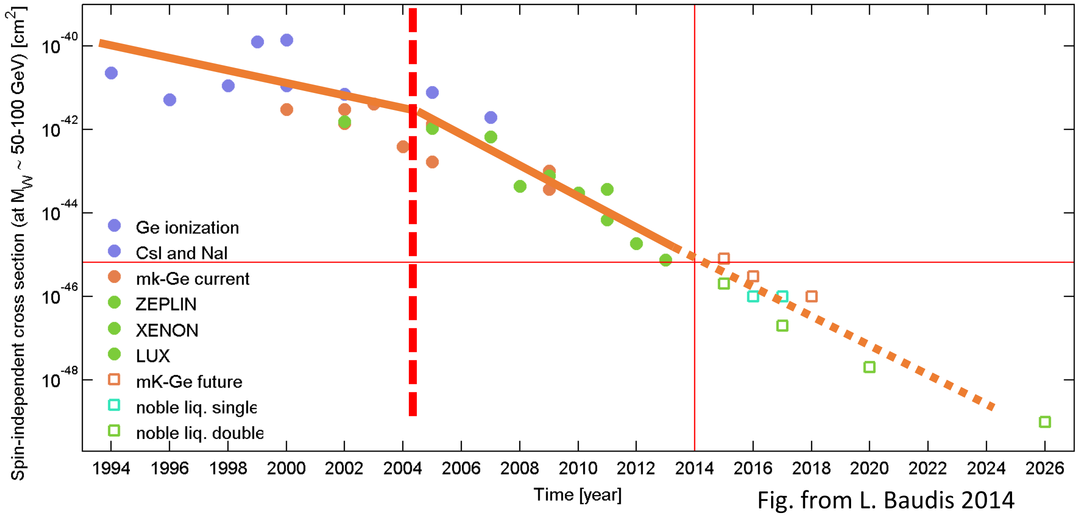
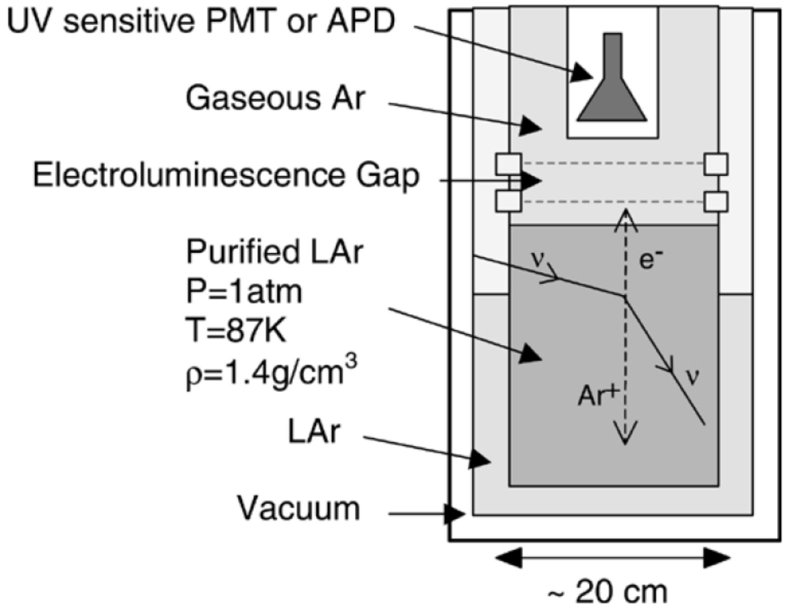


Fig. from L. Baudis 2014

1st proposal (in 2004); LAr detector



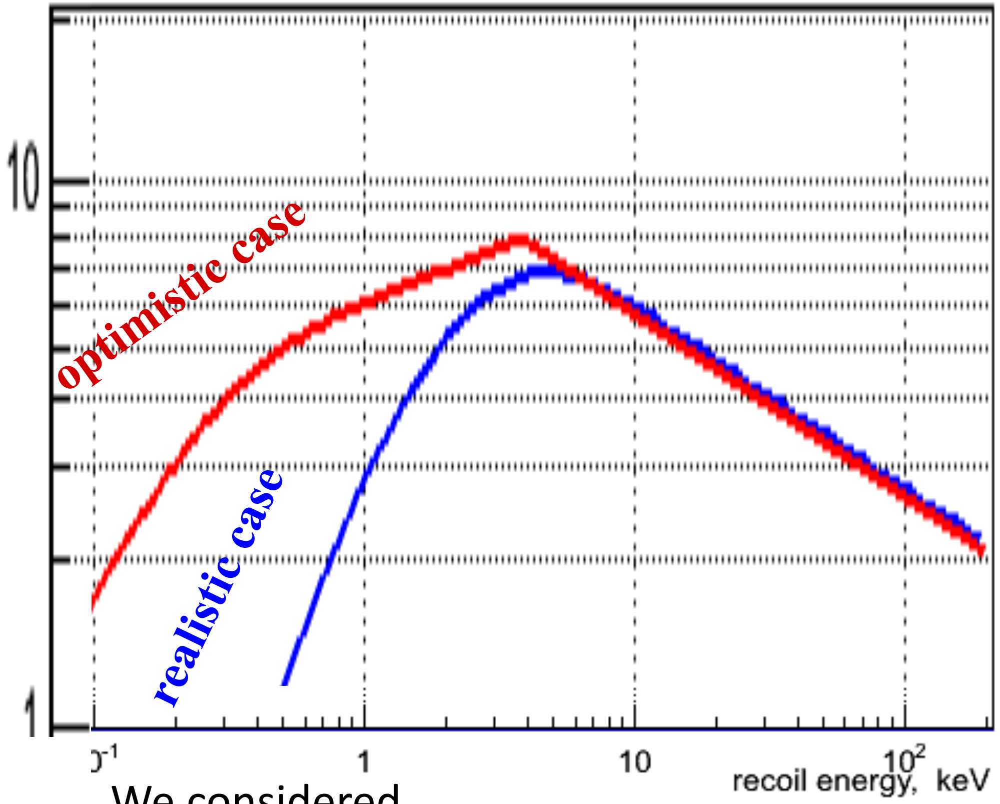
C. Hagmann and A. Bernstein,
Two-Phase Emission Detector for Measuring Coherent Neutrino-Nucleus Scattering
IEEE Trans.Nucl.Sci. 51 (2004) 2151

From Akimov D. talk @ INSTR20

Ionization yield for sub-keV nuclear recoils

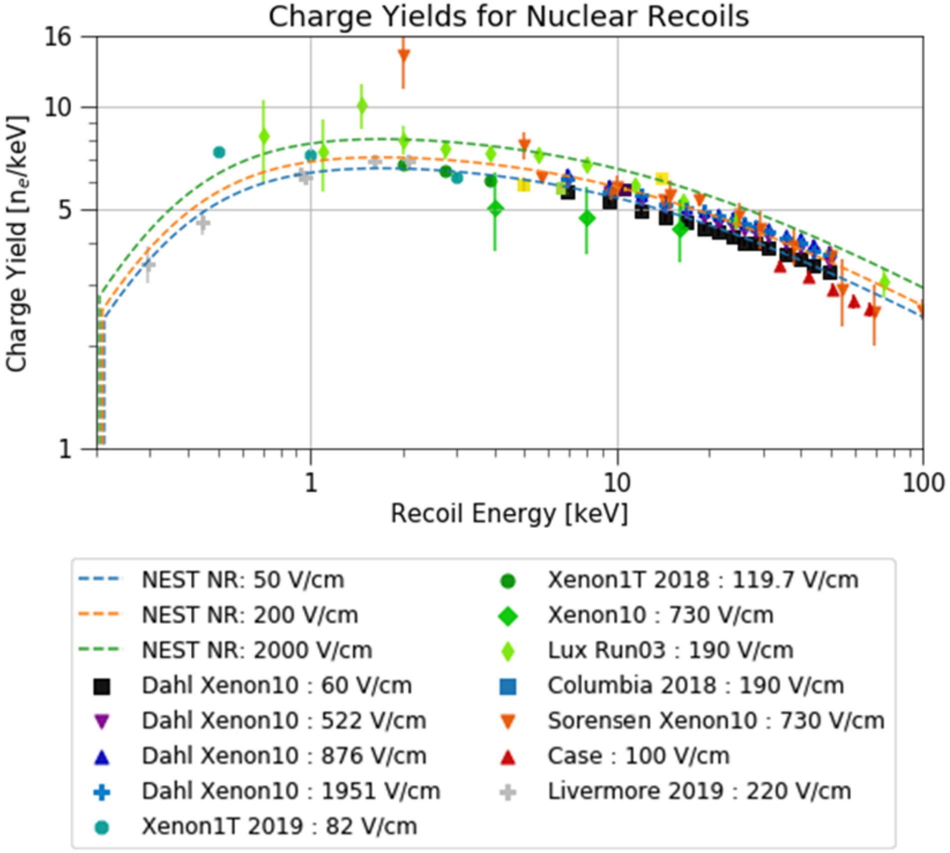
7 years ago

There were no data < 4 keV_{nr}



We considered
"optimistic" and "realistic" scenarios

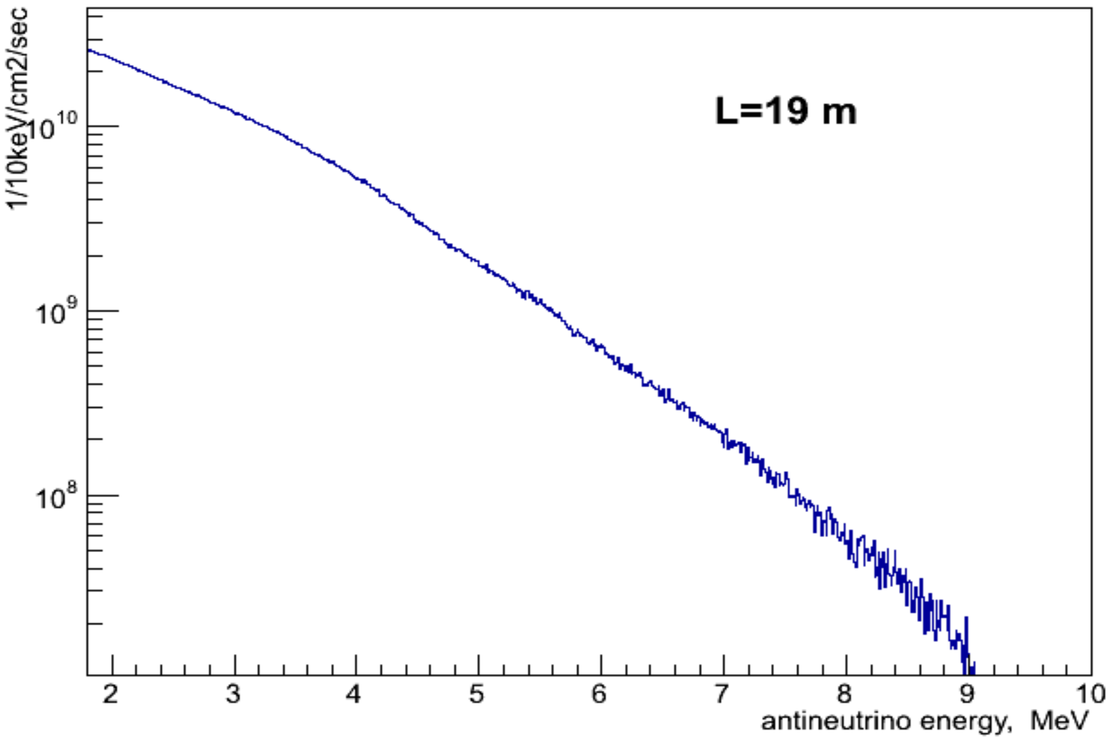
Now



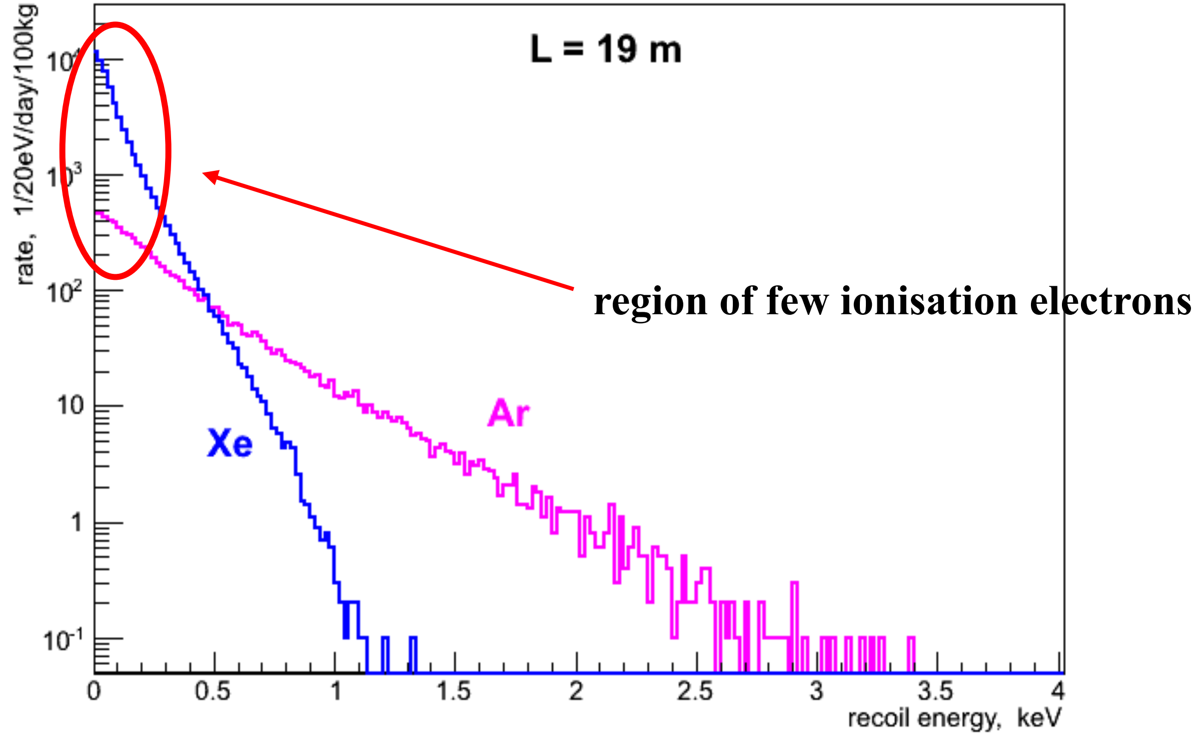
From Akimov D. talk @ INSTR20

Energy spectrum

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



Xe and Ar nuclear recoil spectra

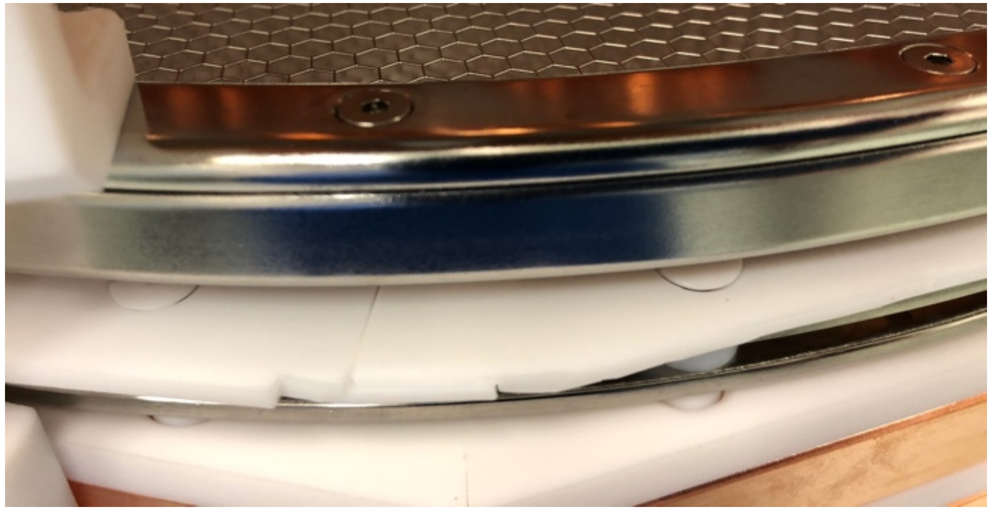


This is very challenging task, but feasible!

Additional improvements to improve CEvNS/bckg

1 To increase EEE by increasing extraction (G2-A) electric field ⟹ CEνNS signal ⇧, however SE rate ⇧, but not significantly

For this purpose, additional Teflon isolator is installed between G2 and A



2 To introduce smart blocking for the muon events: the higher muon deposited energy, the longer blocking time of the shutter (up to several hundred ms)

3 To study the influence of LXe purity on the rate of spontaneous SE events

4 To improve algorithm of of point-like events selection

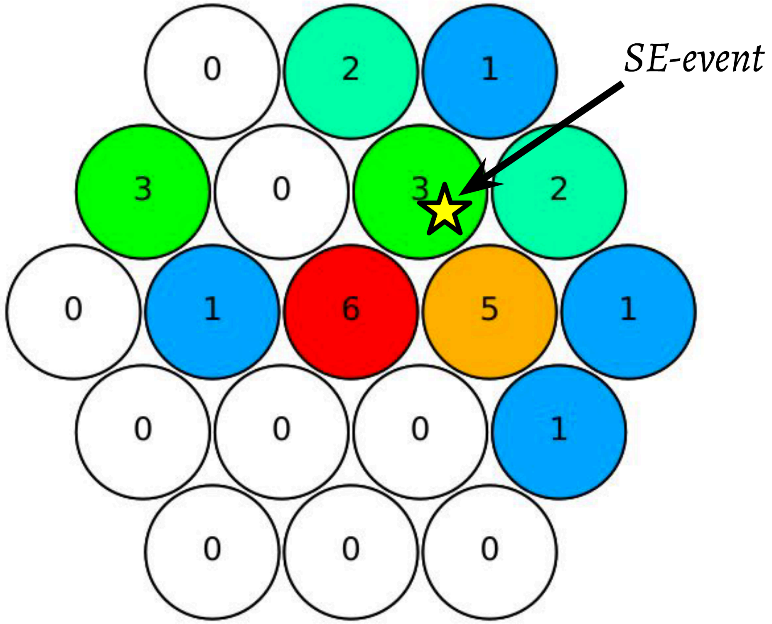
Simulating of optical photons distribution

The optical simulation of RED-100 is done via ANTS-2 software. Number of photons in electroluminescence from single electron was estimated with NEST code (v.2.0.1)

The simulated event is a set of numbers of photons detected by each PMT in top array.
Simulated events: 1SE, 2SE, …, 6SE

Background events: 1+1, 1+1+1, 2+1, 2+2, 1+3… (sum≤6) in different points uniformly scattered on the XY plane.

CEvNS events: 2,3,4,5 or 6 SE in one point

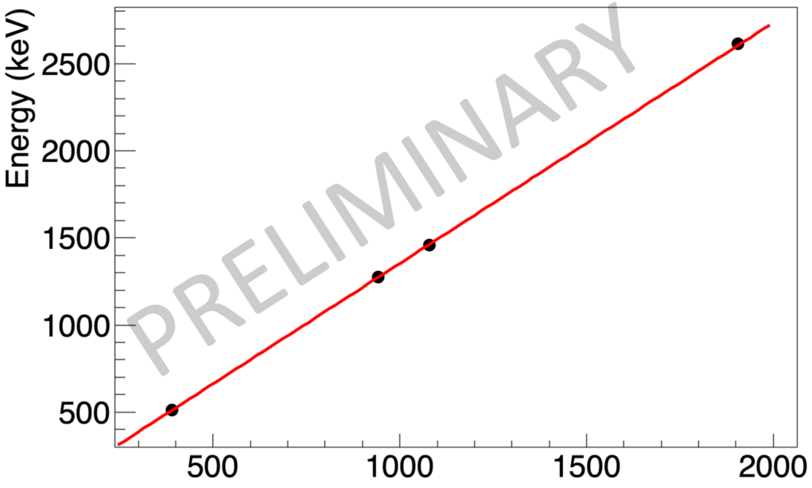


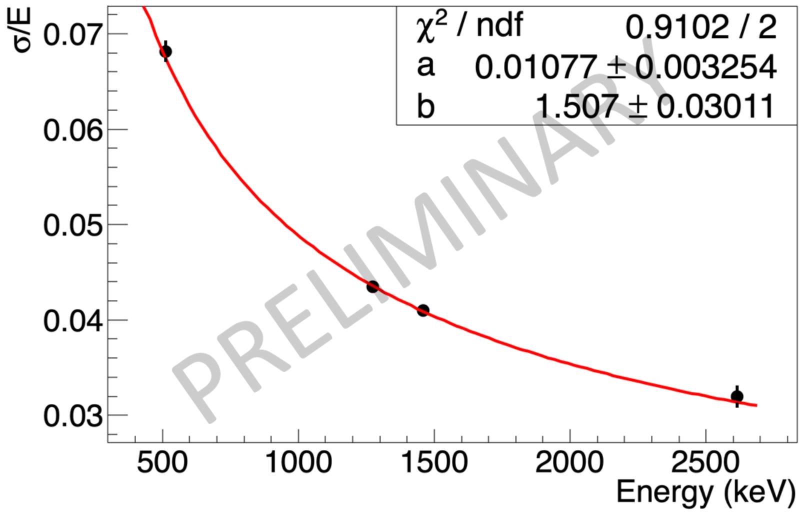
Example of simulated event (1 SE)
Numbers in circles are the detected photons by PMTs in top plane.

A. Morozov, et al. "ANTS2 package: simulation and experimental data processing for Anger camera type detectors." Journal of Instrumentation 11.04 (2016): P04022.

Background measurements with NaI[Tl]

- Calibrated NaI[Tl] detector was used for the background study
- Thick Cu+Pb shielding was used to get internal + muons background
  - 15 cm of Pb from the bottom
  - At least 15 cm Cu from each side
  - 5 cm Pb belt
- Publication is under preparation





Gamma background @ KNPP measured by DANSS colab.

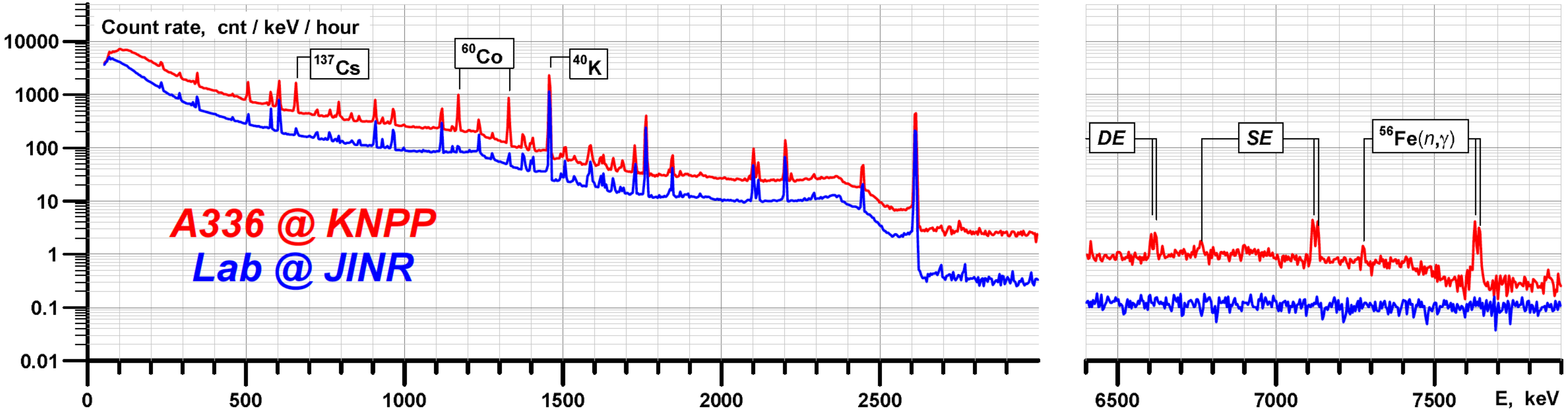


Figure 2: Gamma-background measured with 1.3 kg HPGe detector at the DANSS position in the KNPP room A336 and in the JINR laboratory.

arXiv:1606.02896v3