The RED-100 results&prospects

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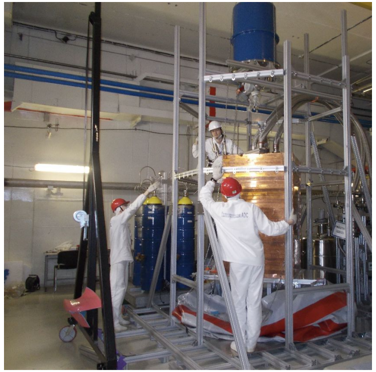
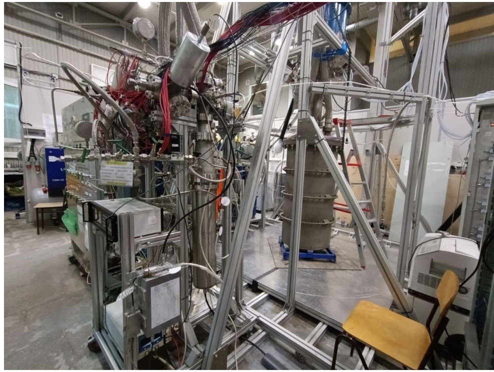


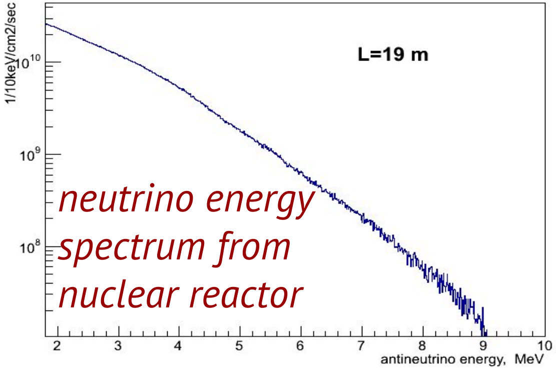


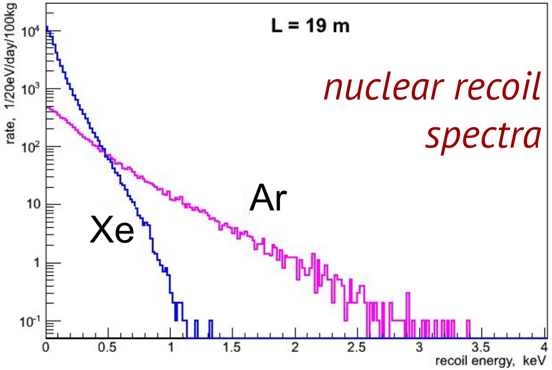
Magnificent CEvNS 2024

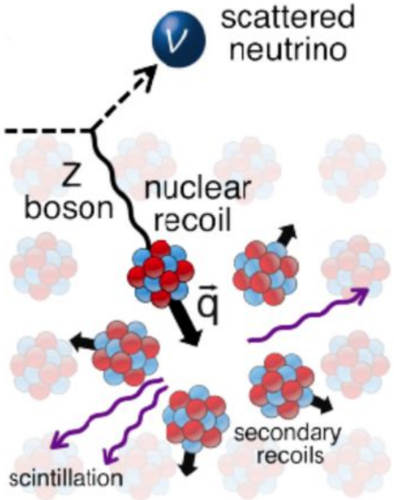
Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\Big([1-4\sin^2\theta_W]Z - N\Big)^2\Big[1-\frac{T}{T_{max}}\Big]F_{nucl}^2(q^2) \propto N^2$$

$$T_{max} = 2E_\nu^2/(M+2E_\nu)$$







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

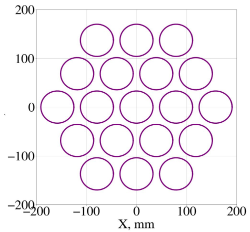
Motivation of experiments:

- fundamental physics (supernova dynamics)
- SM verification
- practical goals (monitoring of nuclear reactors)

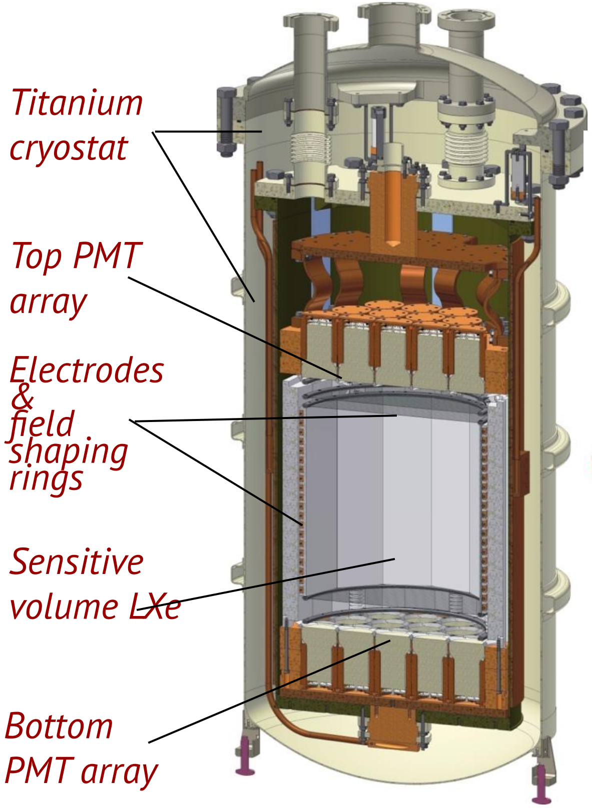
D.Z. Freedman, Phys. Rev. D 9 (1974) 1389
D.Akimov, J. Albert, P. An et.al., Science. – 2017.
Kopeliovich V B, et.al., JETP Lett. 19 145 (1974); Pis'ma Zh. Eksp. Teor. Fiz. 19 236 (1974)

RED-100 detector

- Contains
~200 kg of LXe
(~ 100 kg in the active volume)
or ~100 kg of LAr
(~50 kg in the active volume)
- 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)

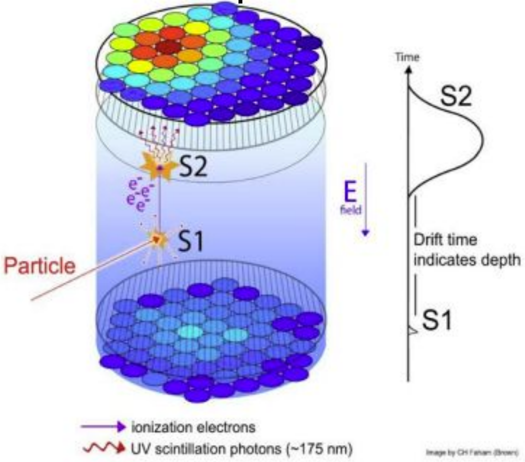


[B. A. Dolgoshein et al, JETP Lett. 11, 513 (1970)]

[D.Y. Akimov et al 2020 JINST **15** P02020]

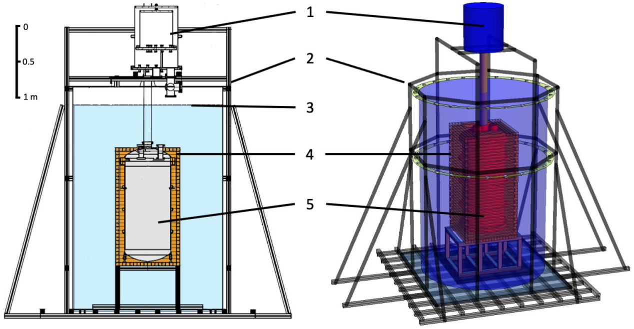
Two-phase emission detector technique

- is widely used in dark matter experiments



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

RED-100 at Kalinin NPP



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 gammas
- 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

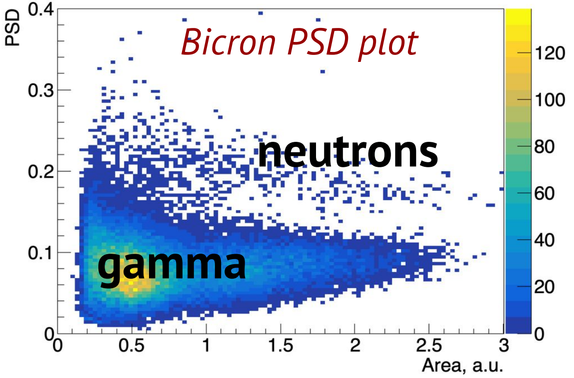
[Akimov D.Y., et al. JINST 17.11 (2022), T11011]

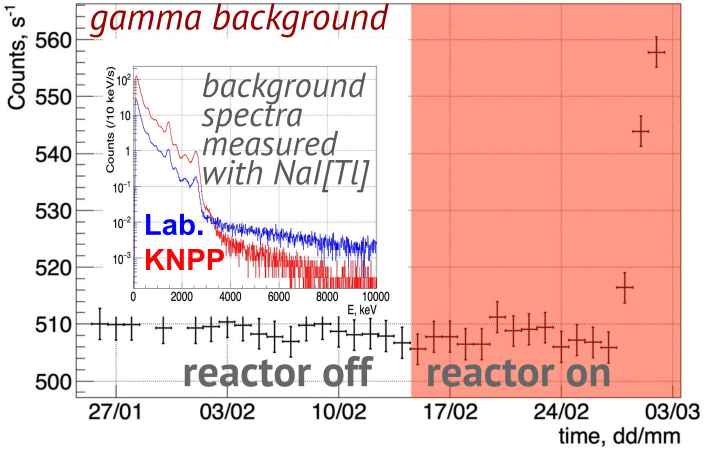
External background conditions

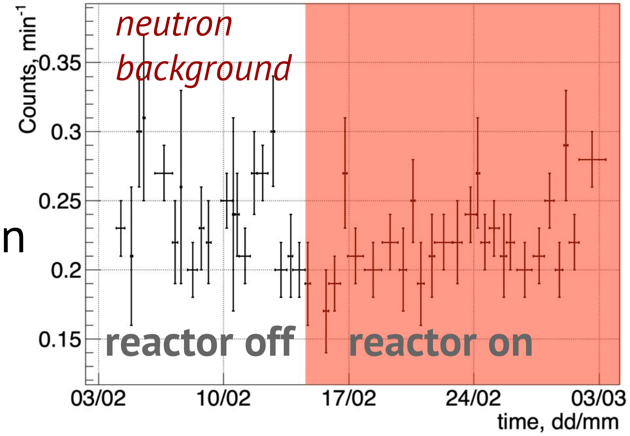
- background was measured with RED-100 itself and with different additional detectors:

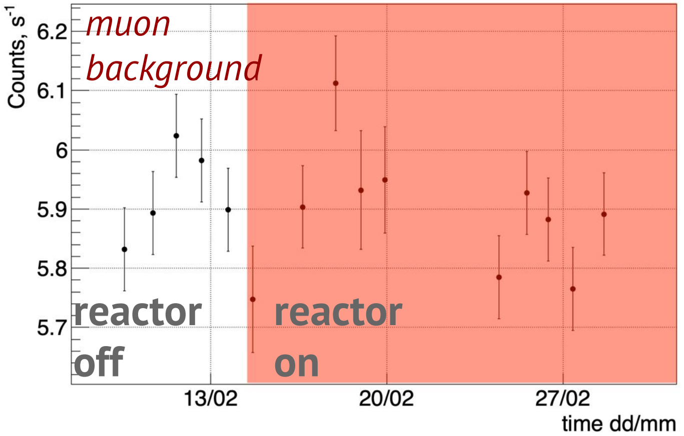
  – NaI[Tl] – gamma background

  – Bicron (BC501A liquid scintillator) – neutron background
- muon background (source of the random SE) was measured using RED-100
- no significant correlation in external background count rate with reactor operation





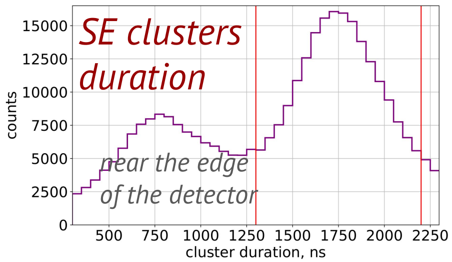


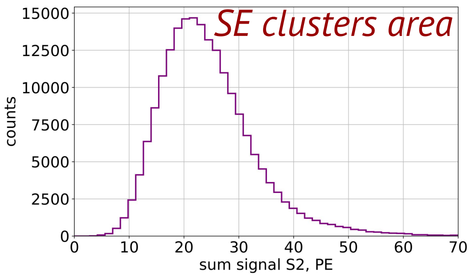


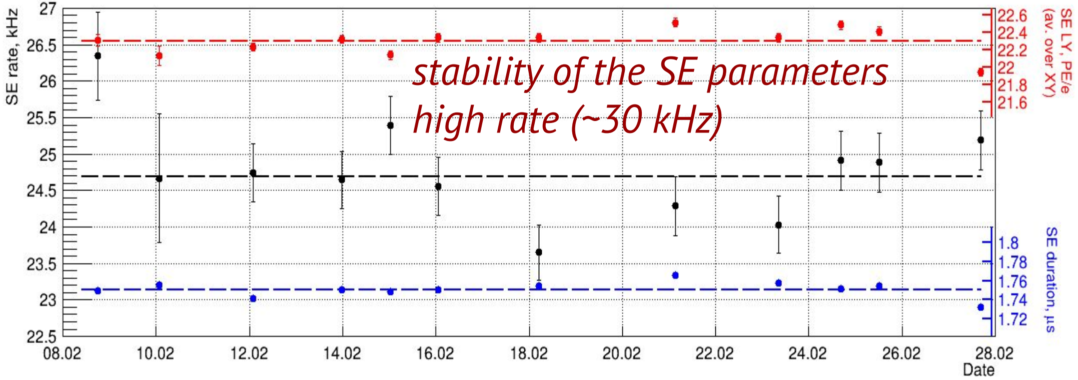
[D.Y. Akimov et al 2023 JINST **18** P12002](#)

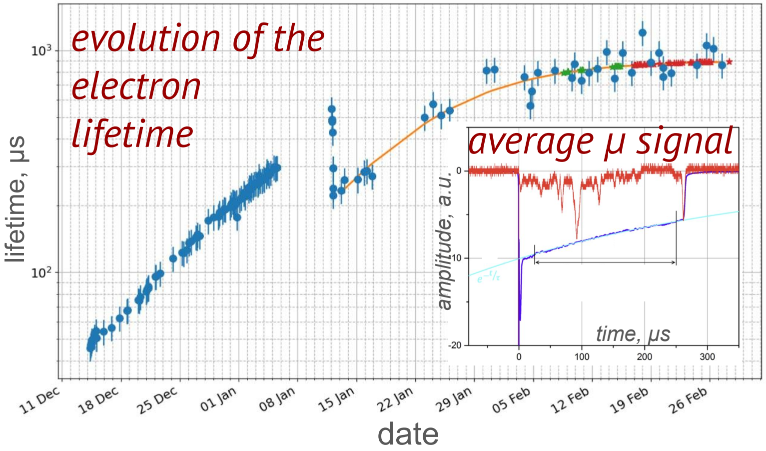
Calibration and characterization of the detector

- LED calibration (for the SPE parametrization)
- SE (single electron) calibration (with zero hardware threshold)
- calibration with the cosmic muons (for the electron lifetime measurement)



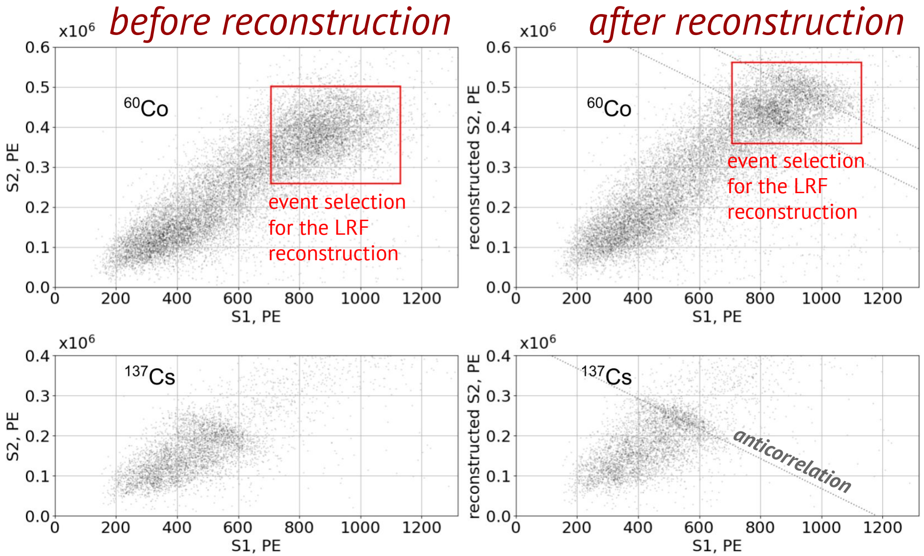


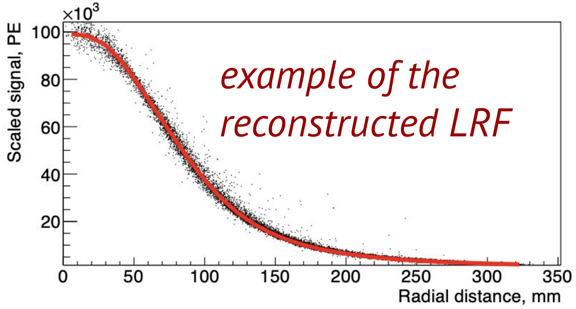


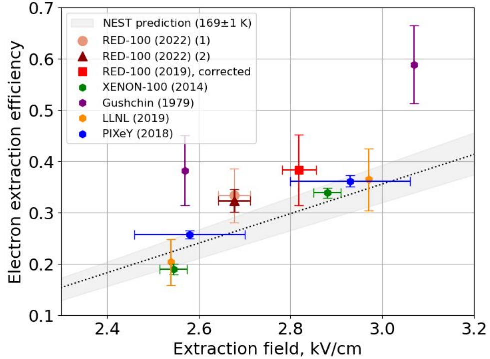


https://arxiv.org/abs/2403.12645

Calibration and characterization of the detector







- calibration with gamma-sources (^{137}Cs and ^{60}Co) for the light response functions (LRFs) reconstruction with ANTS2
- LRFs were used for the position and energy reconstruction of all data types

- electron extraction efficiency (EEE) was calculated with two approaches:

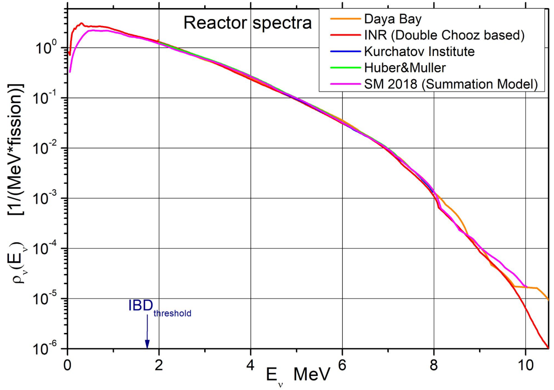
– *using comparison visible QY with NEST QY prediction*

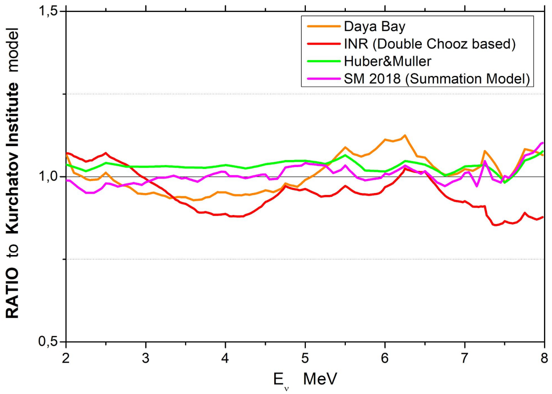
– *using S1-S2 anticorrelation coefficient*

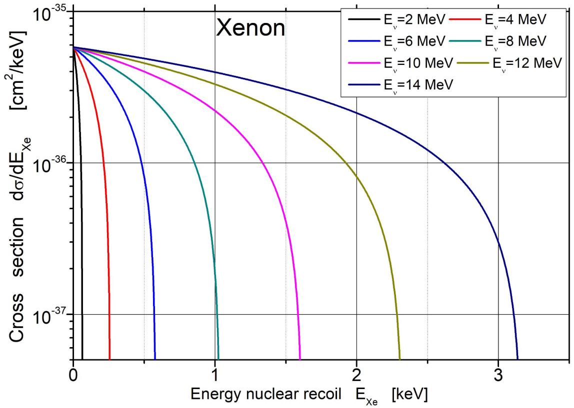
https://arxiv.org/abs/2403.12645

A. Morozov et al 2016 JINST **11** P04022

Reactor antineutrino spectra

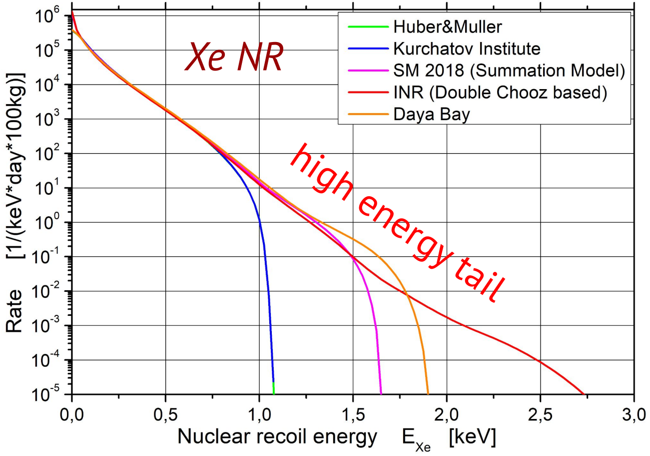






CEvNS cross section

- contribution of the high energy tail is significant in our ROI (>4 extracted ionization electrons)
- the partial shares of the isotopes of nuclear fuel were considered unchanged throughout the data taken period
- the average energy per fission is ~205.3 MeV

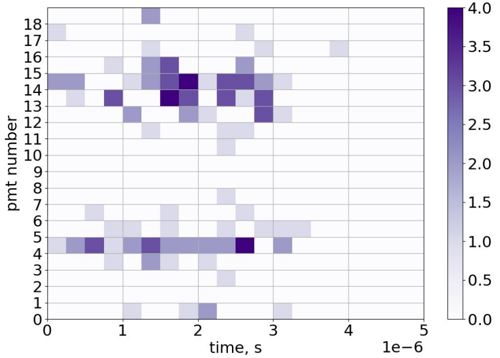


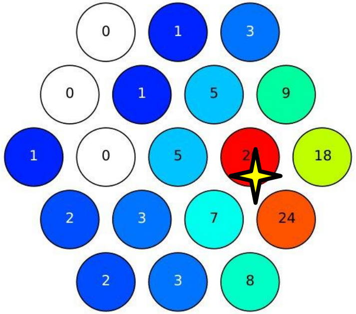
T. A. Mueller et al, Phys. Rev. C 83, 054615 (2011)
P. Huber, Phys. Rev. C 84, 024617 (2012)
V. I. Kopeikin et al, Phys. Rev. D 104, L071301 (2021)
M. Estienne et al, Phys. Rev. Lett. 123, 022502 (2019)
F. P. An et al, Chinese Physics C 45, 073001 (2021)

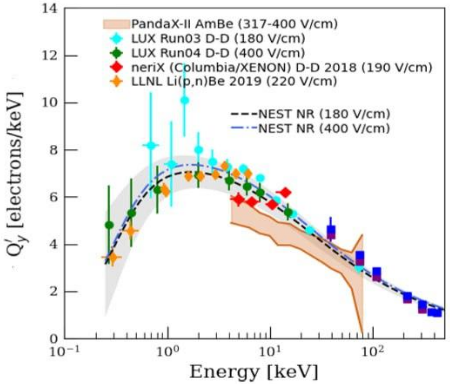
CEvNS simulation

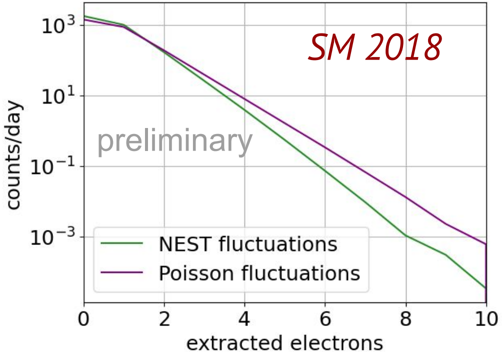
- charge yield was calculated using NEST v 2.4
- significant dependence on the charge yield dispersion model

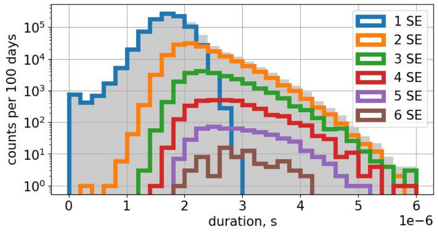
example of the simulated 6SE event

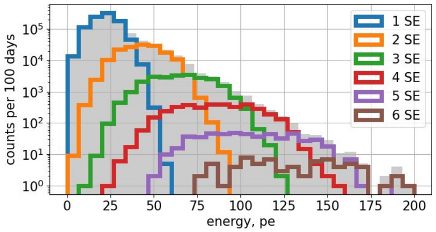












- The Poisson fluctuations model is based on assumption that QY is a result of counting experiment
- The NEST fluctuations model is based on the mechanism of total quanta distribution to scintillation and ionization channels with correction to non-binomal component

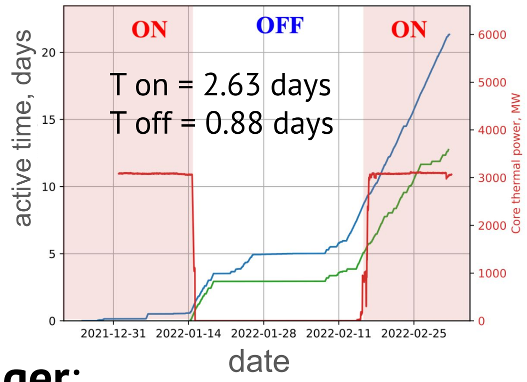
Signal simulation:

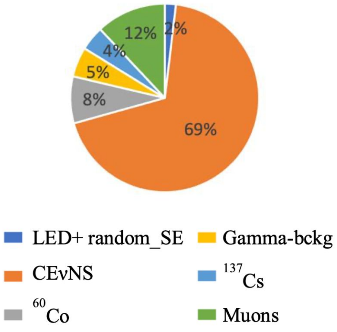
- every signal consists of several SE signals
- SE signals were simulated using measured SE parameters and reconstructed LRFs

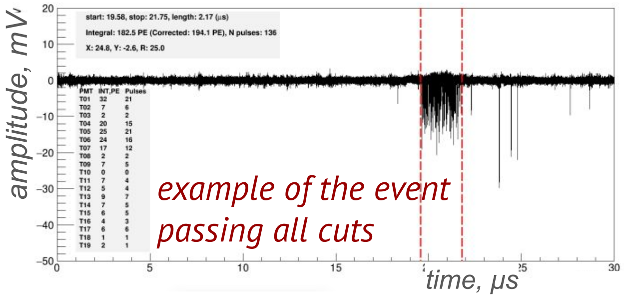
https://nest.physics.ucdavis.edu/

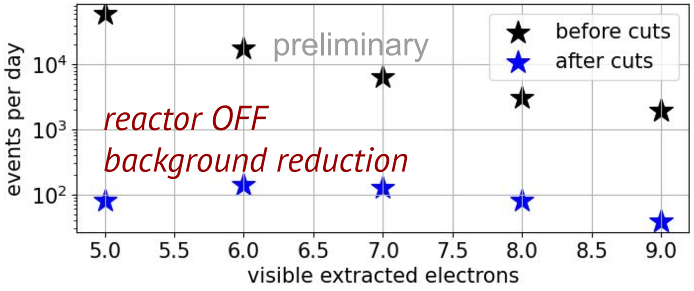
Data in ROI

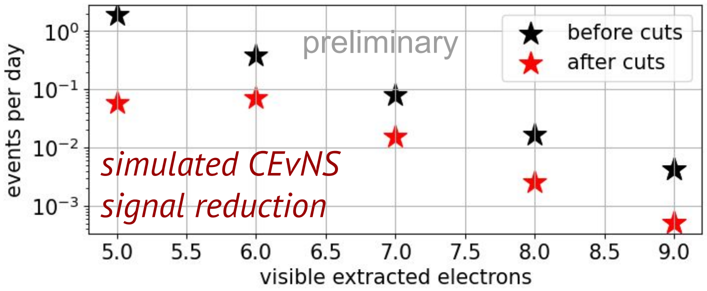
Data collection at KNPP





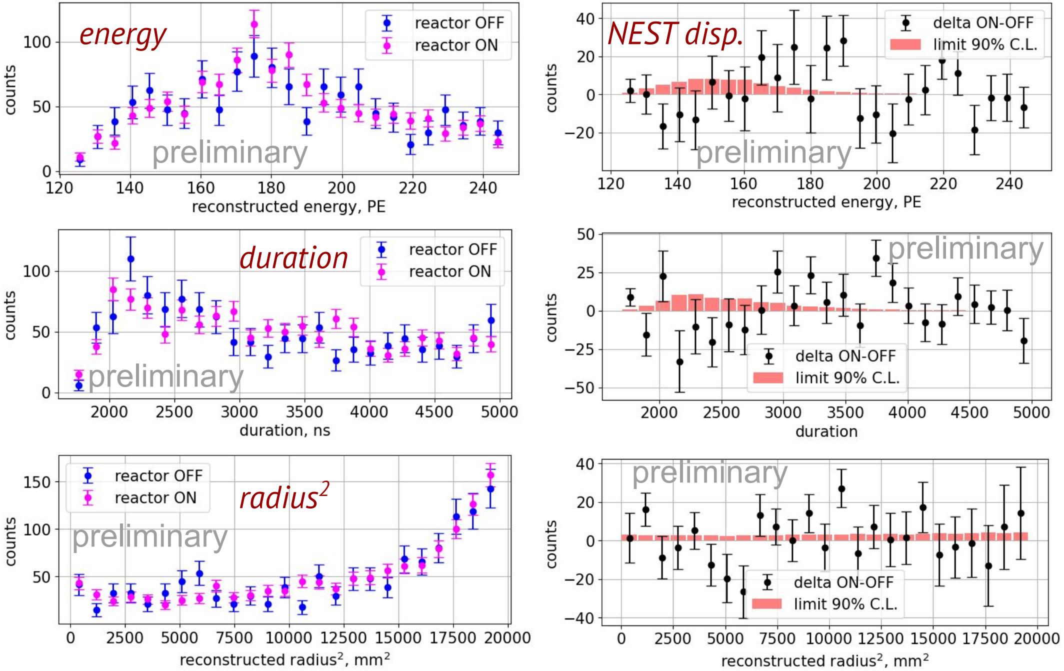




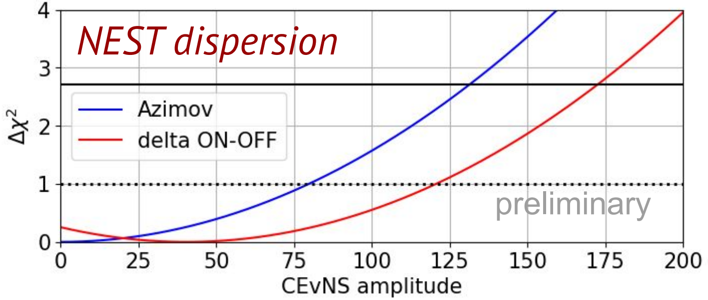


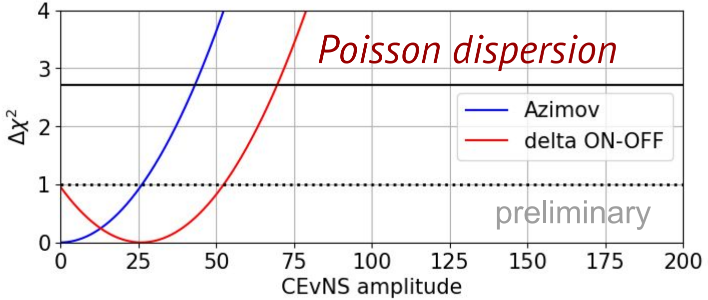
- **Trigger**:
  – counts SPEs in individual channels in 2μs time
  – veto on the high SPE rate
  – vetos after muons and gammas
  – has livetime ~60%
- **Cuts**:
  – on the number of random pulses on the wf
  – on the energy (>4.5 visible ionization electrons)
  – on the reconstructed radius (<140 mm)
  – on the duration (cut depends on energy)
  – pointlike cut by two neural networks

reactor ON - reactor OFF analysis



- combined histogram (reconstructed energy+radius+duration)
- Azimov dataset for sensitivity calculation
- delta ON-OFF for CEvNS limit calculation





- ***90% C.L.:***

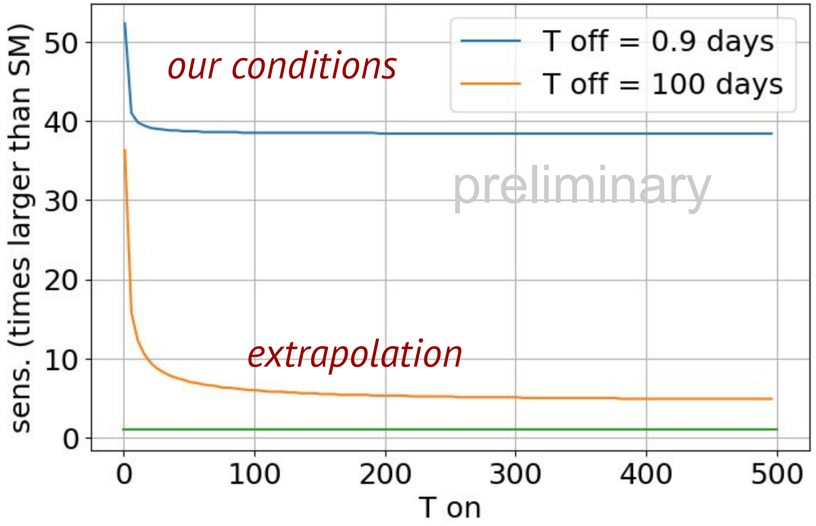
NEST fluctuations: sensitivity ~131 and upper limit ~172
Poisson fluctuations: sensitivity ~43 and upper limit ~70
(times larger than SM prediction)

Significant dependence on the fluctuations model!

Overview LXe results

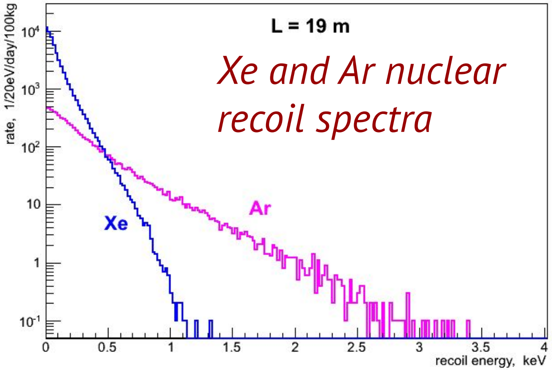
- the possibility of the detector operation with stable parameters at NPP was demonstrated
- threshold 4.5 SE
- the sensitivity to single ionization electrons was shown (SEG = 27.4±0.03 SPE/SE)
- advanced data analysis methods were applied
- ~190 times background suppression in ROI (~16 times signal suppression) (NEST fluctuations)
- **unexpectable pointlike background in ROI**
- **significant result dependence on the fluctuation model**

with **optimistic** Poisson fluctuations:

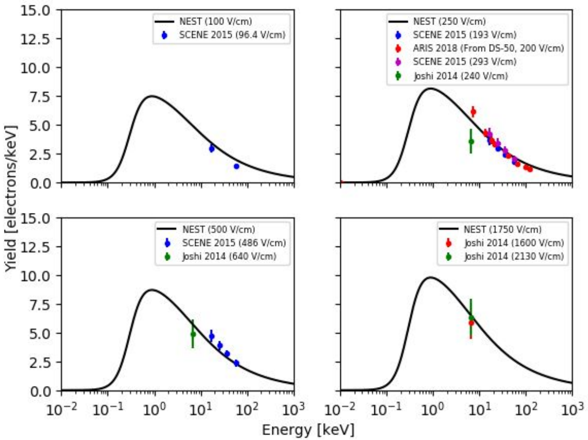


100 days reactor OFF livetime requires at least 10 years detector exposition at the KNPP

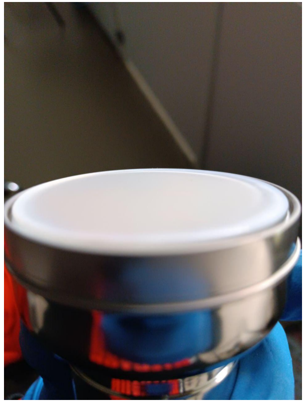
RED-100/LAr



Charge Yields in LAr



RED-100 PMT coated with TPB



- higher nuclear recoils energies → more electrons per CEvNS event
- ~100% EEE

Engineering tests are ongoing
– PMTs were coated with TPB
– the cooling system was upgraded
– the extraction field was raised to 5kV/cm
– LY and SE study is ongoing

Plans:
– test in the lab. with full shielding
– ^{39}Ar and ^{85}Kr level measurements
– calibration with ^{37}Ar

Conclusion

- RED-100 was successfully deployed and collected data at industrial NPP:
  - *stable parameters*
  - *threshold 4.5 SE*
  - *the sensitivity to single ionization electrons was shown (SEG=27.4±0.03 SPE/SE)*
  - *advanced data analysis methods were applied*
  - *~190 times background suppression in ROI (~16 times signal suppression)*
- Data analysis is almost finished
- Sensitivity and CEvNS upper limit values were calculated

  90% C.L.: *NEST fluctuations: sensitivity ~131 and upper limit ~172*

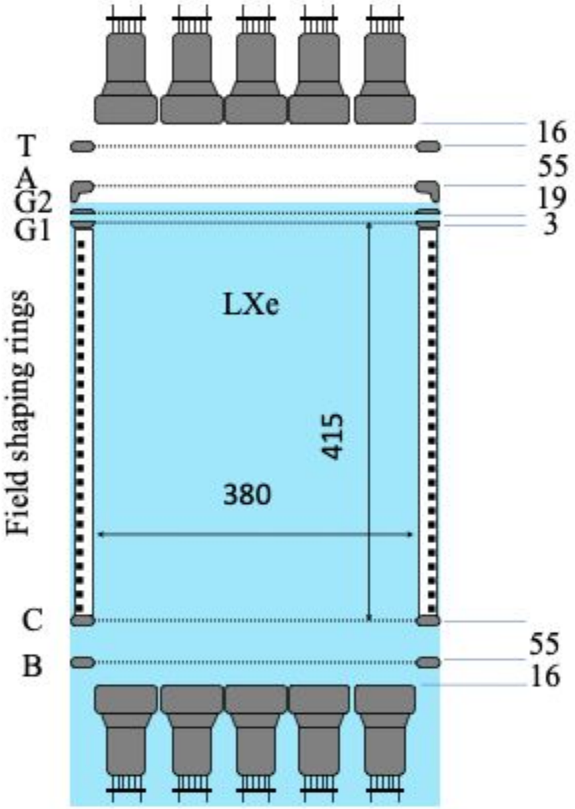
  Poisson fluctuations: sensitivity ~43 and upper limit ~70

  (times larger than SM prediction)
- Upgrade with LAr is ongoing

Thank you for your attention!

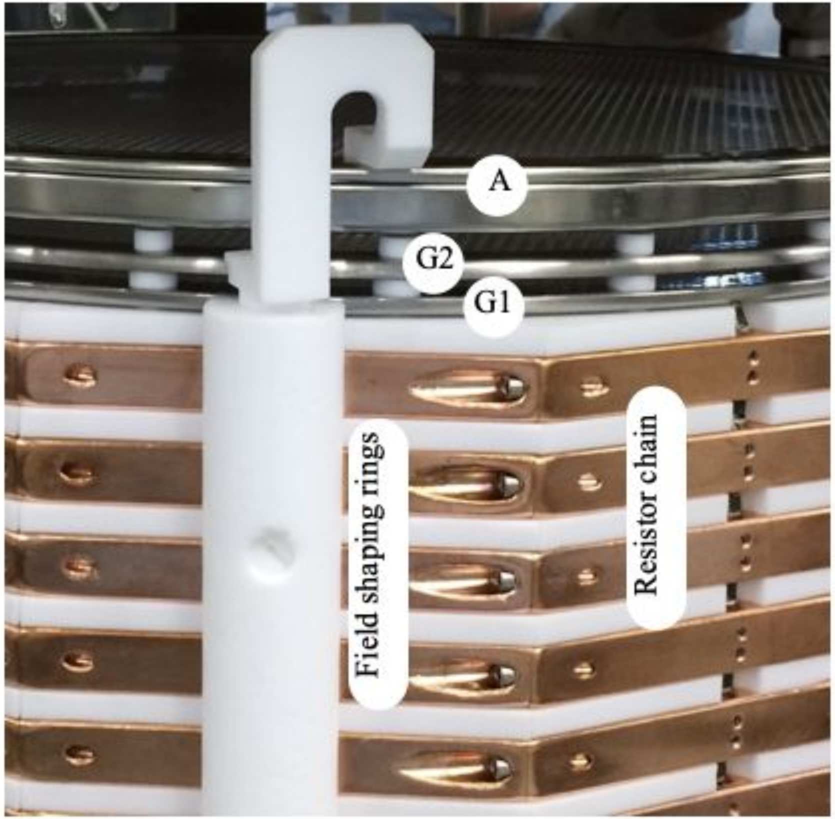
Backup

RED-100: schematic layout of grids and PMTs



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

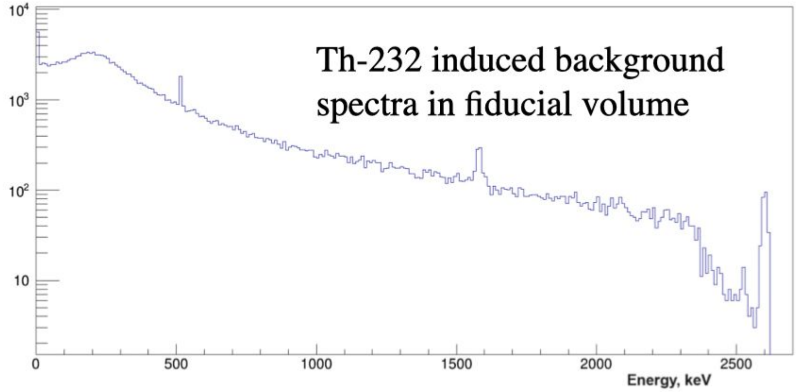
T and B – top and bottom grounded grids,
A – anode grid,
G1 – electron shutter grid,
G2 – extraction grid,
C – cathode grid



RED-100 backgrounds

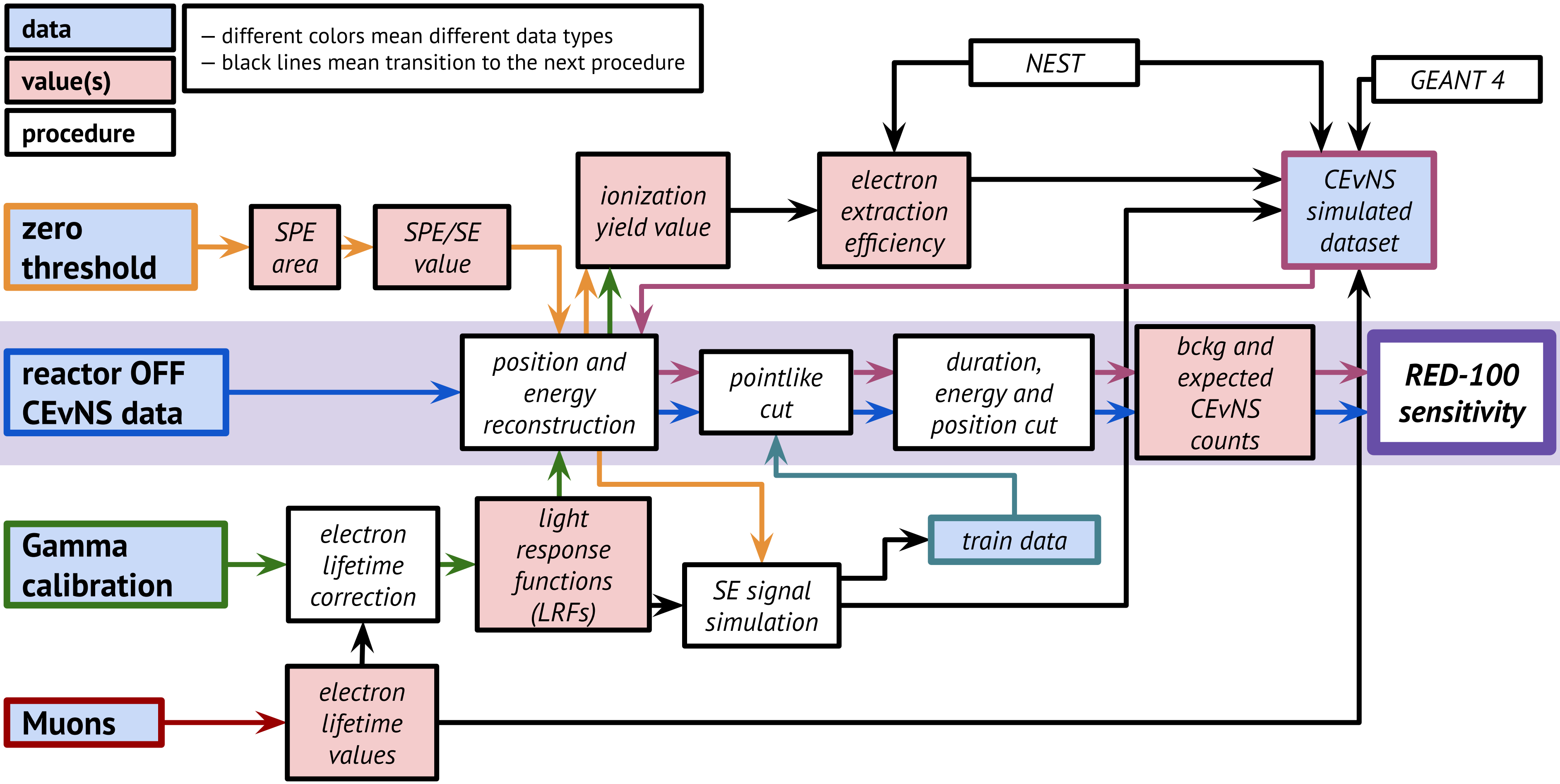
- Neutron background was measured by additional BC501A Bicron detector and simulated in RED100-MC model
  - Estimated amount of ROI events is ~1 event/day
- Muon-induced background simulations were based on experimentally observed muon angular distributions
  - Estimated amount of ROI events is ~30 events/day

https://arxiv.org/abs/2311.00870



- According to our and DANNS group measurements, external gamma background is caused by Th-232, U-238 and K-40 decay chains in concrete
- Gamma simulation is currently ongoing

Analysis scheme (reactor OFF data)



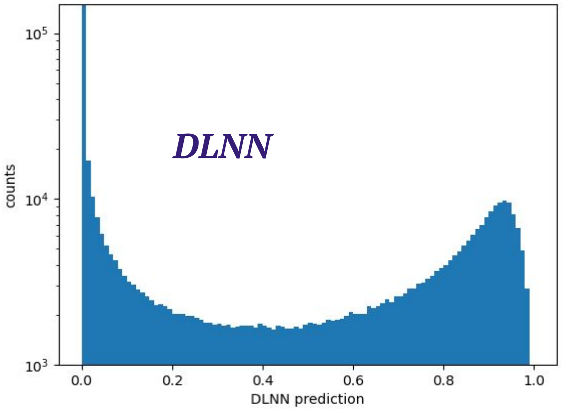
Neural networks

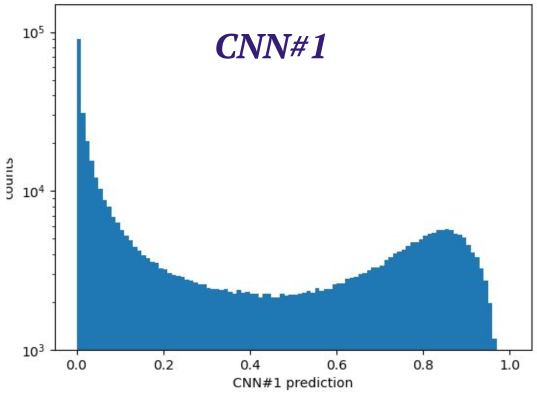
— significant part of real background is pointlike
— now we use optimized on sensitivity 2d cut based on DLNN and CNN#1:

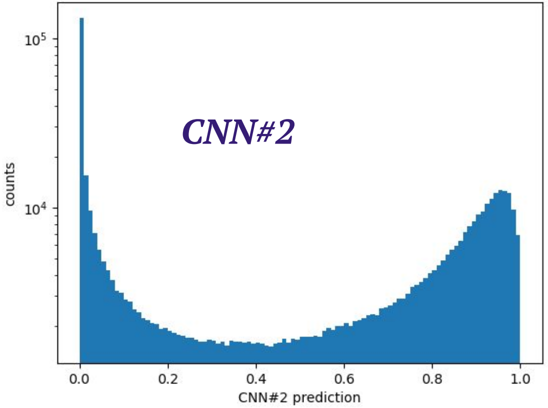
DLNN threshold: 0.6
CNN#1 threshold: 0.2

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

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





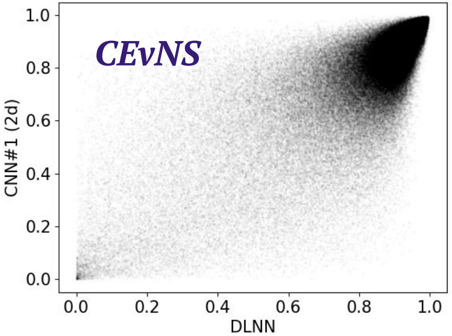


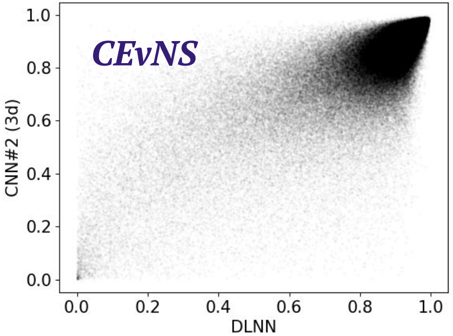
NNs predictions on real data. *A lot of background events with high probability to be pointlike.*

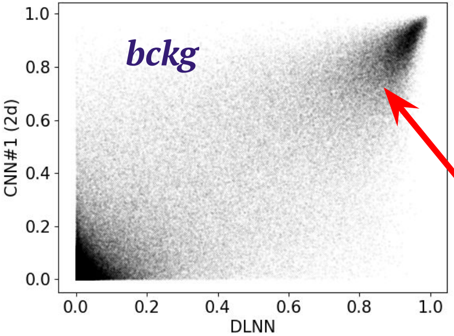
Comparison using test dataset

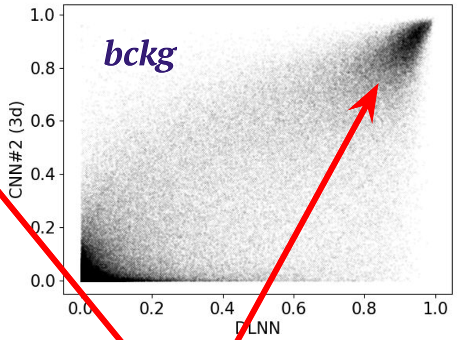
— there is a correlation between NN predictions on validation dataset

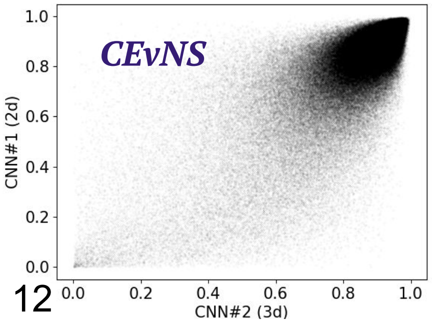
2d distributions with NNs predictions *(probability of pointlikeness according to NNs)*



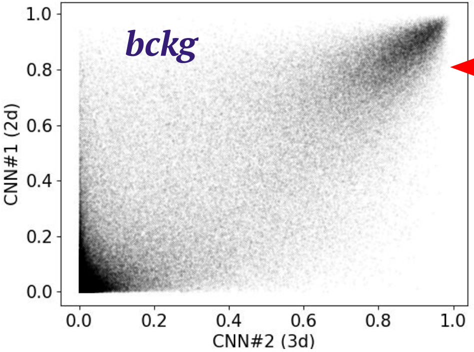






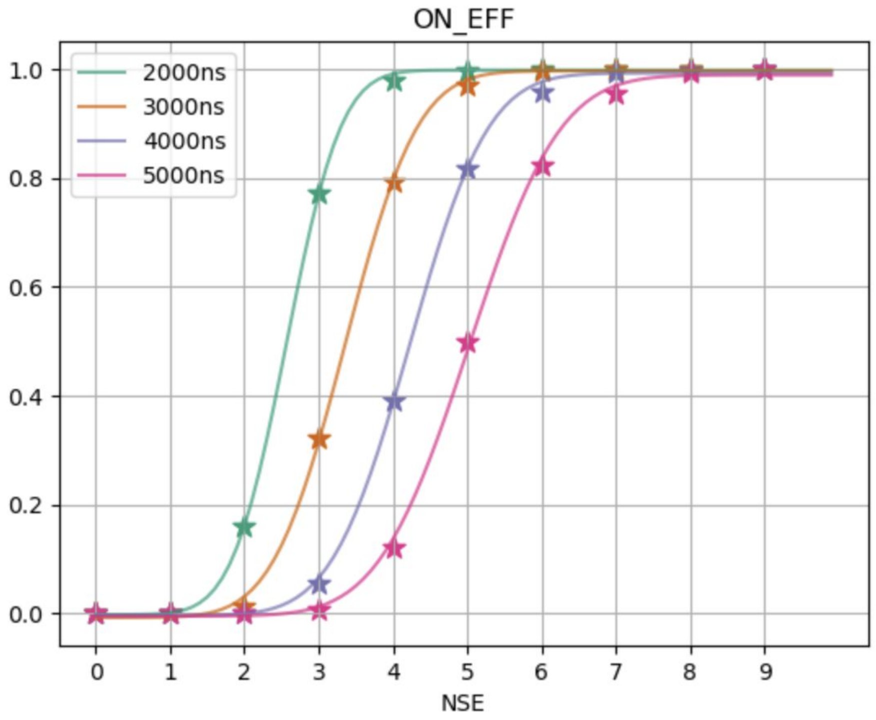


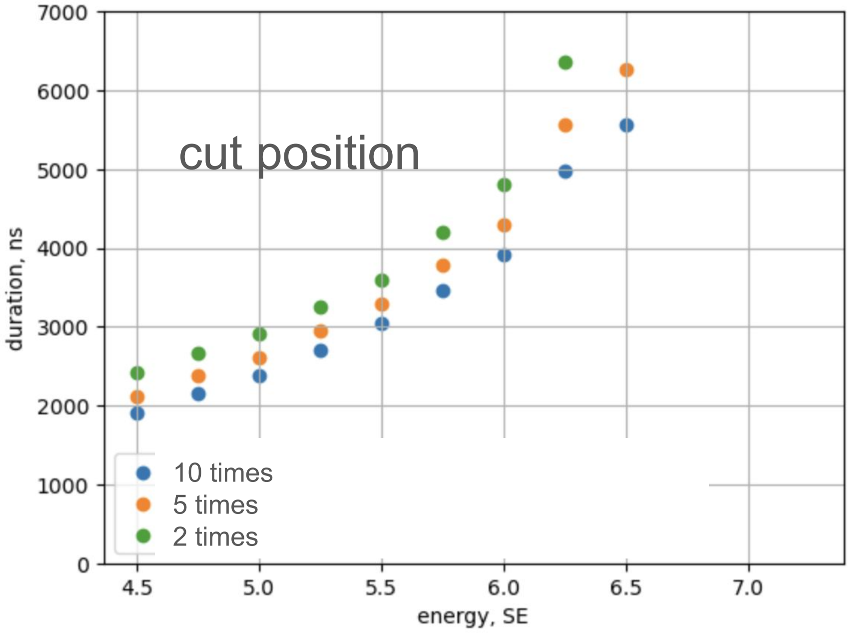
Pointlike events concentrate in one place

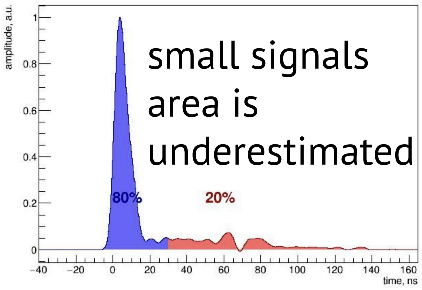


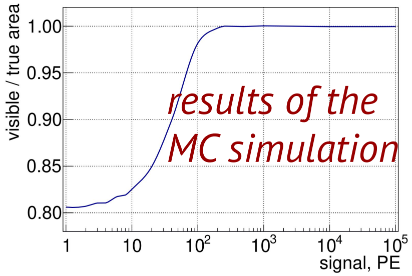
a lot of background events with high probability to be pointlike

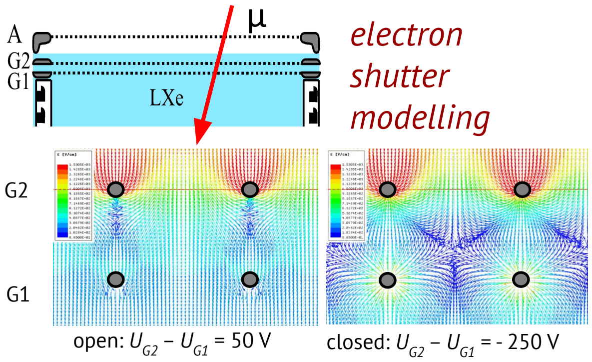
Trigger efficiency dependence on temperature











- **Electron shutter**:
  – To block the muon signals and minimize short component of SE background
  – Still very high SE rate (30 kHz)