NATIONAL RESEARCH NUCLEAR UNIVERSITY «MEPhI»
Institute for Nuclear Physics & Technology

Laboratory for Experimental Nuclear Physics
http://enpl.mephi.ru/

РОССИЙСКИЙ ЭМИССИОННЫЙ ДЕТЕКТОР

Alexander Bolozdynya

Review of achievements in the development of two-phase emission detector technology and setting up experiments in modern particle physics

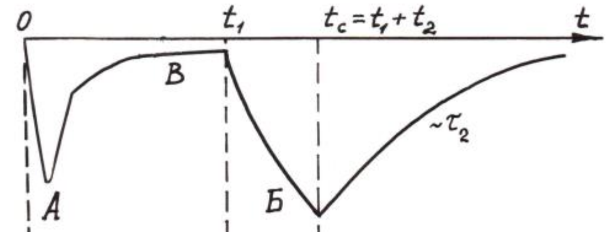
ICPPA
25 October 2024

The birth of Technology

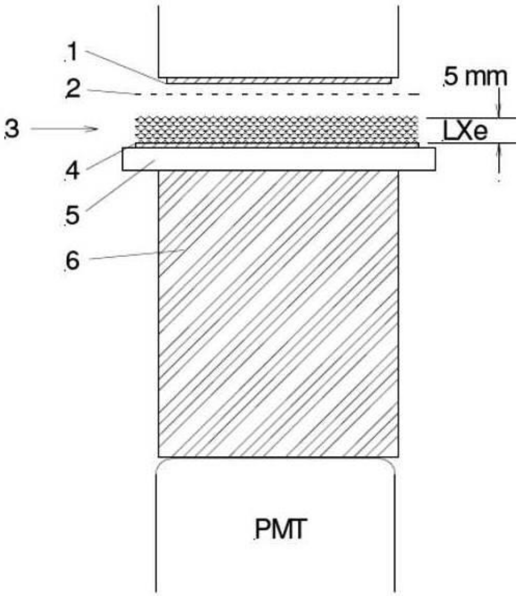
1976-1983 First Electroluminescence Emission Detectors (MEPhI)

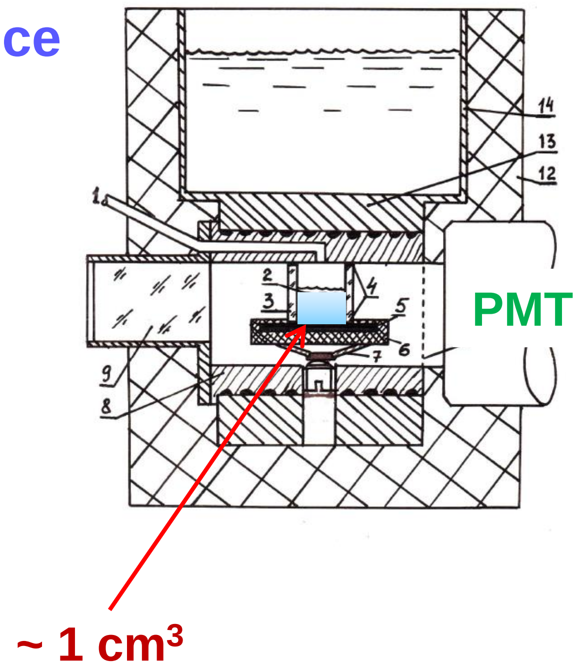
***S1* - Scintillation**

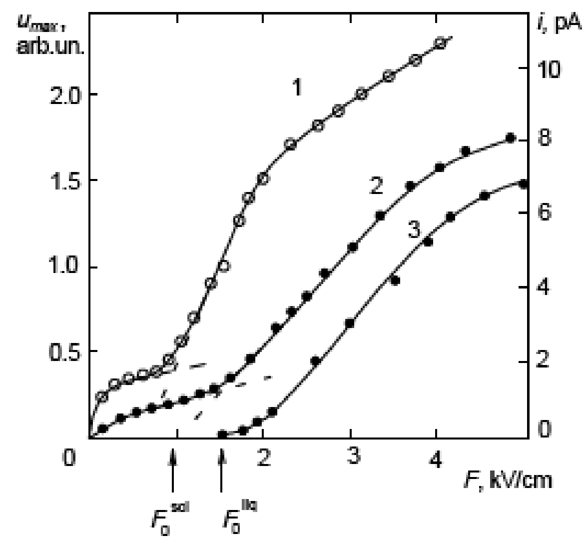
***S2* - Electroluminescence**



S1 **S2**





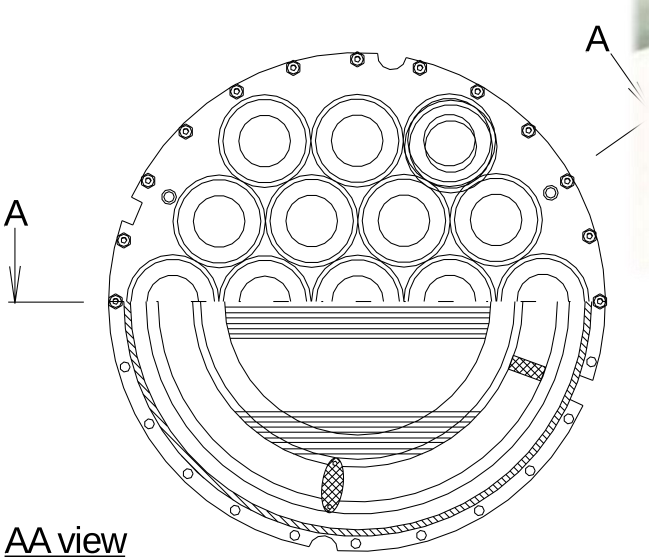


Lansiart A. Seigneur A., Moretti J.-L., Morucci J.P. Development research on a highly luminous condensed xenon scintillator. *Nucl. Instrum. Meth.* 135(1976)47-52

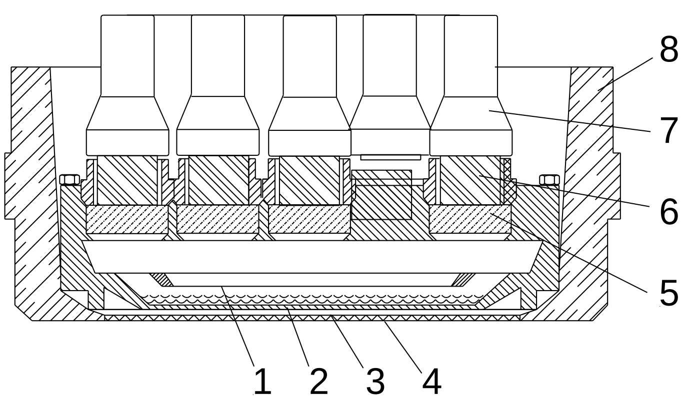
Bolozdynya A., Miroshnichenko V. Rodionov B. Electrostatic emission of free electrons from liquid and solid argon. *Letter in Journal of Technical Physics* 2(1977)64-67 (in Russian).

1983-1985 Electroluminescence Emission Gamma-Camera for Nuclear Medicine

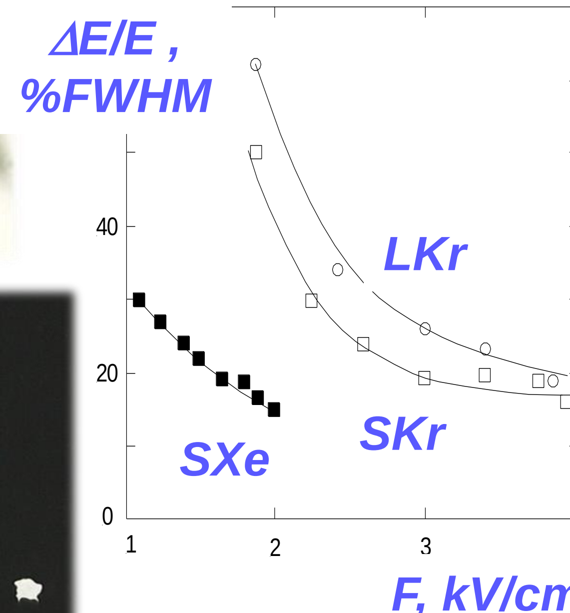
Medal of USSR Academy of Science

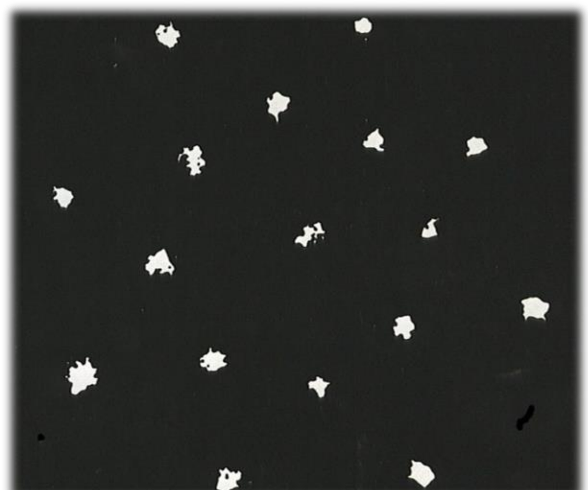


AA view



MEPhI / ITEP

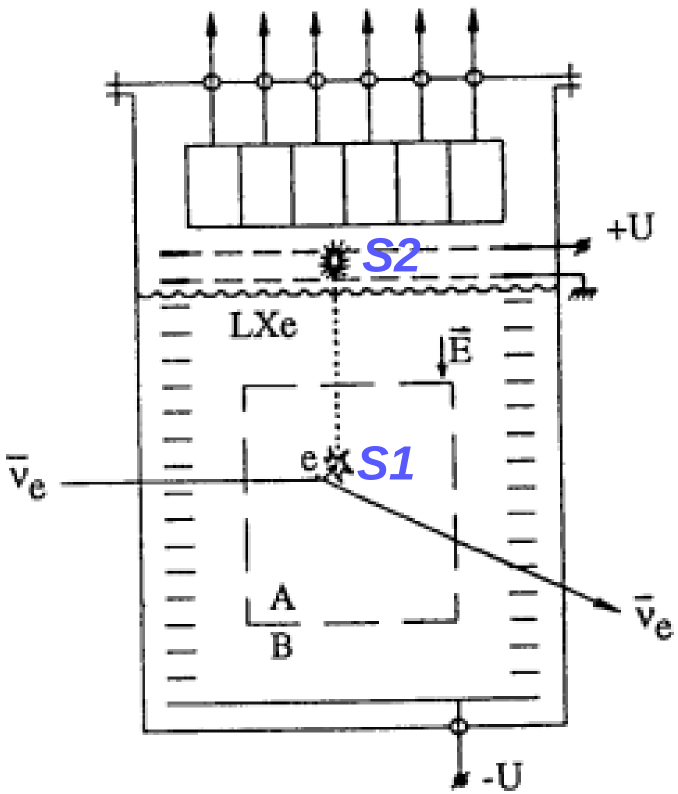




S2 = f(x,y)   122 keV

Egorov, V. V., Miroshnichenko, V. P., Rodionov, B. U., Bolozdynya, A. I., Kalashnikov, S. D. and Krivoshein, V. L. Electroluminescence emission gamma-camera *Nucl. Instrum. Meth.* 205 (1983) 373-374.

1995 The idea of the "wall-less" principle of particle detection with two-phase emission detectors



Emission detectors are extremely sensitive to low ion radiation even if it produces only single electrons in condensed matter. They are proposed for use as imaging detectors in different fields: in underground physics for searching cold dark matter and double beta-decay, for measuring magnetic moment of neutrino, and in nuclear medicine for gamma imaging.

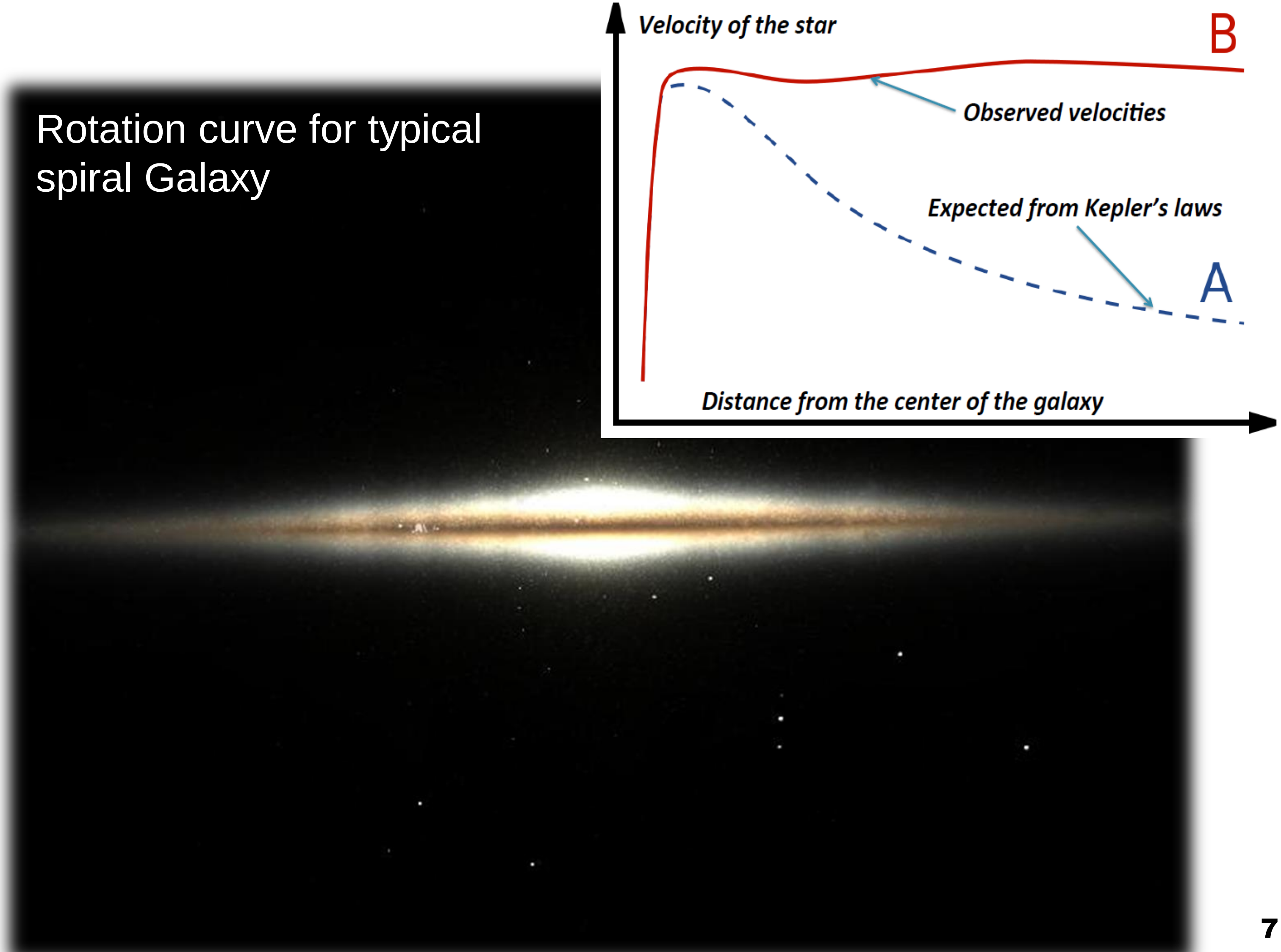
Two-phase emission detectors

1) are sensitive to single ionization electrons;
2) 3D position sensitive for "point-like" events;
3) can provide «wall-free» detection technology;
4) may have a big mass of working medium;
5) can be used for
   (1) dark matter search,
   (2) neutrino detection,
   (3) double beta decay search

A. Bolozdynya, V. Egorov, V. Miroshnichenko, B. Rodionov.
IEEE Trans. Nucl. Sci. 42 (1995) 565-569

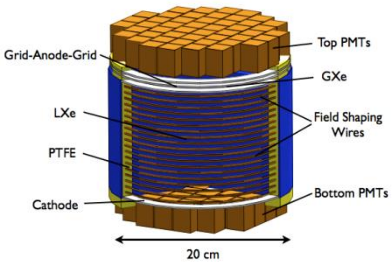
Dark Matter
Search Experiments

A problem of the «mass deficit» in the Universe

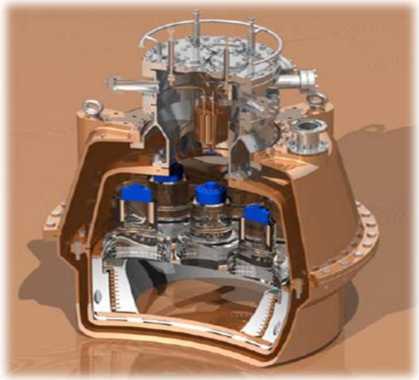


2003-2024

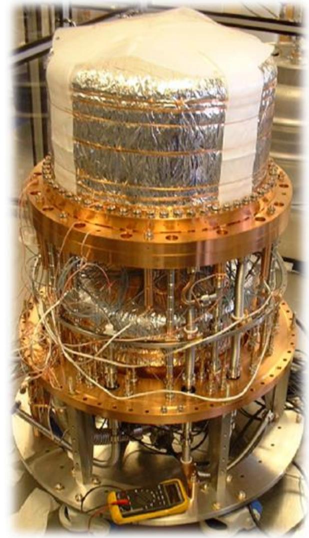
Emission detectors to search for Dark Matter



XENON 10



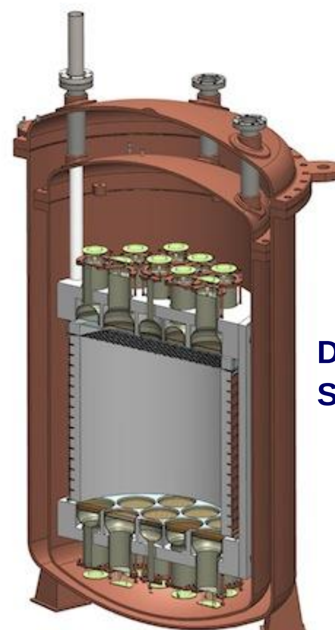
ZEPLIN II



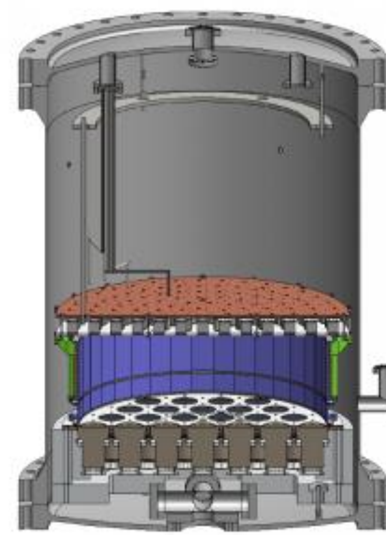
ZEPLIN III

LUX

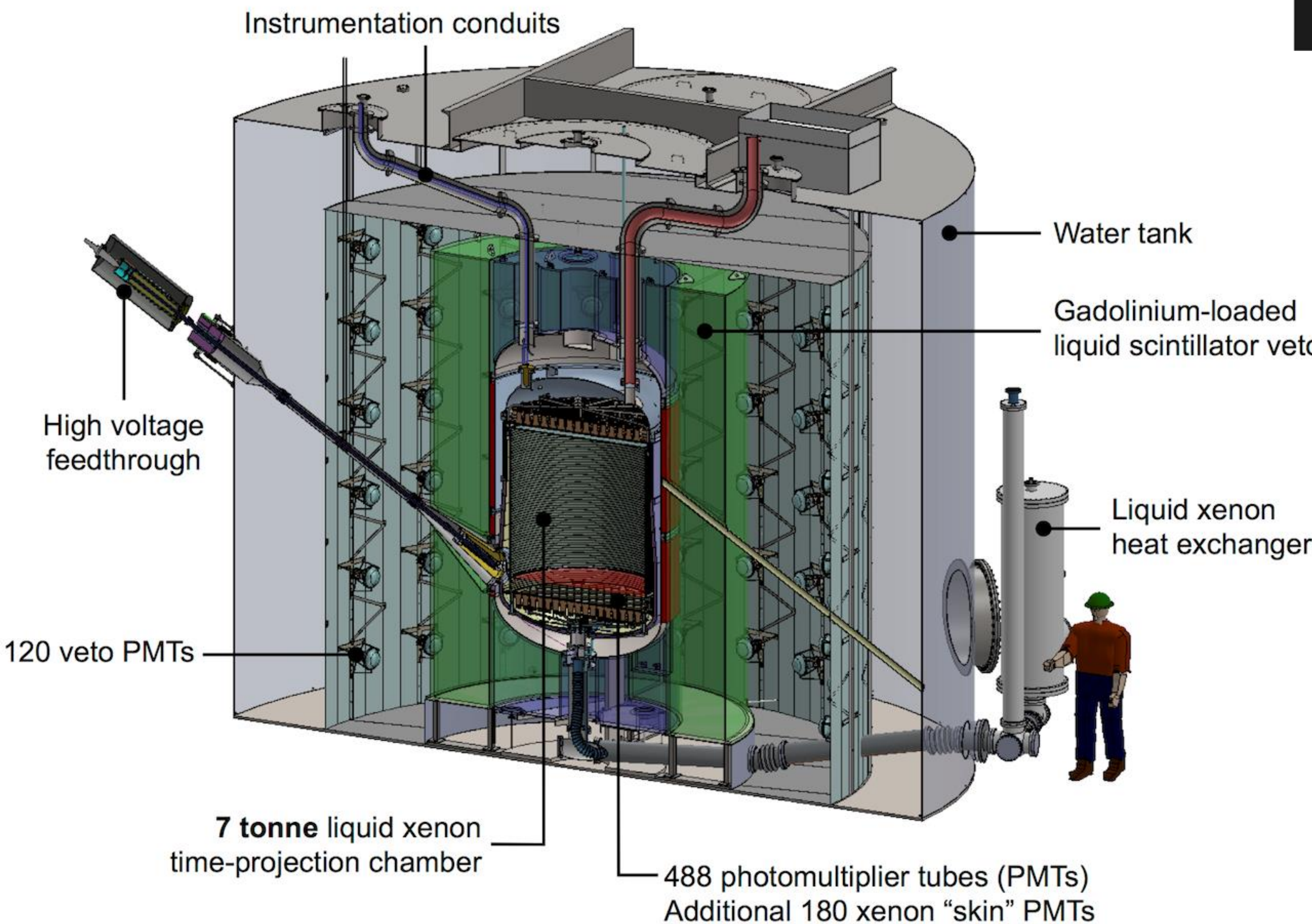
XENON 100

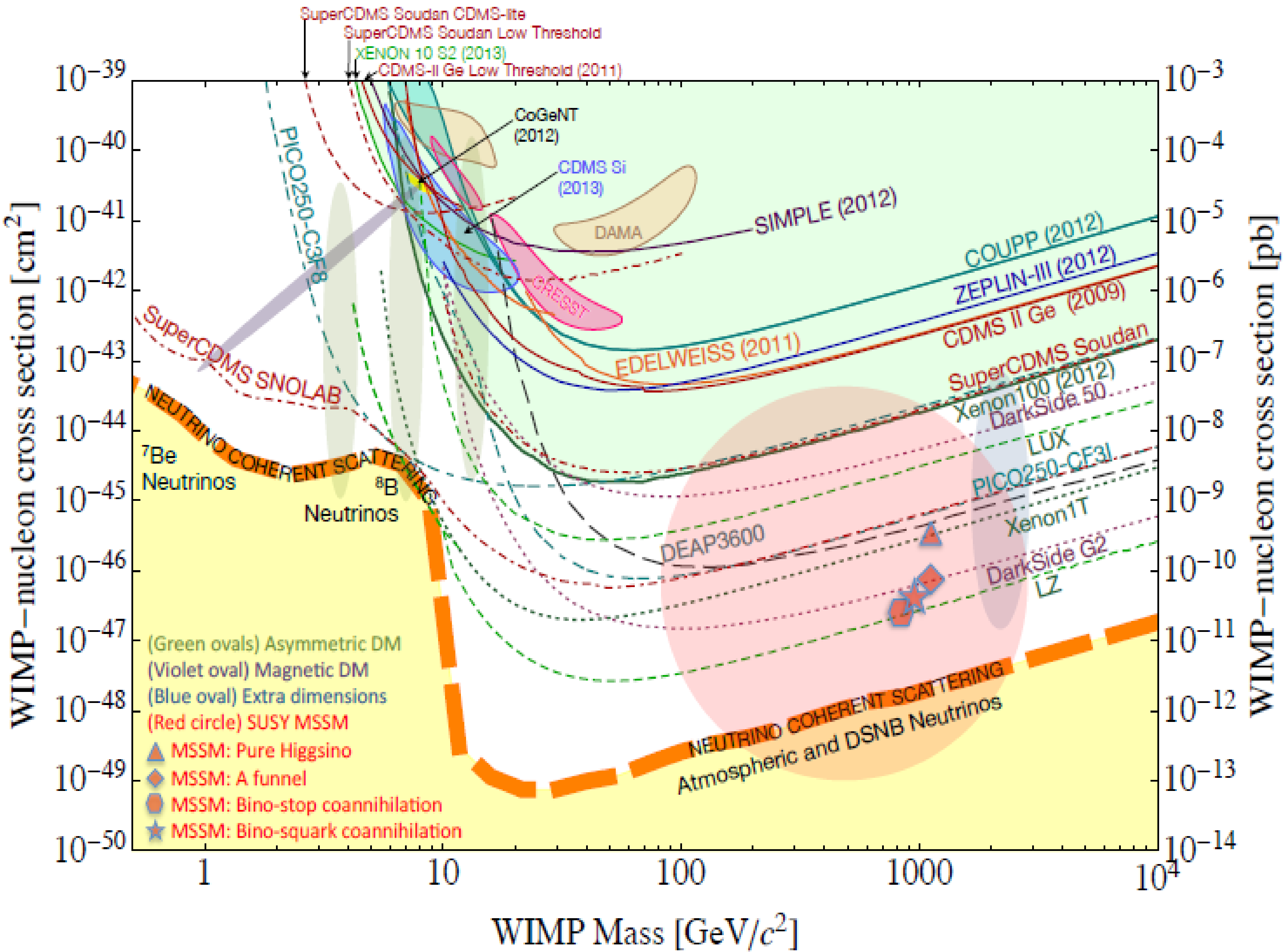


DARK SIDE



PANDA-X


Instrumentation conduits
Water tank
Gadolinium-loaded liquid scintillator veto
High voltage feedthrough
Liquid xenon heat exchanger
120 veto PMTs
7 tonne liquid xenon time-projection chamber
488 photomultiplier tubes (PMTs)
Additional 180 xenon “skin” PMTs

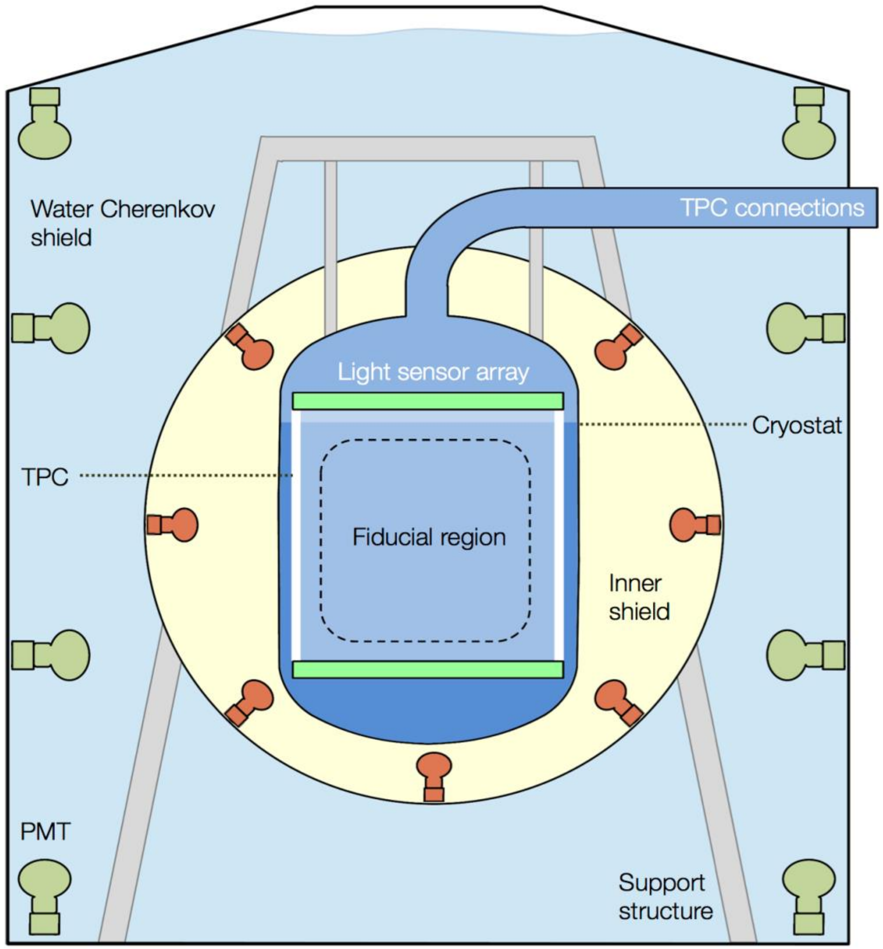

SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]

A Next-Generation Liquid Xe Observatory for Dark Matter and Neutrino Physics

Aalberts J. et al. *J. Phys. G: Nucl. Part. Phys*. 50 (2023) 013001

77 pages, 40 figures, 1262 references, 559 authors, 145 organizations

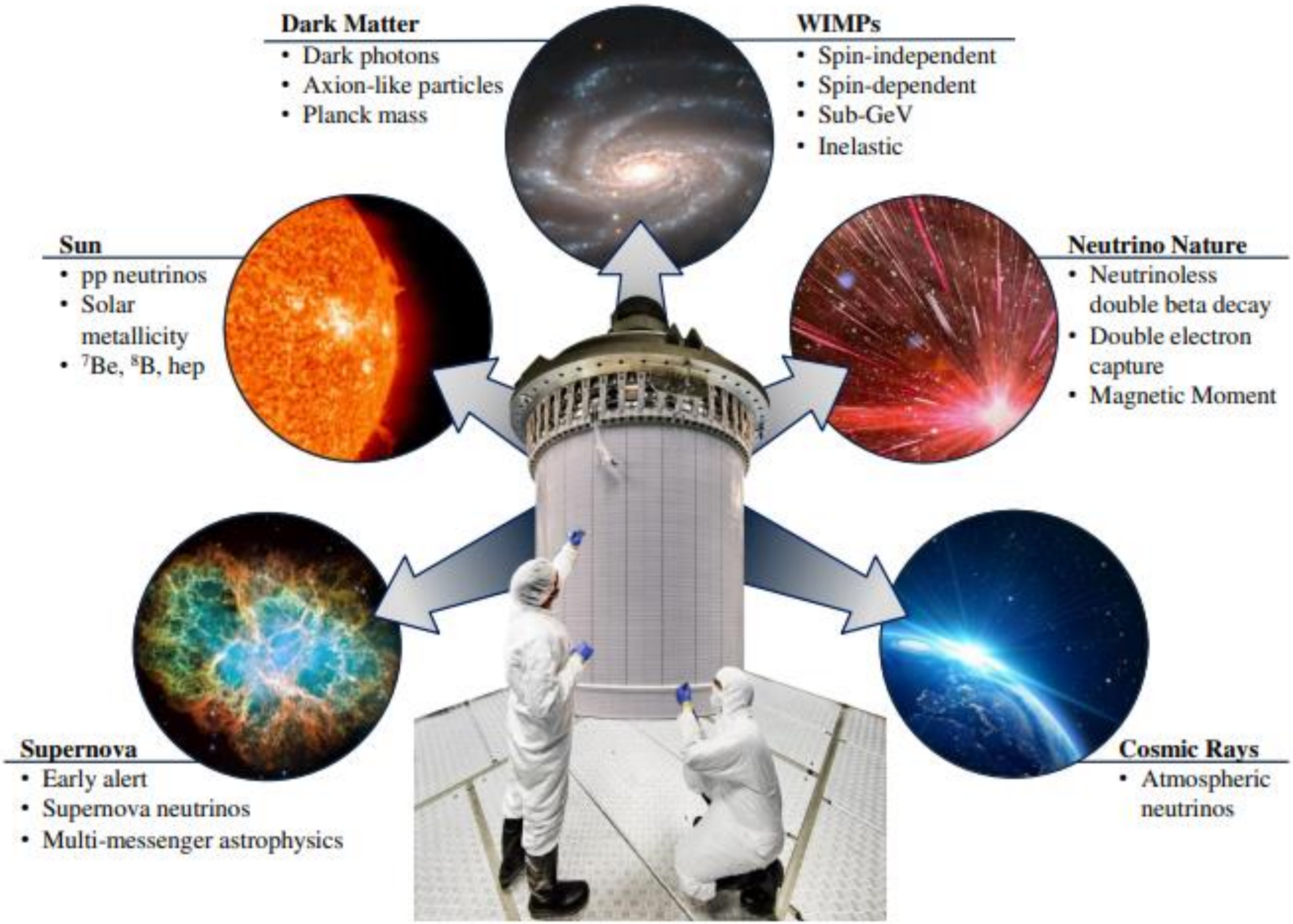
A world-class joint project



DARWIN

40-50 тонн LXe

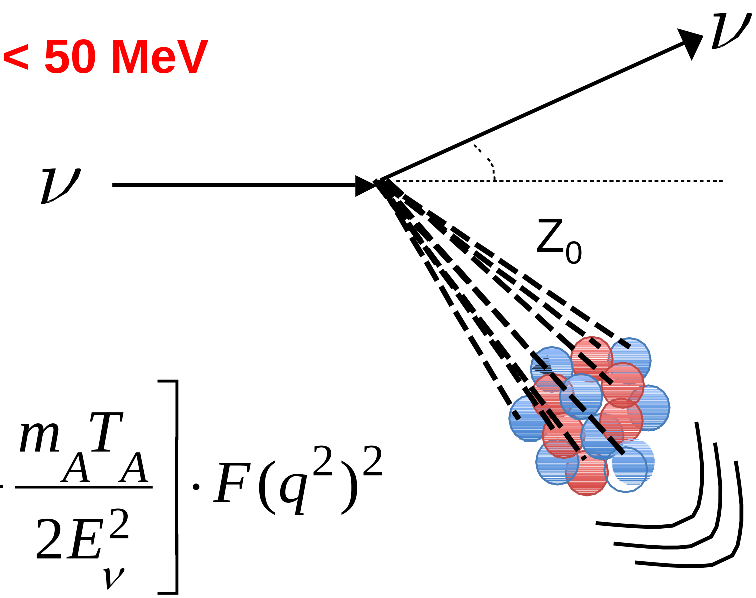
Next-Generation Liquid Xe Observatory



Search for Coherent Elastic Neutrino Scattering off Atomic Nuclei (CEνNS)

$$\nu + A \to \nu' + A'$$

E_ν < 50 MeV



$$\Delta x_i \Delta p_i \geqslant \frac{\hbar}{2}$$

$$\frac{d\sigma}{dT_A} = \frac{G_F^2}{4\pi} m_A [Z(1-4\sin^2\theta_W) - N]^2 \left[1 - \frac{m_A T_A}{2E_\nu^2}\right] \cdot F(q^2)^2$$

m_A – mass of *A* atomic nuclei, ***T_A*** – kinetic energy of recoil nuclei, ***E_ν*** – neutrino energy, ***Z*** – charge of nuclei, ***N*** – number of neutrons in nuclei, ***$F(q^2)$*** – nuclear form factor, ***θ_w*** – Vainberg' angle, **$\sin^2\theta_w \approx 0.22$**; $(1 - 4\sin^2\theta_w) = o(1)$

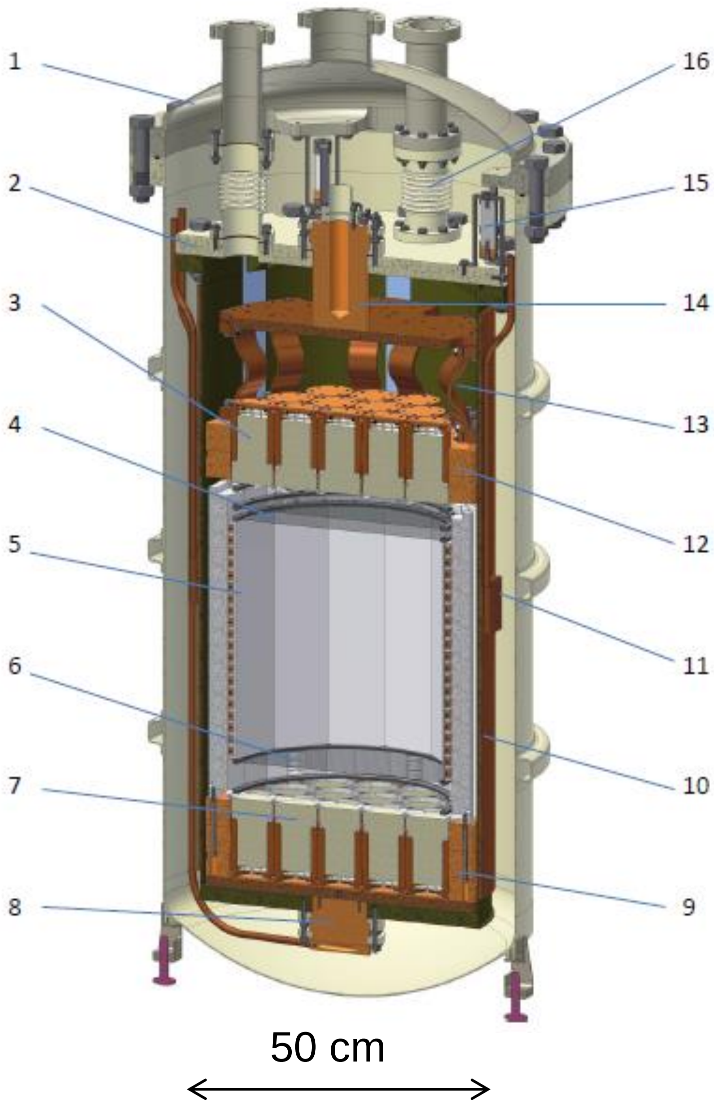
D.Z. Freedman, D.N. Schramm, and D.L. Tubbs. *Ann. Rev. Nucl. Part. Sci. 27, 167 (1977)*

$$\sigma \sim N^2$$

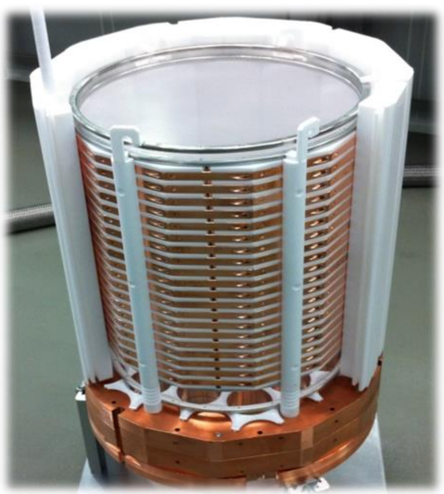
The effect was observed for the first time ***in 2017 by the COHERENT international collaboration*** in the Oak Ridge National Laboratory of USA at the high-currency proton accelerator of SNS, generating a mixture of three types of neutrinos with energy of about 50 MeV

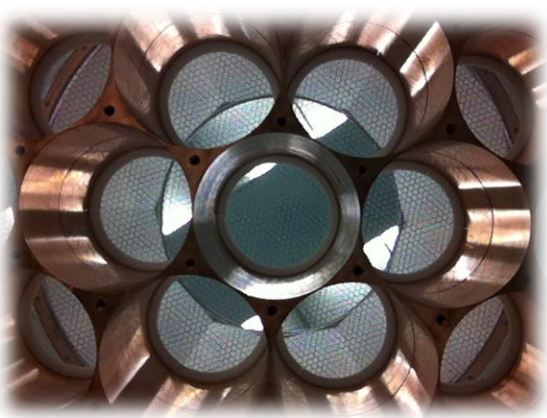
D.Y. Akimov et al (COHERENT). Observation of coherent elastic neutrino-nucleus scattering, ***Science 357 (2017) 6356 1123*** *[arXiv:1708.01294].*

RED-100 detector



1 - outer titanium vessel
2 - internal titanium vessel
3 - 19 Hamamatsu R11410-20 PMTs
4 - gridded anode and electron shatter
5 - drift electrodes
6 - cathode
7 - low matrix of 19 PMTs
8 - cooler for low thermosyphone
9 - copper collar for lower photomultipliers
13 – heat screen in the cold vessel
14 – cooler for the top thermosyphone
15 – heat insulator
16 – bellows

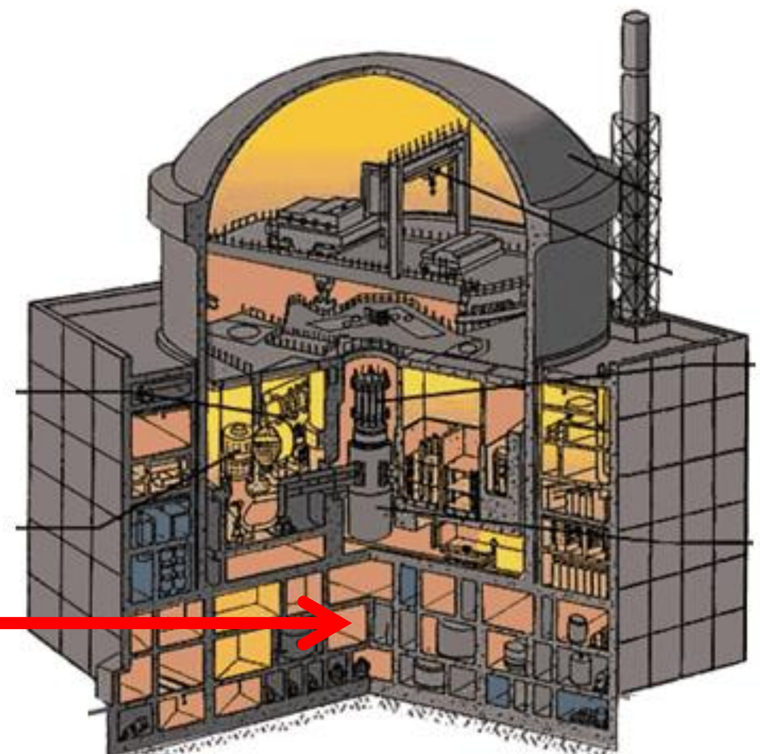




Assembling RED-100 in a “clean” room of the Laboratory for Experimental Nuclear Physics of NRNU MEPhI

Location at 4th block of KNPP:

- 19 m from active zone of the reactor
- $\bar{\nu}_e$ 5 m.w.e. vertical
- flux is ~$1.35 \cdot 10^{13}$ $cm^{-2}s^{-1}$



Location of RED-100

RED-100 at KNPP

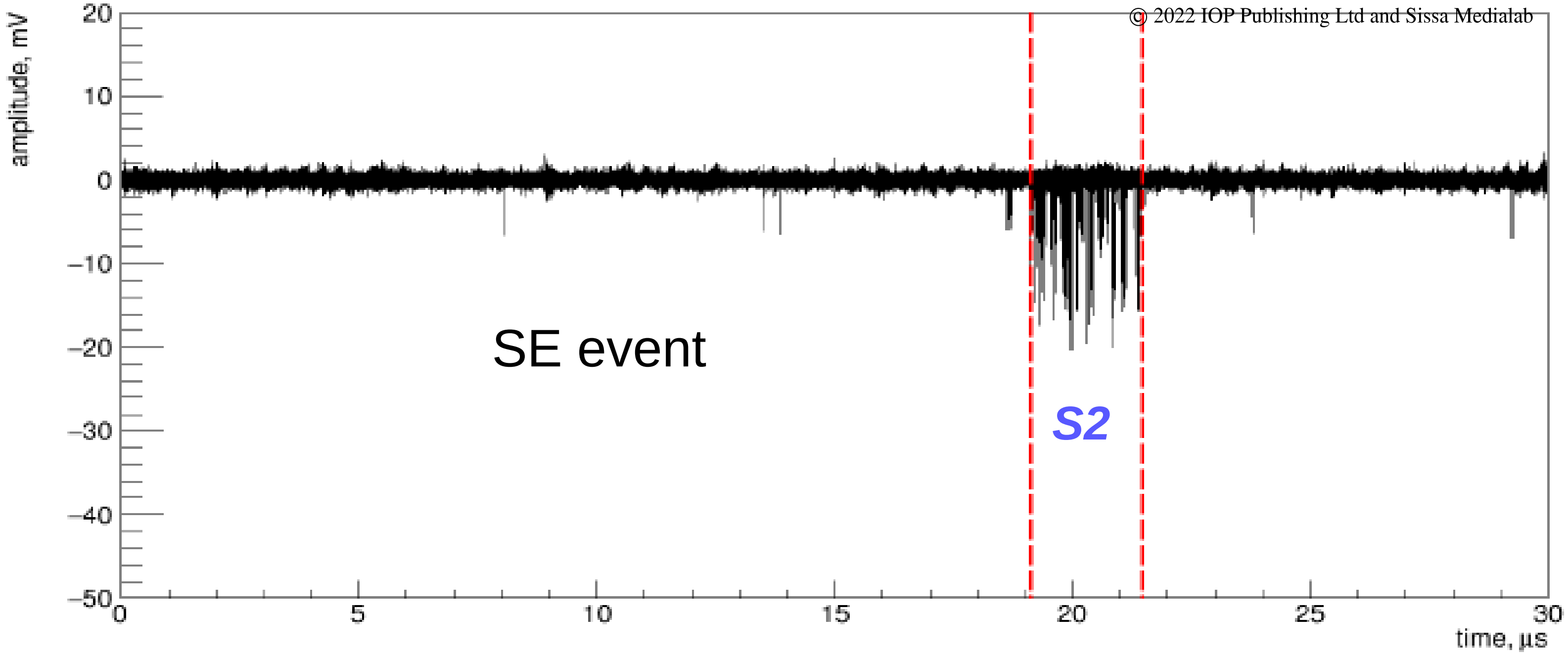
May-June 2021: background measurements
August-October 2021: express analysis and settings
November-December 2021: purification of LXe
January-February 2022: data set

CEνNS candidates: SE signals correlate with Reactor ON mode

Data analysis in the ***REACTOR ON/OFF*** modes

Signal selection parameters SIG/sqrt(BG):

- shape
- duration
- coordinates
- distribution over PMT matrix

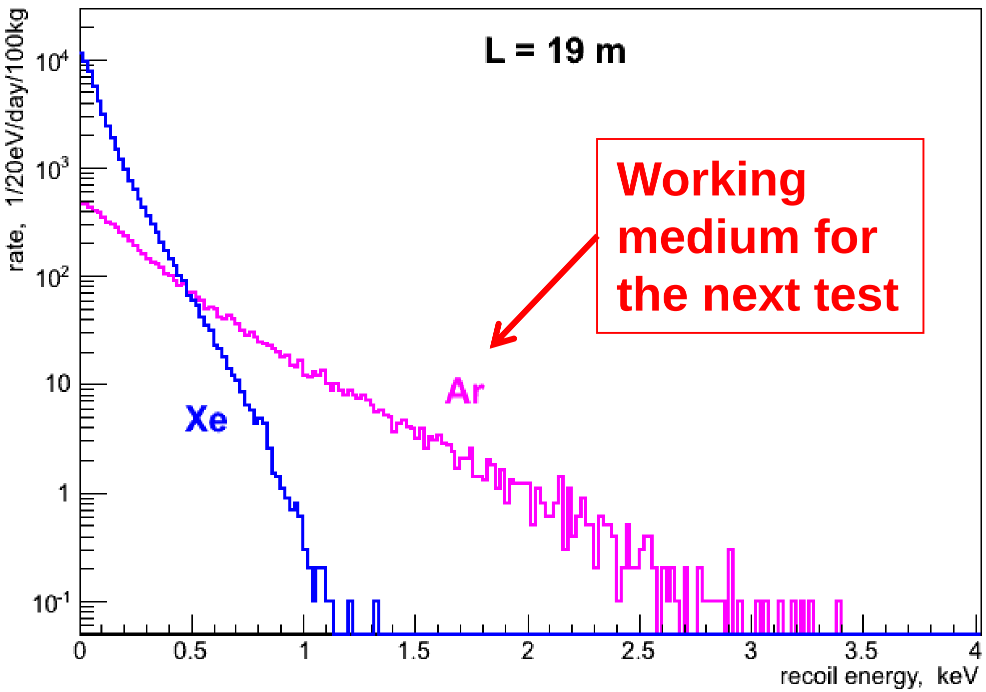


Preliminary results:

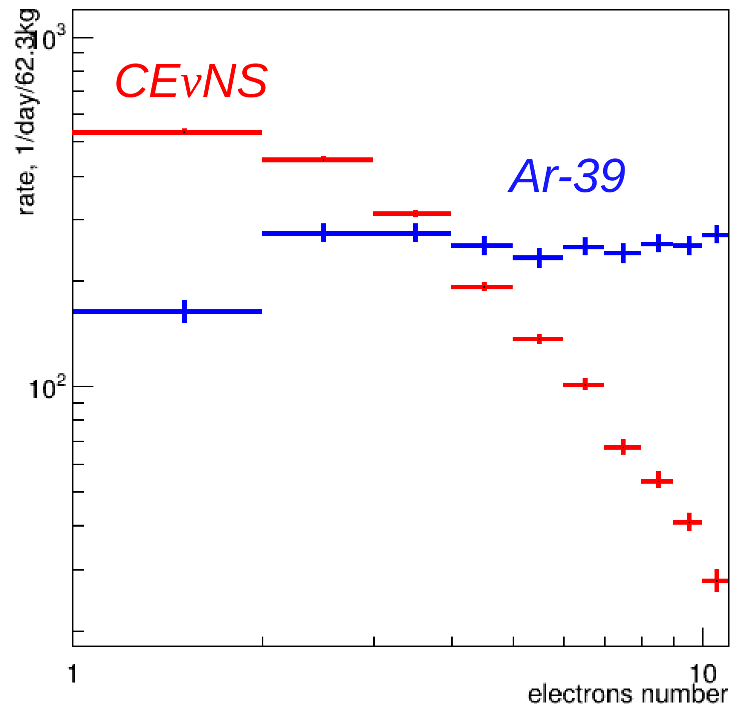
Count rate of background *SE* signals in LXe are 50 times higher than expected *CEνNS*

Detector operating media in RED-100 experiment at KNPP

CEνNS recoil spectrum

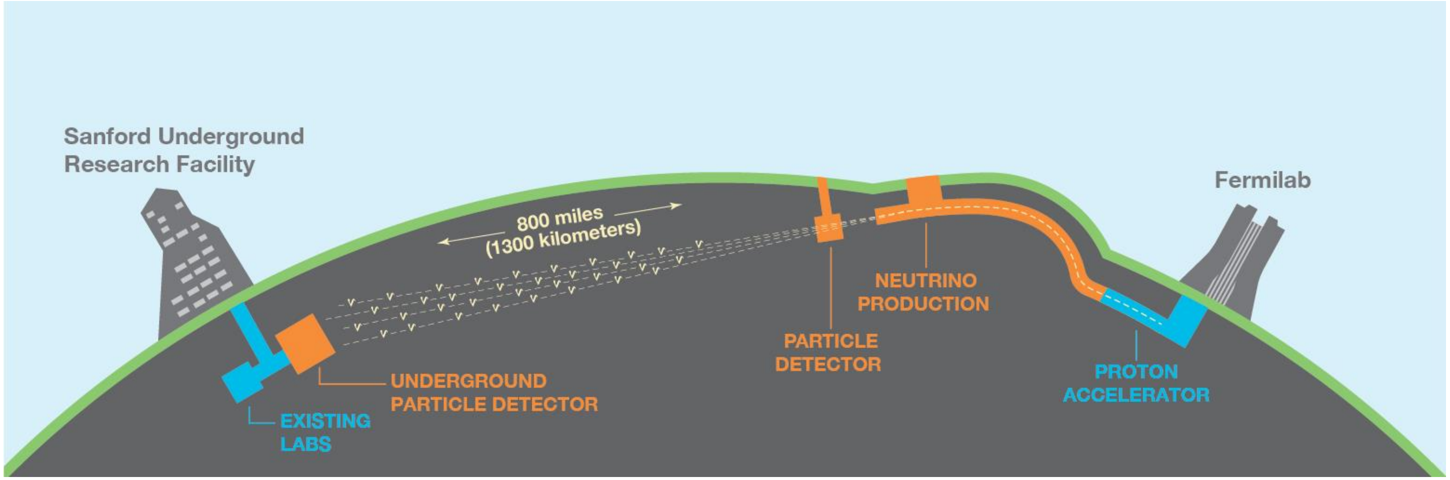


Expected CEνNS rate in LAr

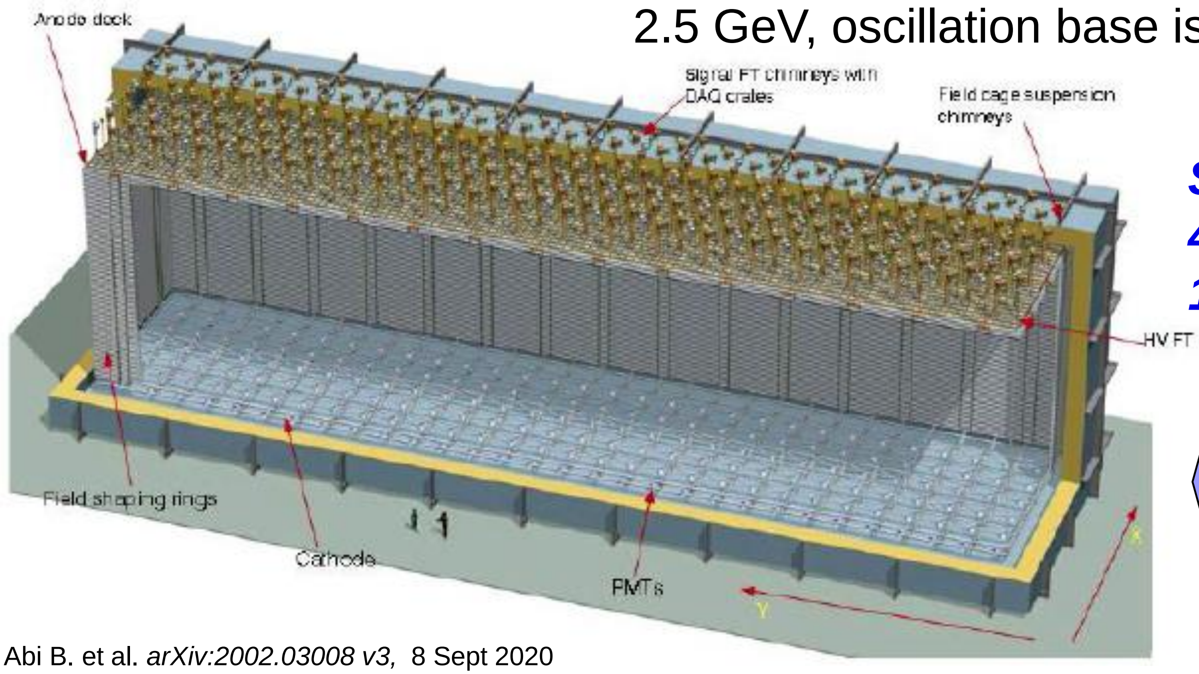


High Energy Neutrino Detection

High-energy neutrino oscillations



Deep Underground Neutrino Experiment (**DUNE**) + astrophysics + proton decay: 1.2 – 2.5 MW proton beam, a broad spectrum of neutrino energies that peaks at 2.5 GeV, oscillation base is 1300 km, ~20 years exposition.

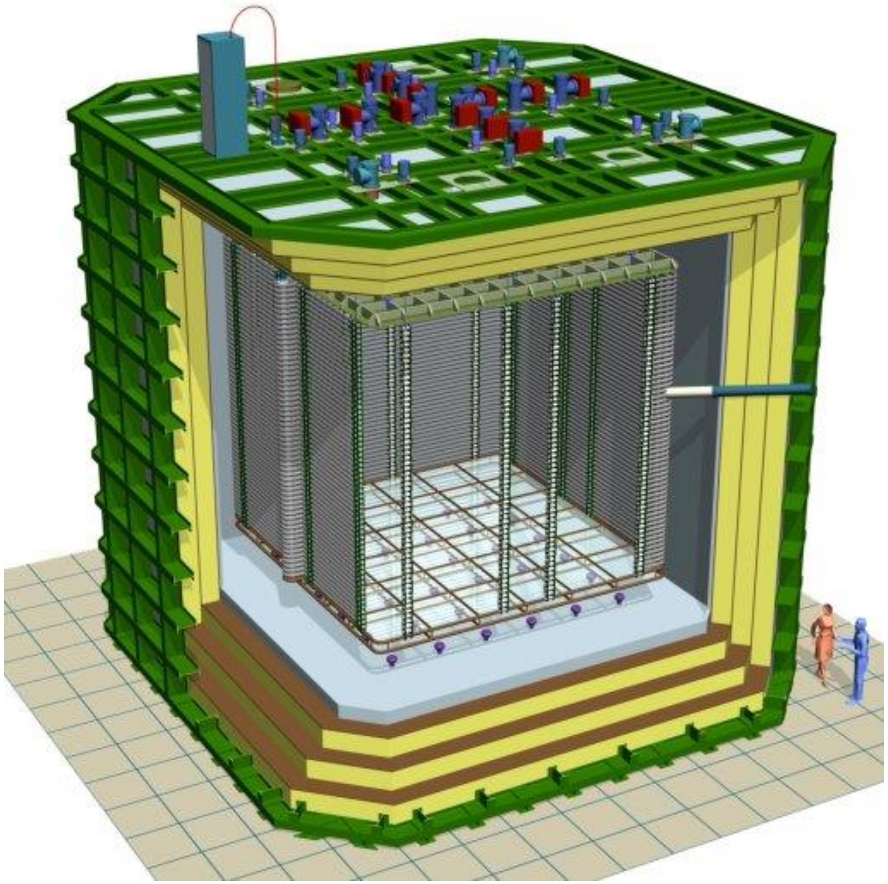


Sanford detector includes ***4*** modules with ***10 килотонн LAr*** in each

One of the modules is ***DUNE-DP emission detector***

Abi B. et al. *arXiv:2002.03008 v3,* 8 Sept 2020

ProtoDUNE-DP emission detector (6x6x6 m^3 with 300 tons of LAr) is under testing in the *CERN Neutrino Platform*.



S1 signals: 36 pcs. 8” window diameter Hamamatsu R5912-02MOD PMTs

S2 signals are detecting by THGEM or LEM detectors (GEM technology).

1. Belver D. et al. Cryogenic R5912-20Mod Photomultiplier Tubes Characterization for the ProtoDUNE Dual Phase Experiment, *arXiv:1806.04571v4* [physics.ins-det] 5 Oct 2018.
2. Cuesta C. on behalf of DUNE collaboration (2019). Status of ProtoDUNE Dual Phase, *arXiv:1910.10115 v1,* 22 Oct 2019; European Physical Society Conference on High Energy Physics - EPS-HEP2019 - 10-17 July, 2019
3. Abed Abud A. et al. Scintillation light detection in the 6-m drift-length ProtoDUNE Dual Phase liquid argon TPC, *arXiv:2203.16134* 3 Jun 2022

Conclusion

- ***Emission Two-Phase Detectors*,** introduced into Experimental Physics at MEPhI 50 years ago, have evolved from miniature research devices of about ~***1 gram*** mass to up to ***THOUSANDS tons*** installations for solving fundamental problems of modern science: *growth factor* ***>1 million times !!!***
- ***The modern*** experiments for direct detection of dark matter such as LZ, XENONnT and PandaX are already using emission detectors containing up to ***10 tons*** of liquid Xenon.
- ***The Laboratory for Experimental Nuclear Physics of NRNU MEPhI*** is using this technology to develop an innovative method for neutrino monitoring of active zone of nuclear reactors with LXe and LAr working media.
- ***The next generation*** of emission detectors with a liquid xenon mass up to ***50 tons*** is expected to be used to solve several fundamental problems simultaneously with ***Next-Generation Liquid Xe Observatory.***
- ***ProtoDUNE-DP (300 tons of LAr) emission detector*** is under testing at CERN. In next decade, emission detectors with a mass of ***10,000 tons*** of LAr will be used for high-energy neutrino physics and astrophysics.