



# Astroparticle physics in Ukraine

(main results over the last 5 years)



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**Lepton Physics Department**

<http://lpd.kinr.kiev.ua>

Wassily Kandinsky, «*Composition VIII*», 1923

# Study of particle properties using astronomical data

Main astronomical observatory of the National Academy of Sciences of Ukraine

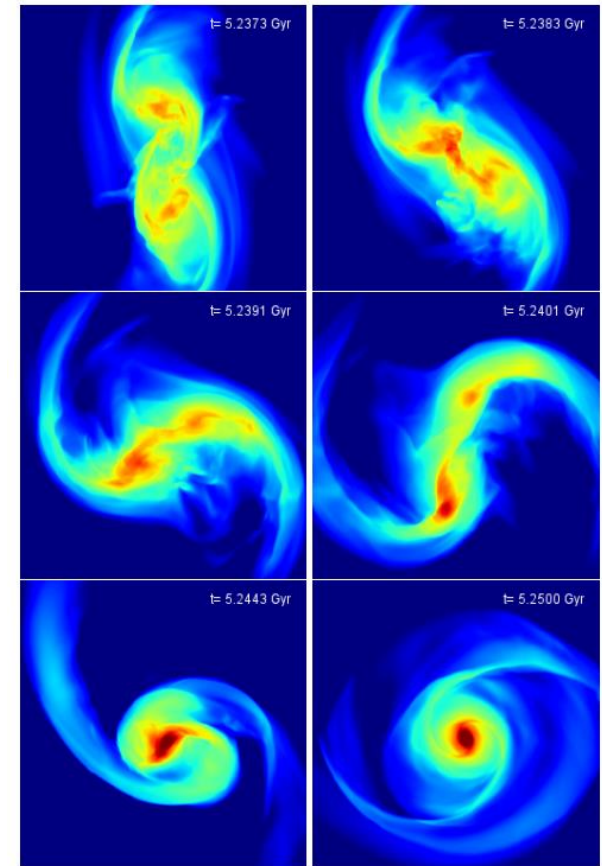
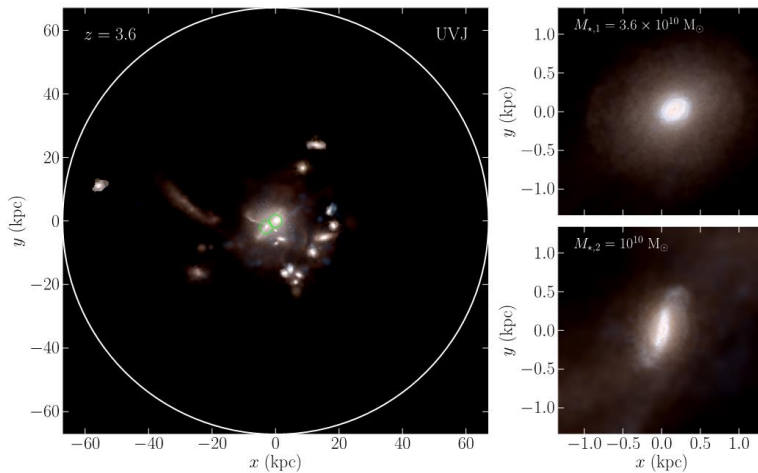
## Dynamical mechanisms of accretion in galactic nuclei.

Study of stability, accretion, and tidal disruption near supermassive black holes (BH) with advanced parallel computer technologies.

Department of Physics of Stars and Galaxies.

Head of dep., Dr.Sci. Peter Berczik.

Galaxy collisions = Supermassive BH collisions!



Last 5 years ~40 publications.

Revisit the Rate of Tidal Disruption Events: The Role of the Partial Tidal Disruption Event, The Astrophysical Journal, (2022) 933, 96

Eccentricity evolution of massive black hole binaries from formation to coalescence, Monthly Notices of the Royal Astronomical Society, (2022) 511, 4753

Merging timescale for the supermassive black hole binary in interacting galaxy NGC 6240, Astronomy and Astrophysics, (2021) 652, A134

Properties of loss cone stars in a cosmological galaxy merger remnant, Astronomy and Astrophysics, (2021) 649, A41

Direct N-body Simulations of Tidal Disruption Rate Evolution in Unequal-mass Galaxy Mergers, The Astrophysical Journal, (2019) 883, 132

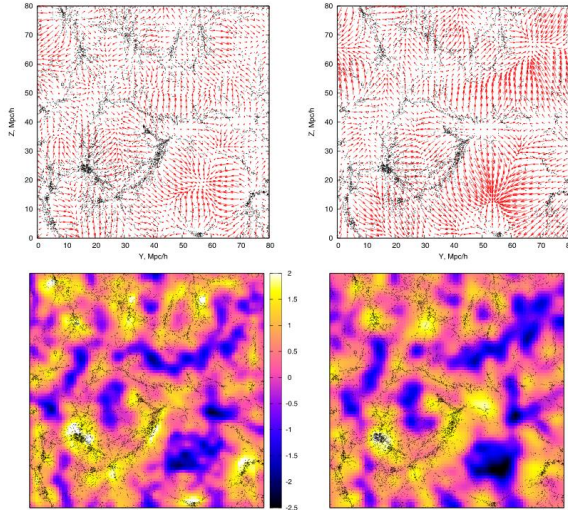
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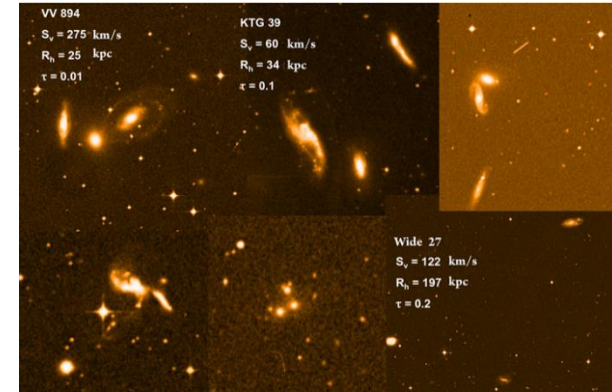
# Study of particle properties using astronomical big data

Main astronomical observatory NAS of Ukraine

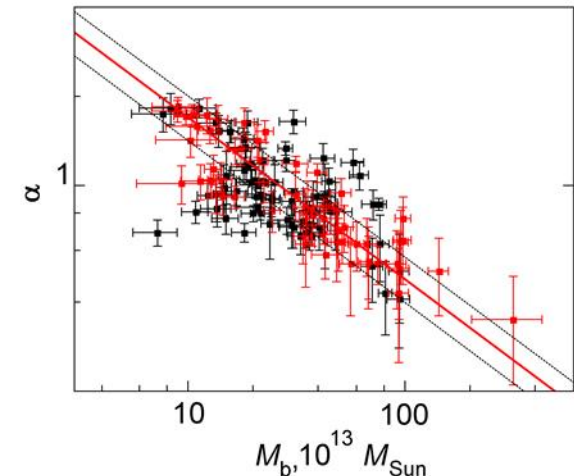
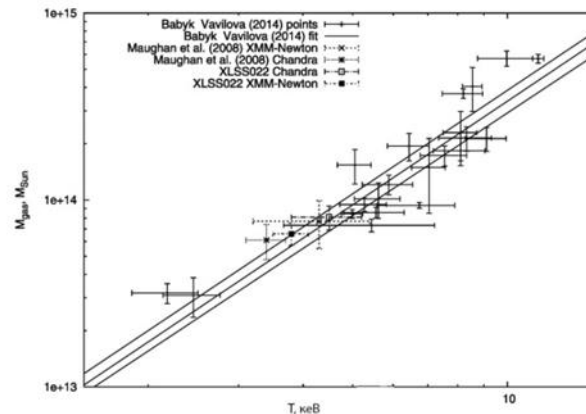
The Department for Extragalactic Astronomy and Astroinformatics



- Large data surveys for recovering the matter distribution in large-scale structures of the Universe
- Estimation of virial masses (dark/baryonic) in different galaxy systems (for example, galaxy triplets, right figure)
- Properties of the matter and non-zero magnetic fields in voids and search for astroparticles



- Multi-wavelength properties of galaxies and clusters, study of X-ray spectra, to derive masses of baryonic and dark matter
- Dark matter halo
- Dark matter density profiles (for example, 22 X-ray galaxy clusters and search for dark matter evolution using a wide range of redshifts)



# Ukraine joined the CTA Consortium in 2015; participation in LISA, THESEUS, ATHENA

## TELESCOPES

**Large-Sized (23 m):** low energy range 20 GeV - 3 TeV

**Medium-Sized (12 m):** core energy range, 100 GeV - 10 TeV

**Small-Sized (~4 m):** high energy range, 1 - 300 TeV



Ukrainian scientists contribute to the following  
CTA Key Science Projects:

- Dark matter programme [1]
- Galactic Centre Survey [2]
- Large Magellan Cloud Survey [1], Transients [3], Galaxy Clusters [4]

[1] Bernardos et al. RICAP18, EPJ Web Conf. 209, 01021, 2019

[2] Viana et al. 36th ICRC2019, PoS 817, 2019

[3] Satalecka et al. 36th ICRC2019, PoS 784, 2019; López-Oramas et al. 37th ICRC2021, PoS 784, 2021; Sergijenko et al. 37th ICRC2021, PoS 975, 2021; Patricelli et al. 37th ICRC2021, PoS 998, 2021

[4] Adam et al. Astron. Astrophys. 644, A70, 2020

Participant Institutions from Ukraine:

- Astronomical Observatory of the Taras Shevchenko National University of Kyiv
- Astronomical Observatory of the Ivan Franko National University of Lviv
- Pidstryhach Institute for Applied Problems in Mechanics and Mathematics of NAS Ukraine
- Main astronomical observatory of NAS Ukraine

Contribution to LISA:

- Cosmology Working Group (WG) [5]
- Astrophysics WG [6]
- LISA Data Challenge WG

Also participation in THESEUS WGs [7]  
and ATHENA multi-messenger WG

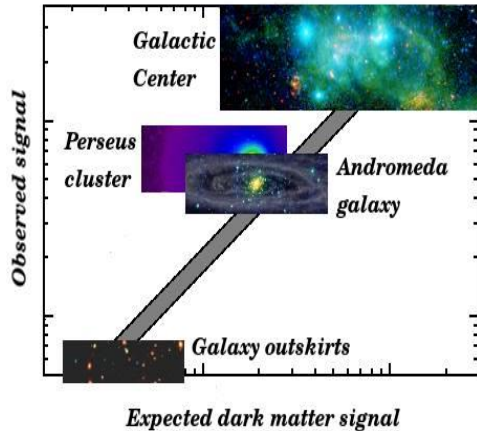
[5] Auclair et al. arXiv:2204.05434

[6] Amaro-Seoane et al. arXiv:2203.06016

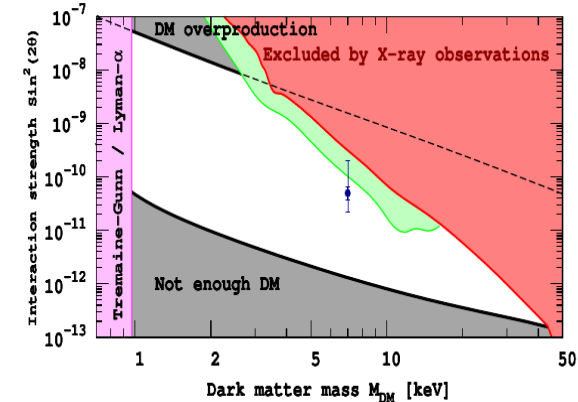
[7] Tanvir et al. Experimental Astronomy 52, 219, 2021;  
Ciolfi et al. Experimental Astronomy 52, 245, 2021; Rosati et al. Experimental Astronomy 52, 407, 2021

# Restrictions on the parameters of dark-matter-candidate particles from astrophysical and cosmological observations

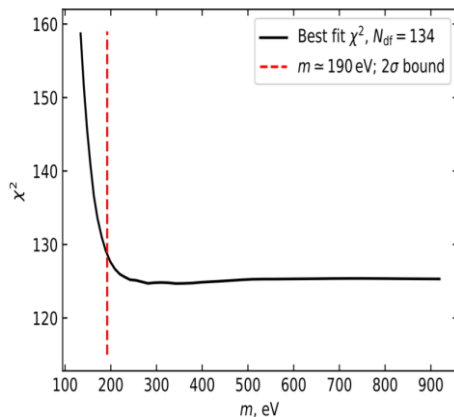
Bogolyubov Institute for Theoretical Physics of NAS Ukraine (Kyiv, Ukraine)



Search for astrophysical signal of light-sterile neutrinos decays (X-rays with energy of 3.5 keV) - candidates for dark matter particles, indication of the signal [1]

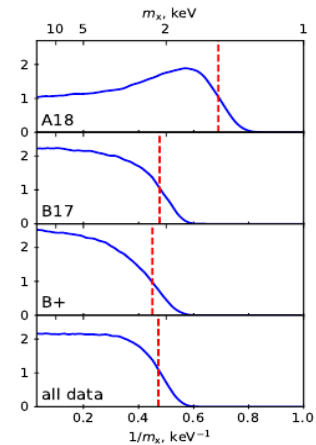


Restriction on the mass of a particle of light fermionic dark matter based on the data:



kinematics of dwarf spheroidal galaxies  
 $m \gtrsim 200$  eV, 95% C.L. [2]

the distribution of galaxies at large redshifts  
 $m \gtrsim 2$  keV, 95% C.L. [3]



[1] A. Boyarsky et al., Phys. Rev. Lett. 113 (2014) 251301

[2] D.Savchenko, A.Rudakovskiy, Mon. Notices Royal Astron. Soc. 487 (2019) 5711

[3] A.Rudakovskiy et al., Mon. Notices Royal Astron. Soc. 507 (2021) 3046

# Gravity theory, dark matter, extension of the Standard Model

Astronomical Observatory of the Odessa I.I. Mechnikov National University

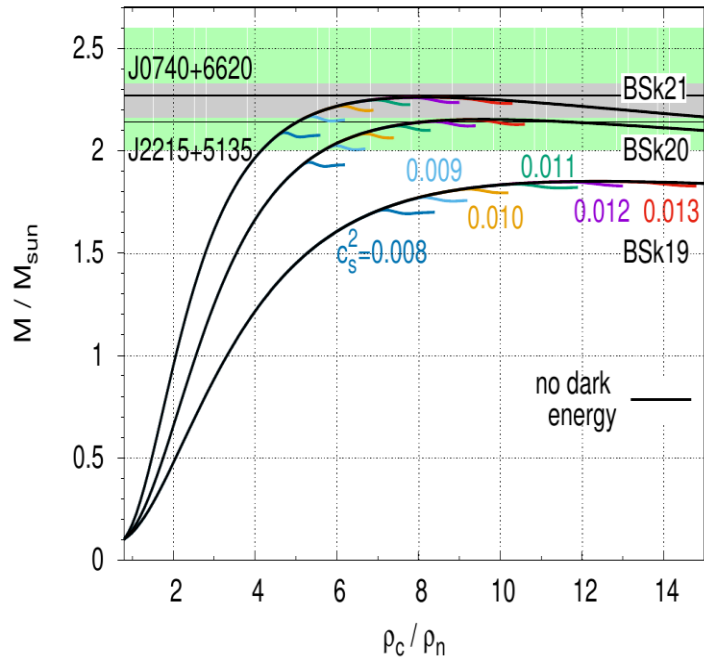
- Extra dimensions is one of the areas of development of the extension of the Standard Model
- Conformal excitations of internal spaces are candidates for the role of dark matter
- On the base of various gravitational models it was shown that gravitational masses do not contradict gravitational tests if they have a negative pressure in the interior spaces

Eur. Phys. J. C 77 (2017) 721; Physical Review D 97 (2018) 044024; Physics Letters B 778 (2018) 190; Physical Review D 101 (2020) 024004;  
Eur. Phys. J. C 80 (2020) 379; Eur. Phys. J. C 81 (2021) 246; Physics Letters B 826 (2022) 136911; Frontiers in Physics 10 (2022) 875757

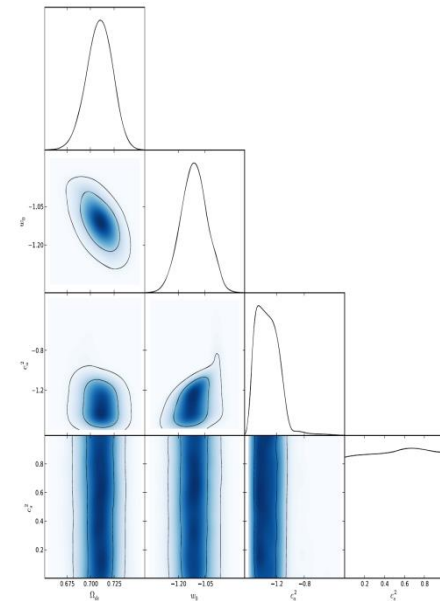
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# Dark matter and dark energy on astrophysical and cosmological scales

Astronomical Observatory of the Ivan Franko National University of Lviv



Influence of dynamic dark energy on the equilibrium of neutron stars



Constraints on dark energy parameters based on cosmological data: CMB, BAO, SN Ia

S. Smerechynskiy, M. Tsizh, B. Novosyadlyj, J. Cosmol. Astropart. Phys. 02 (2021) 045  
S. Smerechynskiy, M. Tsizh, and B. Novosyadlyj, Phys. Rev. D 101 (2020) 023001

## Several Ukrainian institutions and universities are members of the EuCAPT consortium

- Bogolyubov Institute for Theoretical Physics of the NAS of Ukraine
- Taras Shevchenko National University of Kyiv, Department of the Quantum Field Theory and Astroparticle Physics
- Ivan Franko National University of Lviv, Astronomical Observatory
- Astronomical Observatory of Odesa I.I. Mechnikov National University
- Institute of Radio Astronomy, NAS of Ukraine

\* The European Consortium for Astroparticle Theory



# Participation in the Hyper-Kamiokande and DUNE

Department of Nuclear Physics, Taras Shevchenko National University of Kyiv



Cherenkov detector with  
260 thousand tons of water,  
40 thousands  
photomultipliers  
<https://www.hyperk.org/>

A group of the Department of Nuclear Physics of the Taras Shevchenko National University of Kyiv is involved in detector calibration, development of the IWCD intermediate detector, data analysis.

Prof. V.E. Aushev is a member of the Steering / Resource Board of the Hyper-Kamiokande collaboration



The Hyper-Kamiokande and DUNE projects will determine the development of neutrino physics in the next two decades.

**Main goals:**

- 1. neutrino oscillations (neutrino mass)**
- 2. Violation of CP-parity**
- 3. Proton decay**
- 4. Observation of neutrinos from supernova explosions**
- 5. Atmospheric and solar neutrinos**



The world's largest long-base neutrino detector: 40 thousand tons of liquid argon at 1300 km from the neutrino beam source  
<https://lbnf-dune.fnal.gov/>

The group is involved in the near ND DUNE detector R&D and the ProtoDUNE testing (CERN-Fermilab).

Prof. V.E. Aushev is a member of the Institutional Board of the DUNE collaboration.

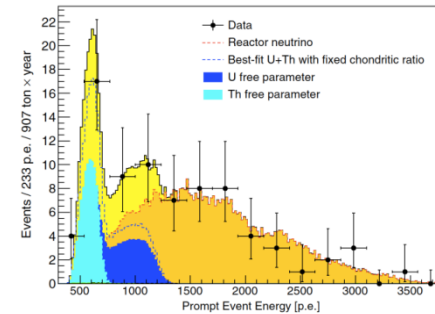
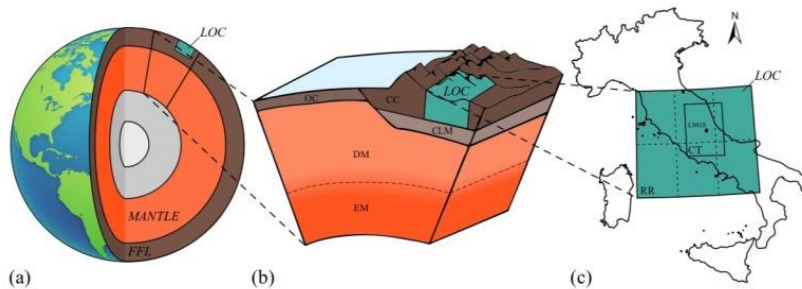
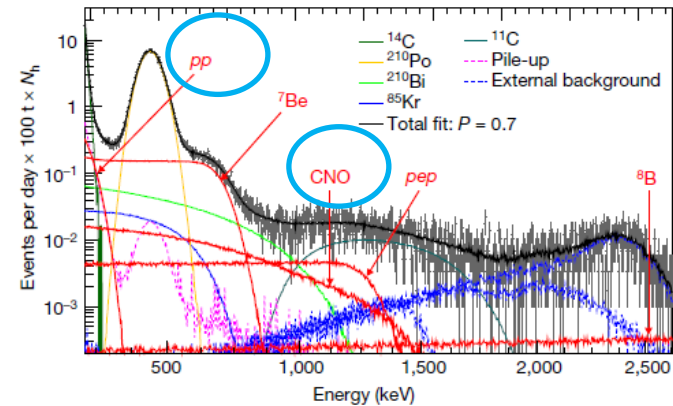
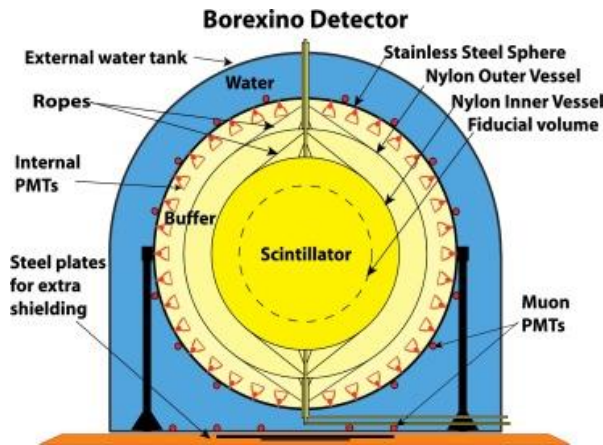


## Participating Countries

Armenia	Czech Republic
Brazil	Finland
Canada	France
CERN	Georgia
Chile	Germany
China	Greece
Colombia	Hungary
	India
Israel	Paraguay
Italy	Peru
Japan	Poland
Madagascar	Portugal
Mexico	Romania
Netherlands	Russia
Paraguay	Serbia
Peru	South Korea
Spain	
Sweden	
Switzerland	
Turkey	
Ukraine	
United Kingdom	
USA	9/17

# Borexino: neutrino from the Sun, geoneutrino, etc

Institute for Nuclear Research of the National Academy of Sciences of Ukraine



- Accurate measurements of  $^7\text{Be}$  neutrinos from the Sun [1]
- The first observation of solar pp neutrinos in a direct experiment [2,3]
- First observation of solar CNO neutrinos [4]
- Observations of geo-neutrinos from the decay of radioactive elements in the Earth [5]

[1] M. Agostini et al., First Directional Measurement of Sub-MeV Solar Neutrinos with Borexino, PRL 128 (2022) 091803

[2] M. Agostini et al., Simultaneous precision spectroscopy of pp,  $^7\text{Be}$ , and pep solar neutrinos with Borexino Phase-II, PRD 100 (2019) 082004

[3] M. Agostini et al., Comprehensive measurement of pp-chain solar neutrinos, Nature 562 (2018) 505

[4] M. Agostini et al., Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun, Nature 587 (2020) 577

[5] M. Agostini et al., Comprehensive geoneutrino analysis with Borexino, Phys. Rev. D 101 (2020) 012009

# Double $\beta$ , rare $\alpha$ and $\beta$ decay, effects beyond the Standard Model

Institute for Nuclear Research of NAS Ukraine

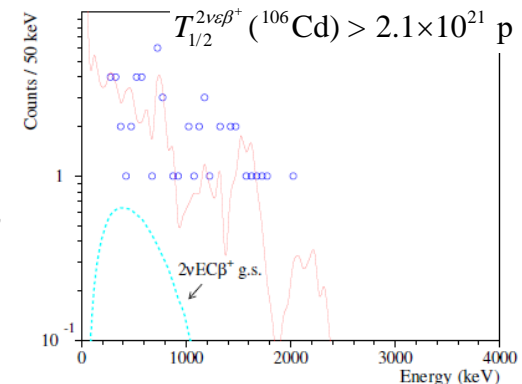
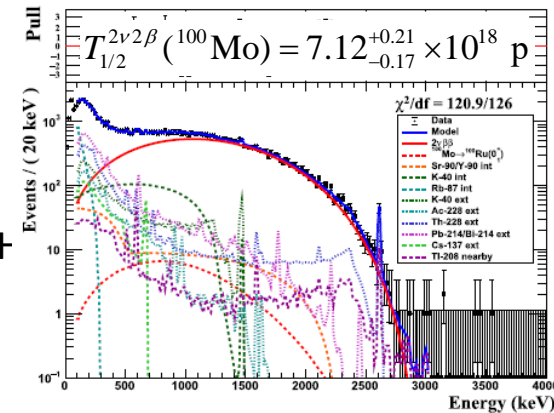
<http://lpd.kinr.kiev.ua>

since 1979

- Measurement of the  $2\nu 2\beta$  decay of  $^{100}\text{Mo}$  and  $^{116}\text{Cd}$  with the highest accuracy [1,2], the most stringent limit on the  $0\nu 2\beta$  decays [1,2]
- One of the most stringent restriction on the neutrino mass [3]
- Most sensitive experiments to search for  $2\beta$  decay of Er [4], Yb [5], Sm [6], T [7],  $^{106}\text{Cd}$  [8],  $^{150}\text{Nd}$  [9],  $^{184,192}\text{Os}$  [10],  $^{190,198}\text{Pt}$  [11]
- First search for  $4\beta$  decay [12]
- Search for naturally occurring seaborgium [13]
- Search for axions from Sun [14]
- Rare  $\alpha$  and  $\beta$  decays [15-18]
- Development of low counting experiments [many publications in NIM, JINST, EPJA, EPJC, APL, PRC]

[1] Phys. Rev. D 98 (2018) 092007  
 [2] Eur. Phys. J. C 80 (2020) 674  
 [3] Phys. Rev. Lett. 126 (2021) 181802  
 [4] J. Phys. G 45 (2018) 095101  
 [5] Nucl. Phys. A 990 (2019) 64  
 [6] Eur. Phys. J. A 55 (2019) 201  
 [7] Eur. Phys. J. A 56 (2020) 5  
 [8] Universe 6 (2020) 182

[9] Phys. Rev. C in preparation  
 [10] J. Phys. G 48 (2021) 085104  
 [11] Eur. Phys. J. C 82 (2022) 29  
 [12] Phys. Rev. Lett. 119 (2017) 041801  
 [13] Phys. Scr. 97 (2022) 085302  
 [14] JETP Lett. 107(2018)589-594  
 [15] Eur. Phys. J. A 55(2019)140  
 [16] Phys. Rev. C 102(2020)024319  
 [17] Phys. Rev. C 102(2020)024605  
 [18] arXiv:2206.06559v2



- 2016: State Prize of Ukraine in the field of science and technology (with KIPT and ISMA)



# Deep purification of metals for low counting experiments

Kharkiv Institute of Physics and Technology of NASU (in cooperation with INR NASU)

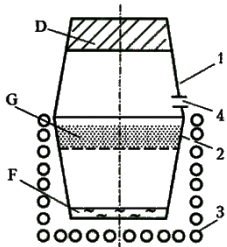


Fig. 1

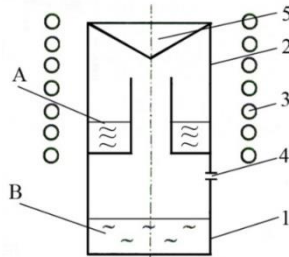


Fig. 2

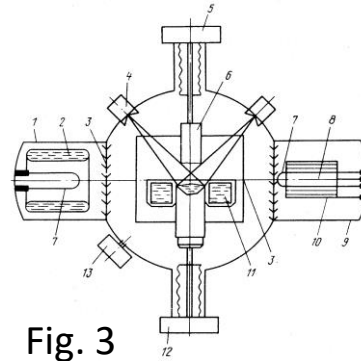


Fig. 3

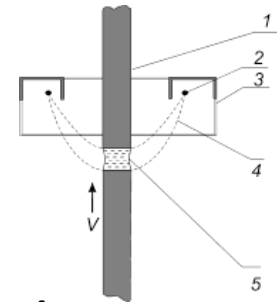


Fig. 4

Schemes of installations for the purification of cadmium by heating, filtration and distillation through a getter filter (Fig. 1), purification of lead by distillation with condensation of metal vapor into the liquid phase (Fig. 2), for electron beam melting (Fig. 3) and zone melting (Fig. 4) of refractory metals

Purification of Cd [1-3] and Pb [4] more then by a factor 100 with a very low (2%-4%) losses



Cadmium  
99.99995%



Cadmium 106  
> 99.999%



Cadmium 116  
99.99996 %



Archaeological lead  
99.9996 %



Osmium  
> 99.99 %

Samples of ruthenium (>99.99%) [5], hafnium (>99.8%) [6,7], and osmium (>99.99%) [8,9] of very high purity with low radioactive contamination were obtained for  $2\beta$  and rare  $\alpha$  decay experiments.

[1] PRD 98 (2018) 092007; [2] Universe 6 (2020) 182; [3] Functional Materials 18 (2011) 121  
[4] arXiv:2203.07441v1 [5] PRC 87 (2013) 034607;

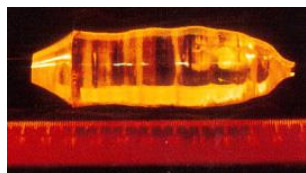
[6] NPA 996 (2020) 121703; [7] EPJA 56 (2020) 5 [8] JPG 48 (2021) 085104; [9] 102 (2020) 024605



# Development of low-background scintillators

Institute of scintillation materials NAS Ukraine (in cooperation with INR NASU,  
Taras Shevchenko National University of Kyiv)

Investigations of  $2\beta$ , rare  $\alpha$  and  $\beta$  decays call for detectors containing certain element (isotope)



$^{116}\text{CdWO}_4$  from enriched  $^{116}\text{Cd}$  for the Solotvina  $2\beta$  experiment [1]



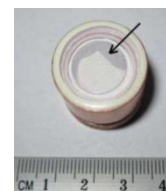
Radiopure  $\text{CdWO}_4$  to study  $\beta$  decay of  $^{113}\text{Cd}$  [2]



$\text{MgWO}_4$  – A new crystal scintillator [3]



$\text{ZnWO}_4$  to search for  $2\beta$  decay of Zn and W [5,6]



$\text{Srl}_2(\text{Eu})$  crystal scintillator to search for  $2\beta$  decay of  $^{84}\text{Sr}$  [7]



$\text{archPbWO}_4$  bolometers to detect neutrino from astrophysical sources [8]

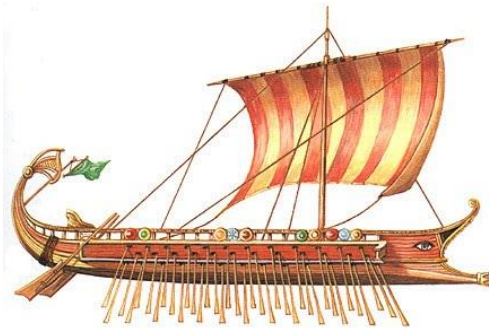
Study of luminescence at the  
Taras Shevchenko National University of Kyiv [9]

- [1] F.A.Danevych et al., Search for  $2\beta$  decay of cadmium and tungsten isotopes: Final results of the Solotvina experiment, PRC 68 (2003) 035501
- [2] P.Belli et al., Investigation of  $\beta$  decay of  $^{113}\text{Cd}$ , PRC 76 (2007) 064603
- [3] F.A. Danevych et al.,  $\text{MgWO}_4$  – A new crystal scintillator, NIMA 608(2009)107.
- [4] L.Gironi et al., Performance of  $\text{ZnMoO}_4$  crystal as cryogenic scintillating bolometer to search for double beta decay of molybdenum, JINST 5(2010)P11007
- [5] P.Belli et al., Final results of an experiment to search for  $2\beta$  processes in Zn and W with the help of radiopure  $\text{ZnWO}_4$  crystal scintillators, JPG 38(2011)115107.
- [6] P. Belli et al., Radioactive contamination of  $\text{Srl}_2(\text{Eu})$  crystal scintillator, NIMA 670 (2012) 10
- [7] J.W. Beeman et al., Radiopurity of a kg-scale  $\text{PbWO}_4$  cryogenic detector produced from archaeological Pb for the RES-NOVA experiment, arXiv:2203.07441v1
- [8] A.S. Barabash et al., Improvement of radiopurity level of enriched  $^{116}\text{CdWO}_4$  and  $\text{ZnWO}_4$  crystal scintillators by recrystallization, NIMA 833 (2016) 77
- [9] NIMA 889 (2018) 89; NIMA 949 (2020) 162784; Optik 206 (2020) 164273; NIMA 1029 (2022) 166400; J. Luminesc. 249(2022)11902

# Neutrinos from astrophysical sources

INR, KIPT, ISMA (NAS Ukraine)

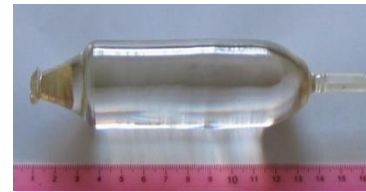
Purification of archaeological lead at KIPT [2]



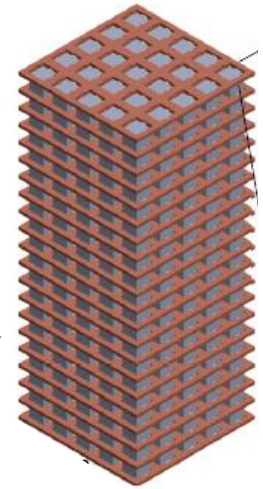
The Greek ship sank in the first century BC near the Crimean peninsula (Ukraine)



Lead ballast stones of the Greek ship [1]



$\text{archPbWO}_4$  crystal scintillator grown at ISMA



RES-NOVA project with  $\text{archPbWO}_4$  bolometers to detect neutrino from astrophysical sources [3]

Recently the  $\text{archPbWO}_4$  crystal was tested as bolometer with excellent performance. This crystal is by far the  $\text{PbWO}_4$  with the highest radiopurity level ever measured [4]

[1] F.A. Danevych et al., Ancient Greek lead findings in Ukraine, NIMA 603 (2009) 328

[2] R.S.Boiko et al., Ultrapurification of archaeological lead, Inorganic Materials 47 (2011) 645

[3] L. Pattavina et al., Neutrino observatory based on archaeological lead, Phys. Rev D 102 (2020) 063001

[4] J.W. Beeman et al., Radiopurity of a kg-scale  $\text{PbWO}_4$  cryogenic detector produced from archaeological Pb for the RES-NOVA experiment, arXiv:2203.07441v1, submitted to EPJC

# CUPID: search for $0\nu 2\beta$ decay of $^{100}\text{Mo}$ with a sensitivity $\langle m_\nu \rangle \sim 0.01$ eV

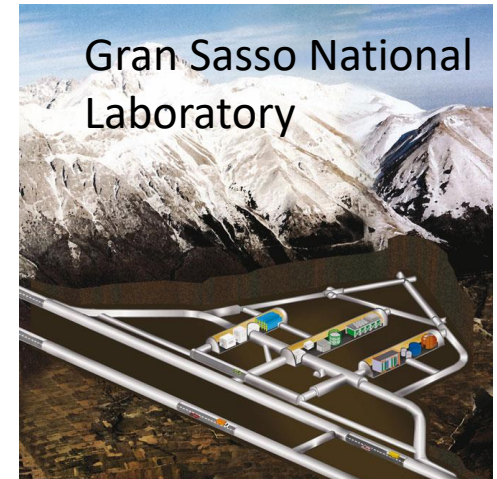
Institute for Nuclear Research of NAS Ukraine



CUPID is a project for the experimental search of  $0\nu\beta\beta$  decay of  $^{100}\text{Mo}$  using isotopically enriched  $\text{Li}_2\text{MoO}_4$  scintillating crystals [1] operated as cryogenic calorimeters [2, 3]

A projected sensitivity:

$$\lim T_{1/2}^{0\nu 2\beta} \approx 10^{27} \text{ yr}, \quad \langle m_\nu \rangle \approx (0.01 - 0.02) \text{ eV}$$



R&D for CUPID is carried out in the framework of two projects:

**CROSS:** development of new methods of reducing the background of bolometric detectors from radioactive contamination of surfaces [4]

**BINGO:** background reduction of bolometric detectors in anticoincidence with cryogenic  $\text{ZnWO}_4$  (BGO) scintillators [5]

[1] O.P. Barinova et al., First test of  $\text{Li}_2\text{MoO}_4$  crystal as a cryogenic scintillating bolometer, NIMA 613(2010)54.

[2] CUPID Collaboration, CUPID: CUORE (Cryogenic Underground Observatory for Rare Events) Upgrade with Particle IDentification arXiv:1504.04599

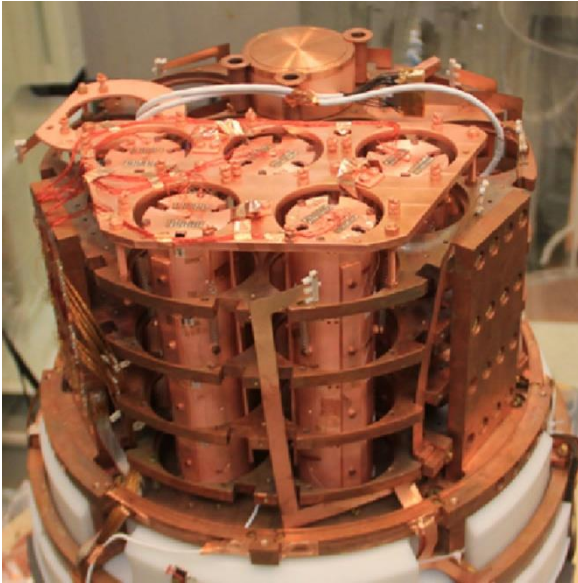
[3] CUPID Collaboration, CUPID pre-CDR arXiv:1907.09376

[4] I.C. Bandac et al., Phonon-mediated crystal detectors with metallic film coating capable of rejecting  $\alpha$  and  $\beta$  events induced by surface radioactivity, Appl. Phys. Lett. 118 (2021) 184105

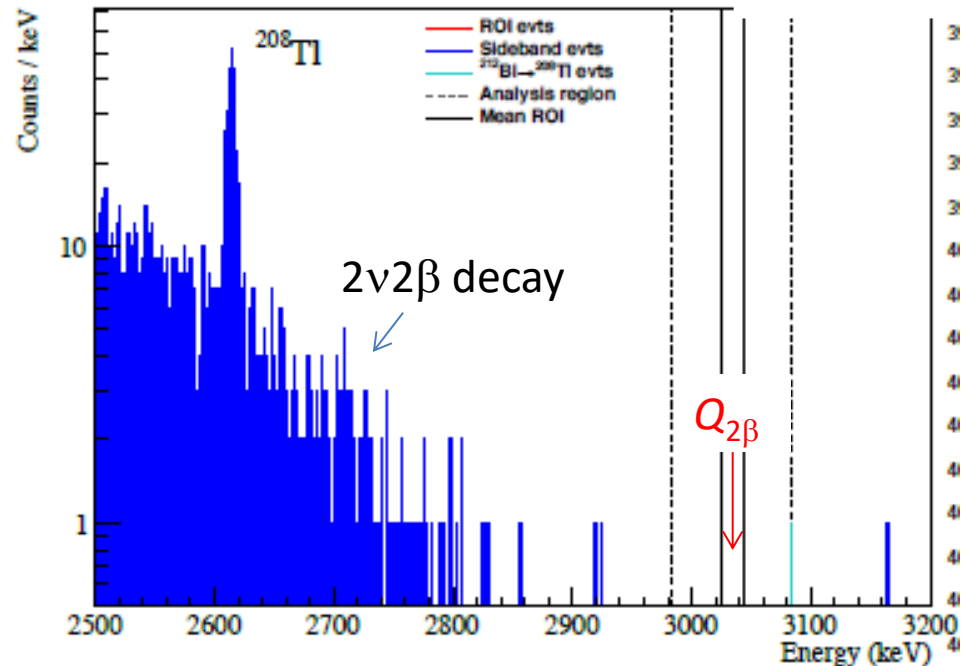
[5] A. Armato et al., First cryogenic tests on BINGO innovations, arXiv:2204.14161v1

# CUPID-Mo

Institute for Nuclear Research of NAS Ukraine



Low temperature scintillation bolometers based on enriched  $\text{Li}_2^{100}\text{MoO}_4$  crystal scintillators (Modane underground laboratory, France)



$$T_{1/2}^{0\nu 2\beta} \geq 1.5 \times 10^{24} \text{ yr}, \langle m_\nu \rangle \leq (0.31 - 0.54) \text{ eV} [1]$$

$$T_{1/2}^{2\nu 2\beta} = [7.12_{-0.14}^{+0.18} (\text{stat}) \pm 0.10 (\text{syst})] \times 10^{18} \text{ yr} [2]$$

- [1] E.Armengaud et al., A new limit for neutrinoless double-beta decay of  $^{100}\text{Mo}$  from the CUPID-Mo experiment, PRL 126 (2021) 181802  
 [2] E.Armengaud et al., Precise measurement of  $2\nu 2\beta$  decay of  $^{100}\text{Mo}$  with the CUPID-Mo detection technology, EPJC 80(2020)674



# Conclusions and outlook

1. Astroparticle physics has been developing rapidly for the last 20-30 years, outstanding results have been obtained, in particular, the first effect beyond the Standard Model of particles and interactions (mass of neutrino)
2. There are several groups in Ukraine working effectively in different experimental and theoretical activities of astroparticle physics
3. Participation in the APPEC will be definitely the very suitable and reliable basis for Ukrainian scientists to participate in the research in the field in Europe

*Anna Danevych, 4 years, "Starry sky", 2020*