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Alona MOZGOVA¹, PhD (Phys. & Math.)
ORCID ID: 0000-0002-8490-4327
e-mail: alenamozgova@knu.ua

Bohdan HNATYK¹, DSc (Phys. & Math.), Prof.
ORCID ID: 0000-0001-7113-4709
e-mail: bhnatyk@knu.ua

Lidiia ZADOROZHNA¹, PhD (Phys. & Math.)
ORCID ID: 0000-0002-3337-9753
e-mail: lidiia.zadorozhna@knu.ua

Vassyl DANYLEVSKY¹, PhD (Phys. & Math.), Senior Researcher
ORCID ID: 0000-0001-8311-0907
e-mail: vdanylevsky@knu.ua

Olexandr GUGNIN¹, PhD Student
ORCID ID: 0000-0003-4585-8812
e-mail: alexgugin@knu.ua

¹Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

OPENING THE HIGH-ENERGY SKY: FROM CITIZEN SCIENCE TO TRAINING THE NEXT GENERATION

Background. Modern physics is based on the Standard Model of particle physics and the Standard Cosmological Model, both of which require data from astrophysical observations for further development. This has led to the emergence of high-energy astrophysics – a field that explores fundamental interactions through gravitational waves, neutrinos, photons, and cosmic rays. Recent discoveries have given rise to new branches of astronomy: gravitational wave astronomy, neutrino and multi-messenger astronomy. Ukrainian scientists are actively involved in international projects such as CTAO, GCOS, and CREDO, which focus on the study of these phenomena. In 2024, the team from Taras Shevchenko National University of Kyiv (TSNUK) joined the international project – Astrophysics Center for Multi-messenger Studies in Europe (ACME, <https://www.acme-astro.eu/>), which unites the research infrastructure of participating countries to conduct collaborative astrophysical studies. The project also aims to popularize science among the wider public – particularly school and university students – and to involve non-professionals in the analysis of real scientific data. This paper presents the experience of the Ukrainian team in implementing citizen science principles and training young researchers – including students and schoolchildren – within the framework of the ACME project.

Methods. The following methods were used in this work: selecting key information to create presentation materials, developing slide presentations with lecture support, and disseminating information about the project through conferences, lecture series, social media and other public events. To engage the public in scientific research, our future plans include organizing roundtable discussions, a summer school and educational activities for young researchers using online communication platforms.

Results. As a part of the ACME project objectives, which include disseminating the results of the grant agreement and informing and engaging the public in experiments involving the intelligent analysis of scientific data, the Ukrainian team participated in organizing and conducting a number of events. These included the online event "Multi-messenger Citizen Science: Training Event for Amateur Astronomers", the university-wide open day KNU EXPO Spring 2025, the international meeting "Recovery Plan for Ukrainian Astronomy: Supporting Post-war Recovery in Ukraine through Astronomy", the national scientific conference "Astronomy and the Present Day", and a series of lectures held at the Junior Academy of Sciences of Ukraine, all of which are described in detail in this article.

Conclusions. In addition to advancing scientific knowledge, it is essential to engage the public – especially talented youth – in research through citizen science initiatives. Modern infrastructure projects increasingly involve non-professionals, including school and university students, in meaningful scientific work. At TSNUK, researchers collaborate with students via international projects such as CTAO and ACME, and also through initiatives like the High-Energy Astrophysics Training School, which promotes data analysis skills and multi-messenger astrophysics. Ukrainian researchers and students benefit from access to tools like the MMODA platform (<https://www.astro.unige.ch/astroordas/mmoda>) and the European Open Science Cloud (<https://eosc.eu/eosc-about/>), ensuring their integration into the global scientific community. Early involvement in such projects fosters critical thinking, deepens scientific curiosity, and helps prepare the next generation of innovators.

Keywords: ACME, citizen science, high-energy astrophysics, multi-messenger astronomy, cosmic rays, nonthermal gamma-ray emission

Background

The forefront of constructing the modern physical picture of the world involves two fundamental theories – the Standard Model of particle physics, which accurately describes electromagnetic, weak, and strong interactions between particles, and the Standard Cosmological Model, which describes the evolution of the Universe from the moment of the Big Bang to the present state of large-scale structure and provides predictions for its future development.

The further development of these theories requires experimental data in energy ranges far beyond the capabilities of terrestrial accelerators. We can obtain such data only from astrophysical objects and phenomena through astronomical observations. As a result, a new field of astronomical research – high-energy astrophysics – has become the experimental foundation for modern physics of fundamental interactions.

In recent years, high-energy astrophysics has yielded groundbreaking results. Notably, gravitational waves from the mergers of black holes and neutron stars have been detected, marking the beginning of gravitational wave astronomy (Abbott et al., 2017). A high-energy neutrino with an energy of 270 TeV was observed from the active galactic nucleus

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(blazar TXS 0506+056) (Halzen et al., 2019), initiating neutrino astronomy. The detection of a kilonova – a merger of two neutron stars – accompanied by both gravitational waves and a gamma-ray burst (GRB 170817A) (Abbott et al., 2017), opened the era of multi-messenger astronomy, which involves the observation of astrophysical objects in several of the four possible channels: electromagnetic, cosmic-ray, gravitational wave and neutrino.

There is also growing anticipation for the emergence of ultra-high-energy cosmic ray astronomy. Although detectors such as Auger and the Telescope Array regularly register events with energies around 10^{20} eV (Abdul Halim et al., 2023; Telescope Array Collaboration, 2023; Prechelt et al., 2022), the deflection of cosmic rays by magnetic fields currently prevents the identification of their astrophysical sources.

The main goal of multi-messenger astronomy is to study high-energy physical processes in astronomical objects using modern telescopes and detectors of high-energy messengers – cosmic rays, photons, neutrinos and gravitational waves. Ukrainian astronomers participate in a number of international collaborations focused on the construction and operation of advanced astronomical equipment, including:

- Cherenkov Telescope Array Observatory, CTAO (<https://www.ctao.org/>);
- The Global Cosmic Ray Observatory, GCOS (<http://particle.astro.ru.nl/gcos/>);
- Cosmic-Ray Extremely Distributed Observatory, CREDO (<https://credo.science/>).

In 2024, the scientific team from Taras Shevchenko National University of Kyiv (TSNUK) joined the international infrastructure project "Astrophysics Center for Multi-messenger studies in Europe (ACME)" (<https://www.acme-astro.eu/acme-project/>). The aim of this project is to provide researchers from the participating countries with access to existing scientific equipment, unified under an astrophysical center with open access to observational data and methods for data processing.

The main scientific objective of ACME is to conduct advanced research through joint scientific teams, based on the shared use of infrastructure capabilities. At the same time, an equally important direction of the ACME project is the promotion of scientific knowledge not only among professional researchers but also among the general public interested in science – especially school students and university students (not only those in natural sciences). Moreover, there is already significant experience involving non-professionals in real scientific research, particularly where human (natural, not-artificial) intelligence is needed to analyze large amounts of observational data – as in the discovery of new exoplanets, for example. Today, all major collaborations, including those mentioned above involving Ukrainian scientists, include as one of their key activities the involvement of non-professionals in scientific research through observation data analysis.

In our work, we present a description of how the Ukrainian team has implemented the principles of citizen science and the training of young researchers, including school and university students, within the framework of the ACME project.

Methods

This work was carried out within the framework of the ACME project tasks, specifically Work Package 7 – ACME for Environment and Society. We selected key information to create presentation materials for upcoming outreach events aimed at informing and engaging the public in data-driven scientific experiments conducted by professional researchers. The goal is to assist scientists in processing the large volumes of scientific data currently being generated. We prepared a set of presentation materials, including slide decks and corresponding lecture notes.

The events in which we presented the ACME project are described in the next section of this article. Information about the ACME project's opportunities and our involvement in it has been disseminated through conference presentations, international meetings, open days at TSNUK, national lecture series and social media platforms. In the future, we also plan to organize roundtable discussions with scientists and engaged citizens to discuss scientific results obtained within the ACME project, as well as a summer school for PhD students, early-career researchers and Master's students. This school will focus on theoretical foundations and practical tools for the analysis and interpretation of observational data in the field of high-energy astrophysics using various messengers.

Results

Among the work packages of the ACME project, a number of tasks involve organizing various activities aimed at disseminating the results of this grant agreement, as well as informing and engaging the public in experiments involving intelligent data analysis carried out by professional scientists. The goal is to assist researchers in processing the growing volume of scientific data. These efforts form part of the broader objective of the ACME project – to ensure wider, simplified, and more effective access to the best research infrastructures available to researchers in the astronomy and astroparticle physics communities (<https://citizen-science.sciencesconf.org/>).

Such initiatives are implemented through specific events, including virtual trainings and workshops. On June 10, 2025, the ACME online event titled "Multi-messenger Citizen Science: Training Event for Amateur Astronomers" was held. This hands-on virtual workshop aimed to enable the amateur astronomy community to engage with professional research communities working with multi-messenger technologies and to learn about the tools they can use to contribute to astrophysical research on multi-messenger and transient events through citizen science. The seminar included presentations, demonstrations, and practical guides delivered by both professional astronomers and amateur astronomers. The goal was to inform the amateur astronomy community about best practices, introduce them to what the research community needs in terms of data, and explore available tools for collecting, storing and utilizing such data (<https://citizen-science.sciencesconf.org/>). We carried out a number of outreach efforts to promote the event and extended invitations to: students of the Junior Academy of Sciences of Ukraine (JASU), including active participants and winners of national and international competitions in astronomy and astrophysics, pupils from various Ukrainian schools, students of TSNUK, professional astronomers, amateur astronomers and interested members of the public. According to the event registration data (<https://citizen-science.sciencesconf.org/resource/listparticipants#A>), around 18 of the 66 registered participants were from Ukraine.

Participant engagement in the ACME event was also supported by a prior event held on May 17, 2025, at TSNUK. The university-wide Open Day "KNU EXPO Spring 2025" is a large-scale career guidance event organized by one of Ukraine's most prestigious universities. This educational festival brings together all institutes, faculties, colleges and the lyceum of TSNUK to help prospective students choose their future professional paths. On this day, prospective students and their parents have the opportunity to get acquainted with the University, learn about academic programs, educational opportunities,

student life and future career prospects after graduation (<https://knu.ua/ua/knu-expo>). As part of this event, we represented the University's Astronomical Observatory and informed participants about our scientific capabilities and the projects we are involved in, including the opportunities offered by the ACME project (Fig. 1). In total, over 40 visitors attended our location, where astronomy was promoted and public outreach was conducted.



Fig. 1. The university-wide Open Day "KNU EXPO_Spring2025"

From June 9 to 13, 2025, an international meeting titled "Recovery Plan for Ukrainian Astronomy: Supporting Post-war Recovery in Ukraine through Astronomy" took place (Albergaria et al., 2025). The meeting with international colleagues was held at the Leiden Observatory of Leiden University (The Netherlands) as part of the Erasmus+ICM international exchange program. The goal of the international meeting was to develop a long-term strategy for the restoration and integration of Ukrainian astronomy into European research infrastructures. The event began with introductions of participants and presentations by staff members representing various astronomical observatories in Ukraine, as well as by representatives of prominent European institutions and organizations, including: Sara Lucatello (The President of the European Astronomical Society), Willy Benz (The President of the International Astronomical Union), Ignas Snellen (The Director of Leiden Observatory), Mamoru Doi (The Director General of the National Astronomical Observatory of Japan), Michiel Rodenhuis (The Executive Director of the Netherlands Research School for Astronomy, NOVA), Michael Wise (The General Director and Scientific of the Netherlands Institute for Space Research, SRON), Violette Impellizzeri (The Head of the Astronomy Department at the Netherlands Institute for Radio Astronomy, ASTRON), Michiel van Haarlem (The Executive Director of LOFAR ERIC), Giuseppe Cimo (The Head of Space Science and Innovation at JIV-ERIC), Saskia Matheussen (Netherlands Research Council, NWO, Deputy Chair of ASTRONET), Pavlo Plotko (Scientific Coordinator, German Centre for Astrophysics, DESY). Ukrainian representatives also gave presentations, including Oksana Berezhna (Director General of Innovation and Science Liaison with the Real Sector of Economy Directorate, Ministry of Education and Science of Ukraine), Ganna Tolstanova (Vice-Rector for Research, TSNUK), Svitlana Babichuk (The Head of the GIS and Remote Sensing Laboratory, JASU).

Alona Mozgova represented the Astronomical Observatory of Taras Shevchenko National University of Kyiv in the working group "Rebuilding infrastructure and research facilities", which focused on developing an action plan for restoring and preserving telescopes and other scientific equipment in Ukraine. Some of the telescopes have been destroyed and require reconstruction, while other instruments and equipment are outdated and need modernization. The group also discussed potential options and prospects for integrating Ukraine's existing astronomical equipment into various international scientific projects, including participation of the Ukrainian scientific team in the ACME project.

As a result of the meeting, a draft document was prepared outlining a long-term strategy for the recovery and integration of Ukrainian astronomy into European research infrastructures. The final version is currently being refined and will be signed by, among others, distinguished Nobel laureates. It will then be submitted for approval by the European Commission. If endorsed by the Commission, the document will become an official roadmap.

Every year on April 12, on the International Day of Human Space Flight – or shortly before it – the All-Ukrainian Scientific Conference "ASTRONOMY AND MODERNITY" is held in Ukraine, hosted by Vinnytsia Mykhailo Kotsiubynskyi State Pedagogical University (<https://vspu.edu.ua/?event=7225>). This year, the conference brought together over 100 participants, including scientists, school and college teachers, students, and pupils. It provided an excellent opportunity to inform a broad audience about the goals, objectives, and potential of the ASME project. Alona Mozhgova gave a presentation highlighting the key areas of the project's activities, particularly focusing on citizen science, public engagement in scientific initiatives, and expanding access to research infrastructure within the framework of multi-channel astrophysical studies.

The aforementioned JASU is a state specialized out-of-school educational institution with a scientific profile (<https://man.gov.ua/>). Its primary mission is to promote science and scientific education, disseminate innovative forms of working with children through teacher training, and provide effective tools to students for engaging in research, scientific, engineering, inventive, and exploratory activities.

The National Center JASU ensures the organization and coordination of students' research activities by overseeing educational institutions within the JASU system. The structure of JASU includes 25 territorial branches, among them 15 regional junior academies of sciences, 8 municipal, and 2 district junior academies. JASU creates a supportive educational environment for the intellectual development and career orientation of gifted children and youth. These regional branches conduct scientific and educational projects aimed at engaging students in extracurricular research and experimental activities.

The educational activities of the JASU are implemented through student participation in nationwide educational projects, the organization and administration of contests, tournaments, festivals, Olympiads, and other intellectual competitions, as well as by supporting student participation in international intellectual competitions (<https://mon.gov.ua/osvita-2/pozashkilna-osvita/derzhavni-tsentri-pozashkilnoi-osviti/natsionalniy-tsentri-mala-akademiya-nauk-ukraini-man>).

Among these activities, regular lecture series are also held at JASU for younger and middle school students, delivered by instructors from the children's academy "Futurum." Notable examples include the nationwide project "Step to Science" (<https://man.gov.ua/en/online-projects/vseukrayinsskij-proyekt-krok-do-nauki>) and "Complicated things in simple words: science for children" (<https://man.gov.ua/en/online-projects/prosto-pro-skladne-nauka-dityam>). These lectures are conducted via online platforms, allowing students from all over Ukraine to participate. Typically, up to 100 participants attend each lecture, sometimes even more. This creates an excellent opportunity to promote science among the younger generation, highlight the latest achievements in astrophysics, space research, and Ukraine's role in international scientific projects, engage children in data analysis, citizen science projects, and foster motivation to study natural sciences. During several of these lectures, attendees were informed about the goals, objectives, and citizen science component of the ACME project, as well as the participation of Ukrainian school students and university students in related initiatives.

Furthermore, on April 22 and 25, 2025, during lectures aimed at professional development for teachers from various Ukrainian schools, the participation of Ukraine in the ACME project was presented. The purpose was to inform educators about opportunities for integrating the Ukrainian educational community into international scientific initiatives, especially by involving students in research programs.

Ukraine is home to a significant number of talented and motivated students who achieve outstanding results in Olympiads, competitions, and scientific projects. It is extremely important to create conditions that provide these gifted children with access to modern science, expose them to cutting-edge research areas, and enable them to realize their potential in collaboration with the professional scientific community. In this context, special significance is given to the High-Energy Astrophysics Training School – an international educational initiative aimed at providing young researchers, students, and high school students with solid training in the field of modern high-energy astrophysics, multi-messenger research, big data analysis, and participation in global experiments. A special part of the lecture program is adapted for senior school students, and special attention is given to them to encourage their continued interest in astrophysics and involvement in scientific initiatives.

The ACME Training School on High-Energy Astrophysics will be organized at TSNUK in the third year of the ACME project. The school will provide a broad introduction to the physics behind the most energetic processes in the Universe and their significance for the rapidly developing field of multi-messenger astrophysics. Its main goal is to provide PhD students, early-career researchers, and advanced Master's students with both theoretical foundations and practical tools to analyze and interpret high-energy data across different messengers.

The school will cover the physics of compact objects, relativistic jets, gamma-ray bursts, active galactic nuclei, galaxy clusters, cosmic rays, and high-energy neutrinos. Special attention will be given to the synergies between X-ray, gamma-ray astronomy, neutrino and Ultra-High-Energy Cosmic Rays (UHECR) detections, as well as real-time multi-messenger alerts. Participants will be introduced to data archives, pipelines, and analysis tools developed within ACME (e.g., Multi-Messenger Online Data Analysis (MMODA), Gammapy, multi-messenger data workflows) and to the implementation of FAIR (Findable, Accessible, Interoperable, Reusable) data principles in practice.

The teaching staff will include internationally recognized experts from the ACME consortium and associated infrastructures, representing space- and ground-based observatories (X-ray, gamma-ray, neutrino, UHECR (see Table 1)). Hands-on tutorials will be complemented by keynote lectures, roundtable discussions, and a final hackathon-style group project.

The school is expected to gather around 40–50 participants from Europe and associated countries, with dedicated support for young researchers from Ukraine. The format will be hybrid: in-person at TSNUK, with live streaming and interactive online participation to ensure accessibility.

By the end of the school, participants will:

- Understand the key physical mechanisms behind high-energy astrophysical phenomena.
- Gain familiarity with modern analysis tools and datasets from high-energy observatories.
- Develop the skills to integrate high-energy observations with other messengers in a multi-messenger framework.
- Build a professional network with peers and leading scientists across Europe.

This training school will not only contribute to building the next generation of multi-messenger researchers but also strengthen the visibility and integration of Ukrainian science within the European Research Area.

Table 1

Key Facilities in High-Energy and Multi-messenger Astrophysics

Facility	Messenger	Energy Range / Domain
INTEGRAL (International Gamma-Ray Astrophysics Laboratory)	X-ray / γ -ray (space mission)	3–35 keV (JEM-X); 15 keV–10 MeV (IBIS); 20 keV–8 MeV (SPI)
SWIFT (Neil Gehrels Swift Observatory)	X-ray / γ -ray (space mission)	0.3–10 keV (XRT); 15–150 keV (BAT)
MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescopes)	VHE γ -ray (ground-based)	50 GeV–100 TeV
CTAO (Cherenkov Telescope Array Observatory)	VHE γ -ray (ground-based)	20 GeV–300 TeV (planned)
KM3NeT (Cubic Kilometre Neutrino Telescope): – ORCA (Oscillation Research with Cosmics in the Abyss); – ARCA (Astroparticle Research with Cosmics in the Abyss)	Neutrinos (GeV–PeV)	1–100 GeV (ORCA); 100 GeV–10 PeV (ARCA)
ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch)	Neutrinos (precursor of KM3NeT)	100 GeV–100 TeV
IceCube Neutrino Observatory	Neutrinos (South Pole)	1 TeV–10 PeV
PAO (Pierre Auger Observatory)	UHECR (Ultra-High-Energy Cosmic Rays)	1–100 EeV

Discussion and conclusions

Alongside the pursuit of purely scientific objectives – such as expanding our understanding of the structure and evolution of the Universe – an important task for the scientific community is to communicate new research findings to the general public and to engage talented young people in scientific research. A distinctive feature of the current stage of scientific progress is the growing opportunity to effectively involve non-professionals in serious scientific research. In support of this emerging field – "citizen science" – activities are planned within all modern infrastructure projects in the natural sciences. The astronomical community also pays great attention to working with non-professionals, as well as with school and university students. In particular, astronomers and physicists at TSNUK engage them in international infrastructure projects such as CTAO, ACME, and others. This work outlines the key areas and outcomes of these activities.

In particular, within the framework of the planned training school "The High-Energy Astrophysics School" we are going to train young researchers in theory and data analysis, applying citizen science and FAIR principles to expand multi-messenger astrophysics in Europe. Importantly, the MMODA platform is deployed on the computing cluster at TSNUK, which will be further expanded with a new high-performance computing system. This development, together with access to the European Open Science Cloud, ensures that Ukrainian researchers and students are fully integrated into the European research landscape and have the tools needed to contribute at the highest international level.

Engaging students of the JASU in research activities is extremely important for shaping a new generation of scientists, researchers, and innovators. At this age the interest in science, critical thinking, and information-processing skills are actively developed. Participation in research projects allows school students not only to gain a deeper understanding of the world but also to contribute to solving current scientific and societal challenges. Moreover, collaboration with scientists motivates students toward further professional growth and integration into the international academic community.

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Альона МОЗГОВА¹, канд. фіз.-мат. наук
ORCID ID: 0000-0002-8490-4327
e-mail: alenamozgova@knu.ua

Богдан ГНАТИК¹, д-р фіз.-мат. наук, проф.
ORCID ID: 0000-0001-7113-4709
e-mail: bhnyat@knu.ua

Лідія ЗАДОРЖНА¹, канд. фіз.-мат. наук
ORCID ID: 0000-0002-3337-9753
e-mail: lidia.zadorozhna@knu.ua

Василь ДАНИЛЕВСЬКИЙ¹, канд. фіз.-мат. наук, ст. дослідник
ORCID ID: 0000-0001-8311-0907
e-mail: vdanylevsky@knu.ua

Олександр ГУГНІН¹, асп.
ORCID ID: 0000-0003-4585-8812
e-mail: alexgugin@knu.ua

¹ Київський національний університет імені Тараса Шевченка, Київ, Україна

ВІДКРИВАЮЧИ ВИСОКОЕНЕРГЕТИЧНЕ НЕБО: ВІД ГРОМАДЯНСЬКОЇ НАУКИ ДО ПІДГОТОВКИ НОВОГО ПОКОЛІННЯ ВЧЕНИХ

Вступ. Сучасна фізика ґрунтується на Стандартній моделі фізики частинок і Стандартній космологічній моделі, для розвитку яких потрібні дані з астрофізичних спостережень. Це зумовило появу астрофізики високих енергій – напряму, що вивчає фундаментальні взаємодії через гравітаційні хвилі, нейтрино, фотони та космічні промені. Останні відкриття започаткували нові напрями: гравітаційно-хвильове, нейтринну та багатоканальну астрономію. Українські вчені беруть участь у міжнародних проєктах СТАО, GCOS і CREDO, що досліджують ці явища. У 2024 р. команда Київського національного університету імені Тараса Шевченка долучилася до міжнародного проєкту ACME (Astrophysics Center for Multi-messenger studies in Europe), що об'єднує наукову інфраструктуру країн-учасниць для проведення спільних астрофізичних досліджень. Проєкт також спрямовано на популяризацію науки серед широкої аудиторії, зокрема школярів і студентів, та на залучення непрофесіоналів до аналізу реальних наукових даних. У нашій роботі представлено досвід української команди у впровадженні принципів науки для непрофесіоналів і підготовки молодих науковців із школярів та студентів у межах проєкту ACME.

Методи. Використано такі методи: відбір ключової інформації для створення презентаційних матеріалів, розроблення слайдових презентацій із лекційним супроводом, а також поширення інформації про проєкт через конференції, лекторії, соціальні мережі та інші публічні заходи. З метою залучення громадськості до наукових досліджень заплановано проведення в майбутньому круглих столів, літньої школи й освітніх заходів для молодих науковців із використанням онлайн-комунікаційних платформ.

Результати. У межах завдань проєкту ACME, що передбачають поширення результатів грантової угоди й інформування і залучення громадськості до участі в експериментах з інтелектуального аналізу наукових даних, українська команда взяла участь в організації та проведенні низки заходів, зокрема це: онлайн-захід ACME "Multi-messenger Citizen Science: Training Event for Amateur Astronomers", загальноуніверситетський день відкритих дверей KNU EXPO Spring 2025, міжнародна нарада "План відновлення української астрономії: підтримка післявоєнного відновлення України за допомогою астрономії", Всеукраїнська наукова конференція "Астрономія і сьогодення", низка лекцій на базі Малої академії наук України, які детально описано в статті.

Висновки. Крім розвитку наукових знань, важливо залучати громадськість, особливо талановиту молодь, до досліджень через громадянські наукові ініціативи. Сучасні інфраструктурні проєкти все частіше залучають непрофесіоналів, включаючи учнів шкіл та університетів, до змістовної наукової роботи. У Київському національному університеті імені Тараса Шевченка дослідники співпрацюють зі студентами через міжнародні проєкти, такі як СТАО й ACME, а також через такі ініціативи, як Наєчальна школа астрофізики високих енергій, яка сприяє розвитку навичок аналізу даних і багатоканальної астрофізики. Українські дослідники та студенти мають доступ до таких інструментів, як платформа MMODA та Європейська хмара відкритої науки, що забезпечує їхню інтеграцію у світову наукову спільноту. Рання участь у зазначених проєктах сприяє критичному мисленню, поглиблює наукову допитливість і допомагає підготувати наступне покоління новаторів.

Ключові слова: ACME, громадянська наука, астрофізика високих енергій, багатоканальна астрономія, космічні промені, нетеплове гамма-випромінювання.

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