2025

High-energy heavy-ion physics is connected to a large variety of physics disciplines. Researches probe fundamental concepts of classical and modern thermodynamics, hydrodynamics, and quantum theory. Therefore, they have several theoretical and practical topical research directions covering a wide spectrum, such as: thermodynamics, perturbative and non-perturbative QCD, high-energy nuclear effects, hadronization, hadron phenomenology, phenomenology of compact stars, and gravity/cosmology. These studies are strongly motivated by the needs of several recent and planned large-scale facilities, such as collaborations at the LHC (CERN, Switzerland) and RHIC (BNL, USA), and future experiments at Hi-Lumi LHC or FCC (CERN), and FAIR (GSI, Germany). They have continued these theoretical investigations in the direction of high-energy physics phenomenology connected to existing and future state-of-the-art detectors. Concerning international theoretical collaborations, they have established joint work with the Goethe Institute (Germany), University of Wroclaw, (Poland), LBNL (USA), CCNU, MAP (China), UNAM (Mexico), University of Madrid (Spain), IIT Indore ((india) and ERI (Japan). The most important published results are highlighted below.

Investigating heavy-ion collisions — High-energy heavy-ion collisions are one of the best testbeds for the non-ideal, non-equilibrium, finite systems, these methods are especially successful in the theoretical description of small systems. Together with the Indian Institute of Technology (IIT) Indore they further investigated the momentum asymuthal anisotropy parameter (v_2 – the second Fourier component), measured in non-central collisions of Oxigen nuclei at LHC energies. They calculated the effect of nuclear structure parameter on the asymuthal anysotropy parameter [1]. In collaboration with the University of Berkeley (USA) and IoPP CCNU (Wuhan, China), they further developed the HIJING++ heavy-ion Monte Carlo Generator with G. Papp (ELTE) and X.N. Wang (IoPP CCNU, LBNL). In a joint project between Wigner RCP and the ICN UNAM, they identified the limit between the soft and hard part of the hadron spectra.

Multi-wavelength astronomy and investigations of extreme matter in the Universe — They investigated the Kaluza-Klein compact stars, and fund the speed of sound is different from the standard conformal limit for such objects. They also calculated the the maximal mass of the object in case of multiple extra dimensions [2]. The universe's expansion rate (the Hubble constant) measured nearby differs from that inferred from the early-universe cosmic microwave background, creating a "Hubble tension." They proposed that a slow, global rotation of the cosmos could reconcile these conflicting measurements [3]. Using a Gödel-inspired dark-fluid model, they find that an angular speed today of about $\omega_o \approx 2 \times 10^{-3}$ Gyr^{-1} (≈0.002 Gyr^{-1}) matches the locally measured Hubble value. This rotation rate lies just below the maximal speed allowed before closed time-like loops would appear, keeping the model physically viable. The rotation evolves as $|\omega(t)| = \omega_o\, a^{-2}(t)$, conserving angular momentum during matter domination. Extrapolating back to the time of recombination gives an initial spin of roughly $\omega(t_{CMB}) \approx 3.5$ Myr^{-1}, still compatible with many theories. The approach uses Newtonian Euler–Poisson equations with a Sedov-type self-similar solution, avoiding the complexity of full general-relativistic calculations. Numerical checks confirm that the rotating model reproduces the standard Friedmann expansion when $\omega \to 0$, ensuring consistency with

well-tested cosmology. The paper suggests that rotation could be an alternative to other proposals (e.g., dark photons) for solving the Hubble puzzle (Fig 1).

The effective field theory of the strong interaction — They surveyed modern low-energy QCD approaches, emphasizing effective models that incorporate mesons, glueballs, and constituent quarks. They reviewed the extended Linear Sigma Model (eLSM), where physical meson fields are used and gluonic effects enter through a dilaton-like glueball field Historical chiral models such as the Nambu–Jona–Lasinio (NJL) framework are discussed, highlighting their ability to generate constituent quarks via the chiral condensate. Dyson–Schwinger equations (DSE) are presented as a bridge between QCD Lagrangian dynamics and hadronic bound states, with recent successes in glueball mass predictions. QCD sum-rule techniques are summarized for connecting quark/gluon currents to resonance properties and condensates. Functional renormalization group (FRG) methods are introduced as non-perturbative tools to flow from classical Lagrangians to low-energy quantum behavior. Holographic and Veneziano-type models are mentioned as alternative avenues for studying hadronic spectra. Their work compares these approaches, noting that while each captures different aspects of confinement and chiral symmetry breaking, none is fully comprehensive on its own. Applications to thermodynamics, such as calculating pressure in a glueball resonance gas, illustrate the phenomenological relevance of these models. The authors conclude that a unified description likely requires merging insights from several frameworks, with the eLSM providing a versatile baseline for further extensions [4].

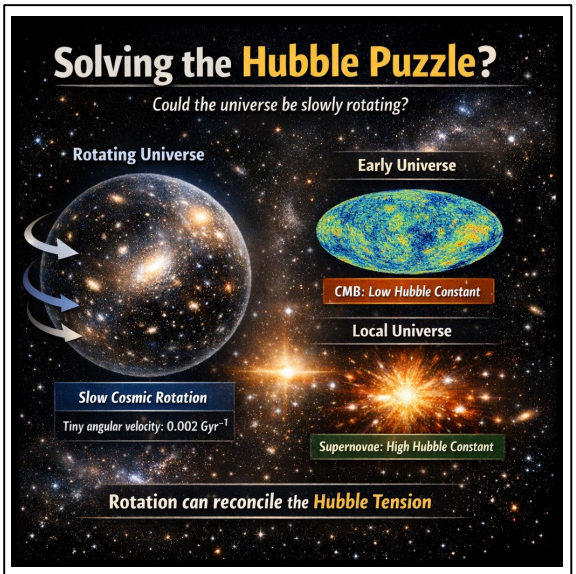

Figure 1: Can rotation solve the Hubble tension?

Jánossy Underground Research Laboratory (JURLAB). --- They further developed the JURLAB, with more control on the humidity and temperatures. They also carried out test measurements, data processing and documentation writing in the second phase of the R&D project SeismoCell, using seismic and infrasound sensors. Rare and anomalous radionuclei decay of ^{137}Cs measurements were investigated during the year at the JURLAB. They connected to the National Radon Program with Radon decay measurement underground. To perform high-precision studies of nuclear decay anomalies they used a high-purity germanium (HPGe) detector setup. They finished the 3-years period of measurement, which has been summarized in a paper.

Coordination of the Hungarian ALICE Group and participation in the Bergen pCT collaboration. — They coordinate the Hungarian contributions to CERN's largest heavy-ion experiment ALICE. This activity is many-folded: In addition to data analysis, our group has constructed and developed a new specialized Analysis Facility for the CERN ALICE Collaboration in the WSCLAB at the Wigner RCP. This HPC unit is dedicated for Big Data challenges as a joint activity with the Vesztergombi High-energy Physics Laboratory (VLAB), which awarded the TOP50 Hungarian research infrastructure title in 2021. Until September

2025, they used intensively with the new ALICE O^2 software framework hyperloop on the Wigner Analysis Facility.

They were involved in the ITS3 and the FoCal projects of the ALICE phase II upgrades. A next generation heavy-ion experiment at the LHC is ALICE3, which was presented for the RRB and got the final layout. They strongly engaged with this large-scale R&D project, and contributed to the beam measurements of the Muon ID (MID) detector and the DAQ development for the RICH detector subprojects as well. The main hadrware R&D contributions are: the data acquisition system (DAQ) and multi-wire proportional chambers (MWPCs).

They also contributed to the Bergen pCT collaboration, where the detector prototype of the tracking calorimeter has been built, and analysis tracking softwares were developed based on machine learning techniques. They have two PhD students on this field.

Coordination of the Wigner Scientific Computational Laboratory (WSCLAB) — WSCLAB, as the TOP50 research infrastructure of the Hungarian national grant agency, NRDIO, were involed in several national and international projects. These are primary dedicated to massively parallel classical and quantum computing at various field of sciences. They have improved the CERN ALICE Analysis Facility, the CERN WLCG Grid T2 site of the CERN's ALICE and CMS collaborations, and the Wigner GPU Laboratory. They participated in the EU's AI Factory ANTENNA project together with the SzTAKI and the HUN-REN. Their computing capacity was intensively used by several projects such as the Nanoplasmonic Laser Fusion National Laboratory, the Astronomy Department of the Eötvös University, the LIGO gravitational wave signal search, Heavy-ion Research Group of the Wigner RCP together with the University of Oxford, John Hopkins University (Baltimore). They supportoed several individual 'Lendület' projects. Academy-industry cooperation were established with the Lombiq LTD, Ericsson Research, and SeismoCell.

The WSCLAB has organized the "WSCLAB GPUDay 2025" conference for the 15th times and the "Lectures on Modern Scientific Programming 2023". They participated in the "CERN-Wigner Artificial Intelligence Academia-Industry Matching Event (AIME 2025)" and supported the Virtual Institute Association 'SciComp' to provide the platform to prolongate data science in Hungary. As a Hungarian representative of the CERN's Quantum Technology Initiative they started the 2nd phase of the QTI project with the principal investigator Sofia Vallecorsa.

Education, PR and prizes. — They had 6 young PhD fellows associated with the research group. Senior colleagues are members of the ELTE, BME, PTE doctoral programmes. Balázs Pál has submitted his PhD theses to the the ELTE Physics Doctoral School. Gábor Bíró become the CERN ALICE's deputy computing coordinator. Members Gergely Gábor Barnaföldi, Gábor Bíró, Gyula Bencédi, Péter Lévai, Mónika Varga-Kőfaragó, Róbert Vértesi, shared the Breakthrough prize for the "Awarded to thousands of researchers from the **ATLAS, CMS, ALICE, and LHCb** collaborations at CERN for their work on the Higgs boson and exploration of nature at the shortest distances."

Group members played key role in the following workshop, conference and seminar organizations: "WSCLAB GPU Day 2025" at the at Wigner RCP; "Zimányi Winter School 2025," Budapest, Hungary, Lectures on Modern Scientific Programming 2025, The AIME 2025 Academy-Industry Maching Event. Group members participated in PR activities at their alma mater and high-school invitations, indeed the 'Researcher's Night.

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[3] Szigeti, Balazs Endre ; Szapudi, Istvan ; Barna, Imre Ferenc ; Barnafoldi, Gergely Gabor , Can rotation solve the Hubble Puzzle?, MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY 538 : 4 pp. 3038-3041. , 4 p. (2025)

[4] Giacosa, F. ; Kovács, P. ; Jafarzade, S. Ordinary and exotic mesons in the extended Linear Sigma Model PROGRESS IN PARTICLE AND NUCLEAR PHYSICS 143 Paper: 104176 , 76 p. (2025)

The blue part connects to WSCLAB, ALICE and JURLAB.