2025

A Gauge-Invariant Definition of Angular Momentum

István Rácz introduced a new framework for representing rotation and defining angular momentum by generalizing the notion of rotation to topological two-spheres without symmetries. Within this framework, angular momentum is assigned to regions of spacetime bounded by such two-surfaces, provided a well-defined center of mass exists. This construction is fully gauge invariant and applies generically to any geometrized theory of gravity.

Infinity at Our Hand

In 1963, Roger Penrose introduced a novel geometric framework for the description of isolated, self-gravitating systems. His approach makes it possible to adjoin a fictitious boundary representing infinity to physical spacetime, effectively bringing infinity to a finite distance with respect to a conformally related, non-physical metric. The construction relies crucially on the smoothness—that is, infinite-order differentiability—of the underlying mathematical structures.

In the mid-1990s, these smoothness assumptions were challenged using the only available analytical method at the time, which suggested that generic hyperboloidal initial data contain logarithmic terms that obstruct smoothness.

Károly Csukás and István Rácz argued that these challenges overlooked the role of physically meaningful quantities such as the total (Bondi) energy and angular momentum. By employing the evolutionary method recently developed by István Rácz, they showed that whenever these quantities are finite, the associated hyperboloidal initial data sets are smooth throughout the entire domain, including the boundary representing infinity. Their results therefore reaffirm the smoothness assumptions underlying Penrose's conformal framework.

Kerr–Schild Spacetimes in Scalar-Tensor Gravity

Kerr–Schild spacetimes are constructed from a seed spacetime whose light cones share a common null congruence. In general relativity, Xanthopoulos established in 1978 the remarkable result that all vacuum Kerr–Schild metrics arising as perturbations of vacuum seed spacetimes are exact solutions. In other words, solutions of the linearized Einstein equations also solve the full nonlinear field equations. This result was extended to non-vacuum settings by László Árpád Gergely more than two decades ago, identifying the classes of energy–momentum tensors for which this property continues to hold.

Recently, there has been renewed interest in scalar–tensor theories of gravity, motivated by their potential to address outstanding problems such as dark matter, dark energy, inflation, and the quantization of gravity. The subset of these theories that is compatible with current cosmological, astrophysical, and gravitational-wave observations, while also satisfying the necessary stability conditions, is known as kinetic gravity braiding. This class includes generalizations of quintessence, k-essence, and various Galileon models, and constitutes a simpler subclass of Horndeski theories.

Bence Juhász and László Árpád Gergely extended the earlier results on Kerr–Schild spacetimes in non-vacuum Einstein gravity to geometries sourced by minimally coupled, but otherwise generic kinetic gravity braiding scalar field. For the simpler case of a k-essence scalar field, they showed that a perturbative Kerr–Schild-type solution becomes exact only if either the k-essence Lagrangian is linear in the kinetic term, with the Kerr–Schild congruence being autoparallel, or the Lagrangian is unrestricted provided the scalar gradient along the congruence vanishes. A similar reasoning for the proper kinetic braiding scalar-tensor model led to the conclusion that either the Lagrangian must vanish or the scalar field must be constant along the congruence. From the scalar dynamics they also derived an accompanying constraint.

Finally, they examined plane-fronted waves with parallel propagation (pp-waves) as a concrete example of Kerr–Schild spacetimes generated by a k-essence scalar field that is constant along the Kerr–Schild congruence and associated with a vanishing Lagrangian. This framework enabled the construction of a Fock-type space consisting of a hierarchy of Kerr–Schild maps: starting from flat spacetime to produce a vacuum pp-wave; then generating a k-essence–supported pp-wave from the vacuum solution; and ultimately constructing an arbitrary number of k-essence pp-waves with distinct metric functions depending on retarded time.

Benchmarking Modelling Approaches for Nonlinear Heat Conduction

Thermal effects play a critical role in gravitational wave detectors, which operate at cryogenic temperatures where nonlinear phenomena are significantly amplified. This makes it essential to rigorously benchmark both modelling strategies and numerical solution methods. Róbert Kovács and collaborators investigated heat conduction beyond Fourier's law, transient evaporation processes, and wave propagation in supercritical fluids.

Using discrete numerical modelling, they demonstrated that macroscopic non-Fourier thermal behaviour in metal foams arises from geometric heterogeneities in parallel transport channels rather than from intrinsic material properties. They further showed that conventional diffusive models are incapable of capturing the dual time-scale transients inherent to these complex porous structures.

Extending their analysis of internal thermal gradients to multiphase systems, they revealed that droplet evaporation at high pressure requires spatially resolved continuum models to account for strongly nonlinear variations in transport properties. Traditional lumped-parameter approaches break down under non-equilibrium conditions, particularly when large Biot numbers drive the system away from thermal uniformity.

To address the strong coupling between thermal and mechanical transport near the critical point, they developed a structure-preserving numerical scheme based on reversible–irreversible vector-field splitting to simulate the thermoacoustic piston effect. By solving the linearized compressible Navier–Stokes–Fourier equations on a staggered space–time grid, the method cleanly separates the symplectic integration of hyperbolic acoustic modes from the dissipative integration of parabolic heat diffusion. This thermodynamically consistent approach eliminates numerical dispersion and dissipation errors, enabling precise resolution of the widely separated timescales characteristic of critical speeding-up phenomena.

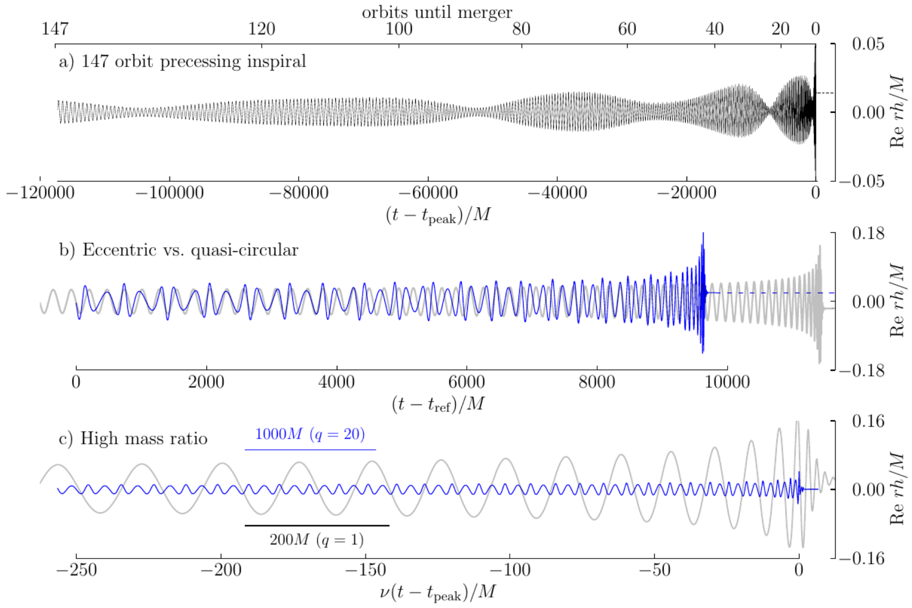

Figure 1. The effect of spin precession (upper panel), eccentricity (blue, mid panel) and uneven mass ratio (lower panel) on the gravitational waveform (SXS Catalog).

Participation in International Gravitational Research Networks and Collaborations

As members of the Einstein Telescope (ET) Collaboration, Dániel Barta, Balázs Kacskovics and László Árpád Gergely contributed to *The Science of the Einstein Telescope*, a comprehensive monograph summarizing the scientific objectives and potential of the ET detector. This 600-page work is already available on the arXiv repository and is scheduled for publication in 2026 in the Journal of Cosmology and Astroparticle Physics.

Dániel Barta, Károly Csukás, Edit Fenyvesi and Balázs Kacskovics were active contributors to the Virgo Collaboration. Their work included modelling the interiors of compact objects and the dynamics of eccentric compact binaries, improving an infrasound monitoring system, and establishing a Tier-2 computing cluster to support the collaboration's computational needs.

Károly Csukás also played an active role in the Simulating eXtreme Spacetimes (SXS) Collaboration, contributing to the development of the Spectral Einstein Code used for simulating binary black hole dynamics. In 2025, the collaboration released *The SXS Collaboration's Third Catalog of Binary Black Hole Simulations*, a publicly available waveform catalogue comprising 3,756 waveforms and covering a substantially expanded region of the parameter space.

László Árpád Gergely participated in the COST Action CA21136, Addressing Observational Tensions in Cosmology with Systematics and Fundamental Physics (CosmoVerse). In 2025, the collaboration published *The CosmoVerse White Paper: Addressing Observational Tensions in Cosmology with Systematics and Fundamental Physics*, an extensive monograph reviewing the current challenges and open questions in cosmology.

In addition, László Árpád Gergely contributed to the COST Action CA23130, Bridging High and Low Energies in Search of Quantum Gravity (BridgeQG). The collaboration published in 2025 the *White Paper and Roadmap for Quantum Gravity Phenomenology in the Multi-Messenger Era*, providing a comprehensive overview and future directions for the field.

References: https://tinyurl.com/WignerGPGPub2025