2023 Research Highlights

Wigner Gravitational Physics Research Group

Spacetime Singularities and Curvature Blow-ups

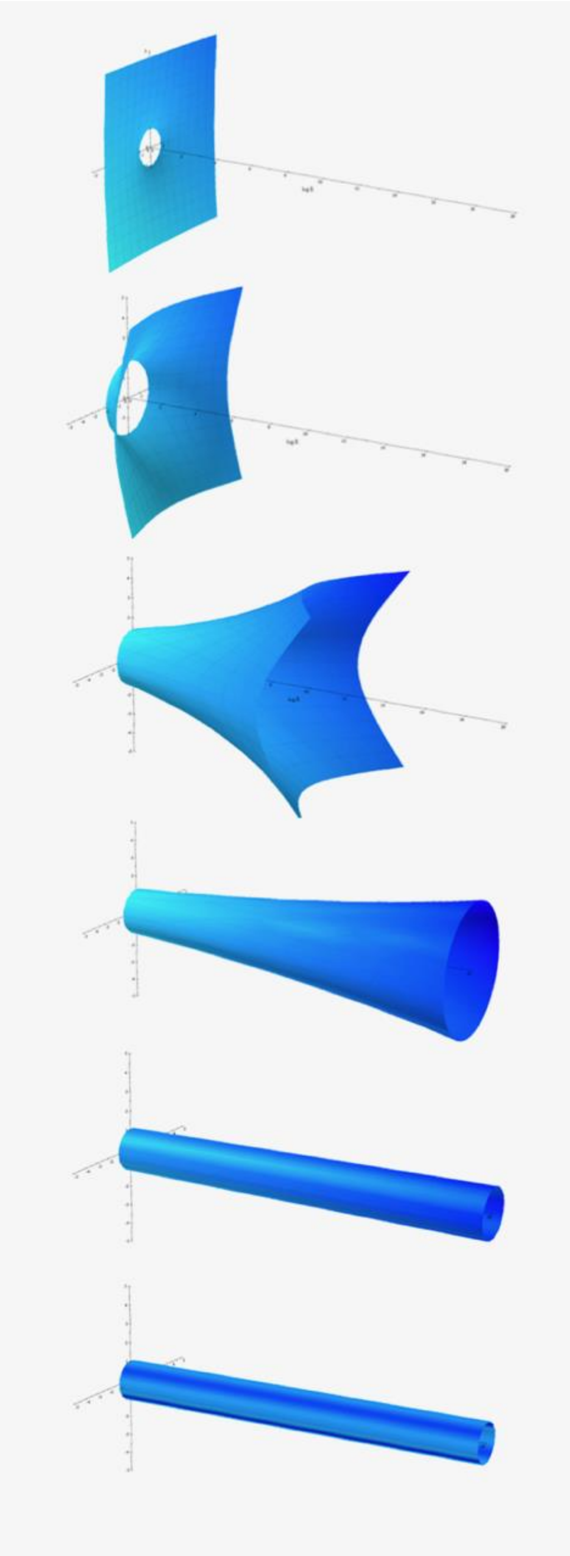
The "singularity theorems" of Penrose, Hawking, and Geroch predict only the existence of incomplete inextensible causal geodesics in a wide range of physically adequate spacetimes modeling the gravitational collapse of stars and the expanding universe. In contrast, on physical grounds, singularities are expected to be associated with the blow-up of some physical quantities. The aim of this seminar is to give a brief overview of the basic concepts related to our current understanding of spacetime singularities. Special attention will be given to some aspects of the initial value formulation of general relativity, the cosmic censor hypotheses proposed by Penrose, and also to results on spacetime extensions. These preparations will be used to outline an argument that could provide important insights into the generic properties of spacetime singularities. In particular, it will be argued that if a suitable low regular form of the strong cosmic censor hypothesis holds, then a parallelly propagated blow-up of either the tidal force or the frame-drag part of the curvature must occur in "generic" timelike geodesically incomplete maximal Cauchy developments [1].

Symmetries of spacetimes with a compact Cauchy horizon and the cosmic censor

We outline an argument proving that any smooth vacuum spacetime containing a compact Cauchy horizon with surface gravity that can be normalized to a nonzero constant admits a Killing vector field. This proves a conjecture of Moncrief and Isenberg from 1983 under the assumption on the surface gravity and generalizes previous results due to Moncrief–Isenberg and Friedrich–Rácz–Wald, where the generators of the Cauchy horizon were closed or densely filled a 2-torus. This result implies that the maximal globally hyperbolic vacuum development of generic initial data cannot be extended across a compact Cauchy horizon with surface gravity that can be normalized to a nonzero constant. Our result thus supports the validity of Penrose's strong cosmic censorship conjecture in the class of spacetimes considered [2].

Geometrical and physical interpretation of the Levi-Civita spacetime in terms of the Komar mass density

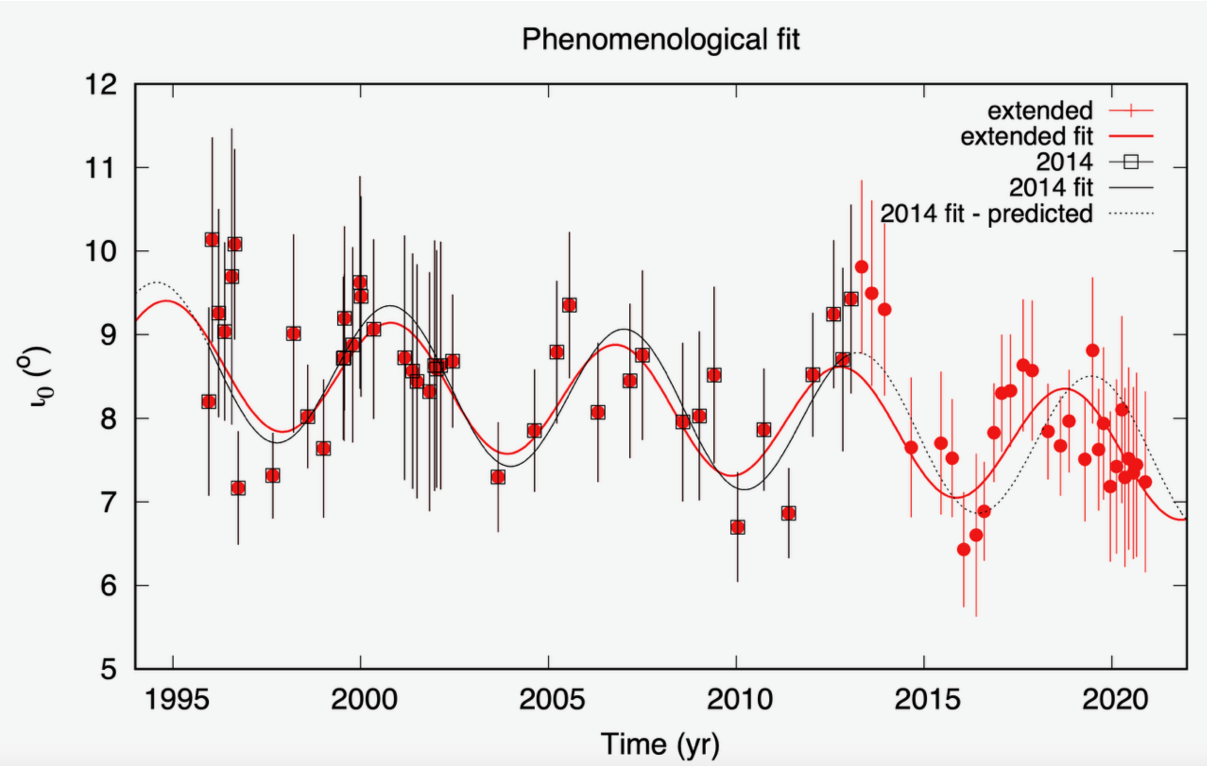
We revisit the interpretation of the cylindrically symmetric, static vacuum Levi-Civita metric, known in either Weyl, Einstein-Rosen, or Kasner-like coordinates. The Komar mass density of the infinite axis source arises through a suitable compactification procedure. The Komar mass density μ_K calculated in Einstein-Rosen coordinates, when employed as the metric parameter, leads to several advantages. It eliminates double coverages of the parameter space, vanishes in flat spacetime and when small, it corresponds to the mass density of an infinite string. After a comprehensive analysis of the local and global geometry, we proceed with the physical interpretation of the Levi-Civita spacetime. First, we show that the Newtonian gravitational force is attractive, and its magnitude increases monotonically with all positive μ_K, asymptoting to the inverse of the proper distance in the radial direction. Second, we reveal that the tidal force between nearby geodesics (hence gravity in the Einsteinian sense) attains a maximum at μ_K=1 /2 and then decreases asymptotically to zero. Hence, from a physical point of view the Komar mass density of the Levi-Civita spacetime encompasses two contributions: Newtonian gravity and acceleration effects. An increase in μ_K strengthens Newtonian gravity but also drags the field lines increasingly parallel, eventually transforming Newtonian gravity through the equivalence principle into a pure acceleration field and the Levi-Civita spacetime into a flat Rindler-like spacetime. In a geometric picture the increase of μ_K from zero to ∞ deforms the planar sections of the spacetime into ever deepening funnels, eventually degenerating into cylindrical topology in an appropriately chosen embedding [3].



Caption: The (blue) surfaces perpendicular to the symmetry axis have a curved geometry, depicted by their embedding into a 3-dimensional space. With increasing Komar mass density (from top to bottom), at first the curvature, hence gravity in Einsteinian sense also increases (generating tidal forces). With further increase, however, the surfaces become increasingly cylinder-like, with no inner curvature, hence no Einsteinian gravity left [3].

Signatures of a spinning supermassive black hole binary on the mas-scale jet of the quasar S5 1928+738 based on 25 years of VLBI data

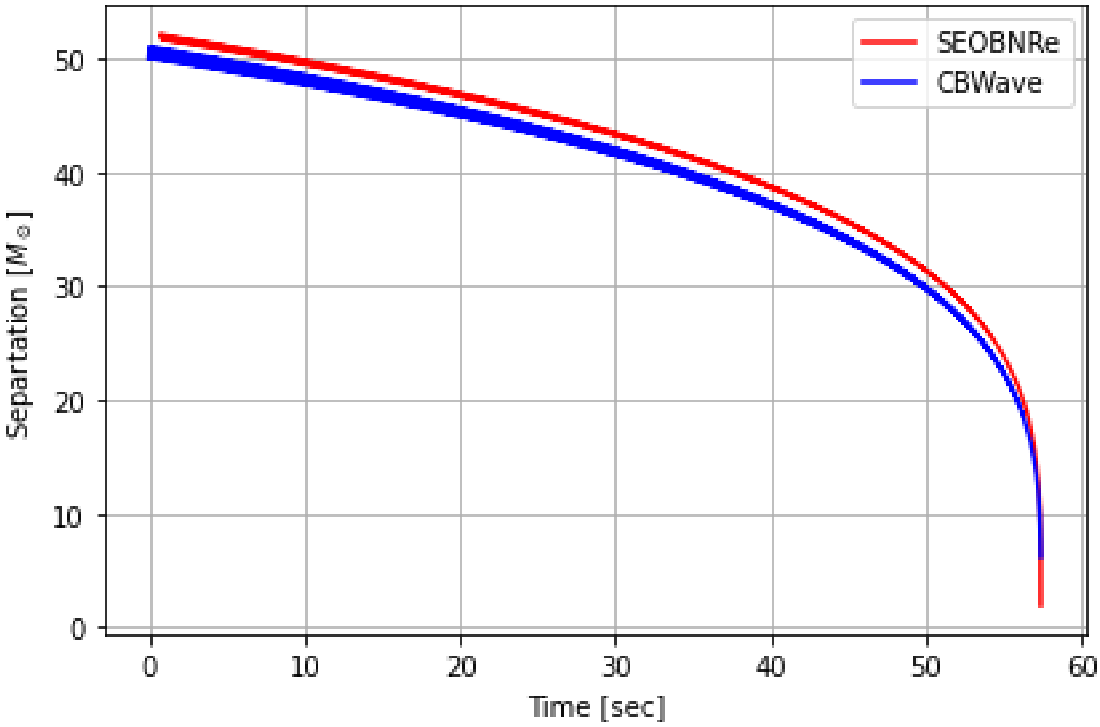
In a previous work, we have identified the spin of the dominant black hole of a binary from its jet properties. Analysing Very Long Baseline Array (VLBA) observations of the quasar S5 1928+738, taken at 15-GHz during 43 epochs between 1995.96 and 2013.06, we showed that the inclination angle variation of the inner (<2 mas) jet symmetry axis naturally decomposes into a periodic and a monotonic contribution. The former emerges due to the Keplerian orbital evolution, while the latter is interpreted as the signature of the spin-orbit precession of the jet emitting black hole. In this paper, we revisit the analysis of the quasar S5 1928+738 by including new 15-GHz VLBA observations extending over 29 additional epochs, between 2013.34 and 2020.89. The extended data set confirms our previous findings which are further supported by the flux density variation of the jet. By applying an enhanced jet precession model that can handle arbitrary spin orientations κ with respect to the orbital angular momentum of a binary supermassive black hole system, we estimate the binary mass ratio as $\nu = 0.21 \pm 0.04$ for $\kappa = 0$ (i.e. when the spin direction is perpendicular to the orbital plane) and as $\nu = 0.32 \pm 0.07$ for $\kappa = \pi/2$ (i.e. when the spin lies in the orbital plane). We estimate more precisely the spin precession velocity, halving its uncertainty from (-0.05± 0.02) to $(-0.04\pm0.01)^\circ$ yr^{-1} [4].



Caption: The evolution of the inclination of the jet over 25 years can be decomposed into a superposition of a sinusoidal component with a monotonic decrease. The latter can be explained in terms of the (very slow) spin-orbit precession of the spinning black hole at the jet base [4].

Numerical analysis of PN and EOB waveforms of eccentric sources

We are studying matched gravitational waveforms with eccentric inspirals computed by CBwaves and SEOBNRe, respectively. Specifically, the parameter space (M, e) is explored for configurations with the five highest mass-rations observed through O2-O3 observational runs. According to our preliminary investigations, due to the circularization of the orbits during the inspiral phase, there is a higher overlap at high-frequency sections of the matched waveforms, however the dissimilarity in the low-frequency part is increase exponentially with initial orbital eccentricity. The assessment of the relative error in the radiated energy relative to the theoretical prediction has been performed in each framework.



Caption: Radial dependence of SEOBNRe and CBWave frameworks.

Einstein Telescope: site selection and thermal behavior of rocks

The Wigner group, in collaboration with researchers from the Budapest University of Technology and ATOMKI has contributed to the site selection studies of the Einstein Telescope. These included detector monitoring synchronization tasks, upgrading a dedicated infrasound monitoring system, rock characterization studies with emphasis on the viscoelastic contribution to the Newtonian noise and its effect on filtering.

In this regard, the thermal behavior of rocks is also essential, especially the thermo-mechanical coupling via thermal expansion, which can contribute to the underground noise. The related studies, together with numerous further applications and modeling approaches, were reviewed and published in Physics Reports [5].

References:

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