2022

Rapidly rotating neutron stars with realistic nuclear matter equation of state. — We performed the comparison of three different numerical codes for constructing equilibrium models; (I) a code for static equilibrium configurations, (II) an implementation of the Hartle–Thorne slow-rotation approximation, (III) a numerical solution of the full Einstein equations by LORENE. We aimed to construct sequences of uniformly rotating configurations at various rotation frequencies up to the Keplerian frequency for a hybrid hadronic–quark matter EOS where a smooth transition is provided between two separate phases. We investigated the difference between the results computed by the implementation of Hartle–Thorne slow-rotation approximation and by LORENE/nrotstar, respectively. We have concluded that the slow-rotating approximation—apart from very low energy densities and frequencies—underestimates the results of corresponding configurations computed by LORENE. This discrepancy decreases with the growing energy density, but it exponentially increases with the frequency, reaching 6.67% for the maximal mass configuration rotating. The configuration with maximum mass of 2.49M⊙ for LORENE, and 2.34M⊙ for slow-rotating method at Keplerian frequency of 1350.03, and 1275.33 Hz, respectively. This analysis of discrepancy in these computations p+roved the accuracy of LORENE in high-frequency regime.

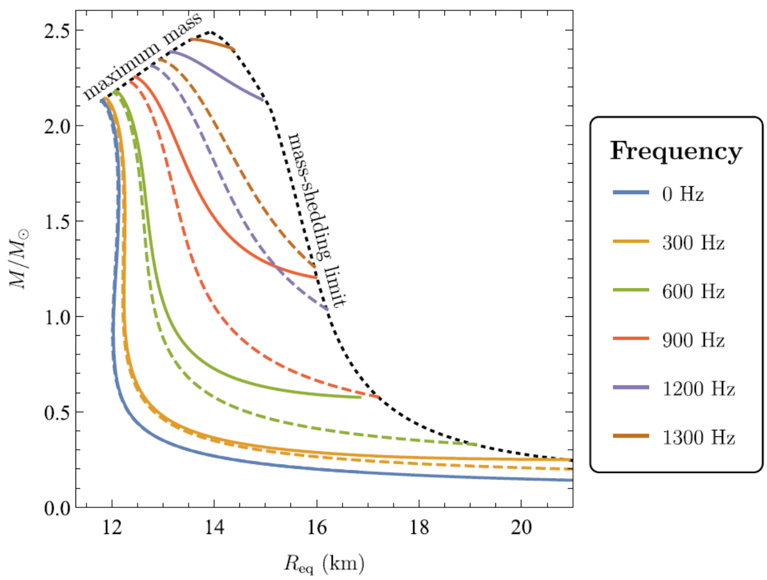


Figure 1. The gravitational mass–equatorial radius relations for static and rotating compact stars with a combined EOS of SFHo/DD2 models inside their core. The solid lines represent sequences computed by LORENE, and dashed lines represents those of our slow-rotating model on different frequencies.

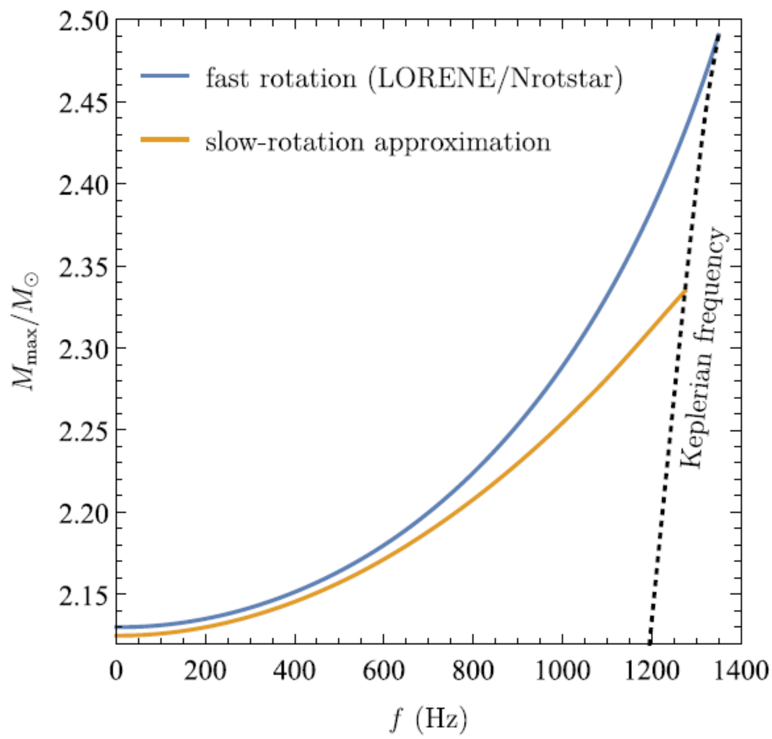
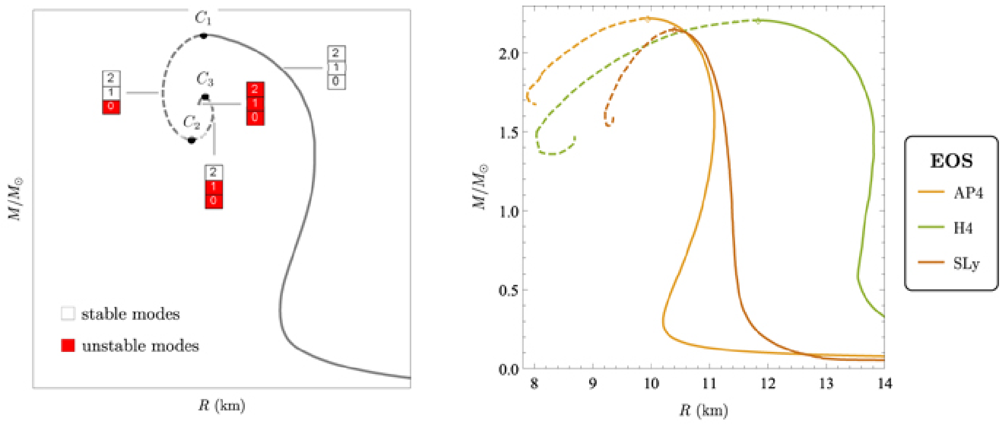


Figure 2. The maximum gravitational mass reached with the fast- and slow-rotating approach as the function of the frequency. Furthermore, the black dashed line denotes the mass-shedding limit, which contains all the configurations at the Keplerian frequency.

2021

Oscillation of neutron stars for realistic EoS. — This piece of research complements our earlier qualitative study of the effect of viscosity and thermal conductivity on the radial oscillation and relaxation of non-rotating neutron stars. The fundamental and first two lowest-frequency excited modes of radial oscillation have been computed in the high nuclear density regime for a set of seven realistic equations of state (EoS) as functions of central energy density. Various types of zero-temperature EoS of cold nucleonic and hybrid nucleon–hyperon–quark matter models are used in the inner core to determine the internal structure in and around the hydrostatic equilibrium states and investigate the influence of each EoS on the dynamical behavior of non-rotating neutron stars. We confirm the principal results of earlier, related studies that suggest an underlying correlation between the frequency spectrum of the fundamental oscillation mode and the variation of the adiabatic index over the high nuclear-density regime. We provide valuable information to impose further constraints on the plausible set of realistic EoS models, in addition to the practical applications for the rapidly evolving field of asteroseismology of compact objects.



(a) Schematic mass–radius relation illustrating the spiral structure of the unstable branch.

(b) Numerical mass–radius relation for three selected EoSs extended beyond the stable branch which was depicted in Fig. 5a.

Figure 1. The left panel schematically illustrates whereas the right panel displays for three selected EoS (APR4, H4, SLy4) the structure of M(R) curves for dynamically stable (solid lines) and unstable states (dashed lines). Critical points are denoted by C1, C2, C3. The fundamental mode and two higher-order excited modes of radial oscillation are represented on a given segment by a column of numbers n = 0, 1, 2 in cells, with stable oscillation modes in unfilled and unstable modes filled in red, respectively.

Gravitation waves from supermassive black hole binaries. — We have computed the orbital evolution and the emitted gravitational radiation of the supermassive black hole binary OJ 287. Here we used the initial data provided by the outburst structure of the system. We considered the spin-spin, spin-orbit, and the next-to-next leading order fourth post-Newtonian (4PN) corrections in our analysis. In this way, we could make an accurate examination of unstable orbits ($3M < r <6M$) of the secondary black hole. We tested the 4PN terms by analyzing the total and radiated energy, compared the post-Newtonian parameters and the separation of the two black holes for 3PN and 4PN. In conclusion, the 4PN corrections provided a significantly more accurate tool for analyzing unstable orbits than earlier 3PN terms. Furthermore, in this paper, we demonstrate the strain of gravitational waves emitted by supermassive black hole binary system OJ 287 during its complete orbital evolution including unstable orbits.

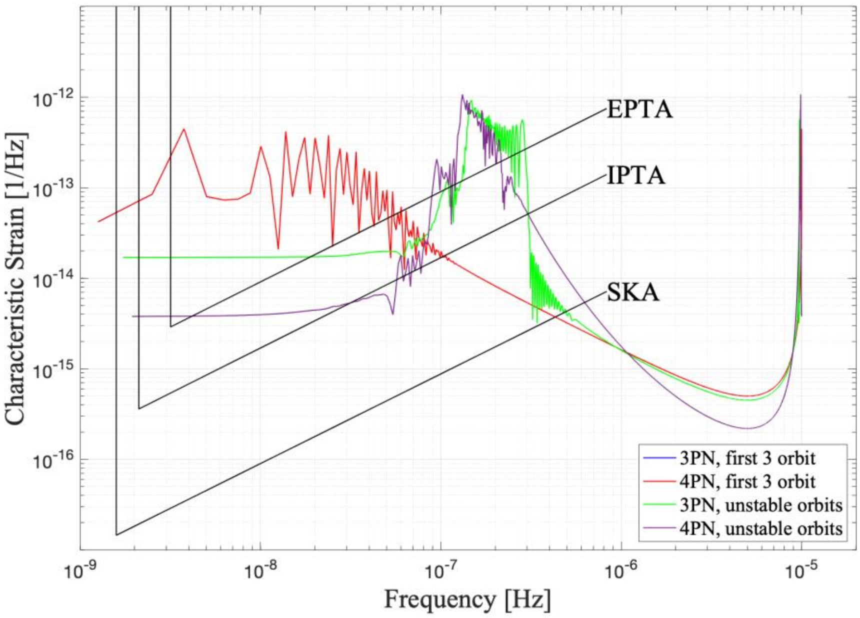


Figure 2. In this figure, we have shown the characteristic strain of OJ 287. Red and blue lines represent the strain for 4PN and 3PN initial orbit. Similarly, purple and green lines represent the strain for unstable orbit. Furthermore, we provided the detector sensitivity for EPTA, IPTA, and SKA experiments with black lines. Let us note that, for the initial orbit, the contribution of the 4PN term is so tiny that the 3PN- and 4PN-accurate strains cannot be individually distinguished by the naked eye.

Dynamics of linear spin fields on Kerr background. — Superradiant scattering of linear spin s = 0; ±1; ±2 fields on Kerr black hole background is investigated in the time domain by integrating numerically the homogeneous Teukolsky master equation. The applied numerical setup has already been used in studying long time evolution and tail behavior of electromagnetic and metric perturbations on rotating black hole background. To have a clear setup the initial data is chosen to be of the compact support, while to optimize superradiance the frequency of the initial data is fine tuned. Our most important finding is that the rate of superradiance strongly depends on the relative position of the (compact) support of the initial data and the ergoregion. When they are well-separated then only a modest—in case of s ¼ 0 scalar fields negligible—superradiance occurs, whereas it can get to be amplified significantly whenever the support of the initial data and the ergoregion overlap.

Outreach. — As members of the Virgo Outreach Group, we are responsible for announcements of these observations of new events and upgrades of the instruments to the Hungarian public. Also we have been engaged in the promotion of gravitational physics by making it more accessible to the public. In the framework of the dissemination and public deliverable activities of COST Action CA16214 – "PHAROS: The multi-messenger physics and astrophysics of neutron stars" a computer simulation has been created which demonstrates the effects of residual orbital eccentricity of inspiraling binary black holes. One of our researchers gave an interview in the Hungarian popular science radio program "Szigma, a holnap világa" on the community radio station InfoRádió to discuss the observation of the gravitational-wave signal GW170817.

References:

[1] DOI: 10.1088/1361-6382/ac12e2
[2] https://arxiv.org/abs/2105.12496
[3] DOI: 10.1103/PhysRevD.103.084035

2020

The Gravitational Physics Research Group at Wigner RCP has been engaged the study of gravitational phenomena through theoretical investigations and simulations. Our group members are addressing problems in general relativity and particle physics in these science areas. We are also members of the Virgo Scientific Collaboration and the European Gravitational Observatory which is responsible for operating the Virgo detector.

In 2020 the third data taking period O3 of the LIGO and VIRGO observatories came to completion. During this period the three detectors were operated as a global observatory taking highly sensitive scientific data. Through Open Public Alerts several dozens of event candidates have been registered and has been announced to the physics and astronomy community. The classification and definitive analysis of the 39 events detected by Virgo and LIGO in the third observation period (which ran from April to October 2019) has been made publicly available in the GWTC-2 catalogue.

A short summary of the results achieved by our group in 2020 is presented below.

Dispersion of gravitational waves in cold spherical interstellar medium — An erratum to an earlier research paper has been published and addressed the inconsistencies found in the original paper. This study provided a numerical result for the frequency-shift of GWs due to dispersion in interstellar medium. In order to adjust the metric functions of the originally improperly matched ‘background’ spacetime, the authors have adopted Darmois–Israel junction conditions. The code used in the original paper erroneously computed the magnitude of frequency-shift for the transient event GW150914 due to a missing conversion factor. In both cases where numerical errors and potential contradictions have been identified and eliminated, adjustments were undertaken in order to maintain consistency with closely-related earlier studies.

Site-selection criteria for the Einstein Telescope — The Einstein Telescope (ET) is a proposed next-generation, underground gravitational-wave detector to be based in Europe. It will provide about an order of magnitude sensitivity increase with respect to the currently operating detectors and, also extend the observation band targeting frequencies as low as 3 Hz. One of the first decisions that needs to be made is about the future ET site following an in-depth site characterization. Site evaluation and selection is a complicated process, which takes into account science, financial, political, and socioeconomic criteria. In this paper, we provide an overview of the site-selection criteria for ET, provide a formalism to evaluate the direct impact of environmental noise on ET sensitivity, and outline the necessary elements of a site-characterization campaign.

Numerical investigations of the asymptotics of solutions to the evolutionary form of the constraints — Systematic numerical investigations of the asymptotics of near Schwarzschild vacuum initial data sets is carried out by inspecting solutions to the parabolic–hyperbolic and to the algebraic–hyperbolic forms of the constraints, respectively. One of our most important findings is that the concept of near Schwarzschild configurations, applied previously, is far too restrictive. It is demonstrated that by relaxing the conditions on the freely specifiable part of the data a more appropriate notion of near Schwarzschild initial data configurations can be defined which allows us to generate asymptotically flat initial data configurations.

Outreach — The third observational period has ended a month earlier than anticipated due to the COVID-19 pandemic. Despite this setback, a large number of observations have been made and the evaluation of the candidate events found during the run is still in progress. The pace of developments have also slowed down somewhat, nevertheless the instrument are still being upgraded continuously. The purpose of improvements to prepare the detectors for the successful participation in O4 data-taking period.

As members of the Virgo Outreach Group, we are responsible for announcements of these observations of new events and upgrades of the instruments to the Hungarian public. Also we have been engaged in the promotion of gravitational physics by making it more accessible to the public. In 2020 we gave lectures on popular science events such as "Coffee with physicists of Wigner RCP" in Csodák Palotája or on the European Researcher's Night. Two of our researchers gave an interview in the Hungarian popular science radio program "Utópia" on the commercial radio station Klubrádió.

References:

[1] DOI: 10.1142/S0218271820920017
[2] DOI: 10.1063/5.0018414
[3] DOI: 10.1088/1361-6382/ab8fce

2019

The main research projects of the Gravitational Physics Research Group at Wigner RCP are connected to the study of gravitational phenomena in theoretical physics. With solid background in general relativity and particle physics our group members are investigating problems in these science areas. Being members of the Virgo Scientific Collaboration operating the VIRGO detector, the European gravitational wave observatory, our motivation of research interest is also emerges from gravitational wave physics. The scientific results of the last year are summarized as follows.

Gravitational waves. — 2019 marks the year of the third data taking period O3 of the LIGO and VIRGO observatories. During this period the two collaborations registered science data continuously, and the three detectors were operated as a global observatory. Since the end of the second observation run O2, the two collaborations have intensively worked on their interferometers to improve the sensitivity and reliability. Scientists have also improved their offline and online data analysis methods and developed further the procedures for releasing Open Public Alerts. These alerts notified the physics and astronomy community within minutes when a potential gravitational wave event had been observed. Due to the increased sensitivity of the observatories the number of potential detections and public alerts have reached a weekly rate, in average.

In 2019 the main emphasis for our group members was put on the participation in the activity of the Compact Binary Coalescence (CBC) group with contributions to the description of compact binary sources and neutron stars. We have improved and tested the accuracy of the software package *CBwaves* developed by our group to analyze the motion and gravitational radiation of compact binary sources. It was used to study the effects of higher post-Newtonian terms in binary evolution and radiation for generic, eccentric orbits.

Effect of viscosity and thermal conductivity in relativistic stars. — Several models have been used to describe neutron stars in recent years, which in most cases neglected the effects of thermal conductivity and viscosity of the material. We have developed a generic formulation of the linearized dynamical equations governing small adiabatic radial oscillations of relativistic stars, like neutron starts. The dynamical equations are derived by taking into consideration those effects of viscosity and thermal conductivity of neutron star matter which directly determine the minimum oscillation period of observable pulsars. With the application of a variational principle we have derived a discrete set of eigenfunctions with complex eigenvalues. The real and imaginary parts of eigenvalues represent the squared natural frequencies and relaxation time of radial oscillations of non-rotating neutron stars, respectively. We provided a suitable framework which may be supplemented with various potential species of cold-nuclear-matter models to compute the spectra of the normalized eigenfrequencies with a certain numerical precision. Moreover, we have provided a qualitative estimation of the rate at which viscosity and thermal conductivity drain the kinetic energy of radial oscillation mode in reasonably uniform neutron stars, without relying on explicit numerical computations.

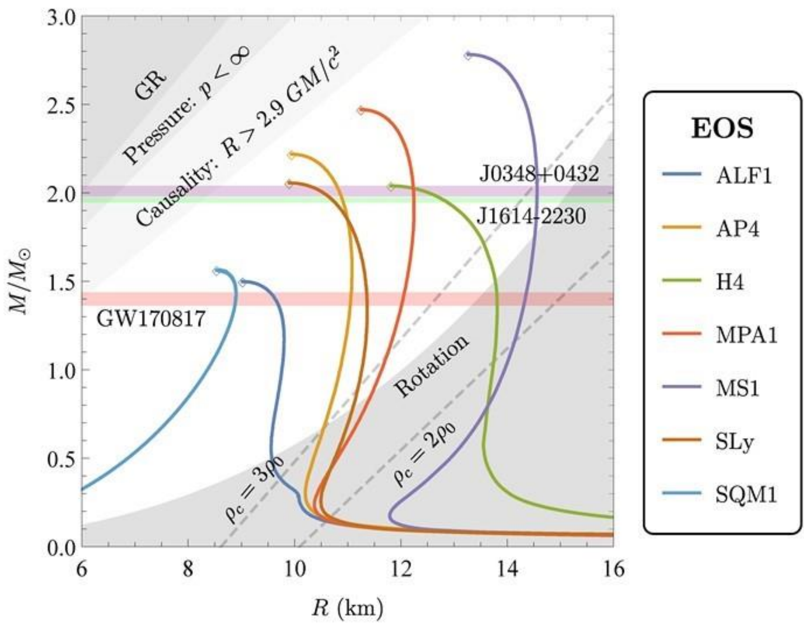


Figure 1. Typical M–R relations for non-spinning neutron-star models corresponding to the realistic EOSs. M–R curves for typical nucleonic EOSs (AP4, MPA1, MS1, SLy) are shown as light-coloured curves, blue curves refer to self-bound quark stars (ALF1, SQM1), and the green line to a strange star model (H4). The diamond symbols mark the maximal-mass configurations. Most EOS involving non-nucleonic matter, such as kaon condensates or hyperons, tend to predict an upper limit around 2 $M_\odot$for the maximal mass of neutron stars. The purple and the green bands indicate the rapidly rotating neutron stars in millisecond pulsars, cataloged as PSR J1614-2230 and J0348+0432, with the highest-known mass of 1.97 ± 0.04 MΘ and 2.01 ± 0.04 MΘ. The light red band shows the interval of total binary NS masses inferred from gravitational-wave signal GW170817. The dashed gray lines refer to stars whose central density pc is double or triple that of nuclear saturation density ρ0, respectively. The upper left areas of different shades of grayscale refer to regions of the M–R plane excluded by general relativity constraint for R>2 GM/c2, by finite pressure for R> 2.25GM/c^2 , and by causality for R>2.9 GM/c^2 .

Classical and quantum aspects of general relativity. — The study of long-time evolution of various linear fields on a given black hole background have served as a base method for the more involved study of linear and possibly nonlinear stability of the background black hole solutions themselves. In our study we have used numerical methods to determine the time evolutions and behavior of perturbations of spin s = ± 1, ± 2 fields on a Kerr background. We have investigated the energy and momentum balance relations for these fields in the distant, asymptotic region of the spacetime for an accurately description of gravitational waves.

Mátra Gravitational and Geophysical Laboratory. — To explore the low frequency regime

1 – 10 Hz of the gravitational wave spectrum underground operation of observatories is required. The scientific value of existing plans of the European initiative Einstein Telescope increased considerably in this period. Its improved sensitivity and extended frequency range suggest a remarkable discovery potential. However, preparation for the underground operation of gravitational wave detectors requires careful analysis of the proposed locations in advance. We have completed long-term seismic, infrared and electromagnetic measurements in the Mátra Gravitational and Geophysical Laboratory. With the evaluation of measurement data of more than two years we have identified the most important features and characteristics that can help the site selection process of next-generation detectors, such as the Einstein Telescope.

Outreach. — The third LIGO-Virgo survey for gravitational waves has provided scientists with a rich pool of observations. The one year observation run O3 started on the 1st of April, 2019. Sensitivity improvements and the fact that the three LIGO-Virgo instruments have been operating simultaneously enabled high detection rate. Public alerts shortly after the detection of credible transient gravitational waves candidates were provided for the first time. These alerts have facilitated follow-up observations by other telescopes enhancing the possibility of multi-messenger observations. Being members of the VIRGO Outreach group, we have participated the public announcements of these new events related to the observatories. We have popularized the field in scientific and public lectures for scientists and students and promoted the European based 3rd generation gravitational wave observatory, the Einstein Telescope.

2018

The research projects of the Gravitational Physics Research Group at Wigner RCP are focusing on investigations in theoretical physics related to gravitational phenomena. Our group members have solid background in general relativity and particle physics. As members of the Virgo Scientific Collaboration operating the VIRGO detector, the European gravitational wave observatory, the main motivation of our research interest originates from gravitational wave (GW) physics. The scientific results of the last year are summarized below.

Gravitational waves. — The joint 1 month data taking period of the LIGO and VIRGO observatories at the second half of 2017 has been concluded with important results. The first three detector observation of a black hole collision was achieved. Moreover, the merger of two neutron stars was also recorded with gravitational waves and electromagnetic observations representing a breakthrough in multi-messenger astronomy. 2018 marks the preparation for the upcoming observation period starting early in 2019. Following the two observation campaigns the time for an extensive upgrade of the observatories has come. As a result of the enhancements an overall 1.5-2 fold increase in sensitivity is expected resulting in an increase in detection rate during the next observation run.

In 2018 the members of our group have participated in the work of the Compact Binary Coalescence (CBC) group with contributions to the description of compact binary sources and their radiation. The accuracy of the software package CBwaves developed by our group for the description of the motion and gravitational radiation of compact binary sources was further improved. It was used to study high mass systems and binary evolution in eccentric orbits.

Fast prediction and evaluation of eccentric inspirals using reduced-order models. — A large number of theoretically predicted waveforms are required by matched-filtering searches for the gravitational wave signals produced by compact binary coalescence. In order to substantially alleviate the computational burden in gravitational wave searches and parameter estimation without degrading the signal detectability, we proposed a novel reduced-order-model (ROM) approach with applications to adiabatic 3PN-accurate inspiral waveforms of nonspinning sources that evolve on either highly or slightly eccentric orbits. We provided a singular-value decomposition-based reduced basis method in the frequency domain to generate reduced-order approximations of any gravitational waves with acceptable accuracy and precision within the parameter range of the model. We constructed efficient reduced bases comprised of a relatively small number of the most relevant waveforms over 3-dimensional parameter space covered by the template bank (total mass $2.15M_\odot \leq M \leq 215M_\odot$, mass ratio $0.01 \leq q \leq 1$, and initial orbital eccentricity $0 \leq e_0 \leq 0.95$). The ROM was designed to predict signals in the frequency band from 10 Hz to 2 kHz for aLIGO and aVirgo design sensitivity. Besides moderating the data reduction, finer sampling of fiducial templates improved the accuracy of surrogates. Considerable increase in the speedup from several hundreds to thousands has been achieved by evaluating surrogates for low-mass systems especially when combined with high-eccentricity.

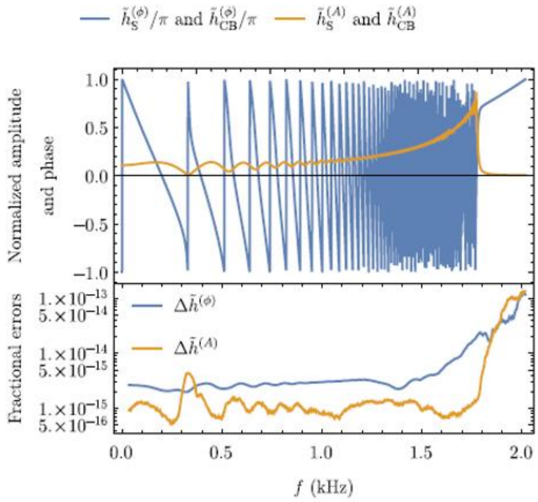


FIG. 9: *Top panel:* The amplitude and the phase part of the waveform associated with $l = 1$. There is visual agreement among the fiducial *CBwaves* waveform and its surrogate prediction throughout the entire frequency range. *Bottom panel:* The relative errors (42) with moving average of 50 points, defined by Eq. (42), in the amplitude and the phase difference between the fiducial waveform and its surrogate model prediction. The differences are smaller than the errors intrinsic to the surrogate model itself, as well as those of state-of-the-art numerical relativity simulations.

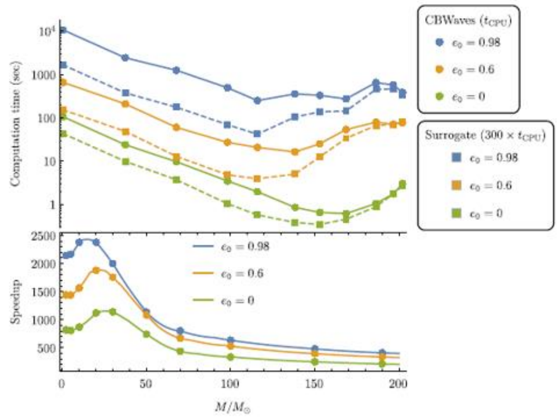


FIG. 10: *Top panel:* Computational time $t_{\rm CPU}$ to generate fiducial waveforms by CBwaves code (dots; connected by solid lines) against the cost of evaluating corresponding surrogates by ROM (rectangles; connected by dashed lines). The computational time was measured for three different initial eccentricities of equal-mass configurations, each associated with different colours. *Bottom panel:* The speedup in evaluating the surrogate model is several thousand times faster around $10 - 50\ M_\odot$ than generating CBwaves waveforms. For high total mass the speedup falls off to several hundreds. The speedup is roughly twice as great for configurations having extremely high initial eccentricity at $e_0 = 0.98$ (blue line) as for circular ones at $e_0 = 0$ (green line).

Classical and quantum aspects of canonical gravity — General relativity is usually formulated in terms of equations for the space-time metric through the Einstein equations. In the canonical formulation of gravity the field equations are reformulated into a set of constraints and a set of evolution equations to form a constrained Hamiltonian system. These equations then allow for a well-defined initial value problem. In this canonical picture we have introduced a completely new evolutionary form of the constraint equations in Maxwell theory, in analogy with some recent results on the constraints of general relativity, regardless of the signature and dimension of the ambient space. As an important additional result a new geometric characterization and identification of the Kerr black hole was given in the set of distorted black hole spacetimes.

Mátra Gravitational and Geophysical Laboratory. — The low frequency part of the gravitational wave spectrum below 20 Hz in inaccessible by present ground based observatories. To detect signals in this low frequency band a new infrastructure is planned. The European initiative Einstein Telescope aims to reduce the effect of seismic and Newtonian noises with underground operation, cryogenic facilities and additional technical improvements.

In the Mátra Gravitational and Geophysical Laboratory we have carried out long term seismic, infrasound and electromagnetic measurements. In 2018 based on the almost 2 years of data collected so far the members of our group were working on the specification of the quantities for the site selection of 3rd generation underground GW facilities. As a recommendation to the community we have analyzed and presented different seismic noise measures to use in site characterization. Moreover, with the analyzation of the available long term measurements we have examined the monthly and yearly variation of seismic noise, which are important local features for e.g. the Einstein Telescope.

Outreach. — To prepare for the next observation period gravitational wave observatories have undergone significant upgrades and changes in 2018 resulting in a 1.5-2 fold increase in their sensitivity. Meanwhile, thoroughly analyzing the data already collected during the previous scientific data taking periods, the collaboration announced four new gravitational wave events not published before. As members of the VIRGO Outreach group, we have actively participated in public outreach, the public announcement of data from previous measurements and the first gravitational wave transient catalog containing all the 11 events registered so far. Moreover, several scientific and public lectures were held by our group members for scientists and students. They have actively participated also in the popularization of the European based 3rd generation gravitational wave observatory, the Einstein Telescope.

2017

The Gravitational Physics Research Group of the Wigner RCP is carrying out research in theoretical physics related to gravitational phenomena. The members of the group have solid background in particle physics and general relativity. Moreover, they have experience in the development of optimal numerical algorithms and implementation of these algorithms into efficient computer procedures that can be run on grid and GPU clusters. Being a member of the Virgo Scientific Collaboration operating the VIRGO detector, the European gravitational wave observatory one of the main motivations of our research interest originates from gravitational wave (GW) physics. The scientific results of the last year are summarized below.

Gravitational waves. — 2017 represents a rich and exciting year in gravitational physics. The main objective of GW research has been achieved in 2015 with the first direct observation of gravitational waves from coalescing black holes with the Advanced LIGO detectors. Following an upgrade period of few years the European VIRGO detector started its operation with improved sensitivity in February 2017. As an important milestone, the first three detector observation was achieved in August, 2017, during the 1 month joint data taking period of the LIGO and VIRGO detectors. Only a few days later, an other very significant event, the collision of two neutron stars was recorded with gravitational waves and electromagnetic observations also. The original alert of the Fermi satellite initiated an observation campaign with the participation of nearly 70 observatories. Due to the improved sky localization of the source with three GW detectors scientists from all over the world could follow the GW and electromagnetic signal of the collision within a few weeks period. This parallel gravitational and electromagnetic observation of NS collision represents a breakthrough in multi-messenger astronomy. This remarkable observation was preceded by long years of developments and upgrade periods. The efforts of the gravitational community were awarded with the Nobel Prize in October 2017 for the direct detection of gravitational waves.

Joining to the international LIGO-Virgo collaboration our research projects aimed to analyze important and interesting compact binary sources of GWs and study the astrophysical and cosmological implications of the observations. For ground-based interferometric GW detectors compact binary systems of stellar mass black holes and neutron stars are important sources considering the present sensitivity of GW detectors. Specific waveform templates are ready for offline searches and parameter estimation studies for these kind of sources within the software package of the LIGO-Virgo Collaboration, e.g. the *PyCBC* and *GstLAL* packages. In data analysis processes matched template filtering is the most optimal method for the identification of theoretical waveforms and source parameter estimation. Matched filtering for compact binary sources is implemented in the PyCBC software package which is available on Institutional resources, i.e. the *Wigner Cloud*.

Continuous gravitational waves. — Continuous GWs are faint signals for gravitational wave detector produced by systems with almost constant and well-defined frequency, e.g. single stars rotating about their axis with a large mountain or other irregularity on it. These sources are expected to produce weak gravitational waves since they evolve over longer periods of time and are usually less catastrophic than sources producing inspiral or burst GW. The collaboration with our colleague Michal Bejger aims the optimization of an all-sky data-analysis pipeline developed initially by the Polish POLGRAW group. The pipeline is an implementation of the targeted search for almost-monochromatic gravitational-wave signals from rotating, non-symmetric, isolated neutron stars. During the visit, the CUDA accelerated all-sky search application underwent a major rewrite with several motivating factors behind this effort. The GPU codebase was an evolutionary step going forward from the serial and OpenMP parallelized codes. As a result, it has accumulated many deprecated dependencies as many dead code paths. During the rewrite, the entire source base was analyzed and dead code paths were eliminated, as linking to unused libraries were dealt with. Moreover, the codebase originally targeted Linux systems, but it was our intent to bring the codebase over to Windows Systems, which would increase the potential user base, as well as enable Windows-only developer tools to be employed on the code base. To further widen the potential end systems and users that the program targets, we not only created a cross-platform version, but this code is also cross-vendor, having moved from naked CUDA, cuFFT and cuBLAS to naked OpenCL, clFFT and clBLAS. Thus AMD and Intel Phi architecture support opened up, as well as mitigating the need to maintain the OpenMP codebase, due to OpenCL being able to target multi-core CPUs. Furthermore the code refactoring enabled us to implement various features which are of interest to further analysis (parametrize on the types on various points of the pipeline), as well as applying global code cleaning (compiling the sources without compiler warnings, eliminating potential sources of hidden bugs) resulting in a more maintainable codebase. Having made these changes, the way is made clear to implement multi-device and cluster parallelism, which can now be implemented in a significantly less amount of time. Being the result of a major refactoring, the code requires testing to its functionality.

Mass and radius of neutron stars. — Neutron stars (NS) are important sources of gravitational waves. The most intense part of the observed GW signal is coming from the merger part of the coalescence carrying essential information about the NS characteristics and the merger itself. Advances ground-based interferometric GW detectors allow the observation of such sources at their present sensitivity. In August 2017, the LIGO-Virgo collaboration has detected the first binary neutron star inspiral (so-called GW170817), and 70 other observatories collaborated to detect its electromagnetic counterpart. In our work we have analyzed neutron star interiors with the assumption of spherical symmetry. In this case the metric tensor is time dependent and the equations characterizing the neutron star interior are decouple to the Tolman-Oppenheimer-Volkov (TOV) equation and a differential equation for the time evolution of the radius. For a two-component polytrophic equation of state we have analyzed the Mass-Radius relation for neutron stars. The analysis was extended to other equation of states describing Newtonian and neo-Newtonian stars, and neutron star matter with hyperon content. The recent observation of GW170817 presents bounds on NS mass and limits the parameter range of possible equation of states.

Frequency and dissipation of gravitational waves in interstellar medium. — The propagation of locally plane, small-amplitude, monochromatic gravitational waves through cold compressible interstellar gas was studied in order to provide a more accurate picture of expected waveforms for direct detection. Gravitational waves were treated as linearized perturbations on the background inner Schwarzschild spacetime. The perturbed quantities lead to the field equations governing the gas dynamics and describe the interaction of gravitational waves with matter. We have shown that the transport equation of these amplitudes provides numerical solutions for the frequency-alteration. The decrease in frequency is driven by the energy dissipating process of GW-matter interactions. The decrease is significantly smaller than the magnitude of the original frequency and too small to be detectable by present second- and planned third-generation detectors. The effect exhibits a power-law relationship between original and decreased frequencies. For sources in the 1–2 kHz frequency range, the influence of the interaction on the signal may increase significantly compared to that of the value on initial frequency of 100–200 Hz. Such high-frequency signals are expected to be emitted from the post-merger phase of low-mass neutron-star (NS) collisions such as the GW event GW170817 which originated from a BNS system. The frequency deviation was examined particularly for the first observed transient signal GW150914.

Black hole geometries and holographs. — In our recent work we combined two results of the quasilocal theory of black holes (BH). Near horizon geometries (NHG) of extremal BHs are exact solutions of the Einstein equations obtained by a naturally defined limit of neighborhoods of extremal (degenerate) Killing horizons. The second topic is the recent stationary black hole holograph (BHH) relying on the characteristic Cauchy problem for the electrovacuum Einstein's equations. If two transversal null surfaces are nonexpanding, then they become components of a bifurcated Killing horizon. Based on the observation that NHGs also admit bifurcated Killing horizons NHGs can be referred as special cases of the BHHs. In our work we have determined conditions on the BHH data that are necessary and sufficient for the corresponding hologram spacetime to be a NHG. This result may be considered as the first step in using the BHH construction in a quest for an interesting generalization of the NHG idea. For simplicity, our work was restricted to 4D spacetimes and the vacuum Einstein's equations.

The idea that inequalities arise from the geometrical attributes of different objects is not new. One of the best known example is the isoperimetric inequality which states that among closed planar curves with fixed length the circle has the smallest area. In general relativity similar reasoning yields relations between physical parameters through the coupled nature of geometry and physics. The most successful application of these kind of relations is putting constraints on black hole evolution. Black holes are relatively simple objects described by few parameters but their evolution can easily develop complex structures. Nevertheless the geometrical nature of black holes results in relations between its parameters which remain valid even in extremely complicated cases.

We studied the case of spherically symmetric spacetimes. In spherical symmetry there is a highly accepted notion for defining the amount of mass included within a domain, the Misner-Sharp mass. This notion makes possible to investigate such inequalities in more general spacetimes than before and domains that are not necessarily black holes but normal bodies instead.

Matra Gravitational and Geophysical Laboratory. — The lower frequency bound of the Advanced GW observatories are around 20 Hz. For the planned European next generation GW detector this value is 2 Hz. There are three fundamental limitations at low frequency of the sensitivity: seismic noise, the related gravitational gradient noise (so-called Newtonian noise) and the thermal noise of the mirrors. To circumvent these limitations the new infrastructure is planned as an underground site to reduce the effect of seismic and Newtonian noise with cryogenic facilities to cool down the mirrors to directly reduce the thermal vibration of the test masses. The Mátra Gravitational and Geophysical Laboratory was constructed 88 m deep below the surface in an unused mine near Gyöngyösoroszi in 2015. In a collaboration with several Institutes the aim of the Laboratory is to perform long-term seismic, infrasound and electromagnetic noise measurements, and monitor the variation of the cosmic muon flux. After the publication of the first data taking period, March and August, 2016, the second one has been started from August, 2016. In this period, the members of our group focused on the study of the seismic noises by improving and specifying the processing algorithm and by clarifying the derived quantities for the site selection of any 3rd generation GW underground facilities. By the end of 2017, more than 600 days of data have been collected and analyzed in order to study monthly and yearly change of seismic noises which is essential for a next generation GW detector. By the collected data from Mátra 400 m and the Jánossy-mine (located at the KFKI Campus) the reduction of seismic noises with depth could also be studied.

Outreach. — With the first direct detection of the collision of two neutron stars with gravitational and electromagnetic waves this year marks a significant breakthrough in multi-messenger astronomy. The announcement of the first detection of gravitational waves with three GW detectors and other black hole mergers was generated a very intense public interest and attention to this research field. It was further intensified that the Nobel Prize in Physics this year was awarded for the direct observation of gravitational waves. Similarly to the previous year's appearances our group members were actively participated in public outreach. We have given several successful scientific and public lectures, radio and TV interviews about the detection of gravitational waves and neutron star collisions.

* This is an intergroup organization with P. Ván, R. Kovács, E. Fenyvesi, G.G. Barnaföldi from the Heavy Ion Physics Research Group (R-B) and Z. Zimborás form Field Theory Group (R-A).