Final Report

This research project encompassed all research related to gravitational theories (both general relativity and modified gravity theories) and related astrophysics (gravitational waves, black holes, radio jets, multimessenger aspects) undergoing at the University of Szeged, between 1st September 2017 and 30 November 2023. The participants were L Á Gergely (the PI), Z Keresztes (senior member), E Kun (postdoc), M Tápai, B Racskó, C Nagy (PhD students) and many MSc and BSc students.

Our research project, originally of 4 years span was due to terminate on 31 August 2021, however extension until 30 November 2023 was applied (without additional funds), due to legislation meant to minimize the negative impact of the Covid19 pandemic. During the extension period we achieved additional important results in connection with the planned research topics.

Publication summary

Our research during the total span of the project resulted in

1) 25 short author list journal papers, with the grant number indicated in the Acknowledgements, published in
    a) Astrophysical Journal Letters (1)
    b) Monthly Notices of the Royal Astronomical Society (3)
    c) Physical Review D (5)
    d) Astronomy and Astrophysics (2)
    e) Classical and Quantum Gravity (2)
    f) Annalen der Physik (1)
    g) European Physical Journal Plus (1)
    h) Symmetry (2)
    i) Universe (5)
    j) Romanian Astronomical Journal (3)
2) 1 short author list paper in Advances in Space Research, without the grant number
3) 2 review papers, authored by 141 and 320 researchers, respectively, including L Á Gergely, entitled *New Horizons for Fundamental Physics with LISA*, published in Living Reviews of Relativity and *Prospects for fundamental physics with LISA*, published in General Relativity and Gravitation
4) 1 review paper, authored by 162 invited authors, including L Á Gergely, entitled *Quantum gravity phenomenology at the dawn of the multi-messenger era*, published in Progress in Nuclear and Particle Physics
5) 1 white paper by 102 authors of the same collaboration, entitled *White Paper and Roadmap for Quantum Gravity Phenomenology in the Multi-Messenger Era*, submitted to Classical and Quantum Gravity
6) 1 book chapter, entitled *Gravitational Lensing*, written by L Á Gergely by invitation, included in the monography *Modified Gravity and Cosmology: An update by the CANTATA Network*, published by Springer

7) 91 LIGO Scientific Collaboration papers (which mention NKFIH in the Acknowledgements, but not the grant number, as per collaboration rules).

None of the papers we published implied any publication fees.

Conference attendances and talks

Despite the difficulties due to the Covid19 pandemic, our research was disseminated at international conferences through 27 talks and several poster presentations:

<u>1st grant period</u> (12 months)
- Gravity Malta 2018 - COST Meeting CA16104 Gravitational waves, black holes and fundamental physics (GWverse), talk by Z Keresztes.
- Solvay Workshop "SuGAR 2018: Searching for the sources of galactic and extra galactic cosmic rays", Brussels, Belgium, talks by L Á Gergely, poster by C Gergely.
- Cosmology Group, University of Szczecin, Poland, talks by L Á Gergely, C Gergely.
- Fifteenth Marcel Grossmann Meeting - MG15, University of Rome "La Sapienza", Italy, talks by L Á Gergely, Z Keresztes, E Kun (2), C Gergely.

L Á Gergely has participated at the second CANTATA Meeting in Frankfurt, M Tápai at the PyCBC meeting in Hanover and remotely at the spring LSC meeting.

<u>2nd grant period</u> (12 months)
The group presented a total of 11 lectures + 1 poster at international conferences, 1 lecture + 1 poster at a Hungarian conference and 3 other Hungarian lectures. The members of the group participated in a total of 10 conferences and other meetings.

Talks:
- E Kun: High-energy particle emission of active galactic nuclei.

ELFT Summer School, Astroparticle Physics, 3-7 September 2018, Mátraháza, Hungary
- L Á Gergely: Alternative gravitational theories confronted with observations.

ELFT Summer School, Astroparticle Physics, 3-7 September 2018, Mátraháza, Hungary
- B Racskó: Thin shells and shockwaves in generalized Brans-Dicke theories.

FUture Gravitational Alternatives Meeting, 3-4 October 2018, Valencia, Spain
- C Gergely: Gauge-fixing of black hole perturbations in the beyond Horndeski theories.

FUture Gravitational Alternatives Meeting, 3-4 October 2018, Valencia, Spain
- L Á Gergely: The legacy of Stephen Hawking.

MAFIHE Tea House lecture, 29 November 2018, University of Szeged, Hungary
- L Á Gergely: Black hole perturbations in effective field theories of modified gravity.

Gravitational Waves, Black Holes and Fundamental Physics, 21-24 January, Athens, Greece
- L Á Gergely: The discovery of gravitational waves and the 2017 Nobel Prize in Physics.

Statutory meeting of the Szeged Branch of the Hungarian Academy of Sciences, 21 February 2019 Szeged, Hungary

- C Gergely: Black hole perturbations in scalar-tensor gravitational theories.

XXXIV OTDK in Physics, Geosciences and Mathematics, Eszterházy Károly University, 23-26 April 2019, Eger, Hungary

- Z Keresztes: The evolutions of spinning bodies moving in rotating black hole spacetimes.

Second Hermann Minkowski Meeting on the Foundations of Spacetime Physics, 16-19, May, Albena, Bulgaria

- L Á Gergely: Testing and stability analysis of modified gravity theories.

Modern Theories of Gravitation, Hungarian Academy of Sciences, 8 May 2019, Budapest, Hungary

- C Gergely, Z Keresztes, L Á Gergely: Gravitational dynamics in a 2+1+1 decomposed spacetime along nonorthogonal double foliations: Hamiltonian evolution and gauge fixing.

Recent developments in Astronomy, Astrophysics, Space and Planetary Sciences, 27-29 May 2019, Cluj, Romania

- Z Keresztes: The motion and spin evolution of extended bodies in rotating black hole spacetimes.

Recent developments in Astronomy, Astrophysics, Space and Planetary Sciences, 27-29 May 2019, Cluj, Romania

- B Racskó, L Á Gergely: Null shells in kinetic gravity braiding scalar-tensor theories.

Recent developments in Astronomy, Astrophysics, Space and Planetary Sciences, 27-29 May 2019, Cluj, Romania

- L Á Gergely: Modified gravity theories and their testing.

Hungarian Physics Meeting, Eötvös Loránd Physics Society, August 21-24, Sopron, Hungary

International conference poster:
Z Keresztes: Static and spherically symmetric black hole solution in a Born-Infeld inspired modified gravity. Athens 2019: Gravitational Waves, Black Holes and Fundamental Physics, 21-24 January 2019, Athens, Greece

3rd grant period (12 months)
3 lectures (L Á Gergely in Barcelona and Tuzla, C Gergely in Portsmouth, Z Keresztes in Tartu) + 4 posters presented at international conferences, 2 other Hungarian lectures. A total of 15 conference participations.

4th grant period (12 months)
Due to Covid travel restrictions, we had only 3 online conference talks (1 by Z Keresztes at the LISA Conference and 2 by C Nagy at the Gravitex 2021 Conference).

5th grant period (12 months)

- Third Annual Conference of the Quantum Gravity in the Multimessenger Approach, Napoli (talk by C Nagy)
- 12th Central European Relativity Seminar, Budapest (posters by C Nagy and B Racskó)

6th grant period (12 months)
L Á Gergely presented scientific talks on the compact binary sources of gravitational waves at the international conference "Special Colloquium for Peter Biermann's 80th Birthday, Bochum, Germany" and in the framework of the online seminar series "Star – UBB Seminar Series in Gravitation, Cosmology and Astrophysics", organised by T. Harko.

7th grant period (3 months)
L Á Gergely presented a scientific talk on cylindrically symmetric gravitational waves at the international cosmology workshop in Corfu (September 2023).

Formation of the future generation of researchers

Complementing the research activities, the students in our group successfully defended the following theses, all in the research topics of the proposal:

6 MSc theses:

a) B Racskó: *Lightlike shock waves in scalar-tensor theories* (2018, supervisor L Á Gergely)
b) B Deák: *Galaxy rotation curves in the Navarro—Frenk—White dark matter model and Verlinde's theory* (2019, supervisors Z Keresztes, E Kun)
c) B Kacskovics: *Fourth post-Newtonian order study of extreme mass ratio, eccentric binaries* (2019, supervisors M Vasúth, L Á Gergely)
d) C Gergely: *Hamiltonian evolution and black hole perturbations in scalar-tensor gravitational theories* (2019, supervisor Z Keresztes)
e) G Berta: *Space-time of a slowly rotating, axially symmetric star* (2021, supervisor Z Keresztes)
f) A Fóris: Exact spacetimes generated by high frequency gravitational waves (2023, supervisor L Á Gergely)

11 BSC theses:

a) O Fekete, *Cylindrically symmetric gravitational waves* (2018, supervisor L Á Gergely)
b) G Berta, *Discussion through examples of line elements with symmetries and of junction conditions of spacetime regions* (2018, supervisor Z Keresztes)
c) K Kolozsi, *Screening mechanism in scalar-tensor gravitational theories* (2020, supervisor L Á Gergely)
d) V Hegedűs, *The gravitational magnetoelectric effect* (2020, supervisor L Á Gergely)
e) A Fóris, *Geometrical optics approximation of gravitational waves* (2021, supervisor L Á Gergely)

f) Á Kovács, *Study of spherically symmetric irradiated spacetimes in the geometrical optics approximation* (2022, supervisor L Á Gergely)
g) Á Csókási, *The Hamiltonian dynamics of gravity* (2023, supervisor L Á Gergely)
h) A Sajgó, Gravitational information paradox (2023, supervisor L Á Gergely)
i) D Szili, *Interstellar and science* (2023, supervisor L Á Gergely)
j) T Tordai, *The H0 and S8 tensions in cosmology* (2023, supervisor L Á Gergely)
k) B Cirok, The effects of magnetic dipole moments on the secular spin dynamics of compact binaries (2023, supervisor Z Keresztes)

Our students also participated in the Scientific Student Conferences, obtaining a total of 5 prizes at the local phase and 2 prizes at the national phase:

a) B Racskó, Light-like shock-waves in generalised Brans-Dicke theories (2018, supervisor L Á Gergely, 1st prize U Szeged)
b) C Gergely, *Black hole perturbations in scalar-tensor gravitational theories* (2018, supervisor Z Keresztes, 2nd prize U Szeged, 1st prize at the Theoretical Astrophysics and Astrodynamics Section, XXXIV. National Scientific Student Conference, Eger, 2019)
c) V Hegedűs, *The gravitational magnetoelectric effect in static black hole and cosmological space-times* (2020, supervisor L Á Gergely, 1st prize Szeged U, Special prize at the Extragalactic Astrophysics and Gravitational Research Section, XXXV. National Scientific Student Conference, Szeged, 2021)
d) A Fóris, *High frequency gravitational waves and their backreaction in strong field* (2022, supervisor L Á Gergely, 2nd prize U Szeged)
e) Á Kovács, *Spherically symmetric spacetimes in the presence of high frequency gravitational waves* (2022, supervisor L Á Gergely, 2nd prize U Szeged)

There are also three PhD theses from our group in the process to be completed and submitted:

a) M Tápai, in the topic of *gravitational waveforms and gravitational wave detection algorithms* (supervisors L Á Gergely, Z Keresztes)
b) B Racskó, in the topic of *junction conditions in gravitational theories* (supervisor L Á Gergely)
c) C Nagy, in the topic of black hole perturbations in scalar-tensor theories (supervisor Z Keresztes)

Awards and distinctions of group members

During the more than 6 years span of the project, the members of the group obtained a number of awards, prizes and fellowships in relation with their project-related research:

- Order of Merit of the Hungarian Republic, Officer's Cross – L Á Gergely
- Ad Astra Award – L Á Gergely
- Junior Prima Award – E Kun
- MTA Premium postdoctoral fellowship – E Kun

- New National Excellence fellowships – Z Keresztes (3), B Racskó (3), C Nagy (6), V. Hegedűs
- 1st Prize in Natural Sciences, MTA Szeged Branch - C Gergely, B Racskó

Research results

We proposed research in 8 distinct, but related topics:

A) <u>The study of the geometrical optics limit of various generalised gravity theories in strong field regime, with special emphasis on GW production and nonlinearities.</u>

We discussed the ***perturbations of spherically symmetric and static space-times*** in the framework of our newly developed 2+1+1 decomposition (see task B), achieving an ***unambiguous gauge fixing for scalar-tensor theories***, unavailable in this context before. This result has been presented first as a poster at the Solvay Workshop; also, as a parallel section talk at the MG15, University of Rome by C Gergely.

Next, we investigated ***the fluid equivalence interpretation of minimally coupled scalar fields***. While in a cosmological setup the interpretation of a time-evolving scalar field as a perfect fluid is well-understood, the situation is more intricate when the scalar field is static, but has a spatial gradient, a situation motivated by black hole perturbations in scalar-tensor theories. Then ***the scalar field was interpreted as either a particular imperfect fluid of type I or a superposition of a pair of leftgoing (incoming) and rightgoing (outgoing) null dusts with a perfect fluid***. Finally, when the scalar gradient is null, it has been found equivalent to an imperfect fluid of type II, degenerating into null dust when the energy conditions are imposed. We also proposed the suitable action in terms of the fluid pressure components for each case and discussed the variational principle for a generic class of minimally coupled scalar fields. These results have been published in a research paper by C Gergely, Z Keresztes, L Á Gergely, Phys. Rev. D 102, 024044 (2020).

We also presented a poster on ***gravitational lensing signatures on deviations from general relativity*** at the Quantum Gravity in the Multimessenger Approach meeting (10-13 March 2020, Granada, Spain).

We studied ***gravitational waves in the geometrical optics approximation in a subset of scalar-tensor theories***, the cubic Galileon models (with no algebraic dependence of the scalar, hence translationally invariant). High frequency gravitational wave perturbations backreact to the background, as shown by Isaacson in general relativity. We included both high frequency gravitational and scalar wave perturbations and quasi-stationary perturbations characterising a weak gravitational field, like in the Solar System. This configuration allows to study the Vainshtein mechanism, switching on the modifications induced by the scalar field only above the Vainshtein radius, to be in agreement with Solar

System tests. The first results were presented as an online talk at the Gravitex 2021 Conference by C Nagy.

Gravitational wave generation and propagation are modified not only in scalar-tensor theories, but by the nature of their sources too, leading to degeneracies. We have included in the discussion of the most frequent type of gravitational wave sources, ***compact binaries with components either neutron stars or black holes but also boson stars or gravastars***. These sources are characterised by different ranges of their quadrupole parameter. We derived the secular evolution equations to second post-Newtonian order accuracy, with leading-order spin-orbit, spin-spin and mass quadrupole-monopole contributions included. We found large flip-flops of the smaller spin when the larger spin is almost coplanar with the orbit. ***We also identified new; quadrupole induced flip-flops occurring when the neutron star with dominant spin has the quadrupolar parameter 3.*** We analysed the evolutions of the spin angles numerically, comparing the cases when the black hole companion is either a gravastar, another black hole or a boson star with identical mass and we identified differences in the amplitude and frequency of the flip-flop, also in the azimuthal evolution. Next, we carried out a ***linear stability analysis*** of the aligned and more generic coplanar configurations of the spins and orbital angular momentum as fix points. We identified differences in stability behaviour depending on the quadrupole parameter, resulting in differences in the predictions for neutron star, black hole, gravastar, boson star components.

These results were published in two Physical Review D papers and popularised at a conference:

Z Keresztes, L Á Gergely, Stability analysis of the spin evolution fix points in inspiraling compact binaries with black hole, neutron star, gravastar or boson star components, Phys. Rev. D 103, 084025 (2021)

Z Keresztes, M Tápai, L Á Gergely, Spin and quadrupolar effects in the secular evolution of precessing compact binaries with black hole, neutron star, gravastar or boson star components, Phys. Rev. D 103, 084024 (2021)

Z Keresztes, L Á Gergely, Secular dynamics of compact binaries and stability analysis of the evolution fix points, 13th International LISA Symposium (1-3 September 2020)

A ***monography of quantum gravity effects, in relation with gravitational wave and particle physics measurements***, has been completed by the COST Action CA18108. This was published in Progress in Nuclear and Particle Physics under the title Quantum gravity phenomenology at the dawn of the multi-messenger era — A review. L Á Gergely authored Sec. 3.2.7 (Binaries of black holes and other compact objects) of the review. He was also a section coordinator.

Gravitational wave generation and propagation are modified both by the underlying gravitational theory and by their possibly exotic sources. We investigated the ***dynamics of spinning test bodies***, moving in rotating black hole spacetimes, including beside ***Kerr*** also ***Bardeen-like and Hayward-like black holes***. Along spherical orbits and for high spin, we found ***an amplitude modulation in the harmonic evolution*** of the spin precessional angular velocity, caused by the spin-curvature coupling. Near and inside the

ergosphere, the variation of the spin direction can be very rapid. The effects of the spin-curvature coupling were also investigated, observing different effects for the considered black hole spacetimes.
A paper summarizing these finding was published in Annalen der Physik, entitled: Spin dynamics of moving bodies in rotating black hole spacetimes (authors: B Mikóczi and Z Keresztes).

A Fóris and L. Á. Gergely has studied the backreaction of cylindrical gravitational waves and found that ***the radiating Levi-Civita (Rao) metric arises as*** such a ***backreaction, through the high frequency (geometrical optics) approach, by applying the WKB approximation and the Brill-Hartle averaging scheme***. A. Fóris presented these results at the National Scientific Student Conference and a research paper is currently prepared from this result.

B) <u>Working out new 2+1+1 decompositions of space-time and of gravitational dynamics, with either non-orthogonal double foliation, or with one of the singled-out directions having vorticity.</u>

We worked out a ***new 2+1+1 decomposition of space-time, based on a non-orthogonal double foliation***. By this we reintroduced the tenth metric variable (missing in previous approaches), and we have proven that it is related to both the vorticity of the employed normal basis vectors and to the angle of Lorentz rotation between the two bases. The ***key variables*** are the ***induced metric*** of the surface and the geometric quantities characterising the embedding. These are ***the extrinsic curvatures, the normal fundamental form and normal fundamental scalar***. There are two sets of each, one of them playing a dynamical role as momenta canonically conjugated to the gravitational variables arising from the metric. We worked out the geometrodynamics in this non-orthogonal 2+1+1 decomposition in the framework of general relativity, with emphasis on the constraints and boundary terms. We have published a paper presenting the preliminary results in the journal Universe. We have written up the final results into a manuscript, which also included a comparison of the unambiguous gauge choice with other existing choices, proving that our gauge is the closest to the widely explored Regge-Wheeler gauge of General Relativity. The paper was published in the journal Physical Review D. Another invited refereed paper has been published in the subject in Romanian Astron. J.

C) <u>Application of the above decompositions for the perturbations of spherically symmetric space-times in generalised gravity theories. Study of the dynamics and stability under even mode perturbations.</u>

We have established the correct functional form of the effective field theory action of scalar-tensor gravity and proceeded with its lengthy variation to second order, included in the dissertation "Black hole perturbations in scalar-tensor gravitational theories" by C Gergely at the Theoretical Astrophysics and Astrodynamics Section of the XXXIV OTDK in Physics, Geosciences and Mathematics.

We have finalised an improved version of the 2+1+1 spacetime decomposition based on nonorthogonal foliations. The improvement consisted in the ***choice of the frame adapted to constant scalar field hypersurfaces*** (as opposed to the frame adapted to constant time hypersurfaces, previously explored in the Hamiltonian analysis). This was published as part of the paper:
C Nagy, Z Keresztes, L Á Gergely, Spherically symmetric, static black holes with scalar hair, and naked singularities in nonminimally coupled k-essence, Phys. Rev. D 103, 124056 (2021)

A review of the COST Action CANTATA has been published at Springer as an open access book, entitled: Modified Gravity and Cosmology: An update by the CANTATA Network. L.Á. Gergely authored Section 26, entitled: Gravitational Lensing, which presented a ***review of the spherically symmetric lensing phenomena in various modified gravity theories***.

The effective field theory of gravity, as the low-energy limit of the possible quantum gravity, is a suitable way to describe physics beyond general relativity. Applying the formalism of nonorthogonal double foliation, we have derived the equations describing a static and spherically symmetric spacetime. In order to investigate the ***stability*** of these spacetimes, we have derived the ***equations governing the even- and the odd-type perturbations***. This has been presented by C Nagy as a conference talk at the Third Annual Conference of the Quantum Gravity in the Multimessenger Approach, Napoli and as a poster at the 12th Central European Relativity Seminar, Budapest.

D) <u>Analytical and numerical study of the spherically symmetric space-times and of exact GWs (for example under cylindrical symmetry) in generalised gravity theories.</u>

We have considered the static and spherically symmetric vacuum spacetimes in a ***Born-Infeld inspired alternative gravity model***. The derived spacetime describes a ***black hole*** significantly different (inside the event horizon) from the Schwarzschild-functions ***not diverging at the centre*** as in General Relativity, the curvature singularity occurs. The results were presented in a conference poster in Athens.

Next, we focused on ***generalised kinetic gravity braiding scalar-tensor theories*** (the subclass of Horndeski scalar-tensor gravitational theories compatible with the gravitational wave observations) with static and spherical symmetry. We derived the equations of motion for the background in an effective field theory (EFT) approach of modified gravity.
For the models with generic G2 and G4 functions depending only on the scalar field, but G3 and G5 vanishing, we proved the ***unicity theorem*** that no action beyond Einstein-Hilbert allows for the Schwarzschild solution. We also obtained ***new spherically symmetric solutions characterised by mass, tidal charge, cosmological constant and a fourth parameter. They represent naked singularities, black holes or have the***

double horizon structure of the Schwarzschild—de Sitter spacetime. Homogeneous Kantowski—Sachs type solutions also emerged. One of the solutions obtained for the function G4 linear in the curvature coordinate in certain parameter range exhibits an intriguing logarithmic singularity lying outside the horizon. The results were published in the paper:
C Nagy, Z Keresztes, L Á Gergely, Spherically symmetric, static black holes with scalar hair, and naked singularities in nonminimally coupled k-essence, Phys. Rev. D 103, 124056 (2021)
And also presented in an online talk at the Gravitex 2021 Conference:
C Nagy, Spherically symmetric, static black holes in nonminimally coupled k-essence theory, International Conference on Gravitation: Theory and Experiment, Gravitex 2021, Durban, South Africa, 9-12 August 2021, Abstracts p. 16.

In the absence of a Birkhoff type theorem, cylindrical symmetry allows for a multitude of vacuum solutions known as the Einstein-Rosen class, including propagating and standing waves, also solitons. Their static limit is the ***Levi-Civita spacetime***. The parameter of this solution has been interpreted as the mass density on the symmetry axis, however this interpretation stands only in a narrow parameter range, as shown by the existence of a quadruplet of values for which the spacetime is flat. We introduced a ***new metric parameter: the Komar mass density in the Einstein-Rosen frame***, which halved the degeneracy in the parameter space. The metric is flat when it vanishes or diverges only. The latter case corresponds to a Rindler limit. Be exploring the Królak and Tipler criteria we showed that the ***singularity on the axis is strong***, correcting some previous claims. We also discussed how ***Newtonian gravity increases monotonically with the Komar mass density***, asymptoting to a finite value; while ***Einsteinian gravity (tidal forces) exhibit a maximum, then drop to zero***. From a physical point of view the Komar mass density of the Levi-Civita spacetime encompasses two contributions: Newtonian gravity and acceleration effects, which are related the field lines becoming increasingly parallel with ***the increase of the Komar mass density, 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 transforms planar sections of the Levi-Civita spacetime into ever deepening funnels, eventually degenerating into cylindrical topology.
This project has been published in:
B Racskó, L Á Gergely, Geometrical and physical interpretation of the Levi-Civita spacetime in terms of the Komar mass density, Eur. Phys. J. Plus 138, 439 (2023).

E) <u>Analysing GW propagation in generalised gravity theories by working out the corresponding junction conditions along null hypersurfaces.</u>

In General Relativity, matching two spacetime regions along a space-like or time-like hypersurface is described by Israel's junction conditions, which prescribe the continuity of the induced metric and relate the jump in the extrinsic curvature to the matter content of the junction surface. Israel's formalism breaks down when the surface is null, as is the case for shockwaves propagating at the speed of light, and must be modified by introducing an arbitrary transversal vector field, a method due to Barrabés and Israel. Recent observations have confirmed that gravitational waves propagate with the speed of light, and as such, impulsive gravitational waves may be perceived as null hypersurfaces in space-time, the ***Barrabés—Israel formalism*** describing them. A unified formalism for treating all kinds of hypersurfaces, including possible causal character change of the hypersurface emerged as a special case of the formalism by Mars and Senovilla. We explored the formalism ***for the junction of space-time regions in the context of scalar-tensor gravitational theories***. Both the null junction and non-null junction conditions arise as limiting cases of the general algorithm. We applied this for the case of Brans-Dicke theories and published the results in the journal Universe.

The most general scalar-tensor theory with second order field equations, Horndeski's theory has been severely constrained by the gravitational wave observations. ***We derived generic junction conditions for the subclass of allowed Horndeski theories with linear dependence on the scalar field's kinetic term***, using a transverse vector that is applicable to all hypersurfaces, and specify an easy-to-use form of the junction conditions valid only for null hypersurfaces, exploring a formalism involving double null vectors along the surface. From this, we obtained ***equations relating the energy density, surface current and isotropic pressure on the null-surface to the jumps and means of geometric quantities.***
The preliminary results were presented by L Á Gergely at the MG15, University of Rome meeting and the final version in the journal Symmetry. The paper was the cover story of the May 2019 issue of the journal.

We reproduced the equations of motion, by varying the various contributions to the Lagrangian of the ***kinetic gravity braiding scalar-tensor class***. Next, we adapted Poisson's formalism based on two null vector fields in order to derive the ***generic junction conditions on null hypersurfaces*** with one of the null vectors as its tangent and the other one transverse to it. Preliminary results were presented on a poster at the 30th Texas Symposium on Relativistic Astrophysics (15-20 December 2019, Portsmouth, UK). An invited refereed paper has been published in the subject in RomAstronJ.

In order to include perturbations which possibly modify the local light-cone structure, we derived ***junction conditions and thin shell equations along a hypersurface of arbitrary causal character***. B Racskó has derived matching conditions along a hypersurface of two solutions in general relativity through a variational formulation of shells where the signature of the boundary surface is completely unconstrained. This was accomplished through the use of a novel ***boundary term recently discovered by Parattu et al.*** Alternative approaches that do not directly involve this boundary term were also discussed and compared. This work has been presented as a poster at the 12th Central European Relativity Seminar, Budapest. B Racskó published a paper with these results in Classical and Quantum Gravity.

We found that ***in the modified gravity scene the calculation of junction conditions*** may lead to ambiguities and conflicts between the various formulations. This topic was addressed in the paper:

B. Racskó, Junction conditions in a general field theory, to be published in Classical and Quantum Gravity (2024).

The paper introduces a ***general framework to compute junction conditions in any reasonable classical field theory*** and analyses their properties. It proves, that in any variational field theory it is possible to define ***unambiguous and mathematically well-defined junction conditions, either by interpreting the Euler-Lagrange differential equation as a distribution or as the extremals of a variational functional*** and these two coincide. An example is presented, highlighting why ambiguities in the existing formalisms arise, essentially due to incorrect use of the distributions in the literature. Relations between junction conditions, the boundary value problem of variational principles and Gibbons—Hawking—York-like surface terms were examined. The methods presented rely on the use of coordinates adapted to represent the junction surface as a leaf in a foliation and a technique for reducing the order of Lagrangians to the lowest possible in the foliation parameter. We expect that the presented reduction theorem can generate interest independent from the rest of the topics considered in the paper. This work will be the backbone of the PhD thesis of B Racskó.

F) <u>Testing specific dark matter models vs. modified gravity predictions on galactic scale by available rotation curve data.</u>

We started by ***expanding our already existing photometric database*** of 15 high and 15 low surface brightness galaxies with dwarf galaxy data from the available literature. We derived the ***best-fit baryonic parameters from their surface brightness profile***. We confronted various well established dark matter models with the initial set of rotation curves, establishing that ***none of the investigated models (pseudoisothermal sphere, Navarro-Frenk-White, Einasto) applies successfully for the full set*** and we published these results in the journal Astronomy and Astrophysics.

We proceeded with testing a Bose-Einstein condensate (BEC), with possibly massive graviton, as a dark matter model.

A slowly rotating Bose-Einstein condensate (BEC) qualifies as a 3-parameter dark matter model. We assembled a database of 12 dwarf galaxies with optical density, together with their spectroscopic rotation curves. The model of a slowly rotating BEC combined with the baryonic model fits 11 galaxies out of 12 within 1 sigma significance, improving the fit of the static BEC. Our paper on the slowly rotating Bose–Einstein condensate (BEC) dark matter model tested on a database of 12 dwarf galaxies with accurate optical and near-infrared (NIR) surface brightness density profiles together with spectroscopic rotation curve data has been published in E Kun, Z Keresztes, L Á Gergely, Astron. Astrophys., 2020, 633, 75.

The research topic planned for the 2nd year concerned the ***emergent gravity model of Verlinde as a substitute for dark matter***. We tested this model with the rotational curve data of 10 dwarf galaxies, finding it ***incapable to fit both the rotation curves and observations of the surface brightness density of the baryonic matter***. The results are summarised in the MSc Thesis of Bence Deák entitled "Galaxy rotation curves in the Navarro—Frenk—White dark matter model and Verlinde's theory".

The research topic planned for the 4th year concerned a ***non-relativistic Bose–Einstein Condensate model of light bosons interacting gravitationally either through a Newtonian or a Yukawa potential***. We confronted this with the observed rotational curves of 12 dwarf galaxies. The purely baryonic fit being unsatisfactory, a dark matter component was needed. The rotational curves of 5 galaxies could be explained with high confidence level by the BEC model with ***massive gravitons*** and stringent ***upper limit on the graviton mass derived, which is three orders of magnitude stronger than the limit derived from recent gravitational wave detections.*** The paper reporting on these has been published in the journal Symmetry.

Two reliable databases of High Surface Brightness and Low Surface Brightness galaxies, respectively, have been assembled for future use in testing dark matter models.

Concerning the investigations of dark matter models by galactic rotation curves, we are happy to report that we have completed the work plan of all 4 years already after two years.

G) <u>Analysis of periodic structures in Active Galactic Nuclei (AGN) jets in order to identify possible supermassive BH (SMBH) binaries at its base, which are sources of low-frequency GWs for the LISA space mission.</u>

We analysed very long baseline interferometric ***(VLBI) data of the jet of BL Lac object S5 1803+784***. We found the temporal variability in the Doppler boosting of the ridge line results in jet regions behaving as flaring "radio lanterns". We proposed a ***jet kinematical model relying on an orbiting supermassive black hole binary***, which is able to explain the long-term behaviour of the ridge line. Based on the model we estimated the binary parameters, ***constrained the mass ratio, spin-precession period and gravitational lifetime*** of the binary. This work has been published in Monthly Notices of the Royal Astronomical Society and presented by E Kun in a talk at the MG15, University of Rome.

We continued our work regarding the ***high-energy neutrino emission of the active galactic nuclei*** and their connection with radio data of the jets, publishing the results in the journal Universe and E Kun presented a related talk at the MG15, University of Rome.

We further ***analysed the VLBI radio structure and core-brightening of the high-energy neutrino emitter blazar TXS 0506+056***. We found its jet ridge line behaves very similar to the jet of S5 1803+784, implying the inclination angle of the jet is small. We found the radio jet pointing towards the Earth is the key property of the blazar TXS 0506+056 enabling its multimessenger observations. These findings are included in a paper submitted to Monthly Notices of the Royal Astronomical Society.

We presented a poster on the connection of the high-energy neutrinos and the radio-loud active galactic nuclei at the 30th Texas Symposium on Relativistic Astrophysics (15-20 December 2019, Portsmouth, UK).

We also published a related paper in international collaboration discussing the ***connections between the supernova explosions of massive stars and cosmic rays*** in the journal AdvSpaceResA.

In our previous research, we emphasised the connection between the high-energy neutrinos detected by the IceCube Collaboration and the radio-loud active galactic nuclei. A prominent example was the blazar TXS 0506+056. Continuing this line of research, we reported on ***three candidate sources of cosmic neutrinos recorded by IceCube, pointing out an active outflow suppressed in the gamma regime coincident with the neutrino emission.*** We have shown through the maximum likelihood analysis, that the Fermi-LAT gamma-flux of the blazar PKS 1502+106 had a local minimum coincident with the IceCube high-energy neutrino IC-190730A. This was similar to the local gamma-suppression in the fluxes of blazars TXS 0506+056 (MAGIC TeV) and PKS B1424-418 (Fermi-LAT) at the time of coincident IceCube neutrino detections.
This has been published as:
E. Kun, I. Bartos, J. Becker-Tjus, P. Biermann, F. Halzen, G. Mező, Cosmic Neutrinos from Temporarily Gamma-suppressed Blazars,
Astrophys. J. Lett 911, L18 (2021).

Following our earlier work on the Roos quasar, for which ***we analysed the jet data and identified for the first time the spin of the dominant black hole at the jet basis due to its spin-orbit precession,*** we revisited the same source ***by exploring 25 years of accumulated data in a new paper:***

E. Kun, S. Britzen, S. Frey, K. É. Gabányi, L. Á. Gergely, 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, to be published in Monthly Notices of the Royal Astronomical Society (2023).

Abstract:
In a previous work, we have identified for the first time 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 $\nu=0.21\pm0.04$ for $\kappa=0$ (i.e. when the spin direction is perpendicular to the orbital plane) and as $\nu=0.32\pm0.07$ for $\kappa=\pi/2\kappa$ (i.e. when the spin lies in the orbital plane). We estimate more precisely the spin precession velocity, cutting half of its uncertainty from $(-0.05\pm0.02)^{\circ}\ \mathrm{yr}^{-1}$ to $(-0.04\pm0.01)^{\circ}\ \mathrm{yr}^{-1}$.

Our collaboration in the Fundamental Physics workgroup of LISA resulted in a Living Reviews of Relativity paper: New Horizons for Fundamental Physics with LISA, in which L.Á. Gergely is one of the 141 authors.

H) Analysis of the data collected by Advanced LIGO for direct GW detection, performed in the framework of the LIGO Scientific Collaboration.

As part of the LIGO Scientific Collaboration Compact Binary Coalescence group, we took part in the analysis of the data gathered during the O2 run of Advanced LIGO with PyCBC, a Python based toolkit for gravitational wave signal analysis and a major LSC (LIGO Scientific Collaboration) pipeline.

M Tápai participated in the development of multi (3+) detector analysis with PyCBC.

L Á Gergely took part in the collaboration effort establishing a lower limit for the Brans—Dicke parameter from the gravitational wave measurements.

B Fekecs participated in the PyCBC search for subsolar mass binary signals. The lack of this type of detections allowed imposing constraints on models predicting such binaries. A poster has been presented on this research at the Einstein Telescope meeting in Budapest.

B Cirok and L Á Gergely participated in assessing the effects of modified gravity on LIGO measurements through modified dispersion relations. B Fekecs performed duties on the O4 Live rota.

As members of the LIGO Scientific Collaboration L Á Gergely and M Tápai have been co-authors in several publications.