Quantum space-time, gravity and cosmology (QSGravCos)

Long program description

Introduction

General Relativity (GR) is a classical theory of gravity, well tested on the scales of our Solar system. Theoretical and experimental arguments point to a modification of GR at other scales. At very small scales (Planck scale) the quantum mechanical aspects of gravity are non-negligible, and a quantum gravity (QG) theory is required. QG is needed to discuss singularities of black holes and the evolution of the very early Universe (inflation, Big Bang). On the other hand, at galactic scales Dark Matter (DM) is needed to account for the experimental results on rotations curves of galaxies. Finally, at cosmological scales, to explain the accelerated expansion of Universe, Dark Energy (DE) is introduced.

During the last thirty years lots of cosmological experimental data has been collected. These include precise measurement of CMB radiation, detection of accelerated expansion of Universe, detection of gravitational waves, an image of the black hole at the center of the supergiant elliptical galaxy Messier 87 provided by Event Horizon Telescope and many others. The development of observational cosmology is partially a result of numerous dramatic improvements in technology: space missions, gravitational detectors, new telescopes, computer performance and many more. The importance of collected data is confirmed and acknowledged by several Nobel prizes in physics in the last decade(s). In the years to come new data form observational cosmology are expected due to both improved and new gravitational waves detectors (LIGO, LISA…) and numerous experiments searching for Dark Matter and Dark Energy, like AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space and many others.

In order to understand these collected data lots of work has been done in developing various theoretical models of effective QG and physics beyond Standard Model (SM). All major attempts to unify GR and Quantum Mechanics theories rely on delocalization of particles; that is, either the concept of a particle is changed so that these new objects have dimensions (e.g. String Theory), and/or space-time is modified to explain delocalization by either making space-time discrete (e.g. Loop Quantum Gravity) or by smearing space-time by introducing uncertainty relations for positions of particles (e.g. Noncommutative Geometry). In this network we focus on String theory, Noncommutative geometry and effective theories of modified gravity.

QSGravCos network is a natural extension of the existing CEEPUS network RS-1514-03-2223 Gravitation and Cosmology. Gravitation and Cosmology networks that was approved for funding in 2020/21. During 2021/22 and 2022/23 this network was/is an umbrella status. Despite the Covid-19 pandemic and the umbrella status we have managed to organize several successful mobility exchanges (Niš-Banja Luka, Niš-Craiova, Belgrade-Wroclaw…) and develop our scientific collaborations. As a result of these efforts, for the period 2022/23 we added a new node: University of Zagreb, Faculty of Science, Department of Physics, extending the network to include Croatia. In the application for QSGravCos network we are including two more new nodes: University of Belgrade, Faculty of Pharmacy, Department of Physics and Mathematics and Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics. In this way we are adding Slovakia as a new country in the network and we are showing that the original network is slowly growing to include institutions and researchers in effective QG, quantum field theory and particle physics.

Previous collaborations

QSGravCos network based on previously existing collaborations and in particular on the SEENET-MTP (Southeastern European Network in Mathematical and Theoretical Physics) network that has been connecting high-energy physicists in the region of Southeastern Europe for twenty years. The high level of scientific collaboration (Zagreb-Belgrade-Niš, Bratislava-Belgrade, Sofia-Bucharest, Niš-Craiova…) s reflected in the published papers, see References, organized workshops, training schools and conferences. Moreover, most of the nodes have been actively involved in two very successful COST actions MP1405 Quantum structure of spacetime (2014-2019) and CA18108 Quantum gravity phenomenology in the multimessanger approach (2018-2023), which brought together scientists from the whole Europe working on various aspects of effective descriptions of Quantum Gravity, and helped to ignite several fruitful collaborations and interactions.

Through this network we plan to continue with the good practice of:
-scientific collaboration,
-introduction of students and young researchers to this research field,
-promoting scientific and cultural heritage of each country included in the network.

Objectives of the network

There are two main objectives of this network. The first objective is to combine different expertise of each node into an effort of constructing realistic theoretical models of effective quantum gravity, inflation and cosmology. Having in mind young researchers who would like to develop their scientific career in this field, the second main objective of the network is to intensively discuss and make first steps towards joint master and PhD programs between the nodes.

Work plan: research and teaching

To achieve our first objective, we will continue the existing collaborations and establish new ones. In particular, we will concentrate on the following research topics (problems):

1. Effective QG models and their phenomenological consequences

In the absence of the full Quantum Gravity theory, we focus on effective theories, such as gravity on a noncommutative spacetime, modified gravity from string theory, gravity with torsion, etc. Having in mind advances in gravitational waves detection (LIGO/VIRGO, …) we plan to focus on

-(noncommutative) quasinormal modes of black holes,
-phenomenological consequences of quantum structure of spacetime for propagation of gamma ray bursts across cosmological distances.

2. Black hole physics

The natural intersection between gravity and the quantum physics is currently investigated on the level of the most compact and heavy objects in the Universe: black holes.

-black hole thermodynamics
-entropy and evaporation of black holes

3. Early Universe and inflation

Currently there are lots of activities and experimental data in observational cosmology. We plan to continue our research on cosmological models coming from modified gravity theories and their phenomenological properties. We also plan to extend our research in the field of inflation and early Universe to include analytical and numerical calculation of inflation parameters in the framework of different cosmological models. The plan is to extend research interest to cosmological inflation with two-field models and inflationary models with constant-roll regime.

4. Gauge/gravity (holographic) correspondence

The holographic duality between gauge field theories and gravitational (string) theories is an incredible achievement in perturbative and non-perturbative physics. It allows one to study strongly coupled sectors of different theories. We will focus on two different approaches:

-top-down approach, focusing not mostly on description of local features of strongly interacting quantum fields (for instance anomalous dimensions, correlators etc.), but also on some global ones, for instance entanglement entropy and thermodynamic features
-bottom-up approach, which includes bulk reconstruction and global physical features on both sides of holographic duality. The reconstruction of bulk theory poses fundamental questions going beyond the current paradigms, for instance the concept of emergent gravity.

5. Construction and analysis of quantum noncommutative field theories

The theoretical motivation for introducing a non-trivial algebra of coordinates in order to modify the space-time structure comes from ideas and results found in various fields of research. Historically, the first proposal was put forward as a proposal for regularization of divergences. More recently, the realization that open strings ending on D-branes in presence of a background antisymmetric B-field give rise to NC effective field theories boosted the research of field theories on an NC space-time. Finally, since NC spaces are well defined space with quantum structure, they are a great toy model for investigating its consequences on physical theories. We plan to investigate quantum properties of two particular models of NC deformation: braided NC field theory and fuzzy field theory. In particular, we will work on:

-matrix model formulations of fuzzy field theories and discussion of their properties such as phase structure, correlation functions, entanglement entropy, etc. – by analytic techniques of random matrix theory and numerical techniques of Monte Carlo simulations,
-renormalizability properties of braided NC field theories and UV/IR mixing problem, using the formalism of homological perturbation theory.

We will publish scientific papers in internationally recognized journals and organize one scientific workshop. We will also present the achieved results at international conferences and workshops.

To achieve our second objective, we will:

1. Promote the network among our master and PhD students and encourage them to apply for mobility grants. We will in particular encourage combined master and PhD thesis (partially done in two different institutions from the network).

2. Promote the network among the lecturers at our institutions and encourage them to actively participate in the mobility program.

3. Organize specialized intensive courses at the institutions from the network with invited lecturers from different nodes.

4. Include incoming students and lecturers in the lectures during the semester.

5. Organize three on-line meetings and one in-person meeting to discuss the development of the joint master and PhD programs.

6. Organize one summer school for master and PhD students. The plan is to hold the summer school at the end of the august in Slovakia, organized by the Bratislava node. The school will consist of courses on the relevant topics by senior teachers and student presentations on their ongoing work in the field. This way the participants will be exposed to both well-established knowledge and new emerging ideas, and students will have a unique possibility to present their work in front of their peers. This event will build on history of a previously organized event and will include students from outside of the network.

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Planned activities

-starting coordination meeting

-students and teachers exchange

-participation of incoming teachers and students (undergraduate, graduate, PhD) in lessons and lectures at host universities;

-intensive courses

-organization of summer schools

-participation in international conferences, workshops

-development of joint master and PhD programs

Selection criteria for mobility

Students need to have a working knowledge of English and/or the language of the institution. They should also show the quality of the planned study/research visit by writing a motivation letter for the visit with the explicit visit plan included.

Teachers should have a valid teaching position at the home University. The preference will be given to teachers who lecture topics uncovered by the host institution and to those who plan to stay more than one week.

Coordination and monitoring of the network

We will organize regular coordination meetings. In particular, we will organize one meeting at the beginning of the academic year to discuss the organization and plans for fulfilling our objectives. At the end of the academic year we will also organize one meeting to discuss our achievements and an application for the next academic year. During the academic year we will organize on-line meetings

via zoom platform to discuss current status, potential problems and the corresponding solutions. In this way we will try to optimize the performance of our network.

Local coordinators of each node of the network will also establish good and efficient communication with the corresponding NCOs to ensure smooth mobility within the network.

We will develop a web portal of the network, where all the details of activities (scientific results, possible mobilities, planned intensive courses, topics for master theses, summer school…) will be visible.

Risk management

There are potential risks issues related with a success of the proposed network. Here we list a few most important ones and briefly describe actions we plan to take to overcome them.

Students and teachers are not informed about the network and the possibilities it offers.

We will promote the network within our institutions and motivate students to apply for mobility grants. We will set up a webpage of the network and put all relevant information there (possible mobility grants, planned intensive courses, topics for master thesis…)

Money provided by the CEEPUS network is not enough to cover planned visits.

We will try to overcome this issue by using additional funding, such as national grants and SEENET-MTP grants.

Limited travel possibilities due to a pandemic or different reasons

We will organize planned meetings, courses and even visits on line or in a hybrid way, using Zoom and other platforms.

The special role of the partners

University of Belgrade, Faculty of Physics (UniBgFF), Group for Gravitation, Particles and Fields

At this moment the group for Gravitation, Particles and Fields at the Faculty of Physics, University of Belgrade consists of three full professors, three assistant professors, one postdoc and four PhD students. Our research focuses mostly on quantum aspects of spacetime, in particular noncommutative deformations of spacetime and the corresponding field theories and gravity. We are interested in studying noncommutative (gauge) field theories, their classical, quantum and phenomenological applications. In particular, we are interested in quantization of newly proposed noncommutative gauge field theories, braided NC theories. We plan to investigate these research problems using the techniques of L-infinity algebras, Batalin-Vilkovisky formalism and homological perturbation theory. Also, we study various noncommutative gravity solution, such as BTZ black holes and cosmological solutions. Another topic of our research is the black hole physics, in particular the evaporation and the entropy of black holes. During the last 5 years our group published numerous papers on these topics in the recognized international journals.

In the previous years we have been actively collaborating with the groups from Institute of Ruđer Bošković and Department of Physics, Particles and Fields (Zagreb), Faculty of Pharmacy (Belgrade),

Institute of Theoretical Physics (Wroclaw). In addition, we have a very good collaboration with our colleagues from Faculty of Science and Mathematics (Niš) with respect to organization of various scientific events (workshops, conferences, schools for PhD students…). We have been active members of three COST actions: MP1405 QSPACE, CA18108 QG-MM and CA21109 CALISTA and organized two training schools within these actions at the Faculty of Physics in 2016 and 2022.

We have an interdisciplinary overlap with almost all nodes of the network. More explicitly:
-NC quantum field theories: Belgrade, Bratislava, Wroclaw and Craiova node,
-(NC) quasinormal modes: Zagreb and Sofia nodes,
-Black hole physics: Sofia and Zagreb nodes,
-AdS/CFT holography: Niš and Sofia nodes.

We can provide the following intensive courses:
Supersymmetry, Advanced quantum field theory, General relativity, Quantum field theory in curved spacetime, Noncommutative field theories (construction and quantization), Noncommutative gravity (star-product and frame formalism).

University of Niš (UNI), Faculty of Sciences and Mathematics, Physics department

The group for cosmology and gravitation at the Physics department of Faculty of Sciences and Mathematics, University of Niš currently consists of one full professor, two assistant professors and several teaching assistants and PhD students. Our research focuses on early Universe, cosmological inflation, nonarchimedean and noncommutative Quantum Theory, black holes, and extra dimension in the cosmological context. More specifically the group's subject of interest are:
-tachyon field dynamics,
-RSII and holographic inflationary models,
-dynamics of nonlinear (DBI) systems and nonarchimedean black holes.

During the last 5 years this group published numerous papers in the recognized international journals with an accent on the Computational methods in Cosmology and General Relativity.

The current focus of the UNI group is on the analytical and numerical calculation of inflation parameters in the framework of different cosmological model. The plan is to extend research interest to cosmological inflation with two-field models and inflationary models with constant-roll regime, but also to contribute in the International collaborations on Quantum Gravity, AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space and EuCAPT: The European Consortium for Astroparticle Theory.

The group at UNI has been one of the founders, the coordinating node, and very active in the SEENET-MTP Network with a reach experience in realization of the Network programs. UNI is participant in the COST actions QGMM 18108, actively participated in CANTATA 15117, as well as in a few previous COST and other EU programs. As the leader and the participating unit in the CEEPUS (QS) GraCos application, the group at UNI has had long-term collaboration with groups at: University of Craiova, University of Belgrade, University of Sofia, University of Banja Luka, Institute Ruđer Bošković (IRB), Zagreb.
In addition, we also actively collaborate with several institutions outside of this Network: ICTP Trieste, CERN-TH Geneva (The Framework Agreement KN3487), LMU and MPI Munich and other.

UNI group will contribute to this network by:

-Accepting bachelor, master and PhD students from all participating institutions of the QSGraCos network, working on specific topics related to their MS and PhD thesis in the fields of cosmology and gravitation in which UNI has strong references and records,
-Hosting students from other nodes in the network to attend and follow the courses in cosmology, general and special relativity, symmetry, particle physics, as well as classical and quantum field theory. In addition, we will host students and researchers in computational physics.
-Giving short intense courses at partner institutions at the topics of local interest and offer the co-mentoring and participation in the quality assurance process in the partner institutions, with an accent on Cosmology, Inflation theory and DBI dynamics.
-Organizing workshops, conferences, and other scientific events on the network's topic.

Sofia University "St. Kliment Ohridski" (SUKO), Department of Theoretical Physics

There are three actively working scientific groups within the department: Sofia String Theory Group (STG), Quantum Information and quantum optics, Gravity and Astrophysics.

The research in these groups mostly focuses on:
-AdS/CFT (holographic) correspondence and gauge/gravity generalization;
-Supergravity and exactly solvable models;
-Information spaces and information geometry;
-Quantum computation (including physical implementations of quantum gates and quantum algorithms);
-Quantum simulations, quantum sensing and metrology;
-Computational astrophysics, modified theories of gravity, gravitational waves, black holes

Particular possibilities for collaboration within the CEEPUS project appear in the line of black hole physics and cosmology, where String theory and Gravity and Astrophysics groups have large interdisciplinary overlap with many of the other nodes of the project. Particularly, STG can partner with University of Niš for understanding Brane cosmology, while collaborating with Belgrade University we can effectively study radiation of black holes and the influence of quantum space-time on gravitational waves and quasi-normal mode spectra. Black hole thermodynamics can also be considered as a particular starting point of future productive collaborations with some of the other nodes in the program.

We can provide the following intensive courses: Superstring theory, Gauge gravity (holographic) correspondence, Black hole physics, Quantum field theory in curved spacetime.

University of Craiova, Department of Physics (UCV)

Department of Physics, University of Craiova consists of three groups: Theoretical Physics including QFT, Cosmology, Constrained and Nonlinear Dynamics; Plasma Physics with accent on the Anomalous Transport in Plasmas; Physics of Materials, with competences in studying the electrical, thermal and optical properties.

The group for Theoretical Physics focuses on the following research topics:
-Quantization of (reducible) gauge theories, extended BRST symmetries.
-Topological field theories and consistent interaction vertices.
-Constrained and Nonlinear Dynamics, constrained and integrable systems.

We can offer intensive courses on (Advanced) quantum field theory, integrable systems, Hamiltonian analysis. In addition, we can also offer courses on computational physics with applications to cosmology and quantum filed theory.

The Department of Physics from UCV was and is still involved in many EU programs addressed both to education (Tempus, Erasmus, Erasmus+) and to research (NATO Integration grants, FP7, Horizon 2020). We are an important and active node of SEENET-MTP with 12 countries from the region.

The group at UCV organized or was involved in many activities devoted to the promotion of sciences and of science education, as for example (relevant for the proposed network):
-Uni Craiova is the owner of one of the five radio-telescopes connected in an EU network in the frame of the Erasmus program "Hands on Universe".
-In the field of Theoretical Physics, the Department is organizing each two years, starting from 1998, an International School and Workshop in "QFT and Hamiltonian Systems".

The Department of Physics is ready to contribute to the objectives of the project by:
-Hosting researchers and students interested in coming to Craiova University.
-Organizing intensive courses for students.
-Participating in the events organized in the frame of the project by our partners.
-Actively contributing to fulfillment of all the tasks related to the project.

University of Zagreb, Faculty of Science, Department of Physics (UZG), Particles and Fields

The department of Particles and Fields consists of two groups: Gravitation and Black Holes and Phenomenology of Elementary Particles and Fields.

In particular, the group for Gravitation and Black Holes consists of two associate professors, one professor emeritus and two PhD students. Research is mainly part of theoretical gravitational physics, with particular focus on the black hole physics and theories with higher spin fields. Papers published over the past five years in leading international journals in the field of gravitational and high energy physics contain results on
-spacetimes with nonlinear electromagnetic fields (uniqueness theorems, constraints on resolution of black hole singularities, black hole thermodynamics, perturbative solutions)
-construction of a covariant higher spin field effective action
-trace anomalies
-symmetry inheritance (scalar and electromagnetic fields)

We have active collaborations with groups at the Ruđer Bošković Institute (Zagreb) and Faculty of Physics (Belgrade). We are ready to contribute to the objectives of the proposed network by:
-hosting researchers and students willing to come to the Department of Physics, Faculty of Science, University of Zagreb; especially we can provide intensive courses on Advanced general relativity, Black hole physics, formal aspects of gauge field theories.
-participating in the events organized in the frame of the network by our partners;
-actively contributing to fulfillment of all the tasks related to the network.

University of Wroclaw, Institute of Theoretical Physics (UniWIOP).

The research at the Institute focuses on the following fields:
-Accelerated cosmological models in Ricci squared gravity and in first-order nonlinear gravity.
-Dark matter and Dark Energy as effects of modified gravity.
-(quantum) Kappa-Minkowski spacetime as the result of Jordanian twist deformation.
-Accelerated cosmological models in modified gravity tested by distant supernovae SNIa data.

UniWIOP will contribute through outgoing visits of teachers and students and participating in the Network events. We can provide intensive courses on formal aspects of noncommutative geometry and noncommutative field theory, such as Hopf algebras and twist deformation techniques.

University of Banja Luka, Bosnia and Herzegovina (UBL)

The Faculty of Natural Sciences and Mathematics at the University of Banja Luka was established in 1996, and consists of the following departments: Physics, Biology, Geography and Ethnology, Mathematics and Informatics, Chemistry, Ecology and Environment Protection and Spatial Planning. Second cycle studies are held at the study programs of Physics and other departments. All the study programs are based on the three-stage model of studies (4+1+3).

Small theoretical group of astrophysicists participates in the wide interdisciplinary research on black holes, gravitational waves and fundamental physics. In particular we have an active collaboration with the group at Faculty of Science and Mathematics, University of Niš. Being a very small group we cannot provide intensive courses for students. However, we are ready to contribute to the objectives of the proposed network by:
-participating in the events organized in the frame of the network by our partners;
-actively contributing to fulfillment of all the tasks related to the network.

Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics (FMPH)

The research group at FMPH mostly focuses on various aspects of physics in spaces with quantum structure – particularly on noncommutative spaces – so there is a great overlap in scientific interest with the two different nodes in Belgrade. However there is some interest also in all the other topics of this network and thus the members of the group – both students and teachers – will greatly benefit from collaboration with the other nodes as well.

We will be able to provide the following courses: noncommutative spaces and noncommutative field theory, matrix models in theoretical physics, numerical simulations of matrix models. We also plan to organize the networks' summer school at the end of August 2024.

University of Belgrade, Faculty of Pharmacy, Department of Physics and Mathematics

One of our research fields relevant to this network is noncommutative quantum field theory and its phenomenology. More specifically, we currently study phase transitions in matrix models on a curved background noncommutative space. We also investigate how this background affects the renormalizability of the hosted models. As one of the critical tools for gaining insight into nonperturbative results, we perform numerical Monte Carlo simulations.

Our work significantly overlaps with that of the Bratislava node and is related to the work of the main Belgrade node (Faculty of Physics).

We are ready to contribute to the objectives of the proposed network by:
-participating in the events organized in the frame of the network by our partners;
-actively contributing to fulfillment of all the tasks related to the network.

Silent Partners

Quantum gravity and mathematical physics group, Institute Ruđer Bošković, Zagreb, Croatia (IRB)

Quantum gravity and mathematical physics group at Ruđer Bošković Institute in Zagreb is a part of the Theoretical physics division at the same institution. It consists of 10 scientists (6 senior and 6 younger scientists (PhD students and postdocs)).

Research activities of the group are focused on:
-understanding of the structure and properties of spacetime at very small length scales.
-exploration of the symmetries of spacetime as seen by fields and strings.

The methods used in a research include standard field theory methods, deformation quantization, theory of Lie groups and Lie algebras, as well as modern methods of differential geometry such as noncommutative and nonassociative geometry. In particular, the study of a quantum spacetime deformation of black hole QNM spectra in various noncommutative models is very intensive one.

The members of the group have a widespread collaboration with many different scientific institutions throughout the world and Europe in particular, including some nodes of the CEEPUS network. Here, cooperation with groups from Beograd, Niš and Wroclaw is underlined.

Physics Department, University of Ioannina, Greece (UIPD)

The High Energy Physics group of the Theory Division of the Physics Department of the University of Ioannina currently comprises five staff members, one post-doc, 10 PhD students, two teaching assistants and four emeritus members.

The research activities of the members of the group cover a broad range of topics. In particular:

-Theoretical Physics of Elementary Particles constitutes the main scientific interest of a large number of members. More specifically, the modern Gauge Theories, Supersymmetry, Superstring Theories and the Unification of Fundamental Interactions between the elementary particles are among the topics studied. The phenomenological investigation of models that follow from these theories leads to predictions that may be compared to experimental data.
-cosmological consequences of the particle physics models, as well as the Cosmology itself, also constitute an important research topic of the group (Black Holes, Inflationary Universe etc.)

Members of the group developed an important number of international collaborations, participate in EU funded research projects and organized in Ioannina a number of international conferences in the field, including "Planck 2015", "StringPheno 2016" and "SUSY 2021". Recently,
members of the group have also organized the SEENET-MTP Balkan School on High Energy and Particle Physics: Theory and Phenomenology (BS2019). Currently, the SEENET-MTP Council president is I. Rizos, professor at UIPD.