Brussels, 17 May 2024

COST 043/24

DECISION

Subject: Memorandum of Understanding for the implementation of the COST Action "Bridging high and low energies in search of quantum gravity" (BridgeQG) CA23130

The COST Member Countries will find attached the Memorandum of Understanding for the COST Action Bridging high and low energies in search of quantum gravity approved by the Committee of Senior Officials through written procedure on 17 May 2024.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA23130
BRIDGING HIGH AND LOW ENERGIES IN SEARCH OF QUANTUM GRAVITY (BridgeQG)

The COST Members through the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action, referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any document amending or replacing them.

The main aim and objective of the Action is to investigate the interface between high-energy quantum gravity and quantum aspects of gravity in the low-energy regime, using both theoretical and experimental tools, in order to construct a phenomenologically viable theory of quantum gravity. This will be achieved through the specific objectives detailed in the Technical Annex.

The present MoU enters into force on the date of the approval of the COST Action by the CSO.

OVERVIEW

Summary

Recent advances in both high-energy astrophysics and high-precision table-top experiments are pushing our capability to test nature in regimes where gravity meets quantum physics. Astrophysical observations are now potentially sensitive to tiny residual effects of Planck-scale physics, while table-top experiments are reaching the precision needed to test the interplay between gravity and quantum systems at ultra-low energies. Investigations of these regimes, in particular once they are combined, will provide important clues towards the understanding of the full-fledged theory of quantum gravity.

The main aim of the Action is to bring together scientists with a variety of complementary expertise: theorists working on quantum gravity or the interplay between gravity and quantum physics with quantum information and quantum optics tools, and experimentalists involved in astrophysical searches for quantum gravity, or investigating the effects of gravitational interactions on quantum systems. The resulting interdisciplinary collaboration will develop a common language and a shared framework which will boost investigations at the interface between high-energy quantum gravity and quantum aspects of gravity in the weak-field regime. The Action will also facilitate cross-disciplinary training and exposure of young scientists to different communities with a common goal, serving as a career accelerator. The synergy within this newly-formed community will be essential to systematically search for quantum gravity on all scales, and possibly find the first signatures of new physics.

The topics covered by BridgeQG are particularly suited for outreach. The Action will promote interest in fundamental physics among the general public and in particular school pupils.

Areas of Expertise Relevant for the Action	Keywords
● Physical Sciences: Quantum physics ● Physical Sciences: Fundamental interactions and fields (theory) ● Physical Sciences: Ultra-cold atoms and molecules ● Physical Sciences: Relativity ● Physical Sciences: High energy and particles astronomy, X-rays, cosmic rays, gamma rays, neutrinos	● Phenomenology of quantum gravity ● Gravity in quantum systems ● Multi-messenger astrophysics ● Lorentz invariance violation and deformation ● Table-top gravity measurements

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

● To initiate a long-lasting exchange between scientists searching for QG on the highest and lowest energy scales, achieved by setting up Training Schools and STSMs dedicated to YRIs, providing young scientists with the interdisciplinary expertise needed to approach the scientific questions posed by searches for QG on all scales.

● To develop a common understanding of the theoretical challenges posed by the development of a theory encompassing gravitational and quantum effects into a unified framework, at low and high energies. This will be facilitated by Action meetings, STSMs, the creation of a vademecum and the writing of a “living review”.

● To systematically place experimental results coming from high-energy astrophysical observations and

high-precision low-energy table-top experiments into a unified parameter space. Annual Action meetings, STSMs and the writing of the living review will be instrumental to this objective.
● To explore the possibility of detecting direct or indirect quantum-gravity signatures by combining results from low-energy table-top experiments and from high-energy astrophysical observations, or by devising new experiments which combine the technological know-how of the two experimental communities.
● To disseminate new research results to the general public and stakeholders. This will raise the awareness in the public and policy makers about the impact of this research area on the development of fundamental science. A special effort will be devoted to communicating with companies and start-ups in COST ITCs.

Capacity Building
● To promote the exchange of expertise across the different communities involved and build a joint research agenda aimed at understanding the interplay between gravitational and quantum physics.
● To develop a multi-disciplinary approach to the challenge and bridge the separate communities that are currently working on different aspects of QG and gravitational interactions in quantum systems.
● To strengthen the newly-formed community investigating QG on all scales by supporting and providing opportunities for recognition and visibility to YRI, to researchers from ITC and researchers from the underrepresented gender in the field.
● To promote Diversity, Equity and Inclusion (DEI) principles in the community by creating and sharing a code of conduct for Action participants, to be followed during opportunities for interaction, and devoting specific time slots during conferences and Training Schools to discuss career development in relation to DEI.

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

TECHNICAL ANNEX

1. S&T EXCELLENCE

1.1. SOUNDNESS OF THE CHALLENGE

1.1.1. DESCRIPTION OF THE STATE OF THE ART

One of the main fundamental open problems in physics is the **unification of quantum theory and general relativity**. Its solution is expected to require a refoundation of basic notions such as spacetime, particles and fields, and, presumably, a modification of the basic principles of quantum mechanics.

For several decades, this research program has followed mainly a theoretical path, resulting in a number of candidates for a theory of quantum gravity (QG). However, so far there is neither any experimental clue nor a generally accepted theoretical argument that would help selecting a preferred approach. Indeed, QG effects are expected to become relevant for probes testing extremely small distances (of the order of the Planck length, ~10^{-35} m) or high-energies (of the order of the Planck energy, ~10^{19} GeV), where the combined limitations of quantum mechanics and general relativity have severe implications [Rovelli2004, Kiefer2012]. Historically, qualitative arguments like this motivated the belief that tests of QG are hopelessly beyond the reach of experiments, both in the short and long term.

This situation has changed drastically in the last decades. Since the beginning of the century, the prospect of a **phenomenology of QG** has gradually emerged as a **realistic possibility**.

Astroparticle physics is now recognized as an ideal ground to test effective QG models. For example, this works particularly well for those classes of theories that can be described within the frameworks of Lorentz Invariance Violation (LIV) [Colladay1998, Mattingly2005, Liberati2009] and Deformed Special Relativity (DSR) [Amelino-Camelia2002, Kowalski-Glikman2002, Magueijo2002, Amelino-Camelia2013], that introduce modifications to special relativity driven by the high-energy QG scale. Even though these are tiny at energies lower than the Planck scale, the effects on the propagation of very high-energy particles over cosmological distances accumulate, producing signatures observable with current or near-future experiments. Moreover, threshold reactions involving astrophysical particles could be modified, affecting the detected fluxes. Searches for QG effects in astrophysical signals constitute nowadays an established field of basic research that involves theoretical and experimental physicists. The **continuously increasing quantity of experimental data** that has been available in recent times has given a large boost to the field; LIV models are now very strongly constrained by modified threshold studies [Jacobson2003, Albert2020, Addazi2022], while DSR models, having much milder impact on modified threshold reactions, are still a viable phenomenological possibility.

On the opposite side of the energy spectrum with respect to (ultra-)high-energy astrophysical observations, **gravitational quantum physics** is now opening a new frontier to test quantum effects in gravity at **completely different scales** and with **very different methodologies** with respect to standard approaches to QG. Thanks to the technological improvements of high-precision table-top measurements, frontier experiments in quantum physics are now advancing fast in **understanding the role of gravity in quantum systems** and testing the possibility that gravity itself is quantized. One can conceive and develop low-energy experiments whose outcome might determine whether gravity is a classical field [DeWitt2011, Bose2017, Marletto2017, Lami2023] or that show how classical and quantum gravity intertwine with quantum mechanical systems [Lämmerzahl1996, Zych2011, Anastopoulos2013, Blencowe2013, Kafri2014, Bassi2017, Anastopoulos2018, Tino2020].

As discussed in the following paragraphs, investigations of these two extreme regimes will provide important complementary clues towards the understanding of the full-fledged theory of QG, in particular once they are combined. However, at the moment they are being investigated by disconnected communities of physicists. The **cooperation** of the high-energy astrophysics and low-energy quantum systems communities of both theoretical and experimental physicists will be **essential to obtain an overall picture of the phenomenological signatures of QG**, and help solving several currently open questions in the field.

One of the main questions in low-energy quantum physics research concerns identifying which observations would constitute a **compelling proof of the quantum nature of gravity,** and more generally **which quantum aspects of gravity could be tested with future table-top experiments**. Experimentalists working on table-top setups are striving to increase the mass of systems that can be kept in a quantum superposition of states for a time long enough to measure the gravitational field of a quantum source [Aspelmeyer2022]. For instance, this could be realised by detecting whether two masses can become **entangled via gravitational interaction** [DeWitt2011, Bose2017, Marletto2017]. This also entails improving the techniques to measure the **gravitational field of very light objects** [Westphal2021]. Currently, experiments are limited by decoherence resulting from technical noise, and efforts are aimed at reducing the noise from different sources. Theoretical efforts instead aim at understanding the implications of such low-energy experiments for the quantum nature of gravity. Any result in this respect will have profound implications for theoretical research on the high-energy regime of QG as well. It will contribute to answering the **question of whether and on what length scales gravity and matter are coupled**, and which degrees of freedom are dominant at the Planck scale. Besides the ones known from general relativity and the standard model of particle physics, there could emerge additional geometric degrees of freedom coming from an extended spacetime geometry, topology, or dimensionality, as well as degrees of freedom from additional matter fields [Loll2022].

Closely linked to the identification of the dynamical degrees of freedom to be accounted for in the development of a theory of QG is the question of which symmetries are present in a given formulation of QG. On this note, experimental efforts in the high-energy astrophysical community are currently aimed at **testing the spacetime symmetries and discrete symmetries** governing the behaviour of very high energy particles. In recent years the **Planck-scale benchmark** was reached for several observables, allowing to set preliminary constraints on effective models of QG-matter interplay [Ackermann2009, Vasileiou2013, Acciari2020m, Addazi2022, Abbasi2022]. Efforts of the astrophysics community in this respect are currently aimed at developing more accurate models for the production and propagation of astrophysical messengers (photons, neutrinos, cosmic rays), and developing techniques for data analysis to produce robust constraints on Planck-scale physics, accounting for the uncertainties inherently associated with astrophysical modelling [Perennes2020]. On the QG-theoretical level, the focus is on the identification of phenomenological consequences of different models and frameworks of QG. These results would be of **great interest also for the low-energy community**, since QG effects can violate the separation of scales that is implicitly assumed in effective field theory. Prototypical examples in which one loses an expected separation of scales are found in quantum-gravity models with **"infrared/ultraviolet mixing"**, a mechanism such that nontrivial effects can percolate to the infrared regime even if the new physics is introduced through a purely ultraviolet scale, and an emergent infrared scale appears [Minwalla1999, Craig2019]. In this respect, the possibility of constraining deformations of relativistic symmetries using **atomic interferometry** and other high-sensitivity low- energy experiments was demonstrated [Amelino-Camelia2009b, Arzano2010, Mercati2010].

The **role of observers and reference frames in QG and quantum physics** is another question that concerns both the low-energy and high-energy communities. The so-far disconnected investigations of this issue could profit greatly from convergence of efforts. Recent findings in studies of some QG models have exposed a nontrivial role of observers in the interpretation of astrophysical observations. Inferences on far-away sources based on astrophysical data collected on earth might be affected by nontrivial symmetry properties of spacetime at the Planck scale. The resulting effects range from an apparent fuzziness of otherwise point-like sources to apparent loss of locality for events produced in highly boosted sources, such as gamma-ray bursts, or even incorrect identification of the origin of high-energy signals due to anomalous effects in the direction transverse to propagation [Christiansen2006, Amelino-Camelia2012, Amelino-Camelia2013b]. Theoretical efforts currently aim at the formalisation of the properties of quantum observers in quantum spacetime, for example describing them in the context of quantum groups of relativistic symmetries [Amelino-Camelia2009, Lizzi2019, Lizzi2022]. Parallel to these investigations, theoretical research in quantum physics has raised the possibility that reference frames should be associated with quantum systems, thus defining quantum reference frames [Bartlett2007, Giacomini2019]. The group properties of the transformations linking these observers are currently under study [Hamette2020, Ballesteros2021]. Preliminary investigations suggest that such quantum reference frames might describe a low-energy counterpart of the high-energy quantum observers, once the appropriate limiting procedure has been identified. A joint effort of the high-energy and low-energy communities is needed to clarify this issue.

Finally, the same experiments that could test quantum aspects of gravity in the weak-field regime could also test **QG-motivated scenarios that percolate to the low-energy regime**. For instance, a possibility that is receiving increasing attention is that matter might undergo **decoherence** due to the omnipresent (quantum) gravitational environment. Theoretical studies are investigating how different decoherence processes are linked to different gravity-matter interaction models, and how to distinguish decoherence effects induced by quantum and classical gravity [Anastopoulos2013, Blencowe2013, Kafri2014, Bassi2017, Oppenheim2018, Arzano2023]. On the experimental side, gravitational decoherence can be tested using both table-top experiments [Donadi2021, Vinante2016, Vinante2020, Schrinski23, Fadel23] and astrophysical observations, where decoherence is expected to induce anomalies in the neutrino flavour oscillation pattern [Lisi2000, Mavromatos2004, Barenboim2004, Mavromatos2007, Aartsen2018, Abbasi2022]. Moreover, several QG approaches predict that the implementation of a fundamental preferred length scale in a mesoscopic quantum field theory appears in a Lorentz invariant form, for example by turning the Box operator of the Klein-Gordon equation into a function thereof [Eliezer1989, Koshelev2012, Aslanbeigi2014]. The non-relativistic limit of such models induces **modifications of the Schrödinger equation**, which can be tested, e.g., within high-precision opto-mechanical experiments [Belenchia2015, Belenchia2016].

1.1.2. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

The beginning of the exploration of QG effects anticipated at both the high-energy and low-energy ends of the energy spectrum have opened a promising new field of research in recent years. These effects manifest themselves in the physics of particles at extremely high energies, as well as in the behaviour of quantum systems intertwined with gravity. However, connecting these distinct physical regimes presents a formidable challenge due to the stark contrasts in physics, scales, and instrumentation involved. Each community of physicists embarking on these pursuits possesses unique expertise, poses distinct questions, and employs diverse terminologies.

While high-energy and low-energy phenomena often require vastly different theoretical and experimental tools for their exploration, they nevertheless offer complementary and sometimes interlacing insights. Such a fruitful symbiosis has been the staple of searches for physics beyond the standard model: from a particle physics perspective on the one hand, and at the high-precision frontier with acoustic, molecular and optical (AMO) systems on the other hand. The Action aims for a similar complementarity between the two regimes for the study of QG as well.

The main aim of BridgeQG is **to bring together scientists with a variety of complementary expertise with the goal of investigating the interface between high-energy QG and quantum aspects of gravity in the low-energy regime,** using both theoretical and experimental tools. This network will serve as a **unique platform** where both theoretical and experimental physicists working on models of QG, QG phenomenology, astroparticle physics, gravitational effects on quantum mechanical systems, quantum optics, foundations of quantum mechanics and quantum information will come together and combine their efforts to construct a phenomenologically viable theory of QG.

The Action will approach the challenge from multiple sides. In particular, BridgeQG will:

- **Identify the fundamental questions that are of critical relevance for both the high and low energy regimes of QG, and create a common language and a common framework to address them from both sides**. This will stimulate the creation of a synergic approach to build a consistent picture of QG on all scales. As an example, both in QG and gravitational quantum physics the characterisation of quantum observer and reference frames has recently been recognized as key in allowing further progress. However, how to integrate such notions in the current framework is being discussed using very different languages and assumptions within the different communities. Therefore, the relation between the quantum reference frames description developed in the context of quantum mechanics, and the quantum observers that emerge in research on the quantum structure of spacetime is unclear. A series of workshops, "Quantum Observers", which recently had its third edition, has started a communication channel between these communities. The Action will build on these first contacts to move towards a full understanding of quantum observers on all relevant regimes.

- **Develop an all-encompassing framework to interpret experimental information coming from high-energy astrophysical observations and high-precision table-top experiments**. These different experiments aim to answer complementary questions concerning QG and the interaction between gravity and quantum systems. Understanding how different pieces of information from different regimes are related to the unknown overall picture, and developing a unified framework to interpret experimental results will allow the community to make progress towards a consistent picture. For example, measurements of gravitational decoherence are being performed using both table-top experiments and astrophysical neutrino observations. Each of these experiments is especially sensitive to different decoherence models, depending on the energy, time, or mass scales involved. Describing experimental outcomes within a unified framework and parameter space will allow us to fully characterise gravitational decoherence.

- **Encourage dedicated investigations on the interplay between the high-energy and low-energy regimes of QG.** On the one hand, this entails deriving the non-relativistic/low-energy limit of phenomenological QG models that are currently being tested with astrophysical observations and identifying possible signatures available to table-top experiments. On the other hand, the possibility that no separation of scales is possible will be accounted for, including scenarios of infrared/ultraviolet (IR/UV) mixing. IR/UV mixing plays an important role in the structure of noncommutative quantum field theory (QFT): its proper handling in a toy model led to the discovery of the first example of a QFT that is well-defined at all energy scales [Grosse2003]. Beyond ad-hoc models, some form of IR/UV mixing seems to be a model-independent feature of QG [Cohen1999]. From the perspective of QG phenomenology, exploring its consequences represents a valuable and underexplored opportunity. Finally, another aspect where joint investigations would be beneficial concerns tests of the quantum nature of gravity. This is being investigated within the quantum physics theoretical and experimental communities [Aspelmeyer2022, Quach2015, Marletto2017, Bose2017, Norte2018] with analyses on gravitational entanglement, gravitational time dilation, quantum versions of the Equivalence Principle, gravitational Casimir effect and more. These investigations ultimately concern conceptual questions that also arise in fundamental approaches to QG dealing with the nature and dynamics of spacetime at the Planck scale.

1.2. PROGRESS BEYOND THE STATE OF THE ART

1.2.1. APPROACH TO THE CHALLENGE AND PROGRESS BEYOND THE STATE OF THE ART

As argued above, **theoretical and experimental developments of the last decade** put the scientific communities involved in an **optimal position to address questions concerning the fundamental nature of gravity and its interaction with quantum systems**. Bringing these communities together will allow for a dedicated synergic effort, **placing Europe at the forefront of this research field**, with far-reaching consequences for scientific and technological developments that cannot be overestimated.

Addressing the following questions is **key in advancing in the area**:

- Is gravity quantized, and what constitutes a quantum signature of gravity?
- Which observations cannot be explained using a classical theory of gravity, and which quantum aspects of gravity can we hope to test?
- Is there a separation of scales in gravitational interactions, or shall we expect ultraviolet effects to percolate to low energies?
- How does gravity (both classical and quantum) affect the dynamics of quantum systems?

To address these questions, the communities of QG theorists, quantum information and quantum optics theorists working at the interface between gravity and quantum theory, experimentalists involved in astrophysical searches for QG, and experimentalists investigating the effects of gravity on quantum systems must work together. Over **the next few years the efforts should be devoted to**:

- **Developing experimental setups** that can test the quantum nature of gravity, and devising theoretical frameworks to interpret the possible outcomes;
- **Investigating the interplay between high-energy and low-energy QG effects**, with a special focus on infrared/ultraviolet mixing;
- **Developing a unified framework to assess experimental results** in both the high-energy and low-energy regimes;
- **Understanding the relation between the quantum reference frames** description studied in the context of quantum mechanics **and the quantum observers** that emerge in research on the quantum structure of spacetime.

BridgeQG will create an **interdisciplinary network** that can effectively tackle this program. Its **innovative approach** relies on a number of factors.

First, the general questions exposed above are currently being investigated independently within separate communities that rarely have the opportunity to interact and discuss questions that are common to the different fields. Several networks exist in Europe or internationally that aim to address only some aspects of the overall challenge: the QISS (Quantum Information Structure of Spacetime) consortium and the ISRQI (International Society for Relativistic Quantum Information) network take a quantum information approach to the interplay between gravity, relativity and quantum systems; the ISQG (International Society for Quantum Gravity) network and the network stemming from the former QSPACE (Quantum Structure of Spacetime) COST Action focus on theoretical investigations of QG from a high-energy perspective; the network stemming from the former QGMM (Quantum Gravity Phenomenology in the Multi-Messenger Approach) COST Action focuses on the high-energy phenomenology of QG. **The innovative approach of BridgeQG relies on establishing contacts and collaborations between members of all the relevant communities.** This will be facilitated by monthly online seminars, Annual Conferences, Training Schools and Short Term Scientific Missions (STSMs).

Second, **BridgeQG advocates for a holistic approach to the scientific questions it aims to answer, encompassing all-scale theoretical and experimental investigations which will inform the overall development.** For example, experimental results on gravitational decoherence motivated by high-energy QG models can be used to constrain the interaction of quantum systems with gravity. The understanding of quantum observers/reference frames will provide a framework to interpret the constraints on propagation anomalies derived from observations of high-energy astrophysics signals. Table-top experimental results on quantum aspects of gravity will enable us to address conceptual questions that arise in fundamental approaches to QG, e.g., how quantum clocks -- and hence time -- behave in a nonclassical gravitational field. These results can then be used as benchmarks for constructing a full theory of QG. **This approach is innovative since so far investigations on the low-energy and high-energy regimes of (quantum) gravity have been disconnected.**

Third, **BridgeQG will provide an excellent environment for training a new generation of young researchers** and provide them with a new **transversal scientific profile** combining the skills of different fields: high-energy QG and its phenomenology, quantum information and quantum optics, experimental aspects of astrophysical searches for QG, experimental aspects of investigations of the interplay between gravity and quantum systems. They will become familiar with theoretical tools and experimental techniques, and will be able to follow progress in the different relevant subareas. This is an innovative strategy because **such a scientific profile does not exist yet**. It will be of the greatest importance to have this type of experts in Europe to lead the future development of QG research and related quantum technologies.

1.2.2. OBJECTIVES

1.2.2.1. Research Coordination Objectives

BridgeQG will coordinate the efforts of strong communities that work on different aspects and regimes of the interplay between gravity and quantum theory and on the possible quantum nature of gravity, using an array of theoretical and experimental techniques. The synergic combination of the tools used by these communities will facilitate progress in understanding these fundamental aspects of nature and will bring Europe at the forefront of the field. Specific objectives of the Action are the following.

1. **To initiate a long-lasting exchange between scientists searching for QG on the highest and lowest energy scales.** This will be achieved by setting up Training Schools and STSMs dedicated to Young Researchers and Innovators (YRI), providing young scientists with the interdisciplinary expertise needed to approach the scientific questions posed by searches for QG on all scales.
2. **To develop a common language and understanding of the theoretical challenges posed by the development of a theory encompassing gravitational and quantum effects into a unified framework, at low and high energy scales.** This will be facilitated by annual Action meetings, STSMs, the creation of online resources with a **vademecum** about relevant concepts developed within the different approaches and the writing of a "**living review**", which will initially report the status of the research at the interface between QG at high energy and gravitational quantum physics and later will be updated with the results stemming from the Action. It will include complementary approaches to theoretical questions and complementary limits on QG effects from the low-energy and high-energy sides.
3. **To systematically place experimental results coming from high-energy astrophysical observations and high-precision low-energy table-top experiments into a unified parameter space.** This will provide an all-encompassing picture of the experimental status of searches for QG and the interplay between gravity and quantum systems. It will eventually lead to developing combined search strategies for QG effects on highest-energy astrophysical and cosmic scales and highest-precision local quantum system scales. Annual Action meetings,

STSMs and the writing of the living review will be instrumental to this objective.

4. **To explore the possibility of detecting direct or indirect quantum-gravity signatures by combining results from low-energy table-top experiments and from high-energy astrophysical observations, or by devising new experiments which combine the technological know-how of the two experimental communities.** This will include precision spectroscopy, atomic clocks, matter-wave interferometers, mechanical oscillators in the quantum regime (i.e., opto- and electro-mechanics, levitated particles) on the low energy side, and very-high energy gamma rays, cosmic rays and astrophysical neutrino observations on the high-energy side.
5. **To disseminate new research results and insights to the general public and to stakeholders.** This will raise the awareness in the public and policy makers about the impact of this research area on the development of fundamental science, with the goal of diverting additional attention on the field. Moreover, it will increase the chances of **technological developments with possible applications in quantum communication and metrology**. A special effort will be devoted to communicating with companies and start-ups in COST Inclusiveness Target Countries (ITCs) to boost their scientific and technological development.

1.2.2.2. Capacity-building Objectives

The following objectives aim at creating a **critical mass of researchers with complementary skills**, suitable to develop the field of QG and gravitational quantum physics in a synergic approach between high and low energy scales. These objectives will have a **lasting impact even after the end of the funding period**, influencing the development of the field in the long run.

1. **To promote the exchange of expertise across the different communities involved and build a joint research agenda aimed at understanding the interplay between gravitational and quantum physics**. This will be achieved by providing tools and environments to foster discussions and the development of new collaborations, such as in-person and online meetings and by stimulating collaboration and exchange of ideas during the writing of the living review and the preparation of the online vademecum document.

2. **To develop a multi-disciplinary approach to the challenge and bridge the separate communities that are currently working on different aspects of QG and gravitational interactions in quantum systems.** The Action will provide tools for mobility and scientific collaboration between members of different Working Groups (WGs). In particular, STSMs grants will be assigned with priority to proposals involving members of different WGs.

3. **To strengthen the newly-formed community investigating QG on all scales by supporting and providing opportunities for recognition and visibility to YRI, to researchers from ITC and researchers from the underrepresented gender in the field**. For instance, the Action will encourage their assignment in leadership positions as e.g. WG leaders or others.

4. **To promote Diversity, Equity and Inclusion (DEI) principles in the community** by creating and sharing a code of conduct for Action participants, to be followed during opportunities for interaction, and devoting specific time slots during conferences and Training Schools to discuss career development in relation to DEI.

2. NETWORKING EXCELLENCE

2.1. ADDED VALUE OF NETWORKING IN S&T EXCELLENCE

2.1.1. ADDED VALUE IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

BridgeQG will provide the crucial connection between the theoretical and observational searches for QG at high-energy scales, relevant for cosmic/astrophysical tests, and low-energy scales, relevant for table-top quantum systems. **Currently, such a network** that is dedicated to bridge these efforts and enables the researchers to merge their findings into an all-scale picture about QG **is missing and thus significant progress and breakthroughs are hindered**.

Existing or past networks focussed on aspects of QG on either the cosmic or the laboratory scale only. The recently established International Society for Quantum Gravity (ISGQ) includes researchers working towards a self-consistent fundamental theory of QG, while the Quantum Information Structure of Spacetime (QISS) and the International Society for Relativistic Quantum Information (ISRQI) initiatives focus on the relation between fundamental concepts in gravity and quantum information theory. Past COST Actions like "Quantum gravity phenomenology in the multi-messenger approach" (QGMM, ended 2023) or Quantum structure of spacetime (QSPACE, ended 2019) focussed on cosmic scales searches and specific theoretical approaches like non-commutative geometry, respectively. The European Consortium for Astroparticle Theory (EuCAPT) includes a limited number of members whose research includes astrophysical searches for QG.

BridgeQG will be the platform for researchers of the different networks and communities to exchange ideas, develop a common language, and combine their results to forge a coherent all-scales picture of the state of the art about QG. This consolidation of knowledge will allow the formulation of an improved theoretical framework and search strategy for QG at all scales.

2.2. ADDED VALUE OF NETWORKING IN IMPACT

2.2.1. SECURING THE CRITICAL MASS, EXPERTISE AND GEOGRAPHICAL BALANCE WITHIN THE COST MEMBERS AND BEYOND

The network of proposers represents all the scientific areas that the Action challenge requires: high-precision laboratory experiments; measuring the properties of quantum systems interacting with gravity; observation and data analysis of astrophysical messengers with large telescope and observatory collaborations; fundamental and phenomenological aspects of QG; the interaction between (quantum) gravity and quantum systems and quantum information. The network includes some of the **leading experts in the mentioned fields**, as well as a considerable number of **YRI who have already given substantial contributions** to themes that are relevant for the Action challenge. Given that these areas of research are currently disconnected and pursued by different groups scattered in several countries and institutions, it is important that the relevant competences are all represented already at the proposal stage, ensuring that an all-scale overview over the classical and quantum properties of gravity and its interaction with quantum systems is available. Once the Action starts, the expertise of this group of researchers will enable them to identify the most promising observables and the most promising technology to detect QG effects. To gain further experience on newly developed quantum technologies, a connection to the projects within the European Quantum Technologies Flagship shall be established and participants in these projects will be invited to join the Action.

The network of proposers consists of 105 members from 26 Cost Member Countries (of which 14 are ITC, more than 50%), as well as 2 International Partner Countries (Canada and United States). Moreover, the group of proposers includes almost 28% female researchers, which is a significantly better balance than the current average in Physics, which is less than 20% [Holman2018], and includes almost 45% YRI. Therefore, **already from the start BridgeQG achieves a good balance of all the groups that are usually underrepresented**, and this will allow the Action to ensure that members of these groups have **prominent roles** in the leading positions and in contributing to the Action activities. During the Action lifetime, an effort will be made to maintain and possibly improve the diversity currently characterising the network of proposers, concerning age, gender, and geographical distributions.

2.2.2. INVOLVEMENT OF STAKEHOLDERS

Main stakeholders of the Action are the scientists working on the search for QG at different scales, on the experimental/observational and theoretical sides. They are organised in a large number of **universities, institutes and collaborations**, which **will benefit from this new network as hosts or initiators of BridgeQG activities**. Institutions like universities and research centres will be the hosts of the Annual Conference and Training Schools. Particular attention will be paid that **at least 50% of these activities will take place in ITCs** to support the local scientific community and to increase their visibility.

YRIs, especially those from ITCs, will be supported by STSMs and ITC conference grants to enable them to forge their network and research collaborations. Moreover, YRIs will be embedded in the network in **leading positions**, such as Working Group and committee leaders, and be invited to present their research results to a large audience in the online monthly seminars and Annual Conferences. This will increase their **visibility within the scientific community**, therefore boosting their opportunities for **career development**. Finally, through Training Schools and STSMs, YRIs will acquire a multidisciplinary background also suitable for their career development outside the academia, for example within companies involved in the development of quantum technologies.

Existing **European and international networks** such as ISGQ, QISS and EuCAPT will be contacted to establish a close connection and exchange between the BridgeQG network and these teams. Whenever possible, dedicated joint sessions at the Annual Conferences and joint online seminars will be organised. **Experimental collaborations** working on high-energy astrophysics, such as H.E.S.S., LST, MAGIC, VERITAS, HAWC, LHAASO, IceCube, Auger will be involved. Despite recent advancements in astrophysical searches for effects of QG [see, e.g., Abdalla2019, Acciari2020, Cao2022], these studies are still mostly regarded as side projects in astrophysical experiments, and observatories are developed and optimised for purely astrophysical studies. Defining the characteristics of an instrument optimised for searches of QG effects with astrophysical observations would considerably advance the field of QG phenomenology. Contacts will be established with the relevant experimental communities to explore this possibility, by inviting representatives to the Annual Conferences and to online discussions.

The European Union is compromised to invest one billion euro on a 10-year timescale into research on quantum technologies and its applications through the **European Quantum Technologies Flagship**, with focus on quantum computing, quantum simulation, quantum communication, quantum metrology and sensing, as well as on basic science addressing foundational challenges for the development of quantum technologies. The potential reach of this effort will be enhanced by BridgeQG in two ways. On the one hand, BridgeQG will point out quantum technologies which are particularly well suited to identify and enhance QG effects [Lu2022, Rideout2012, Xu2019]. With this, the technological development of the European Quantum Technologies Flagship will be supplemented by applications in fundamental physics research. On the other hand, scientific developments fostered by BridgeQG might lead to the development of new technologies relevant to the European Quantum Technologies Flagship. These possibilities will be explored by contacting research groups involved in the European Quantum Technologies Flagship. Dedicated discussion sessions will be organised within the online monthly seminar series and representatives of these groups will be invited to the Annual Conferences.

Another stakeholder is the **general public**, who will be invited to interact with the BridgeQG network in an array of dissemination events. Besides the evening **outreach talk** that will be part of every Annual Conference, an **online interface** to reach the BridgeQG researchers will be set up, where questions can be submitted. In regular intervals, short texts or video clips will be published to answer these questions. Moreover, dedicated **events for pupils at schools** will be organised, such as online seminars of BridgeQG researchers to inspire young pupils for the research on fundamental physics. In all dissemination events, particular attention will be devoted to **providing a diverse representation of scientists**, ensuring that YRIs, researchers from ITCs, and researchers from the underrepresented gender are involved.

Finally, BridgeQG will reach out to **start-ups and private companies working on quantum communication and metrology**. Representatives of these companies will be invited to join the network and to present their activities during the Annual Conferences and in the regular online seminars.

3. IMPACT

3.1. IMPACT TO SCIENCE, SOCIETY AND COMPETITIVENESS, AND POTENTIAL FOR INNOVATION/BREAKTHROUGHS

3.1.1. SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS (INCLUDING POTENTIAL INNOVATIONS AND/OR BREAKTHROUGHS)

A complete **understanding of QG** would have a revolutionary impact on our understanding of nature, with **far reaching consequences on science, technology and society**. While reaching a satisfactory formulation of the theory will likely require a timescale much longer than the lifetime of the Action, **BridgeQG will give a considerable contribution in that endeavour**.

The theoretical advancements expected within BridgeQG and the toolbox developed in the context of table-top experiments will have a considerable **impact on near-future technologies**. Specifically, the high-precision and quantum-enhanced measurement devices and protocols that are going to be developed for the detection of gravitational effects and physics beyond standard quantum mechanics will have a broad range of applications. Examples include **sensors for electromagnetic fields, forces, and time** (clocks), including those being deployed within **small satellites designed for quantum**

communications, which are of primary interest for the industry. Moreover, advances in the theory and characterization of quantum reference frames and of all kinds of quantum spacetime descriptions dealing with the superposition of trajectories will contribute to the field of **quantum communications**. In fact, quantum communication between two parties without a shared reference frame or with bounded reference frames requires developing targeted techniques using some sort of quantum reference frames [Bartlett2009, D'Ambrosio2012]. Techniques to remove noise induced by entanglement with the quantum reference frame will benefit the **core application areas of the European Quantum Technologies Flagship**.

On the short term (during the lifetime of the Action), BridgeQG will:

- Create **strong connections between physicists with complementary skills and expertise**, investigating quantum aspects of gravity in the astroparticle domain, and in the high-precision quantum systems table-top experiments;
- Facilitate the **communication and exchange of ideas between different working groups** of the Action by composing a vademecum containing an exhaustive glossary of terms used by researchers in different fields;
- **Advance each of the involved research fields individually** by importing knowledge, experience and techniques from the other fields, both at the theoretical and experimental level;
- Train a **new generation of researchers** capable of investigating QG in all regimes;
- Through the outreach programs, **push forward the ideas of diversity, equality, and inclusiveness**, aiming at gender balance, enabling YRIs, and broadening geographical inclusiveness;
- Through the outreach and dissemination programs, **promote to the general public the importance of fundamental research**, and inform the decisions of policy makers.
- **Establish a new forum for the discussion of fundamental concepts** like the separation of scales, reductionism, the quantum/classical regimes, background notions like reference frames etc. by communities that never confronted each other on these topics.

On the long term (after the end of the Action), BridgeQG will:

- **Establish a new multidisciplinary community** of researchers directing their joint efforts towards the discovery of QG;
- **Develop high-precision and quantum-enhanced measurement techniques** that will have a direct impact on technology and industry;
- **Influence the design and requirements on future experiments** both in astroparticle physics and in high-precision measurements;
- **Contribute substantially to the formulation of a full-fledged theory of QG.** This will arguably be the most impactful result in physics since the discovery of quantum mechanics, influencing profoundly our understanding of the physical world and leading to unpredictable but likely very impactful developments for society.

3.2. MEASURES TO MAXIMISE IMPACT

3.2.1. KNOWLEDGE CREATION, TRANSFER OF KNOWLEDGE AND CAREER DEVELOPMENT

In recent advancements, the high-energy astrophysics and the high-precision quantum systems table-top experiments were identified as promising domains where combined quantum and gravitational effects could be measured. However, these domains are at the opposite ends of the energy spectrum, with the relative communities mostly disconnected. **Through** regular **online seminars** (possibly **monthly), Annual Conferences, and STSMs, the methods and techniques employed in each field will be shared with researchers in other fields.** This regular communication will stimulate the creation of a joint vocabulary, facilitating communication between researchers.

An extensive vademecum containing common concepts from each field thoroughly explained will have important role in the transfer of knowledge between different research fields. **The vademecum will be made publicly available in the Action webpage.** In addition, BridgeQG will publish and maintain **a living review of the status of research at the interface between QG at high energy and gravitational quantum physics**. Its main purpose will be to keep researchers of QG in the high-energy regime up to date with methods, techniques and results of the investigations in the low-energy regime, and vice versa.

In order for the transfer of knowledge to have a long-term impact, a particular attention will be paid to involvement of young researchers. A new generation of researchers versatile in various approaches to theoretical and experimental investigations of QG will be brought up through Training Schools. There, **young scientists will be exposed to the knowledge, methods, and techniques from the fields not directly related to their own topic of research.** This will make young researchers more competitive in the job market. The multidisciplinary background that they will acquire will also boost their career development in case they decide to pursue it in the private industry working, for instance, on quantum communications. Moreover, **they will be given the opportunity to present their work on equal footing as experienced scientists,** giving them visibility within the community.

To accelerate the knowledge transfer to the technological sector, the Action will engage in **discussions with existing companies and start-ups working in the technological fields related to the Action**. For example, company representatives will be invited to participate in the Annual Conferences and in the online seminars.

3.2.2. PLAN FOR DISSEMINATION AND/OR EXPLOITATION AND DIALOGUE WITH THE GENERAL PUBLIC OR POLICY

All the news regarding the Action will be published in a dedicated **webpage and social media profiles**.

The scientific results will be disseminated through **high-level scientific journals** (e.g., Nature, Science, Physical Review Letters, JHEP, JCAP, Phys. Rev. D, A&A, ApJ, Quantum) and **conferences, seminars, and workshops** both organised by BridgeQG and others attended by BridgeQG participants. The support by COST will be acknowledged in all publications resulting from the Action. The journal papers, as well as proceedings, will be published in the preprint server arXiv (https://arxiv.org) making them **publicly and freely available** regardless of the open science policy of the publication journals.

Lectures from the Training Schools will be recorded and made **freely available** in the Action YouTube channel, while the **lecture notes will be published as dedicated editions in the Proceedings of Science, and on arXiv**, with acknowledgement of the COST support.

The Action will have a considerable impact on society by **promoting the role of fundamental research in Europe**. Several activities will bring researchers in close contact with the public. Specifically, the Action will be presented to a larger scientific community and the general public through **profiles in the most popular social media** (Facebook, YouTube, Twitter, Instagram, Telegram), where the news regarding the Action activities and investigations on QG will be published. Every **Annual Conference will be accompanied with an outreach talk** by an Action participant. In order to promote gender balance and young scientists, **precedence will be given to female scientists and YRIs**. Moreover, BridgeQG will set up an **online interface** on its website where the public can submit questions, and in regular intervals short text/video clips will be published to answer these questions. Finally, BridgeQG will organise dedicated **online seminars aimed at school students**.

4. IMPLEMENTATION

4.1. COHERENCE AND EFFECTIVENESS OF THE WORK PLAN

4.1.1. DESCRIPTION OF WORKING GROUPS, TASKS AND ACTIVITIES

The Action will be governed by a Management Committee (MC), chaired by the Action Chairperson, assisted by a Vice-Chair, both elected during the MC inaugural meeting. The MC will coordinate the Action's activities and supervise the use of the COST funds to ensure the achievement of the final objectives. The MC will also elect other key leadership positions that, together with the Chair and Vice-Chair, will constitute a Core Group (CG) in charge of the operative management of the Action: the six Working Groups (WGs) Leaders and Vice-leaders, a Science Communication Coordinator, and a Grant Awarding Coordinator. The CG will be responsible for the preparation of all documentation required for the MC meetings.

The activities of the COST Action will be organised into **six WGs**. WG1 and WG2 will focus, respectively, on the theoretical development and the experimental tests of QG models and properties at high energies. WG3 and WG4 will focus, respectively, on theoretical development and experimental tests of the gravitational interaction in quantum systems. WG5 will be the central engine of the Action, taking charge of developing the links between high-energy QG and gravitational quantum physics and catalysing joint development. Members of this WG will identify and study the questions that lie at the interface between the two regimes, comparing the different approaches that the communities of high- energy QG and gravitational quantum physics have so far undertaken and developing inter-disciplinary methods to address them. They will also analyse available experimental results both from astrophysical and table-top experiments to develop comprehensive constraints on specific models and features relevant for all regimes. WG6 will supervise the organisation of the Annual Conferences to join all participants of the Action, as well as the Training Schools for young researchers. Moreover, WG6 will be in charge of organising regular online meetings and gender and outreach activities. A graphical depiction of the interrelations between WGs is provided in Fig. 1.

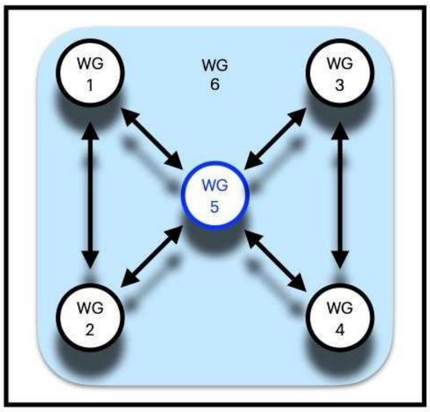


Figure 1: Graphical representation of the different WGs showing their inter-relation. WG6 activities are depicted as encompassing all the other WGs.

WGs description and tasks (WG1-5)

WG1: High-energy quantum gravity theory

This group will gather researchers working on fundamental approaches to QG, on phenomenological models of QG relevant to very high-energy physics, and on the systematic prediction of astrophysical observables from fundamental approaches to QG. This group will directly interact with WG2 in order to perfect the phenomenological models relevant for astrophysical studies. Moreover, interaction between WG1 and WG3 will be facilitated by WG5 to build a common language and understanding to address questions that are common to the two groups. WG1 tasks are:

i) **To further develop frameworks for phenomenological predictions from fundamental approaches to QG.** In particular**,** improve the mathematical self-consistency of models like non-commutative geometry, generalised uncertainty principles, Lorentz invariance violations (LIV), doubly/deformed special relativity (DSR) and relative locality, constructing their rigorous implementation on curved spacetimes, relevant for astrophysical and cosmological applications.
ii) **To surpass the current limitations in the theoretical calculations of decay widths and cross sections in the LIV and DSR frameworks** and highlight the different predictions of both frameworks.
iii) **To clarify the impact of DSR/LIV on the production mechanisms of astrophysical particles**, thus filling gaps in the time-of-flight and interaction analyses that usually only focus on LIV/DSR effects on the propagation of these messengers.
iv) **To develop the implications of quantum observers and reference frames for astrophysical observations** of sources with large boost factors.
v) **To establish and keep connections to other international collaborations working on fundamental aspects of QG**, such as the ISQG.

WG2: High-energy quantum gravity experiment

This group will include researchers performing experimental searches for signatures of QG in multi-messenger astroparticle experiments (ultra-high-energy cosmic ray observatories, gamma ray observatories, neutrino detectors). These experiments mostly test phenomenological models of QG developed by the members of WG1. However, a close collaboration with WG4 will be encouraged in order to create a joint effort relying on the complementarity of approaches and methods of these working groups. The very establishment of such a close collaboration would already be a success of BridgeQG with possible far-reaching consequences. WG2 tasks are:

i) **To establish standards for data analysis in astrophysical searches for effects of QG.** In recent years certain analysis techniques have been identified as optimal for searches of QG effects in astrophysical data [Bolmont2022]. However, there are a number of possible improvements that can be made: the commonly used likelihood method can be improved by removing certain assumptions on the emission from astrophysical sources; new analysis techniques can be proposed, such as the use of machine learning; different simultaneous effects of QG (energy-dependent group velocity, modified interactions) should be merged in a single analysis method and tested as a whole.
ii) **To develop a base for multi-messenger data analysis for searches for signatures of QG.** Multi-messenger detections are extremely rare [Aartsen2018], nevertheless, analysis tools for searches of QG effects utilising multi-messenger observations can be discussed and developed, in order to be implemented on future detections. Furthermore, there are preliminary studies using multi-messenger data that show intriguing results [Amelino-Camelia2023]. These will be discussed, improved, and refined. Vital ingredient of astrophysical tests of QG is proper modelling of astrophysical sources. Unfortunately, their behaviour is rather unpredictable and still poorly understood. Therefore, an important aspect of this task will be maintaining strong collaborations with astrophysicists working on source modelling and introducing realistic models in the QG analysis tools.
iii) **To search for signatures of QG expected in both regimes.** In collaboration with other working groups, in particular with WG4 and WG5, propose and perform tests of QG effects that manifest in both regimes. For example, quantum decoherence investigated in the table-top experiments can also be induced in astrophysical signals (e.g. neutrinos) by quantum properties of spacetime.
iv) **To establish and maintain close contacts with the relevant experimental collaborations**, such as H.E.S.S., LST, MAGIC, VERITAS, HAWC, LHAASO, IceCube, Auger.

WG3: Low-energy gravitational effects in quantum systems

This WG focuses on the investigation of gravitational effects in quantum systems. It addresses theoretical questions on the nature of gravity and observers and identifies how these could be tested in quantum systems. This theoretical discussion connects with the experiments in WG4, and with concepts explored in WG1 and WG5. WG3 tasks are:

i) **To set up and develop a systematic framework to identify how gravity impacts the behaviour of quantum clocks** in experimentally meaningful scenarios (e.g. interferometers with atoms/molecules), accounting for both classical and quantum gravitational effects. This encompasses studies of gravitational time dilation, new limits in the measurability of time induced by gravity (e.g. due to noise or quantum properties of spacetime), modification to the atomic spectrum/frequency of the clocks.
ii) **To classify models of gravitationally-induced decoherence**, both motivated by effective approaches to gravity in the low-energy regime and by fundamental QG approaches, and identify distinctive differences among them which would allow an experiment to distinguish between the models.
iii) **To study alternative protocols to the generation of gravitationally-induced entanglement** between massive bodies whose outcome discriminates between a classical and quantum description of gravity in a table-top experiment.
iv) **To develop a formulation of the concept of quantum reference frames** in a gravitational scenario.
v) **To characterise the group structure of quantum reference frames** and determine whether the resulting group admits a localisation limit. Connect such a localisation limit with the resource theory of quantum reference frames in the quantum information community.

WG4: Low-energy high-precision experiment

This WG4 will be mostly composed by experimentalists working with table-top setups (e.g., cold atoms, mechanical oscillators, levitated particles), and by theorists familiar with these low-energy platforms. WG4 will work in close collaboration with WG3 to identify possible observable gravitational phenomena in quantum systems and to develop frameworks to interpret the experimental results. Moreover, facilitated by WG5, it will communicate with WG2 to devise possible all-scale experiments. WG4 tasks are:

i) **To study the dynamics of quantum systems in a classical gravitational field, and the gravitational field resulting from non-classical mass density distributions.**
ii) **To use massive many-body systems to investigate decoherence and the quantum-to-classical transition**, with a special focus on the role that gravity might play in these processes.
iii) **To use massive quantum systems to investigate the structure of space-time at the Planck scale**, such as through indirect observations of Planck-scale violations of the Heisenberg uncertainty

relation, violations of fundamental symmetries and modifications of the Schrödinger equation.
iv) **To make use of quantum metrology protocols** to enhance the measurement precision for the above-mentioned effects.

v) **To frame the open questions identified with WG3 and WG5 into realistic observables and experiments** that are feasible with state-of-the-art and near-future low-energy table-top setups. Realisation of these experiments, and interpretation of the measured data.
vi) **To strengthen the connection between the QG community and the experimental quantum technology community**.

WG5: Connection between low-energy and high-energy quantum gravity

WG5 will include scientists working at the interface between high-energy QG and gravitational effects in quantum systems, either at theoretical or phenomenological level. It will be responsible for establishing connections between WGs 1-4 and catalysing the development of models for QG on all scales. WG5 tasks are:

i) **To identify and investigate the questions that lie at the interface between the two regimes**, comparing the different approaches that the communities of high-energy QG and gravitational quantum physics have so far undertaken and developing inter-disciplinary methods to address them.
ii) **To analyse available experimental results from astrophysical and table-top experiments**, to establish the best constraints on given models and identify the features that are relevant for all regimes.
iii) **To coordinate between all WGs the writing of a living review** about the state of the art in research at the interface between QG at high energy and gravitational quantum physics. The review will be updated when new results stemming from the Action are available.
iv) **To coordinate between all WGs the preparation of an online document serving as a vademecum**, thoroughly explaining the key concepts from each field, with the goal of clarifying and unifying the languages of the different communities.
v) **To investigate theoretical scenarios with infrared/ultraviolet mixing** and propose new experimental strategies to test them.
vi) **To explore the signatures of LIV and DSR at low energy**, like modifications to relativistic kinematics that become relevant for low-energy or large-mass particles, deformations of Bose/Fermi statistics and violations of selection rules. Identify experimental setups to test those effects, for example, precision measurements of the energy-momentum of low-energy particles and their conservation laws, tests of CPT symmetries, violations of the Pauli exclusion principle.
vii) **To explore the possibility of developing new, dedicated low-energy experimental setups to investigate the properties of quantum reference frames**.

WGs Activities (WG1-5)

i) The main aim of BridgeQG, of joining scientists from different communities and backgrounds, and forming a strong network will mostly be achieved through **Annual Conferences** (to be held in person) and **monthly online seminars** in which ideas, knowledge, experience, and methods will be shared between the involved communities.
ii) The secondary aim of creating a long-lasting community by bringing up a new generation of researchers by holding **Training Schools**.
iii) Tight communication within WGs, and in particular between members of different WGs will be established, maintained and boosted by means of **STSMs**, for which precedence will be given to inter-WG visits.
iv) In addition to these joint activities, **each WG will organise their own in-person workshops and online meetings** to accomplish the tasks of individual WGs.
v) **Each WG will prepare publications and presentations** to communicate their results and toolbox to other WGs for further work towards the Action goals. **Presentations in workshops and conferences external to the Action** will disseminate results to the broader scientific community.
vi) Each WG will contribute to the **communication and outreach activities** organised by WG6 (see below).

WG6: Dissemination and Diversity

In addition to WGs 1-5, which will focus on specific aspects of research towards the Action scientific goals, BridgeQG will contain a WG that will be in charge of **organising the Action networking and dissemination activities and to work towards promoting diversity in the Action**. To this latter aim, for all the events organised (Annual Conferences, Training Schools, online seminars, dissemination activities) **WG6 will ensure that speakers, lecturers and participants are balanced with respect to**

gender, age and geographical distribution. WG6 tasks are:

i) To oversee the organisation of the Annual Conferences.
ii) To oversee the organisation of the Training Schools for young researchers.
iii) To organise regular (possibly monthly) online seminars aimed at the Action members.
iv) To organise the outreach seminar to be held during each Annual Conference.
v) To organise online seminars devoted to school students.
vi) To set up and maintain the Action web page and social media.
vii) To organise initiatives on social media and in dissemination events to make visible the role of underrepresented groups in the Action.
vii) To set up a publicly available page to collect questions from the general public and to produce and publish online short texts/videos answering the most common questions.

4.1.2. DESCRIPTION OF DELIVERABLES AND TIMEFRAME

In the following table is listed the Action deliverables. The month(s) indicated in the first column denote the time within the Action lifetime by which the deliverable will be completed (for repeated events, each indicated month denotes the time by which one of the events will be held).

Month	Deliverable	WG
12,24,36,48	Publication of the recordings/slides of seminars delivered in the Action Annual Conference	WG1-6
24,36,48	Publication of the recordings and notes of the Training School lectures	WG1-6
12,24,36,48	Publication of at least 8 papers per year in high impact, international journals	WG1-5
48	Publication and maintenance of a living review summarising the state of the art in the field. To be updated once the last three deliverables in this table are completed	WG1-5
6	Set up of Action web page and social media	WG6
12,24,36,48	Report on Public outreach event attached to each Action Annual Conference	WG6
24	Publication of an online document (to be maintained) providing a vademecum to clarify and unify language between communities	WG1-5
12, 24,26,48	Publicly available page to collect questions from the general public. Production and publication of short texts/videos answering the questions	WG1-6
12,24,36,48	Report on the annual online outreach event aimed at school students	WG6
48	Publication of the recordings/slides of the online seminars	WG1-6
30	Survey and comparison of different decoherence mechanisms induced by quantum and classical gravity effects	WG1, WG3, WG5
36	Systematic collection of available experimental constraints on QG and gravitational interaction with quantum systems	WG2, WG4
48	Survey on the notions of observers in quantum information and QG, clarifying the notions employed in both approaches and bringing them closer to each other	WG1, WG3, WG5

4.1.3. RISK ANALYSIS AND CONTINGENCY PLANS

In the following the main risks are identified, as well astheir level and a contingency plan is provided.

Ineffective coordination and interaction between the involved communities. The communities involved in BridgeQG are currently disconnected and there is very little overlap among their members. This results in the adoption of very different languages and tools, which might be an obstacle in the interaction and coordination among WGs. To counter this, a dedicated WG (WG5) is set up to stimulate scientific development at the interface of the relevant fields. Moreover, regular online meetings where the same general topic is addressed by at least two talks exposing the approach undertaken by different communities will facilitate the flow of scientific knowledge between the communities. Finally, the writing of the living review and the vademecum will catalyse interaction and collaboration.

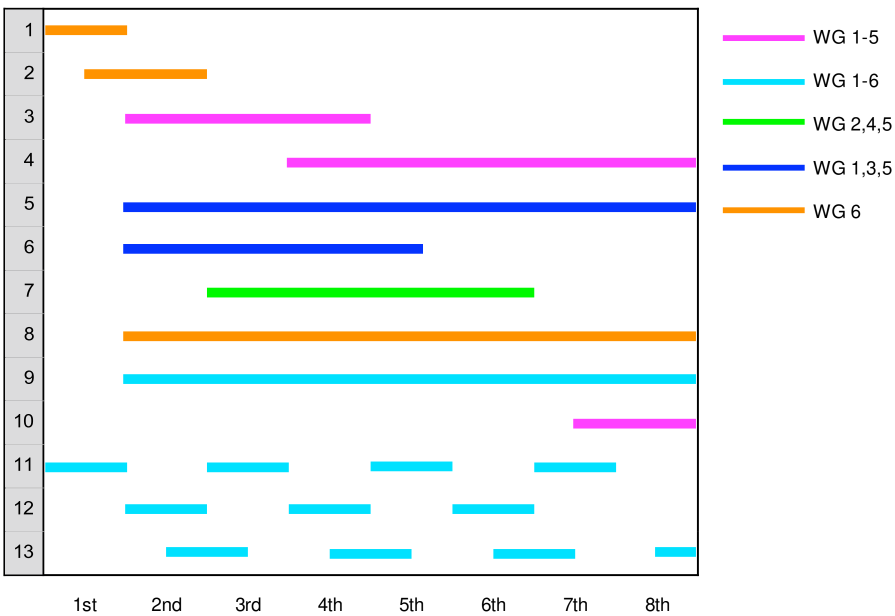
Travel restrictions. The enforcement of new travel restrictions across Europe is not likely. However, even if this were to happen, several online working tools are available, and the Annual Conference and Training Schools can be organised in a hybrid format, using the now widely available technology.

Slow progress on theoretical developments. One might not be able to reach a full understanding for some of the theoretical science objectives, but even just clarifying the difficulties encountered would contribute to the advancement of knowledge. Any progress and difficulty will be reported in the living review, in order to make the knowledge available to a wider community. This will increase the chances that other research groups might get involved and contribute to the field.

Delay in achieving experimental results. The main goal of the Action would not be strongly affected by this. Concerning table-top experiments, several groups across Europe are already working on the development or on improving sensitivity of existing setups. Even if ground-breaking new measurement results might take longer than the duration of the Action, BridgeQG would have set in place the theoretical tools to interpret them once available and will design experimental setups optimised for (quantum) gravity searches. Concerning astrophysical experiments, the observatories are taking data which can potentially be used for QG studies. In addition, upgraded or new experimental facilities are under development. The only foreseeable risk is that no adequate data (e.g. multi-messenger events) are taken in the course of the Action. Even in this case, BridgeQG will make progress by developing optimised measurements strategies and codes to implement them.

4.1.4. GANTT DIAGRAM

The following GANTT diagram reports the duration of each activity along the lifetime of the Action. Numbers on the horizontal axis indicate the semester in the lifetime of the Action. Numbers on the vertical axis indicate the task/activity number, as listed below.



Tasks/Activities: 1. Setup Action Homepage, 2. Setup social media accounts, 3. Preparation and publication of the vademecum, 4. Preparation and publication of the Living Review, 5. Clarify the notion of quantum observers, 6. Survey decoherence mechanisms, 7. Collection and comparison of data from cosmic and quantum systems observations, 8. Regular online seminars, 9. Answering the submitted questions from the public, and redacting them for social media, 10. Discussing the extension of the network beyond the Action lifetime, 11. Preparation of Annual Conference, 12. Preparation of Training Schools, 13. Annual Outreach Activity for Schools.

REFERENCES

[Aartsen2018] Aartsen et al. [IceCube Collaboration], Science 361, 1378 (2018).

[Abbasi2022] Abbasi et al. [IceCube Collaboration], Nature Phys.S 41567 (2022) 022-01762.

[Abdalla2019] Abdalla et al., ApJ 870, 93 (2019).

[Acciari2020] Acciari, et al. [MAGIC Collaboration], Phys.Rev.Lett. 125, 021301 (2020).

[Ackermann2009] Ackermann et al. [Fermi GBM/LAT Collaboration], Nature 462 (2009) 331-334.

[Addazi2022] Addazi, et al., Prog. Part. Nucl. Phys. 125, 103948 (2022).

[Albert2020] Albert et al. [HAWK Collaboration] Phys.Rev.Lett. 124 (2020)131101.

[Amelino-Camelia2002] Amelino-Camelia, Int.J.Mod.Phys.D 11 (2002) 35.

[Amelino-Camelia2009] Amelino-Camelia, Gubitosi, Marciano, Martinetti, Mercati. Phys.Lett.B 671 (2009) 298-302.

[Amelino-Camelia2009b] Amelino-Camelia, Lämmerzahl, Mercati, Tino, Phys.Rev.Lett. 103 (2009) 171302.

[Amelino-Camelia2012] Amelino-Camelia, Barcaroli, Loret, Int.J.Theor.Phys. 51 (2012) 3359.

[Amelino-Camelia2013] Amelino-Camelia, Living Rev. Rel. 16 (2013) 5.

[Amelino-Camelia2013b] Amelino-Camelia, Astuti, Rosati, Phys.Rev.D 87 (2013) 8, 084023.

[Amelino-Camelia2023] Amelino-Camelia, Di Luca, Gubitosi, Rosati, D'Amico, Nat Astron 7, 996–1001 (2023).

[Anastopoulos2013] Anastopoulos, Hu, Class. Quant. Grav. 30.16 (2013) 165007.

[Anastopoulos2018] Anastopoulos, Hu, Class. Quant. Grav. 35.3 (2018) 035011.

[Arzano2010] Arzano, Kowalski-Glikman, Walkus, EPL 90 (2010) 3, 30006

[Arzano2023] Arzano, D'Esposito, Gubitosi, Commun.Phys. 6 (2023) 1, 242.

[Aslanbeigi2014] Aslanbeigi, Saravani, Sorkin, JHEP 06 (2014) 024 .

[Aspelmeyer2022] Aspelmeyer, From Quantum to Classical: Essays in Honour of H.-Dieter Zeh. Cham: Springer International Publishing, 2022. 85-95.

[Ballesteros2021] Ballesteros, Giacomini, Gubitosi, Quantum 5 (2021) 470.

[Barenboim2004] Barenboim, Mavromatos, JHEP 01 (2005) 034.

[Bartlett2007] Bartlett, Rudolph, Spekkens, Rev. Mod. Phys. 79.2 (2007) 555.

[Bartlett2009] Bartlett et al., New J. Phys. 11.6 (2009) 063013.

[Bassi2017] Bassi, Großardt, Ulbricht, Class. Quant. Grav. 34.19 (2017) 193002.

[Belenchia2015] Belenchia, Benincasa, Liberati, JHEP 03 (2015) 036.

[Belenchia2016] Belenchia, Benincasa, Liberati Marin, Marino, Ortolan, Phys.Rev.D 95 (2017) 2, 026012.

[Blencowe2013] Blencowe, Phys.Rev.Lett. 111.2 (2013) 021302.

[Bolmont2022] Bolmont et al., ApJ 930 (2022) 75.

[Bose2017] Bose, Sougato, et al. Phys.Rev.Lett. 119.24 (2017) 240401.

[Cao2022] Cao et al. [LHAASO Collaboration], Phys.Rev.Lett. 128 (2022) 051102.

[Christiansen2006] Christiansen, Ng, van Dam, Phys.Rev.Lett. 96 (2006) 051301.

[Cohen1999] Cohen, Kaplan, Nelson, Phys.Rev.Lett. 82 (1999) 4971.

[Colladay1998] Colladay, Kostelecky, Phys.Rev.D 58 (1998) 116002.

[Craig2019] Craig, Koren, JHEP 03 (2020) 037.

[D'Ambrosio2012] D'ambrosio et al., Nat. Commun. 3.1 (2012) 961.

[DeWitt2011] DeWitt, Rickles. “The role of gravitation in physics: report from the 1957 Chapel Hill Conference”. Edition Open Access, 2011.

[Donadi2021] Donadi et al. Nat. Phys. 17.1 (2021) 74-78.

[Eliezer1989] Eliezer, Woodard, Nucl. Phys. B325, (1989) 389.

[Fadel23] Fadel, arXiv:2305.04780.

[Grosse2003] Grosse, Wulkenhaar, JHEP 12 (2003) 019.

[Giacomini2019] Giacomini, Castro-Ruiz, Brukner, Nat. Commun. 10.1 (2019) 494.

[Hamette2020] de la Hamette, Galley, Quantum 4 (2020) 367.

[Holman2018] Holma , Stuart-Fox, Hauser, PLoS Biol 16(4) (2018) e2004956.

[Jacobson2003] T. Jacobson, S. Liberati, D. Mattingly, Nature 424 (2003) 1019.

[Kafri2014] Kafri, Taylor, Milburn, New J. Phys. 16.6 (2014) 065020.

[Kiefer2012] Kiefer, Oxford University Press, ISBN: 978-0-19-958520-5.

[Koshelev2012] Koshelev, Rom. J. Phys. 57 (2012) 894.

[Kowalski-Glikman2002] Kowalski-Glikman, Nowak, Phys. Lett. B 539 (2002) 126.

[Lämmerzahl1996] Lämmerzahl, Gen.Rev.Grav. 28 (1996) 1043-1070.

[Lami2023] Lami, Ludovico, Pedernales, Plenio, arXiv:2302.03075.

[Liberati2009] Liberati, Maccione, Ann. Rev. Nucl. Part. Sci. 59 (2009) 245.

[Lisi2000] Lisi, Marrone, Montanino, Phys.Rev.Lett. 85 (2000) 1166-1169.

[Loll2022] Loll, Fabiano, Frattulillo, Wagner, PoS CORFU2021 (2022) 316.

[Lizzi2019] Lizzi, Manfredonia, Mercati, Poulain, Phys.Rev.D 99 (2019) 8, 085003.

[Lizzi2022] Lizzi, Scala, Vitale, Phys.Rev.D 106 (2022) 2, 025023.

[Lu2022] Lu et al., Rev Mod. Phys. 94.3 (2022) 035001.

[Magueijo2002] Magueijo, Smolin, Phys.Rev.Lett. 88 (2002) 190403.

[Marletto2017] Marletto, Vedral, Phys.Rev.Lett. 119.24 (2017) 240402.

[Mattingly2005] Mattingly, Living Rev. Rel. 8 (2005) 5.

[Mavromatos2004] Mavromatos, Lect. Notes Phys. 669 (2005) 245.

[Mavromatos2007] Mavromatos, Meregaglia, Rubbia, Sakharov, Sarkar, Phys.Rev.D 77 (2008) 053014.

[Minwalla1999] Minwalla, Van Raamsdonk, Seiberg, JHEP 02 (2000), 020.

[Mercati2010] Mercati, Mazon, Amelino-Camelia, Carmona, Cortes et al., Class.Quant.Grav. 27 (2010) 215003.

[Norte2018] Norte, Forsch, Wallucks, Marinković, Gröblacher, Phys.Rev.Lett. 121 (2018) 030405.

[Oppenheim2018] Oppenheim, arXiv:1811.03116 (2018).

[Perennes2020] Perennes, Sol, Bolmont, A&A 633 (2020) A143.

[Quach2015] Quach, Phys.Rev.Lett. 114, 081104 (2015).

[Rideout2012] Rideout et al., Class.Quant.Grav. 29.22 (2012) 224011.

[Rovelli2004] Rovelli, Quantum Gravity (Cambridge Monographs on Mathematical Physics), Cambridge University Press. ISBN: 978-0-52-171596-6.

[Schrinski23] Schrinski, Yang, von Lüpke, Bild, Chu, Hornberger, Nimmrichter, Fadel, Phys.Rev.Lett. 130 (2023) 133604.

[Tino2020] Tino et al., Progress in Particle and Nuclear Physics 112 (2020) 103772.

[Vasileiou2013] Vasieliou et al., Phys.Rev.D 87 (2013) 12, 122001.

[Vinante2016] Vinante, Mezzena , Falferi , Carlesso , Bassi, Phys.Rev.Lett. 119 (2017) 11, 110401.

[Vinante2020] Vinante., Gasbarr, Timberlake, Toroš, Ulbricht, Phys.Rev.Res. 2 (2020) 043229.

[Westphal2021] Westphal et al., Nature 591.7849 (2021) 225-228.

[Xu2019] Xu, Ping, et al., Science 366.6461 (2019) 132-135.

[Zych2011] Zych et al. Nature communications 2.1 (2011) 505.