European Cooperation in the field of Scientific and Technical Research - COST -

Brussels, 14 November 2014

COST 112/14

MEMORANDUM OF UNDERSTANDING

Subject :	Memorandum of Understanding for the implementation of a European Concerted Research Action designated as COST Action MP1405: Quantum structure of spacetime (QSPACE)

Delegations will find attached the Memorandum of Understanding for COST Action MP1405 as approved by the COST Committee of Senior Officials (CSO) at its 191th meeting on 12-13 November 2014.

MEMORANDUM OF UNDERSTANDING

For the implementation of a European Concerted Research Action designated as

COST Action MP1405
QUANTUM STRUCTURE OF SPACETIME (QSPACE)

The Parties to this Memorandum of Understanding, declaring their common intention to participate in the concerted Action referred to above and described in the technical Annex to the Memorandum, have reached the following understanding:

1. The Action will be carried out in accordance with the provisions of document COST 4114/13 "COST Action Management" and document 4112/13 "Rules for Participation in and Implementation of COST Activities", or in any new document amending or replacing them, the contents of which the Parties are fully aware of.

2. The main objective of the Action is to exploit the existing complementary expertise of different research groups in Europe to enhance the understanding of the relations between Noncommutative Geometry and leading theories of Quantum Gravity.

3. The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 76 million in 2014 prices.

4. The Memorandum of Understanding will take effect on being accepted by at least five Parties.

5. The Memorandum of Understanding will remain in force for a period of 4 years, calculated from the date of the first meeting of the Management Committee, unless the duration of the Action is modified according to the provisions of Section *2. Changes to a COST Action* in the document COST 4114/13.

TECHNICAL ANNEX

A. ABSTRACT AND KEYWORDS

Noncommutative geometry (NCG) is at the heart of quantum physics, and its many facets and developments have widely influenced both physics and mathematics. In particular, NCG is related to a quantum theory of gravity and a possibly unified perspective on the fundamental forces of Nature. This Action aims to create a Network with world experts from across Europe in the interconnected research subjects of NCG and gravity. As data emerges from Cosmic Microwave Background and quantum interferometry experiments, a prime objective of the Action will be to seek measurable signatures of quantum spacetime. It will achieve a wider and deeper understanding of theory/experiment connections to produce world-leading advances in quantum geometry, and applications to String Theory, Quantum Field Theory, Particle Physics, and Cosmology. This will be achieved through collaborations and scientific activities, which will in particular ensure fair gender representation and foster participation of early stage researchers. The Action will impact on science and society at large through the revolutionary understanding of fundamentals of space and time that it achieves, and through the organisation of a digital respository for NCG related resources.
Keywords: Noncommutative/Nonassociative Geometry, String Theory, Quantum Interferometry, Particle Physics Phenomenology and Cosmology, Quantum Gravity and Modified Gravity Models

B. BACKGROUND

B.1 General background

The quantisation of gravity and its incorporation into a consistent quantum theory of fundamental interactions is one of the deepest and most challenging open problems in theoretical physics. In spite of the impressive success of General Relativity describing gravity, and of Quantum Field Theory (QFT) describing the other fundamental interactions of Nature, there is up to now no satisfactory way to reconcile them. Reconciliation of incompatible physical theories has in the past led to far-reaching implications, as is witnessed by the consistency of gravity with special relativity or of electromagnetism with Galilean relativity.

Gedanken experiments using quantum particles for testing the structure of spacetime show that the classical picture of a continuum of points breaks down, and that a quantum texture is needed, typically characterised by a coarser structure where indeterminate relations and noncommutative (NC) structures arise. This has led to a novel approach to understanding Nature at the Planck scale based on Noncommutative Geometry (NCG), which is a generalised framework for geometry that applies the basic principles of quantisation to geometric spaces. It is related to other quantum gravity models of current interest: String Theory (ST), which arose as an attempt to understand all particle interactions in a unified manner, and Loop Quantum Gravity (LQG), which is related to spin networks and is particularly useful for understanding quantum gravity in three dimensions. NCG offers an approach to build a QFT of spacetime that may address the challenges of a fundamental theory of quantum gravity in a simpler framework than the currently favoured theories, and at the same time connect to future data coming from the Large Hadron Collider (LHC) and cosmic observation.

New experimental techniques, such as those based on quantum correlated light interferometry, might give new insights into the structure of quantum spacetime. Signatures of these structures may also be present in cosmological data: Thanks to Cosmic Microwave Background (CMB) data and inflationary models we are gathering information about quantum matter at spacetime epochs a few orders of magnitude away from regimes characterised by Planck scale energies. Scenarios involving Big-Bang models can also be reconsidered with models involving NC spacetimes. Modifications of gravity that arise once one considers General Relativity on NC spacetime can provide a complementary approach to phenomenologically testing modified gravity theories such as f(R) theories or higher derivative theories.

The dichotomy between spacetime and matter can be overcome through synergies between NCG, ST and LQG. A rethinking of this paradigm is implicit in NCG kinematic features due to dynamics of gravitational backreaction, and in ST when extra dimensions are compactified and further when the geometry of fluxes is considered: here background matter (fluxes) can be interpreted as a modified spacetime structure which can be even non-geometric in character, including NC and more generally nonassociative (NA) structures. The geometry of fluxes is a lively subject in theoretical physics which has led to new results in mathematical physics, for instance in Cartan geometry. It also involves higher geometric structures similar to those of LQG. The common features of NCG, ST and LQG as complementary approaches to quantum gravity in fact go much further and involve topics such as matrix models and quantum groups.

The main objective of this Action is to create a strong interconnected network of experts working on theoretical aspects of NCG and Quantum Gravity, alongside phenomenologists and experts in quantum optics who will explore experimental signals of quantum spacetime structure.

The interdisciplinarity of the methods needed to advance in the exploration and understanding of quantum gravity will characterise this Action as overcoming the borders of the different existing scientific communities tackling the subject. Thus this Action will ensure that all leading experts are included in an open and flexible network. This interdisciplinary Action will provide the scientific and cultural infrastructures (conferences, schools, working groups, cotutelle of students, knowledge transfer among different scientific communities) for the growth of a new generation of leading scientists. Promotion of emerging young talents will also be achieved by providing strategic support for their future careers, fostering development of appropriate scientific and technical skills, and via their interactions with the experts in the fields. This Action is thus a modern version of the influential schools of thought once linked to specific University chairs.

This Action will focus on networking and collaboration leading to important scientific progress that will reinforce European leadership in quantum gravity research, and to positive outcome for society. Thus COST offers the best framework.

B.2 Current state of knowledge

This Action will focus on current research into aspects of quantum spacetime that can be roughly divided into three major topics:

Noncommutative Geometry Applications. This topic centers around phenomelogical models and experimental searches. Research into understanding physical implications of modified spacetime structures and confronting them with observations has focused on two directions.
On one hand, after modifying spacetime structure one can analyse the implications on physical fields, and in particular on gravity. In this regard, significant efforts have been devoted to connecting NC QFT with realistic phenomenological models, including the Standard Model and Cosmology. The Spectral Action provides a concise geometric and calculable description of the Standard Model, including its coupling to gravity. QFT on Moyal spaces has been used to calculate phenomenological/experimental predictions via the Seiberg-Witten map. Some of these models enjoy better renormalisation features than their commutative counterparts, and there are already indications that they can be used to construct a non-trivial renormalisable QFT in four dimensions. Another class of renormalisable Particle Physics models comes from higher-dimensional theories where the extra dimensions are described by fuzzy (discrete) spaces, yielding novel controllable examples of

dynamical symmetry breaking in the Standard Model. Gravity theories on NC spaces can be defined by deforming either the local spacetime symmetries or the geometry itself; these models are higher derivative gravity theories which can be compared with other modified theories of gravity such as f(R) gravity.

On the other hand, phenomenological predictions can also be made from studying possible ways to detect modifications of spacetime in current experiments, as a number of new physical effects come directly out of quantum spacetime such as energy-dependence of the speed of light and of gravitational time dilation, and suppression of inertial and gravitational masses for macroscropic quantum states. Observational data relevant for physics at high-energy scales has been accumulating over the years from various sources. One source is astrophysical processes, where measurements of gamma-ray bursts from the MAGIC and GLAST telescopes have been compared to modifications of dispersion relations due to NCG. Another source of data will come from ultra-high energy collider experiments at the LHC. A completely different source of data comes from quantum optics experiments in metrology, which deal with quantum light and matter; it can inspire the appropriate theoretical modelling of spacetime structure and its implementation in future quantum correlated light interferometry experiments.

Noncommutative Geometry Structures. This topic centers around the different approaches to NCG, and their extensions to NA and higher geometries. Understanding the physical implications of NCG requires an in-depth analysis of the properties of QFT defined on concrete models of quantum spacetime. Models range from mathematically rigorous frameworks based on spectral triples, to more heuristic examples of spaces where minimal length scales are introduced. Algebraic approaches based on Drinfeld twists and Hopf algebroids elucidate the role that quantum groups play in the description of quantum spacetime symmetries; in fact, quantum groups themselves provide examples of NCGs which can sometimes be described very explicitly, and they are moreover crucial to understanding the role of NCG in LQG, particularly in three dimensions where their occurence implies quantisation of the cosmological constant. Fuzzy spaces provide a class of NCGs built explicitly from matrices and other finite-dimensional algebraic objects; QFT on such spaces is manifestly finite and can be studied using matrix models. In many of these examples interesting NC generalisations of nonperturbative degrees of freedom such as solitons, vortices, instantons, monopoles, and skyrmions can be explicitly constructed. Understanding the corresponding QFT requires in part to understand the construction of the associated moduli spaces on NC manifolds.

Certain models of quantum spacetime and NCG are realised in ST in the context of D-branes in a constant magnetic field. In the presence of higher-form background fields, such as those which arise in M-theory or in flux compactifications of closed strings, higher geometric structures arise; they also arise in LQG. The quantisation of these structures is related to the geometry of gerbes and multisymplectic forms, and they have illuminated how to consistently incorporate NA structures into NCG and quantum mechanics, together with how they relate to old NA quantisation ideas in Nambu mechanics. The geometry of fluxes in ST has led to new advances in generalised geometry, as the relations between twisted Courant algebroids and Cartan geometry shows; both structures are relevant in ST, respectively in the formulation of membrane sigma-models which provide a means for geometrising and quantising non-geometric fluxes, and in supergravity. In this way they have also been important for the understanding of Double Field Theory and non-geometric models in ST. Flux backgrounds feature effective brane QFTs given by higher gauge theories, for instance of Nambu-Poisson type, and their Riemannian geometry is described in the language of generalised geometry.

Gravity Models. This topic centers around quantum gravity, ST and LQG. String compactifications, together with F-theory, heterotic and D-brane models, are avenues in which to connect the appearence of NC and NA structures in ST with real-world physics, particularly in the context of string phenomenology and cosmology.

While matrix models are used in NC QFT, particularly in the case of fuzzy spaces, and in models of emergent noncommutativity and gravity, they also appear in the group field theory approach to LQG, and as conjectural nonperturbative completions of ST where they appear in various flavours of type IIB/IKKT, orbifold IKKT, BFSS and BMN. Intensive numerical and analytic work over the years has produced a wealth of results clarifying the appearence of late time Cosmology and the Standard Model in matrix models, together with constructions of branes, brane-world models, and dynamical compactifications of extra dimensions. Numerical work in this subject has in particular focused on resolving the complex action problem in Monte Carlo simulations of matrix models and QFTs. Matrix models have a natural higher extension to random tensor models, which are non-local QFTs whose Feynman amplitudes can be interpreted as dynamical triangulations of spacetime pondered by a discretised form of Einstein-Hilbert gravity; these models may also have consequences for Condensed Matter in a random geometric environment.

All three strands of problems are fundamentally connected and their common pursuit requires a close alliance between groups working on vastly different aspects of the same problem. This Action will provide the innovative means to forge this alliance through unification and coordination of this broad range of activities.

Progress into these problems has been primarily achieved by world-leading researchers at Institutions in Europe, Japan and North America. In Japan and North America productivity in this avenue of research has been boosted through the creation of research centers, such as the *Perimeter Institute for Theoretical Physics* and the *Institute for Physics and Mathematics of the Universe*, which have brought together world experts in a diverse range of theoretical approaches to quantum gravity under one umbrella in an environment which strives to connect fundamental scientific research to real-world applicability and public understanding. The COST framework offers the unique opportunity to create an Action that will have a similar effect in the European community, thus enhancing EU leadership in this area and putting the EU community in competitive alignment with other communities around the world.

B.3 Reasons for the Action

The "Quantum Structure of Spacetime" Action will provide an innovative common platform in unifying research activities in the areas described in Section B.2. It will involve experts in different facets of NCG, in theory and experiment, and in related mathematical aspects. Many of the applicants have participated in previous nationally and internationally funded collaborations on related subjects, and have established longstanding research links and collaborations through regular workshops, conferences and schools. . Participants of the Action have over three decades of experience in fostering research and training of young researchers through running of scientific meetings. There is no current networking project that fosters this scientific depth, range and applications of fundamental quantum gravity research.

This Action is focused on networking and collaboration which will achieve scientific progress and societal outcome. Thus COST offers the best framework for coordinating these activities.

The Action will promote interactions between theoretical physicists and mathematicians, working broadly in the area of NCG, with theorists and experimentalists working in related areas of quantum optics, and with phenomenologists working in the areas of Particle Physics and Cosmology. As data emerges from CMB, LHC and quantum interferometry experiments, exciting experimental tests of quantum spacetime structure over the next few years will become accessible. Given the current developments in theory and experiment, this is a particularly timely point to launch this Action.

Early stage researchers will find a platform that will bring them into contact with the leading groups in quantum gravity research. Moreover, the outcomes of this Action will lead to new concepts for training the next generations of young scientists. The interdisciplinary character of the Action will enable these young scientists to engage with different communities of research, thus broadening their knowledge and enhancing their possibility to pursue further research.

B.4 Complementarity with other research programmes

Because of its cross-disciplinary nature, this Action is complementary to the MPNS Action 1210, which is based on integrated research in String Theory and its applications to Particle Physics, Condensed Matter, Cosmology and Quantum Gravity. Some of the scientists participating in this Action are also naturally involved in this network, and strong links and collaboration in the organisation of joint workshops and seminars will be fostered. This will ensure the transfer of knowledge between the Actions.

C. OBJECTIVES AND BENEFITS

C.1 Aim

The main objective of the Action is to exploit the existing complementary expertise of different research groups in Europe to enhance the understanding of the relations between Noncommutative Geometry and leading theories of Quantum Gravity, and the applications of Noncommutative Geometry to Particle Physics and Cosmology.

C.2 Objectives

The main expected deliverables of this Action are:

- Invigorate communication between experienced researchers in broader areas of Physics and Mathematics in order to foster new applications of Noncommutative Geometry.
- Develop new insights into deep central questions in theoretical physics with important implications on Particle Physics, Cosmology, and Gravity.
- Connect formalism with realistic models and experiment.
- Consolidate research efforts in fundamental theoretical physics in areas where Europe is world-

leading.

- Intensify scientific exchange of expertise in quantum gravity research, particularly between economically developed and less developed regions in Western and Eastern Europe.
- Reinforce and develop important collaborations and meetings that currently lack funding.
- Promote and support top young EU talent in the field with provisions for them to establish themselves in the relevant fields.
- Provide a platform for the joint training of young researchers.
- Promote scientific culture and awareness to school pupils, young women and the general public through outreach schemes.

C.3 How networking within the Action will yield the objectives?

The objectives of the Action will be achieved through:

- Regular Working Group meetings, workshops, training schools and joint seminars.
- Short-term staff and young researcher exchanges between the participating groups in order to facilitate scientific collaboration.
- Development of cross-disciplinary research activities.
- Development of joint cross-disciplinary training programmes for students and early stage researchers.
- Expansion of the initial Action by integrating further participants Dissemination of the work to the scientific community.
- Pedagogical dissemination of activities and outputs to wider public and political audiences.
- Creation of a digital repository of Noncommutative Geometry related materials which will serve as a starting point for young researchers as well as a reference site for more experienced researchers.
- Specific outreach activities for school pupils, young women and the general public.

C.4 Potential impact of the Action

Scientific benefits of the Action will be:

- Defragmentation of research efforts in quantum gravity across Europe.
- Strengthening the internationally leading role of Europe in the area of quantum gravity and its related Physics and Mathematics areas.
- Impact on early stage researchers who shall benefit from high-level cross-disciplinary education

and exposure to up-to-date overviews of the most important topics in the different fields.

- Impact on industry and society through the training of skilled people in independent thinking, complex problem-solving and competitive international leadership.
- Impact on University courses that will be innovated according to this Action vision, for example Quantum Mechanics courses complemented with quantum optics experiments and Classical Mechanics clarified using geometric notions similar to those needed in general relativity.
- Reduction in the gap between experiment and theoretical approaches to quantum gravity.
- Reinforcement and development of long-term collaborations.
- More visibility for early stage researchers and women scientists within the scientific community.
- Possibilities for young researchers to come into contact with different communities of experimental, theoretical and mathematical physicists.
- Increased understanding and attraction of the general public towards the fascinating properties of quantum spacetime structures.
- Reinforcement of scientific education and awareness of pupils, young students and society in general through the preparation of outreach activities and materials.

C.5 Target groups/end users

The main target group addressed in this Action are scientists and young researchers in European institutions (Universities and Research Centers), over 100 of which have been contacted and indicated their interest in the Action. Beyond that, the generated knowledge will be shared globally with the international scientific community.

Special attention will be paid to achieve gender balance and involvement of young researchers in all aspects of this Action.

This Action will also engage in an educational programme devoted to the pedagogical dissemination of its activities among the general public, including a special outreach section of its NCG resources repository.

This is a project which primarily concerns fundamental science without direct technical application, but its impact on industry and society at large will stem from the training of highly skilled people in independence, complex problem solving, and leadership within a largely competitive environment.

Moreover, the theoretical underpinnings that this Action will generate in conjunction with proposals for experiments in quantum optics are likely to have implications for the development of applications in industry.

Policy makers will be supported by this Action in promoting scientific culture.

Finally, highly motivated researchers normally make up excellent teachers training the future generation of engineers, scientists and mathematicians, which will form the backbone of the European economy of the future.

D. SCIENTIFIC PROGRAMME

D.1 Scientific focus

As described in Section C, an innovative feature of this Action is that it will invigorate communication between experienced researchers in broader areas of Physics and Mathematics in order to foster new applications of NCG. Synergy among different research expertises will lead to important new perspectives into testing spacetime structure as well as elaborating its theoretical modelling. Such an ambitious task could only be realised as a Action, as it unites the internationally recognised research efforts on quantum gravity research in Europe under one umbrella. The open nature of Actions is significantly appropriate for this rapidly evolving field. In particular, the tasks outlined in this Section are flexible and liable to alterations should new participants and unforeseen activities become available during the implementation. According to Section B.2, the scientific activity will be organised into three main topics:

Noncommutative Geometry Applications. This topic centers around phenomenological models and experimental searches. The structure of spacetime at small distances or high energies and the behaviour of quantum fields, including gravity, in this regime is one of the deepest long-standing problems of theoretical physics; there is as yet no satisfactory quantisation of gravity. For a long time a part of the problem was the lack of direct experimental data in this regime, as the relevant energy scales (grand unification and Planck) are too high to be reached by present day detectors. Hence the only information concerning properties of spacetime, matter and interactions at these scales stems from pathologies in our current models, due to internal inconsistencies of the existing theories (singularities in General Relativity, divergences in QFT) and their mutual incompatibility.

However, in recent years observational data at the relevant scales have been accumulating. Astrophysical measurements of gamma-ray bursts (MAGIC, GLAST telescopes) have been used as testing grounds for quantum gravity models, and of CMB radiation (Hubble, WMAP, Planck and BICEP telescopes) have ignited revolutionary new insights in Cosmology. A different source of data comes from collider experiments at the LHC, which will confirm details of the Standard Model of Particle Physics and search for structures beyond the Standard Model (such as supersymmetry). A major focus of this Action is to confront experimental data with models based on NCG, which is a framework for quantum gravity which emphasises modifications of spacetime structure and in which gravity appears as a version of quantum geometry. In particular, General Relativity on NC spacetime is equivalent to a higher derivative gravity theory, and hence gives a complementary approach to phenomenologically testing modified gravity theories such as f(R) theories. One aim of the Action is to give bounds to physical parameters which are measured in experiments such as noncommutativity parameters or parameters of Lorentz violation; such estimates could be valuable in the design of future experiments to detect quantum spacetime structure.

The Action will exploit the tools of NCG to study realistic models of Particle Physics and Cosmology, such as the Standard Models. In particular, the Spectral Action will be studied in detail.

The Action will also focus on the construction of NC QFTs, including gravity. A concentrated effort will be placed on understanding renormalisability of particle models in NCG, such as Seiberg-Witten expanded gauge theories. QFTs on Moyal spacetimes will be fully developed as their potential for renormalisability at present seems best; in particular, it is hoped that they may provide the first examples of interacting nonperturbative QFTs in four dimensions. Constructions of new realistic Particle Physics and Cosmological models in the framework of QFT on fuzzy (discrete) extra dimensions will also be studied, together with their predictions in accelerators and cosmological searches, and their renormalisability. New constructions of QFT on spacetimes with non-constant noncommutativity will also be developed. Practitioners of NCG will work alongside experts in high energy phenomenology (including strong interactions, B-physics, beyond Standard Model physics) to explore the connections with realistic scenarios.

Heisenberg quantum mechanics was born out of Gedanken experiments with classical matter and light; while this has radically altered our understanding of matter, it has had limiting effect on our perception of spacetime. After over a century, experiments with quantum light and Planck mass matter are being carried out. These new experiments, based on quantum correlated light interferometry and on cavities with Planck mass macroscopic harmonic oscillators (microresonators), may give new insights into the manner in which quantum matter sources and moves in a quantum spacetime. This Action will aim to create new synergies between experts in quantum optics and in NCG that will lead to new experiments (including Gedanken experiments) to test spacetime structure with quantum light rather than classical matter. These synergies will lead to a new paradigm on our understanding of space and time.

Noncommutative Geometry Structures. This topic centers around the different approaches to NCG, and their extensions to NA and higher geometries. Short distance physics requires a profound rethinking of the structure of spacetime and matter at the Planck scale. A major focus of this Action will involve Theoretical Physicists working alongside Mathematicians to study the geometries of quantum spacetime, i.e. the geometries arising from (or required for) quantum gravity, and also underlying QFT, LQG and ST. Detailed understanding of these geometrical structures will be accompanied by significant advances in the different formulations of a consistent theory of quantum gravity.

The Action will study in detail the mathematical structures of NCG underlying quantum spacetime. It will focus on the very notions of NCG structures which have potential relevance for the construction of physical theories, including concrete examples of NC spaces, (supersymmetric) spectral triples, NC principal bundles, and deformation quantisation of ordinary geometry.
An ambitious goal of this Action is to advance the related but largely undeveloped topic of the quantisation of higher order structures. These structures naturally appear in ST, for example where higher gauge fields are fluxes living on M2-branes; in particular, quantisation of M2-M5 brane configurations is a higher analog of the D1-D3 brane systems that are well described using the NCG of fuzzy spheres. They also appear in non-geometric flux compactifications of ST, for example in the case of closed strings on a twisted three-torus in the presence of fluxes. They further arise in spin foam models of LQG, and as categorifications of the usual gauge theory of particles. Just as NC gauge theories arise and provide useful descriptions of certain dynamics in ST, NC higher gauge theories arise and are expected to provide useful descriptions of M-theory and non-geometric ST. In particular, the Action will actively pursue the proper quantisation of higher Poisson structures, such as Nambu brackets. A challenging task for this Action will be to unify and explore the synergies between these different realisations, and how they are related to other approaches to the geometry of fluxes based on algebroids, generalised geometry, double field theory, NC and NA geometry, and Cartan

geometry.

Gravity Models. This topic centers around quantum gravity, ST and LQG. An aim of the Action is to deepen the connections of NCG with ST, LQG and other models of gravity, and to clarify the synergies and relationships between the various approaches to quantum gravity. A crucial guiding principle will be the motivation to define and understand the meaning of a functional integral over NCGs, and in particular the common idea that the short-distance cutoff at the Planck scale is a manifestation of noncommutativity. A variety of different treatments and models of quantum gravity will be treated by experts within the Action. Effective target space theories in non-geometric ST and their connections to NA models of gravity will be developed, for example using suitable higher generalisations of the Seiberg-Witten map in NCG. The NCG of Quantum Groups will be further applied in LQG, allowing for example a deeper understanding of NC Fourier transform and its applications. Moreover, as gravity on NC spacetime may be regarded as a deformation of the usual Einstein-Hilbert gravity, the Action will also study alternative formulations of classical gravity in order to enable detailed comparison.

A particularly tractable way to make sense of NC QFT is through the language of matrix models, which are also related to notions of NCG and ST as they generate a plethora of interesting solutions corresponding to strings, D-branes and their interactions, as well as to NC and fuzzy spaces such as fuzzy tori and spheres. This Action will engage in a concentrated effort to further develop the effective descriptions of quantised gravity from matrix models, and explore in detail their relations to ST, Cosmology and the Standard Model of Particle Physics, using both innovative analytic means and sophisticated Monte Carlo simulations. The Action will also develop new types of non-local renormalisable QFTs of matrix and tensor type, as part of a broader effort to understand random geometry in higher dimensions. A particularly challenging task for this Action is to describe the extent to which these models serve as attractive candidates to quantise gravity.

In spite of the division of scientific activities into the three main topics above, techniques and concepts will permeate through all three topics throughout the duration of the Action, and this synergy amongst different topics and research groups is indeed a major reason for the implementation of this Action: The overall goal is to approach an all-embracing understanding of the structure of quantum spacetime.

D.2 Scientific work plan methods and means

The Action will be organised into five Working Groups (WGs), the first three WG1-WG3 according to the topics described in Section D.1. WG4 will coordinate the first three WGs, with its primary focus on knowledge transfer, exchanging technical tools, and cross-WG research activities. WG5 will work on gender and outreach activities.

WG1: **Noncommutative Geometry Applications.** The aim is to further develop tools that connect NCG with realistic phenomenological models, including the Standard Models of Particle Physics and Cosmology.

The scientific work plan includes:

- Construction and study of concrete models of the Standard Model and beyond, and in general of realistic particle theories, using the tools of NCG.
- Quantisation of lattice gauge fields using NCG.
- New constructions and applications of QFTs on spacetimes with non-constant noncommutativity, for example gauge theory models on kappa-Minkowski space with the inclusion of neutrinos.
- Search for signals of quantum spacetime in current experimental data, such as the LHC and the CMB spectrum, including modifications of dispersion relations at high energies (e.g. for photons), and properties of the CMB related to torsion or noncommutativity.
- Construction of new realistic models in the framework of theories with fuzzy extra dimensions, study of their renormalisation, and exploration of their predictions in collider physics and cosmological searches.
- Exploration of the extent to which soft supersymmetry breaking terms that lead to spontaneous generation of extra fuzzy dimensions result from dimensional reduction of a higher-dimensional unified theory.
- Construction of a dynamical theory of spacetime noncommutativity, so that quantum matter sources both curvature and noncommutativity of spacetime, and study of the corresponding NC gravity and Cosmology theories.
- Development and elaboration of NCG predictions through modelling of quantum spacetime structures in experiments exploiting quantum correlated light in coupled interferometers.

Methods and means used to achieve these objectives are:

- Detailed study of the spectral action, its expansion and its symmetries.
- Development of a new approach to the Standard Model based on NC and NA geometry.
- High energy phenomenological studies of strong interactions (QCD), B-physics and beyond Standard Model physics.
- Studies of group theory aspects of gauge/gravity duality and applications to Particle Physics

phenomenology.

- Exploitation of recent advances from theoretical and experimental quantum optics in interferometry techniques with quantum entangled photons for setting up experiments to test quantum spacetime structure.

WG2: Noncommutative Geometry Structures. The aim is to produce new constructions of fields, matter and quantum spacetimes in NCG.

The scientific work plan includes:

- Comparison of new constructions of models of quantum spacetime with spaces having minimum length scales.
- Further studies of gauge theories in NCG: Their nonperturbative configurations such as instantons, and gauge theory invariants of NC spaces.
- Clarification of the various notions of symmetry in NCG: Symmetries in the continuum versus symmetries in the discrete and NCG, variational principles and notion of gauge symmetry in the NC world.
- Formal developments of a theory of NC principal bundles, together with duality, NC gauge transformations and automorphisms, and NC parallel transport.
- Construction of QFTs, including gravity, on fuzzy spaces which properly incorporate spinors.
- Further development of the geometry of fluxes by relating generalised geometry and double field theory to their dual descriptions in terms of NC and NA geometry.
- Development of quantisation schemes for higher geometry, such as multisymplectic phase spaces, relevant for NA geometry.

Methods and means used to achieve these objectives are:

- Rigorous constructions of new examples of spectral triples in NCG, and in particular of finite-dimensional spectral triples and their relation to fuzzy geometries.
- Development of KK-factorisation in bivariant K-theory, and further studies of K-theory and K-homology of NC spaces.
- Further developments of connections between quantum groups and NCG, including studies of quantum group internal symmetries and integrability in QFT, and the Weil homomorphism for Hopf algebras.
- Further developments of spin geometry and other facets of the NCG of fuzzy spaces, using finite matrices and projectors, and explicit constructions of projective modules and Dirac operators on fuzzy complex projective spaces, Grassmannians and flag manifolds, and also on fuzzy spheres.

- Developments of new (multi-)matrix model techniques suitable to the study of QFT on fuzzy spaces.
- Extensions of Drinfeld twist techniques to study the geometry of NC gauge transformations and NC parallel transport, including the study of non-formal Drinfeld twists.
- Development of NC descriptions of algebroids and Cartan geometry, and their occurences in topological sigma-models.
- Developments of (higher-)categorical generalisations of NCG.
- Extensions of the Seiberg-Witten map and its higher versions.
- Further studies of Nambu-Lie three-algebras and fuzzy three-manifolds.

WG3: Gravity Models. The aim is to develop deeper connections between NCG and other models of gravity.

The scientific work plan includes:

- Analysis of non-geometry on Calabi-Yau spaces and its phenomenological consequences in de Sitter vacua.
- Clarification of the roles of NC and NA structures in non-geometric ST, and particularly their relations to double field theory and string field theory.
- Generalisation of the appearence of NC and NA structures in non-geometric ST to M-theory.
- Constructions of effective NC and NA theories of gravity appropriate to non-geometric string vacua.
- Elucidation of the dynamical relevance of Cartan geometry and twisted Courant algebroids in (gauged) supergravity and dually related theories.
- Calculations of ST corrections and models of gravity in a target space approach based on associative/nonassociative duality ("strings without strings").
- Further studies of cosmological models in group field theories, and phenomenological and cosmological consequences of deformed general relativity and effective actions from LQG.
- Further studies of effective descriptions of quantised gravity from matrix models, and elucidation of their relations with ST and supergravity, with focus on brane-world modelling versus holographic aspects.
- Understanding the role and effect of quantum Born reciprocity/curved momentum space, quantum groups and NCG/discreteness in quantum gravity, and how they fit into purely geometric models of matter.
- Quantisation of Lorentzian matrix models, and studies of their cosmological solutions.
- Detailed studies of effective matrix models for real-world physics: Dynamical compactification

of extra dimensions, dynamical emergence of a four-dimensional expanding Universe, origin of the Standard Model and realisations of chiral fermions.

- Construction and classification of novel renormalisable non-local QFTs of spacetime of tensor type, and exploration of their properties as viable models of quantum gravity.
- Comparisons with other models of gravity: Poincare and affine gauge theories of gravity in three and four dimensions (representing matter by finite or infinite dimensional spinor representations), new massive gravity, brane-world models, models of non-local modified gravity and cosmology, and new mechanisms for dynamical supersymmetry breaking in supergravity.

Methods and means used to achieve these objectives are:

- Constructions of instantons in special geometry and their moduli spaces, and in heterotic flux vacua.
- Exploitation of analogies between NC and NA geometry, and magnetic charge distributions.
- Study of the role of homotopy algebras as a framework for nonassociativity in ST.
- Relation of phase space model of non-geometry to (relaxations of) the strong constraint in double field theory.
- Study of the role of kappa-symmetry versus commutative/noncommutative duality in M-theory and supergravity.
- Developments of new innovative analytic tools appropriate to the study of emergent gravity phenomena from matrix models.
- Developments of new nonperturbative and Monte Carlo tools appropriate for numerical simulations of phase structures and gravity phenomena in random matrix models.
- Advancements of Monte Carlo simulations of systems with complex actions, such the IIB matrix model and simple QFTs, and methods for effective simulations of such systems including studies of the effectiveness of the factorisation method.
- Development of properties of random geometry in higher dimensions.
- Development of emerging interface between combinatorics and physics, and links with computer science.

WG4: Cross-WG research activities, short-term scientific missions (STSMs).

WG5: Gender and outreach activities.

E. ORGANISATION

E.1 Coordination and organisation

The Action "Quantum Structure of Spacetime" will build a strong network around the objectives described in Sections C and D. Its participants are world leading experts in quantum geometry and spacetime who are scattered throughout Europe and who would benefit from such coordination. The organisation of the Action will follow the COST documents "Rules and procedures for implementing Actions" and "Action Management".

Management: The Action will be governed overall by a *Management Committee* (MC), chaired by the Action Chair assisted by a Vice-Chair, both elected during the 1st MC Meeting, who will coordinate all research initiatives for the final objectives. The operative management work of the Action will be executed by a *Core Group* (CG) within the MC. It will be composed of the Chair, the vice-Chair, the Working Group (WG) leaders (see Section E.2), including the coordinators for the Short Term Scientific Missions (STSM) and for gender and outreach. The CG will be responsible for the preparation of all documentation required for the MC meetings.

The *STSM Coordinator* will lead WG4 and will prepare the annual plan for MC meetings. Decisions will be taken by the CG and reported to the MC.

The *Gender and Outreach Coordinator* will lead WG5 and will supervise the gender, outreach and dissemination activities of the Action, and will be responsible for upkeeping of the repository.

Coordination and networking:

Scientific coordination and networking will be achieved through:

- **One annual Workshop and three interdisciplinary Training Schools** will be organised throughout the duration of this Action by WG4 to promote interactions between young researchers and scientists from different nodes. The final Action activity will consist of an international conference to be held in Brussels.
- Dissemination of the Action will be undertaken by the outreach group. In addition, a **Website** will be established in conjunction with the COST Office requirements and will contain information such as partner groups, general introduction to the Action, research activities, workshops, training schools, training courses and seminars, gender forum, and forthcoming events. The Website will

also feature a Research Blog with all updates on appearing preprints, preprints accepted by journals, talks given by members of the Action and announcements of events, which will be forwarded to an Action Twitter account. A periodic newsletter on the Website will provide up-to-date information to participants and the general public.

- In accordance with aims of the European Digital Agenda, and with the 2014 "Venice Declaration", the Action aims at having a **digital platform for the exchange of ideas** and the introduction of young scientists to the field. The physics community is already highly digitalised, with virtually all of its publications available on open archives and a vast amount of resources in the form of slides and recordings of contributions at conferences. The Action will keep a permanent record of all scientific contributions to our meetings. All of these resources will be organised and made available in a Public Repository, where the public at large may find non-technical outreach introduction, young researchers will find introductory lectures and reviews, and experienced researchers will have access to requisite technical contributions. Enlistment of professional support is planned for the organisation of a web portal which will provide all of this information in a coherent form.

Milestones and deliverables: This Action will run for a duration of four years. The main milestones and deliverables are:

Year	Milestones	Deliverables
1	*Month 1*: Inaugural meeting with MC, CG, WGs, Workplan all set up. *Month 9*: MC Meeting 1; WGs Meeting 1; Workshop 1.	WGs Reports, Annual Report, STSM Report, Publications, Outreach Activities, Workshop 1, Gender and Outreach Activities, Website installed, Repository goes on-line.
2	*Month 14:* MC Meeting 2; WGs Meeting 2; Training School 1. **Month 21**: MC Meeting3; WGs Meeting 3; Workshop 2.	WGs Reports, Annual Report, STMS Report, Publications, Training School 1, Workshop 2, Gender and Outreach activities.
3	*Month 26*: Mid-term Scientific Strategic Meeting (MC+CG+all participants); WGs Meeting 4; Training School 2. *Month 33*: MC Meeting 4; WGs Meeting	WGs Reports, Annual Report, STSM Report, Publications, Workshop 3, Training School 2, Gender and Outreach activities.

	5; Workshop 3.	
4	*Month 38:* MC Meeting 5; WGs Meeting 6; Training School 2. *Month 45*: MC Meeting 6; WGs Meeting 7; Final Conference.	WGs Reports, Annual Report, STSM Report, Publications, Training School 3, Gender and Outreach Activities; Final Conference and Proceedings; Final Report.

E.2 Working Groups

Three working groups WG1, WG2, WG3 will organise research activities within the main areas described in Section D. A fourth working group WG4 will coordinate activities for scientific exchange among these three WGs, including Workshops, STSMs, Training Schools, joint seminars and training courses for early stage researchers (ESRs). A fifth working group WG5 will organise outreach activities for the general public, be responsible for gender issues, drive knowledge transfer through regular updates posted to the Action Website, maintain the Public Repository and provide mentoring and career advice to postgraduate students. Each WG will have a Leader and a vice-Leader who are selected by and report to the MC; they will provide the scientific input to the Annual Reports.

The WGs will have regular intergroup communications. Synergy between these WGs will increase significantly in the course of the duration of the Action, thus maximising the impact of this Action.

E.3 Liaison and interaction with other research programmes

Some participants of this Action are also involved in another research programme (see Section B.4). They will foster the organisation of joint workshops, invitations of speakers to the Action workshops and schools, short-term scientific visits and scientific collaborations. Interaction with other European and international programmes, as well as possible future Actions, will be maintained throughout the duration of this Action, paying particular attention to the crossed mobility of young researchers.

E.4 Gender balance and involvement of early-stage researchers

Besides the handling of diversity management in general and life-work, the active participation of women scientists within this Action will be a main directive of WG5 who will foster activities which are mostly handled by minority group researchers involved in the Action, including:

- Ensure the presence of highly qualified women in scientific committees and as speakers in Workshops and Training Schools. They will serve as role models for emerging female scientists.
- Organise scientific outreach activities at Universities (e.g. colloquia, seminars, "Women in Physics Days") in order to encourage young women to pursue doctoral studies in physics or mathematics.
- Identify best practices across Europe for addressing the strong gender imbalance as well as subconscious biases regarding race, ethnicity, age or physical disabilities in the field.
- Promote closer collaboration between Schools and Universities to create positive images of women in Science and present role models.
- Offer a dedicated forum on the Action Website where minority group scientists can exchange their experiences, offer advice and practical hints, with a special section for mentoring programmes where established scientists will give advice to emerging scientists.
- Offer a forum for young scientists to discuss and achieve an appropriate work-life balance during their career, in particular during a family phase including parental leave.
- Informal meetings of all female participants held during Training Schools and Workshops of the Action.
- Constantly monitor data on the number of minority group lecturers and seminar speakers, and the number of such participants in Training Schools and Workshops.

In addition to gender issues, and fulfilling its outreach mission, WG5 will also tackle family issues promoting the modern idea of female/male scientists as members of the general public, with all the common human aspirations including that of a family, and further promoting mobility for scientists and families.

All participating Institutions are actively involved in training ESRs and have long-standing experience in doctoral training. This Action will provide high-level cross-disciplinary training to ESRs aimed at educating well-rounded students with a wide range of interdisciplinary expertise, including:

- Collaboration between experienced researchers and ESRs at all levels, including devolvement of managerial tasks and outreach activities to ESRs.
- Participation of ESRs in WG meetings, workshops and conferences.
- Training Schools and Workshops that will expose ESRs to the current state-of-the-art research activities and open scientific problems. WG leaders will encourage the invitation of ESRs to

present communications.

- STSMs focused primarily on encouraging the mobility of ESRs.

F. TIMETABLE

This Action will run over a period of four years; an interim timetable is shown below. Due to the open and flexible nature of the Action, some readjustments of the scientific and organisational activities may become necessary; any such required changes will be identified by the MC and performed by the CG. The first six months will be dedicated to initiating the entire Action: The MC and CG will ensure the smooth start and operation, with the WGs as outlined in Section D.

Activity	**Year 1**				**Year 2**				**Year 3**				**Year 4**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
WG1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
WG2	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
WG3	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
WG4	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
WG5	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Other Activities																
Inaugural Meeting	x															
Establish MC, WGs	x															
Establish Workplan	x															
Launch Website/ Repository		x														
MC, WG Meetings			x		x		x		x		x		x		x	
Mid-term Meeting									x							
Workshop			x				x				x					
Training School					x				x				x			
Outreach/ Gender issue activities			x	x	x	x	x	x	x	x	x	x	x	x	x	x
Final Conference															x	

G. ECONOMIC DIMENSION

The following COST countries have actively participated in the preparation of the Action or otherwise indicated their interest: AT, BE, BG, CH, CZ, DE, DK, EL, ES, FR, HR, IE, IT, LU, NL, PL, PT, RS, UK. On the basis of national estimates, the economic dimension of the activities to be carried out under the Action has been estimated at 76 Million € for the total duration of the Action. This estimate is valid under the assumption that all the countries mentioned above but no other countries will participate in the Action. Any departure from this will change the total cost accordingly.

H. DISSEMINATION PLAN

H.1 Who?

The MC, assisted by WG5, will be responsible for the Outreach and Dissemination Strategy of the Action. The dissemination material will be adapted to the needs of each of the following different target groups which have been identified:

- Scientists, young researchers and PhD students active in Noncommutative Geometry and Gravity, and their related areas such as Condensed Matter, Particle Physics and Cosmology, as well as in related branches of pure Mathematics
- Universities and Research Institutions joining this Action, and other regional or European projects
- European and regional scientific research policy makers
- National and European funding agencies
- Media: scientific and non-scientific press, internet, etc.
- School pupils, high school students and teachers, and the general public

H.2 What?

All participants will promote the Action on their research group's website and announce progress or achievements as appropriate, with reference to the COST promoted international collaboration behind the Action.

Website: The MC will oversee the work of WG5 in setting up a Website in line with the COST Office requirements, which will contain three different areas:

Public Area will contain information such as participating groups, general introduction to the topic of the Action, research activities, workshops and schools, forthcoming events, contact persons for scientific and COST related enquiries, and a link to the main COST webpage. The general introduction to the topic of Quantum Spacetime will communicate in a non-technical (yet accurate) language the aims and outcome of the Action, and more generally to attract the general public towards the most fundamental questions concerning the short-distance quantum structure of spacetime.
Scientific Area for scientists with activity reports, information about events, and a publication database.
Internal Area will be password protected and contain information available to the MC, such as MC minutes, reports, agenda, etc. A web-based mailing list for participants of the Action only will be set up for rapid information exchange.

A special section of the digital repository will be dedicated to the publications produced within the Action.

Publications: Research articles will be published in peer-reviewed scientific journals, and will acknowledge support by COST. All scientific publications (journal articles, books, contributions to books, proceedings) will be data-based and constitute the main component of the dissemination strategy of this Action. They will all be available as open access.

Events: The Action will organise Training Schools, Workshops, Conferences, and STSMs targeted at scientists and PhD students. At the conclusion of the Action, a major international conference will be organised in Brussels, with conference proceedings published in an international journal. A final report summarising the research of the Action will be produced. All events will be open to all interested researchers.

Outreach: Dissemination among the general public will be achieved through specific outreach activities and non-technical public talks. Information about the scientific functioning of the Action, and its involvement in social issues, will be presented to policy makers, funding agencies and the media. A special section of the digital repository will be specifically devoted to outreach material.

H.3 How?

The website will be one of the main dissemination tools concentrating all information regarding the

Action, including:

- Information about the management of the Action, scientific reports, financial reports, minutes and information about MC and WG meetings.
- Mailing lists for the committees and members of WGs that will allow coordination and information exchange at each level.
- Periodically updated list (with links) of scientific publications.
- Information of past and upcoming events of both this Action and of relevant Workshops, Conferences and Training Schools worldwide.
- Information about weekly seminars held in the participating Institutions of the Action.
- Information about training courses for ESRs.
- Articles, book reviews, and information about events that are of interest to the general public, together with information about social issues regarding women in Science and young researchers.

Dissemination will also be achieved through the digital repository through special sections devoted to publications and outreach.

The events and scientific exchanges organised by the Action are the natural source of dissemination between scientists, bringing them together to allow intensive discussion, debate and brainstorming new ideas. The MC will encourage participation of scientists from outside the Action in order to considerably expand and invigorate its synergies. Each major event will feature a talk for the general public, delivered by a prestigious scientist who will explain in common language the ideas, results, puzzles and challenges facing fundamental quantum gravity research. The MC will set up encounters with policy makers and funding agencies to discuss and inform about scientific progress, and how to improve the efficiency, needs and problems that scientists face in their work environment. The Action will further monitor and inform on the progression of young scientists in their careers and offer advice on how to improve their situation in today's highly competitive research environment.

The MC will produce a revised dissemination plan each year and will include it in the Annual Report of the Action.