Brussels, 12 February 2016

COST 021/16

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Quantum Technologies in Space" (QTSpace) CA15220**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Quantum Technologies in Space approved by the Committee of Senior Officials through written procedure on 12 February 2016.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA15220
QUANTUM TECHNOLOGIES IN SPACE (QTSpace)

The COST Member Countries and/or the COST Cooperating State, accepting 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 (the 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 new document amending or replacing them:

a. “Rules for Participation in and Implementation of COST Activities” (COST 132/14);
b. “COST Action Proposal Submission, Evaluation, Selection and Approval” (COST 133/14);
c. “COST Action Management, Monitoring and Final Assessment” (COST 134/14);
d. “COST International Cooperation and Specific Organisations Participation” (COST 135/14).

The main aim and objective of the Action is to develop core technologies for space applications of quantum mechanics and the understanding of the foundations of physics.. This will be achieved through the specific objectives detailed in the Technical Annex.

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 92 million in 2015.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

COST is supported by the EU Framework Programme Horizon 2020

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<u>**TECHNICAL ANNEX**</u>

OVERVIEW

Summary

The scientific and technological legacy of the 20th century includes milestones such as quantum mechanics and pioneering space missions. Both endeavours have opened new avenues for the furthering of our understanding of Nature, and are true landmarks of modern science.

Quantum theory and space science form building blocks of a powerful research framework for exploring the boundaries of modern physics through the unique working conditions offered by experimental tests performed in space. Space-based sources of entangled photons promise the formation of global quantum communication networks, long-distance tests of quantum theory and the interplay between relativity and quantum entanglement. Long free-fall times enable high-precision tests of general relativity and tests of the equivalence principle for quantum systems. Harnessing microgravity, high vacuum and low temperature of deep space promises allowing the study of deviations from standard quantum theory for high-mass test particles. Space-based experiments of metrology and sensing will push the precision of clocks, mass detectors and transducers towards the engineering of novel quantum technologies.

Such an exciting framework is what “Quantum Technologies in Space (QTSpace)” aims at providing. By fostering concerted research efforts directed towards the development of a new paradigm for quantum technologies, QTSpace will embody a visionary opportunity for furthering the comprehension of fundamental mechanisms of physics in an entirely new context. This Action puts together a network of genuine European dimensions. Its technical and scientific excellence, strongly inclusive character, and ambitious research vision will lead QTSPace towards the achievement of inter-sectorial benefits of fundamental and applied nature.

Areas of Expertise Relevant for the Action	Keywords
● Physical Sciences: Quantum physics ● Physical Sciences: Lasers, ultra-short lasers and laser physics ● Physical Sciences: Relativity ● Physical Sciences: Metrology and measurement (theory) ● Physical Sciences: Ultra-cold atoms and molecules	● quantum technology ● space ● foundations of physics ● relativity ● matter waves

Specific Objectives

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

<u>Research Coordination</u>

- Identify fundamental questions to be addressed as well as the scientific/technical requirements to perform related experimental tests in space.
- Identify possible applications of quantum technology in space, define the scientific and technical requirements.
- Identify principles that should be demonstrated on ground, coordinate which experiments to perform.
- Share knowledge with respect to available technologies and experimental techniques for performing experiments in space-relevant settings.
- Identify common challenges regarding technology needs, mission parameters, mission design.
- Technology development in international cooperation, with space agencies and with industrial partners.

● Share experience and coordinate efforts in hardware testing in space-relevant environments (vibrations, radiation hardness, vacuum, cryogenic environment, temperature cycling, etc.).
● Identify funding opportunities, communication with funding agencies.
● Further broaden international support by researchers and their respective national space agencies.
● Identify and coordinate technology-development or mission-proposal opportunities, communication with industry and space agencies.

Capacity Building
● Identify common ground and possible synergies.
● Exchange know-how related to hardware testing, space-relevant proof-of-principle experiments, data acquisition and evaluation, mission design, ground-segment operation.
● Share relevant contacts to industry, funding agencies and national agencies.

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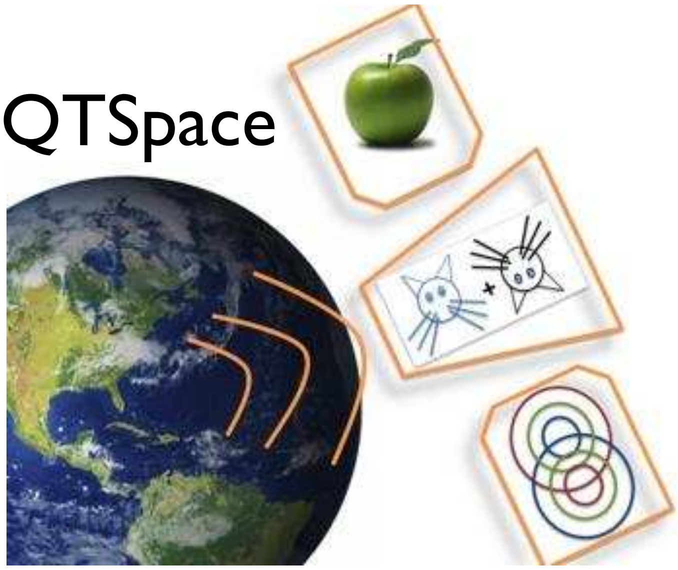

1. S&T EXCELLENCE

1.1. Challenge

1.1.1. Description of the Challenge (Main Aim)

The Challenges QTSpace aims at attacking are the development of core technologies enabling space applications of quantum technology and the achievement of a technology-enabling understanding of the foundations of physics. This Main Aim will be addressed by increasing the technological readiness of quantum technology, by investigating the foundations of quantum mechanics when pushed to the macroscopic domain and by harnessing the unique opportunities offered by a space environment. The goals of the Action will be pursued by fostering collaborative theoretical, experimental and industrial research towards both fundamental and technological goals.

Progress in space and quantum technology has led to international efforts aimed at harnessing quantum technology for space applications, space-based experiments and the realization of proof-of-principle experiments in space-relevant settings. Research in this direction aims at developing concepts and technology, achieving the working regimes suited to space missions, and adapting ground-based experience to the challenges of space-based endeavours. Notwithstanding the daunting nature of such challenges, progress along such directions are rarely collaborative across different communities, leading to parallel developments and independent research efforts, which hinders the acquisition and sharing of much needed space-related know-how.
In particular, all of those efforts face related challenges:

- Acquisition of space-related know-how by addressing the following targeted questions: Which advantages does space provide? How does one optimally harness them? Which technologies are available? Which are missing or need further development?
- Identification of technological and conceptual needs for the translation of ground-based know-how to space-relevant settings
- Mission design, technology development & hardware tests in partnership with industrial actors and space agencies
- Secure funding for technology development and proof-of-principle experiments
- Communication with industry and national/international space agencies
- Coordination of the preparation of proposals for mission opportunities, identifying cases for shared missions

QTSpace aims at creating a collaborative framework for jointly attacking such common challenges. By providing a ‘common house’ for both fundamental and technological progress, QTSpace will complement in a significant way national and institutional research efforts towards the Main Aim addressed by QTSpace, enable a pan-European research effort on a visionary research goal, and foster synergy in a trans-national way that will surely lead to inter-sectoral benefits of both fundamental and applied nature.

1.1.2. Relevance and timeliness

Progress in space technology over recent years forms the basis for novel high-precision tests of the foundations of physics but also for novel applications in positioning, frequency standards, satellite navigation and Earth observation. However, when aiming to implement devices with even higher precision, classical technology may soon reach its ultimate limits. At the same time, that technological progress is beginning to render space a promising platform for quantum technology promising to overcome those classical limitations and to enable novel tests of the foundations of physics as well as space-based applications such as quantum communication, quantum key distribution and quantum metrology. In section 1.3.1, the state-of-the-art in space and quantum technology is described. QTSpace will build on such achievements and, by fostering international collaboration, help pushing the technological readiness of quantum and space technology towards next-generation high-precision tests of the foundations of physics, quantum communication, and a host of new space-based applications.

1.2. Specific Objectives

1.2.1. Research Coordination Objectives

Several international efforts in distinct physical fields aim at harnessing novel quantum and space technology to realize first proof-of-principle experiments in space-relevant settings but also to explicitly develop space-based instruments taking advantage of quantum technology. Those efforts often operate independently of each other, leading to parallel developments, duplicate research efforts and inefficiency in acquiring and sharing space-related know-how. In particular, QTSpace will concentrate on four existing research efforts aimed at harnessing quantum technology in space:

- <u>Optical quantum communication.</u> Efforts aiming at ground-to-space and possibly space-to-space quantum communication. In the near-term or mid-term, one can expect quantum-communication instruments to be hosted on existing `platforms' or on dedicated future missions.
- <u>Cold-atom interferometry in microgravity.</u> Cold-atom interferometry in space promises novel high-precision tests of the foundations of general relativity and may provide benchmarks for possible deviations from the standard model of physics.
- <u>High-mass matter-wave interferometry & Optomechanics.</u> Both matter-wave interferometry with high-mass test particles and optomechanics with massive mechanical oscillators in space promise to allow tests of the foundations of physics in a novel parameter regime.
- <u>Space-based optical atomic clocks.</u> Optical atomic clocks in space promise significantly improved accuracy compared to traditional atomic clocks and have been proposed for high-precision tests of relativity, and for improving precision in positioning and Earth observation.

Rather naturally, international collaborations are inevitable when it comes to space-related efforts or even space missions. The necessary manpower, know-how, time, and the much needed participation of relevant industrial actors are often too demanding pre-requisites for success to be secured and managed by a single nation. This bottleneck can be bypassed only through coordinated initiatives such as QTSpace. Apart from benefiting from international collaborations, mission proposals will also gain from interdisciplinary collaboration, e.g., from the combinations of multiple instruments with compatible mission parameters in a single mission. For example, in the 2010 proposal of STE-QUEST, the involved research communities for space-based atomic clocks and cold-atom interferometers joined their efforts in a combined mission proposal. Moreover, QTSpace addresses explicitly the requests for *inclusiveness* that is at the core of COST: the Network of Proposers includes 9 of the COST-identified ‘Inclusiveness Target Countries’ (ITC), specifically Czech Republic, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Slovakia, and Turkey. The QTSpace network will, without any doubt, facilitate the participation of such countries in consortia and research programs aimed at spearheading quantum-oriented space missions. This is particularly relevant for those ITC countries that currently do not have a space programme.

The quantum-optics community, as well as the community for quantum optomechanics and high-mass matter-wave interferometry, started out their efforts towards space applications virtually independently.

To achieve the goals of this COST Action, four interdisciplinary working groups will be identified:

1. **Fundamental science studies**: Identify fundamental questions to be addressed as well as the scientific/technical requirements to perform related experimental tests in space
2. **Applications**: Identify possible applications of quantum technology in space, define the scientific and technical requirements
3. **Proof-of-principle experiments**:
    a. Identify principles that should be demonstrated on ground, coordinate which experiments to perform.
    b. Share knowledge with respect to available technologies and experimental techniques for performing experiments in space-relevant settings.
4. **Implementation**:
    a. Identify common challenges regarding technology needs, mission parameters, mission design.
    b. Technology development in international cooperation, with space agencies and with industrial partners.
    c. Share experience and coordinate efforts in hardware testing in space-relevant environments (vibrations, radiation hardness, vacuum, cryogenic environment, temperature cycling, etc.).
    d. Identify funding opportunities, communication with funding agencies.
    e. Further broaden international support by researchers and their respective national space agencies.
    f. Identify and coordinate technology-development or mission-proposal opportunities, communication with industry and space agencies.

QTSpace will support meetings within the respective thematic teams and strongly encourage interdisciplinary attendance, input and problem-solving strategies.

1.2.2. Capacity-building Objectives

QTSpace will include members of the four research efforts indicated in order to develop a common understanding in terms of:

- Identifying common ground and possible synergies
- Exchanging know-how related to hardware testing, space-relevant proof-of-principle experiments, data acquisition and evaluation, mission design, ground-segment operation
- Sharing relevant contacts to industry, funding agencies and national agencies

To fulfil these needs, four working groups are defined, which focus on the challenges discussed in section 1.2.1.

1.3. Progress beyond the state-of-the-art and Innovation Potential

1.3.1. Description of the state-of-the-art

Recent years have witnessed rapid progress in space technology over a wide range of fields. Developments for LISA (Laser Interferometer Space Antenna), LISA Pathfinder (LPF) and the LISA Technology Package (LTP) as well as for laser-enhanced high-precision instruments like the GRACE follow-on mission have rendered space an attractive platform for high-precision optical experiments. The demand for accurate orbit control has led to the need for increasingly accurate frequency standards in space, e.g., for enabling relativistic corrections in the Global Positioning System (GPS). New developments in micro propulsion and high-precision accelerometers now allow for excellent drag-free attitude-control systems and microgravity.

At the same time, the development of quantum technology has led to improvements in high-precision metrology, long-distance quantum communication as well as quantum control over increasingly massive physical systems. Using squeezed light and novel mirror coatings with reduced thermal noise, inspired by optomechanical concerns, can increase the sensitivity in optical interferometry for gravitational wave detection. Atom interferometry is fast becoming a ubiquitous technology for high-sensitivity accelerometers with a host of applications like, e.g., submarine navigation. Novel

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technological developments in atom chips promise further technological advances of such quantum sensors. Atom interferometers may allow for novel high-precision tests of the equivalence principle. Matter-wave interferometry with high-mass test particles like large molecules and clusters may lead to even more sensitive devices and novel tests of the foundations of physics. The current mass record is 10^4 atomic mass units (amu). Advances towards achieving quantum control over increasingly massive and complex physical systems promise the advent of experiments testing the foundations of physics in a new parameter regime and possible applications of quantum technology beyond what seemed impossible only a decade ago.
Overview of the state of the art in the four research efforts considered:

- Optical quantum communication. In a series of experiments, the technological readiness of optical quantum communication has been pushed to a point where optical links for quantum communication with satellites in Low-Earth Orbit (LEO) are within reach.
- Cold-atom interferometry in microgravity. Immense progress has been made in this respect using atom fountains, demonstrating atom interference on parabolic "zero-g" flights (ICE) and, in particular, in experiments in the Bremen drop tower (QUANTUS), which will soon lead to the first atom-interferometry experiments on a sounding rocket (MAIUS).
- High-mass matter-wave interferometry & Optomechanics. In 2010, the mission proposal MAQRO suggested using a space environment for high-mass matter-wave interferometry harnessing quantum optomechanics with trapped dielectric spheres to test the foundations of physics. In 2015, an updated form of this mission was proposed.
- Space-based optical atomic clocks. In 2016, a Cs clock (PHARAO) will be launched to the international space station, and the mission proposal STE-QUEST suggested to use an improved version of the PHARAO clock or even an optical atomic clock to test the gravitational redshift in a highly elliptical orbit and to synchronize atomic clocks on ground.

1.3.2. Progress beyond the state-of-the-art

QTSpace will aim at significantly pushing the four research efforts under consideration beyond state-of-the-art. In particular, all of these efforts will benefit from the interdisciplinary nature of the Action, from the combined, larger community supporting those efforts and from the chance of sharing resources, experience, contacts and know-how.
For example, one can consider combined missions harbouring instruments for all four research efforts sharing the same spacecraft, launch, orbit and ground segments. Another huge benefit could be performing drop-tower experiments similar to those already in progress for cold-atom interferometers. In particular, the communities working on high-mass matter-wave interferometry and space-based atomic clocks could benefit from the drop-tower and sounding-rocket experience of the atom-interferometer community. On the other hand, the different mission parameters envisioned for high-mass matter-wave interferometry may provide interesting opportunities for other communities, e.g., sun-observation missions at the L1 Earth-Sun Lagrangian Point, for long-distance quantum communication links, or for gravitational-wave missions like Astrod-I. In some mission scenarios it is crucial, for instance when testing for dark matter, to have multiple instruments aboard to perform simultaneous measurements in complementary parameter ranges.

In particular, with respect to technology development, QTSpace will provide significant advantages in coordinating research efforts proposing to meet technological challenges using complementary methods. For example, a core technology that needs to be developed for future space-based high-mass matter-wave interferometry is a reliable source of massive test particles fulfilling the strict prerequisites of matter-wave interferometry (e.g. low velocity, narrow velocity distribution, specific requirements on the number of charges allowed, low internal temperature of the test particles, operation in ultra-high vacuum). Several candidate technologies are in development at the moment, and these efforts need to be coordinated to efficiently realize the optimal solution for this specific challenge. Other challenges are space-qualified narrow-band laser sources needed for future quantum experiments in space (e.g. narrow-band, stable, diode-based laser sources at various wavelengths for addressing atomic transitions, for phase gratings in matter-wave interferometry, for spontaneous parametric downconversion) and space-qualified detectors (e.g. for single-photon detection, for homodyne detection, for detecting scattered light).

1.3.3. Innovation in tackling the challenge

Harnessing Quantum Technology is one of the most important challenges in present-day efforts in R&D. QTSpace meets the need to tackle QT in a space environment: to join four distinct international research efforts that started nearly independently to tackle the formidable challenges to be met when trying to push new technology to the readiness level needed for space-based experiments and applications. This COST Action will join those efforts into a unified approach to tackle these challenges. Bringing all European quantum scientists together in this way will help solidify the world-leading position of Europe with respect to quantum technology in space and testing the foundations of physics using quantum technology.

1.4. Added value of networking

1.4.1. In relation to the Challenge

In QTSpace, networking is more than simply an added value: it lies at the heart of this Action. The goal is to bring different communities together to **(1)** jointly tackle the challenges faced by space-related efforts; **(2)** form a broad basis for quantum technology in space; **(3)** push the technological readiness level of quantum technology one level higher to meet the requirements of next-generation high-precision experiments in space and thus enable novel applications.

1.4.2. In relation to existing efforts at European and/or international level

The various research efforts themselves have been pursued in a number of international efforts, receiving funding also on a European and international level over the last years. With respect to cold-atom interferometry and atomic clocks:
STE-QUEST: the communities for cold-atom interferometry and atomic clocks in space were selected for a study phase in the course of the M3 call of the European Space Agency for the mission proposal STE-QUEST.
ACES: the ACES mission is to be launched and then installed on the ISS in 2016. It will contain a Caesium atomic clock (PHARAO).
Space Optical Clocks (SOC): an international research effort funded by ESA (2007-2010) as a follow-up for ACES to develop technology for optical clocks in space.
Space Optical Clocks 2 (SOC2): An FP7-funded research effort following SOC with the goal of demonstrating transportable optical atomic clocks with higher precision than microwave ones.
Cold Atom Laboratory (CAL): in April 2016, NASA will launch an instrument for performing experiments with Bose-Einstein-Condensates with Rubidium atoms on the ISS. Later on, the instrument will allow experiments with Potassium atoms as well as dual-species BECs.
Cold Atom Interferometry (CAI): an ESA-funded effort to harness atom interferometry in space.
I.C.E.: a French-led action that demonstrated cold-atom interferometry on zero-g parabolic flights.
Since the early 2000s, there have been international efforts towards developing quantum communication with ground-to-satellite as well as satellite-to-satellite links:
Space-quest: an international effort that led, in 2007, to the formation of an ESA “Topical Team” aiming at putting a source of entangled photons as well as a source of decoy pulses on the ISS, including optical telescopes for ground links. The goal would be to enable global quantum key distribution and Bell-type tests of the foundations of physics.
Quantum Science Satellite: Chinese scientists aim at launching a satellite within the next few years aiming at similar goals as Space-quest.
NanoQEY: a Canadian effort proposing to use nanosatellites (e.g., CubSATs) for global quantum key distribution.
CubeSAT QKD: in Singapore, efforts are on the way to build space-proof hardware for the implementation of QKD using CubeSAT nanosatellites.

QubSat: efforts to build a CubeSAT platform for a single ground-to-space link for quantum communication.

In comparison to the other fields, using quantum optomechanics and high-mass matter-wave interferometry in space is a comparatively new field: in 2010, the **MAQRO** mission was proposed to test the foundations of physics in deep-space environment using quantum optomechanics and high-mass matter-wave interferometry. In 2015, an updated version of the mission proposal was published addressing critical issues and including an improved mission design.

QTSpace will form a common platform for international collaboration for those efforts, fostering efficient coordination between the various communities, academia, industry and space agencies.

2. IMPACT

2.1. Expected Impact

2.1.1. Short-term and long-term scientific, technological, and/or socioeconomic impacts

Short-term scientific impact. QTSpace will enable tests in completely new parameter regimes set by space-based environments. The Action will bring together a wide range of scientists with the expertise required to successfully plan and execute space missions on testing of fundamental physics theories. It will shape the community to concentrate and collaborate towards this important scientific goal. It will give rise to new experimental platforms for the investigation of mechanical systems at the quantum level, of cold atomic systems in free fall as well as entangled photons at large distances. They bridge the gap between disparate areas of investigation, from fundamental areas (general relativity, quantum physics, quantum gravity, macrorealism, collapse models, quantum decoherence) to technical progress in the management of fragile quantum states exposed to the action of hostile environments.

QTSpace will advance both the state-of-the-art of experiments and the theoretical underpinnings of the field. Further impact is expected for specific scientific disciplines: cavity optomechanics using optically trapped particles [high-mass matter-wave interferometry (HMWI)], matter-wave interferometry [atom interferometry (AI), HMWI], laser stabilization and ultra-stable optical components [HMWI, AI, optical atomic clocks (OAC), quantum communication (QC)], material science and handling of mesoscopic particles and quantum systems [HMWI], laser physics for generating higher-harmonic UV light [HMWI, QC], thermal engineering for passive radiative cooling [HMWI], bonding technology for optical space instrumentation [HMWI, OAC], high-sensitivity accelerometers [HMWI, AI], optical detectors [HMWI, QC], physics of decoherence [HMWI].

Long-term scientific impact. QTSpace will increase our understanding of quantum theory and gravity, the theoretical and experimental study of quantum systems towards the macroscopic, and the study of physics at the Planck scale [especially Planck mass], where manifold alterations of both gravity and quantum theory have been already predicted. Special Relativity will be tested by checking the universality of Lorentz invariance, which is a basic ingredient for the formulation of all Quantum Field Theories. Non-locality, which seems to be an intrinsic feature of nature in agreement with quantum theory, will be tested by Bell-type experiments and long-distance teleportation with entangled photon pairs. The equivalence principle, core to the framework of General Relativity will be tested by atom interferometry with two atomic species of different mass, and by high-precision optical atomic clocks. The unique opportunities provided by a space environment will allow for a new generation of more precise tests of those fundamental concepts and effects, dramatically changing our understanding of the underlying principles of nature.

Technological impact. QTSpace will develop new types of quantum technologies, offering, e.g., unrivalled measurement sensitivity of time, frequency and position. Although the primary goal is to explore the foundations of physics, the techniques that QTSpace members will develop, will have significant impact outside basic science and have the potential for significant technological and industrial impact. This includes the technological ability to detect tiny forces and displacements with unparalleled precision. Potential applications include inertial sensing and chemical/biological characterisation via precise measurement of the frequency of trapped complex particles.

The increase of technological readiness of quantum technology towards space readiness will result in reliable and robust quantum devices able to operate in harsh environments. Strict requirements on space hardware in terms of space and energy resources will foster increased efficiency in quantum protocols and data handling. Examples of technology that may profit from QTSpace are high-precision sensors and quantum communication. Moreover, these developments will benefit ground-based efforts for next-generation quantum technology. High-precision quantum-enhanced metrology will lead to advances in Earth observation, clock synchronization, tests of the foundations of physics and future global quantum-communication networks. For example, the ability to resolve high-mass particles in traps, in combination with novel methods for loading such particles in traps, as proposed for the MAQRO mission, will allow the extension of analytic techniques such as mass spectrometry to much larger proteins and viruses.

Photonic quantum communication in space will revolutionize communication devices and technology, on the one hand, for secure long-distance communication, on the other hand, for new quantum-enhanced long-distance communication and for global quantum networks for future quantum computers. At the same time, long-distance quantum communication will allow for new Bell-type tests of quantum physics, potentially also with high relative velocities between sender and receiver, testing relativistic influences on distributed entanglement.
Findings from quantum optomechanics are already revolutionizing high-precision interferometry on Earth, in particular, impacting gravitational-wave detectors. Adapting these technologies to a space-based environment will open the door for similar enhancements in space-based high-precision instruments.

Finally, research outcomes triggered by QTSpace will allow a more complete fundamental understanding of the laws of nature in quantum mechanics and gravity. These findings will have important technological implications for the fundamental limits in operating the increasing number of nanoscale quantum devices developed for sensing, simulation and information processing.

Socioeconomic impact. QTSpace will implement and develop new links between academia and space industry of high economic value. Even partial achievement of the declared goals of this Action would be sufficient to have substantive socioeconomical repercussions at the European level, *de facto* igniting the development of new technological products (transducers, sensors, clocks) and thus resonating with the EU job market. For instance, as new technology is core to QTSpace, innovative **spin-off companies** will result from the development of the necessary elements for a space mission. Earth-based proof-of-principle experiments will especially have impact in the emerging quantum technologies, which sees first entrepreneurial attempts.

The ideas explored in QTSpace are at the heart of our understanding fundamental physics about quantum mechanics and gravity, which continue to **inspire wide interest in the general public** thanks to paradoxes such as Schrödinger's Cat and the rift between the microscopic and macroscopic world. QTSpace will embark on a concerted effort to ensure that the general public is well-acquainted with the overarching scientific/technological goal of the Action.

QTSpace will bring together leading groups in the EU and beyond with a wide range of scientific, technological and management expertise to tackle problems of both fundamental and technical significance. The areas of expertise are both synergetic and complementary. The interlinked nature of the COST Action, coupled with practical and intellectual exchange that will occur, will inspire all participants. The network is geographically diverse and provides a unique opportunity for **effective inclusiveness** (via the participation of already 9 ITCs at the proposal stage) and **widened participation in European science**, promoting scientists in a field of much relevance to science, technology, and society, and empowering new actors on the stage of the scientific and technological areas tackled by the COST Action. Of particular importance will be the **integration of younger scientists**. This will provide them with knowledge and experience and will equip them with the breadth of intellectual and management skills that will be required for **future technological leadership**.

The expertise developed in QTSpace will put members in an excellent position to provide **expert advice to government and industry** on potential applications and worldwide trends in this technology, adding considerably to the EU's competitiveness in emerging quantum technologies.

2.2. Measures to Maximise Impact

2.2.1. Plan for involving the most relevant stakeholders

The most relevant stakeholders include: senior scientists, junior scientists (in particular Early Career Investigators - ECIs), industries, space agencies, policy makers, media, the general public.

Communication will be targeted to specific audiences:
1) For senior physics researchers. *i. Action website*: It will contain the list of scientific publications related to Action members, and the list of WG meetings, workshops, conferences and other events. *ii. Specialized Press*: Press releases of the most important findings will be prepared and submitted to the specialized press.
2) For junior physics researchers, in particular ECIs. *i. Action's website:* It will contain a list of WG meetings, workshops, conferences and other events. *ii. Participation to schools:* Schools will be organized, to train ECIs in specific fields related to QTSpace. *iii.* Posting of video-abstracts to Quantiki and/or New. J. Phys., and videos explaining QTSpace's activities.
3) For industrial partners. *i. Reports:* Technical reports about QTSpace and its development. *ii. Visits:* Invitations to visit groups and labs, and to group meetings. *iii: Outreach activities:* Talks to people in charge of industry R&D. Activities will be carried out both during and after the end of the Action. Moreover, industry stake holders will be invited to participate in scientific meetings and workshops organized in the course of QTSpace.. iv. Activities in QTSpace may lead to collaborations with industry partners in national and international projects.
4) For space agencies & policy makers. *i. Reports:* Technical reports about QTSpace and its development. *ii. Visits:* Invitations to visit groups and labs, and to group meetings. *iii: Outreach activities:* Representatives of space agencies and policy makers will be invited to participate in the Action. Space-agency representatives will be invited to seminars and workshops. Such activities will be carried out both during and after the end of the Action. *iv*: QTSpace will foster the start-up of novel projects with the involvement of space-agencies for exploratory studies, technological development and hardware testing.
5) For the general public. *i. Popular Press:* Research findings will be advertised on local/national newspapers and popular scientific magazines. *ii. Specialized Social Networks:* Relevant blogs (e.g. FQXi) will be addressed, to introduce QTSpace and its findings in a jargon-free language. Interaction with the public (e.g. via comments on posts) will be encouraged. *iii. Local scientific events*: QTSpace members will proactively organise local events targeted to the general public.

2.2.2. Dissemination and/or Exploitation Plan

Dissemination will be carried out primarily through the following channels: **Action Website**. It will contain the list of QTSpace-related papers, and a summary of findings. **Publication of research papers on high-impact peer-reviewed journals:** Research papers will be published on peer-reviewed journals with high impact factor. These include: Nature Publishing Group, Science, APS, IoP. **Publicly available preprints.** Copies of the research papers prepared with the support of QTSpace will be posted to the Cornell repository available at arxiv.org and on the Action's website. **Presentation of papers at scientific conferences.** Action members are frequently invited to major international conferences related to quantum physics and nano-science, which will be perfect contexts to disseminate the results related to QTSpace. **Invited Seminars**. Action members are regularly invited for seminars and colloquia at international institutions, where research results will be presented to peers.

Appropriate mechanisms for the sharing of intellectual property arising from collaborations within the members of the Action rights will be put in place by the COST Action Management Committee [cf. Section 3.2], supported by the legal offices at the respective institutions. QTSpace members shall bear responsibility for ensuring that they do not knowingly infringe third party property rights.

2.3. Potential for Innovation versus Risk Level

2.3.1. Potential for scientific, technological and/or socioeconomic innovation breakthroughs

The scientific plan upon which QTSpace is built is inherently ambitious and manifestly visionary. It combines potentially ground-breaking goals in modern quantum mechanics, whose validity will be tested right at the border between microscopic and macroscopic world, with the challenges of exploring completely unprecedented working conditions, such as those enabled by space-based experiments. By doing this, QTSpace will lay the foundation of a research programme that aims at merging two of the major scientific and technological accomplishments of the 20th century: quantum mechanics and space exploration. A whole new ground for quantum mechanical investigations at the macroscopic scale will be offered by the success of QTSpace, whose potential achievements will 'infect' science and technology at the fundamental and applied level.

Members of QTSpace will investigate the possibilities of new, more reliable ways of measuring time, positions and masses based on the laws of quantum mechanics, therefore potentially impacting on the market of sensing and metrology in a strong, original way. This will be instrumental to enabling breakthroughs of a more fundamental nature. Through the unrivalled precision of the transducers and interferometers that will be designed and realized through the work within QTSpace, visionary investigations on gravity and its relations to quantum mechanics, quantum communication, and the theory of decoherence will be turned into fundamental and technological progress and understanding. QTSpace will thus fill the gap existing in our understanding of the quantum framework, while providing a solid platform for the development of the quantum technologies that are expected to impact in the societal and economic panorama of this century.

In this respect, the high level of risk that is brought about by QTSpace is perfectly balanced and justified by the potential for enduring breakthroughs of a variegate nature.

3. IMPLEMENTATION

3.1. Description of the Work Plan

3.1.1. Description of Working Groups

QTSpace is structured in four Working Groups, corresponding to the objectives of the Action.

WG1: Fundamental Studies

Objective: Identify fundamental science questions to be addressed as well as the scientific and technical requirements to perform related experimental tests in space.
Tasks:
T1.1) Evaluate tests of fundamental theories in a space environment.
T1.2) Evaluate experimental possibilities to test fundamental theories.
T1.3) Explore the possibility of joint space mission for the different experimental platforms.
Activities:
A1.1) Yearly workshop on fundamental studies which need the space environment.
A1.2) One training school for young scientists, in particular for ECIs, on fundamental studies.
A1.3) WG meetings to trigger collaborative work of scientists to work on quantum experiments with different physical systems.
A1.4) STSMs for interaction within the WG and with other WGs.
Milestones:
M1.1) Revision and definition of key experiments using photons or atoms or large particles.
M1.2) Definition of key fundamental tests to be done.
M1.3) Definition of key parameters for planned experiments.
M1.4) Definition of possible joint missions.
Deliverables:
D1.1) List of experiments with different physical systems [scientific paper].
D1.2) List of fundamental tests [report].
D1.3) List of key parameters to enable tests [technical paper].
D1.4) Information about possible joint mission [report].

WG2: Applications

Objective: Identify possible applications of quantum technology (QT) in space, define the scientific and technical requirements.
Tasks:
T2.1) Technology developments (from proof of principles to applications) with industrial partners.
T2.2) Link to industry partners to develop enabling technologies for space experiment.
T2.3) Investigate applications of quantum technologies outside fundamental tests.
T2.4) Investigate the need of society and industry for QT in space.
Activities:
A2.1) Yearly workshop on applications of quantum technology in space.
A2.2) One training school for young researchers, in particular for ECIs, on applications of QT.
A2.3) WG meetings to coordinate identification of applications of quantum technologies in space in collaboration with industry and policy makers.
A2.4) STSMs for interaction within the WG and with other WGs.
Milestones:
M2.1) Identified applications of quantum technologies in space.
M2.2) Define the technical requirements for QT in space.
M2.3) Define pathway to reach technical requirements.
M2.4) Links to industry.

Deliverables:
D2.1) At least two identified concrete applications of QT in space [white paper].
D2.2) List of technical requirements for each application [technical paper].
D2.3) Two alternative paths for each realization of applications in D2.1 [technical paper].
D2.4) Industrial partners identified with interest/need in QT in space [report].

WG3: Proof-of-Principle Experiments

Objectives:
O3.1) Identification of the principles that should be demonstrated on ground, and coordination about the implementation of the respective experiments.
O3.2) Sharing of knowledge about available technologies and experimental techniques for performing experiments in space-relevant settings.
Tasks:
T3.1) Define the experimental details of each envisaged test in space.
T3.2) Check the technical availability for space approved technology.
T3.3) Definition of outstanding proof-of-principle tests.
T3.4) Planning of Earth-based tests: parabola flights, drop tower, sounding rockets etc.
Activities:
A3.1) Yearly workshop on status of proof-of-principle experiments for QT in space.
A3.2) One training school for young researchers, in particular for ECIs, on proof-of-principle tests.
A3.3) WG meetings to coordinate collaborative work on Earth based experimental tests
A3.4) STSMs for interaction within the WG and with other WGs.
Milestones:
M3.1) Definition of experiments to be done in space.
M3.2) Assessment of status quo of technological readiness for space.
M3.3) Coordination of outstanding proof-of-principle tests.
M3.4) Definition of realistic scenarios for space missions.
Deliverable:
D3.1) List of experimental parameters to be reached for each envisaged test [scientific paper].
D3.2) List of status quo of technology in space [review paper].
D3.3) Delivery of realistic time schedule for outstanding proof-of-principle tests [scientific paper].
D3.4) Plan for strategic preparation of space missions based on experimental reality [white paper].

WG4: Implementation

Objective: Transfer concrete scientific plans for missions into ready proposals.
Tasks:
T4.1) Identify common challenges regarding technology needs, mission parameters and design.
T4.2) Technology development in cooperation with space agencies and industrial partners.
T4.3) Share experience and coordinate efforts in hardware testing in space-relevant environments.
T4.4) Further international support by researchers and their respective national space agencies.
T4.5) Identify and coordinate technology-development and mission-proposal opportunities.
Activities:
A4.1) Yearly workshop on implementation of concepts for QT space missions [strong industry input].
A4.2) One training school for young researchers, in particular for ECIs, on tech implementation.
A4.3) WG meetings are also a platform to coordinate interaction with relevant industry, national and European space agencies as well as policy makers and funding agencies.
A4.4) STSMs for interaction within the WG and with other WGs.
Milestones:
M4.1) Definition of mission parameters for each envisaged mission.
M4.2) Assessment of status quo of technology and definition of further [needed] technologies.

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M4.3) Definition of industrial partners to develop technology to reach mission parameters.
M4.4) Definition of mission opportunities [funding] and pathways to reach technical readiness.
Deliverables:
D4.1) List of mission parameters [report].
D4.2) List of technology [report].
D4.3) List of partners [report].
D4.4) List of opportunities [white paper].

3.1.2. GANTT Diagram (MCm = MC meeting, WGm = WG meeting, Ws = Workshop, TS = Training School, M = milestone, D = deliverable).

Working Groups	Tasks	Year 1	Year 2	Year 3	Year 4
WG1	T1.1	M1.1	D1.1		
Activities: 1 WGm + Ws per	T1.2		M1.1, D1.2	M1.3	D1.3
year. 1 TS, year 1. STSMs.	T1.3				M1.4, D1.4
WG2	T2.1	M2.1	D2.1		
	T2.2		M2.2	D2.2	
Activities: 1 WGm + Ws per	T2.3		M2.3		D2.3
year. 1 TS, year 2. STSMs.	T2.4			M2.4	D2.4
WG3	T3.1	M3.1	D3.1		
Activities: 1 WGm + Ws per	T3.2	M3.2	D3.2		
year. 1 TS, year 3. STSMs.	T3.3		M3.3		D3.3
	T3.4			M3.4	D3.4
WG4	T4.1		M4.1	D4.1	
Activities: 1 WGm + Ws per	T4.2		M4.2		D4.2
year. 1 TS, year 4. STSMs.	T4.3		M4.3		D4.3
	T4.4			M4.4	
	T4.5				D4.4
Kick Off meeting		Month 0			
MC meetings		Month 11	Month 23	Month 35	Month 47
International Action Conferences		With MCm	With MCm	With MCm	With MCm
STSMs					
Progress & Final Report			Month 18	Month 36	Month 48

3.1.3. PERT Chart

In **Figure 1** shows how the different WGs interrelate.

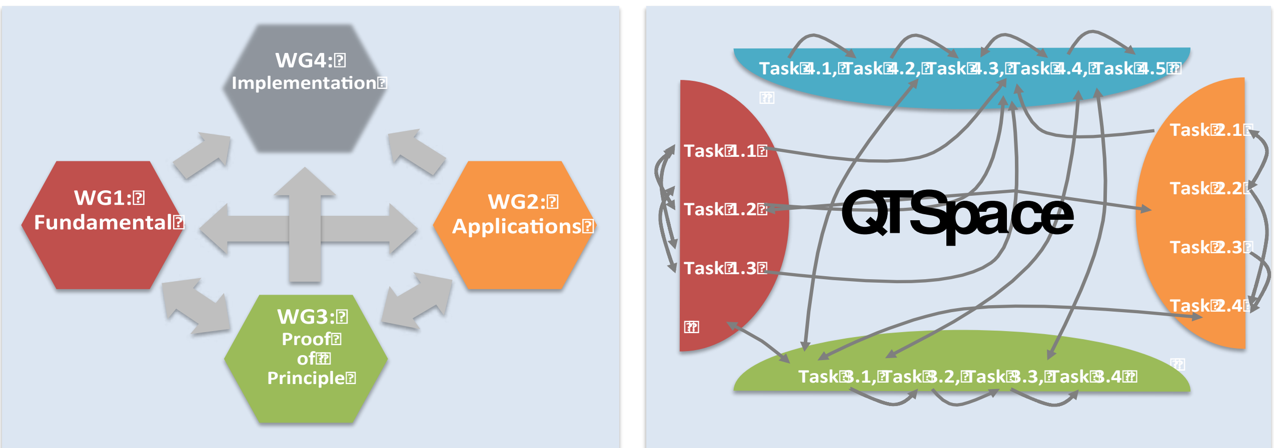

Figure 1: PERT Chart illustrating the interconnections among the WGs.

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3.1.4. Risks & Contingency Plans

The expertise available across QTSpace is deeply rooted into the needs of the Action itself. The Network of Proposers is thus endowed of the degree of excellence needed to achieve the scientific goals of QTSpace successfully. Specific risks and associated mitigation plans are described in Table 3.1.4a.

Table 3.1.4a

Description of WGs risk [*risk level*]	**Risk-mitigation measures**
WG1–Insufficient scientific readiness for space mission [***medium***]	Use alternative scientific questions to be addressed by experiments in space
WG2, WG4–Industrial partners are not interested in the R&D of technology for the envisaged space missions [***low***]	QTSpace, as an EU Action, can contact different/alternative industrial partners also in any participating country.
WG2 – There are no applications of Quantum Technology in space or technical requirements are too challenging [***low***]	Use the EU platform of QTSpace to extend links between the different stake holders [academia, industry, policy makers]
WG3–Proof-of-principle experiments fail [***medium***]	Use expertise within QTSpace to identify alternative solutions or redefine the scope of scientific question.
WG1-4–Violation of MoU by one or more partners, e.g. partners in Action do not share knowledge [***very low***]	Rescheduling of deliverables, removal/substitution of partners
WG4–Industrial/policymakers/funding agencies [IPF] are not supportive of the planned mission and do not support implementation [**medium**]	Use flexibility within COST Action [different countries and infrastructures] to work with different partners, Modification of mission according to input by IPF

3.2. Management structures and procedures

The organization of the Action will conform to the provisions of the document COST 134/14: “COST Action Management, Monitoring and Final Assessment” (9 December 2014). The coordination, implementation and management of the Action will be entrusted by the COST Action Management Committee (MC). It consists of up to two representatives from each Member Country or Cooperating State participating in the Action, and may include up to two representatives from Near Neighbour Countries or International Partner Countries as MC observers. As outlined in section 4.3 of the document COST 134/14, the MC will ensure the coordination, implementation and management of QTSpace, including the supervision of the allocation and use of funds.

A Chair and Vice Chair will be appointed for the whole duration of the Action. The Chair convenes MC and CG (Core Group, see below) meetings, and ensures rapid and efficient communication between the MC. He/She will be assisted by the Vice Chair. An Action secretary will be appointed to assist the Action Chair in preparing the scientific reports, distribute the Action’s newsletters, maintain contacts with the members, and keep the Action Website (see below) updated. A Grant Holder (GH), responsible for the financial management and administration of the Action under the COST Grant System, will be appointed.

Each WG will be chaired by a WG Leader, selected among MC members. WG Vice Leaders will be also appointed. They will be responsible for the management of their respective WGs, ensuring that objectives are met, tasks are performed, activities are carried out and milestones are reached, in accordance with the MoU. They will report to the MC at each MC meeting. A STSMs coordinator will be appointed. He/She will be responsible for implementing the STSM-plan, prepare the selection/review process of the STSM applications. Decisions will be taken by the CG and reported to the MC. COST Mission and Policies Supervisor. He/She will promote and supervise the implementation of COST policies, with special focus on: promotion of gender-balance, support of Early Career Investigators and involvement of COST Inclusiveness Target Countries.

A Core Group (CG) will be nominated to assure more rapid, efficient and flexible coordination of the Action. The CG will be formed by the Chair, Vice Chair, the WG Leaders, by the STSMs manager, and by COST mission and policies supervisor. The CG will prepare all relevant documents (scientific, orientation, reports, etc) for the MC meetings.

The Action will start with a Kick-off meeting, to be held in Brussels and organized by the COST office. All appointed MC members (up to two representatives from each Member Country or Cooperating State who signed the MoU) will be invited. At the Kick-off meeting: *(i)* The Action Chair and Vice Chair, the Grant Holder, the WG Leaders and Vice Leaders, the STSMs coordinator and the COST Mission and Policies Supervisor will be elected. *(ii)* The Core Group will be nominated. *(iii)* Practical rules for the implementation of the Action will be discussed and voted.

MC meetings will be organized once per year, unless unexpected events impose otherwise. The Agenda will be prepared by the CG and approved by the COST office. The yearly Work and Budget Plan will be discussed and approved. In between MC meetings, decisions will be taken by electronic vote, as specified in Article 3, Annex I of document COST 134/14. Each MC meeting will be followed by an International Action Conference, which will include the scientific activities of the four WGs and will be open to the larger scientific community. All other scientific activities will be organized as described in Sections 3.1.1 and 3.1.2.

An Action Website will be set up, with three levels of access: *(a) QTSpace-only level*. This access level will allow private information-exchange between QTSpace members. It will contain all relevant documents, in particular: minutes of meetings, electronic votes and outcomes, scientific and financial reports, STSM reports. *(b) Specialist-access level.* The public area will allow broad dissemination of the Action outcomes in form of common scientific publication database and information on past and upcoming events. This will contain information about the management structure, contact points and activities of the Action, including conferences, Workshops, Training Schools, training events (both within the network and worldwide), a list of potential host groups for technical visits and training. Links to publications and articles in scientific and technical journals, proceedings, job opportunities, PhD and MSc studentships will also be available. *(c) Public-access level.* QTSpace attaches great importance to the accurate dissemination of science to the widest audience. See also Section 2.2.1. This area of the website will provide information about the frontiers of research related to the Action, which is accessible to people without a specific background in physics.

COST Policies. QTSpace will carefully address COST policies, maximising efforts in order to implement them successfully.

Policy on COST Excellence and Inclusiveness. QTSpace will adopt the following measures: *(a) ITC participation*. QTSpace will be advertised to colleagues working in ITCs to encourage their active participation in the Action, above and beyond the level of participation from such countries that have already been secured (9 countries already). Action members from ITCs will be given leading roles in the Action and at least 30% of the QTSpace events will be organized in ITCs. *(b) Gender balance*. QTSpace already includes a significant representation from female scientists (in line with typical percentage in the community). The Action will ensure that female members of QTSpace take leading roles in its management. Moreover, suitable measures will be taken to facilitate the participation of female scientists to any meeting of QTSpace, whenever necessary (for example in the form of childcare facilities). Finally, the Action will liaise with any country-specific initiative for the enhancement of the participation of women in science to establish factual joint-programme for the stimulation of a balanced contribution from all genders. *(c) Early Career Investigators (ECIs)*.

Significant space will be given to ECIs as speakers at workshops and conferences. *ii.* Participation of ECIs to Action's events will be supported through targeted measures of financial support. *iii.* WG Vice Leaders will be selected among ECIs (or, in any case, among junior researchers). *iv.* In the selection of STSMs, priority will be given to ECIs.

Policy on Industrial Dimension. QTSpace will naturally involve space industries, to develop the readiness level of technology needed for future applications in space or for space mission. This is part of the goals of QTSpace. The Action will create a platform for fruitful collaborations between researchers and industry. WG meetings will be open to representatives of the industry, and will allow researchers and industry to meet and foster mutual understanding. QTSpace will increase the impact of research in the industrial sector, by promoting the use and development of technologies, as well as the exploitation of COST Action results and outcomes through dedicated dissemination and exploitation activities targeting small and medium-sized enterprises (SMEs) and large companies in Europe.

Policy on COST International Cooperation. The interest in Quantum Technologies in Space goes well beyond the European dimension. QTSpace will foster international cooperation with big actors in space activities, e.g., NASA. Participation of NNCs, IPCs to Action's activities (WG meetings, workshops, conferences) will be fostered. This will be facilitated by the strong scientific links between participants and the most prominent scientists worldwide in the field. QTSpace will become the driving force for harnessing quantum technology in space and for studying fundamental science in space at EU as well as the international level.

3.3. Network as a whole

QTSpace will bring together world experts in their respective fields to secure the achievement of the Action's objectives. All major EU countries plus 9 COST ITCs already are involved in QTSpace. More countries and institutions will be invited using existing international contacts of participants to organizations like ESA and NASA but also industrial partners and further research institutions.

Specific excellence include: Theory of quantum foundations and of open quantum systems (decoherence) and collapse models, classical and quantum gravity, quantum optics, quantum information and quantum effects at mesoscopic scales; Experiments in atom interferometry and Bose-Einstein condensation, matter-wave interferometry, cavity optomechanics and Bell tests with entangled photons, trapping of atoms, ions and nanoparticles; Theory and experiment of cavity cooling of dielectric particles, realization of high-precision ultra-low noise electronics; design and manufacturing of ultra-stable optical elements, cavities and lasers, laser stabilisation, advanced imaging technology, Material science: synthesis and engineering of colloidal nanoparticles, as well as chemical and structural transformations.

QTSpace involves key players of the different communities for photonic quantum communication, atomic clocks, cold atoms and nanoparticles. This will facilitate extending the overall network to include even more members from those communities. QTSpace will foster and further such collaborations to strengthen the strategic impact for a space mission. QTSpace aims at establishing a bridge to relevant industrial actors and work towards space-ready technology. The four experimental platforms at the core of QTSpace have all previously been considered in proposals for space missions submitted to ESA. Moreover, they are at the core of the interests of industries working in the (quantum) technological and space sector, both within and outside the EU. The links to industry and ESA will be strengthened by the activities of this Action.

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