

PAPER • OPEN ACCESS

Research campaign: Macroscopic quantum resonators (MAQRO)

To cite this article: Rainer Kaltenbaek *et al* 2023 *Quantum Sci. Technol.* **8** 014006

View the [article online](#) for updates and enhancements.

You may also like

- [Disturbance-based measure of macroscopic coherence](#)
Hyukjoon Kwon, Chae-Yeun Park, Kok Chuan Tan et al.
- [Multi-second magnetic coherence in a single domain spinor Bose–Einstein condensate](#)
Silvana Palacios, Simon Coop, Pau Gomez et al.
- [Gravitational effects in macroscopic quantum systems: a first-principles analysis](#)
Charis Anastopoulos, Michalis Lagouvardos and Konstantina Savvidou

Quantum Science and Technology



PAPER

Research campaign: Macroscopic quantum resonators (MAQRO)

OPEN ACCESS

RECEIVED
1 July 2022

REVISED
26 October 2022

ACCEPTED FOR PUBLICATION
17 November 2022

PUBLISHED
5 January 2023

Original Content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Rainer Kaltenbaek^{1,2,39,*} , Markus Arndt³ , Markus Aspelmeyer^{2,3} , Peter F Barker⁴ , Angelo Bassi^{5,6}, James Bateman⁷, Alessio Belenchia^{8,9} , Joel Bergé¹⁰ , Claus Braxmaier^{11,12}, Sougato Bose⁴, Bruno Christophe¹⁰, Garrett D Cole^{13,14} , Catalina Curceanu¹⁵, Animesh Datta¹⁶ , Maxime Debiossac², Uroš Delić³ , Lajos Diósi^{17,18}, Andrew A Geraci¹⁹ , Stefan Gerlich³, Christine Guerlin²⁰, Gerald Hechenblaikner²¹, Antoine Heidmann²⁰ , Sven Herrmann²², Klaus Hornberger²³, Ulrich Johann, Nikolai Kiesel³, Claus Lämmerzahl²², Thomas W LeBrun²⁴, Gerard J Milburn²⁵, James Millen²⁶ , Makan Mohageg²⁷, David C Moore²⁸ , Gavin W Morley¹⁶ , Stefan Nimmrichter²⁹, Lukas Novotny^{30,31} , Daniel K L Oi³² , Mauro Paternostro⁹ , C Jess Riedel³³, Manuel Rodrigues¹⁰ , Loïc Rondin³⁴ , Albert Roura¹² , Wolfgang P Schleich^{35,36,37} , Thilo Schuldt¹², Benjamin A Stickler²³, Hendrik Ulbricht³⁸, Christian Vogt²² and Lisa Wörner¹²

- 1 Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia
- 2 Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Vienna, Austria
- 3 Faculty of Physics, Vienna Center for Quantum Science and Technology, University of Vienna, Vienna, Austria
- 4 Department of Physics and Astronomy, University College London, London, United Kingdom
- 5 Department of Physics, University of Trieste, Trieste, Italy
- 6 Trieste section, Istituto Nazionale di Fisica Nucleare (INFN), Trieste, Italy
- 7 Department of Physics, College of Science, Swansea University, Swansea, United Kingdom
- 8 Institut für Theoretische Physik, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
- 9 CTAMOP, School of Mathematics and Physics, Queen's University Belfast, Belfast, United Kingdom
- 10 Department of Physics, Instrumentation, Environment and Space (DPHY), ONERA, Université Paris Saclay, Châtillon, France
- 11 Institute of Microelectronics, Ulm University, Ulm, Germany
- 12 Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany
- 13 Thorlabs Crystalline Solutions, Santa Barbara, CA, United States of America
- 14 Crystalline Mirror Solutions, Santa Barbara, CA and Vienna, Austria
- 15 Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati (LNF), Frascati (Roma), Italy
- 16 Department of Physics, University of Warwick, Coventry, United Kingdom
- 17 Wigner Research Center for Physics, Budapest, Hungary
- 18 Department of Physics of Complex Systems, Eötvös Loránd University, Budapest, Hungary
- 19 Center for Fundamental Physics, Department of Physics and Astronomy, Northwestern University, Chicago, IL, United States of America
- 20 Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, Paris, France
- 21 Airbus Defence and Space GmbH, Friedrichshafen, Immenstaad, Germany
- 22 ZARM, University of Bremen, Bremen, Germany
- 23 Faculty of Physics, University of Duisburg-Essen, Duisburg, Germany
- 24 National Institute of Standards and Technology, Gaithersburg, MD, United States of America
- 25 Centre for Engineered Quantum Systems, School of Mathematics and Physics, The University of Queensland, Brisbane, Australia
- 26 Department of Physics, King's College London, London, United Kingdom
- 27 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States of America
- 28 Wright Laboratory, Department of Physics, Yale University, New Haven, CT, United States of America
- 29 Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen, Germany
- 30 Photonics Laboratory, ETH Zürich, Zürich, Switzerland
- 31 Quantum Center, ETH Zürich, Zürich, Switzerland
- 32 SUPA Department of Physics, University of Strathclyde, Glasgow, United Kingdom
- 33 Physics & Informatics Laboratories, NTT Research, Inc., Sunnyvale, CA, United States of America
- 34 CNRS, ENS Paris-Saclay, Centrale Supélec, LuMin, Université Paris-Saclay, Gif-sur-Yvette, France
- 35 Integrated Quantum Science and Technology (IQST), University of Ulm, Ulm, Germany
- 36 Hagler Institute for Advanced Study and Department of Physics and Astronomy, Institute for Quantum Science and Engineering (IQSE), Texas A&M University, College Station, TX, United States of America
- 37 Texas A&M AgriLife Research, Texas A&M University, College Station, TX, United States of America
- 38 Department of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 39 Primary Author. Names after the first author sorted alphabetically.
- * Author to whom any correspondence should be addressed.

E-mail: rainer.kaltenbaek@mf.uni-lj.si

Keywords: quantum physics, optomechanics, matter waves, optical trapping, decoherence

Abstract

The objective of the proposed macroscopic quantum resonators (MAQRO) mission is to harness space for achieving long free-fall times, extreme vacuum, nano-gravity, and cryogenic temperatures to test the foundations of physics in macroscopic quantum experiments at the interface with gravity. Developing the necessary technologies, achieving the required sensitivities and providing the necessary isolation of macroscopic quantum systems from their environment will lay the path for developing novel quantum sensors. Earlier studies showed that the proposal is feasible but that several critical challenges remain, and key technologies need to be developed. Recent scientific and technological developments since the original proposal of MAQRO promise the potential for achieving additional science objectives. The proposed research campaign aims to advance the state of the art and to perform the first macroscopic quantum experiments in space. Experiments on the ground, in micro-gravity, and in space will drive the proposed research campaign during the current decade to enable the implementation of MAQRO within the subsequent decade.

1. Science case and motivation

Are there fundamental limits to the size, complexity, or mass of quantum superpositions? Do we fully understand all fundamental sources of decoherence leading to the decay of macroscopic quantum states or will we see deviations due to yet unknown physics? Gravitational time dilation [1, 2] or space-time fluctuations [3], for example, may result in modifications of the Schrödinger equation, decoherence and a quantum–classical transition [4]. Identifying such modifications would provide new insights for understanding the fundamental laws of Nature. With the space-based platform MAQRO proposed here, these questions will be answered by observing free quantum evolution and interference of dielectric test particles with radii of about 100 nm.

Quantum physics predicts that physical systems of arbitrary size and complexity can be in superpositions of distinct states. This is well illustrated by Schrödinger’s dead-and-alive cat gedankenexperiment [5]. While challenging our intuitive understanding of reality, the predictions of quantum theory have been confirmed with large molecules consisting of thousands of atoms and masses of up to 3×10^4 amu (atomic mass units) [6].

MAQRO will investigate sources of decoherence affecting macroscopic quantum superpositions, such as the scattering of residual gas, or solar/cosmic radiation. MAQRO also has the potential to detect some forms of dark or exotic matter [7–9], and for rare scattering processes in a space environment. Results on the interplay between quantum physics and gravity as well as measurements sensitive to dark or exotic matter could provide input for the standard model of cosmology, for possible extensions of the standard model of particle physics, and for a better understanding of the origin of the Universe and the foundations of physics.

1.1. Science objectives

The science objectives (SOs) of the medium-size mission proposal MAQRO submitted to the European Space Agency (ESA) [10, 11] were as follows:

- **SO1:** Testing the predictions of quantum physics in parameter regimes that overlap with ground-based tests.
- **SO2:** Testing standard decoherence mechanisms with test particle sizes and masses beyond existing experiments.
- **SO3:** Testing gravitational decoherence with sufficiently massive test particles.

This research campaign will investigate whether the experiments suggested for MAQRO can be adapted to address additional objectives (AOs) including but not limited to:

- **AO1:** Measuring the effect of decoherence on rotational quantum revivals.
- **AO2:** Using the macroscopic quantum systems on MAQRO or trapped charged particles as highly-sensitive detectors for dark or exotic matter.

MAQRO is based on optomechanics with optically trapped dielectric particles [12–14]. After their release, their free evolution is monitored over long periods of time. While this remains the central approach of MAQRO, we will also investigate the feasibility of measuring rotational quantum revivals as an additional experimental method (AO1 above). This would allow testing quantum physics with independent approaches:

interference in the center-of-mass (CM) and in the orientational degrees of freedom. A high level of orientational control will also benefit the precision of the measurements using CM superposition.

Optically trapped particles may be able to detect dark matter [15] and exotic physics, especially when operated at [16, 17] or beyond [7–9] the standard quantum limit. Attaining the requirements for achieving the primary SOs of MAQRO (SO1–3) will enhance the detection sensitivity to sources of anomalous diffusion [18, 19] to unprecedented degrees. The environmental isolation and large test particle masses in MAQRO provide perfect conditions for detecting impulses or accelerations imparted by relic dark matter particles over a wide range of parameter space for mass and interaction strength [8, 9] (AO2 above). We also expect improved sensitivity to additional models of dark matter including composite particles [15] or ultralight dark matter [20], which will be investigated in detail.

1.2. Science requirements

A macroscopic quantum object in superposition must be isolated from its environment to prevent decoherence by scattering of surrounding particles. Depending on how much information a scattering event carries away, the decoherence will be (a) in the short-wavelength limit, where a single scattering event may destroy the superposition, or (b) in the long-wavelength limit, where the superposition may survive many scattering events [21, 22]. To observe macroscopic superpositions, the probability of short-wavelength scattering events must be negligible [23]. This can be monitored using weakly trapped test particles or their free evolution. In the presence of long-wavelength decoherence, the evolution of a test particle's CM in 1D is given by a Markovian master equation [22]:

$$\dot{\hat{\rho}}(t) = (i/2 m\hbar)[\hat{\rho}, \hat{p}^2] - \Lambda[\hat{\mathcal{O}}, [\hat{\mathcal{O}}, \hat{\rho}]]. \quad (1)$$

\hbar : reduced Planck's constant, m : test-particle mass, dot: time derivative, \hat{x}, \hat{p} : position and momentum operators; $\hat{\rho}(t)$: density operator at time t . $\hat{\mathcal{O}}$ can be replaced by \hat{x} for decoherence in the position basis, or by $\hat{p}^2/(2m)$ for decoherence in the energy basis, such as predicted by theories in the frameworks of general relativity and quantum field theory [24, 25]. The two terms on the right-hand side represent coherent quantum evolution and decoherence, respectively. The decoherence parameter Λ encodes the strength of both environmental decoherence and of fundamental deviations from the predictions of quantum physics.

We will describe the science requirements needed to fulfill the SOs in terms of the range of values of Λ our experiments need to be sensitive to. Based on this, we will derive the required test masses, particle sizes, particle and environment temperatures, and vacuum conditions. To illustrate this for testing gravitational decoherence [4] with transparent, dielectric particles, we will consider the 'K model' of gravitational decoherence by Károlyházy [3, 26] and the 'DP model' of gravitationally induced collapse by Diósi and Penrose [27–30] for continuous mass distributions [31]. For particles below a critical size, the K model predicts a negligibly small Λ . Close to that critical size (~ 100 nm), the predictions of the two models intersect. In MAQRO, we aim to achieve sensitivity to the values of Λ in this range or larger. This corresponds to radii of 100–180 nm, and a mass of $\sim 10^{10}$ amu. Sensitivity in this regime requires the detection of decoherence parameters of $\Lambda \geq 10^{11} \text{ s}^{-1} \text{ m}^{-2}$. For a superposition size Δx comparable to the particle radius, this requires coherence times $1/(\Lambda \Delta x^2) \geq 10^2 \text{ s}$. Reducing these times would require even larger superpositions, which become increasingly difficult to achieve. Free evolution times of a few 100 s may be feasible, depending on the attainable vacuum and on the shielding from electrons [23]. For example, a measurement time of ~ 100 s will require a scattering rate below 10 mHz. In helium gas at 20 K, that value corresponds to $\lesssim 10^{-15}$ mbar. Achieving these extremely high vacuum (XHV) conditions is a critical challenge [23]. An alternative approach may be to apply the method of quantum mechanical squeezing. This could reduce the required free-fall times [19] with the downsides of adding complexity and noise. Equivalently, with access to an XHV environment, squeezing would enable tests of even weaker decoherence effects.

MAQRO will measure Λ using dielectric test particles of varying transparent materials and radii via the following methods [11, 23]:

- (a) monitoring the heating of the CM motion of a weakly trapped particle.
- (b) monitoring the wavepacket expansion of particles released from a trap.
- (c) observing near-field matter-wave interference.

We will investigate the feasibility of integrating further measurement techniques:

- (d) orientational quantum revivals of rotating test particles.
- (e) monitoring trapped charged particles to detect dark or exotic matter.

To define the science requirements, we will focus on method (c). For near-field interferometry with a grating period d , the Talbot time $md^2/(2\pi\hbar)$ determines the time scale. For 10^{10} amu test particles and a grating period of 100 nm, this yields a baseline value of 100 s [11, 32].

To achieve a sensitivity to values of Λ as low as $10^{11} \text{ s}^{-1} \text{ m}^{-2}$, decoherence effects have to be suppressed very efficiently, which means that the requirements on both environment and test particle become very stringent, for example in terms of temperature. The precise limits on these temperatures depend on the material properties of the test particles. For silica particles, the limit is $\lesssim 20$ K for both particle and environment. For silicon particles, the requirements remain more relaxed with temperatures $\lesssim 50$ K.

1.3. The case for space

Experiments testing macroscopic quantum superpositions in space have several key advantages. Some objectives may not be achievable on ground:

(a) *Long coherence times and free-evolution times.*

Observing the evolution of macroscopic quantum states on Earth requires trapping test particles, e.g. via optical [12–14], electrostatic [33] or magnetic fields [34]. Trapping will inevitably couple the systems to vibrations or to noise in the trapping potential or lead to decoherence due to scattering or absorption [35, 36]. Methods to accelerate the time evolution of the quantum state [34] may add excess noise.

(b) *Isolation from low-frequency vibration or Newtonian noise.*

Such noise can, e.g. wash out interference patterns or heat the CM motion of trapped particles. Space can provide excellent microgravity (μg) conditions. For this purpose, orbits around Earth–Sun Lagrange points are good candidates. This was demonstrated impressively by the pathfinder mission for the Laser Interferometer Space Antenna (LISA Pathfinder) [37].

(c) *Avoiding dephasing in gravitational potentials.*

Gravitational time dilation can lead to dephasing between different branches of superpositions in a gravitational field [1, 2]. While this is not an issue for freely falling interfering particles, it may become relevant if guiding potentials are employed [38].

(d) *Avoiding the shielding of dark matter/exotic matter by the atmosphere.*

Some dark and exotic matter candidates within the detection range of MAQRO would be blocked by, or thermalize with, Earth's atmosphere before reaching terrestrial detectors [8, 9]. MAQRO, in space, would have clean exposure to any dark matter flux coming from outside the Solar System, including the anisotropic dark matter 'wind' that would give a directional signal [9]. Exposing the test particle to dark matter/exotic matter while shielding the test particle from electron radiation will be one of the key challenges and an integral part of the proposed research campaign.

2. Mission design and technological readiness

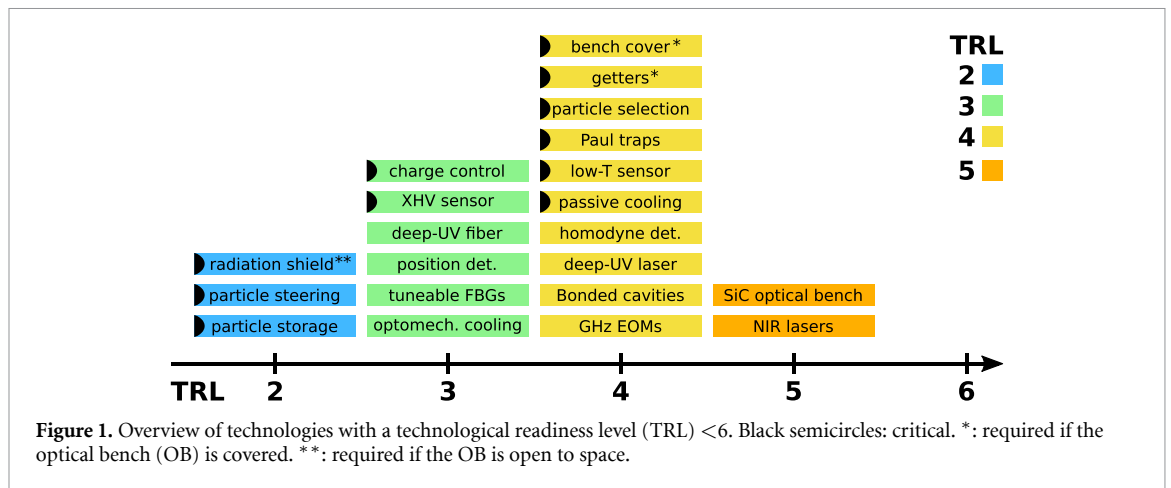
MAQRO can harness a space environment for experiments at cryogenic temperatures and in XHV on an external optical bench (OB) [10, 11]. While earlier studies aimed to achieve the required temperature via passive radiative cooling [39], the 'quantum physics platform' (QPPF) feasibility study [23] proposed additional active cooling to ensure temperatures < 20 K, and to encase the OB, which will prevent electrons from charging the test particles. The cover, however, renders XHV more difficult.

For a successful realization of MAQRO, three *critical issues* (C1–C3) will have to be addressed [23]. An XHV environment will need to be established and the test particles will need to be protected from electrons (C1). These particles need to be loaded into an optical trap, and their charge, mass, radius and material properties must be well characterized (C2). To implement matter-wave interferometry, a phase grating will be used to prepare macroscopic superpositions [11, 40]. For large particles, the scattering of grating photons may decohere the quantum state (C3).

This needs to be done while fulfilling other key requirements including cryogenic temperatures. Developing relevant solutions will be an essential part of this campaign. Experiments on the ground and pathfinders in space will address C1. With respect to C2, groups continue working on reliable methods to load test particles into optical traps in vacuum (e.g. see [41, 42]). Ideas based on QPPF [23] and on an ESA-funded study [43] are being investigated by ESA contractors. With respect to C3, it was shown that matter-wave interferometry is still possible even for large test particles [32]. More work is required to ensure MAQRO's SOs will be achieved, or to develop an alternative approach for preparing macroscopic CM superpositions.

The technological readiness levels (TRLs) of key technologies need to be increased (see figure 1):

(a) optomechanical cooling, (b) electro-optic modulators, (c) near-infrared lasers, (d) open-access cavities,



(e) position detection, (f) a deep ultra-violet (UV) laser source, (g) fibers for deep UV, (h) fiber Bragg gratings, (i) homodyne detection, (j) a silicon-carbide (SiC) OB, (k) passive radiative cooling, (l) XHV pressure sensors, (m) low-temperature (low-T) sensors, (n) particle charge control, (o) Paul traps, (p) particle characterization, (q) storage, and (r) steering. If the OB is covered, the cover (s) and non-evaporable getters (t) have to be developed. If the OB is open to space, electromagnetic shielding (u) must be developed to protect the test particles from electrons.

3. The research campaign

Technology development during the current decade could enable the implementation of MAQRO before 2040. We envisage in-orbit demonstrations to de-risk the critical components identified above and leveraging small satellite systems to accelerate mission development [44].

Figure 2 provides an overview of key activities of this research campaign:

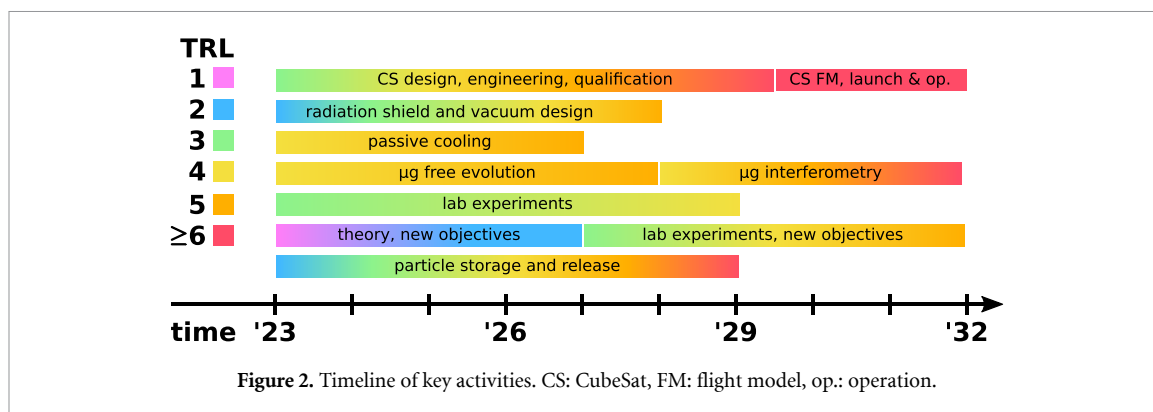
- theoretical analysis of new SOs, the corresponding scientific requirements, and the feasibility of addressing these objectives with MAQRO.
- laboratory experiments on matter-wave interferometry, rotational revivals, and proof-of-principle tests addressing potential new SOs.
- design and test passive cooling for MAQRO and CubeSat pathfinders.
- design and test radiation shields for MAQRO and CubeSat pathfinders to protect the test particles from electrons on platforms open to space.
- experiments on free quantum evolution in μg may reach TRL 3 by 2023. These will be followed by matter-wave interferometry in μg .
- several methods for particle storage, release and characterization are under investigation and may reach TRL 3 by the time this campaign starts.

Experiments will aim to close the gap between state-of-the-art ($\sim 3 \times 10^4$ amu [6]) and the minimum test masses in MAQRO ($\sim 10^8$ amu) with CM interference [40, 45], orientational quantum revivals [46, 47] or electrostatically levitated objects [33, 48].

3.1. MAQRO Pathfinders

μg and space experiments will be essential to better understand the effects of a space environment on macroscopic quantum superpositions, and how to achieve XHV and protection from radiation. This will be addressed by CubeSat pathfinders:

- MAQRO Pathfinder 1 (MAQRO-PF1) CubeSat: low-Earth orbit (LEO) demonstrator for key technologies, e.g. passive-cooling concepts [39, 49] or trapped particles as XHV sensors after a wakeshield [50–52].
- MAQRO Pathfinder 2 (MAQRO-PF2) CubeSat: ride-share to the Earth–Sun Lagrange point L2: test XHV, radiation conditions & passive cooling. Show long free evolution for macroscopic superpositions.



3.2. Cost Estimate

We estimate the cost at completion of MAQRO as \sim \\$550 M [10, 11, 23], not taking into account remaining research and development. The wet mass of MAQRO is 1700–1900 kg [11, 23]. An orbit around the Earth–Sun Lagrange point L2 is optimal [23].

In addition, we assume \\$50 M for technology development, instrument delivery, spacecraft I&T, and missions operations support. We estimate \\$120 M for the research campaign during this decade. MAQRO-PF2 can be executed for an estimated \\$15 M. The cost and schedule information in this document is of a budgetary and planning nature. It does not constitute a commitment on the part of any of the authors or their host institutions. We encourage a joint ESA-NASA effort to advance MAQRO, in the spirit of the Bose Einstein Condensates and Cold Atoms Lab and other multi-national scientific collaborations. Parallel support would multiply the science return, with this effort leveraging the expertise of partners across Europe and the US.

4. Summary

Experiments and theoretical studies performed in the current campaign will address remaining critical issues in MAQRO and investigate the feasibility of adding novel experimental methods and SOs. Developing key technologies will lay the groundwork for pathfinder CubeSat missions in LEO and around the Earth–Sun Lagrange point L2. These will act as in-orbit demonstrators and provide insights into how the space environment affects quantum systems, and how it can be harnessed for realizing macroscopic quantum experiments.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

The authors acknowledge support from the COST Action QTSpace (CA15220). R Kaltenbaek acknowledges support by the Slovenian Research Agency (N1-0180, J2-2514, J1-9145, P1-0125), and by the Austrian Research Promotion Agency (889767). A Bassi acknowledges financial support from the H2020 FET Project TEQ (Grant No. 766900), the Foundational Questions Institute and Fetzer Franklin Fund, a donor advised fund of Silicon Valley Community Foundation (Grant No. FQXi- RFP-CPW- 2002), INFN and the University of Trieste. A Belenchia acknowledges support from the German Research Foundation (DFG) Project No. BR 5221/4-1. A Datta was supported by UK STFC grants ST/T006404/1 and ST/W006308/1. C Curceanu acknowledges financial support from INFN, from the Foundational Questions Institute and Fetzer Franklin Fund, a donor advised fund of Silicon Valley Community Foundation (Grants No. FQXi-RFP-CPW-2008 and FQXi-MGB-2011) and from the John Templeton Foundation (Grant 62099). L Diósi acknowledges financial support from the National Research, Development and Innovation Office ‘Frontline’ Research Excellence Programme (Grant No. KKP133827), from the Foundational Questions Institute and Fetzer Franklin Fund, a donor advised fund of Silicon Valley Community Foundation (Grants No. FQXi-RFP-CPW-2008), and from the John Templeton Foundation (Grant 62099). D C Moore is supported by NSF PHY-1653232 and ONR N00014-18-1-2409. G W Morley is supported by the Royal Society (RGF\EA\180311 and UF160400), by the UK EPSRC (EP/V056778/1 and EP/T001062/1) and by the

UK STFC (ST/W006561/1 and ST/S002227/1). D K L Oi acknowledges the support of the UK EPSRC (EP/T517288/1, EP/T001011/1, EP/W027011/1). A Roura is supported by the Q-GRAV Project within the Space Research and Technology Program of the German Aerospace Center (DLR).

ORCID iDs

Rainer Kaltenbaek  <https://orcid.org/0000-0002-9991-9919>
Markus Arndt  <https://orcid.org/0000-0002-9487-4985>
Markus Aspelmeyer  <https://orcid.org/0000-0003-4499-7335>
Peter F Barker  <https://orcid.org/0000-0001-9669-9853>
Alessio Belenchia  <https://orcid.org/0000-0002-0347-6763>
Joel Bergé  <https://orcid.org/0000-0002-7493-7504>
Garrett D Cole  <https://orcid.org/0000-0001-7149-3218>
Animesh Datta  <https://orcid.org/0000-0003-4021-4655>
Uroš Delić  <https://orcid.org/0000-0002-1426-7289>
Andrew A Geraci  <https://orcid.org/0000-0001-7009-0118>
Antoine Heidmann  <https://orcid.org/0000-0002-0784-5175>
James Millen  <https://orcid.org/0000-0002-6950-3461>
David C Moore  <https://orcid.org/0000-0002-2358-4761>
Gavin W Morley  <https://orcid.org/0000-0002-8760-6907>
Lukas Novotny  <https://orcid.org/0000-0002-9970-8345>
Daniel K L Oi  <https://orcid.org/0000-0003-0965-9509>
Mauro Paternostro  <https://orcid.org/0000-0001-8870-9134>
Manuel Rodrigues  <https://orcid.org/0000-0002-8573-8068>
Loïc Rondin  <https://orcid.org/0000-0002-4833-2886>
Albert Roura  <https://orcid.org/0000-0002-8049-8982>
Wolfgang P Schleich  <https://orcid.org/0000-0002-9693-8882>

References

- [1] Pikovski I, Zych M, Costa F and Brukner č 2015 Universal decoherence due to gravitational time dilation *Nat. Phys.* **11** 668–72
- [2] Zych M 2017 *Quantum Systems Under Gravitational Time Dilation (Springer Theses)* (Cham: Springer)
- [3] Károlyházy F 1966 Gravitation and quantum mechanics of macroscopic objects *Il Nuovo Cimento A* **42** 390–402
- [4] Bassi A, Großardt A and Ulbricht H 2017 Gravitational decoherence *Class. Quantum Gravity* **34** 193002
- [5] Schrödinger E 1935 Die gegenwärtige Situation in der Quantenmechanik *Sci. Nat.* **23** 807–12
- [6] Fein Y Y *et al* 2019 Quantum superposition of molecules beyond 25 kDa *Nat. Phys.* **15** 1242–5
- [7] Riedel C J 2013 Direct detection of classically undetectable dark matter through quantum decoherence *Phys. Rev. D* **88** 116005
- [8] Bateman J, McHardy I, Merle A, Morris T R and Ulbricht H 2015 On the existence of low-mass dark matter and its direct detection *Sci. Rep.* **5** 8058
- [9] Riedel C J and Yavin I 2017 Decoherence as a way to measure extremely soft collisions with dark matter *Phys. Rev. D* **96** 023007
- [10] Kaltenbaek R, Hechenblaikner G, Kiesel N, Romero-Isart O, Schwab K C, Johann U and Aspelmeyer M 2012 Macroscopic quantum resonators (MAQRO) *Exp. Astron.* **34** 123–64
- [11] Kaltenbaek R *et al* 2016 Macroscopic Quantum Resonators (MAQRO): 2015 update *EPJ Quantum Technol.* **3** 5
- [12] Chang D E, Regal C A, Papp S B, Wilson D J, Ye J, Painter O, Kimble H J and Zoller P 2010 Cavity opto-mechanics using an optically levitated nanosphere *Proc. Natl Acad. Sci. USA* **107** 1005–10
- [13] Romero-Isart O, Juan M L, Quidant R and Cirac J I 2010 Toward quantum superposition of living organisms *New J. Phys.* **12** 033015
- [14] Barker P F and Shneider M N 2010 Cavity cooling of an optically trapped nanoparticle *Phys. Rev. A* **81** 023826
- [15] Monteiro F, Afek G, Carney D, Krnjaic G, Wang J and Moore D C 2020 Search for composite dark matter with optically levitated sensors *Phys. Rev. Lett.* **125** 181102
- [16] Afek G, Carney D and Moore D C 2022 Coherent scattering of low mass dark matter from optically trapped sensors *Phys. Rev. Lett.* **128** 101301
- [17] Carney D *et al* 2021 Mechanical quantum sensing in the search for dark matter *Quantum Sci. Technol.* **6** 024002
- [18] Riedel C J 2015 Decoherence from classically undetectable sources: standard quantum limit for diffusion *Phys. Rev. A* **92** 010101
- [19] Branford D, Gagatsos C N, Grover J, Hickey A J and Datta A 2019 Quantum enhanced estimation of diffusion *Phys. Rev. A* **100** 022129
- [20] Carney D, Hook A, Liu Z, Taylor J M and Zhao Y 2021 Ultralight dark matter detection with mechanical quantum sensors *New J. Phys.* **23** 023041
- [21] Joos E and Zeh H D 1985 The emergence of classical properties through interaction with the environment *Z. Phys., B Condens. Matter* **59** 223–43
- [22] Schlosshauer M A 2007 *Decoherence and the Quantum-to-Classical Transition* (Berlin: Springer)
- [23] Voirin T, Bandecchi M, Falkner P and Pickering A 2019 CDF STUDY REPORT (QPPF, European Space Agency) (available at: <http://sci.esa.int/future-missions-department/61074-cdf-study-report-qppf/> CDF-183(C))
- [24] Blencowe M P 2013 Effective field theory approach to gravitationally induced decoherence *Phys. Rev. Lett.* **111** 021302
- [25] Anastopoulos C, Hu B-L 2021 Gravitational decoherence: a thematic overview (arxiv:2111.02462)
- [26] Frenkel A 1990 Spontaneous localizations of the wave function and classical behavior *Found. Phys.* **20** 159

- [27] Diósi L 1987 A universal master equation for the gravitational violation of quantum mechanics *Phys. Lett. A* **120** 377–81
- [28] Penrose R 1996 On gravity's role in quantum state reduction *Gen. Relativ. Gravit.* **28** 581–600
- [29] Diósi L 2007 Notes on certain newton gravity mechanisms of wavefunction localization and decoherence *J. Phys. A: Math. Theor.* **40** 2989
- [30] Penrose R 2014 On the gravitization of quantum mechanics I: quantum state reduction *Found. Phys.* **44** 557–75
- [31] Kaltenbaek R 2022 Feasibility considerations for free-fall tests of gravitational decoherence *AVS Quantum Sci.* **4** 015604
- [32] Gasbarri G, Belenchia A, Carlesso M, Donadi S, Bassi A, Kaltenbaek R, Paternostro M and Ulbricht H 2021 Testing the foundation of quantum physics in space via Interferometric and non-interferometric experiments with mesoscopic nanoparticles *Commun. Phys.* **4** 155
- [33] Martinecz L, Hornberger K, Millen J, Kim M S and Stickler B A 2020 Quantum electromechanics with levitated nanoparticles *npj Quantum Inf.* **6** 1–8
- [34] Pino H, Prat-Camps J, Sinha K, Venkatesh B P and Romero-Isart O 2018 On-chip quantum interference of a superconducting microsphere *Quantum Sci. Technol.* **3** 025001
- [35] Romero-Isart O, Pflanzner A C, Blaser F, Kaltenbaek R, Kiesel N, Aspelmeyer M and Cirac J I 2011 Large quantum superpositions and interference of massive nanometer-sized objects *Phys. Rev. Lett.* **107** 020405
- [36] Nimmrichter S 2014 *Macroscopic Matter Wave Interferometry (Springer Theses)* (Cham: Springer)
- [37] Armano M et al 2016 Sub-femto-g free fall for space-based gravitational wave observatories: LISA pathfinder results *Phys. Rev. Lett.* **116** 231101
- [38] Roura A 2020 Gravitational redshift in quantum-clock interferometry *Phys. Rev. X* **10** 021014
- [39] Zanoni A P, Burkhardt J, Johann U, Aspelmeyer M, Kaltenbaek R and Hechenblaikner G 2016 Thermal performance of a radiatively cooled system for quantum optomechanical experiments in space *Appl. Therm. Eng.* **107** 689–99
- [40] Bateman J, Nimmrichter S, Hornberger K and Ulbricht H 2014 Near-field interferometry of a free-falling nanoparticle from a point-like source *Nat. Commun.* **5** 4788
- [41] Bykov D S, Mestres P, Dania L, Schmöger L and Northup T E 2019 Direct loading of nanoparticles under high vacuum into a Paul trap for levitodynamical experiments *Appl. Phys. Lett.* **115** 034101
- [42] Nikkhou M, Hu Y, Sabin J A and Millen J 2021 Direct and clean loading of nanoparticles into optical traps at millibar pressures *Photonics* **8** 11
- [43] Schmid P et al Trapped nanoparticles for space experiments Technical report Study under contract with ESA, AO/I-6889/11/NL/CBi (2012–2014)
- [44] Oi D K L, Ling A, Grieve J A, Jennewein T, Dinkelaker A N and Krutzik M 2017 Nanosatellites for quantum science and technology *Contemp. Phys.* **58** 25–52
- [45] Kiałka F, Fein Y Y, Pedalino S, Gerlich S and Arndt M 2022 A roadmap for universal high-mass matter-wave interferometry *AVS Quantum Sci.* **4** 020502
- [46] Stickler B A, Papendell B, Kuhn S, Schriniski B, Millen J, Arndt M and Hornberger K 2018 Probing macroscopic quantum superpositions with nanorotors *New J. Phys.* **20** 122001
- [47] Schäfer J, Rudolph H, Hornberger K and Stickler B A 2021 Cooling nanorotors by elliptic coherent scattering *Phys. Rev. Lett.* **126** 163603
- [48] Penny T W, Pontin A, Barker P F 2021 Sympathetic cooling and squeezing of two co-levitated nanoparticles (arXiv:2111.03123)
- [49] SierraLobo 2015 CryoCube (available at: www.sierralobo.com/cryocube/)
- [50] Wuenscher H 1970 Unique manufacturing processes in space environment. The Space Congress® Proceedings (available at: <https://commons.erau.edu/space-congress-proceedings/proceedings-1970-7th/session-7/4/>)
- [51] Melfi Jr L T, Outlaw R, Hueser J and Brock F 1976 Molecular shield: An orbiting low density materials laboratory *J. Vac. Sci. Technol.* **13** 698–701
- [52] Strozier J, Sterling M, Schultz J and Ignatiev A 2001 Wake vacuum measurement and analysis for the wake shield facility free flying platform *Vacuum* **64** 119–44