# BPS 2023 Science White Paper

# Topical: Quantum Memories for Fundamental Physics in Space

**Principle Author**
Jan-Michael Mol[1]
jan-michael.mol@dlr.de
+49 731 400198803

**Co-Authors**
Luisa Esguerra[2,3]
luisa.esguerrarodriguez@dlr.de
Matthias Meister[1]
matthias.meister@dlr.de
Janik Wolters[2,3]
janik.wolters@dlr.de
Lisa Wörner[1]
lisa.woerner@dlr.de

[1]*Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)*
*Institute of Quantum Technologies, Ulm, Germany*

[2]*Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR)*
*Institute of Optical Sensor Systems, Berlin, Germany*

[3]*Technische Universität Berlin*
*Institut für Optik und Atomare Physik, Berlin, Germany*

## Abstract

Investigations into the foundations of quantum mechanics and their link to gravity and general relativity require sensitive quantum experiments. To provide ultimate insight, the realization of such experiments in space will sooner or later become a necessity. With their advanced state and backed by decades of development, quantum technologies and among them quantum memories are providing novel approaches to reach conclusive experimental results. We therefore want to highlight the use case of quantum memories for investigations of fundamental physics in space, and discuss both concrete experiments as well as platforms and performance of candidate quantum memories.

## 1 MOTIVATION

Quantum technologies are currently expanding into viable public and commercial applications, as well as extending their capabilities for use in engineering and applied science. There is increasing interest to deploy such technologies in space to develop secure quantum communication, improve metrology, and run experimental tests of fundamental physics [1] [2] [3]. Launches of complex quantum systems have already been successfully demonstrated by the Cold Atom Laboratory [4] and MAIUS [5] missions, operating Bose-Einstein condensates (BECs) in space. The upcoming project BECCAL [6] will build on their heritage. It will be able to perform a multitude of new experiments, among them the operation of a quantum memory in space. In general, quantum memories allow to store a given quantum state – like a single photon – for a specific amount of time and then fully retrieve it later on, conserving all previously established quantum properties, e.g. entanglement. In this way they can greatly enhance many scientific and technological applications like quantum state teleportation, Bell tests, quantum communication protocols, and quantum tests of general relativity.

Combining quantum memories and free-space photon links in space helps overcoming several limitations of ground-only experiments; by mitigating loss from long optical fiber links or atmosphere, extending limited line-of-sight, or providing a low-disturbance microgravity environment. Optical losses could in principle also be bridged by memory-based quantum repeaters on earth, but the required number of near-term repeaters poses a substantial challenge. To illustrate the advantage of space operation, the Quantum Experiment at Space Scale aboard the Micius satellite [7] already showed order of magnitude improvement at extending the range of quantum entanglement distribution compared to fiber-based approaches. In its mission, flight hardware carried entangled photon sources, with detection and measurement remaining on-ground. Employing quantum memories at memory-assisted ground nodes in conjunction with multiple satellites is a natural next step to increase the range of entanglement distribution even further. Finally, these intermediary nodes may be moved onto satellites, improving fidelity by avoiding unnecessary light paths through the atmosphere altogether [8]. Building space-borne networks in this way will ultimately serve to probe nature below the standard quantum limit [9].

With this white paper we strive to discuss the necessity of space-borne quantum memories for fundamental quantum physics and present available options as well as requirements and limitations of different implementations.

## 2 QUANTUM MEMORIES IN SPACE

Quantum memories are able to greatly aid Bell tests which experimentally contrast quantum mechanics and the concept of local realism. Indeed, quantum memories can store part of an entangled quantum state until measurements can be carried out in satisfaction of spacelike-separation requirements. A simple setup comprises an entangled photon-pair source in which one photon is locally stored in a quantum memory for later measurement, while the other is sent off to a remote location in the meantime. A first demonstrator could be the installation of a ground-based entangled photon-pair source and quantum memory which sends off one photon for detection to a satellite in low-earth-orbit (LEO). The required coherence time for such a memory lies in the range of milliseconds, which has already been realized in current memories [10] [11].

As a further development, source and memory might be placed on a LEO-satellite (or ISS) and establish a link to a detector orbiting moon. This enables Bell Tests investigating "Freedom-of-Choice" loopholes by letting an experimenter determine the measurement basis during the travel time of the photon. The required memory coherence in this case increases to above one second, which poses a challenge for current memories, but seems feasible in light of long-term developments. Since efficiencies in both the memories and optical links are limited, such missions benefit highly from temporal multiplexing to achieve statistical significance.

In terms of using quantum memories to boost sensitivity of measurements, the storage of quantum states for prolonged time opens up possibilities to probe effects in changing gravitational environments [12]. One proposal puts forward the use of two entangled cold atomic gases to probe gravitation- or acceleration-induced decoherence [13]. In this case, both memories start by preparing an entangled state in the same orbit, after which one of them is boosted into a higher orbit. The authors estimate necessary coherence times above 100 milliseconds, but a more conservative estimate requires seconds to minutes for reasonable sensitivity. Especially interesting in this case are memories which feature spatial multiplexing capabilities to generate high enough signal-to-noise through statistical data.

In [14], the authors propose a quantum network of $N$ clocks in order to increase time keeping precision. The underlying principle also enables operation of distributed sensing in space, where sensitivity scales with $\sqrt{N}$ for a fully quantum-operated network compared to a fully classically-operated one. Large enough networks will therefore lead to sensitive measurements of gravitational effects, possibly linking space-time to quantum physics [12].

Our discussion highlights the special interest to mount quantum memories to spaceborne platforms. As space-based research and technology development always underlies restrictions with respect to size, mass, and power, investigations to integrate quantum technologies into CubeSats are a natural development [15] [16]. Setting CubeSats aside, miniaturization and reduction of power requirements are always key-factors for deployment of memories in space. This goes alongside hardening against harsh environmental requirements, as required for a lunar mission or beyond [17].

With long distances being a major concern in transferring single photons to execute quantum measurements, the feasibility demonstration of quantum-limited signal propagation from geostationary Earth orbit (GEO) to ground by Alphasat I-XL [18] is a major milestone. This underlines that memories in geostationary orbits or as relay stations are a viable and necessary option to bridge long distances.

## 3 QUANTUM MEMORY TYPES

Quantum memories can act as interfaces between flying and stationary qubits. Thus, they are able to absorb and re-emit photonic qubits, either on-demand or after a specific time defined by the system itself. Many different platforms exist for the realization of quantum memories. One can differentiate between ensemble-based platforms, such as cold and warm atomic gases, rare-earth-ion-doped crystals (REIDs), and single emitters such as NV-centers in diamond or single atoms and molecules. Optically active systems serve as prime candidates due to already advanced technology for photonic distribution of quantum states. We therefore focus on these platforms and do not discuss those which currently lack optical interfaces, despite some of them featuring exceptional coherence times and fidelities [19].

A variety of protocols exists to implement quantum storage for different platforms. They can be divided into optically controlled ones, for example electromagnetically induced transparency (EIT) and Raman-type schemes, and engineered absorption schemes, where one finds gradient-echo memory (GEM), controlled-reversible-inhomogeneous broadening (CRIB) and atomic-frequency comb (AFC) protocols. Each platform often supports more than one protocol. Proper selection highly depends on the planned memory application. So far, no single combination yields a sufficient solution for a general-purpose device, i.e. trade-offs exist between large efficiencies, long storage times, temporal and spatial multimode capacity, large bandwidths, high fidelities, etc. In case of memory efficiencies, special attention has to be paid to not only include memory-intrinsic values, but also of the setup as a whole.

In the following subsections, a selection of the most relevant platforms will be described in more detail, and exemplary state-of-the-art implementations will be mentioned. Some of the experiments have been performed storing bright laser pulses containing many photons instead of operating at single-photon level. However, especially for Bell Tests, true single photons are mandatory. Therefore, the memories need to be paired with single-photon sources, which poses an additional challenge on the memory platforms [20], as well as on the development of efficient photon sources [21] matched to the memories.

## 3.1 WARM VAPOR CELLS

Vapor cells are low-complexity systems which can be operated over a wide range of temperatures and conditions without the need for any cryogenic refrigeration and large magnetic fields, which makes them an easily scalable platform. Commonly used are alkaline atoms since they possess energetically low-lying spin states and long coherence times. These states function as storage states in EIT and Raman protocols.

By use of the spin-orientation degrees of freedom of Cs atoms and a special chamber coating, Katz and Firstenberg [22] report memory efficiencies of 9-14% at storage times up to 150 milliseconds. In the same experiment they show storage times up to 1 second, which correspond to a 1/e storage time of 430 milliseconds. They claim that their memory is sufficient to store weak coherent states and squeezed states. Through the hyperfine manifold, they posit possible single photon operation. Guo et al. [23] achieve the highest efficiency to date in warm vapor memories with a value of 82% by an off-resonant Raman scheme in a Rubidium memory. They further obtain fidelities at single photon level up to 98%. Focusing on the interfacing of the memories with a single photon source, in [24] a memory with an acceptance bandwidth of 0.66 GHz is realized, which is suitable for photons from semiconductor quantum dots.

Spatial multiplexing for multimode capacity is feasible in these systems, at the cost of more powerful lasers [25], but has to our knowledge not yet been realized experimentally. Microfabrication techniques have enabled cell dimensions of millimeter size, which may aid miniaturization for CubeSat integration [26].

## 3.2 COLD ATOMIC GASES

In contrast to vapor cells, cold atomic gases are cooled in magneto-optical traps to reduce atomic motion to 100 µK or below which provides a route for reaching long coherence times. The creation of BECs at even lower temperatures requires either stronger lasers for deeper traps or atom-chips for RF-evaporative cooling. Atom-chip assemblies have aided miniaturization [27] and manipulation, but require more careful planning of vacuum feedthroughs and interaction between atom cloud and chip surface.

Cold gases generally implement the same memory protocols as warm gases. High efficiencies and storage times have been achieved; in particular, [28] reports an intrinsic retrieval rate of 76% for storage times of 220 milliseconds in a Rubidium gas. In [10] memory efficiencies of 73% have been achieved, although at lower storage times of 3.2 milliseconds. Multimode capability has been realized through orbital angular momentum [29] or spatial multiplexing [30], and entanglement between two Rubidium memories has recently been demonstrated [31].

Portable versions of cold atomic gases already exist [5] [32] [33] and on-chip optics might in future alleviate the need for bulkier optical components [34]. Nevertheless, the upper limit of photon absorption rate puts a constraint on minimum system size for reasonable BEC creation in the centimeters range. Especially interesting for space applications are developments in miniaturization of passively pumped systems with 1000-day UHV operation using microfabricated magneto-optical traps [35].

Heritage from previous missions MAIUS and CAL make cold atom gases an important contender for space quantum memories, with project BECCAL serving as a future cornerstone.

## 3.3 RARE-EARTH-ION-DOPED CRYSTALS (REID)

The inherent strengths of solid-state based systems lie in their low-complexity, compactness, and micro-integration possibilities. In REIDs, optical modes down to single-photon level are stored in a collective spin wave of the dopant rare-earth ions in the crystal. Prominent dopants are Praseodymium ($Pr^{3+}$) or Europium ($^{151}Eu^{3+}$) embedded in an Yttrium-Orthosilicate matrix ($Y_2SiO_5$).

To achieve long coherence times, physical cooling of the crystal to temperatures between 1–4 Kelvin and dynamical decoupling techniques [36] to suppress spin-wave dephasing are necessary. Systems based on europium donors furthermore enable operation at a magnetically insensitive transition around 1 Tesla, achieving optical coherence times ranging between one to six hours [37] [38].

Most REIDs are operated as hybrid-AFC memories to store a frequency comb in a spin-wave for on-demand retrieval, although EIT memories exist as well [39] [40]. Down-conversion to match telecom wavelength is possible [41] [42] which was recently used for multimode operation between two REID memories [43] or to interface with cold atomic gases [44].

When considering system miniaturization for space flight, the requirement of bulky magnets can be circumvented by operating at smaller but sufficient bias fields [45] [36]. Crystals can also be integrated more tightly using optical waveguides [46]. Recent developments in compact cryocoolers for single photon detectors benefit cooling requirements of solid-state based systems as well [47].

### 3.4 VACANCY CENTERS

Other contenders for a solid-state quantum memory are the various color centers in diamond or silicon carbide [48]. Well studied is the nitrogen vacancy (NV) center in diamond, where a substitutional nitrogen atom next to a vacancy inside the carbon lattice of bulk diamond leads to magnetically tunable fluorescence. In addition to its use as a sensitive magnetometer, the color center has general access to the quantum properties of the associated free electron spin as well as the nitrogen atom and any proximal $^{13}$C nuclei. These nuclei have recently been utilized to form a ten-qubit memory register with coherence times of 75 seconds for arbitrary single-qubit states and more than 10 seconds for two-qubit entanglement [49]. Techniques to improve storage times include entanglement distillation via $^{13}$C nuclei [50], isotopic purification of diamond to minimize inhomogeneous broadening [51], and strain engineering [52].

Although NVs are currently the most mature system, they lack optical efficiency compared to tin-vacancy (SnV) [53] or silicon-vacancy (SiV) [54] centers. In comparison to the low temperatures needed for longer coherence in SiV, similar or better coherence at temperatures above 1 K might be offered by SnV.

Vacancy centers are mostly read out using confocal microscopes which impact system size considerably. Optical cavities [55], photonic chips [56] [57] [58] or photoelectric readout [59] are therefore helpful developments to shrink system sizes.

## 4 CONCLUSION

Space-borne quantum memories have a huge potential in boosting fundamental physics experiments. Once long-distance Bell tests are established, they serve as an excellent platform for more involved measurements of relativistic effects between moving observers or experiments in changing gravitational environments. All these investigations will also be able to support future technological developments for deep-space quantum communications.

Within this whitepaper we have discussed several implementation options. Key performance factors, which are exemplarily summarized in table 1, have to be addressed with respect to experiments to be executed. The list of entries is by no means exhaustive, but should give a representative overview for applications discussed in this paper. It highlights the various tradeoffs to be considered when optimizing for concrete application requirements. Nevertheless, storage times and efficiencies in quantum memories are approaching a useful regime for space applications, and multimode capabilities are currently heavily investigated. Additionally, the many activities which are ongoing in the quantum technology and quantum memory communities, provide an optimistic outlook for improvements in the next few years.

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***Table 1*** *Quantum Memory Types and key performance indices. Efficiencies are typically memory intrinsic, if not marked otherwise. "Store & Retrieve" indicates whether photon storage and/or retrieval are possible.*
*§achieved at multi-photon-level*

| | **Platform** | **Mechanism** | **(S)tore & (R)etrieve** | **Bandwidth** | **Efficiency** | **Storage Time** |
|---|---|---|---|---|---|---|
| **Warm vapor cells** | $^{87}$Rb [23] | Raman | S & R | 77 MHz | 82.0 % | 170 ns |
| | $^{133}$Cs [22] | EIT | S & R | (80 kHz) | 14.0 % | 430 ms§ |
| | $^{87}$Rb [24] | EIT | S & R | 660 MHz | 17 % | 50 ns |
| **Cold atomic gases** | $^{87}$Rb [10] | EIT | R | - | 73 % | 3.2 ms |
| | $^{87}$Rb [28] | EIT | R | - | 76 % | 220 ms |
| **Rare-earth ion-doped crystal** | $^{151}Eu^{3+}:Y_2SiO_5$ [45] | hybrid-AFC | S & R | 1.5 MHz | 7.4 % | 20 ms |
| | $Pr^{3+}:Y_2SiO_5$ [60] | hybrid-AFC | S & R | < 2 MHz | 5 % | 13 μs |
| **Vacancy centers** | NV [61] | Absorption | S | 12 MHz | 1 % | > 10 s |
| | SiV [55] | Dispersive Shift + Time-bin Entanglement | S | ~ 50 MHz | 42 % (heralding) | 0.2 ms |

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