A Case for Quantum Memories in Space

Topical white paper submitted to Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032

Mustafa Gündoğan*[1], Thomas Jennewein[2], Faezeh Kimiaee Asadi[3], Elisa Da Ros[1], Erhan Sağlamyürek[3,4], Daniel Oblak[3], Tobias Vogl[5,6], Daniel Rielander[7], Jasminder Sidhu[8], Samuele Grandi[9], Luca Mazzarella[10], Julius Wallnöfer[11], Patrick Ledingham[12], Lindsay LeBlanc[4], Margherita Mazzera[13], Janik Wolters[14,15], Alexander Ling[16], Mete Atatüre[6], Hugues de Riedmatten[9], Daniel Oi[8], Christoph Simon[3], and Markus Krutzik[1]

[1]Institüt für Physik, Humboldt Universität zu Berlin
[2]Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo
[3]Institute for Quantum Science and Technology, and Department of Physics and Astronomy, University of Calgary
[4]Department of Physics, University of Alberta
[5]Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena
[6]Cavendish Laboratory, University of Cambridge
[7]Fraunhofer Institute for Applied Optics and Precision Engineering
[8]SUPA Department of Physics, University of Strathclyde
[9]ICFO-Institut de Ciències Fotòniques, Barcelona Institute of Science and Technology
[10]Jet Propulsion Lab, California Institute of Technology
[11]Institut für Theoretische Physik, Frei Universität Berlin
[12]Department of Physics and Astronomy, University of Southampton
[13]Institute of Photonics and Quantum Sciences, Heriot-Watt University
[14]Institut für Optik und Atomare Physik, Technische Universität Berlin
[15]Institute of Optical Sensor Systems, Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
[16]Centre for Quantum Technologies, National University of Singapore

October 31, 2021

Abstract

It has recently been theoretically shown that Quantum Memories (QM) could enable truly global quantum networking when deployed in space [1, 2] thereby surpassing the limited range of land-based quantum repeaters. Furthermore, QM in space could enable novel protocols and long-range entanglement and teleportation applications suitable for Deep-Space links and extended scenarios for fundamental physics tests. In this white paper we will make the case for the importance of deploying QMs to space, and also discuss the major technical milestones and development stages that will need to be considered.

*Primary author: mustafa.guendogan@physik.hu-berlin.de; +49 (030) 2093 4907

1 Introduction

A quantum memory (QM) is a device with the ability to store the quantum state of an incoming light pulse and release it on-demand at a later time [3]. QM are required in several protocols in quantum communication, quantum computing and optics. In the context of long-range links, the main function of QMs is to synchronize otherwise probabilistic two (or more)-photon transfer and detection events in order to speed up protocols, such as quantum repeaters [4, 5] and deterministic creation of multiphoton states [6, 7].

There are several figures of merit that characterize the performance of QMs:

- Fidelity (F): the retrieved quantum state, ρ' should be as close as possible to the input quantum state ρ. The fidelity is given by the overlap between these states, and can be calculated as: $\mathrm{F}(\rho) = \mathrm{Tr}\sqrt{\sqrt{\rho'}\rho\sqrt{\rho'}}$.
- Efficiency (η): The memory efficiency is ratio of probability of detecting the output photon to that of the input photon[1]; $\eta = \mathrm{P}_{out}/\mathrm{P}_{in}$. For ensemble based memories, it is usually limited by optical depth of the atomic ensemble and strength and temporal/spectral profile of the control pulses, mediating the storage.
- Storage time (τ): in principle a QM should store the input quantum state as long as possible. This is usually limited by interatomic interactions, thermal effects, external magnetic or electric field noises and can be mitigated with several means. Today, QMs are pushing towards 1 s threshold [9], while classical pulse storage for up to 1 h has been recently demonstrated [10].

2 Quantum memories for space applications

It has recently been theoretically shown that QMs could enable truly global quantum networking when deployed in space [1, 2] thereby surpassing the limited range of land-based quantum repeaters. When combined with a set of tools such as high-fidelity entangled photon pair sources, entanglement swapping [11] and teleportation [12] schemes, QMs will also enhance the distances for very-large scale entanglement and teleportation implementations in space, and enable novel applications and tests of gravity. Specifically, QMs could also find use in long-distance Bell tests [13, 14] where they ensure the space-like separation of the detection events in order to close the locality loophole. This is achieved by delaying one of the pairs by a certain amount τ before the detection event. While short fibre-based delay lines ($\sim \mu$s) are sufficient for some experiments such as optical COW tests as envisioned in [13], QMs are definitely required in space-based experiments that require adjustable delay times of many milli-seconds to seconds, which is in particular the case for scenarios that involve large link distances such as for geostationary orbit to Earth (120 ms), or Earth to Moon (1.3 s). Long-lived QMs achieving high efficiencies ($\eta > 70\%$ for $\tau \sim 200$ ms) have already been demonstrated in the lab [9]. Hypothetically, a fiber delay line for such a storage time[2] comes with a prohibitively high loss of > 5600 dB.

2.1 Ultra-long distance entanglement and teleportation experiments

Long-range entanglement and teleportation experiments are fundamentally interesting for several reasons. Such experiments would open up the path towards long-distance quantum communication [1, 2, 16, 17], all the way towards enabling tests of quantum mechanics across vast distances [13, 14]. Such experiments might also give hints towards the interplay between gravity and quantum physics [18].

Even for realizing a global network across Earth, using ground-based infrastructures alone will possibly be insufficient, and a hybrid quantum repeater network utilizing both space- and ground-based communication links may be the most effective solution, offering a large parameter space to investigate. In such a network, entanglement could be distributed over continental distances (up to a few thousand km) using ground fiber-based quantum repeaters [5, 19], while longer distances could be reached using satellites, e.g. by performing entanglement swapping between quantum memories placed in LEO satellites [1, 2], or by entangling quantum memories located in separate

[1]Although there has been progress towards space-based quantum communication with continuous variable protocols [8] in this white paper we focus on discrete variables as they have a better loss tolerance and the fidelity of the final states do not necessarily depend on channel loss and memory efficiencies.

[2]The best optical fibers have losses of around 0.14 dB/km at 1550 nm [15] which translates into 0.028 dB/μs delay. This makes it clear that any experiment that requires $\tau > 1$ ms will have a transmission of less than 1%, thus making the fiber-based delay line extremely inefficient. Novel ZBLAN fibers are being projected to achieve < 0.01 dB/km attenuation but they remain extremely rare and costly.

ground stations with entangled photon sources located on LEO satellites [16]. As is well established, optical fibers are commonly used to establish metropolitan quantum networks [20, 21].

Teleportation of unknown quantum states between spatially separated locations requires pre-distribution of entangled pairs as well as performing a Bell-state measurement. The result of the latter needs to be transmitted classically such that a correct unitary operation is applied to complete the teleportation protocol. It is, therefore, crucial to employ quantum memories that are capable of storing entangled states during the experiment. For example, teleportation without any post-selection requires a QM with storage times longer than the light's travel time between the measurement stations. For Earth-Moon distance this amounts to ~ 1.3 s, as is considered for NASA's proposed Deep Space Quantum Link (DSQL) [22]. It is within this context that space-based QMs could enable full teleportation that only performs a Bell-state measurement once all required signals are ready, and therefore circumvent the issue of post-selection. This would yield a drastic performance improvement over solutions without memory.

2.2 Long-distance matter-matter entanglement

Tests of Bell's inequality continue to be of great interest due to their connection to the foundations of quantum mechanics. An advantage of performing ultra-long-range Bell tests with space-like separated observers is examining the space-time features on quantum correlations and closing the locality and freedom-of-choice loopholes while experimenting [23, 24, 25, 26]. Furthermore, it has been suggested that the measurement process is finished only once a gravity-induced state reduction takes place [27]. Therefore, testing ultralong-distance entanglement distribution where measurements are associated with the displacement of macroscopic masses and measuring the produced gravitational fields can improve our understanding of quantum gravity theories [28, 29].

A QM would be very helpful for such long-distance experiments in several ways. Utilizing quantum memories to store distributed photons before the detection events take place can provide the required time delay for addressing locality and freedom-of-choice loopholes. Besides, memories can significantly enhance the heralding efficiency when using human observers with free will [30, 31, 32].

3 Physical Quantum Memory Candidate Systems

While many different QM systems are under development, we primarily consider ensemble based QM systems which we deem suitable to satisfy the requirements of the space-based experiments mentioned above. These systems allow input-output type memory operation in a way that they can be interfaced with external single photon or entangled photon pair sources. Furthermore, they can possess important features including multi-mode storage capacity, large spectral bandwidth and being more robust to small beam misalignments. The following systems[3] have thus the potential of being integrated into NASA's planned DSQL.

3.1 Warm vapour memories

Optical storage with room temperature alkali atoms are particularly interesting since it relies neither on complex laser trapping techniques or cryogenic cooling. This makes them promising candidates for field operation such as under sea or in space. Recent years saw significant progress in warm vapor memories. These include development of noiseless, fast memories [35, 36], $\sim$GHz-bandwidth operation [37, 38] and highly efficient ($\eta > 80\%$) storage with fidelities above the no-cloning limit [39]. Furthermore, record storage time of ~ 1 s has been observed with storage of bright pulses [40] by operating at the so-called 'spin exchange relaxation-free' regime. The storage time in these systems has the potential to be pushed beyond hours by transferring the spin excitation from alkali atoms to noble-gas nuclear spins via spin exchange collisions [41].

Amongst others, compact warm vapor-based optical spectroscopy setups have been operated as optical frequency references on sounding rocket missions [42, 43, 44], demonstrating the maturity of diode laser systems and related vapor cell based technologies. Further integration towards cubesat form factor compatible, integrated atomic systems for a frequency reference application has been demonstrated without reduction of performance [45].

3.2 Laser-cooled atomic systems

Laser-cooled atomic systems are well-established platforms for quantum information storage. Even though the setups required to laser cool atomic ensembles are relatively more complex than the ones implemented for warm vapours, the lower temperatures of a cold atom cloud inhibits thermal

[3] Although there is a great progress in quantum networking with single color centers [33, 34], we exclude them in this white paper as memory platforms due to possible incompatibility with the DSQL.

diffusion and grants long coherence times. Of particular interest is photon storage in the ultracold quantum gases such as Bose-Einstein condensates [46, 47, 48]: not only does the reduction of thermal motion offer long storage times, but the large optical depth allows for high write-read efficiency and the refined state preparation increases the fidelity of the storage in the atomic spin state. In the past years optical memory has been demonstrated in these systems achieving high efficiencies [9, 49], long storage time [50], and temporal [49, 51] and spatial multiplexing [52, 53].

In parallel to these efforts, the past decade has witnessed extensive research and technological development to realize cold-atoms based setups for space applications. Deployment of these experiments in a microgravity environment would enable both fundamental research and promise enhanced performance for practical applications in navigation and earth observation. In this context, generation and coherent manipulation of cold atom ensembles and Bose-Einstein condensates have already been demonstrated in microgravity environments including orbiting platforms such as parabolic flights [54, 55], drop-towers [56, 57], sounding rockets [58, 59], and now even on Tiangong-2 [60] and the ISS [61]. Further launches to ISS are planned such as the ACES/PHARAO atomic clock [62], or the dual-species atomic experiment facility BECCAL [63]. Various proposals are in development for deployment on cubesats such as CASPA [64] or as part of large scale missions such as AEDGE [65]. Very similar systems and infrastructures can lay the foundations of future space-based quantum memories for deployment in orbit.

3.3 Rare-earth ion doped crystals (REIDs)

Rare earth ions possess exceptionally long coherence times (narrow homogeneous linewidths) both on optical and spin transitions at cryogenic temperatures. In particular, their narrow optical transitions are directly linked to their unique electronic configurations, in which their active $4f$ orbitals are embedded within the filled outer shells, providing protection from external perturbations. This feature, in conjunction with the absence of thermal motion, render REIDs as a high-performance QM platform. The recent achievements include but are not limited to; heralded entanglement generation between two QMs [66, 67] in a quantum repeater setting, bright pulse storage from minute [68] to hour-long time scales [10] and demonstration of temporal [69, 70, 71] spectral [72, 73] and spatial [74] multimode storage. The other research direction is the miniaturization of these devices: waveguide structures [75, 76, 77] and nanophotonic cavities [78, 79] offer an enhanced compactness and interaction strength. The narrow hyperfine level separation usually limits the storage bandwidth of the on-demand operation to a few MHz [80, 81]; however, the recently demonstrated hybridized electronic-nuclear spin levels in highly anisotropic host materials could enable the storage of large bandwidth photons while retaining long coherence times. [82].

In this way, REIDs can fulfill the requirements of experiments outlined in Sec. 2 by combining compactness with efficient and long-lived storage capability for broadband pulses. They are thus among the promising candidates for space applications with the development of miniature, space-compatible cryostats [83].

4 Memory-compatible photon sources

Photon sources intended to interface with QM systems should match QM-specific bandwidth and wavelength for optimum coupling. They must also have small footprints and robust architecture for operation in space. We consider two types of single photon sources that are both memory-compatible and suitable for operation in a space environment.

4.1 SPDC sources

Spontaneous parametric down-conversion (SPDC) has been the most established method for creating entangled photon pairs for more than three decades [84]. It relies on a nonlinear crystal being pumped with a strong laser beam which creates correlated photon pairs in different degrees of freedoms, e.g. polarization, angular momentum or frequency. They operate at room temperature, and have already been deployed in space. In addition to the entangled photon pair source on board the MICIUS satellite [85], a miniaturized SPDC source on board a cubesat successfully demonstrated entangled state generation [86]. Notably, the robustness of such space-compatible systems was proven by an SPDC source that survived a rocket explosion during its launch without showing a significant reduction of performance [87].

By itself, the emission from SPDC is typically wideband and special techniques are required in order to achieve spectral matching of the SPDC photons with a QM. The SPDC output can be filtered to reduce the photon bandwidth; however, this significantly reduces the brightness of the source. More effectively, the SPDC source can be placed inside a resonant cavity to reduce the linewidth while maintaining a high level of photon counts, which can yield very narrow, tunable bandwidth. For example, a highly degenerate photon-pair source that emits one photon resonant with a Pr-doped REID QM and the other at the telecommunications C-band [88] was successfully used for entangling two crystals [66], and a sub-MHz linewidth source that operates at the Rb D1 line [89] was demonstrated. Even though there is great progress towards creating such narrow band sources, the strict bandwidth requirements can further be relaxed for coupling to larger bandwidth QMs.

4.2 Solid-state single photon sources

Single photon emitters embedded in a solid-state medium are another alternatives to entangled photon pair sources for long-range entangled state creation [90]. A single photon pulse is sent to a beam splitter and thus a path-entangled state is created which can then be used to entangle two distant QMs [69]. Currently the best single photon sources in terms of spectral purity and brightness are semiconductor quantum dots (QDs) [91] that need cryogenic cooling. Even though on-demand storage and retrieval of QD single photons has been proved challenging due to the spectral mismatch between memory and single photons, generation of sub-natural linewidth photons from QDs [92] may become crucial towards achieving this goal. There have also been recent experiments that demonstrated coupling between QD single photons and atomic ensembles in the form of slow light [93] or storage with a predetermined delay time [94]. In parallel to these efforts, there have been recent work towards the realization of a QM based on the nuclear spin ensemble in semiconductor QDs [95, 96]. Such a system would finally realize a perfect single photon source with a built-in QM capability.

Defect centers in diamond are one of the most established single photon sources. Among them, the NV center has a non-zero electric dipole moment, undesirably making it sensitive to electric field noise. Furthermore, its weak zero-phonon line (ZPL) significantly reduces its brightness and operation efficiency. In contrast with NV centers, group-IV color centers, such as SiV and SnV, do not posses an electric dipole moment due to their inversion symmetry, rendering them insensitive to the environmental perturbations [97]. The resulting stable emission line, combined with strong ZPL, transform-limited linewidths down to $\sim$ 30 MHz [98] with access to electronic spins at cryogenic temperatures makes these color centers a strong candidate as single photon sources with built-in QM capability [99].

Finally, single photon emitters in 2D materials [100] are alternatives to semiconductor QDs and diamond defects. Among these, emitters in hexagonal boron nitride (hBN) have further advantage of a large coverage of emission lines from the UV up to the NIR [101, 102]. Although they usually have large linewidth at room temperature, placing them in optical microcavities [103] has proven to be an efficient way to drastically improve the spectral purity and linewidth. Finally, the recent observation of transform limited ($<$ 100 MHz) single photons [104] from hBn defects could bring coupling of these photons to QMs one step closer to reality if the observed spectral diffusion can be mitigated. We should note that these emitters have already been qualified for space applications [105].

5 Critical Technologies and Mission Demonstrations

The deployment of QMs in space will require a sequence of milestones and demonstrations before such a mission can be realized. We should note that the different quantum memory platforms we summarized above are all in different stages of development and they offer different performances for different applications. For example, temporal multiplexing is extremely important for effective quantum communication; however, the REIDs which can possess high temporal multimode capacity in a single memory require cryogenics. On the other hand, long-lived QMs based on warm vapours usually[4] require multiple memory cells or spatial modes for temporal multiplexing [6] but they do not need cryogenics or additional trapping lasers, thus opening a path towards miniaturization and robust integration into satellite platforms. Along these lines a space compatible, miniaturized frequency references based on warm Rb vapour have recently been demonstrated [45]. Converting such a setup for an optical memory seems feasible upon the integration of modulators and other laser sources in the very near future and, thus, it is reasonable to expect the first demonstration of space-based optical storage experiments sometime in the next five years.

5.1 Technological and experimental milestones towards QMs in space

Below we summarize some of the major experimental and technical milestones that we anticipate on the path towards the deployment of a fully functional QMs enhanced link in space:

[4]In principle, there are some experimental works that demonstrate temporal multimode operation with warm vapours [38], but they do not utilize the long-lived ground state storage that is required for the DSQL.

- **Photon Sources:** Demonstrate interfacing of the QM system with single-photon sources. This necessitates that the source can be implemented with sufficient photon extraction and repetition rates, as well as the required level of control over spatial, temporal, spectral modes.
- **Miniaturized and rugged QM platforms:** Miniaturization and integration techniques to successfully develop small-form-factor and space-compatible quantum memories.
- **Free-space Link:** Coupling of the photons travelling over a fluctuating and turbulent channel to the spatial modes required by a QM. This could be either coupling to a single mode beam, or a 'few mode beam'. This may include both active and passive manipulation of the optical beam and wave-fronts.
- **QM operation and synchronisation:** Study aspects of operations, timing synchronisation and reference frame alignment required to enable operations of the QM, in particular using the photon sources and the free-space link technology previously mentioned.
- **Bell-state measurement:** As an important tool for a quantum entanglement distribution or teleportation protocol, the entangling feature of two-photon Hong-Ou-Mandel interference (HOM) must be demonstrated when fluctuating free-space links are considered. The demonstration of HOM interference for true single photons emitted by separate QMs sent over free-space channels must be shown.
- **Satellite to ground link:** The storage of single photons transmitted from a satellite-based photon source to a QM located in a ground station will demonstrate the viability of the scheme. Wave-front shaping techniques will have to be utilized to achieve good coupling of the distorted free-space beam to the QM.
- **Supporting technology:** the operating and manipulating of QM in space will also necessitate the development of space compatible lasers, driver electronics and vacuum systems. In addition to wavelengths that were already operated in space (such as Rb wavelengths at 780 nm and 795 nm) space-compatible lasers at various other quantum memory wavelengths (580 nm, 606 nm, 894 nm, 980 nm, 1530 nm, etc.) should be developed. Another important technology will be miniaturized vacuum and cryogenic systems. Lastly, efficient quantum frequency conversion systems will be needed for the conversion between memory wavelengths and the telecommunication wavelengths that are commonly used in fibre infrastructres.

5.2 Mission scenarios

Here we summarize a possible path towards the realization of the full potential of QMs in space.

- **Proof-of-principle demonstration of in-orbit memory operation:** The first in-orbit memory experiments should demonstrate the robustness and rigidity of these systems and their ability to operate in space environment.
- **Photon-matter entanglement between ground and space:** By implementing Ground to Space, or Space to Ground, transmission and storage of photons from an entangled photon source will demonstrate entanglement of a 'flying' qubit with the matter QM. While only one link is utilized, a long-distance test of entanglement is possible.
- **QM assisted quantum communication:** With the simultaneous loading of two QM with signals sent between two separate ground stations and the satellite, QM assisted quantum communication is achieved in a way explained as downlink or uplink scenarios in Ref. [1] by using protocols in Refs. [106, 107]. Demonstrating such a memory advantage [33, 108] in space is an important first step towards a scalable global quantum network, and is expected to outperform the direct, simultaneous transmission of both entangled photons.

6 Conclusion

The recent advances of QM based on ensemble systems have enabled several important scenarios and implementations of space based quantum networks, that were previously considered infeasible. As an example, NASA's planned DSQL could significantly benefit from the deployment of QMs in space. It is thus critical to develop space suitable QM systems and the required R&D road map for development of key technologies.

References

[1] M. Gündoğan, J. S. Sidhu, V. Henderson, L. Mazzarella, J. Wolters, D. K. Oi, and M. Krutzik, "Proposal for space-borne quantum memories for global quantum networking," *npj Quantum Information*, vol. 7, p. 128, 2021.

[2] C. Liorni, H. Kampermann, and D. Bruß, "Quantum repeaters in space," *New J. Phys.*, vol. 23, p. 053021, may 2021.

[3] M. Afzelius, N. Gisin, and H. de Riedmatten, "Quantum memory for photons," *Physics Today*, vol. 68, pp. 42–47, Dec. 2015.

[4] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, "Quantum repeaters: The role of imperfect local operations in quantum communication," *Phys. Rev. Lett.*, vol. 81, pp. 5932–5935, Dec 1998.

[5] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, "Quantum repeaters based on atomic ensembles and linear optics," *Rev. Mod. Phys.*, vol. 83, pp. 33–80, Mar 2011.

[6] J. Nunn, N. K. Langford, W. S. Kolthammer, T. F. M. Champion, M. R. Sprague, P. S. Michelberger, X.-M. Jin, D. G. England, and I. A. Walmsley, "Enhancing multiphoton rates with quantum memories," *Phys. Rev. Lett.*, vol. 110, p. 133601, Mar 2013.

[7] F. Kaneda, F. Xu, J. Chapman, and P. G. Kwiat, "Quantum-memory-assisted multi-photon generation for efficient quantum information processing," *Optica*, vol. 4, pp. 1034–1037, Sep 2017.

[8] D. Dequal, L. Trigo Vidarte, V. Roman Rodriguez, G. Vallone, P. Villoresi, A. Leverrier, and E. Diamanti, "Feasibility of satellite-to-ground continuous-variable quantum key distribution," *npj Quantum Information*, vol. 7, p. 3, Jan 2021.

[9] S.-J. Yang, X.-J. Wang, X.-H. Bao, and J.-W. Pan, "An efficient quantum light–matter interface with sub-second lifetime," *Nature Photonics*, vol. 10, pp. 381–384, Jun 2016.

[10] Y. Ma, Y.-Z. Ma, Z.-Q. Zhou, C.-F. Li, and G.-C. Guo, "One-hour coherent optical storage in an atomic frequency comb memory," *Nat. Commun.*, vol. 12, p. 2381, April 2021.

[11] J.-W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, "Experimental entanglement swapping: Entangling photons that never interacted," *Phys. Rev. Lett.*, vol. 80, pp. 3891–3894, May 1998.

[12] S. Pirandola, J. Eisert, C. Weedbrook, A. Furusawa, and S. L. Braunstein, "Advances in quantum teleportation," *Nature Photonics*, vol. 9, pp. 641–652, Oct 2015.

[13] D. Rideout *et al.*, "Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities," *Classical and Quantum Gravity*, vol. 29, p. 224011, oct 2012.

[14] C. Simon and W. T. M. Irvine, "Robust long-distance entanglement and a loophole-free bell test with ions and photons," *Phys. Rev. Lett.*, vol. 91, p. 110405, Sep 2003.

[15] Y. Tamura, H. Sakuma, K. Morita, M. Suzuki, Y. Yamamoto, K. Shimada, Y. Honma, K. Sohma, T. Fujii, and T. Hasegawa, "The first 0.14-db/km loss optical fiber and its impact on submarine transmission," *J. Lightwave Technol.*, vol. 36, pp. 44–49, Jan 2018.

[16] K. Boone, J.-P. Bourgoin, E. Meyer-Scott, K. Heshami, T. Jennewein, and C. Simon, "Entanglement over global distances via quantum repeaters with satellite links," *Physical Review A*, vol. 91, no. 5, p. 052325, 2015.

[17] J. S. Sidhu, S. K. Joshi, M. Gündoğan, T. Brougham, D. Lowndes, L. Mazzarella, M. Krutzik, S. Mohapatra, D. Dequal, G. Vallone, P. Villoresi, A. Ling, T. Jennewein, M. Mohageg, J. Rarity, I. Fuentes, S. Pirandola, and D. K. L. Oi, "Advances in space quantum communications," *IET Quant. Comm.*, pp. 1–36, 2021.

[18] C. Kiefer, *Quantum Gravity, volume 155 of International Series of Monographs on Physics.* Oxford: Oxford University Press, 2012.

[19] S. E. Vinay and P. Kok, "Practical repeaters for ultralong-distance quantum communication," *Phys. Rev. A*, vol. 95, p. 052336, May 2017.

[20] R. Valivarthi, Q. Zhou, G. H. Aguilar, V. B. Verma, F. Marsili, M. D. Shaw, S. W. Nam, D. Oblak, W. Tittel, *et al.*, "Quantum teleportation across a metropolitan fibre network," *Nature Photonics*, vol. 10, no. 10, pp. 676–680, 2016.

[21] Q.-C. Sun, Y.-L. Mao, S.-J. Chen, W. Zhang, Y.-F. Jiang, Y.-B. Zhang, W.-J. Zhang, S. Miki, T. Yamashita, H. Terai, *et al.*, "Quantum teleportation with independent sources and prior entanglement distribution over a network," *Nature Photonics*, vol. 10, no. 10, pp. 671–675, 2016.

[22] L. Mazzarella, M. Mohageg, D. V. Strekalov, A. Zhai, U. Israelsson, A. Matsko, N. Yu, C. Anastopoulos, B. Carpenter, J. Gallicchio, B.-L. Hu, T. Jennewein, P. Kwiat, S.-Y. Lin, A. Ling, C. Marquardt, M. Meister, B. Moffat, R. Newell, A. Roura, C. Schubert, G. Vallone, P. Villoresi, and L. Wörner, "Goals and feasibility of the deep space quantum link," in *Quantum Communications and Quantum Imaging XIX* (K. S. Deacon and R. E. Meyers, eds.), vol. 11835, pp. 74 – 82, International Society for Optics and Photonics, SPIE, 2021.

[23] B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau, and R. Hanson, "Loophole-free bell inequality violation using electron spins separated by 1.3 kilometres," *Nature*, vol. 526, pp. 682–686, Oct 2015.

[24] L. K. Shalm, E. Meyer-Scott, B. G. Christensen, P. Bierhorst, M. A. Wayne, M. J. Stevens, T. Gerrits, S. Glancy, D. R. Hamel, M. S. Allman, K. J. Coakley, S. D. Dyer, C. Hodge, A. E. Lita, V. B. Verma, C. Lambrocco, E. Tortorici, A. L. Migdall, Y. Zhang, D. R. Kumor, W. H. Farr, F. Marsili, M. D. Shaw, J. A. Stern, C. Abellán, W. Amaya, V. Pruneri, T. Jennewein, M. W. Mitchell, P. G. Kwiat, J. C. Bienfang, R. P. Mirin, E. Knill, and S. W. Nam, "Strong loophole-free test of local realism," *Phys. Rev. Lett.*, vol. 115, p. 250402, Dec 2015.

[25] M. Giustina, M. A. M. Versteegh, S. Wengerowsky, J. Handsteiner, A. Hochrainer, K. Phelan, F. Steinlechner, J. Kofler, J.-A. Larsson, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, J. Beyer, T. Gerrits, A. E. Lita, L. K. Shalm, S. W. Nam, T. Scheidl, R. Ursin, B. Wittmann, and A. Zeilinger, "Significant-loophole-free test of bell's theorem with entangled photons," *Phys. Rev. Lett.*, vol. 115, p. 250401, Dec 2015.

[26] W. Rosenfeld, D. Burchardt, R. Garthoff, K. Redeker, N. Ortegel, M. Rau, and H. Weinfurter, "Event-ready bell test using entangled atoms simultaneously closing detection and locality loopholes," *Phys. Rev. Lett.*, vol. 119, p. 010402, Jul 2017.

[27] R. Penrose, "On gravity's role in quantum state reduction," *General relativity and gravitation*, vol. 28, no. 5, pp. 581–600, 1996.

[28] D. Salart, A. Baas, J. A. van Houwelingen, N. Gisin, and H. Zbinden, "Spacelike separation in a bell test assuming gravitationally induced collapses," *Physical review letters*, vol. 100, no. 22, p. 220404, 2008.

[29] A. Kent, "A proposed test of the local causality of spacetime," in *Quantum Reality, Relativistic Causality, and Closing the Epistemic Circle*, pp. 369–378, Springer, 2009.

[30] J. Bell, "Free variables and local causality," *Dialectica*, vol. 39, pp. 103–106, 1985.

[31] R. Kaltenbaek, M. Aspelmeyer, T. Jennewein, C. Brukner, A. Zeilinger, M. Pfennigbauer, and W. R. Leeb, "Proof-of-concept experiments for quantum physics in space," in *Quantum Communications and Quantum Imaging* (R. E. Meyers and Y. Shih, eds.), vol. 5161, pp. 252 – 268, International Society for Optics and Photonics, SPIE, 2004.

[32] Y. Cao, Y.-H. Li, W.-J. Zou, Z.-P. Li, Q. Shen, S.-K. Liao, J.-G. Ren, J. Yin, Y.-A. Chen, C.-Z. Peng, *et al.*, "Bell test over extremely high-loss channels: towards distributing entangled photon pairs between earth and the moon," *Physical review letters*, vol. 120, no. 14, p. 140405, 2018.

[33] M. K. Bhaskar, R. Riedinger, B. Machielse, D. S. Levonian, C. T. Nguyen, E. N. Knall, H. Park, D. Englund, M. Lončar, D. D. Sukachev, and M. D. Lukin, "Experimental demonstration of memory-enhanced quantum communication," *Nature*, vol. 580, pp. 60–64, Apr 2020.

[34] M. Pompili, S. L. N. Hermans, S. Baier, H. K. C. Beukers, P. C. Humphreys, R. N. Schouten, R. F. L. Vermeulen, M. J. Tiggelman, L. dos Santos Martins, B. Dirkse, S. Wehner, and R. Hanson, "Realization of a multinode quantum network of remote solid-state qubits," *Science*, vol. 372, no. 6539, pp. 259–264, 2021.

[35] K. T. Kaczmarek *et al.*, "High-speed noise-free optical quantum memory," *Phys. Rev. A*, vol. 97, p. 042316, Apr 2018.

[36] R. Finkelstein, E. Poem, O. Michel, O. Lahad, and O. Firstenberg, "Fast, noise-free memory for photon synchronization at room temperature," *Sci. Adv.*, vol. 4, no. 1, p. eaap8598, 2018.

[37] J. Wolters, G. Buser, A. Horsley, L. Béguin, A. Jöckel, J.-P. Jahn, R. J. Warburton, and P. Treutlein, "Simple atomic quantum memory suitable for semiconductor quantum dot single photons," *Phys. Rev. Lett.*, vol. 119, p. 060502, Aug 2017.

[38] D. Main, T. M. Hird, S. Gao, I. A. Walmsley, and P. M. Ledingham, "Room temperature atomic frequency comb storage for light," *Opt. Lett.*, vol. 46, pp. 2960–2963, Jun 2021.

[39] J. Guo, X. Feng, P. Yang, Z. Yu, L. Q. Chen, C.-H. Yuan, and W. Zhang, "High-performance raman quantum memory with optimal control in room temperature atoms," *Nat. Commun.*, vol. 10, no. 1, p. 148, 2019.

[40] O. Katz and O. Firstenberg, "Light storage for one second in room-temperature alkali vapor," *Nat. Commun.*, vol. 9, no. 1, p. 2074, 2018.

[41] O. Katz, R. Shaham, and O. Firstenberg, "Coupling light to a nuclear spin gas with a two-photon linewidth of five millihertz," *Science Advances*, vol. 7, no. 14, p. eabe9164, 2021.

[42] A. Dinkelaker, M. Schiemangk, V. Schkolnik, A. Kenyon, M. Krutzik, A. Peters, and K. Team, "Kalexus - a potassium laser system with autonomous frequency stabilization on a sounding rocket," in *Frontiers in Optics 2016*, p. FF1H.1, Optical Society of America, 2016.

[43] M. Lezius, T. Wilken, C. Deutsch, M. Giunta, O. Mandel, A. Thaller, V. Schkolnik, M. Schiemangk, A. Dinkelaker, A. Kohfeldt, A. Wicht, M. Krutzik, A. Peters, O. Hellmig, H. Duncker, K. Sengstock, P. Windpassinger, K. Lampmann, T. Hülsing, T. W. Hänsch, and R. Holzwarth, "Space-borne frequency comb metrology," *Optica*, vol. 3, pp. 1381–1387, Dec 2016.

[44] K. Döringshoff, F. B. Gutsch, V. Schkolnik, C. Kürbis, M. Oswald, B. Pröbster, E. V. Kovalchuk, A. Bawamia, R. Smol, T. Schuldt, M. Lezius, R. Holzwarth, A. Wicht, C. Braxmaier, M. Krutzik, and A. Peters, "Iodine frequency reference on a sounding rocket," *Phys. Rev. Applied*, vol. 11, p. 054068, May 2019.

[45] A. Strangfeld, S. Kanthak, M. Schiemangk, B. Wiegand, A. Wicht, A. Ling, and M. Krutzik, "Prototype of a compact rubidium-based optical frequency reference for operation on nanosatellites," *J. Opt. Soc. Am. B*, vol. 38, pp. 1885–1891, Jun 2021.

[46] R. Zhang, S. R. Garner, and L. V. Hau, "Creation of long-term coherent optical memory via controlled nonlinear interactions in bose-einstein condensates," *Phys. Rev. Lett.*, vol. 103, p. 233602, Dec 2009.

[47] S. Riedl, M. Lettner, C. Vo, S. Baur, G. Rempe, and S. Dürr, "Bose-einstein condensate as a quantum memory for a photonic polarization qubit," *Phys. Rev. A*, vol. 85, p. 022318, Feb 2012.

[48] E. Saglamyurek, T. Hrushevskyi, A. Rastogi, L. W. Cooke, B. D. Smith, and L. J. LeBlanc, "Storing short single-photon-level optical pulses in Bose-Einstein condensates for high-performance quantum memory," *New Journal of Physics*, vol. 23, no. 4, 2021.

[49] Y.-W. Cho, G. T. Campbell, J. L. Everett, J. Bernu, D. B. Higginbottom, M. T. Cao, J. Geng, N. P. Robins, P. K. Lam, and B. C. Buchler, "Highly efficient optical quantum memory with long coherence time in cold atoms," *Optica*, vol. 3, pp. 100–107, Jan 2016.

[50] Y. O. Dudin, L. Li, and A. Kuzmich, "Light storage on the time scale of a minute," *Phys. Rev. A*, vol. 87, p. 031801, Mar 2013.

[51] L. Heller, P. Farrera, G. Heinze, and H. de Riedmatten, "Cold-atom temporally multiplexed quantum memory with cavity-enhanced noise suppression," *Phys. Rev. Lett.*, vol. 124, p. 210504, May 2020.

[52] S.-Y. Lan, A. G. Radnaev, O. A. Collins, D. N. Matsukevich, T. A. B. Kennedy, and A. Kuzmich, "A multiplexed quantum memory," *Opt. Express*, vol. 17, pp. 13639–13645, Aug 2009.

[53] Y.-F. Pu, N. Jiang, W. Chang, H.-X. Yang, C. Li, and L.-M. Duan, "Experimental realization of a multiplexed quantum memory with 225 individually accessible memory cells," *Nat. Commun.*, vol. 8, p. 15359, May 2017.

[54] M. Langlois, L. De Sarlo, D. Holleville, N. Dimarcq, J.-F. m. c. Schaff, and S. Bernon, "Compact cold-atom clock for onboard timebase: Tests in reduced gravity," *Phys. Rev. Applied*, vol. 10, p. 064007, Dec 2018.

[55] B. Barrett, L. Antoni-Micollier, L. Chichet, B. Battelier, T. Lévèque, A. Landragin, and P. Bouyer, "Dual matter-wave inertial sensors in weightlessness," *Nature Communications*, vol. 7, p. 13786, Dec 2016.

[56] H. Müntinga, H. Ahlers, M. Krutzik, A. Wenzlawski, S. Arnold, D. Becker, K. Bongs, H. Dittus, H. Duncker, N. Gaaloul, C. Gherasim, E. Giese, C. Grzeschik, T. W. Hänsch, O. Hellmig, W. Herr, S. Herrmann, E. Kajari, S. Kleinert, C. Lämmerzahl, W. Lewoczko-Adamczyk, J. Malcolm, N. Meyer, R. Nolte, A. Peters, M. Popp, J. Reichel, A. Roura, J. Rudolph, M. Schiemangk, M. Schneider, S. T. Seidel, K. Sengstock, V. Tamma, T. Valenzuela, A. Vogel, R. Walser, T. Wendrich, P. Windpassinger, W. Zeller, T. van Zoest, W. Ertmer, W. P. Schleich, and E. M. Rasel, "Interferometry with bose-einstein condensates in microgravity," *Phys. Rev. Lett.*, vol. 110, p. 093602, Feb 2013.

[57] C. Deppner, W. Herr, M. Cornelius, P. Stromberger, T. Sternke, C. Grzeschik, A. Grote, J. Rudolph, S. Herrmann, M. Krutzik, A. Wenzlawski, R. Corgier, E. Charron, D. Guéry-Odelin, N. Gaaloul, C. Lämmerzahl, A. Peters, P. Windpassinger, and E. M. Rasel, "Collective-mode enhanced matter-wave optics," *Phys. Rev. Lett.*, vol. 127, p. 100401, Aug 2021.

[58] D. Becker, M. D. Lachmann, S. T. Seidel, H. Ahlers, A. N. Dinkelaker, J. Grosse, O. Hellmig, H. Müntinga, V. Schkolnik, T. Wendrich, A. Wenzlawski, B. Weps, R. Corgier, T. Franz, N. Gaaloul, W. Herr, D. Lüdtke, M. Popp, S. Amri, H. Duncker, M. Erbe, A. Kohfeldt, A. Kubelka-Lange, C. Braxmaier, E. Charron, W. Ertmer, M. Krutzik, C. Lämmerzahl, A. Peters, W. P. Schleich, K. Sengstock, R. Walser, A. Wicht, P. Windpassinger, and E. M. Rasel, "Space-borne bose–einstein condensation for precision interferometry," *Nature*, vol. 562, pp. 391–395, Oct 2018.

[59] M. D. Lachmann, H. Ahlers, D. Becker, A. N. Dinkelaker, J. Grosse, O. Hellmig, H. Müntinga, V. Schkolnik, S. T. Seidel, T. Wendrich, A. Wenzlawski, B. Carrick, N. Gaaloul, D. Lüdtke, C. Braxmaier, W. Ertmer, M. Krutzik, C. Lämmerzahl, A. Peters, W. P. Schleich, K. Sengstock, A. Wicht, P. Windpassinger, and E. M. Rasel, "Ultracold atom interferometry in space," *Nature Communications*, vol. 12, p. 1317, Feb 2021.

[60] L. Liu *et al.*, "In-orbit operation of an atomic clock based on laser-cooled 87rb atoms," *Nat. Commun.*, vol. 9, no. 1, p. 2760, 2018.

[61] D. C. Aveline, J. R. Williams, E. R. Elliott, C. Dutenhoffer, J. R. Kellogg, J. M. Kohel, N. E. Lay, K. Oudrhiri, R. F. Shotwell, N. Yu, and R. J. Thompson, "Observation of bose–einstein condensates in an earth-orbiting research lab," *Nature*, vol. 582, pp. 193–197, Jun 2020.

[62] P. Laurent, D. Massonnet, L. Cacciapuoti, and C. Salomon, "The aces/pharao space mission," *Comptes Rendus Physique*, vol. 16, no. 5, pp. 540–552, 2015.

[63] K. Frye, S. Abend, W. Bartosch, A. Bawamia, D. Becker, H. Blume, C. Braxmaier, S.-W. Chiow, M. A. Efremov, W. Ertmer, P. Fierlinger, T. Franz, N. Gaaloul, J. Grosse, C. Grzeschik, O. Hellmig, V. A. Henderson, W. Herr, U. Israelsson, J. Kohel, M. Krutzik, C. Kürbis, C. Lämmerzahl, M. List, D. Lüdtke, N. Lundblad, J. P. Marburger, M. Meister, M. Mihm, H. Müller, H. Müntinga, A. M. Nepal, T. Oberschulte, A. Papakonstantinou, J. Perovsek, A. Peters, A. Prat, E. M. Rasel, A. Roura, M. Sbroscia, W. P. Schleich, C. Schubert, S. T. Seidel, J. Sommer, C. Spindeldreier, D. Stamper-Kurn, B. K. Stuhl, M. Warner, T. Wendrich, A. Wenzlawski, A. Wicht, P. Windpassinger, N. Yu, and L. Wörner, "The bose-einstein condensate and cold atom laboratory," *EPJ Quantum Technology*, vol. 8, p. 1, Jan 2021.

[64] D. Devani, S. Maddox, R. Renshaw, N. Cox, H. Sweeney, T. Cross, M. Holynski, R. Nolli, J. Winch, K. Bongs, K. Holland, D. Colebrook, N. Adams, K. Quillien, J. Buckle, A. Karde, M. Farries, T. Legg, R. Webb, C. Gawith, S. A. Berry, and L. Carpenter, "Gravity sensing: cold atom trap onboard a 6u cubesat," *CEAS Space Journal*, vol. 12, pp. 539–549, Dec 2020.

[65] Y. A. El-Neaj, C. Alpigiani, S. Amairi-Pyka, H. Araújo, A. Balaž, A. Bassi, L. Bathe-Peters, B. Battelier, A. Belić, E. Bentine, J. Bernabeu, A. Bertoldi, R. Bingham, D. Blas, V. Bolpasi, K. Bongs, S. Bose, P. Bouyer, T. Bowcock, W. Bowden, O. Buchmueller, C. Burrage, X. Calmet, B. Canuel, L.-I. Caramete, A. Carroll, G. Cella, V. Charmandaris, S. Chattopadhyay, X. Chen, M. L. Chiofalo, J. Coleman, J. Cotter, Y. Cui, A. Derevianko, A. De Roeck, G. S. Djordjevic, P. Dornan, M. Doser, I. Drougkakis, J. Dunningham, I. Dutan, S. Easo, G. Elertas, J. Ellis, M. El Sawy, F. Fassi, D. Felea, C.-H. Feng, R. Flack, C. Foot, I. Fuentes, N. Gaaloul, A. Gauguet, R. Geiger, V. Gibson, G. Giudice, J. Goldwin, O. Grachov, P. W. Graham, D. Grasso, M. van der Grinten, M. Gündogan, M. G. Haehnelt, T. Harte, A. Hees, R. Hobson, J. Hogan, B. Holst, M. Holynski, M. Kasevich, B. J. Kavanagh, W. von Klitzing, T. Kovachy, B. Krikler, M. Krutzik, M. Lewicki, Y.-H. Lien, M. Liu, G. G. Luciano, A. Magnon, M. A. Mahmoud, S. Malik, C. McCabe, J. Mitchell, J. Pahl, D. Pal, S. Pandey, D. Papazoglou, M. Paternostro, B. Penning, A. Peters, M. Prevedelli, V. Puthiya-Veettil, J. Quenby, E. Rasel, S. Ravenhall, J. Ringwood, A. Roura, D. Sabulsky, M. Sameed, B. Sauer, S. A. Schäffer, S. Schiller, V. Schkolnik, D. Schlippert, C. Schubert, H. R. Sfar, A. Shayeghi, I. Shipsey, C. Signorini, Y. Singh, M. Soares-Santos, F. Sorrentino, T. Sumner, K. Tassis, S. Tentindo, G. M. Tino, J. N. Tinsley, J. Unwin, T. Valenzuela, G. Vasilakis, V. Vaskonen, C. Vogt, A. Webber-Date, A. Wenzlawski, P. Windpassinger, M. Woltmann, E. Yazgan, M.-S. Zhan, X. Zou, and J. Zupan, "Aedge: Atomic experiment for dark matter and gravity exploration in space," *EPJ Quantum Technology*, vol. 7, p. 6, Mar 2020.

[66] D. Lago-Rivera, S. Grandi, J. V. Rakonjac, A. Seri, and H. de Riedmatten, "Telecom-heralded entanglement between multimode solid-state quantum memories," *Nature*, vol. 594, pp. 37–40, Jun 2021.

[67] X. Liu, J. Hu, Z.-F. Li, X. Li, P.-Y. Li, P.-J. Liang, Z.-Q. Zhou, C.-F. Li, and G.-C. Guo, "Heralded entanglement distribution between two absorptive quantum memories," *Nature*, vol. 594, pp. 41–45, Jun 2021.

[68] G. Heinze, C. Hubrich, and T. Halfmann, "Stopped light and image storage by electromagnetically induced transparency up to the regime of one minute," *Phys. Rev. Lett.*, vol. 111, p. 033601, Jul 2013.

[69] I. Usmani, C. Clausen, F. Bussières, N. Sangouard, M. Afzelius, and N. Gisin, "Heralded quantum entanglement between two crystals," *Nature Photonics*, vol. 6, pp. 234–237, Apr 2012.

[70] M. Gündoğan, M. Mazzera, P. M. Ledingham, M. Cristiani, and H. de Riedmatten, "Coherent storage of temporally multimode light using a spin-wave atomic frequency comb memory," vol. 15, p. 045012, apr 2013.

[71] A. Seri, D. Lago-Rivera, A. Lenhard, G. Corrielli, R. Osellame, M. Mazzera, and H. de Riedmatten, "Quantum storage of frequency-multiplexed heralded single photons," *Phys. Rev. Lett.*, vol. 123, p. 080502, Aug 2019.

[72] N. Sinclair, E. Saglamyurek, H. Mallahzadeh, J. A. Slater, M. George, R. Ricken, M. P. Hedges, D. Oblak, C. Simon, W. Sohler, and W. Tittel, "Spectral multiplexing for scalable

quantum photonics using an atomic frequency comb quantum memory and feed-forward control," *Phys. Rev. Lett.*, vol. 113, p. 053603, Jul 2014.

[73] E. Saglamyurek, M. Grimau Puigibert, Q. Zhou, L. Giner, F. Marsili, V. B. Verma, S. Woo Nam, L. Oesterling, D. Nippa, D. Oblak, and W. Tittel, "A multiplexed light-matter interface for fibre-based quantum networks," *Nature Communications*, vol. 7, p. 11202, Apr 2016.

[74] T.-S. Yang, Z.-Q. Zhou, Y.-L. Hua, X. Liu, Z.-F. Li, P.-Y. Li, Y. Ma, C. Liu, P.-J. Liang, X. Li, Y.-X. Xiao, J. Hu, C.-F. Li, and G.-C. Guo, "Multiplexed storage and real-time manipulation based on a multiple degree-of-freedom quantum memory," *Nature Communications*, vol. 9, p. 3407, Aug 2018.

[75] E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler, and W. Tittel, "Broadband waveguide quantum memory for entangled photons," *Nature*, vol. 469, pp. 512–515, Jan 2011.

[76] S. Marzban, J. G. Bartholomew, S. Madden, K. Vu, and M. J. Sellars, "Observation of photon echoes from evanescently coupled rare-earth ions in a planar waveguide," *Phys. Rev. Lett.*, vol. 115, p. 013601, Jul 2015.

[77] G. Corrielli, A. Seri, M. Mazzera, R. Osellame, and H. de Riedmatten, "Integrated optical memory based on laser-written waveguides," *Phys. Rev. Applied*, vol. 5, p. 054013, May 2016.

[78] T. Zhong, J. M. Kindem, J. G. Bartholomew, J. Rochman, I. Craiciu, E. Miyazono, M. Bettinelli, E. Cavalli, V. Verma, S. W. Nam, F. Marsili, M. D. Shaw, A. D. Beyer, and A. Faraon, "Nanophotonic rare-earth quantum memory with optically controlled retrieval," *Science*, vol. 357, no. 6358, pp. 1392–1395, 2017.

[79] A. M. Dibos, M. Raha, C. M. Phenicie, and J. D. Thompson, "Atomic source of single photons in the telecom band," *Phys. Rev. Lett.*, vol. 120, p. 243601, Jun 2018.

[80] P. Jobez, C. Laplane, N. Timoney, N. Gisin, A. Ferrier, P. Goldner, and M. Afzelius, "Coherent spin control at the quantum level in an ensemble-based optical memory," *Phys. Rev. Lett.*, vol. 114, p. 230502, Jun 2015.

[81] M. Gündoğan, P. M. Ledingham, K. Kutluer, M. Mazzera, and H. de Riedmatten, "Solid state spin-wave quantum memory for time-bin qubits," *Phys. Rev. Lett.*, vol. 114, p. 230501, Jun 2015.

[82] M. Businger *et al.*, "Optical spin-wave storage in a solid-state hybridized electron-nuclear spin ensemble," *Phys. Rev. Lett.*, vol. 124, p. 053606, Feb 2020.

[83] L. You *et al.*, "Superconducting nanowire single photon detection system for space applications," *Opt. Express*, vol. 26, pp. 2965–2971, Feb 2018.

[84] P. G. Kwiat, E. Waks, A. G. White, I. Appelbaum, and P. H. Eberhard, "Ultrabright source of polarization-entangled photons," *Phys. Rev. A*, vol. 60, pp. R773–R776, Aug 1999.

[85] J. Yin *et al.*, "Entanglement-based secure quantum cryptography over 1,120 kilometres," *Nature*, vol. 582, pp. 501–505, Jun 2020.

[86] A. Villar, A. Lohrmann, X. Bai, T. Vergoossen, R. Bedington, C. Perumangatt, H. Y. Lim, T. Islam, A. Reezwana, Z. Tang, R. Chandrasekara, S. Sachidananda, K. Durak, C. F. Wildfeuer, D. Griffin, D. K. L. Oi, and A. Ling, "Entanglement demonstration on board a nano-satellite," *Optica*, vol. 7, pp. 734–737, Jul 2020.

[87] Z. Tang, R. Chandrasekara, Y. C. Tan, C. Cheng, K. Durak, and A. Ling, "The photon pair source that survived a rocket explosion," *Scientific Reports*, vol. 6, p. 25603, May 2016.

[88] J. Fekete, D. Rieländer, M. Cristiani, and H. de Riedmatten, "Ultranarrow-band photon-pair source compatible with solid state quantum memories and telecommunication networks," *Phys. Rev. Lett.*, vol. 110, p. 220502, May 2013.

[89] M. Rambach, A. Nikolova, T. J. Weinhold, and A. G. White, "Sub-megahertz linewidth single photon source," *APL Photonics*, vol. 1, no. 9, p. 096101, 2016.

[90] N. Sangouard, C. Simon, J. c. v. Minář, H. Zbinden, H. de Riedmatten, and N. Gisin, "Long-distance entanglement distribution with single-photon sources," *Phys. Rev. A*, vol. 76, p. 050301, Nov 2007.

[91] P. Senellart, G. Solomon, and A. White, "High-performance semiconductor quantum-dot single-photon sources," *Nature Nanotechnology*, vol. 12, pp. 1026–1039, Nov 2017.

[92] C. Matthiesen, A. N. Vamivakas, and M. Atatüre, "Subnatural linewidth single photons from a quantum dot," *Phys. Rev. Lett.*, vol. 108, p. 093602, Feb 2012.

[93] J. D. Siverns, J. Hannegan, and Q. Quraishi, "Demonstration of slow light in rubidium vapor using single photons from a trapped ion," *Science Advances*, vol. 5, no. 10, p. eaav4651, 2019.

[94] J.-S. Tang, Z.-Q. Zhou, Y.-T. Wang, Y.-L. Li, X. Liu, Y.-L. Hua, Y. Zou, S. Wang, D.-Y. He, G. Chen, Y.-N. Sun, Y. Yu, M.-F. Li, G.-W. Zha, H.-Q. Ni, Z.-C. Niu, C.-F. Li, and G.-C. Guo, "Storage of multiple single-photon pulses emitted from a quantum dot in a solid-state quantum memory," *Nature Communications*, vol. 6, p. 8652, Oct 2015.

[95] E. V. Denning, D. A. Gangloff, M. Atatüre, J. Mørk, and C. Le Gall, "Collective quantum memory activated by a driven central spin," *Phys. Rev. Lett.*, vol. 123, p. 140502, Oct 2019.

[96] D. A. Gangloff, G. Éthier Majcher, C. Lang, E. V. Denning, J. H. Bodey, D. M. Jackson, E. Clarke, M. Hugues, C. L. Gall, and M. Atatüre, "Quantum interface of an electron and a nuclear ensemble," *Science*, vol. 364, no. 6435, pp. 62–66, 2019.

[97] C. Hepp, T. Müller, V. Waselowski, J. N. Becker, B. Pingault, H. Sternschulte, D. Steinmüller-Nethl, A. Gali, J. R. Maze, M. Atatüre, and C. Becher, "Electronic structure of the silicon vacancy color center in diamond," *Phys. Rev. Lett.*, vol. 112, p. 036405, Jan 2014.

[98] M. E. Trusheim, B. Pingault, N. H. Wan, M. Gündoğan, L. De Santis, R. Debroux, D. Gangloff, C. Purser, K. C. Chen, M. Walsh, J. J. Rose, J. N. Becker, B. Lienhard, E. Bersin, I. Paradeisanos, G. Wang, D. Lyzwa, A. R.-P. Montblanch, G. Malladi, H. Bakhru, A. C. Ferrari, I. A. Walmsley, M. Atatüre, and D. Englund, "Transform-limited photons from a coherent tin-vacancy spin in diamond," *Phys. Rev. Lett.*, vol. 124, p. 023602, Jan 2020.

[99] D. D. Sukachev, A. Sipahigil, C. T. Nguyen, M. K. Bhaskar, R. E. Evans, F. Jelezko, and M. D. Lukin, "Silicon-vacancy spin qubit in diamond: A quantum memory exceeding 10 ms with single-shot state readout," *Phys. Rev. Lett.*, vol. 119, p. 223602, Nov 2017.

[100] M. Toth and I. Aharonovich, "Single photon sources in atomically thin materials," *Annual Review of Physical Chemistry*, vol. 70, no. 1, pp. 123–142, 2019. PMID: 30735459.

[101] R. Bourrellier, S. Meuret, A. Tararan, O. Stéphan, M. Kociak, L. H. G. Tizei, and A. Zobelli, "Bright uv single photon emission at point defects in h-bn," *Nano Letters*, vol. 16, no. 7, pp. 4317–4321, 2016.

[102] R. Camphausen, L. Marini, S. A. Tawfik, T. T. Tran, M. J. Ford, and S. Palomba, "Observation of near-infrared sub-poissonian photon emission in hexagonal boron nitride at room temperature," *APL Photonics*, vol. 5, no. 7, p. 076103, 2020.

[103] T. Vogl, R. Lecamwasam, B. C. Buchler, Y. Lu, and P. K. Lam, "Compact cavity-enhanced single-photon generation with hexagonal boron nitride," *ACS Photonics*, vol. 6, no. 8, pp. 1955–1962, 2019.

[104] A. Dietrich, M. W. Doherty, I. Aharonovich, and A. Kubanek, "Solid-state single photon source with fourier transform limited lines at room temperature," *Phys. Rev. B*, vol. 101, p. 081401, Feb 2020.

[105] T. Vogl, K. Sripathy, A. Sharma, P. Reddy, J. Sullivan, J. R. Machacek, L. Zhang, F. Karouta, B. C. Buchler, M. W. Doherty, Y. Lu, and P. K. Lam, "Radiation tolerance of two-dimensional material-based devices for space applications," *Nat. Commun.*, vol. 10, no. 1, p. 1202, 2019.

[106] C. Panayi, M. Razavi, X. Ma, and N. Lütkenhaus, "Memory-assisted measurement-device-independent quantum key distribution," *New J. Phys.*, vol. 16, p. 043005, apr 2014.

[107] D. Luong, L. Jiang, J. Kim, and N. Lütkenhaus, "Overcoming lossy channel bounds using a single quantum repeater node," *Appl. Phys. B*, vol. 122, p. 96, Apr 2016.

[108] S. Langenfeld, P. Thomas, O. Morin, and G. Rempe, "Quantum repeater node demonstrating unconditionally secure key distribution," *Phys. Rev. Lett.*, vol. 126, p. 230506, Jun 2021.