

# Topical: Blue-detuned box potentials for Earth-bound and spaceborne quantum gases

**Dan Stamper-Kurn<sup>6,7,\*</sup>, Kai Frye<sup>1,2</sup>, Naceur Gaaloul<sup>1</sup>, Matthias Meister<sup>3</sup>, Nir Navon<sup>4</sup>, Matteo Sbroscia<sup>5</sup>, and Rob Thompson<sup>5</sup>**

<sup>1</sup>Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany

<sup>2</sup>Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik, c/o Leibniz Universität Hannover, DLR-SI, Callinstraße 36, 30167, Hannover, Germany

<sup>3</sup>Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

<sup>4</sup>Department of Physics, Yale University, New Haven, Connecticut 06520, US

<sup>5</sup>Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, U.S.A

<sup>6</sup>Department of Physics, University of California, Berkeley, California 94720, USA

<sup>7</sup>Challenge Institute for Quantum Computation, University of California, Berkeley, California, 94720, USA

\*Primary Author; e-mail: [dmsk@berkeley.edu](mailto:dmsk@berkeley.edu), phone: (510) 642-9618

Keywords: Bose-Einstein Condensate; Quantum Optics; Atom Optics; Atom Interferometry; Microgravity; International Space Station

## INTRODUCTION

The invention of laser cooling in the 1980's transformed atomic physics. Rather than focusing just on measuring the internal dynamics of atoms, now atomic physicists could control, observe, and measure the quantum mechanics of atomic center-of-mass motion. The scientific revolution was extended in the mid-90's when quantum degenerate gases were first produced. Throughout the ensuing decades, ultracold atomic gases have become an essential medium for exploring many-body quantum physics and for achieving precise quantum measurements using coherent matter waves. This revolution has had profound impacts in diverse areas, including materials science, quantum information science, precise probes of fundamental physics, and the development of quantum technologies for sensing, navigation, communication and quantum computation. As such, by enabling new capabilities in ultracold atomic physics, we can derive advances in many scientific fields.

Performing ultracold atomic physics in freefall will enable entirely new scientific explorations. On Earth, atomic quantum gases can be formed and studied only by providing an external force to compensate the downward pull of gravity. Such a force is imparted by exposing the atoms (or molecules) to inhomogeneous electromagnetic fields, e.g. dc electric or magnetic fields, or ac fields in the radio, microwave, or optical frequency range. While this approach has been highly successful, and enabled an enormous range of experiments, there remain essential drawbacks. For one, inhomogeneity of the imposed electromagnetic field forces an inhomogeneity onto the atomic gas, precluding experiments that require homogeneous conditions and measurements that require a force-free environment. Second, the response of an atom to such inhomogeneous fields varies with elemental identity, isotope, and atomic internal state. As such, this approach to "gravity compensation" invariably distorts admixtures of quantum gases. Homogeneous conditions can be restored by switching off the gravity compensating fields, but, then, quantum gases can be interrogated only for the short time before they fall to the bottom of the ultrahigh vacuum chambers in which they are produced.

These gravity-compensating inhomogeneities are no longer needed for quantum gases being interrogated in a freely falling instrument. However, some sort of containment is still required in order to study a gas for long times with control over its temperature and density. How can we combine the features of homogeneity and confinement? The answer is to circumscribe the volume of the atomic gas with a sharp repulsive boundary, i.e. to place the gas inside a hard-walled box. Within such a volume, an atom experiences a homogeneous force-free environment. At the sharp boundaries, while atoms experience a strong, state-dependent inhomogeneity, the influence of this inhomogeneity on the properties of the atomic gas vanishes as the boundary sharpens. Experimentally, this sharp boundary can be produced by illuminating the atomic gas with an optical image that is completely dark within an interior volume and that becomes rapidly bright at the volume's edge. When this light has an optical frequency that is blue-detuned from atomic optical transitions, the intense optical boundaries serve as repulsive walls. The gas is, thereby, trapped inside a blue-detuned optical box.

We propose a robust research focus on blue-detuned box potentials as an enabling technology for ultracold atomic and molecular quantum gas research and its application in quantum science and technology. To realize its goals, this research program *must* pursue several simultaneous efforts: (1) ground-based research on using box-potential traps in varied experimental settings with the aim of advancing basic science and its applications, identifying the full range of uses of box-potential traps, pushing the state of the art in ground-based experiments and thus clarifying the unique opportunities opened by conducting quantum-gas experiments in space; (2) developing technologies for spatial light modulation, useful both for producing box potentials and also for other experimental techniques, to make them compatible with space missions; (3) proving experimental methods, establishing technical readiness, and also advancing science by integrating spatial light modulation and box-potential trapping into free-fall experimental testbeds; (4) integrating spatial light modulation and blue-detuned box potential capability into existing and upcoming orbital cold-atom experiments (the Cold Atom Laboratory and BECCAL); (5) supporting exploratory research, proposal development, and prototype development for future ultracold quantum gas experiments in space beyond those presently planned on the ISS, e.g. on other orbiting stations, on future "free-flyer" experiments, and in the open of outer space.

Below, we provide several important and inspiring scientific uses of blue-box potentials to study quantum gases in free fall. These examples alone provide strong motivation for the proposed research focus. Even

so, these examples invariably only scratch the surface of what is possible. The ultracold atomic physics community has been amazingly creative and has made use of quantum gases for an enormous range of scientific applications, most of which were completely unforeseen in the previous years. Similarly, we can expect that a robust research program on space-based quantum gas research will yield benefits far beyond what we can envision at present.

## RESEARCH THEMES

### Scalar Bose gases in large box potentials

We consider first a scalar Bose gas. Here, we use the term “scalar” to imply that the gas is composed of atoms (or molecules) of just one elemental/isotopic identity, and in just one internal state; the counter-term, “spinor,” is used below. We consider that these atoms (or molecules) are bosons, i.e. having integer total spin. The quantum statistics of these bosons imply that this gas may undergo a transition to a Bose-Einstein condensate (BEC) at low temperature.

#### *Necessity for microgravity*

Ground-based experiments on scalar BECs have reached a very advanced state. Much of this experimental opus has been conducted on gases tightly trapped within inhomogeneous trapping potentials, e.g. harmonic magnetic traps, optical traps, optical lattice potentials, optical and magnetic waveguides, etc. Recently, experiments have been performed on box-trapped gases as well. These experiments are enabled by the fact that “gravity compensation,” achieved most typically by applying a finely tuned magnetic field gradient to the quantum gas, works extremely well when the gas is composed of atoms that are all in the same internal spin state and of just a single element and isotope.

Even with this success, we offer that there are compelling scientific targets for research on scalar Bose gases that cannot be performed with gravity compensation on Earth, and that will require achieving true microgravity conditions in a freely falling instrument. There are three specific defects in the Earth-based microgravity approach. First, magnetic-gradient gravity compensation, while being “very good,” is not perfect. According to Maxwell’s equations, in any magnetic gradient field, there remains a non-zero residual field curvature. The inhomogeneity produced by this curvature will ultimately limit the precision of quantum gas experiments conducted on Earth. The impact of this inhomogeneity becomes more severe the larger is the volume occupied by the atomic gas; thus, we can expect the precision limits to become more pronounced as one probes gases in larger volumes/lower densities. As a quantitative example, let us consider that the gravitational gradient is matched, through gravity compensation, to the  $10^{-4}$  level. At this level, the residual uncompensated potential reaches  $\sim L \times 4 k_B$  pK/ $\mu$ m across a box of length  $L$ . This energy becomes comparable to the ground state energy around  $40 \mu$ m; gases with dimensions larger than this length will no longer be in the homogeneous limit. In contrast, a microgravity environment would allow for much larger volumes, at least mm and even cm scale.

Second, magnetic-gradient gravity compensation can be applied only to atoms with a non-zero projection of their magnetic moment. The method is, therefore, not applicable to alkali-earth elements, including, for example,  $^{88}\text{Sr}$  atoms, which are a good candidate for precise atom interferometry owing to their weak collisional interactions and insensitivity to external electric and magnetic fields. For such atoms, it is possible to counter the force of gravity by exposing them to light with an intensity gradient. However, this method is highly susceptible to residual inhomogeneity.

Third, If the magnetic field must be specifically tuned to provide gravity compensation, it cannot also be used for other purposes. Most importantly, many experiments make use magnetic-field-tuned Feshbach resonances to tune the interactions between atoms. Eliminating the need for magnetic levitation enables free and independent use of the magnetic field to impose uniform fields of any strength onto the atoms to reach Feshbach resonances and tune the atomic interaction strength. One may work with any hyperfine internal state, giving easier access to such resonances, whereas on Earth one needs magnetically sensitive internal states in order for magnetic levitation to work.

Altogether, therefore, microgravity emerges as a necessity to study the full range of scalar Bose gases, particularly in the limit of large trapping volume. The aim of these studies may be measuring thermodynamic and dynamic properties of homogeneous, near-infinite-volume Bose gases. As background for such studies, one should cite one of the true highlights of fundamental physics research in low-Earth

orbit: the measurement of the lambda-point of helium 4 aboard the Space Shuttle Columbia in the 1990s [1]. That experiment provided what still stands as the deepest investigation of critical exponents at a phase transition. As is appropriate for high-impact physics, the experiment focused on a simple quantum system – the scalar Bose fluid formed of helium 4. The proposed investigations again focus on the scalar Bose fluid, extending beyond the helium-4 work by considering weak and strong interactions, different geometries and topologies, and dynamical effects.

### ***Outline of investigations***

**Fundamental studies on the nature of the BEC transition.** Near the critical temperature  $T_c$ , large volumes would allow to observe the critical fluctuations at longer length scales and, hence, ever closer to the phase transition. At low densities and weak interactions, the gas may become dominated by kinetic, rather than interaction energy. In this regime, one can study the “Grand Canonical Catastrophe” wherein the condensate number fluctuates thermally at macroscopic scales. At strong interactions, instilled by accessing a Feshbach resonance, one may test the universality hypothesis, which is that close enough to the phase transition, the properties of the system disregard the short-range interaction physics. Another advantage of a large and uniform Bose gas is that while BEC phase transition should occur everywhere at once, crossing the phase transition in a finite time (via “quenches”) implies that distant parts of the gas do so independently. The resulting dynamics represent a dynamical signature of critical phenomena, known as the Kibble-Zurek mechanism [2], which apply generally to a wide variety of physical systems, ranging from condensed matter to the early Universe.

**Bose gases in novel geometries.** CAL already demonstrated spherical bubbles [3], which could extend to e.g. cylindrical traps where, by varying the radii of curvature, the atoms explore either a 3D or a 2D confining volume, leading to interplay between phases that are present only in certain dimensions (such as the BKT transition [4]). Ideal platform for analogue quantum simulation of various physical systems, especially astrophysical ones by employing acoustic waves in the gas as analogues for light: in a gas under rapid expansion (“expanding universe”), events occurring in one location cannot affect those at a distant location owing to causality. This allows study of Sakharov waves [5], Hawking radiation [6], inflationary cosmology [7], and realisation of proposals for the Unruh effect [8]. Restricted, expanding, and curved geometries also allow the study of turbulence [9], the nature of energy cascade and to observe basic processes in superfluid flow such as vortex interactions and dynamics. In addition, freely expanding homogeneous BECs undergo diffractive focusing [10] leading to increased central densities depending on the dimensionality of the system. Moreover, a continuous Bose-Einstein condensate could also be trapped in a large area toroidal trap, or in traps of other non-simply connected geometries. One can measure metastability of vortex states and Bose-Einstein condensates in rotating frames.

**Extremely rarified quantum gases.** Finally, the large volumes and long expansion times enabled by microgravity allow to reach very low spatial densities  $n$ . The three-body loss rate going as  $n^2 a^4$ , where  $a$  is the scattering length quantifying the strength of the interaction, one could balance strong interactions with reduced densities, allowing study of normally short-lived strongly correlated systems, such as Efimov trimers [11].

### **Spinor Bose-Einstein gases in large box potentials**

#### ***Necessity for microgravity***

Spinor gases are composed of atoms with varying orientations of their magnetic moment. On Earth, magnetic levitation can compensate for the force of gravity only for atoms with specific magnetic moments, which renders experiments on spinor gases extremely limited if not impossible. Whilst one may levitate spinor gas atoms with electric fields, such as with a light beam intensity gradient or with a dc electric field gradient, optical levitation requires high optical power over a large volume of space, resulting in spontaneous emission scattering events and hence substantial reduction to the atomic clouds’ lifetimes. This remains true even when the light beam is painted to increase the volume where gravity is cancelled [12]. Also, Stark shifts from strong electric fields will distort the spherical symmetry that is the special characteristic of spinor gases, along with that of the geometry imposed by the blue-box potential. For these reasons, experiments so far have only studied spinor gases in tightly confined optical

traps, thereby restricting their size and dimensionality. Microgravity therefore provides a truly unique opportunity to study and use spinor Bose-Einstein gases in large volume, three dimensional, dark optical traps.

### ***Outline of investigations***

**Fundamental physics of spinor BECs.** Spinor Bose-Einstein gases are quantum fluids that manifest both magnetic order and superfluid order. The spinor gas is composed of atoms in different spin states, and hence states with different magnetic moments. Experiments can obtain more precise characterization of critical dynamics and phase transitions of the spinor Bose gas, such as ferromagnetic (where interactions favor the realization of magnetized spin domains) and antiferromagnetic (non-magnetic structures are favored) ordering. Spinor Bose-Einstein gases also undergo thermal and quantum phase transitions between paramagnetic and ferromagnetic states. These transitions can be crossed rapidly (with quantum quenches [13]) in uniform gases, allowing for detailed studies of the subsequent symmetry breaking dynamics. Using spin-dependent imaging techniques, one may resolve the spin structure in all three directions, in order to uniquely study spin dynamics and the long-term evolution of spin textures [14]. The hydrodynamics of spinor-gas superfluids is also essentially different from that of scalar superfluids, owing to a spin-gauge coupling between magnetization curvature and superfluid velocity: One could perform the first studies of spinor superfluids in three dimensions and test the prediction that superfluid turbulence is characterized by different power law behavior than it is in scalar gases.

**Long-lived coherence in spinor gases.** So far the demonstrated spin coherence times have been as long as three seconds [15] and lifetimes of magnon condensate spin textures as long as ten seconds (without tracking coherence [16]). The long spin coherence in spinor gases enables high resolution magnetometry [17] which, along with pulsed sequences to focus the magnetometry sensitivity to specific temporal frequencies, can demonstrate the impact of this technique in the precise measurement of the magnetic field profile and spectrum within a certain volume. Furthermore, dipolar interactions have been observed [18], and their impact on spin coherence may be studied by spin-echo pulses and judicious choice of trapping geometry (enabled by the blue-detuned light box trap).

**Precision sensing through atomic hyperfine-state coherence** Considering the gas of  $^{87}\text{Rb}$ , a commonly used quantum gas, microwave coherence on the  $|1,0\rangle + |2,0\rangle$  superposition is magnetic-field insensitive and can serve as an atomic microwave clock. Coherence on the  $|1, -1/ + 1\rangle + |2, +1/ - 1\rangle$  superposition is also magnetic-field insensitive, with the two atomic states having the same magnetic moment but opposite spin orientations. As a consequence, the hyperfine frequency becomes sensitive to rotations, so that such superpositions serve as a gyroscope. One could demonstrate the use of such a gyroscope to measure rotations of the ISS. By means of blue box potentials, one could further divide a quantum gas into several spatially separate containers, each of which would host a different superposition of hyperfine states. Reading out the phase of the various superpositions would allow one to reject common-mode noise.

In addition to studying mixtures of different internal states, blue-box potentials in microgravity can also greatly enhance atomic mixtures based on different isotopes and elements. On Earth the spatial overlap of these mixtures is limited by the differential gravitational sag, which completely vanishes in a microgravity environment. Hence, homogeneously confined mixtures would allow to investigate the textbook transition between miscible and immiscible phases in a very clean way for large box sizes.

### **Coherence and interferometry with box-trapped atoms**

#### ***Necessity for microgravity***

Interferometry experiment involve splitting the wavefunction of Bose-Einstein condensates into a superposition of two or more states, and later allowing them to interfere. On the ground, the traps initially holding the BECs are usually tightly focused to counter gravity, hence the interference is under conditions of rather strong interaction energies and correlations. Microgravity would allow one to continue this approach to interferometry, but between samples that are trapped much more loosely, less affected by

their trapping potentials and by interactions.

Most importantly, microgravity allows for separation times that are longer than are attained in Earth-bound fountain experiments. For example, the Stanford interferometer fountain allows for free flight of below 3 seconds. Microgravity experiments with sufficiently low background gas pressure would allow for free flight times in the tens of seconds or longer, allowing one to test a variety of theories over currently extreme time scales.

### ***Outline of investigations***

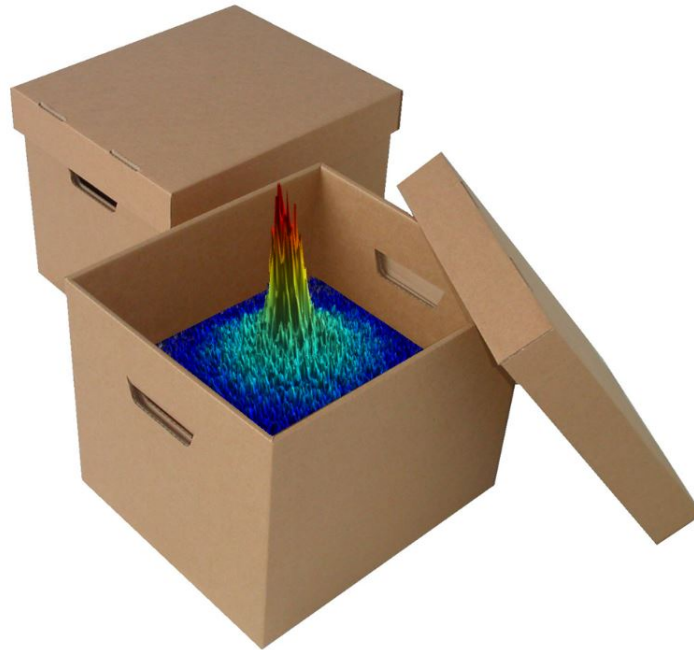
Fundamental physics. Quantum mechanics verifiably describes the microscopic world. The macroscopic world, however, is described quantitatively by classical mechanics. Quantum effects on macroscopic systems have largely not been observed. It therefore remains possible that there is a fundamental mechanism that prevents quantum mechanics from extending to “large” systems. Strawman theories of “spontaneous localization” have been outlined that would reduce quantum mechanical systems to classical ones. The basic notion is that there is some extraneous influence, that has as of yet eluded detection, that effects the localization of particles to a particular length scale within a particular time scale. For example, some chaotic field may be interacting with all massive objects, effectively measuring their position via spontaneous scattering events. The characteristic wavelength of this chaotic field sets the localization length scale, and the strength of interaction with the chaotic field sets the localization time scale. The objective of the proposed research is to set bounds on the length/timescale for this spontaneous localization process. The general scheme is to create a coherent superposition of a particle being located at two distant locations, and then to observe the persistence of that coherent superposition for ever-longer times. In a microgravity environment with blue-detuned traps, it is conceivable to test the persistence of quantum-mechanical superpositions over length scales of several cm, and timescales of up to hundreds of seconds.

One may make full use of the capability of arbitrarily shaping blue-box potentials, by a raising partition in the middle of a trap, and later recombining the two halves to measure the coherence time. Furthermore, one may also separate the two halves into two independent boxes, and, before recombining them, translating them along arbitrary trajectories to, for instance, sense the ISS rotation around the Earth. Microgravity also enabling simultaneous multi-species BECs with different internal states, one can perform interferometry between more than two BECs, in order to measure multiple quantities at once (e.g. rotation vector, potential energy field).

Interferometer with no light pulses. A spinor gas may be used in order to operate an interferometer without any light pulses. A longitudinally polarized gas is subject to a  $\pi/2$  rf pulse and then a magnetic field gradient. The gas separates into two paths, with the spin-up atoms moving one direction and spin down atoms moving the other direction. Another magnetic field gradient pulse in the opposite direction stops their motion, leaving two gases separated by a variable spacing. The coherence between the gases is Zeeman sensitive, but this sensitivity can be reduced by using spin-echo pulses, or perhaps by state-dependent transfer to magnetic-field insensitive states. Another pair of magnetic field gradients pushes the atomic clouds back toward each other and then stops them when the gases overlap. At this point, a measurement of the transverse magnetization of the gas is the equivalent of a readout of the interferometer phase. One would start with one such interferometer in order to test its coherence. From there, one can adapt the scheme to a pair of interferometers: Use the initial pulse/gradient/gradient sequence to prepare to spatially separated clouds (say separated along the x direction). Then another set of pulse/gradient/gradient separates out clouds along an orthogonal direction (say y). Two interferometers operating along the y-axis are now separated from one another along the x direction.

Another advantage of spinor BECs is magnon interferometry [18], which provides a highly accurate method of measuring the magnon recoil frequency. It offers an alternative to Bragg interferometry that is insensitive to atomic interactions to a large degree, thereby offering a viable complementary interferometric technique. Important goals include measuring the polaronic shift in the magnon recoil frequency under various conditions and within homogeneous gases (enabled by boxes), characterizing and

mitigating magnetic dipolar interaction effects, and using magnon interferometry to measure superfluid flow fields.



**Figure 1.** A BEC in a box.

## REFERENCES

- [1] J. Lipa et al., “Lambda point experiment in microgravity”, *Cryogenics* **34**, *Space Cryogenics Workshop*, 341–347 (1994).
- [2] J. Beugnon et al., “Exploring the kibble–zurek mechanism with homogeneous bose gases”, **50**, 022002 (2017).
- [3] [arXiv:2108.05880](https://arxiv.org/abs/2108.05880).
- [4] R. J. Fletcher et al., “Connecting berezinskii-kosterlitz-thouless and bec phase transitions by tuning interactions in a trapped gas”, *Phys. Rev. Lett.* **114**, 255302 (2015).
- [5] C.-L. Hung et al., “From cosmology to cold atoms: observation of sakharov oscillations in a quenched atomic superfluid”, *Science* **341**, 1213–1215 (2013).
- [6] J. Steinhauer, “Observation of quantum hawking radiation and its entanglement in an analogue black hole”, *Nature Physics* **12**, 959–965 (2016).
- [7] S. Eckel et al., “A rapidly expanding bose-einstein condensate: an expanding universe in the lab”, *Phys. Rev. X* **8**, 021021 (2018).
- [8] J. Rodriguez-Laguna et al., “Synthetic unruh effect in cold atoms”, *Phys. Rev. A* **95**, 013627 (2017).
- [9] N. Navon et al., “Synthetic dissipation and cascade fluxes in a turbulent quantum gas”, *Science* **366**, 382–385 (2019).
- [10] P. Boegel et al., “Diffractive focusing of a uniform Bose-Einstein condensate”, *J. Phys. B: At. Mol. Opt. Phys.* **54**, 185301 (2021).
- [11] T. Kraemer et al., “Evidence for efimov quantum states in an ultracold gas of caesium atoms”, *Nature* **440**, 315–318 (2006).
- [12] K. Shibata et al., “Compensation of gravity on cold atoms by a linear optical potential”, *Phys. Rev. Research* **2**, 013068 (2020).
- [13] L. E. Sadler et al., “Spontaneous symmetry breaking in a quenched ferromagnetic spinor bose-einstein condensate”, *Nature* **443**, 312–315 (2006).

- [14] M. Vengalattore et al., “Spontaneously modulated spin textures in a dipolar spinor bose-einstein condensate”, *Phys. Rev. Lett.* **100**, 170403 (2008).
- [15] J. Guzman et al., “Long-time-scale dynamics of spin textures in a degenerate  $f = 1$  87rb spinor bose gas”, *Phys. Rev. A* **84**, 063625 (2011).
- [16] F. Fang et al., “Condensing magnons in a degenerate ferromagnetic spinor bose gas”, *Phys. Rev. Lett.* **116**, 095301 (2016).
- [17] M. Vengalattore et al., “High-resolution magnetometry with a spinor bose-einstein condensate”, *Phys. Rev. Lett.* **98**, 200801 (2007).
- [18] G. E. Marti et al., “Coherent magnon optics in a ferromagnetic spinor bose-einstein condensate”, *Phys. Rev. Lett.* **113**, 155302 (2014).

## ACKNOWLEDGMENTS

Work by MS and RT carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). KF acknowledges the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy – EXC-2123 QuantumFrontiers – 390837967“ and the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under the grant numbers 50 WP 1431 and 1700. DMSK acknowledges support of the NSF QLCI program through grant number OMA-2016245