The Study of Quantum Phenomena with the Cold Atom Lab in Microgravity

www.coldatomlab.jpl.nasa.gov

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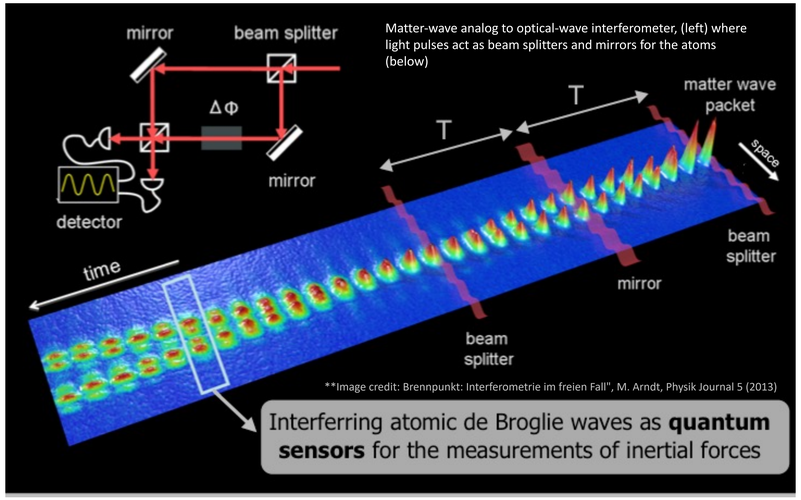
Matter-Wave Interferometry



Ultracold Atoms – an Enabling Technology

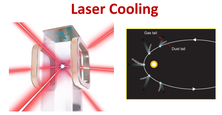
Ultracold quantum gases are studied in hundreds of experiments around the globe. Cold atom research has directly led to **6 Nobel prizes in physics**, and has opened doors for research with novel systems (e.g., a 5th state of matter characterized by macroscopic quantum waves called Bose-Einstein condensates).

The controlled and highly quantum nature of ultracold gases has also matured atom interferometers (AI), which measure subtle phase shifts in atomic matter-waves, to be among the most precise sensors currently available for gravity science and inertial sensing applications.

The **Cold Atom Lab (CAL)** is a multi-user facility that allows the first study of ultracold quantum gases and atom interferometers in the microgravity environment of the International Space Station (ISS).

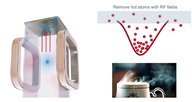
In the effectively force-free environment aboard the ISS, studies with the CAL AI could advance not only technologies for Earth observation, navigation, and metrology, but could also directly address some of the most fundamental – and still unresolved – questions of modern physics: **What is the nature of Dark Energy and what lies at the heart of the disagreement between quantum mechanics and General Relativity?**

Laser Cooling



milliKelvin temperatures (10^{-3} K)

Evaporative Cooling



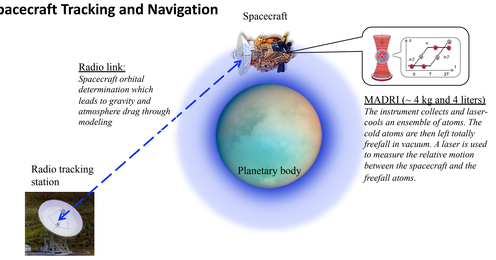
microKelvin to nanokelvin temperatures (10^{-5} K to 10^{-8}K)

Decompression Cooling

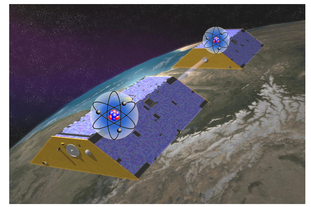
sub-nanoKelvin temperatures (10^{-10} K or below) in microgravity

Atom Interferometry for Earth, Planetary, and Gravity Sciences

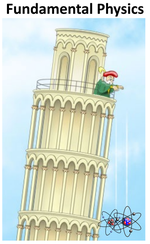
Spacecraft Tracking and Navigation



Gravity Gradiometry



Fundamental Physics



- **High precision gravity sensing for Earth and Planetary Sciences including geodesy, seismology, and subsurface mapping**
- **On-board S/C acceleration sensing for inertial navigation and drag-free referencing**
- **Fundamental Physics:**
  - **Tests of Einstein's Universality of Free Fall**
  - **Gravity Wave detection**
  - **Searches for Dark Matter & Dark Energy candidates …**

NASA's Cold Atom Lab Onboard the ISS

Observation of Bose-Einstein condensates in an Earth-orbiting research lab

David C. Aveline, Jason R. Williams, Ethan R. Elliott,Chelsea Dutenhoffer, James R. Kellogg, James M. Kohel, Norman E. Lay, Kamal Oudrhiri, Robert F. Shotwell, Nan Yu, and Robert J. Thompson

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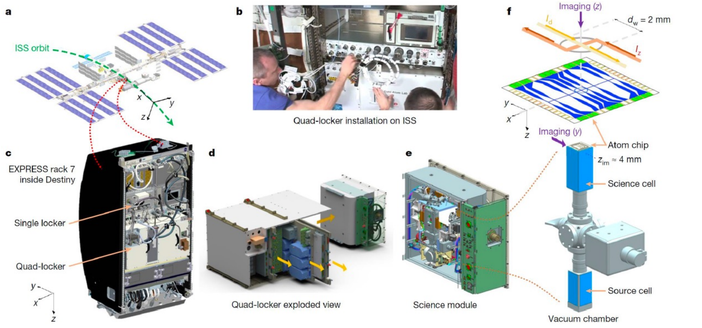


- **First multi-user facility for the study of ultracold quantum gases in space, supported by an international group of scientists.**
- **CAL has operated over 5 years in orbit to support rubidium and potassium experiments and has already collected data from over 100,000 experimental runs for five flight teams.**
- **Unique microgravity environment that circumvents the gravitational limits of terrestrial quantum experiments.**

CAL Science

Benefits of Microgravity:

a) Absence of gravitational sag allows for extreme cooling protocols and overlap of multiple co-trapped atomic species.

b) Long free-fall durations in space allow high-precision measurements within relatively small apparatus sizes.

c) Microgravity enables novel trapping geometries (e.g. shell potentials for BECs) at ultra-low energy scales.

Additionally, space offers access to orbits with variable gravity, earth and planetary sciences, and environments inaccessible to quantum sensors in terrestrial labs.

Ultracold Atomic Bubbles

N. Lundblad Bates College

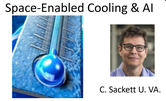
[Carollo *et al.*, Nature, **606** (2022)]

Halo Molecules & AI

J. Williams JPL

[D'Incao *et al.*, *Phys. Rev. A*, **95** (2017)]

Space-Enabled Cooling & AI



C. Sackett U. VA.

[Pollard *et al.*, Micrograv. Sci., **32** (2020)]

CAL Science Achievements:

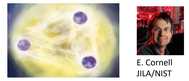
- Demonstrated first Bose-Einstein Condensate (BEC) in orbit
- Exceeded 1s of free-fall in orbit
- Delta-kick cooling to 52 picoKelvin temperatures
- Demonstrated transport with sub-um position control, on par with state-of-the-art ion shuttling experiments
- First realization and studies of a "bubble" BEC
- First demonstration and studies of dual-species BECs in space using ^{41}K and ^{87}Rb
- First explorations of interacting quantum mixtures in space, observed immiscible mixing of rubidium and potassium
- Demonstrated dual-species atom interferometry in space with ^{87}Rb and ^{41}K BECs and pathfinder experiments to explore shear-wave interferometry and quantum sensing on the ISS.

Testing Einstein

N. Bigelow U. Rochester

[Gaaloul *et al.*, Nat. Comm., **13** (2022)]

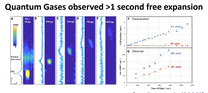
Few-body Physics in Microgravity



E. Cornell JILA/NIST

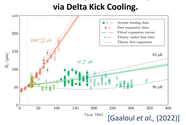
[Xie *et al.*, *PRL*, **125** (2020)]

Quantum Gases observed >1 second free expansion



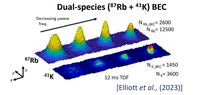
[Aveline *et al.*, (2020)]

Observation of ~52pK effective temperature via Delta Kick Cooling.



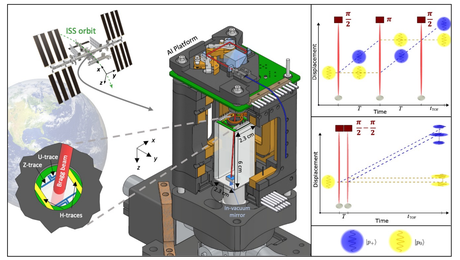
[Gaaloul *et al.*, (2022)]

Dual-species (^{87}Rb + ^{41}K) BEC

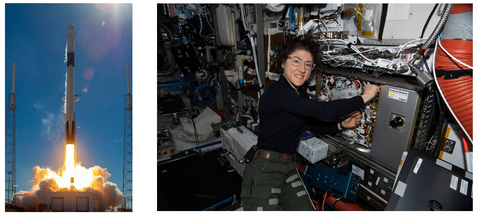


[Elliott *et al.*, (2023)]

CAL Atom-Interferometry On-Orbit Upgrade



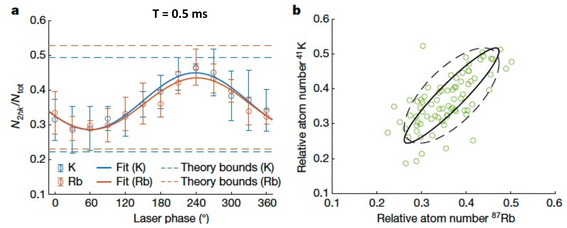
Atom interferometer set up onboard the ISS in CAL. AI configurations tested include three-pulse Mach Zehnder for single-species and dual-species gases (upper right) and two-pulse Ramsey interferometry (middle right)



CRS 19 launch and Christina Koch working on the SM3 installation (2020)

Pathfinder AI with CAL

- PI-recommended upgrade for EEP violation tests and space-technology advancement.
- Dual-species (^{39}K-^{87}Rb), simultaneous atom interferometer.
- Aligned with gravity for sensitivity with quantum test masses in extended freefall.
- Successfully launched to ISS on December 05, 2019, onboard SpaceX Falcon 9 rocket.
- Installed into CAL by Astronauts Christina Kock and Jessica Meir.



Dual-species atom interferometry in space: (a) Normalized population for ultracold samples of ^{41}K (blue) and ^{87}Rb (red) in the excited momentum state 2hk following the application of three Bragg pulses in a Mach–Zehnder configuration. (b) Comparison of the relative population in the excited momentum state of each BEC, showing a correlation between both species.

Elliott, *et al.*, "Quantum gas mixtures and dual-species atom interferometry in space", *Nature* 582, 193-197 (2023)

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