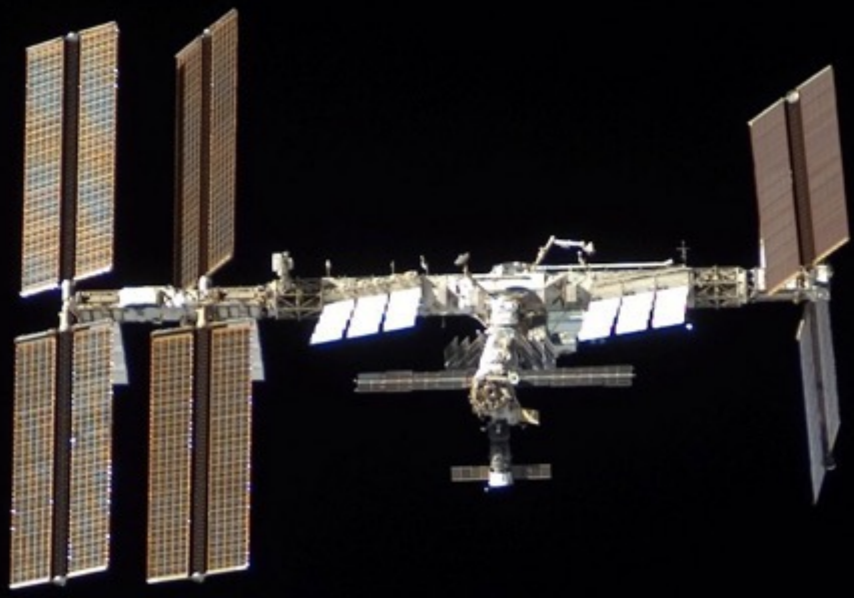
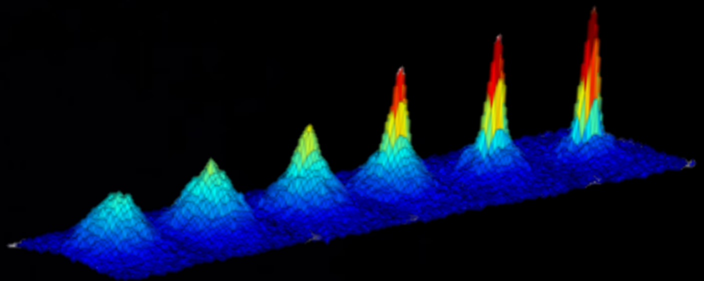
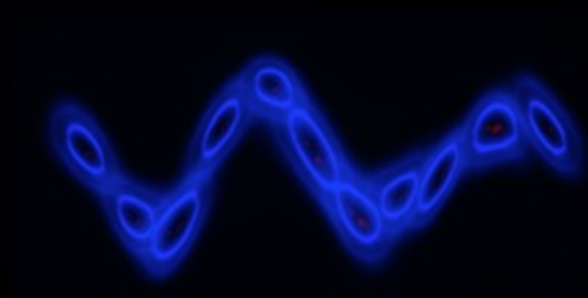






NASA's Cold Atom Laboratory

https://coldatomlab.jpl.nasa.gov/

Jason Williams

CAL Project Scientist and Principal Investigator for Spaceborne Atom Interferometry

CAL
Cold Atom Laboratory

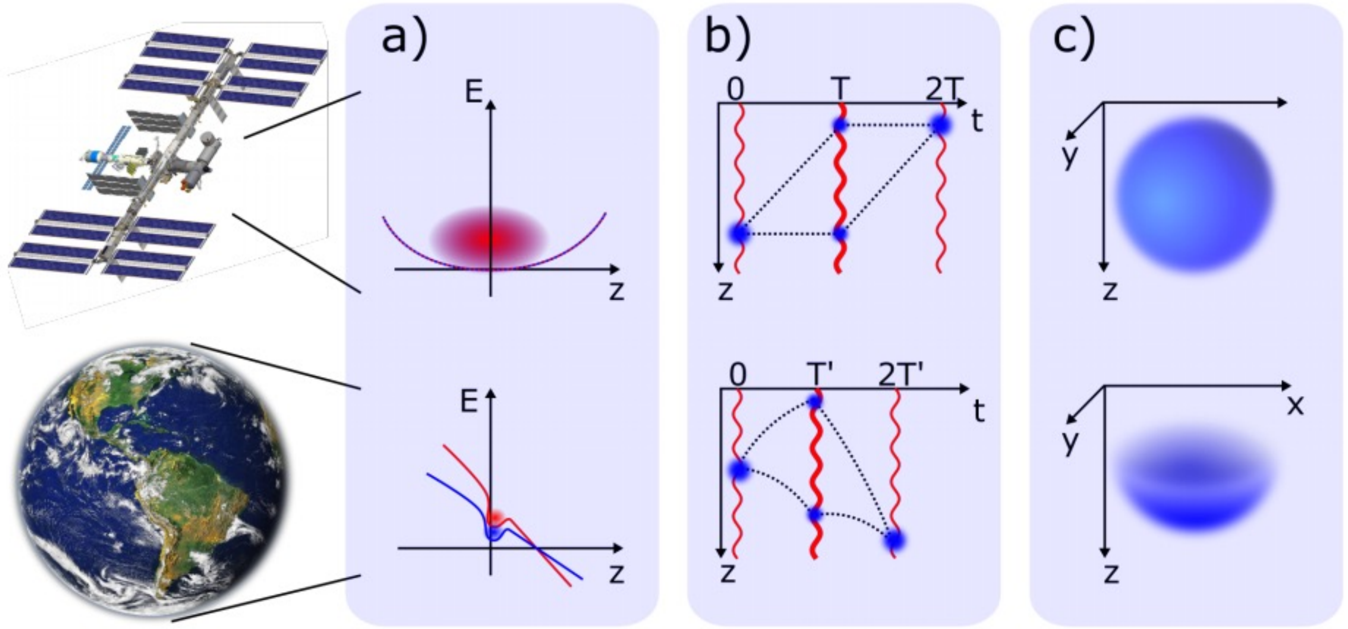
Cold Atom Lab
The Coolest Experiment in the Universe

Utilizes the microgravity environment of the ISS to perform measurements that can't be achieved on Earth.

- **Multiple atomic species: (^{87}Rb, ^{39}K, and ^{41}K)**
- **Bose-Einstein condensates.**
- **Two-axis imaging detection.**
- **Ability to prepare a variety of quantum states and tune their interactions.**
- **Dual-species atom interferometry.**
- **ISS Astronaut-enabled ORUs and upgrades**

The world's first multi-user facility for the study of quantum gases in space

Ultracold Gases in Space



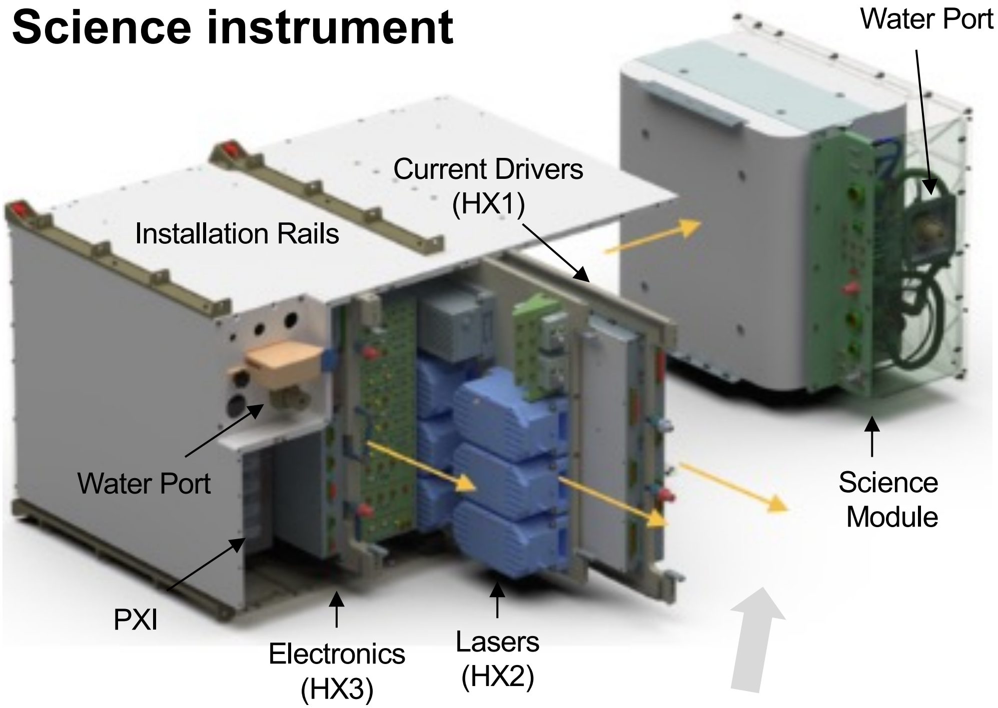
Frye, K., Abend, S., Bartosch, W. *et al.* The Bose-Einstein Condensate and Cold Atom Laboratory. *EPJ Quantum Technol.* **8,** 1 (2021)

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.

CAL Hardware

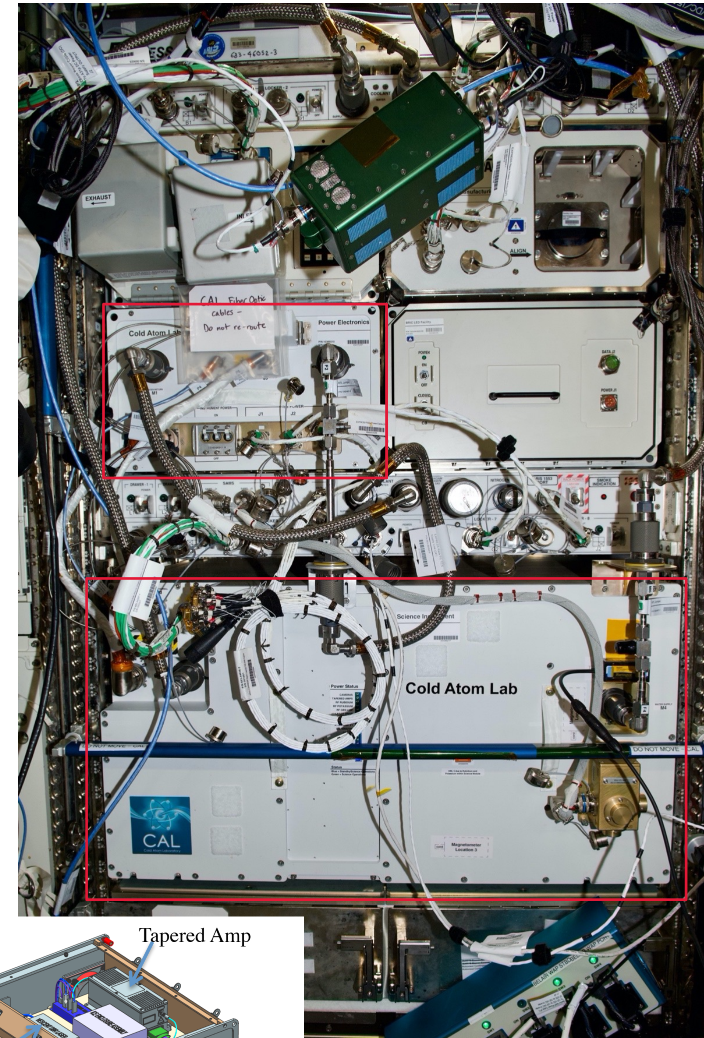
Science instrument

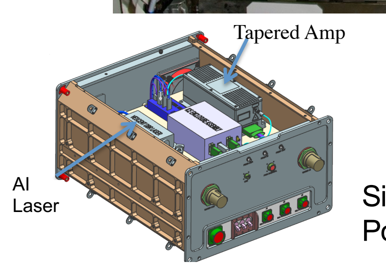


Physics
Package
(ColdQuanta)

Optomechanical
Platform

Express Rack Locker



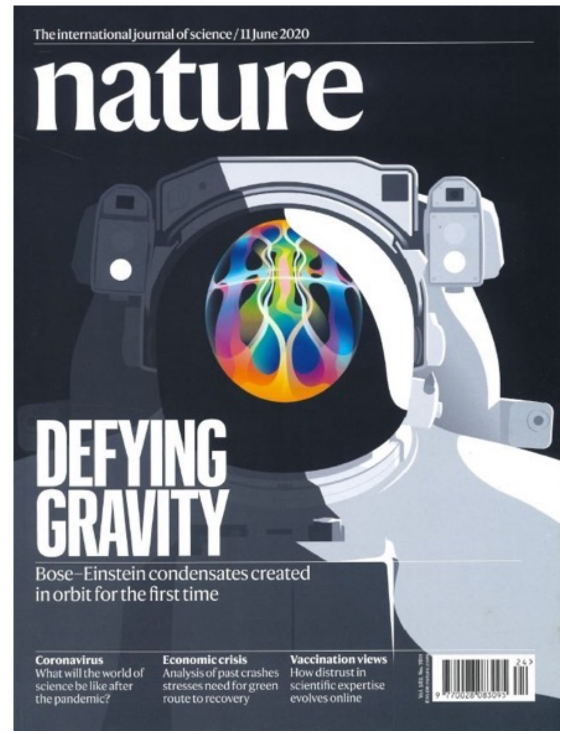


Single Locker w/
Power Electronics

CAL High Level Accomplishments

- **CAL has operated for nearly 4 years in orbit to support rubidium-specific experiments, and has already collected data from tens of thousands of experimental runs for seven flight PIs.**

- **CAL science achievements include:**
  - **First multi-user facility for studying Bose-Einstein condensate in orbit**
  - **Exceeding 1 second of free fall in space**
  - **Cooling to tens of picokelvin effective temperatures**
  - **Realization of an ultracold gas "bubble" in space**
  - **Demonstration of matter-wave interferometry in orbit**
  - **First use of AI as a quantum sensor in space**
  - **First dual-species (^{41}K-^{87}Rb) BEC in space**



*Aveline et al. Observation of Bose-Einstein condensates in an Earth-orbiting research lab, Nature, **582**, 193-197 (2020)*

JPL

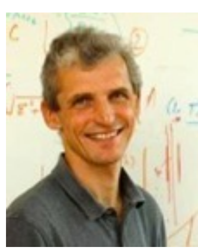
PI Studies with CAL Ultracold Gases

A NASA Research Announcement (NRA) was released on July 11, 2013 to solicit proposals from academic and research institutions to utilize the Cold Atom Lab facility. From this NRA, seven flight investigators were chosen to perform the first experiments studying quantum matter onboard the ISS.

- Zero-G Studies of Few and Many Body Physics (PI E. Cornell, Co-PI P. Engels)
- Consortium for Ultracold Atoms in Space (PI N. Bigelow, Co-PI W. Ketterle, Co-PI W. Phillips)
- Development of Atom Interferometry Experiments for the International Space Station's Cold Atom Laboratory (PI Cass Sackett)
- Fundamental Interactions for Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment (PI Jason Williams)
- Microgravity dynamics of bubble-geometry Bose-Einstein condensates (PI Nathan Lundblad)


C. Sackett
U. VA.


N. Bigelow
U. Rochester


W. Ketterle
MIT


B. Phillips
NIST


N. Lundblad
Bates


E. Cornell
JILA


P. Engels
WSU


J. Williams
JPL

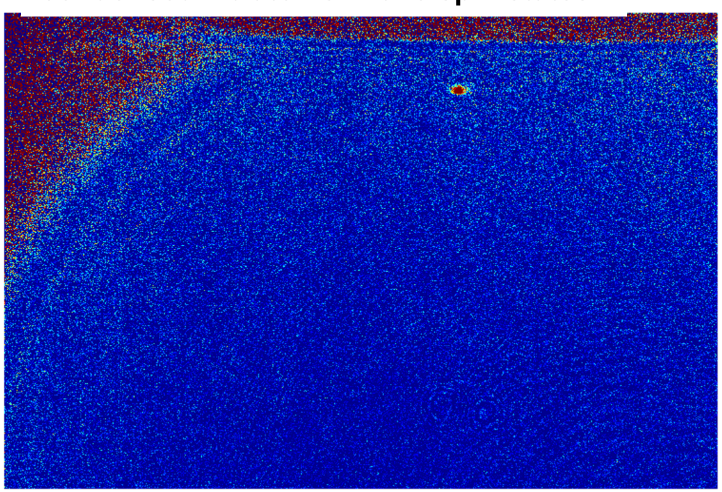
Rubidium Science in CAL

PI Cass Sackett: Adiabatic Cooling at CAL

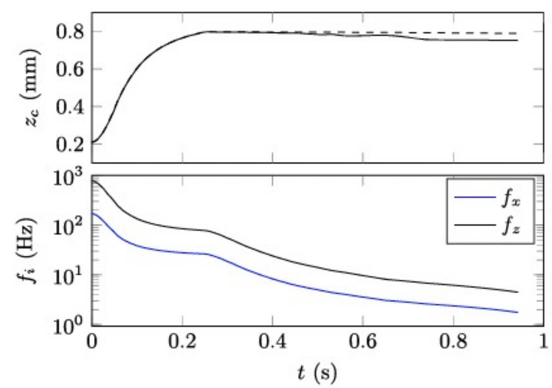
Pollard et al. "Quasi-Adiabatic External State Preparation of Ultracold Atoms in Microgravity", Microgravity Sci.Tech., ***32,*** *1175-1184 (2020)*

- Team has studied dynamics of atoms in exceptionally weak traps (well below what can be achieved on Earth).
- Identified magnetic field background gradients that now limit how weak the traps can be.

Time of flight measurements for Bose-condensed Rb atoms in two spin states



Decompression protocol for achieving ultracold atoms



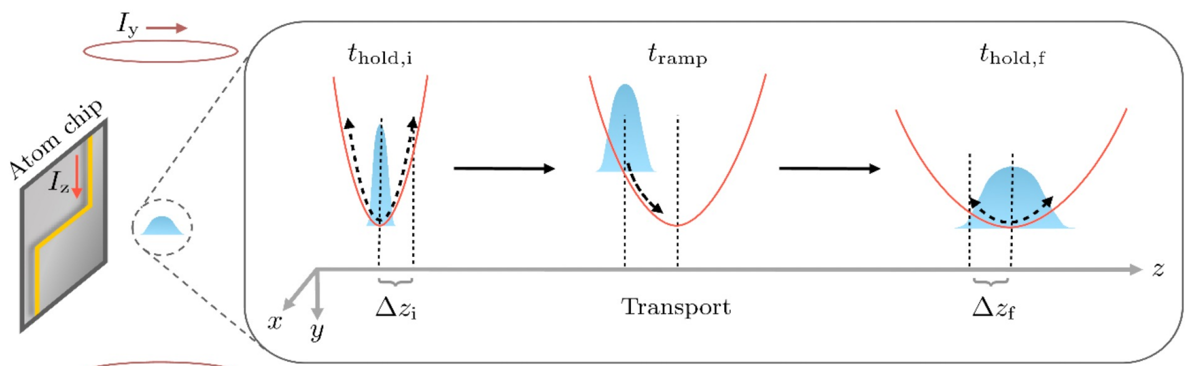
Background gradient field extracted from time of flight measurements

x_0 (mm)	y_0 (mm)	z_0 (mm)	G_{xx} (G/m)	G_{yy} (G/m)	G_{xy} (G/m)	G_{xz} (G/m)	G_{yz} (G/m)
3.3(4)	2.9(7)	0.00(1)	0.4(1.2)	−7.6(6)	−0.1(1)	10(1)	−2(1)

Rubidium only Science in CAL

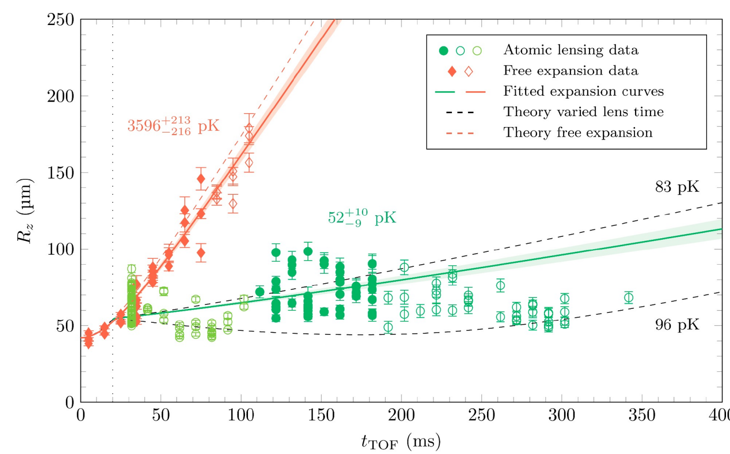
PI Nick Bigelow: Delta-Kick Cooling and Shortcut to Adiabaticity

Gaaloul et al. "A space-based quantum gas laboratory at picokelvin energy scales", arXiv:2201.06919



"Shortcut to Adiabaticity" transport protocol used in CAL

- Demonstrated transport with sub-um position control.
- Successfully demonstrated "Delta Kick Cooling" in space, achieving effective temp below 100 pK.

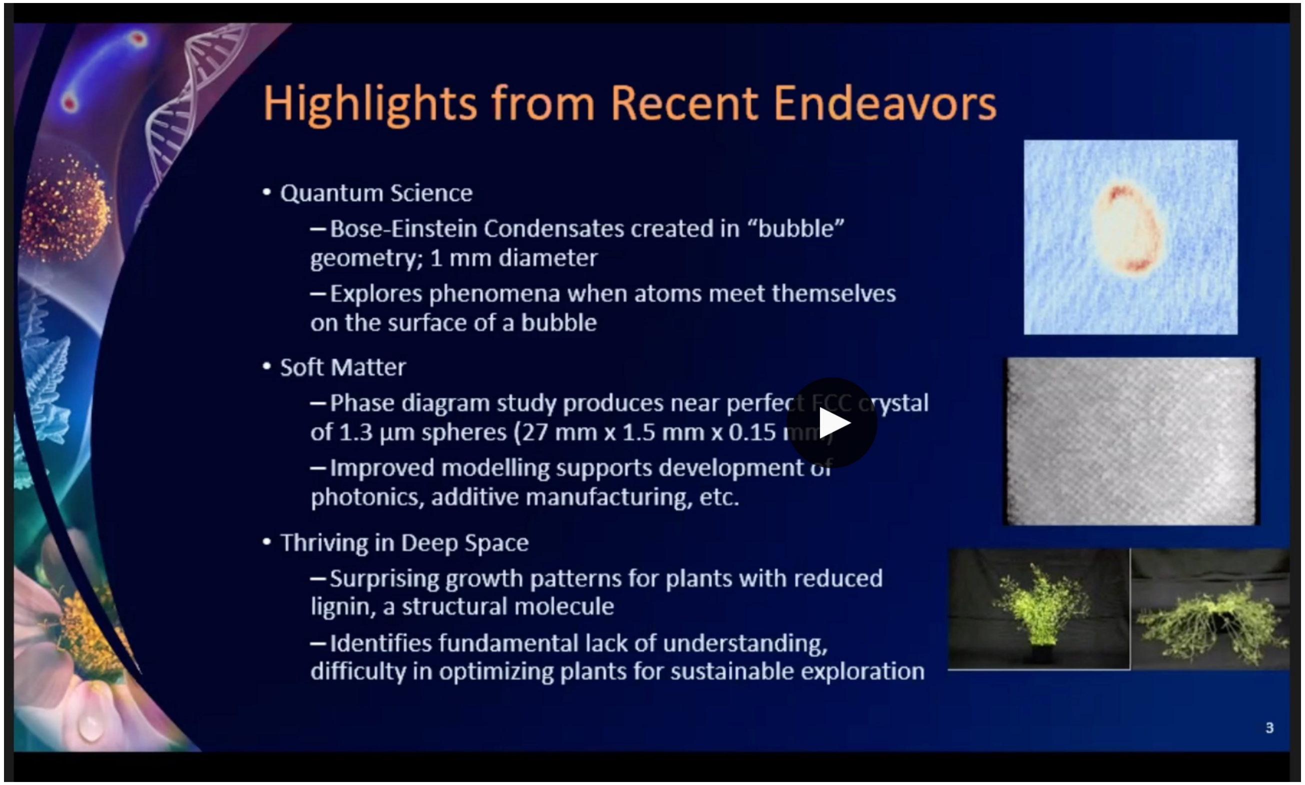


Observation of ~ 52pK effective temperature via Delta Kick Cooling.

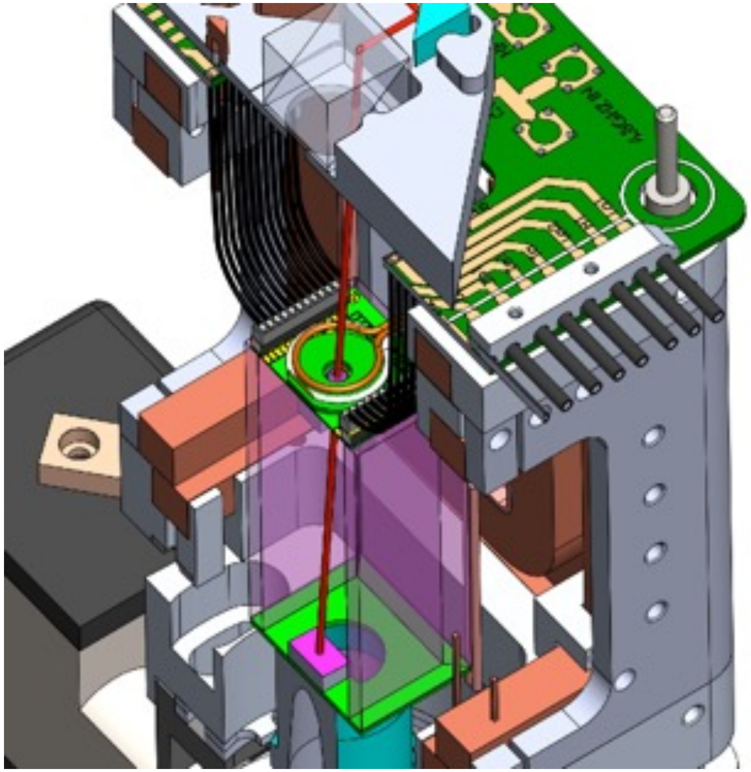
Rubidium only Science in CAL

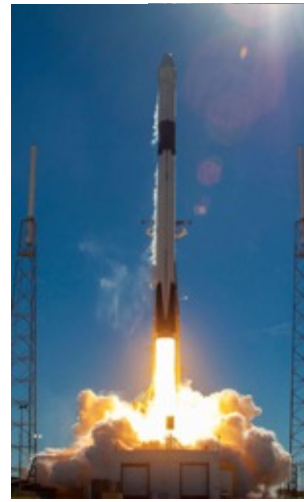
PI Nathan Lundblad: Microgravity dynamics of bubble-geometry Bose-Einstein condensates
Carollo et al. "Observation of ultracold atomic bubbles in orbital microgravity", arXiv:2108.05880
(Accepted for publication in Nature)

Highlight from NASA BPS for Space Science Week (National Academies of Science, Engineering, and Medicine)



Atom Interferometry in CAL





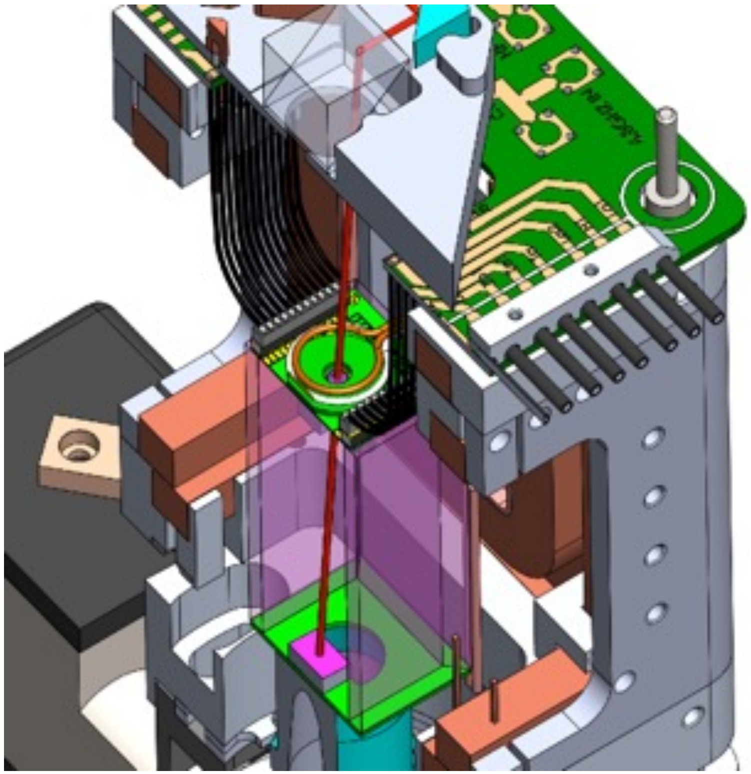
CRS 19 launch 12/05/2019

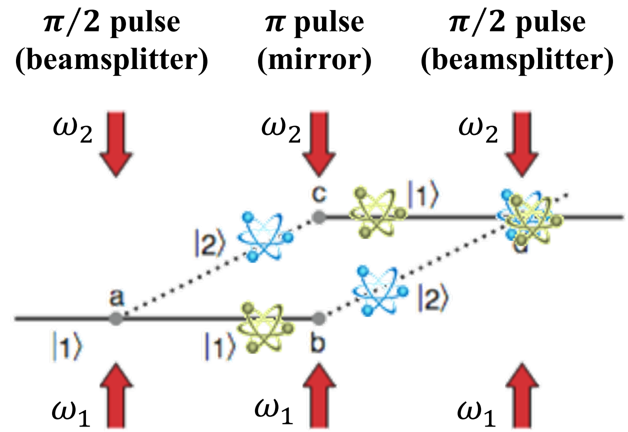
Christina Koch working on the SM3 installation

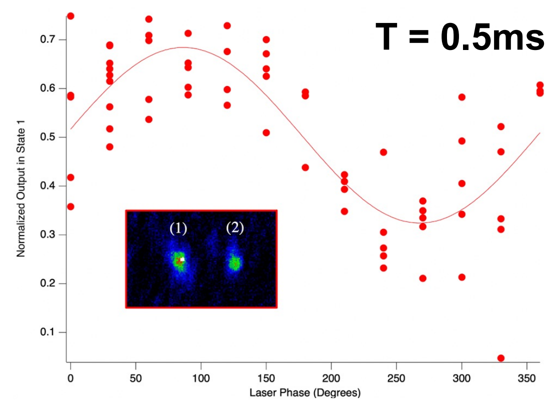
Design for Pathfinder AI with CAL

- PI-recommended upgrade for EEP violation tests and space-technology advancement.
- Dual-species (^{39}K-^{87}Rb), simultaneous atom interferometer
- Bragg diffraction at the “magic” wavelength ($\Omega_{Rb} = \Omega_K$)
- Aligned with gravity (to within 5°) for high sensitivity with quantum test masses in extended freefall.

Atom Interferometry in CAL







Design for Pathfinder AI with CAL

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Rubidium Atom Interferometry (SM3)

Sackett team: Photon recoil measurement

- Interference pattern of imbalanced “shear” atom interferometer provides measurement of photon recoil.

Bigelow team: AI Magnetometer

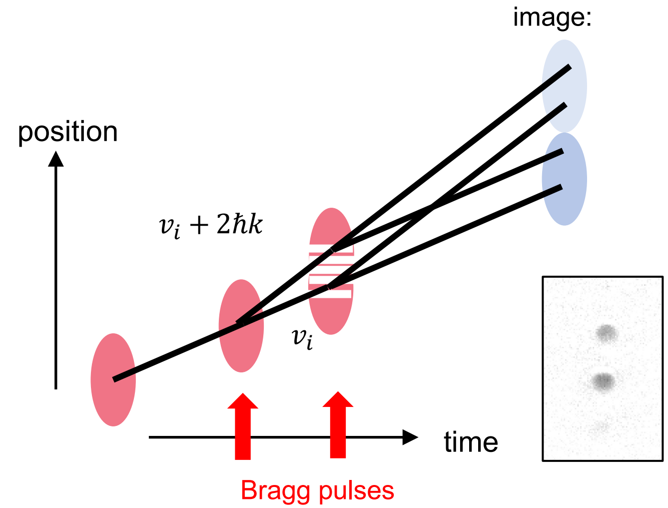
- Measurements of magnetic field gradients using CAL AI.
- Characterization of fringes from shear AI.

Williams team: ISS vibration measurements

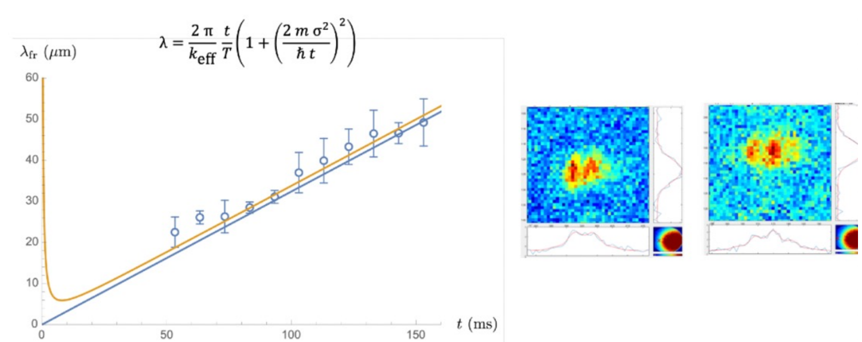
- Use CAL AI to measure boost-induced phase shifts and loss of contrast from vibrations.

Williams, Bigelow, and Sackett teams: ISS rotation measurement from AI-induced phase fringes

- Observation of fringes in each shot from rotation of CAL Physics Package on ISS.

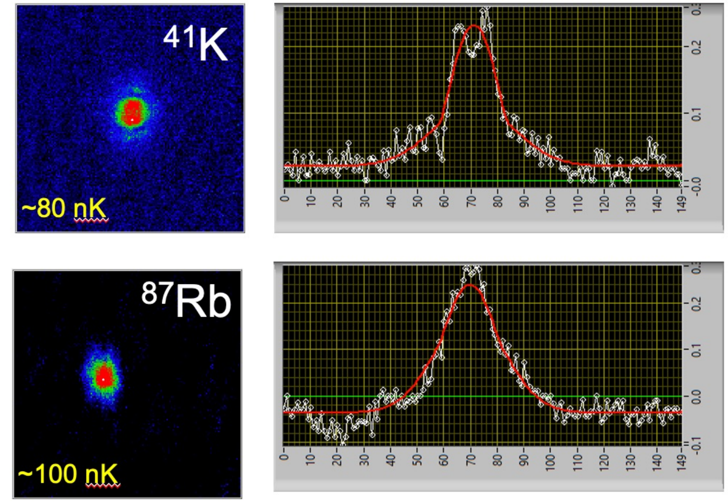


Shear matter-wave interference is used by Sackett team as a sensor of the photon recoil from the AI laser pulses in orbit. The phase is given by the relative distributions of atoms in the outport ports after the AI sequence. Here, the phase is proportional to the initial velocity of the atoms and the frequency where the atoms are resonant with the AI laser.



Shear fringes demonstrated by Bigelow team, the spacing scales linearly with time except at short times where many-body effects dominate

Potassium and Rb-K Mixtures



Absorption imaging of a binary (^{41}K-^{87}Rb) BEC after 12ms of free expansion for ^{41}K and 14ms free expansion for ^{87}Rb. Images of both species, which are averaged over 8 experimental runs, show the characteristic bimodal structure (red fit lines) indicative of the BEC phase emerging from the thermal gas.

- **New microwave source launched on SpX22 (06/21)**
- **Installed by ISS Astronaut Megan McArthur (07/21)**
- **Demonstrated microwave BEC of ^{87}Rb (10/21)**
- **Demonstrated BEC of ^{41}K (02/22)**
- **Demonstrated dual-species ^{41}K – ^{87}Rb BEC (03/22)**

Potassium and Rb-K Mixtures

Tunable interactions and few-body physics

Few-body physics plays a crucial role in solid-state, atomic, molecular, and nuclear systems:

- Superconductivity and superfluidity
- Magnetic ordering
- Strongly correlated systems
- Halo nuclei

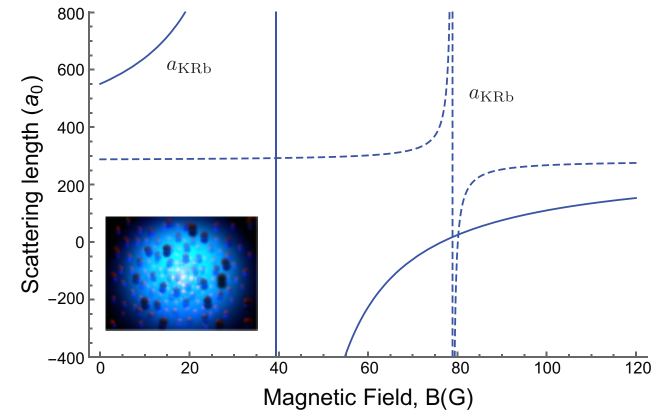
Williams team: The quantum 2-Body problem

- Feshbach resonances (2-body halo states)
- Microgravity enables low temperatures/densities for observation of extremely weakly bound (large) molecules.
- Provide a source of pair-correlated atoms for enhanced dual-species atom interferometry.

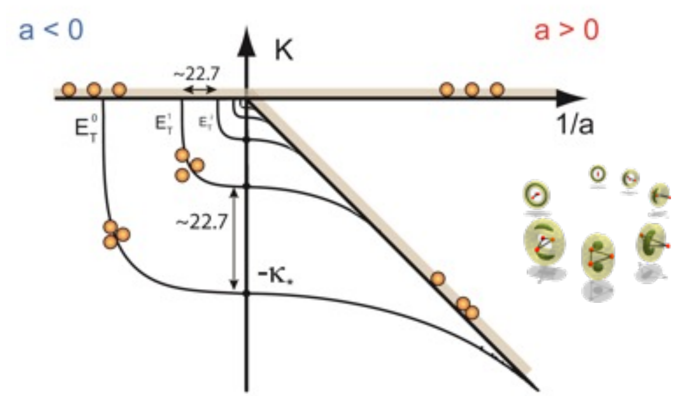
Cornell team: The quantum 3-Body problem

- Efimov resonances (3-body bound states) expected to follow universal laws.
- Microgravity enables low temperatures/densities for observation and study of multiple resonances to test universal laws.

Feshbach Physics: Universal Two-Body Systems

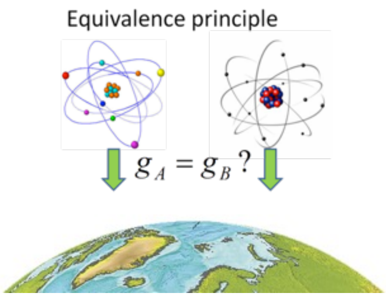


Efimov Physics: Universal Three-Body Systems



Dual-species (Rb-K) AI Science

Equivalence Principle test with ^{87}Rb and ^{39}K quantum gases



Does gravity act differently on rubidium 87 and potassium 39?

$$\eta = 2\frac{g^{87\,\mathrm{Rb}} - g^{39\,\mathrm{K}}}{g^{87\,\mathrm{Rb}} + g^{39\,\mathrm{K}}}$$

CAL (SM3) aims to address the feasibility of making such measurements on the ISS

Fundamental Physics:

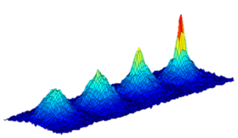
- Equivalence Principle tests,
- Gravity Wave detection,
- Dark Matter,
- Dark Energy,
- Variation of Fundamental Constants,…

Timeline for ISS and Satellite Cold Atom Research

Space Station and/or free-flyer AI missions as recommended by NASA decadal survey

2018 - 2020

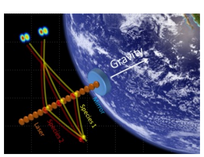
CAL SM2



Established cold atom physics in space

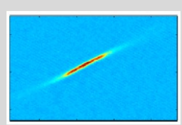
2020 - Present

CAL SM3



Pathfinder dual-species AI in orbit.

CAL SM4



Enhanced CAL based on lessons learned and community inputs

BECCAL

Joint NASA/DLR mission for next-generation multi-user Cold Atom Lab onboard the ISS.

Decadal Survey

Biological and Physical Sciences in Space

Decadal Surveys are community-driven, bottom-up studies produced by the National Academies of Sciences, Engineering, and Medicine (NASEM) that aim to formulate a community consensus about the most compelling science questions for the decade ahead in each of the disciplines. This process provides a rare opportunity for scientists and engineers to share their insights and help shape the scientific endeavors of the next decade.

The CAL Team

And Welcome:

Matteo Sborscia

Christian Schneider

Leah Phillips

Kelly Perry

Leo Cheng

Oscar Yang

Kamal Oudrhiri (Project Manager), **Rob Thompson** (Program Scientist), **Jason Williams** (Project Scientist), **David Aveline** (Ground Test Bed Lead), **Ethan Elliott** (Engineering Model Test Bed Lead), **Chelsea Dutenhoffer, Irena LI, and Shahram Javidnia** (Mission Operations Systems Leads), **James Kellogg** (Launch Vehicle and ISS Integration Lead), **James Kohel** (Laser and Optical Subsystem Lead), **Norman Lay** (Communications Architectures & Research Section Manager), **Robert Shotwell** (Former CAL Project Manager)

Jet Propulsion Laboratory
California Institute of Technology