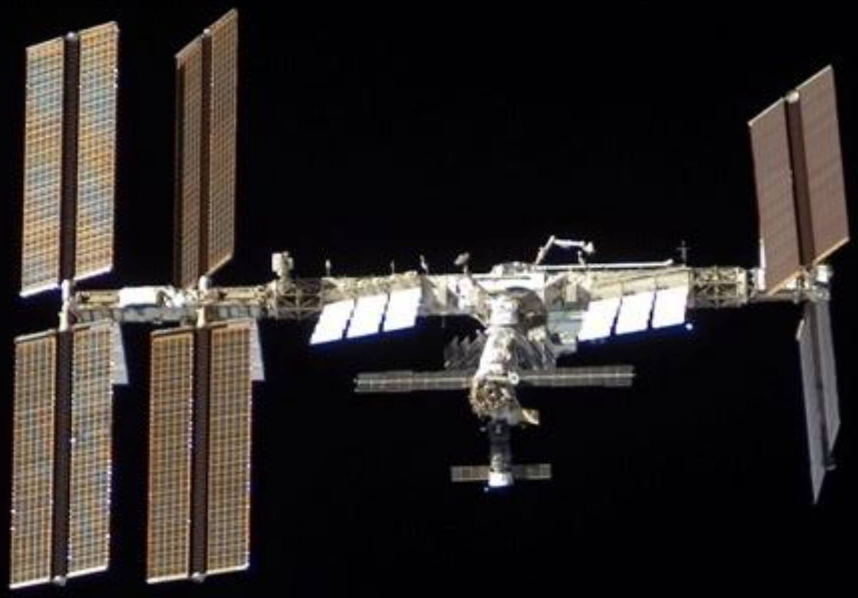
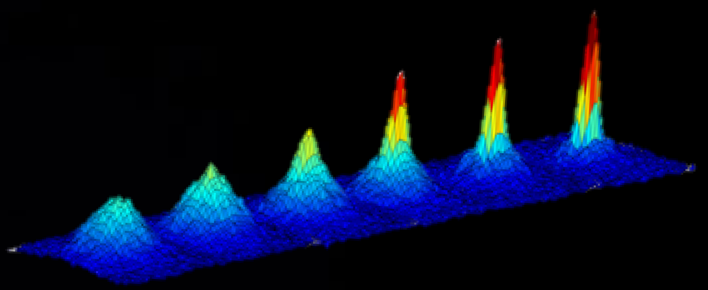




CAL: NASA's Cold Atom Lab operating onboard the ISS

Dr. Jason Williams
Principal Investigator for Spaceborne Atom Interferometry and CAL Flight System Lead

Jet Propulsion Laboratory
California Institute of Technology

Overview

- **Introduction to ultracold atoms and their use as Quantum Sensors**

- **NASA's Cold Atom Lab (CAL)**
  - Multi-user facility for the study of ultracold gases in microgravity
  - Operating onboard the ISS since 2018
  - Science Module upgrade in 2020 enabled AI science.

- **Follow-on missions and Conclusion**
  - BECCAL, CAL II, …

Introduction

Quantum Technology – a field of physics and engineering that utilizes the quantum mechanical properties of light and/or matter for novel/enhanced technological capabilities.

"Quantum 1.0" – existing tech based on quantum effects

- Laser systems
- Semiconductors
- Atomic clocks
- MRI, …

Quantum Optics – based on quantum-optical phenomena (e.g. squeezed light, entanglement, etc)

- Long-baseline interferometry
- LIGO gravity wave detection
- Quantum communications and security, ...

Classical Matter

Classical Optics

Quantum Optics

Quantum Matter

**

Quantum Matter – technologies based on the quantum properties of matter

- Atom Lasers
- Atom Interferometers
- Optical Clocks…

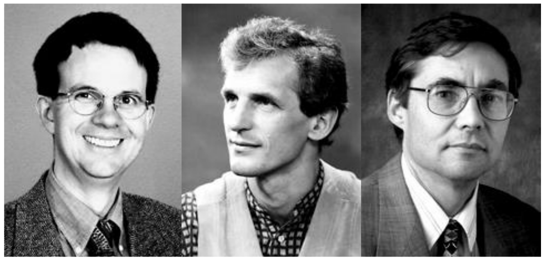
Next Generation Quantum Systems – technologies relying on several quantum properties of light and matter

- Quantum Computers
- Quantum Internet
- Entangled Clocks and AIs…

Introduction

1997 Nobel Prize in Physics
“for development of methods to cool and trap atoms with laser light”

2005 Nobel Prize in Physics
“for their contributions to the development of laser-based precision spectroscopy”



2001 Nobel Prize in Physics
“for the achievement of Bose-Einstein condensation in dilute gases”

Atomic Clocks and Atom Interferometers

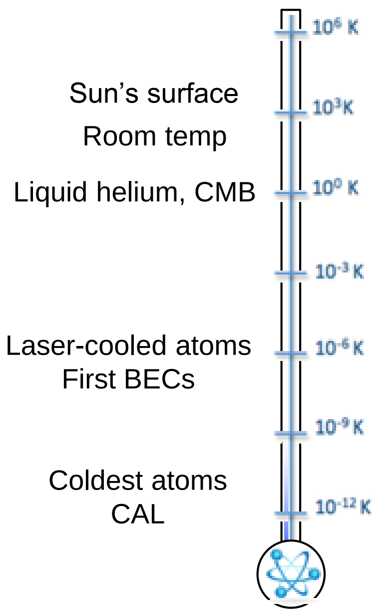
<u>Ultracold gases:</u>

- Isotopically pure (Spectroscopic filtering)
- Exceptional environmental control (UHV, no direct contact)
- Quantum control of collisions (s-wave with Bose/Fermi stats)
- Unprecedented atom-photon coherence (10^{-18} level lattice clocks)

<u>In microgravity:</u>

- Ideal drag-free test mass
- Next-generation of low-temp.

➔ Novel applied and fundamental-physics applications.



Ultracold Gases in Space

Quantum Matter – studies of the quantum properties of matter

- Bose-Einstein condensates and Fermi gases
- Wave-like nature of matter
- Heisenberg uncertainty principle
- Quantum collisions

Atom interferometers

- Utilizes interference of atomic matter waves.
- High-precision measurements of inertial forces, rotations, and gravitational physics

Optical Clocks

- Frequency reference based on metastable optical transitions.
- Stability exceeding 10^{-16} at 1 second and 10^{-18} total accuracy

Studies of complex systems

- Superfluids & superconductors
- Nuclear matter
- Cosmological phenomena

Fundamental Physics

- Weak Equivalence Principle
- Frame-dragging
- Spin-gravity coupling
- Inverse square law
- Dark particle detection
- Gravity wave detection

Planetary Science & Spacecraft PNT

- Drag-free referencing
- One-way navigation
- Gravity sensing for geodesy, subsurface measurement, etc.

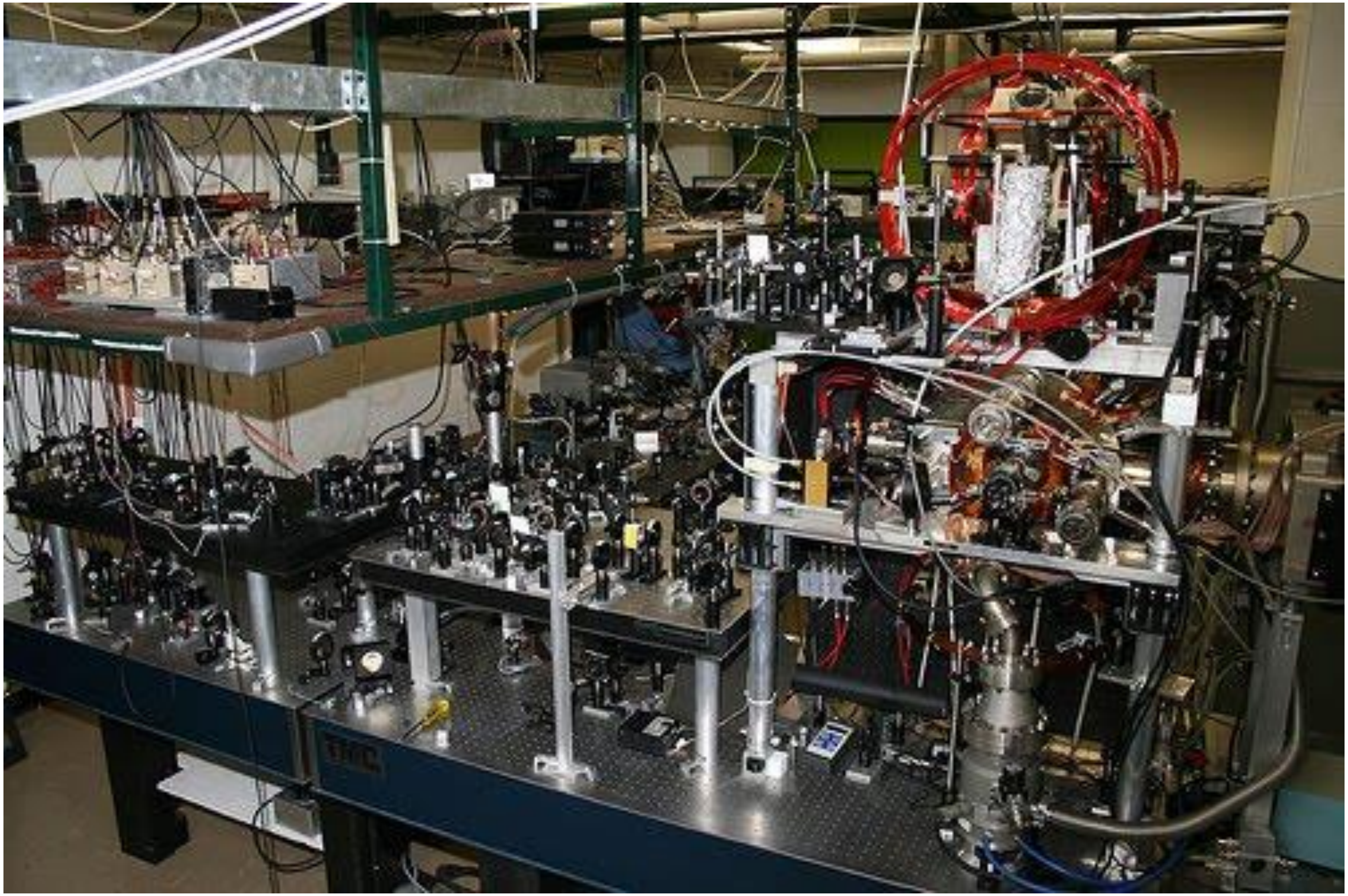
Cold Atom Lab
The Coolest Experiment in the Universe

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.**

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

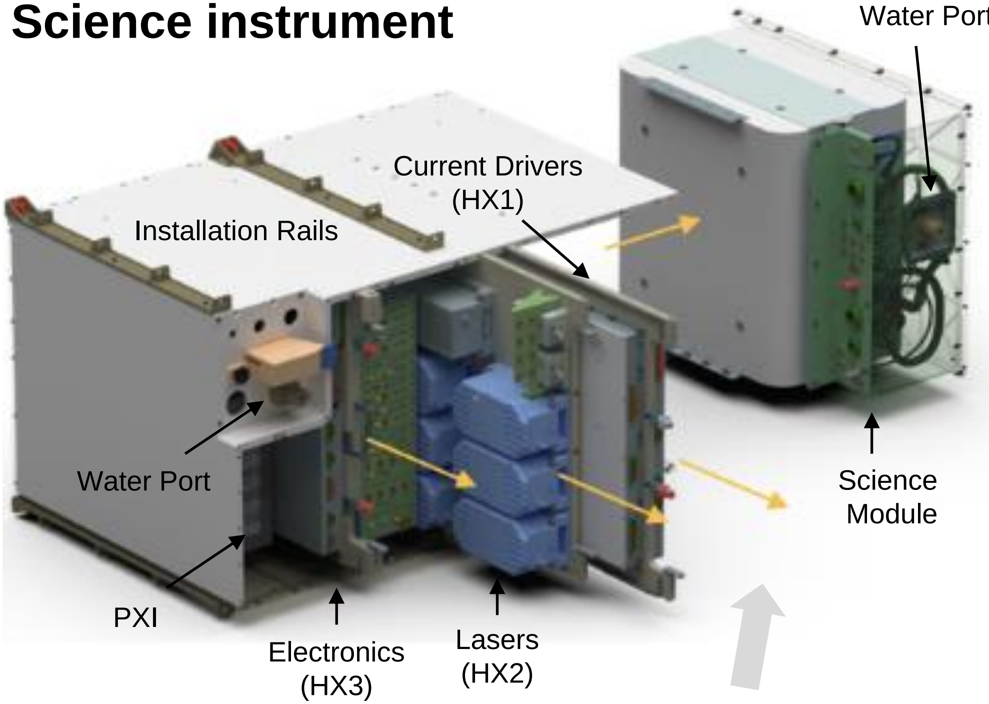
The Road to Ultracold



Nick Bigelow Bose-Einstein Condensation Lab (University of Rochester)

The Road to Ultracold

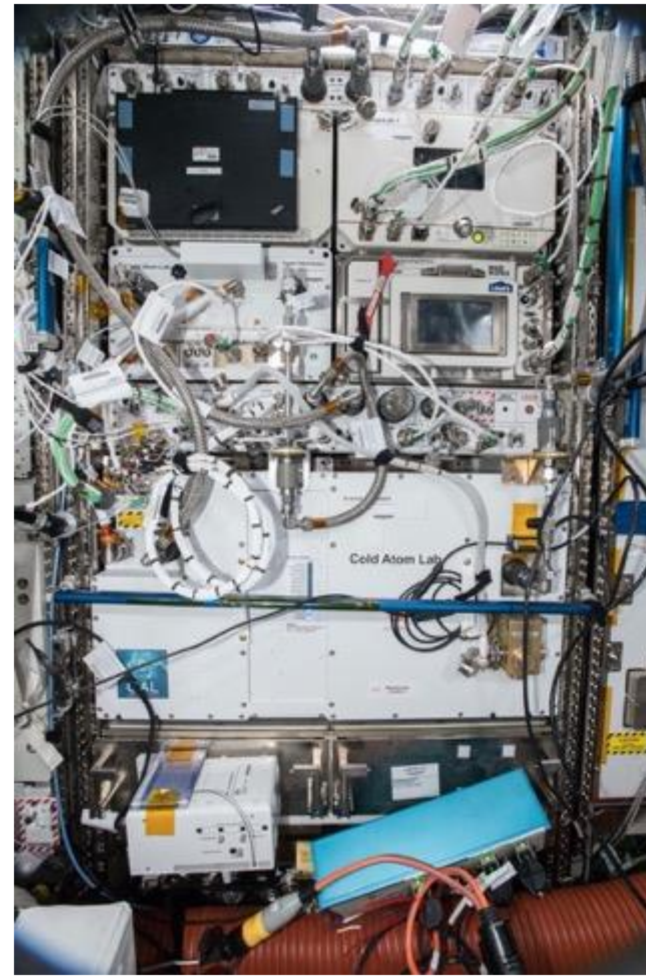
Science instrument



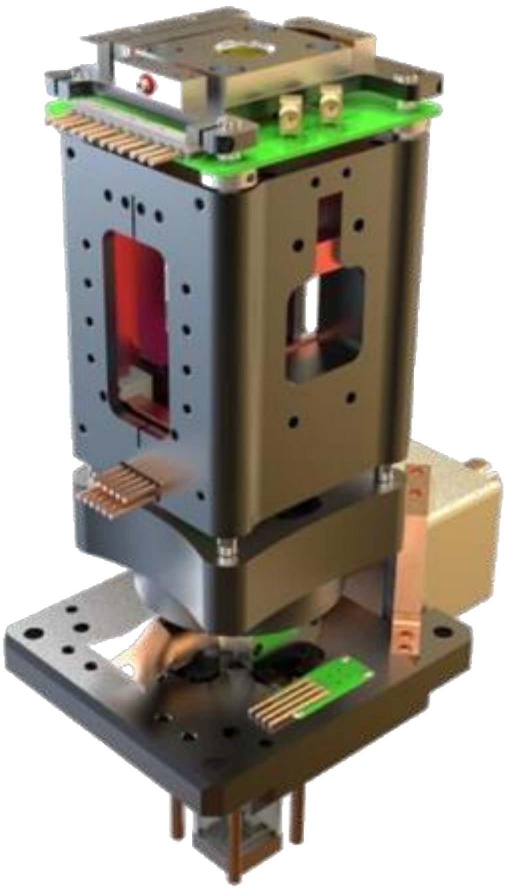
Physics
Package
(ColdQuanta)

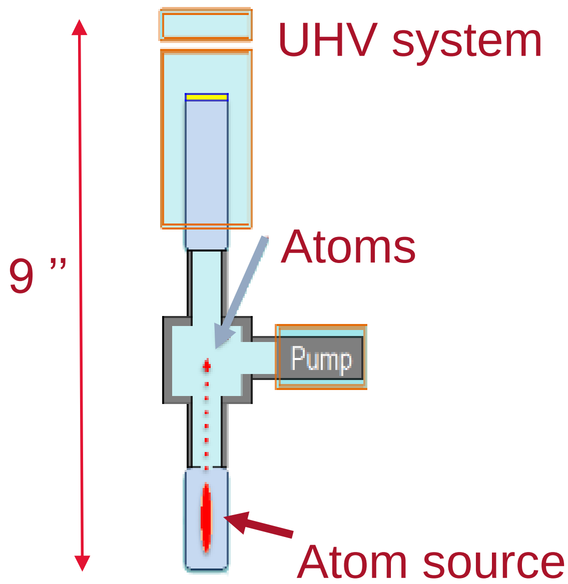
Optomechanical
Platform

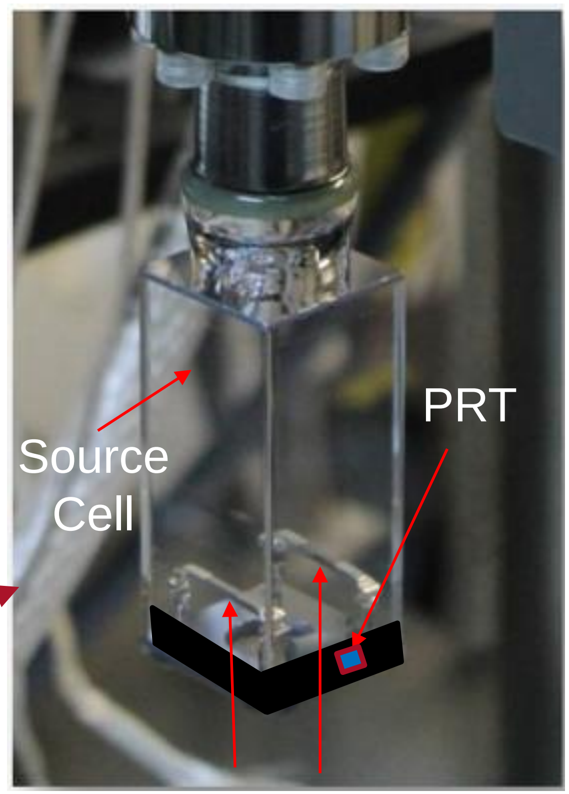
Express Rack Locker



The Road to Ultracold – Atom Source

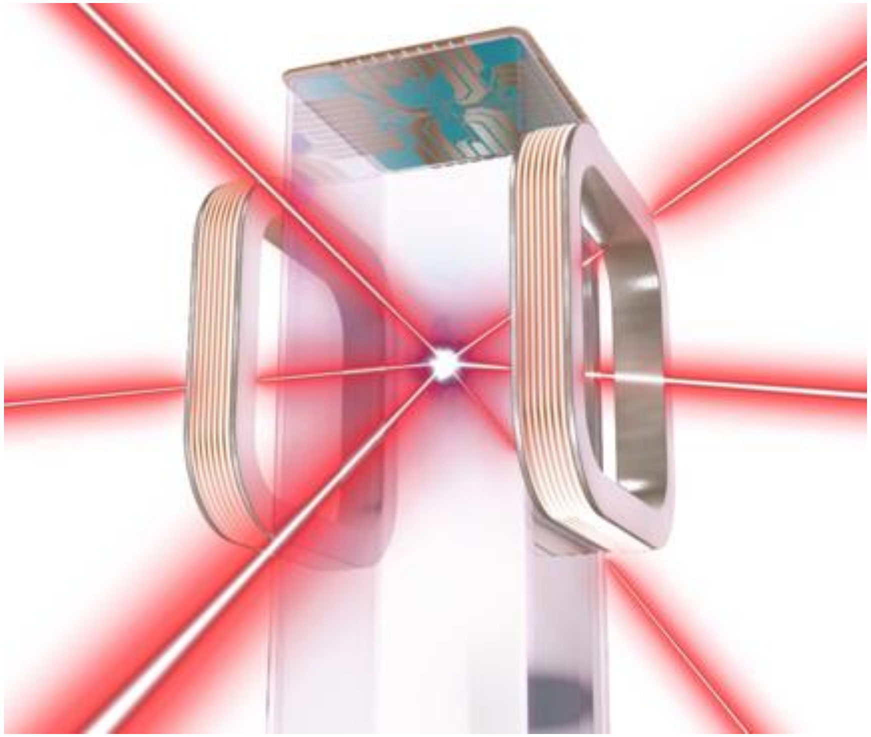


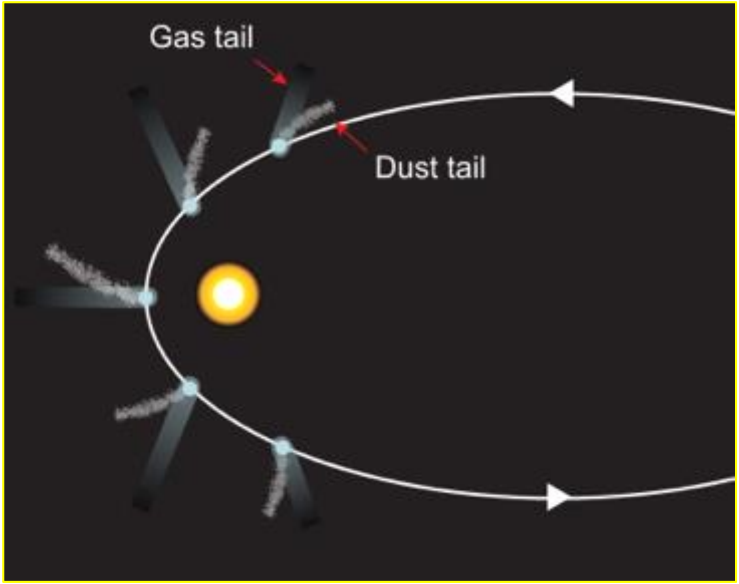




Alkali metal dispensers
Potassium and Rubidium

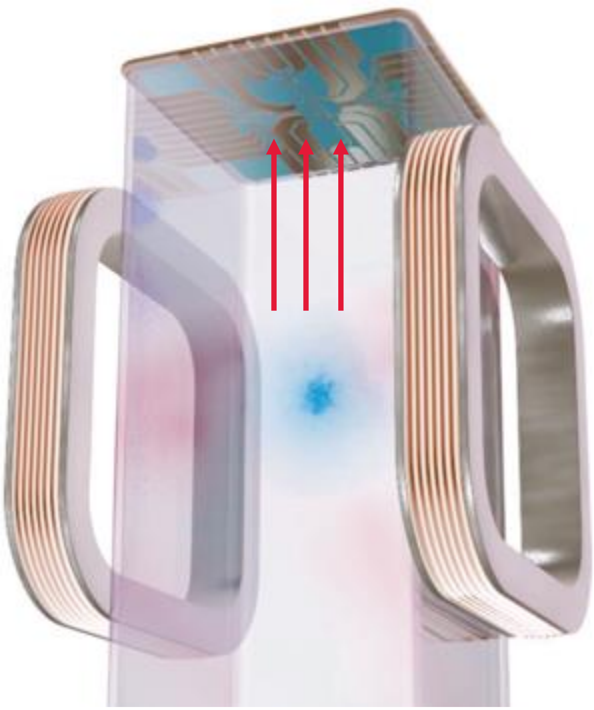
The Road to Ultracold – Laser Cooling

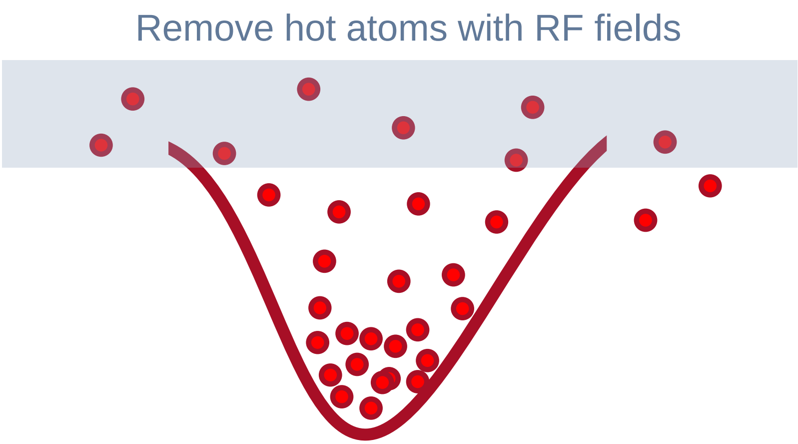




milliKelvin temperatures (10^{-3} K)

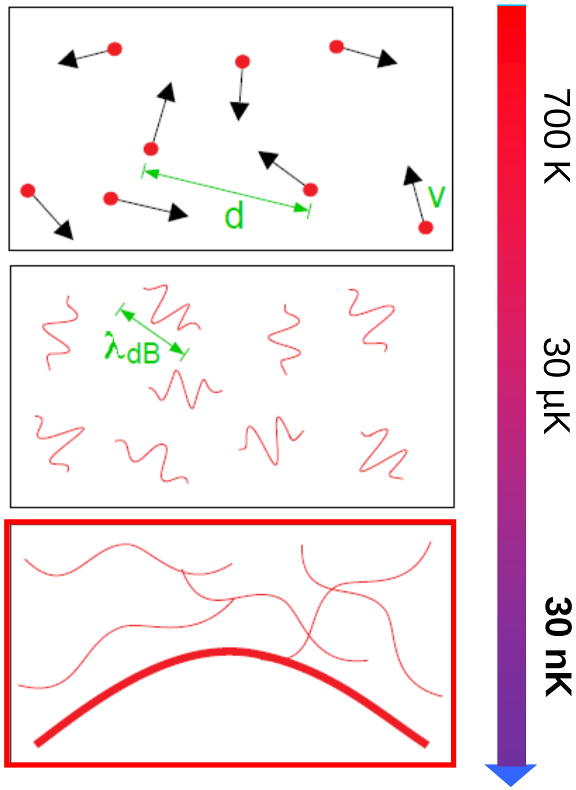
The Road to Ultracold – Evaporation





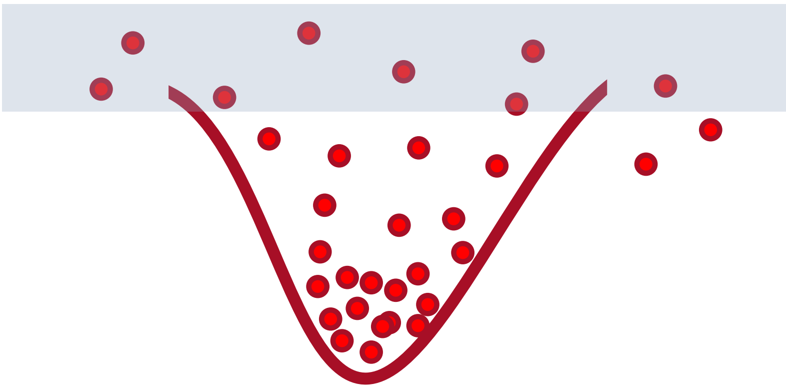
microkelvin to nanoKelvin temperatures
(10^{-5} K to 10^{-8}K)

The Road to Ultracold – Evaporation



Ketterle et al., Proc.of the Intl. Enrico Fermi school, 1999

Remove hot atoms with RF fields



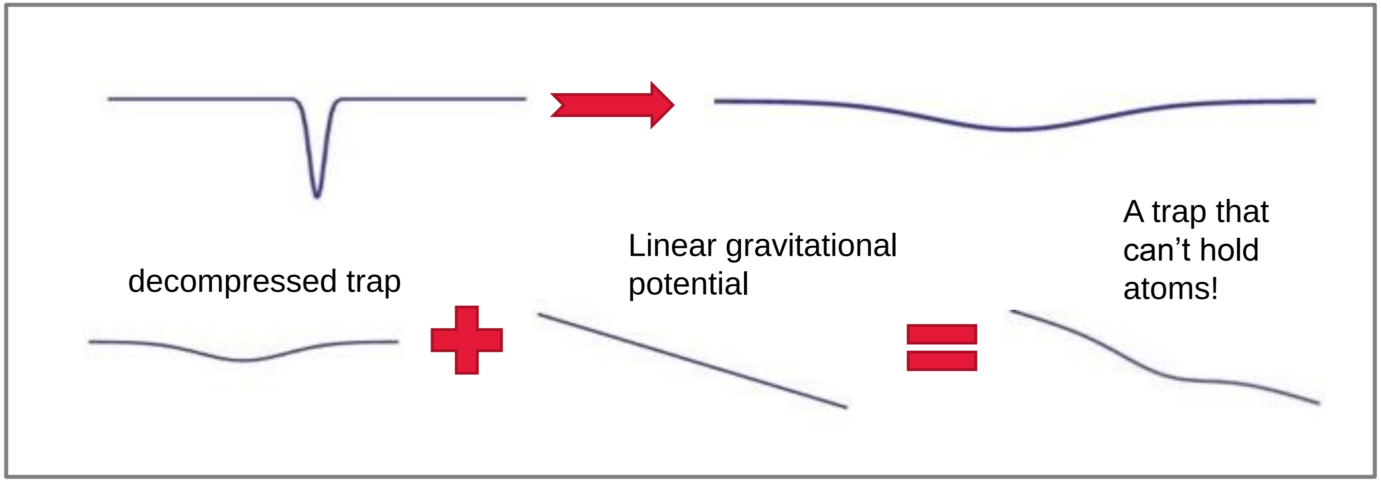
microkelvin to nanoKelvin temperatures (10^{-5} K to 10^{-8}K)

The Road to Ultracold – Evaporation

Advanced cooling techniques enabled in microgravity including:

- Extreme adiabatic decompression
- Delta kick cooling

These ideas and more are explored by various PIs on CAL.



Sub-nanoKelvin temperatures (10^{-10} K or below)

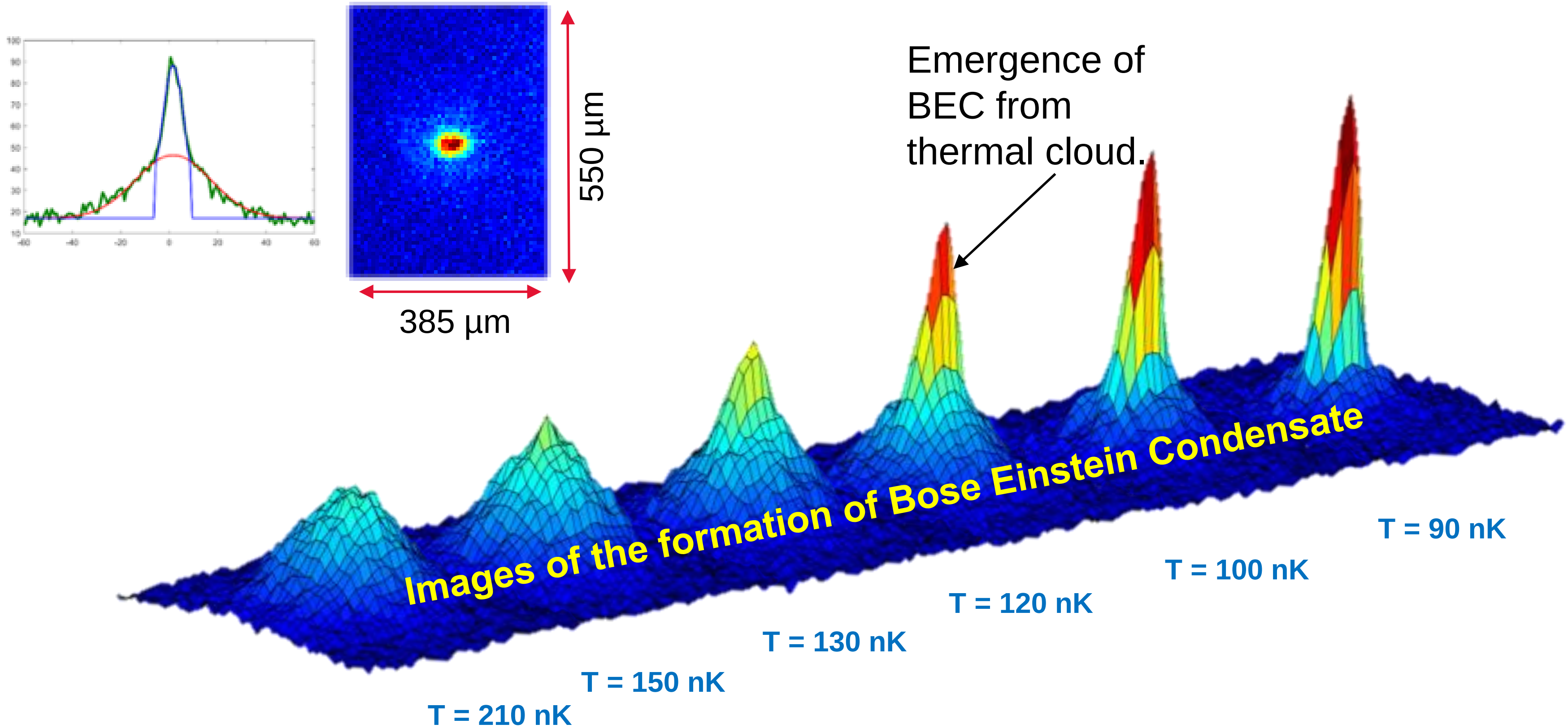
CAL Status

- **CAL has operated for over 27 months 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:**
  - **Achieved first Bose-Einstein condensate in orbit.**
  - **First multi-user facility for quantum gas research in space.**
  - **First dual-species laser cooling in space.**
  - **Exceeding 1 second of freefall in orbit.**
  - **Unprecedented delta-kick cooling to sub-nanoKelvin temperatures.**
  - **First realization of a "bubble" BEC.**
  - **First demonstration of matter-wave interferometry in space.**

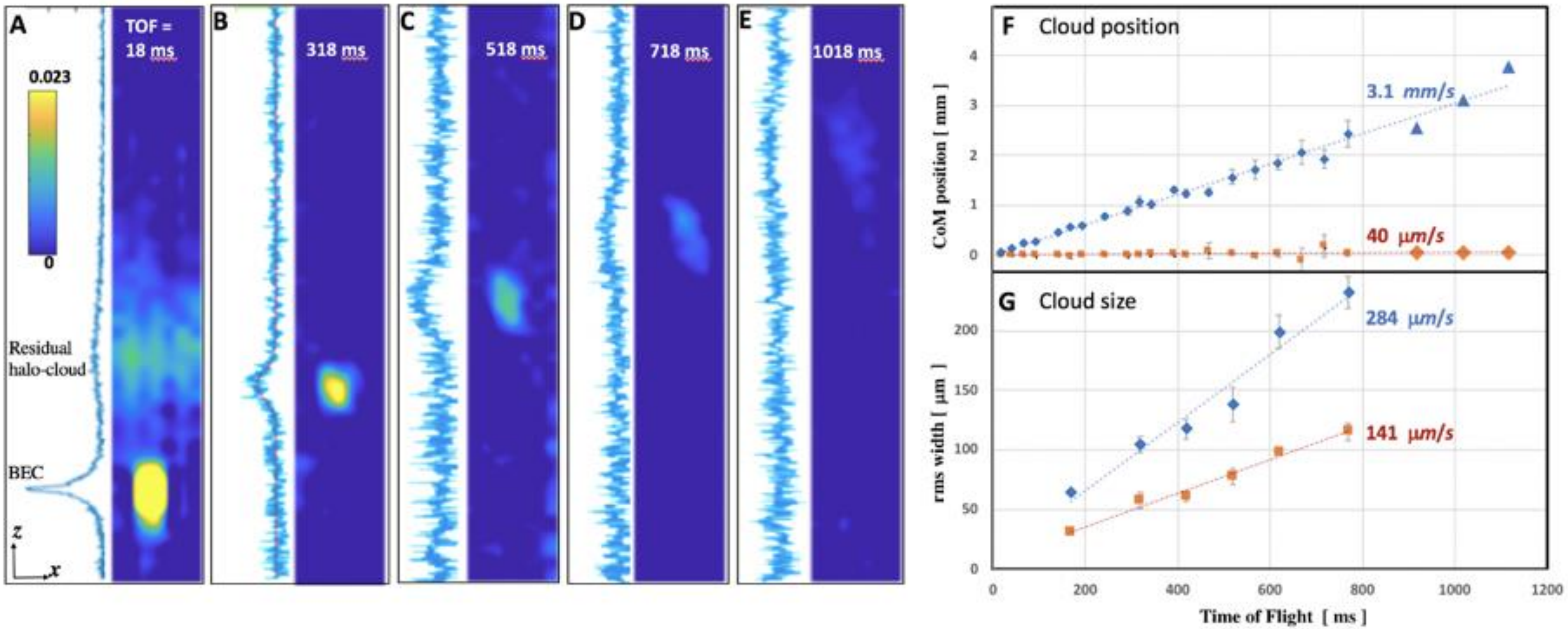
Bridenstine making BECs in orbit

Science Highlights



First Observation of Bose-Einstein Condensate in Orbit

Science Highlights



Quantum Gases cooled to sub-nanoKelvin temperatures and observed after 1 second free expansion

Science Highlights

Article

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

https://doi.org/10.1038/s41586-020-2346-1

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Check for updates

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Quantum mechanics governs the microscopic world, where low mass and momentum reveal a natural wave–particle duality. Magnifying quantum behaviour to macroscopic scales is a major strength of the technique of cooling and trapping atomic gases, in which low momentum is engineered through extremely low temperatures. Advances in this field have achieved such precise control over atomic systems that gravity, often negligible when considering individual atoms, has emerged as a substantial obstacle. In particular, although weaker trapping fields would allow access to lower temperatures[1,2], gravity empties atom traps that are too weak. Additionally, inertial sensors based on cold atoms could reach better sensitivities if the free-fall time of the atoms after release from the trap could be made longer[3]. Planetary orbit, specifically the condition of perpetual free-fall, offers to lift cold-atom studies beyond such terrestrial limitations. Here we report production of rubidium Bose–Einstein condensates (BECs) in an Earth-orbiting research laboratory, the Cold Atom Lab. We observe subnanokelvin BECs in weak trapping potentials with free-expansion times extending beyond one second, providing an initial demonstration of the advantages offered by a microgravity environment for cold-atom experiments and verifying the successful operation of this facility. With routine BEC production, continuing operations will support long-term investigations of trap topologies unique to microgravity[4,5], atom-laser sources[6], few-body physics[7,8] and pathfinding techniques for atom-wave interferometry[9–12].

With the launch and operation of the Cold Atom Lab (CAL), NASA has established the sustained study and development of quantum technologies in orbit. This versatile, multi-user research facility has travelled over 400 million kilometres on board the International Space Station (ISS) since June 2018, under remote operation from the Jet Propulsion Laboratory. Exploiting the microgravity environment of space, researchers can utilize the full sensitivity of ultracold matter-waves to explore fundamental physics and the organizing principles of complex systems from which structure and dynamics emerge—executing major 'thrusts' of the National Research Council's Decadal Survey that define the frontier of space-based fundamental physical science[13].

Understanding quantum mechanics has made possible the now-ubiquitous technologies of lasers, semiconductors and transistors, but remaining elusive is its relationship with general relativity, the physics of gravity, which is well understood at macroscale to astronomic scales. Scaling quantum mechanics to macroscopic sizes is a primary goal of cooling atomic gases towards absolute zero, where wave-like behaviour markedly increases as temperature drops. With enough cooling, each atom's wavelength approaches the interparticle spacing and the system exhibits the macroscopic quantum behaviour of superfluidity. For a dilute gas of bosons—the type of atoms contained in CAL—this phenomenon is known as Bose–Einstein condensation.

These quantum gases, and particularly BECs, have been studied for their intrinsic properties, used as analogues of more inaccessible systems, or applied as inertial sensing matter waves. The state-of-the-art technology has advanced to such a degree that additional cooling techniques are stifled by gravity. For example, the confining potentials that trap the atoms can be adiabatically decompressed to decrease temperature, but only until the local potential minimum is collapsed by gravity's asymmetric pull. Furthermore, following release from an atom trap, gravity-induced centre-of-mass motion greatly limits the system's utility as an inertial sensor. The ideal conditions for engineering macroscopic atom-waves thus becomes ultracold temperatures combined with reduced gravity.

Pioneering cold-atom experiments have mitigated the effects of gravity through a variety of methods. Ground-based levitation techniques accomplish a localized counter-balance to gravity in decompression experiments[1], but they introduce mass- and state-dependent forces that broadly limit atom-wave interferometry and tests between multiple atomic species. Because cold-atom experiments require an ultrahigh vacuum (UHV) to thermally isolate the atoms from the ambient environment, the primary solutions are either to enlarge the size of the UHV chamber or increase the free-fall time of the entire apparatus. Ground-based interferometers have achieved state-of-the-art

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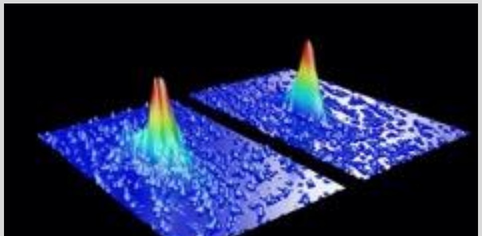
PI Studies with CAL Ultracold Gases

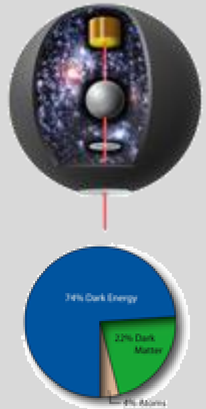


Delta kick cooling (Bigelow Team)

BEC in shell potential

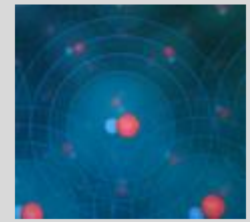
(Lundblad Team)

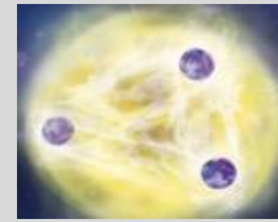
Study their intrinsic properties to test fundamental physical laws and state of the art quantum theories



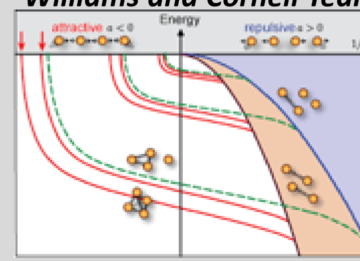
Bigelow, Ketterle, Phillips, and Sackett and Williams Teams

Exploit the sensitivity and quantum nature that comes with being ultracold for precision measurements.



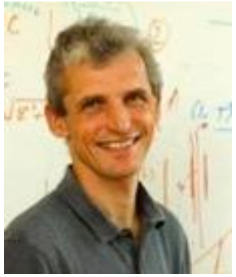


Williams and Cornell Teams



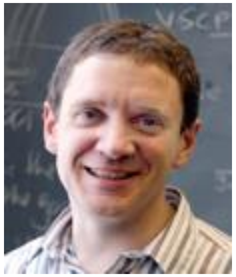
Arrange them to model the physics of more inaccessible systems (Feynman's quantum simulator)

E. Cornell



W. Ketterle

B. Phillips



N. Bigelow

N. Lundblad

J. Williams

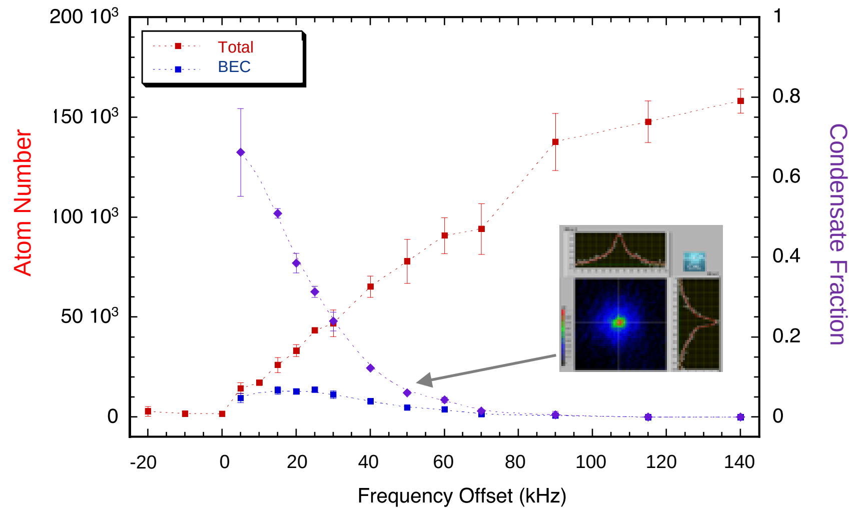
C. Sackett

Science Module 3


CRS 19 launch


Christina Koch working on the SM3 installation

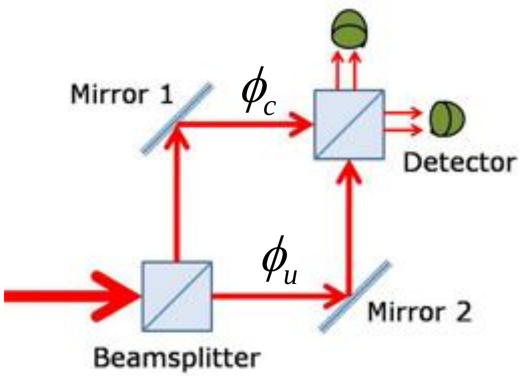
Characterization of BEC formation in SM3

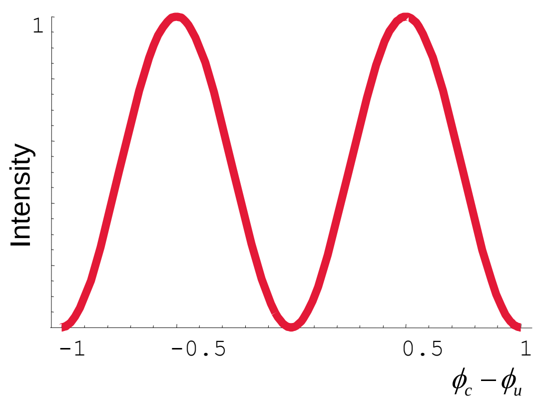


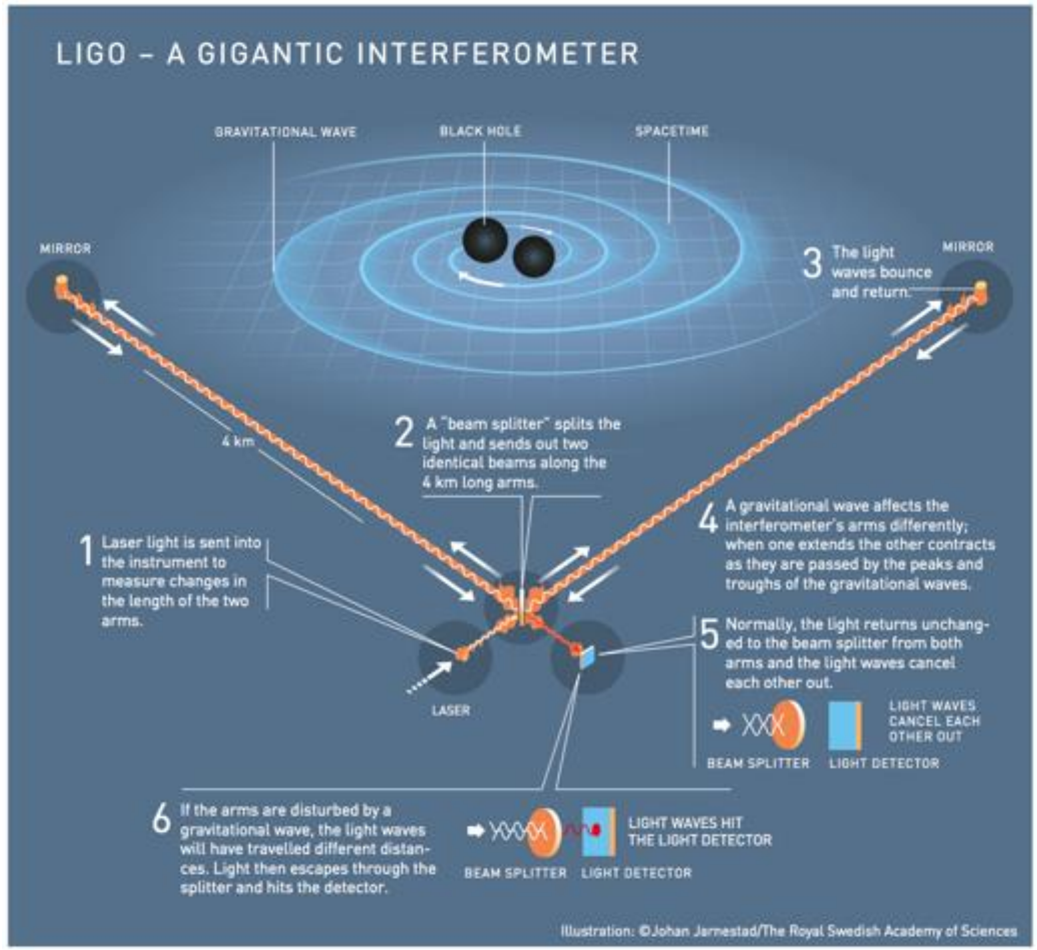
- **SM3 successfully launched to the ISS on December 05, 2019 aboard the SpaceX Falcon 9 rocket.**
- **SM3 installed into the CAL Quad locker and all fiber connections successfully completed on January 30.**
- **Science Module 3 has already created BEC.**
- **Preparations for PI science with the Atom Interferometer (AI) are underway!**

Interferometry

Optical interferometer: Device that utilizes the interference pattern formed by optical waves for e.g. precision measurements.

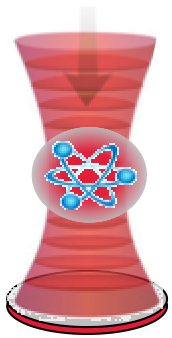






Atom Interferometry (SM3)

Atom interferometer: Device that utilizes the interference pattern formed by matter waves for e.g. precision measurements.



$$\Delta\Phi = 2k\,a\,T^2$$

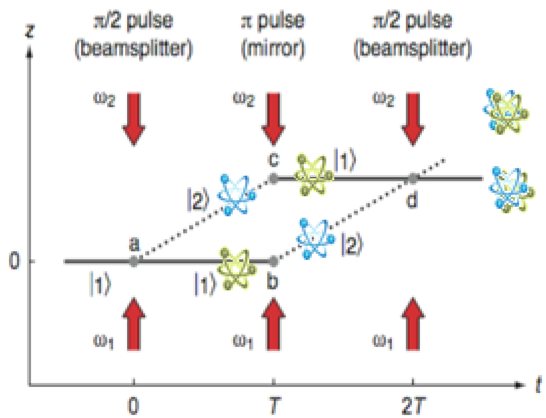
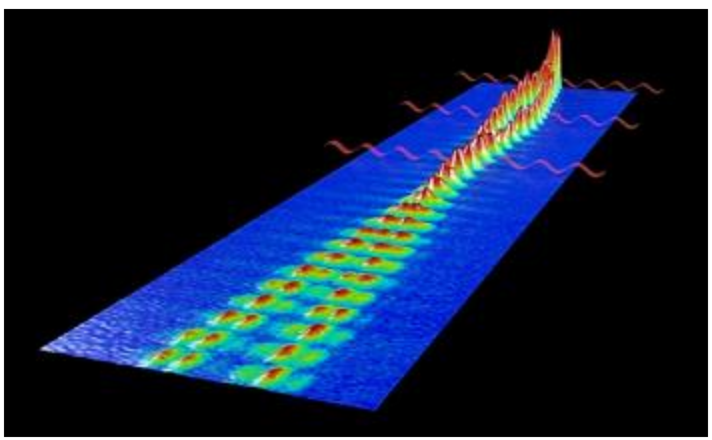
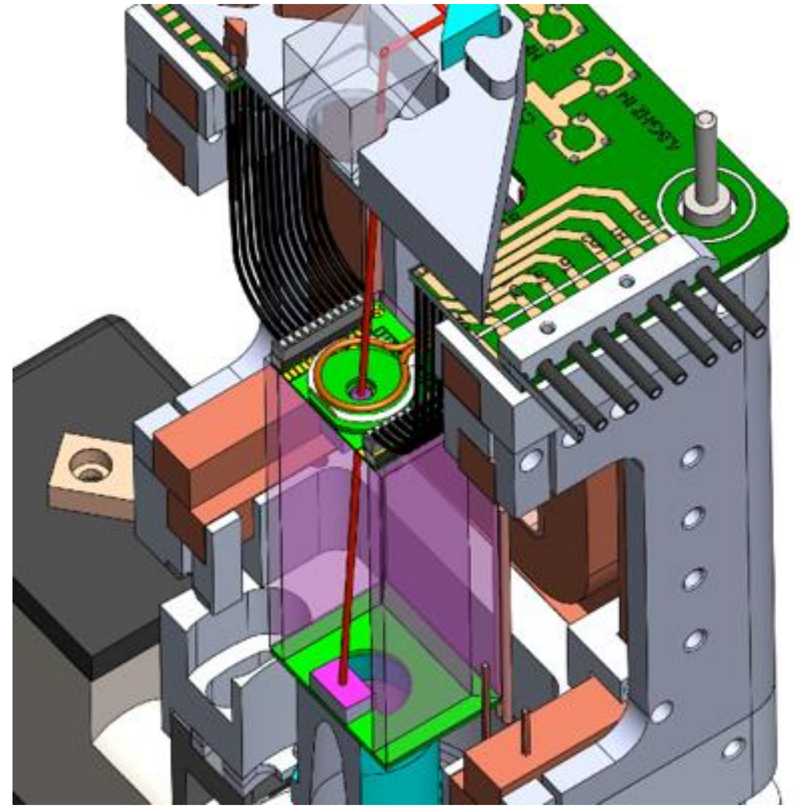


Fig. 1. Light-pulse atom interferometer diagram

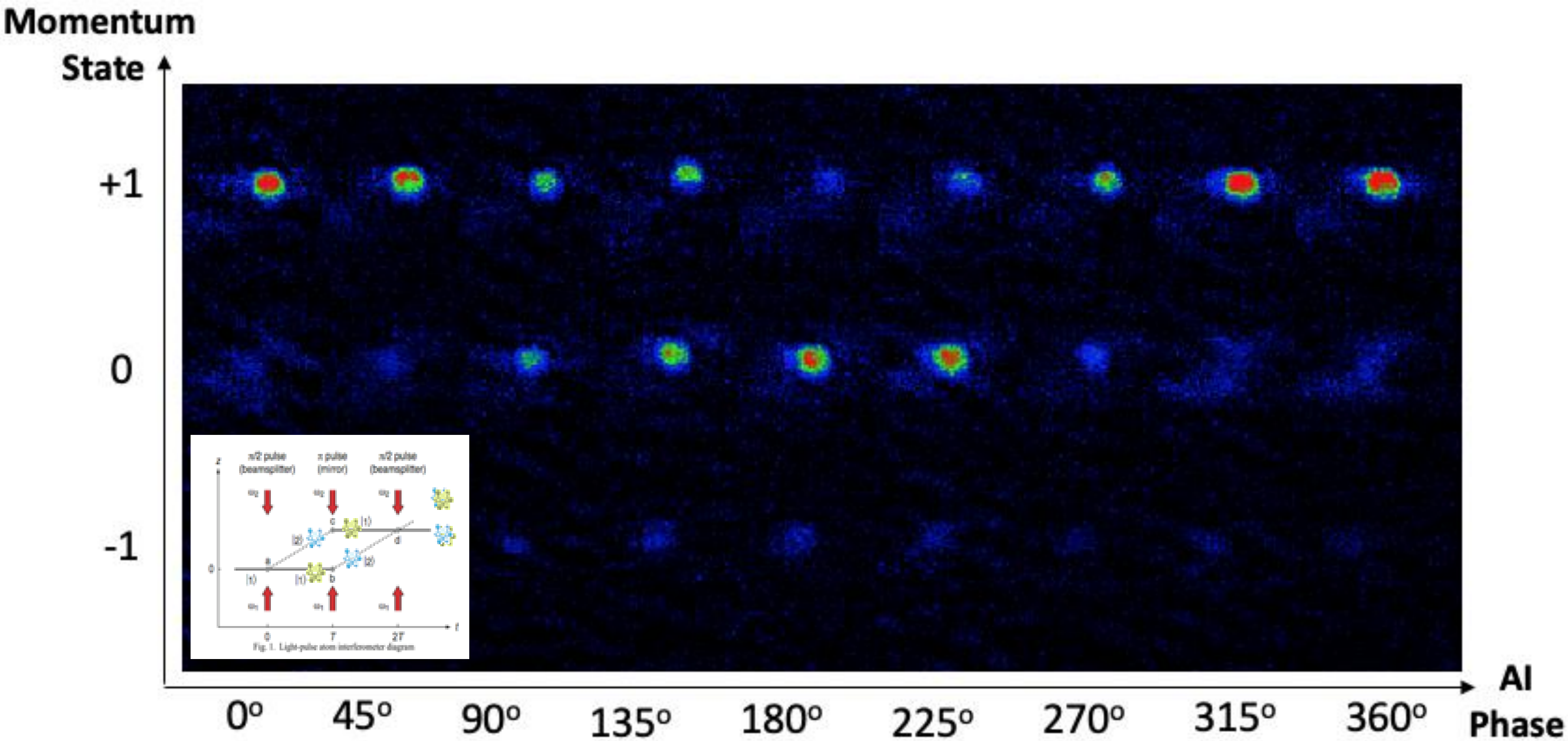


Atom interferometry in QUANTUS drop tower experiment. https://www.iqo.uni-hannover.de



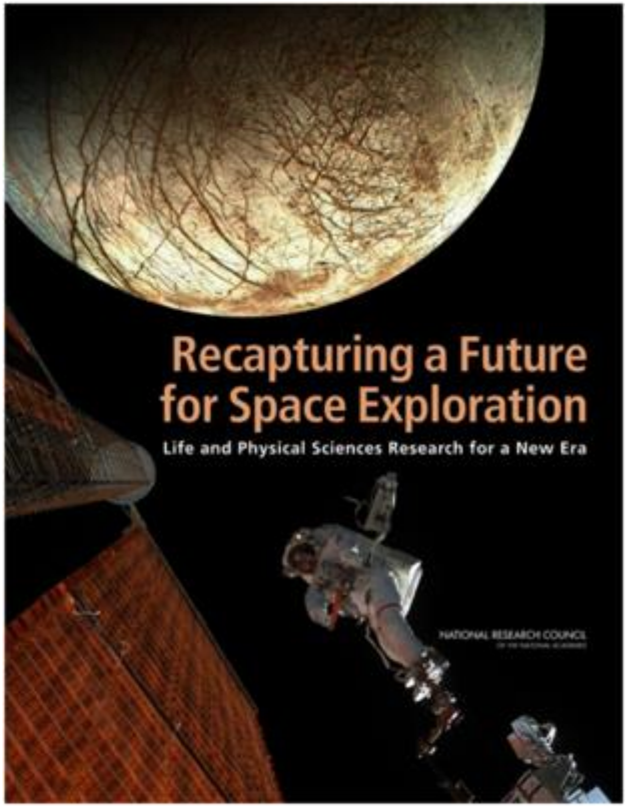
Design of atom interferometer for Science Module 3

Atom Interferometry (SM3)



First demonstration of the interference of matter-waves in space

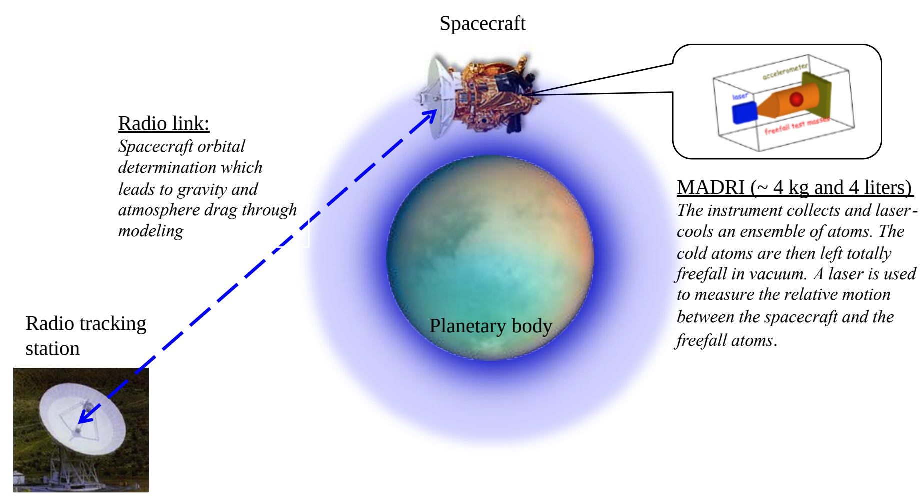
Promise of AI in space



Fundamental Physics:

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

- **Gravity measurements for Gradiometry, Geodesy, Earth, and Planetary Sciences.**
- **On-board S/C acceleration sensing for inertial navigation and drag-free referencing.**



- K. Bongs *et al.*, "Taking atom interferomic quantum sensors from the laboratory to real-world applications", *Nat. Rev. Phys*. **1**, 731 (2019).
- M. S. Safronova *et al.*, "Search for new physics with atoms and molecules", *Rev. Mod. Phys*. **90**, 025008 (2018).
- S. G. Turyshev *et al.*, "Space-based research in fundamental physics and quantum technologies", *Int. J. Mod. Phys*. **D16**(12a), 1879 (2007).

Beyond CAL

Bose Einstein Condensate Cold Atom Lab (ISS-2025):

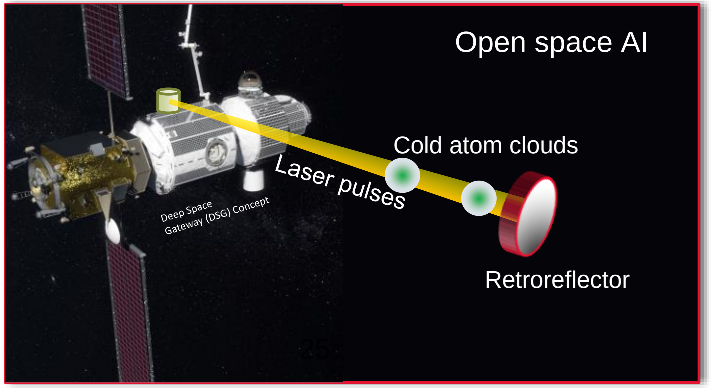
- Joint NASA/DLR mission for a follow-on multi-user Cold Atom Lab onboard the ISS.

Cold Atom Lab II:

- Builds on tech-maturing activities from CAL/BECCAL to address leading recommendations from the next SMD Decadal Survey (2023).
- **Potential for flag-ship mission for SMD BPS (~$100M)**
- Dual-species AI will be the most mature quantum sensor available.

AI Dark Energy and Gravity Experiment Explorer (DSG)

- Demonstration of **open-space** atomic sensors
- Direct detection of **chameleon** dark energy using cold atoms



The CAL Team – Thank you

Kamal Oudrhiri (Project Manager), **Rob Thompson** (Project Scientist), **David Aveline** (Ground Test Bed Lead), **Ethan Elliott** (Engineering Model Test Bed Lead), **Chelsea Dutenhoffer & Irena LI** (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 Shotwel**l (Former CAL Project Manager)

Jet Propulsion Laboratory
California Institute of Technology