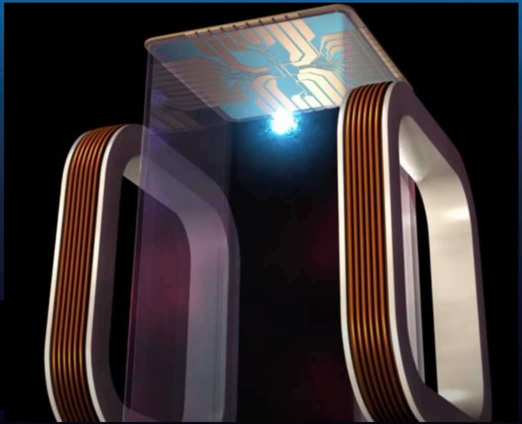
Pathfinder towards PFaST with NASA’s Cold Atom Lab onboard the International Space Station



BPS
BIOLOGICAL AND PHYSICAL SCIENCES

Jason Williams - Project Scientist on behalf of the Cold Atom Lab (CAL) science team

ISS
U.S. NATIONAL LABORATORY

Jet Propulsion Laboratory
California Institute of Technology

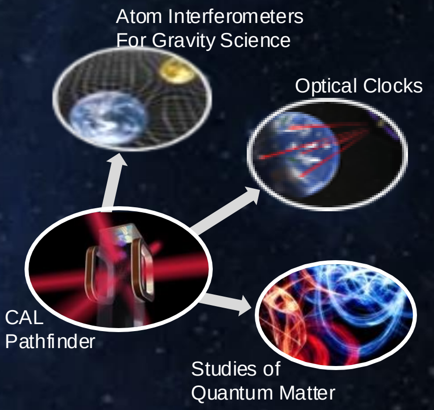
Overview

- Brief introduction to quantum research in space
- Probing the Fabric of Spacetime (PFaST) multi-agency initiative
- Overview of NASA's Cold Atom Lab
- A potential path towards answering the Big Questions

Key Scientific Questions – Fundamental Physics and CAL

KSQ 11: What new physics, including particle physics, general relativity, and quantum mechanics, can be discovered with experiments that can only be carried out in space?

- **Precisely measuring the curvature of spacetime**
- **Searching for violations of fundamental symmetries**
- **Searching for time-variations of fundamental constants**
- **Searching for dark matter and dark energy and other exotic low-mass fields.**
- **Testing whether the gravitational field has quantum aspects**
- **Testing for extensions to GR and/or QM (e.g. Einstein's UFF)**

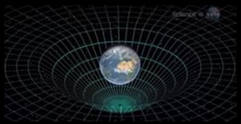
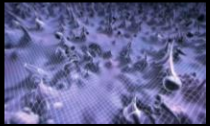
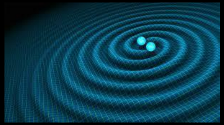


- **These questions can be addressed with precision measurements enabled using quantum technologies in space including;**
  - **Atom interferometers (AI)** – Space will enable long interrogation time (T > 10s), to achieve sensitivities < 10^{-13} g/$\sqrt{Hz}$
  - **Quantum gases (QC)** – picokelvin gases and colder will allow probing matter-wave decoherence over 10s of minutes timescales
  - **Optical Clocks (OC) –** Orbital measurements with accuracy to 10^{-18} and stability to $10^{-16}/\sqrt{Hz}$

Quantum-Gas Research for Fundamental Physics

Jet Propulsion Laboratory
California Institute of Technology

General Relativity (GR) and Quantum Theory (QFT) are fundamentally incompatible:

	GR	QFT
Smoothness of Space-time		 ?
Description of Time		 ?
Gravitational field		 ?

Quantum sensors in space will aim to explore gravity’s effect on quantum matter with high precision

Niels Bohr (Quantum Pioneer) with Albert Einstein (Father of GR) in 1925

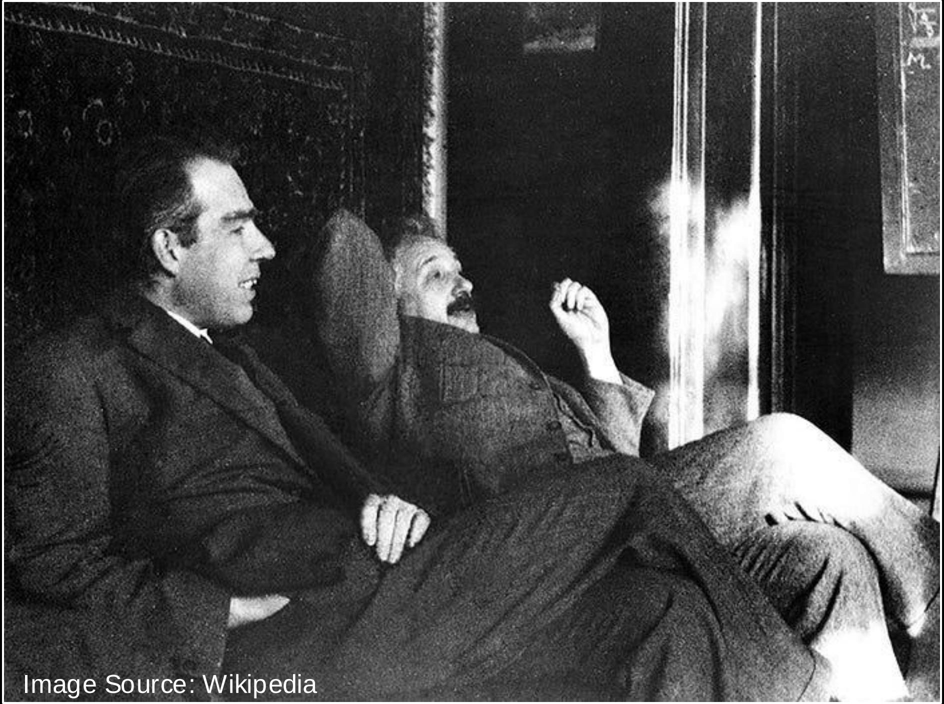


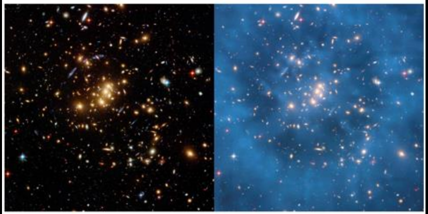
Image Source: Wikipedia

Quantum-Gas Research for Fundamental Physics

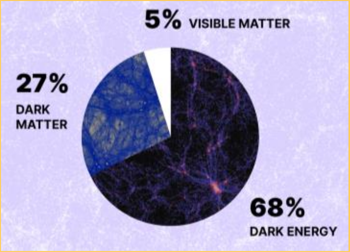
Jet Propulsion Laboratory
California Institute of Technology

CAL PIs are performing pathfinder experiments to mature AI as a precision quantum sensor for near-term missions seeking to understand some of the biggest questions in the universe!

Dark Matter



On the left is a Hubble Space Telescope image of the galaxy cluster Cl 0024+17. On the right is the same image overlaid with a map of the cluster's mass distribution. The ring-like structure evident in the map is one of the strongest pieces of evidence to date for the existence of dark matter. Credit: NASA, ESA, M. J. Jee and H. Ford (Johns Hopkins University) News Release: 2007-17



Hunting for topological dark matter with atomic clocks

A. Derevianko & M. Pospelov

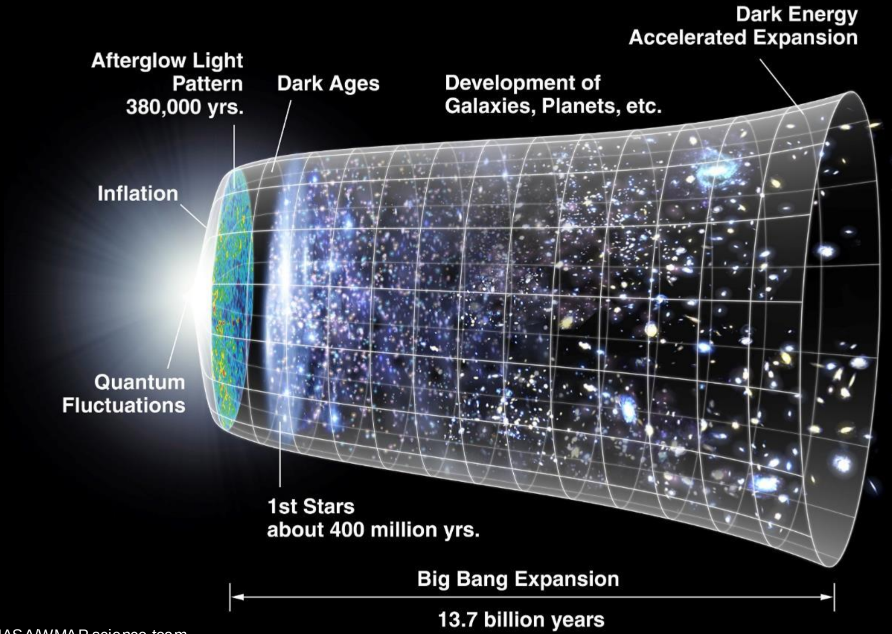
Nature Physics **10**, 933–936 (2014) | Cite this article

Atom-interferometry constraints on dark energy

P. HAMILTON, M. JAFFE, P. HASLINGER, Q. SIMMONS, H. MÜLLER, AND J. KHOURY Authors Info & Affiliations

SCIENCE • 21 Aug 2015 • Vol 349, Issue 6250 • pp. 849-851 • DOI: 10.1126/science.aaa8883

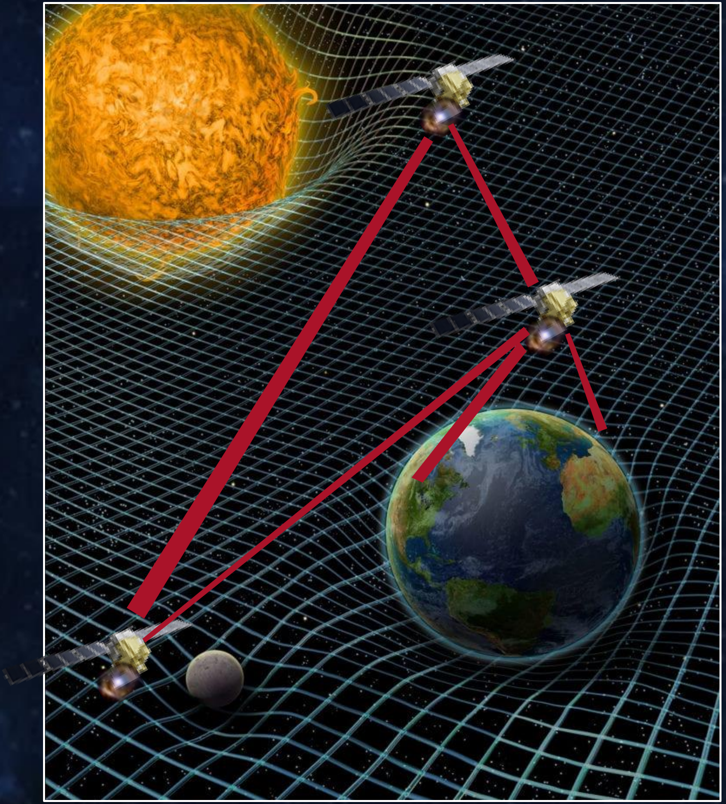
Dark Energy



NASA/WMAP science team

Jet Propulsion Laboratory
California Institute of Technology

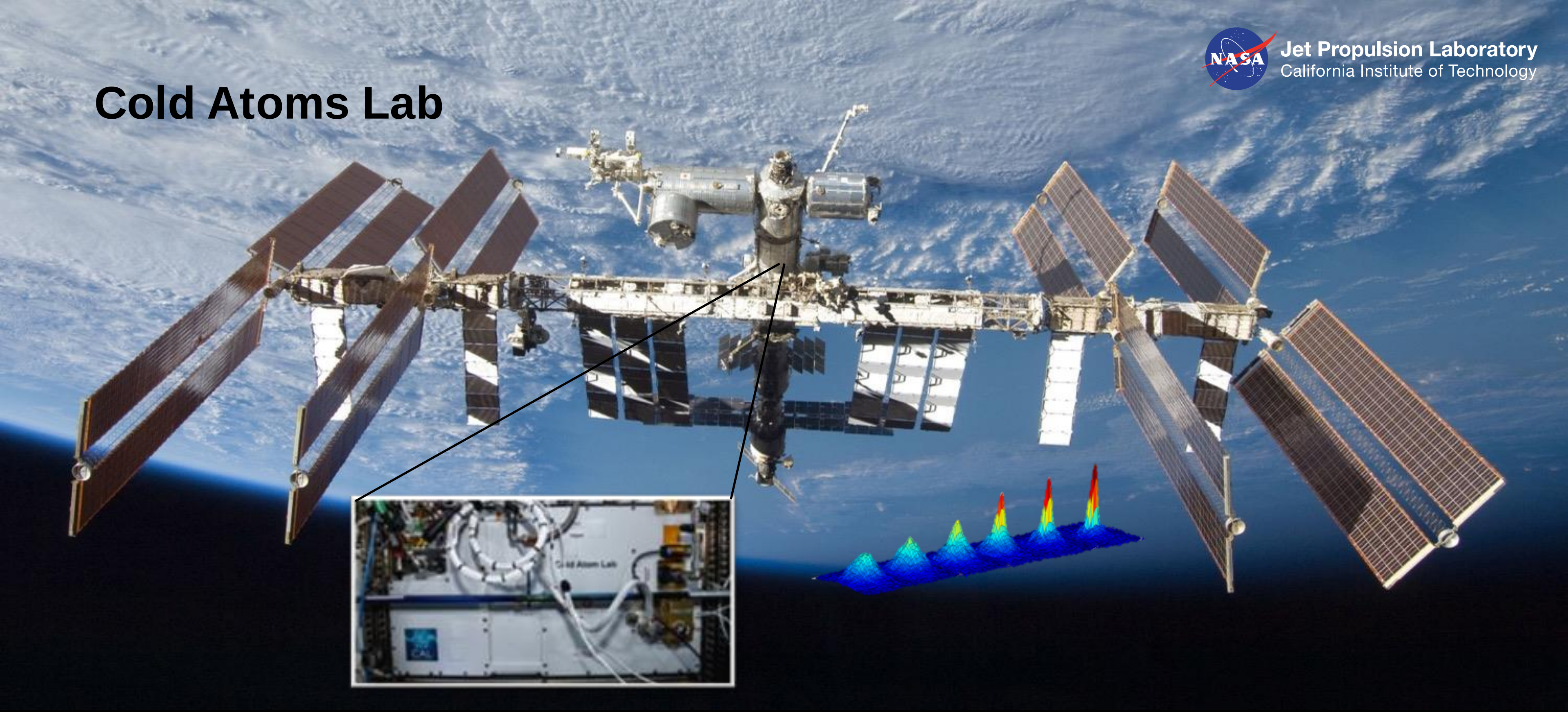
Probing the Fabric of SpaceTime (PFaST)



The PFaST approach is centered on deploying an advanced quantum sensing network whose performance will be many orders of magnitude better than previously thought possible, enabled by scientific discoveries that occurred only recently and that will be continuously refined throughout the decades to come for:

- Precisely measuring the curvature of spacetime
- Searching for dark matter and dark energy
- Detecting gravity waves
- Testing whether the gravitational field has quantum aspects.
- “Solar-system GPS”

Cold Atoms Lab

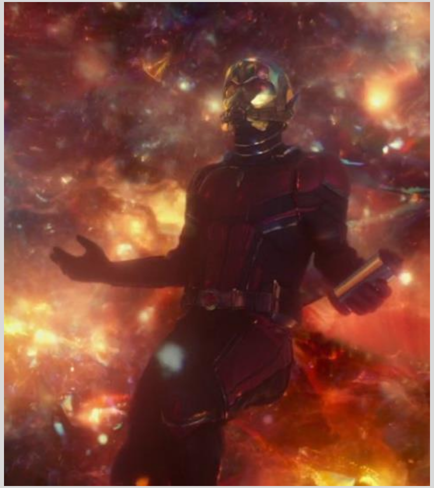


Multiuser facility that Utilizes the microgravity environment of the ISS for measurements with ultracold gases of ^{87}Rb, ^{41}K, and/or ^{39}K that can't be achieved on Earth.

Jet Propulsion Laboratory
California Institute of Technology

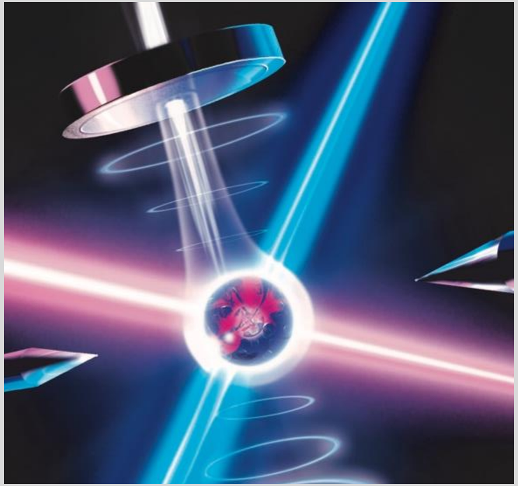
The Science of CAL

Understanding the Quantum Realm



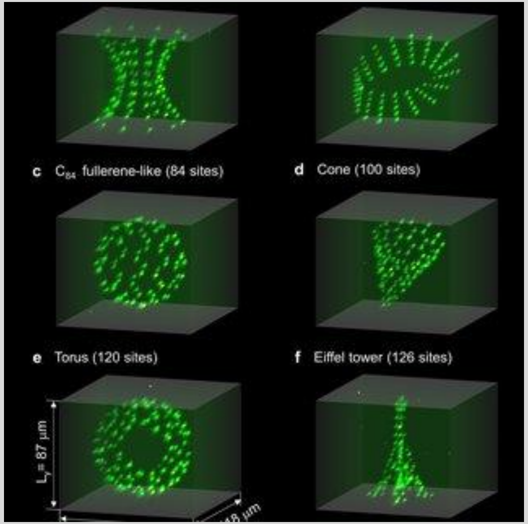
Study intrinsic properties of quantum matter to test fundamental physical laws and state of the art quantum theories

Developing Quantum Technologies



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

Utilizing Quantum Computing



Arrange them to model the physics of inaccessible systems

(Feynman's quantum simulator)

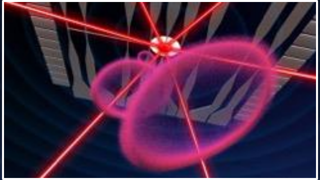
The Science of CAL

N. Lundblad
Bates

C. Lannert
Smith College

S. Vishveswara
UIUC

D. Aveline
JPL

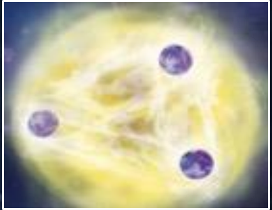


Observation of ultracold atomic bubbles in orbital microgravity[1]

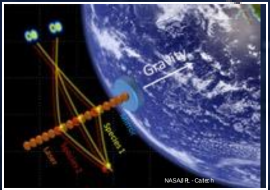
E. Cornell
JILA

P. Engels
WSU

M. Mossman
USD



Zero-G Studies of Few and Many Body Physics[3]



Quantum Control[2] *and Dual-Species Atom Interferometry for tests of General Relativity*

N. Bigelow
Rochester

W. Ketterle
MIT

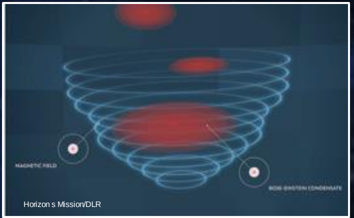
D. Pritchard
MIT

B. Phillips
NIST

H. Müller
Berkeley

C. Sackett
U. VA.

B. Kasch
AFRL



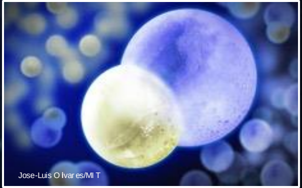
Adiabatic Cooling of Atomic Test Masses for AI[4]

1) *Carollo et al.* "Observation of ultracold atomic bubbles in orbital microgravity", *Nature,* **606**, 281-286 *(2022)* – *Flight Research*
2) *Gaaloul et al.* "A space-based quantum gas laboratory at picokelvin energy scales", *Nature Communications,* **13**, 7889 (2022) - *Flight Research*
3) *Xie et al.*, "Observation of Efimov Universality across a Nonuniversal Feshbach Resonance in ^{39}K", *Phys. Rev. Lett,* **125**, 243401 (2020)
4) *Pollard et al.*, "Quasi-Adiabatic External State Preparation of Ultracold Atoms in Microgravity", *Microgravity Sci. Technol.*, **32**, 1175 (2020) – Flight Research
5) *D'Incao et al.*, "Enhanced association and dissociation of heteronuclear Feshbach molecules in a microgravity environment", *Phys. Rev. A,* **95**, 012701 (2017)

J. Williams
JPL

J. D'Incao
JILA

E. Elliott
JPL



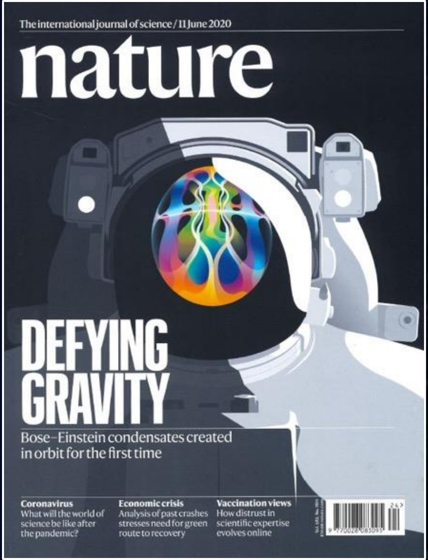
Feshbach molecules[5] *and interacting gases for enhanced atom interferometry*

NASA’s Cold Atom Lab (CAL)

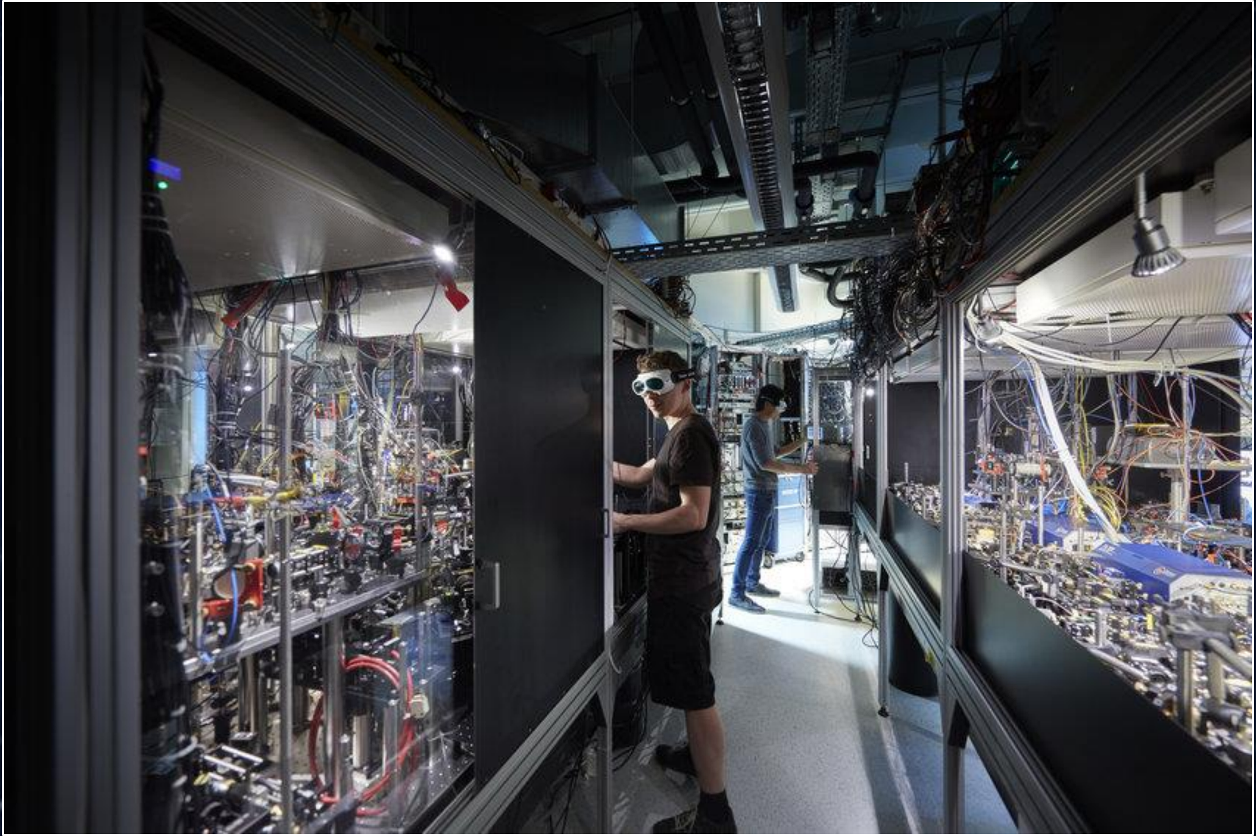
CAL is the first multi-user facility for quantum gas research in space. It has operated in orbit since 2018 and has collected data from over 100,000 experimental runs for five flight teams.

CAL achievements include:

- Persistent Bose-Einstein condensates in orbit. (Nature publication)
- First demonstration of dual-species BECs in space using potassium-41and rubidium-87. (Nature publication)
- Delta-kick cooling to ~ 52 picoKelvin temperatures, the coldest temperature achieved in space. (Nature Communications publication)
- First realization of ultracold gases of quantum bubbles in space. (Nature publication)
- First demonstration of dual-species matter-wave interferometry in space. (Nature publication)
- First explorations of interacting quantum mixtures in space, observed immiscible mixing of rubidium and potassium. (Nature publication)
- First use of atom interferometry as a quantum sensor in space. (Nature Communications publication and another In Preparation)



The Road to Ultracold



Rubidium Quantum Gas Lab (Max Planck Institute)

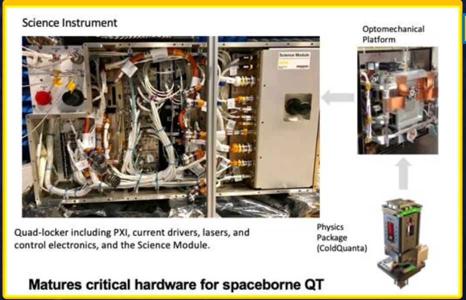
Cold Atom Lab

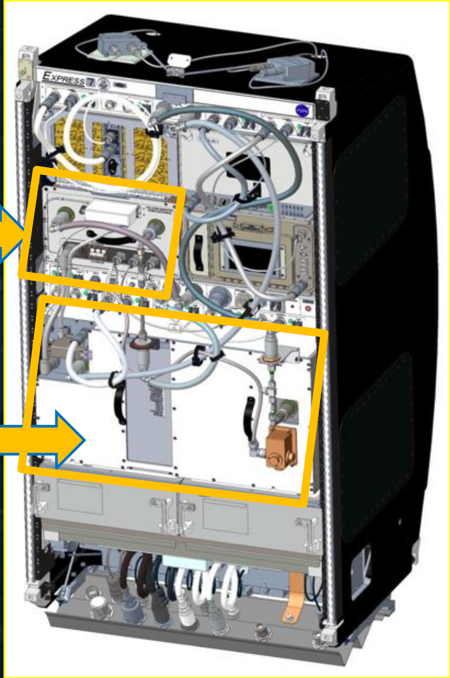
CAL has made a first leap in maturing technologies for space-based quantum science

- Atomically referenced/stabilized laser systems
- Optomechanics and fiber-based laser subsystems
- Cold atom physics packages
- Low-noise electronics and control systems
- High stability, low SWaP, transportable quantum facility in a box
- Remote and autonomously operated lab in space
- Single- and dual-species atom interferometry

Power Electronics

Science Instrument





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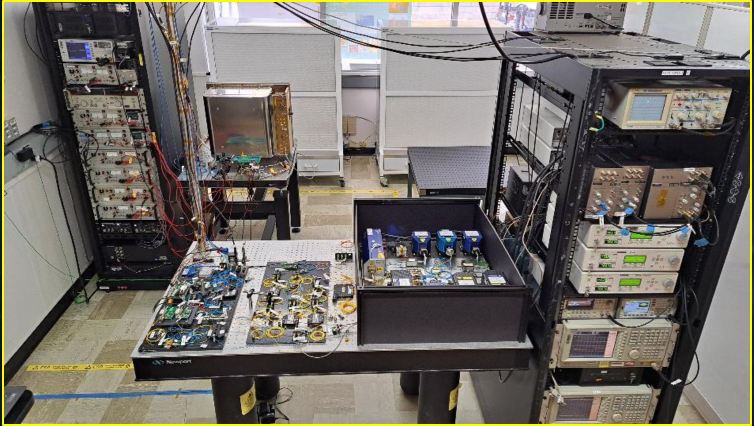
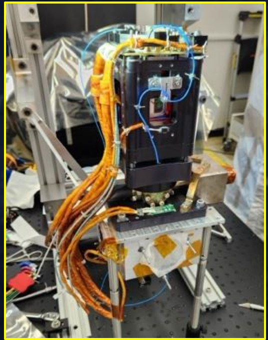
California Institute of Technology

CAL Testbeds

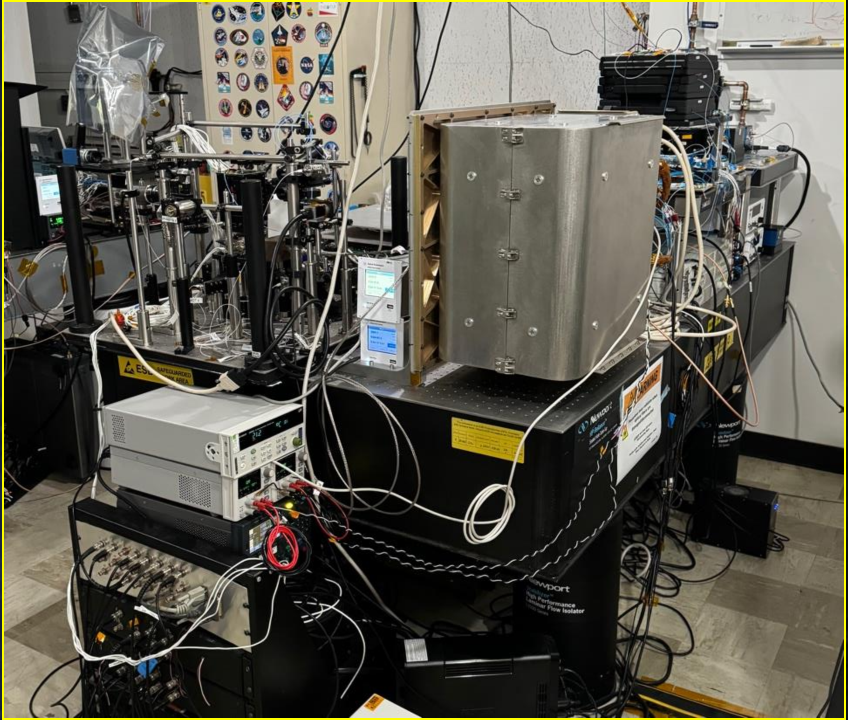


CAL Ground Testbed

SM with open Magnetic Shields



PP w/ MOT Coils



CAL Engineering Testbed

Utilizing the wave-like nature of matter

Schrodinger's Cat and Superposition

Atom Interferometer

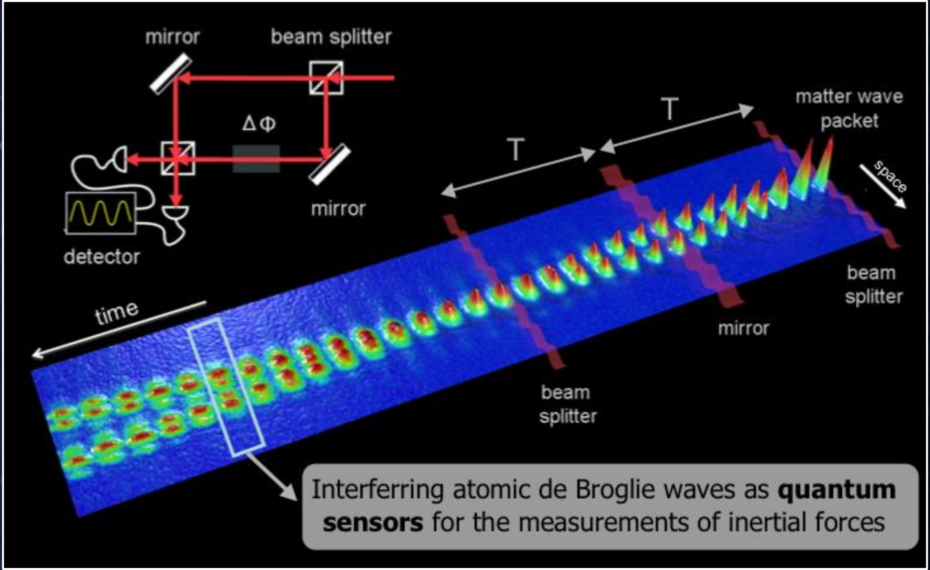


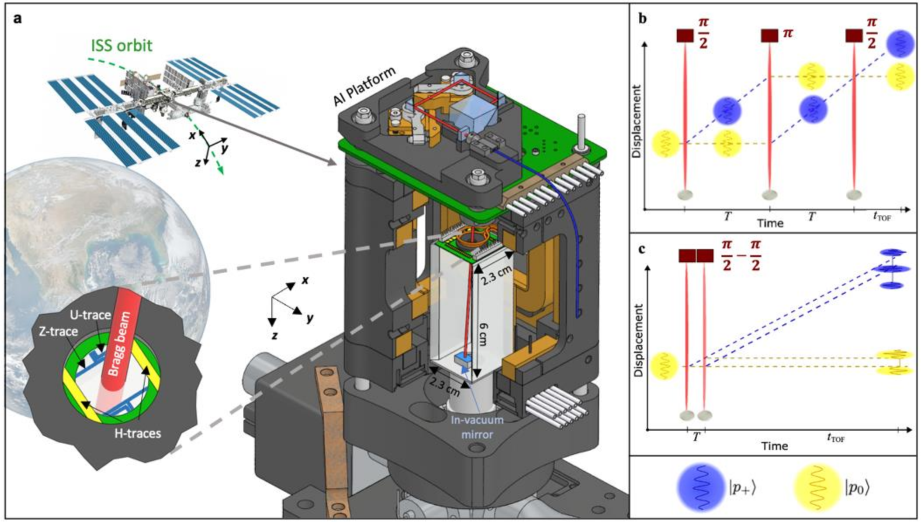
Image credit: Brennpunkt: Interferometrie im freien Fall", M. Arndt, Physik Journal 5 (2013)

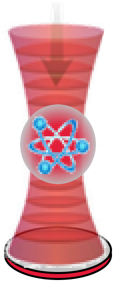
The thought experiment devised in 1935 during a discussion between Schrödinger and Einstein has real-world implications for quantum sensing by enabling "superposition states" of matter.

CAL Atom Interferometer

Atom interferometer: Device that utilizes the interference pattern formed by matter waves for precision measurements of accelerations, gravity, and other forces

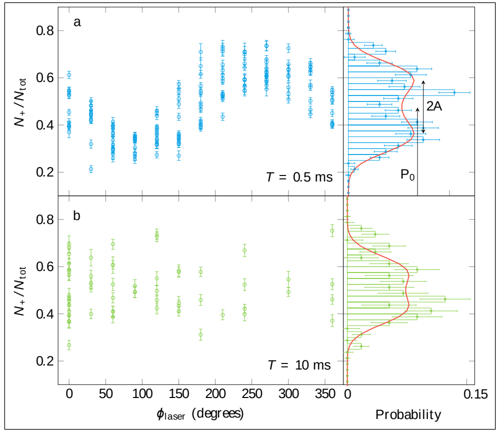
Williams et al. "Pathfinder experiments with atom interferometry in the Cold Atom Lab onboard the International Space Station"
Nature Communications, ***15***, *6414 (2024)*





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

Demonstrate AI and sense the effects of vibrations on the ISS

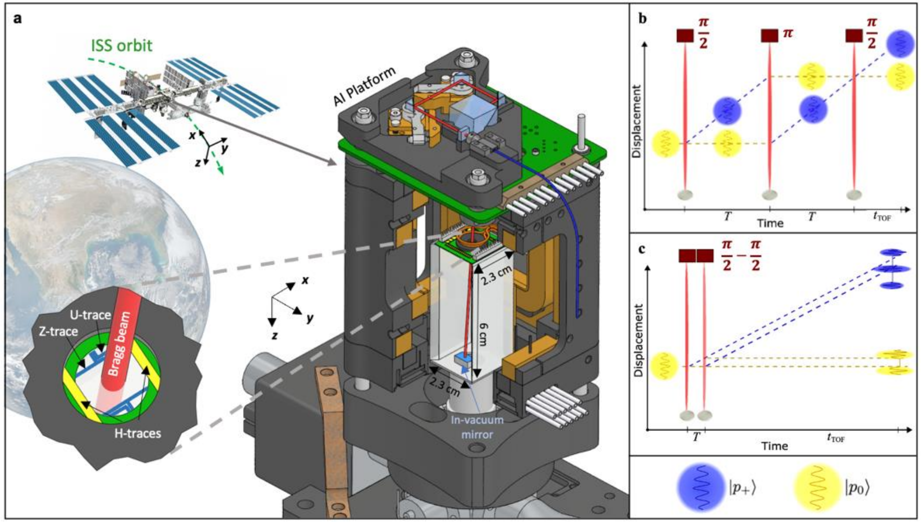


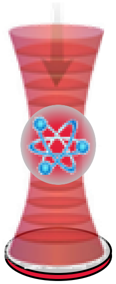
- *Also sensed the AI laser frequency on the ISS from Atomic phase feedback.*
- ***First quantum sensor using atom interferometry in space***

CAL Atom Interferometer

Atom interferometer: Device that utilizes the interference pattern formed by matter waves for precision measurements of accelerations, gravity, and other forces

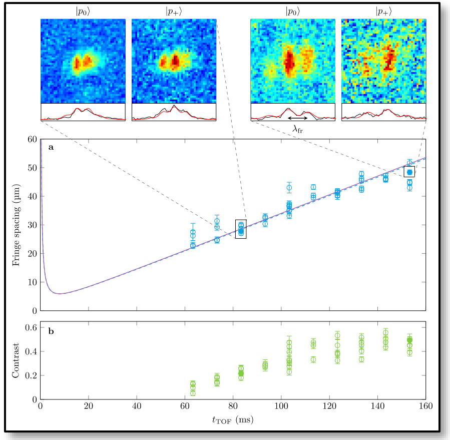
*Williams et al. "*Pathfinder experiments with atom interferometry in the Cold Atom Lab onboard the International Space Station*"*
Nature Communications, ***15,*** *6414 (2024)*





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

Demonstrate phase-shear AI



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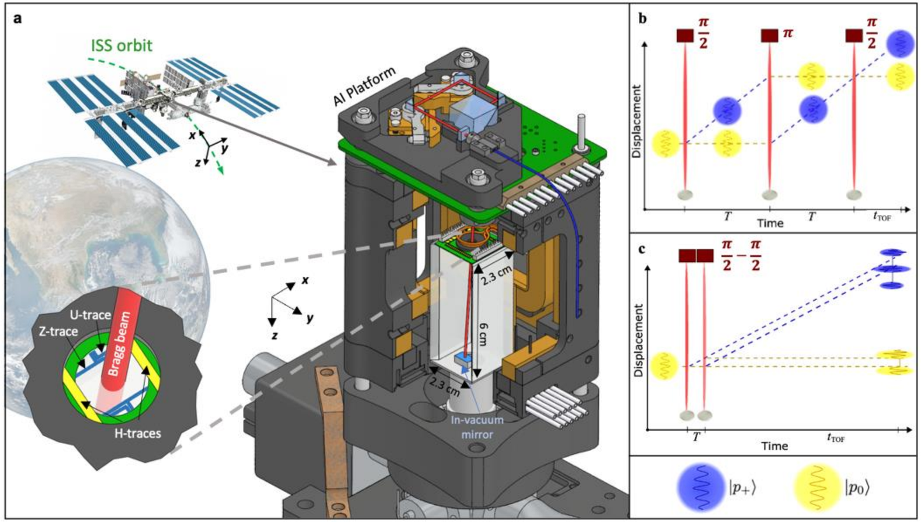
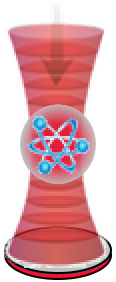
CAL Atom Interferometer

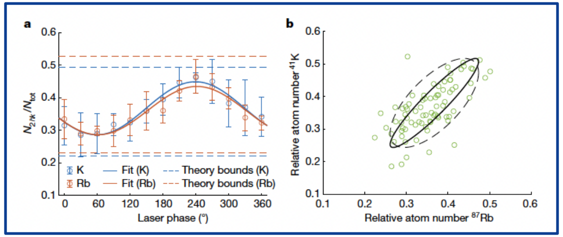
Atom interferometer: Device that utilizes the interference pattern formed by matter waves for precision measurements of accelerations, gravity, and other forces

Elliott et al. "Quantum gas mixtures and dual-species atom interferometry in space",
Nature, ***623***, 502-508 (2023)

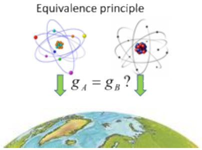




$\Delta\Phi = 2k\, a\, T^2$



Simultaneous interferometry of ^{87}Rb and ^{41}K BECs showing the expected fringes (left) and phase-correlations (right)



Does gravity act differently on BECs of rubidium-87 and potassium-41?

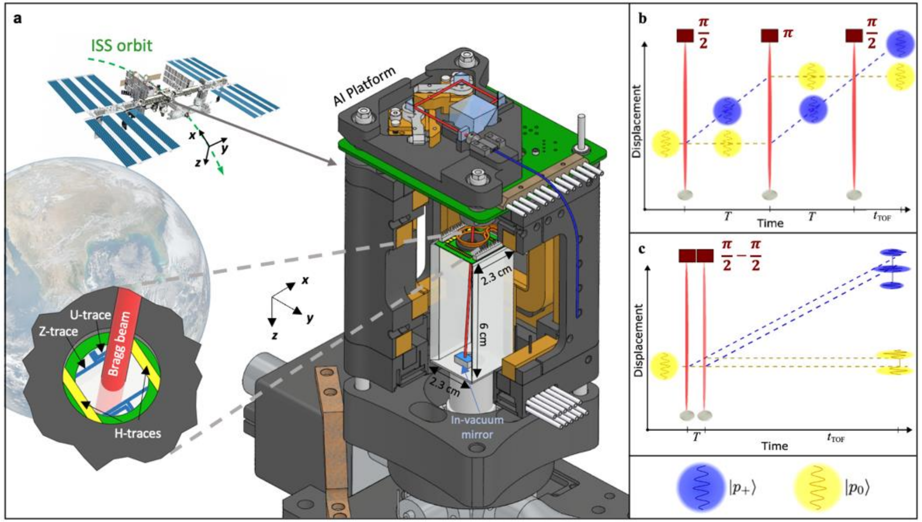
$$\eta = 2\frac{g^{87\,Rb} - g^{41\,K}}{g^{87\,Rb} + g^{41\,K}}$$

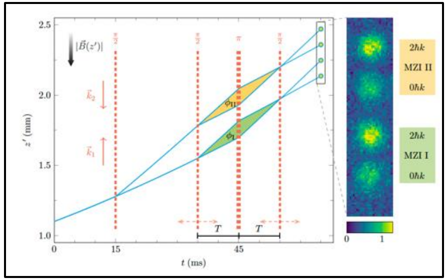
Pathfinder for Equivalence Principle test with ^{87}Rb and ^{39}K quantum gases

CAL Atom Interferometer

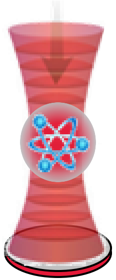
Atom interferometer: Device that utilizes the interference pattern formed by matter waves for precision measurements of accelerations, gravity, and other forces

Meister et al. "Space-deployed magnetic curvature sensing with differential matter-wave interferometry"
In Preparation

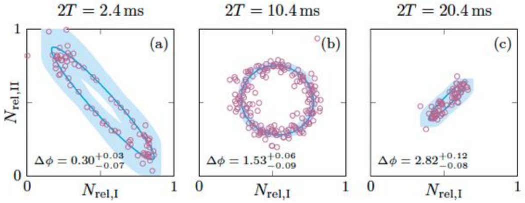




Gradiometer atom interferometry in CAL



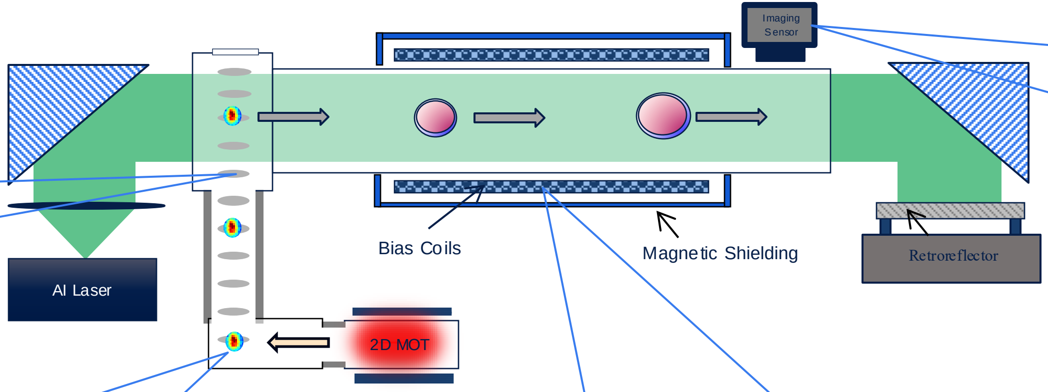
$\Delta\Phi = 2k\,a\,T^2$



Correlations and AI phase shifts due to magnetic field gradients in CAL

CAL is serving to provide maturation capabilities for space-based quantum technologies needed to address key scientific questions from the Decadal Survey:

Atom Interferometer



2) Atom Transport via Optical Tractor beam

- Transport of single- and dual-species gases cooled to picokelvin temperature scales

3) Atom Interferometer Readout

- Emerging phase-readout techniques and data processing will be critical for future AI-based missions

"Principal Component Analysis for Spatial Phase Reconstruction in Atom Interferometry", arXiv:2405.05150

1) Cold-atom source at picokelvin temperature scales

- Large-flux atomic sources required for precision measurement
- Benefits from space for testing of advanced cooling techniques for single- and dual-species gases in space
- Needed studies include tests of confinement, transport away from the chip-trap, and controlled release of dual-species gases

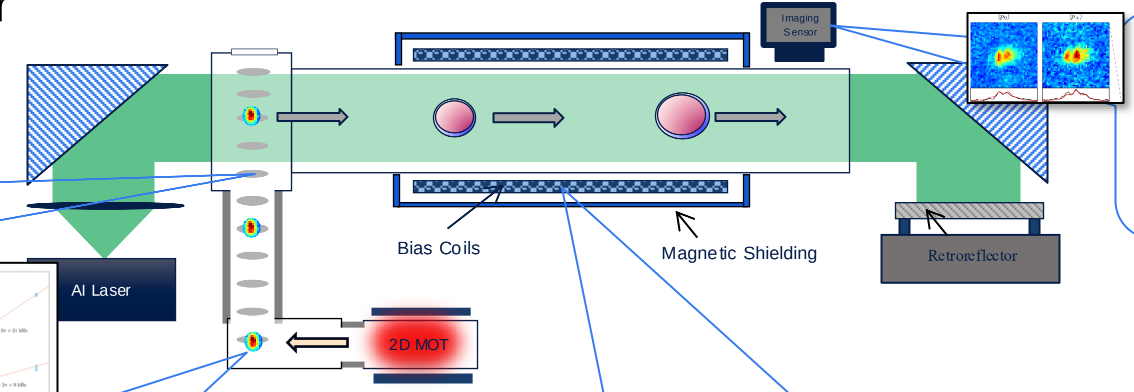
3) Atom Interferometer Sequence in a Dedicated Science Region

- Increased interrogation time and related increased precision for quantum sensing will require not-only system design efforts but also dedicated investigations to control systematics.
- Demonstrations of necessary and unique designs and recipes for space-based AI are needed to guide future AI-based mission concepts

- **Integration of JPL custom and commercial "off the shelf" hardware in low SWaP and rugged design**
- **Autonomous long-term operation of a quantum gas facility in space**

CAL is serving to provide maturation capabilities for space-based quantum technologies needed to address key scientific questions from the Decadal Survey:

Atom Interferometer



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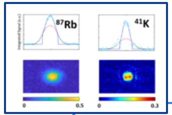

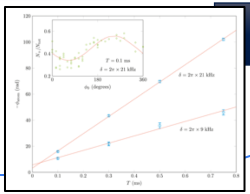

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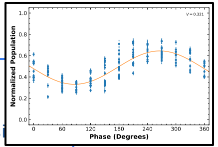

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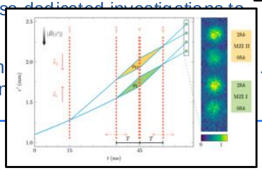
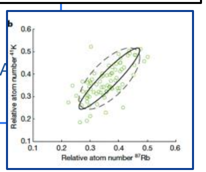
- Demonstrations of necessary and unique design... are needed to guide future AI-based mission co...

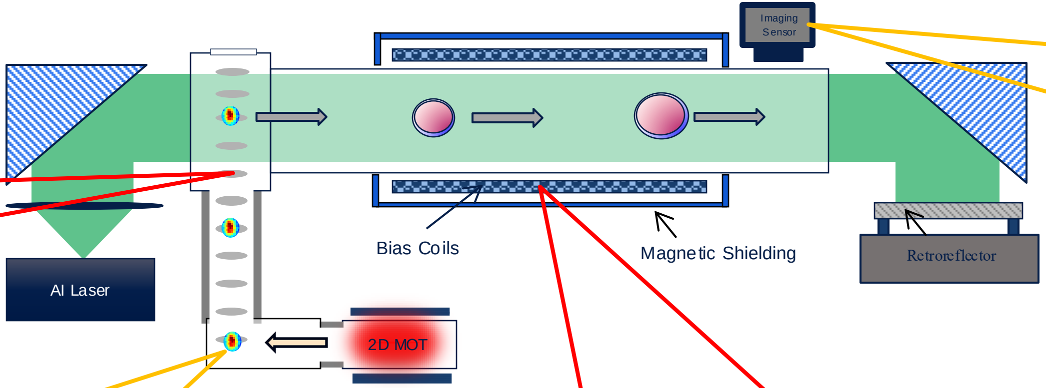




- **Integration of JPL custom and commercial "off the shelf" hardware in low SWaP and rugged design**
- **Autonomous long-term operation of a quantum gas facility in space**

CAL is serving to provide maturation capabilities for space-based quantum technologies needed to address key scientific questions from the Decadal Survey:

Atom Interferometer



2) Atom Transport via Optical Tractor beam

- Transport of single- and dual-species gases cooled to picokelvin temperature scales

3) Atom Interferometer Readout

- Emerging phase-readout techniques and data processing will be critical for future AI-based missions

"Principal Component Analysis for Spatial Phase Reconstruction in Atom Interferometry", arXiv:2405.05150

1) Cold-atom source at picokelvin temperature scales

- Large-flux atomic sources required for precision measurement
- Benefits from space for testing of advanced cooling techniques for single- and dual-species gases in space
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3) Atom Interferometer Sequence in a Dedicated Science Region

- Increased interrogation time and related increased precision for quantum sensing will require not-only system design efforts but also dedicated investigations to control systematics.
- Demonstrations of necessary and unique designs and recipes for space-based AI are needed to guide future AI-based mission concepts

- **Long-time interrogation (10s of seconds in extended free-fall)**
- **Systematics control for precision differential gravity measurements**

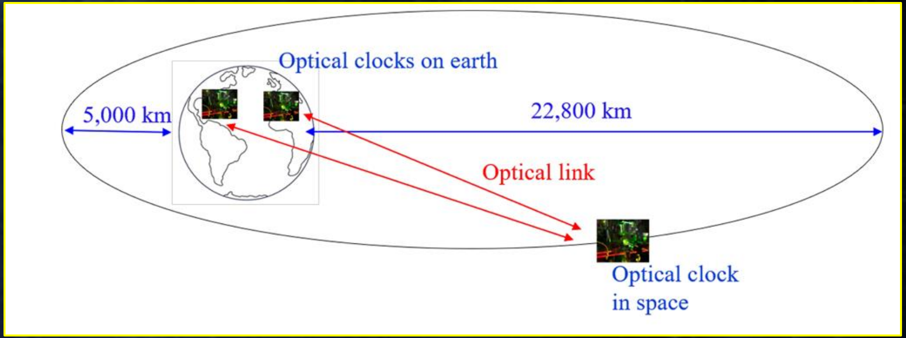
Near-term needs for addressing KSQ#11 and towards the PFaST concept

Optical Lattice Clocks

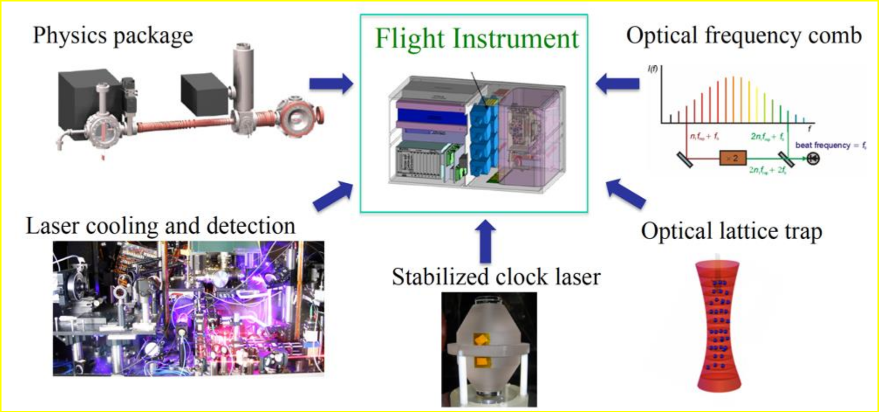
- Earth-space time transfer maintaining 10^{-18} accuracy.
  - Caldwell *et al.*, APL Photonics 9, 016112 (2024)

- SWAP reduction and flight demonstrations of:
  - Atom Source
  - Stabilized clock laser
  - Optical Frequency Comb
  - Automated operation and data acquisition

- Systematics control for precision timekeeping



FOCOS concept submitted to the BPS Decadal Survey comparing Earth and space-based clocks in an elliptical orbit

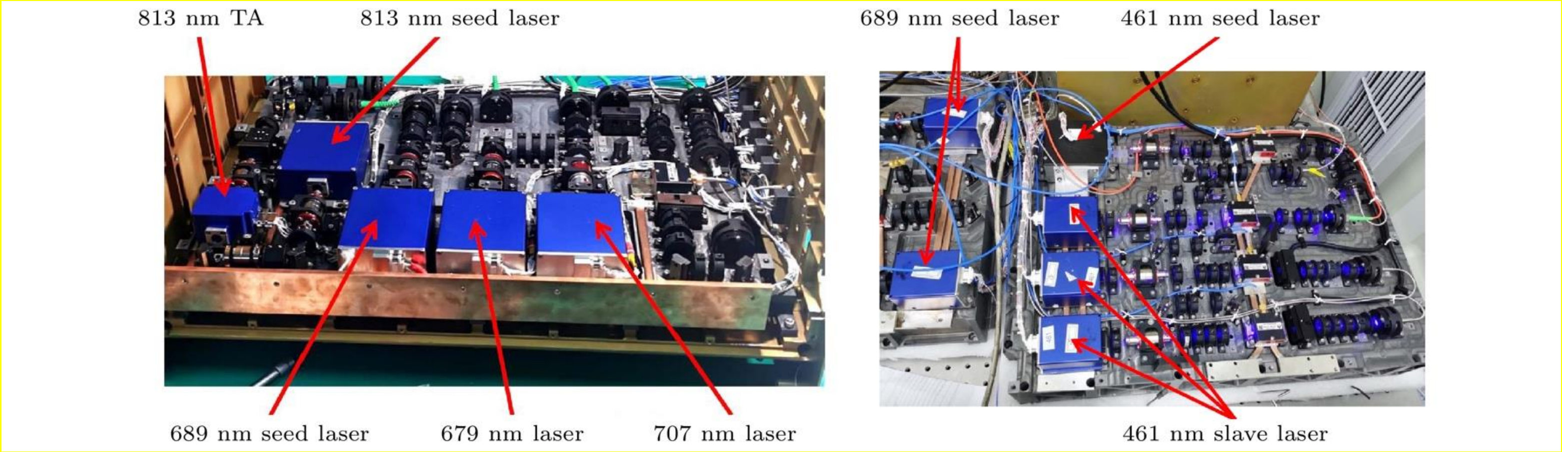


Competition for addressing KSQ#11 and towards the PFaST concept

SPECIAL TOPIC—The 70th anniversary of National University of Defense Technology

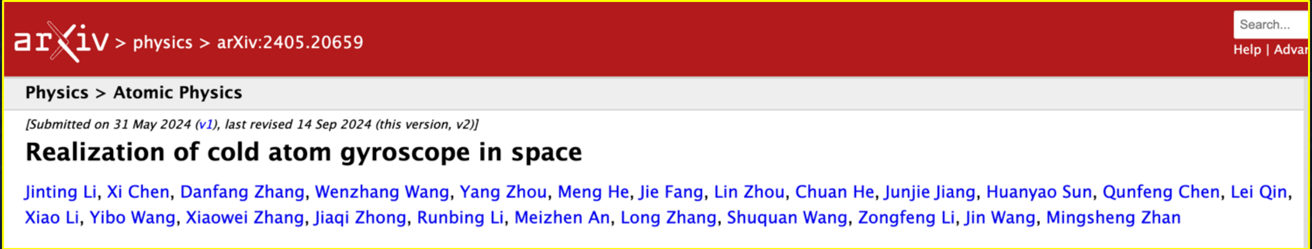
Laser system of cold atom optical clock in China Space Station*

Liu Yun [1)2)] Wang Wen-Hai [1)2)] He De-Jing [1)2)] Zhou Yong-Zhuang [1)2)]
Shen Yong [1)2)] Zou Hong-Xin [1)2)†]



Laser system of the space optical clock (SOC) installed in the China Space Station in 2022

Competition for addressing KSQ#11 and towards the PFaST concept


arXiv > physics > arXiv:2405.20659

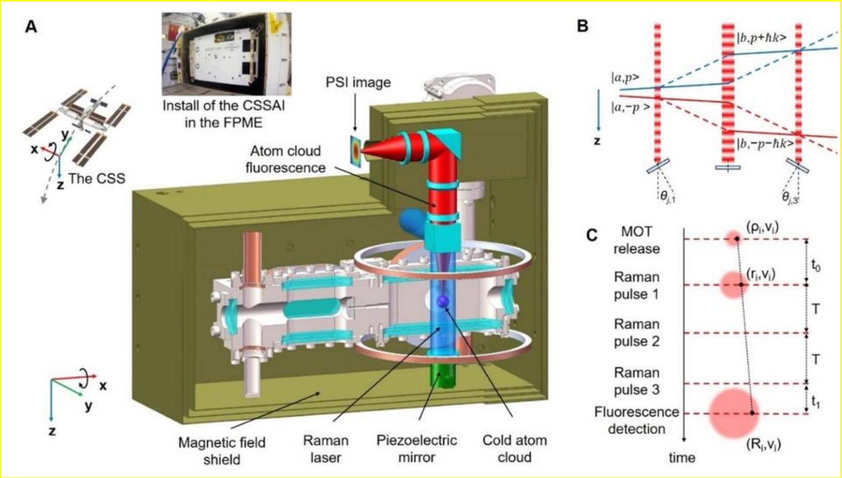
Search...
Help | Advar

Physics > Atomic Physics

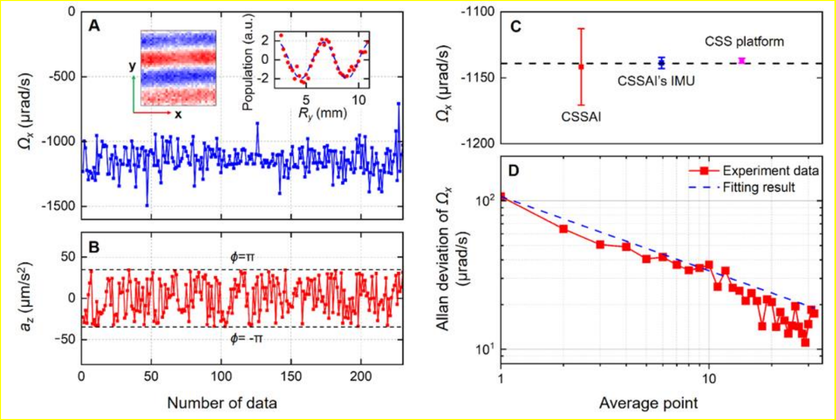
[Submitted on 31 May 2024 (v1), last revised 14 Sep 2024 (this version, v2)]

Realization of cold atom gyroscope in space

Jinting Li, Xi Chen, Danfang Zhang, Wenzhang Wang, Yang Zhou, Meng He, Jie Fang, Lin Zhou, Chuan He, Junjie Jiang, Huanyao Sun, Qunfeng Chen, Lei Qin, Xiao Li, Yibo Wang, Xiaowei Zhang, Jiaqi Zhong, Runbing Li, Meizhen An, Long Zhang, Shuquan Wang, Zongfeng Li, Jin Wang, Mingsheng Zhan



Overview of the China Space Station Atom Interferometer (CSSAI) installed in the China Space Station in 2022



First rotation and acceleration testing results

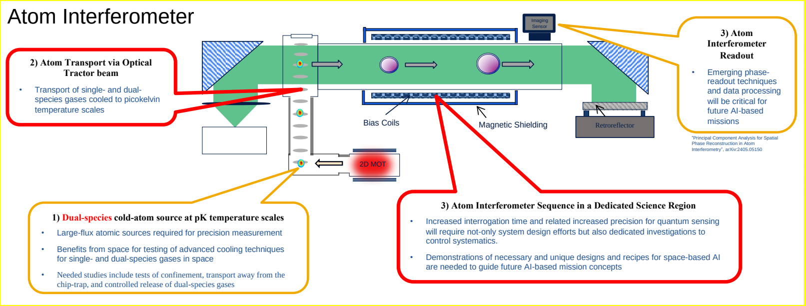
Proposed BPS Technology Needs and Platforms towards PFaST

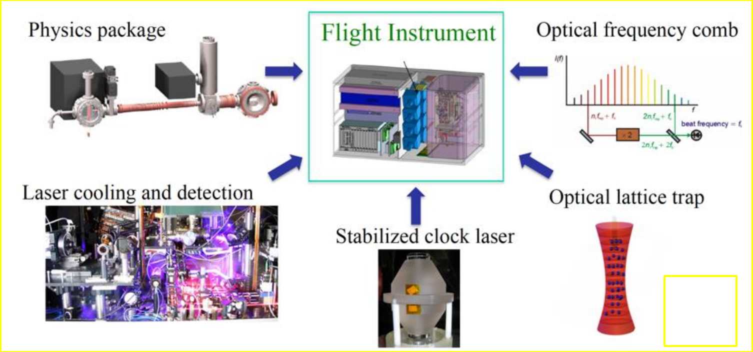
Currently Available

- Planned operation through 2027
- On-orbit upgrades for new research and tech demonstrations

Einstein Elevator HITec (Hannover)

- 40m tower
- 4 second free-fall
- Accommodate EXPRESS rack size payloads





- Demonstrate **technologies** for space (mesoscopic traps, optical transport, ...)
- Develop **techniques** enabled in micro-g (cooling, transport, detection, …)

Proposed BPS Technology Needs and Platforms towards PFaST

Currently Available

CAL

- Planned operation through 2027
- On-orbit upgrades for new research and tech demonstrations

Einstein Elevator

HITec (Hannover)

- 40m tower
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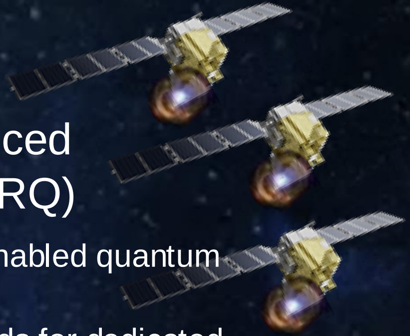
Near-term Opportunities



Space Platform for Advanced Quantum Research (SPARQ)

- Standardized platform for space-enabled quantum research and technologies
- PI-developed and operated payloads for dedicated science campaigns and technology maturations

ISS and Commercial LEO Destinations

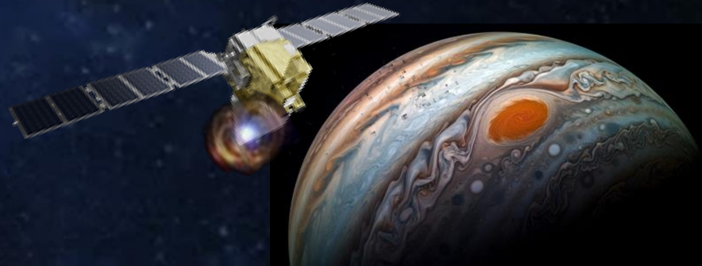
- Bose Einstein Condensate Cold Atom Lab - Joint NASA/DLR
- Opportunity for space optical clock pathfinder
- Opportunity for atom interferometer EEP test < 10^{-12} level and pathfinder for future tests.

Technology needs and platforms

- Concept in development - Space Platform for Advanced Quantum Research (SPARQ)
  - Standardized platform for general space-based quantum science/sensing including power, cooling, communications, telemetry, basic magnetic and EMI shielding, propulsion, position control, etc.

  - PI-developed and operated payloads for dedicated science campaigns using atom interferometers, optical clocks, quantum entanglement, and quantum gases

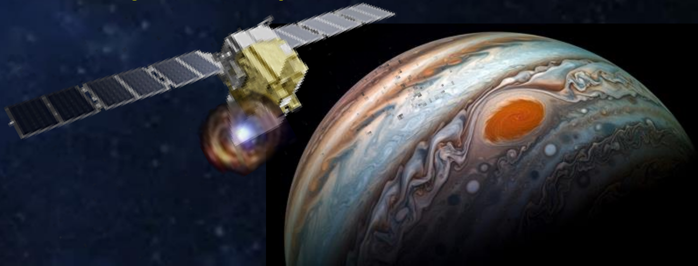
  - Serves as a technology demonstrator to address KSQ11 and enable the PFaST concept
    - In the relevant environment of quantum sensor networks
    - Incrementally mature the hardware needed for the various quantum sensors in space including
      - Lasers
      - Current drivers
      - Control systems
      - Atom sources
      - Autonomous control
      - Entangled photons
      - Single-photon detectors
      - Optical cavities
      - Optical time transfer
      - Free-space quantum optics
      - In situ calibrations
      - Systematics mitigations
      - Optical frequency combs



Space Platform for Advanced Quantum Research

Technology maturation, pathfinder experiments, and science opportunities:

- Space – Earth time transfer (PFaST)
- Space – Space time transfer (PFaST)
- High Finesse Optical cavities testing Lorentz invariance in space (Community Driven)
- Optical atomic clock test of gravitational redshift (PFaST)
- Atom interferometer test of Einstein's Equivalence Principle (PFaST)
- Cavity-based atom interferometer to test for quantized gravity (PFaST)
- Ultracold-atom-based tests of quantum mechanics (Community Driven)
- Quantum gases in curved space (Community Driven)
- Simulation of Hawking radiation with quantum gases (Community Driven)
- Ultracold-atom-based tests of Planck-scale physics and quantum gravity (Community Driven)
- …



The CAL Team

Matteo Sbroscia

Christian Schneider

Sofia Botsi

JPL: Kamal Oudrhiri (Project Manager), **Rob Thompson** (Program Scientist), **Jason Williams** (Project Scientist), **David Aveline** (Science Module build and Ground Test Bed Lead), **Ethan Elliott** (Engineering Model Test Bed Lead), **Kelly Perry (**Instrument Operations Team Lead**), Irena LI, and Shahram Javidnia** (Mission Operations Systems Leads), **James Kellogg** (Launch Vehicle and ISS Integration Lead), **James Kohel** (Flight Hardware Lead), **Norman Lay** (Communications Architectures & Research Section Manager)

CAL PIs: Eric Cornell (JILA, NIST, UC Boulder) & **Peter Engels** (Washington State U.), **Nichols Bigelow** (U. Rochester), **Cass Sackett** (U. Virginia), **Nathan Lundblad** (Bates), **Jason Williams** (JPL)

Acknowledgement

The Cold Atom Lab (CAL) was designed, built, and currently managed by the Jet Propulsion Laboratory. CAL is sponsored by Biological and Physical Sciences (BPS) division of NASA's Science Mission Directorate at the agency's headquarters in Washington and the International Space Station Program at NASA's Johnson Space Center in Houston.

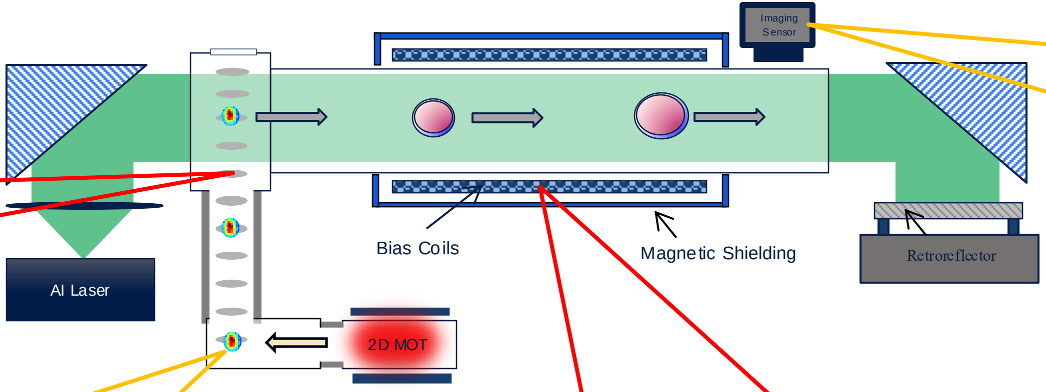
Backup

CAL is serving to provide maturation capabilities for space-based quantum technologies needed to address key scientific questions from the Decadal Survey:

Atom Interferometer

2) Atom Transport via Optical Tractor beam

- Transport of single- and dual-species gases cooled to picokelvin temperature scales



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- **Long-time interrogation (10s of seconds in extended free-fall)**
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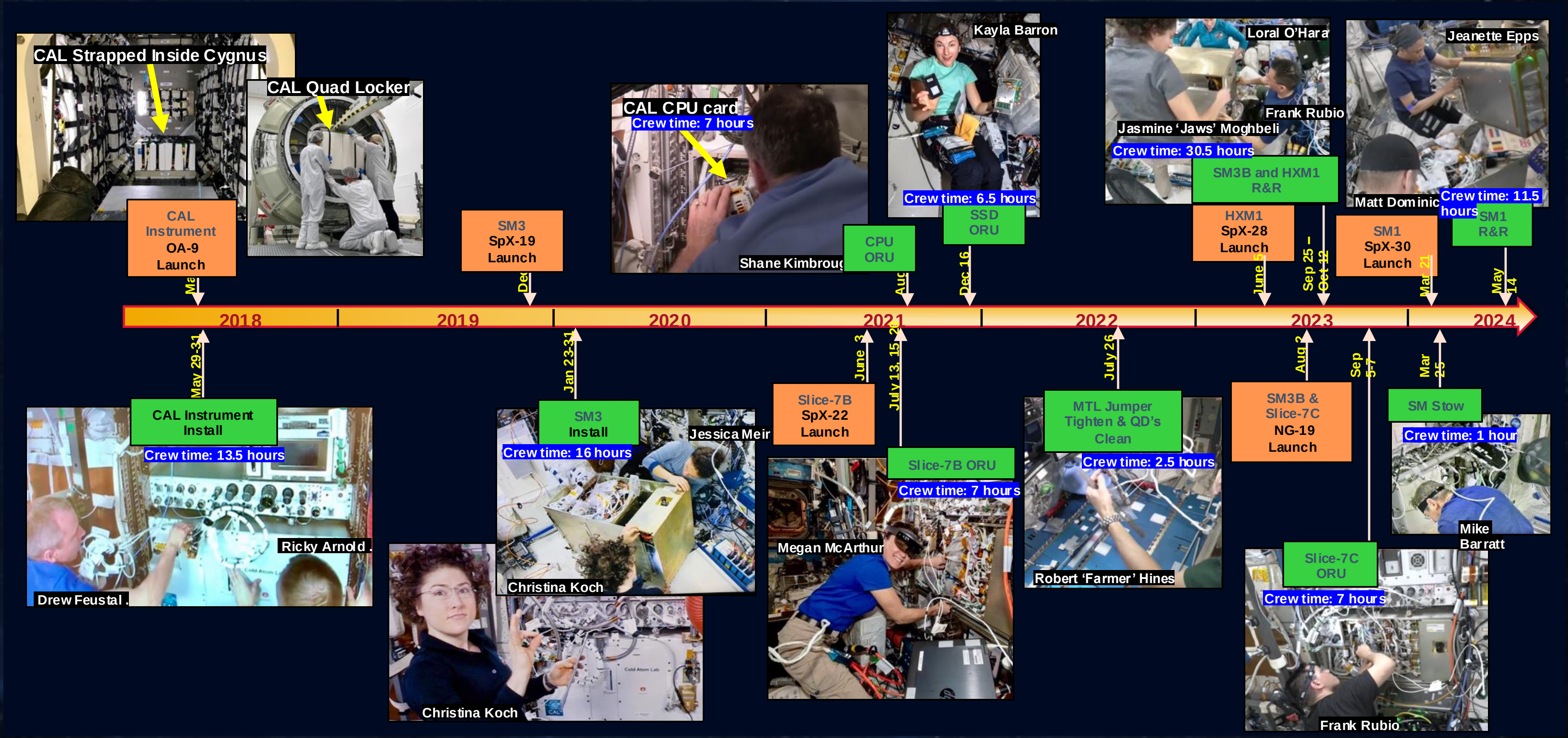
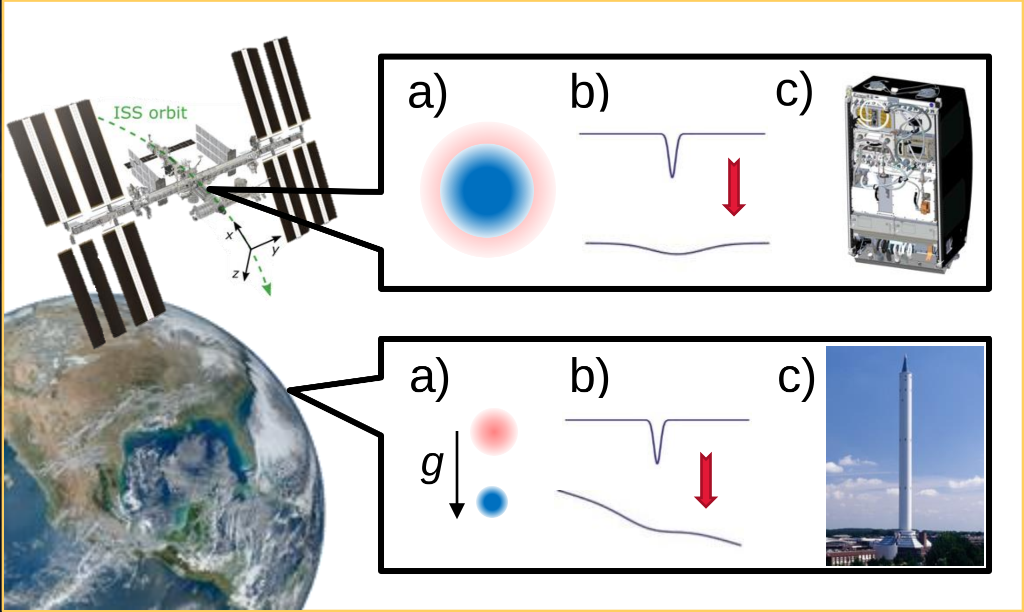
CAL Integration Activities Timeline



Cold Atoms in Space

Jet Propulsion Laboratory
California Institute of Technology



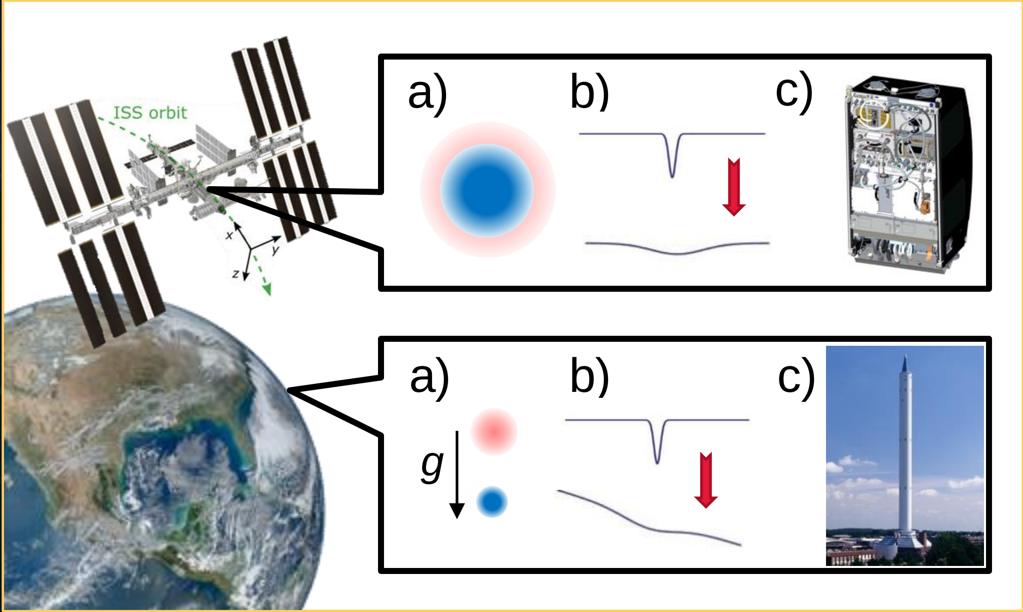
a) Absence of gravitational sag allows for overlap of multiple co-trapped atomic species at ultra-low temperatures

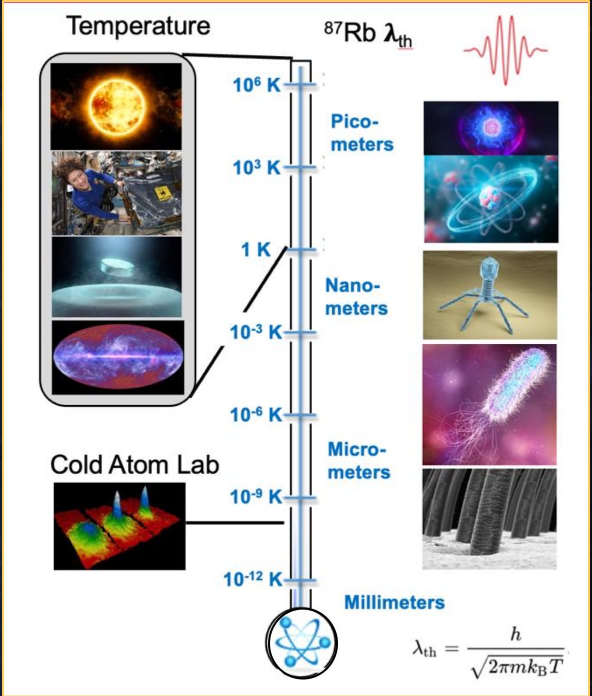
b) Microgravity enables novel trapping geometries (e.g. shell potentials for BECs) and extreme cooling protocols

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

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

Cold Atoms in Space



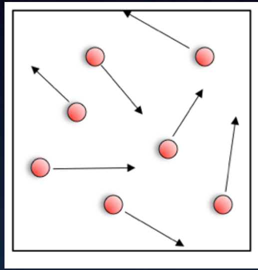


Additionally, space offers access to orbits with variable gravity, earth and planetary sciences, and environments inaccessible to quantum sensors in terrestrial labs.

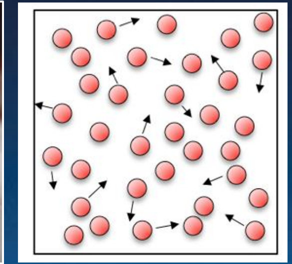
Pursuit of the Cool

Jet Propulsion Laboratory
California Institute of Technology

Classical ⟷ Quantum



Hot gas
- Fast particles
- Less dense

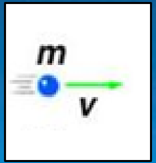


Cold gas
- Slow particles
- More dense

For an ideal gas

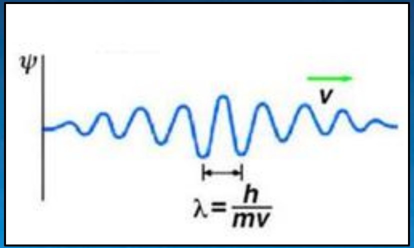
$$Temp \sim mass * speed^2$$

$$Temp \sim Pressure * Volume$$



Louis de Broglie

$$\lambda = \frac{Planck\ Constant}{mass * speed}$$



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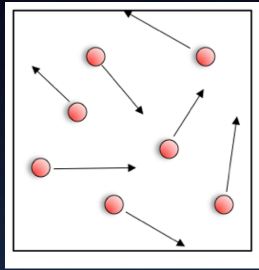

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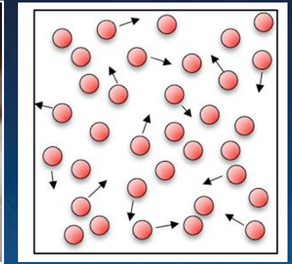

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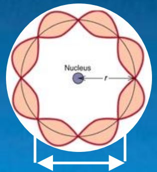
Electrons



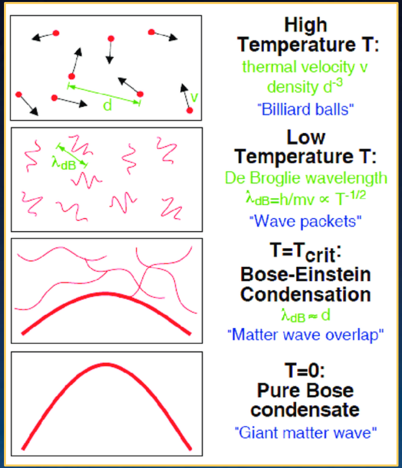
$\lambda \sim 10^{-10} m$

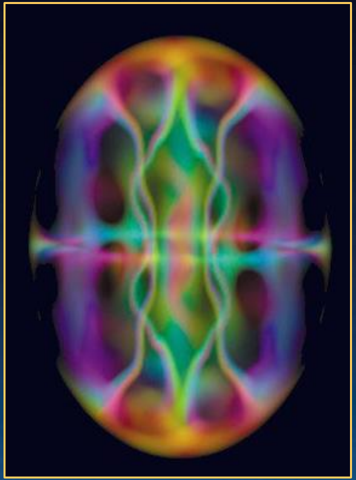
Earth

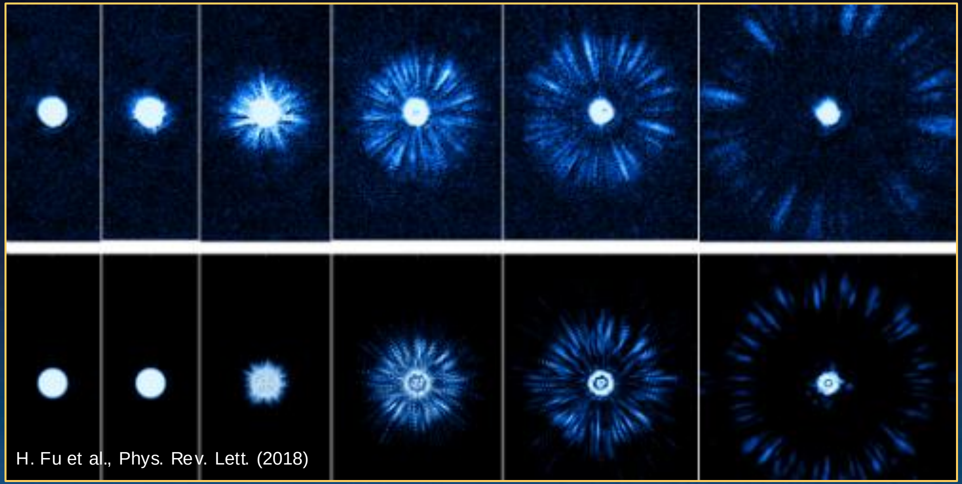
$\lambda \sim 10^{-65} m$

Implications of the quantum nature of matter

New States of Matter







Bose-Einstein Condensate (BEC)

Collapse of a BEC in a "Bosenova" event

In addition to Solids, Liquids, Gases, and Plasmas, a fifth state of matter can emerge for *Bosons* at ultra-low temperature = BEC, in which all particles occupy a single macroscopic wavefunction.

Quantum Technologies

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
- Condensed matter
- Nuclear matter
- Cosmological phenomena

Fundamental Physics

- Is Einstein's GR always correct?
- Are the Fundamental Constants actually constant?
- What is Dark Matter?
- What is Dark Energy?
- Gravity wave characterizations

Planetary Science & PNT

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

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