New physics with space-based experiments : opportunities and challenges

NASEM CBPSS September Meeting 2025

Nathan Lundblad (Bates College)

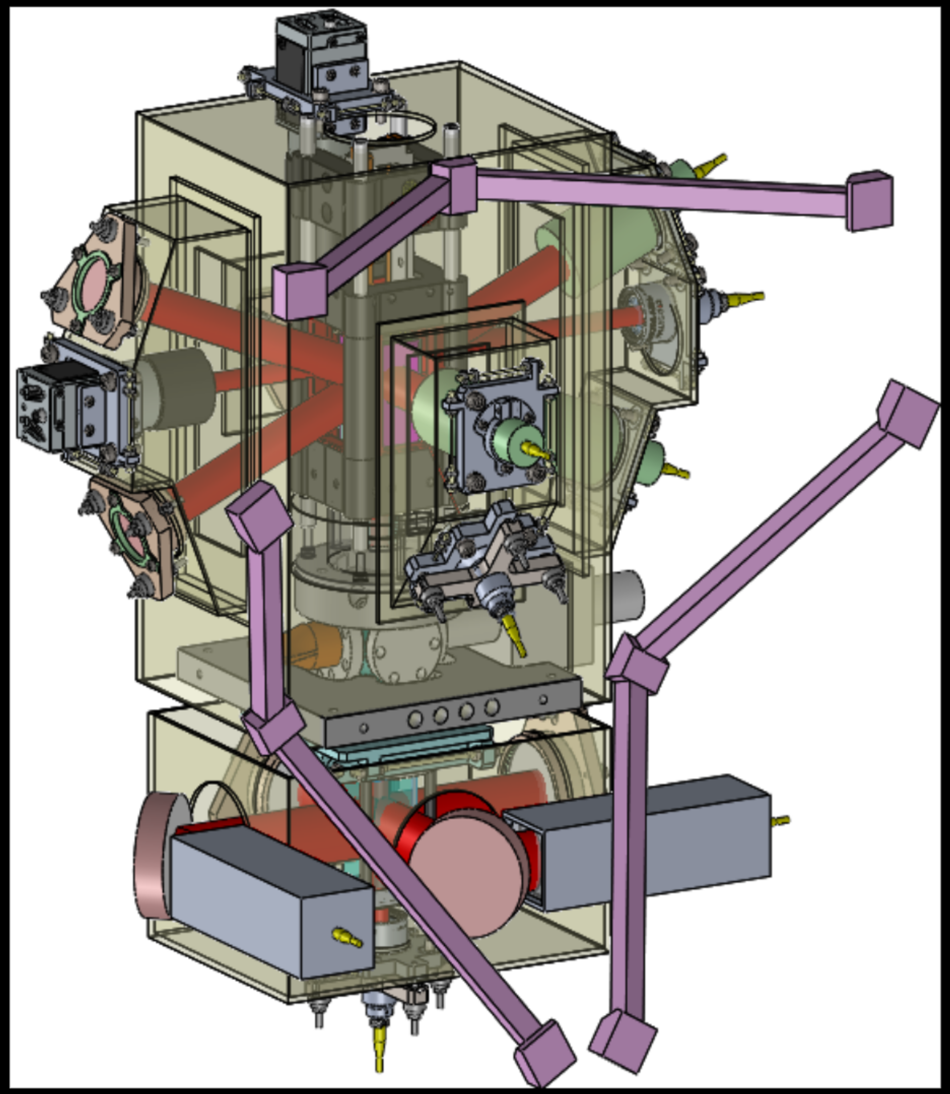
KSQ 11

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

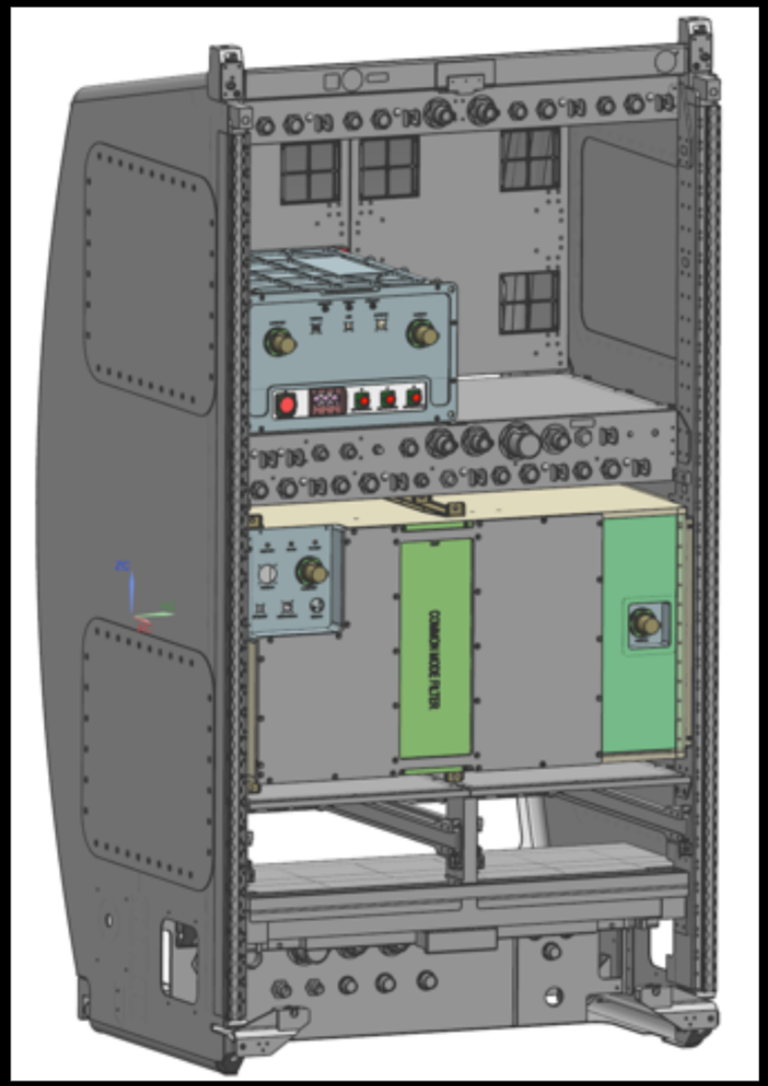
BPS Quantum Leap ideas:

- Cold atoms & atom interferometers
- Quantum entanglement
- Deep-space laser ranging
- Precision clocks

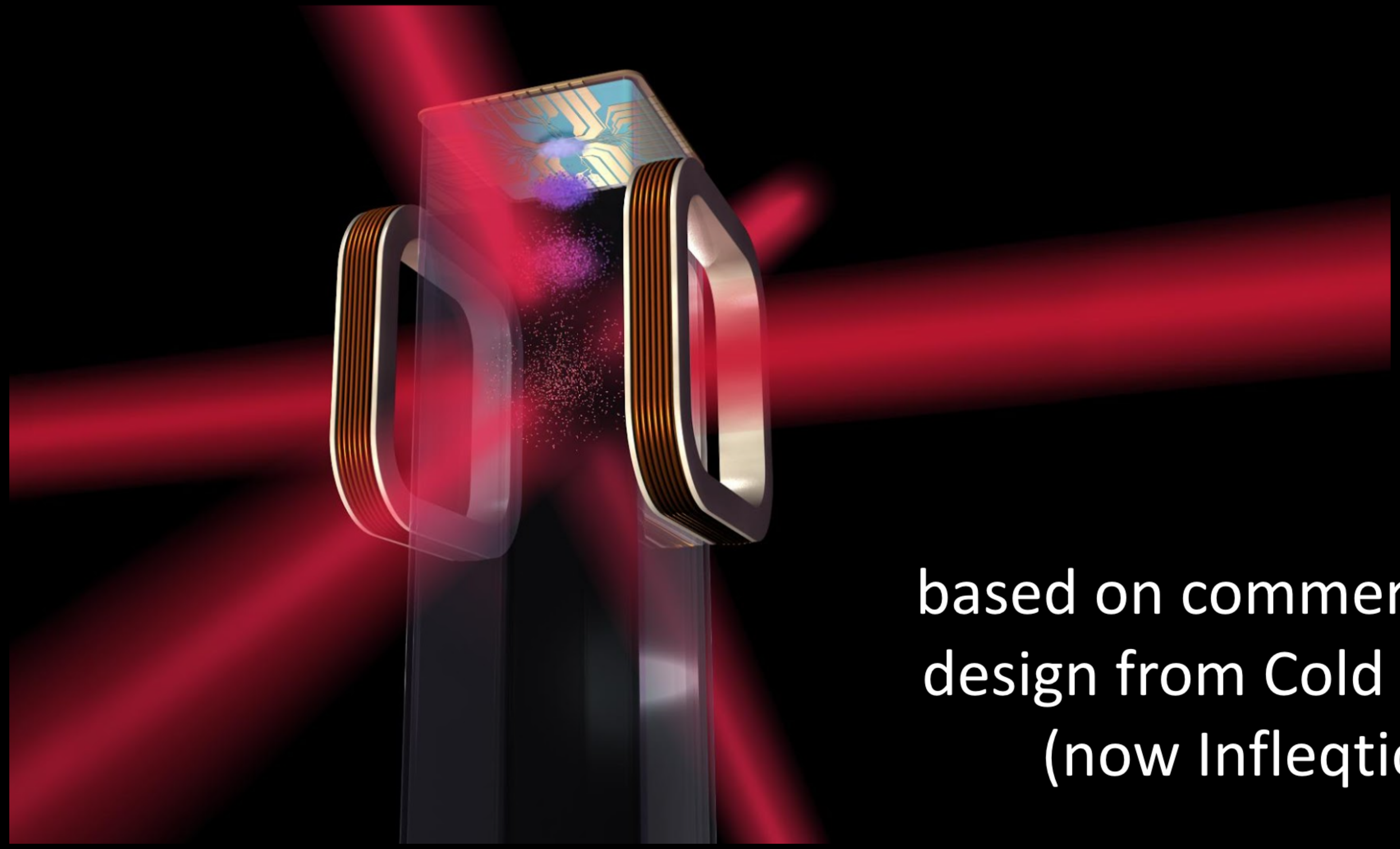
Key context (KSQ11 via cold atoms)



Cold Atom Laboratory on ISS



Nature **582,** 193 (2020)



optics: ruggedized versions of commercial external-cavity diode lasers

based on commercialized design from Cold Quanta (now Infleqtion)

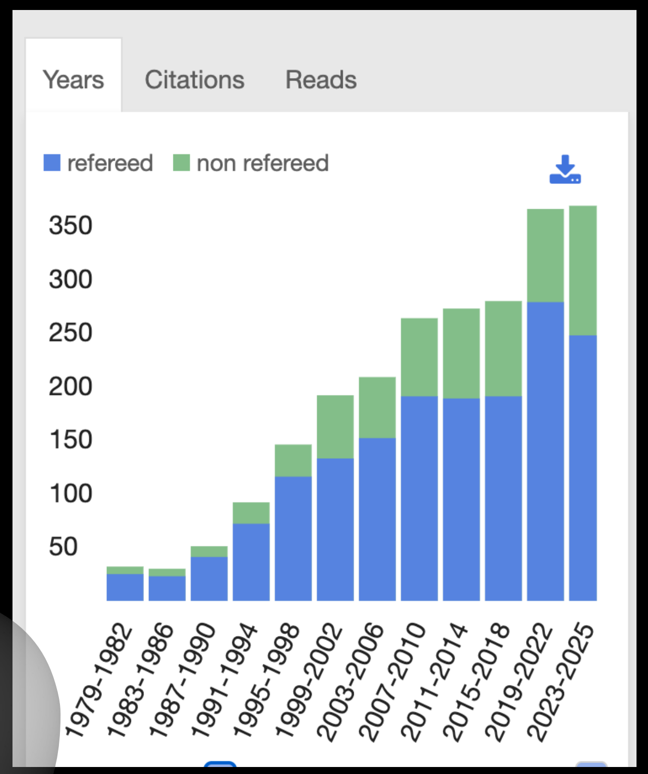
Cristina Koch fiddling with CAL

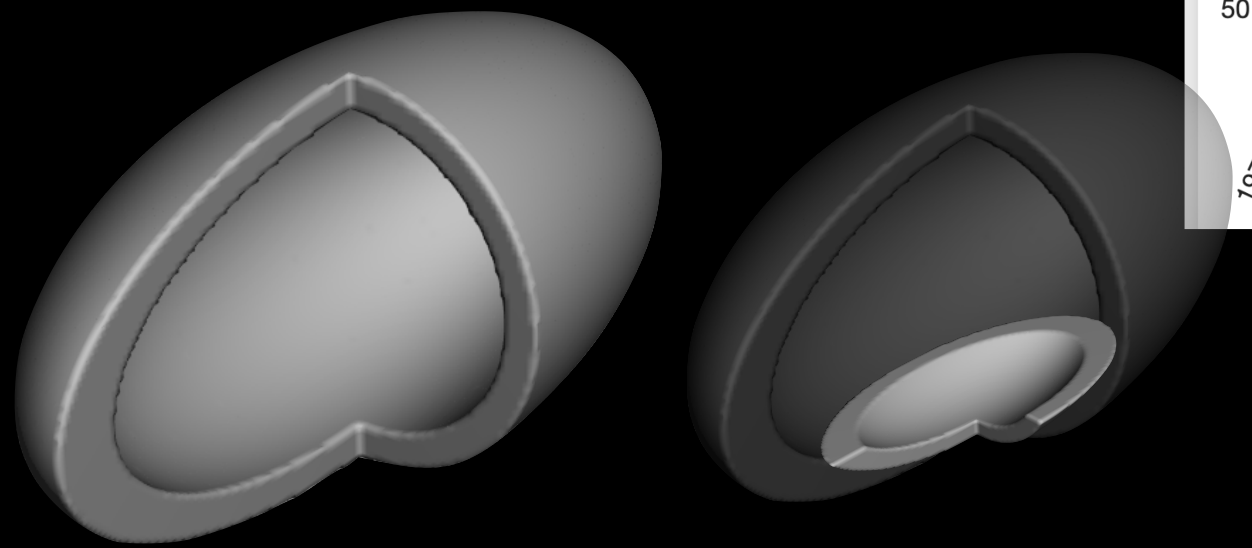
Key context (KSQ11 via cold atoms)

- NASA CAL aboard ISS: “Microgravity Dynamics of Bubble-Geometry Bose-Einstein Condensates”

- quantum physics with open questions, terrestrially inaccessible

- ADS “quantum bubble” topic:





Article

Observation of ultracold atomic bubbles in orbital microgravity

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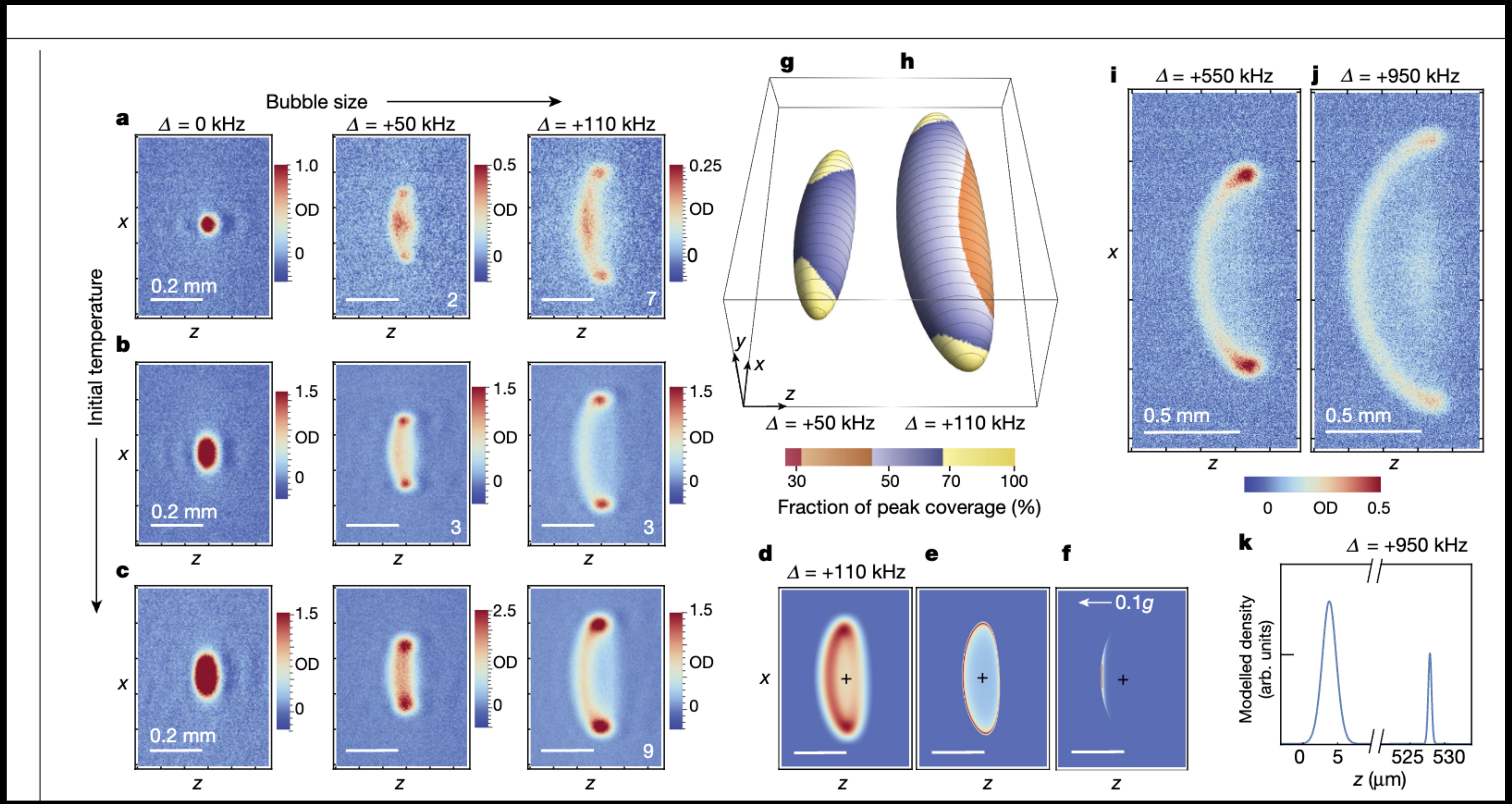
Ongoing ROSES22 “Microgravity Dynamics of Bubble-Geometry Bose-Einstein Condensates”



- Fundamental quantum many-body / topological physics with matter-waves confined to curved manifold (dynamically variable!)

Key context (KSQ11 via atom interferometry)

Article

Quantum gas mixtures and dual-species atom interferometry in space

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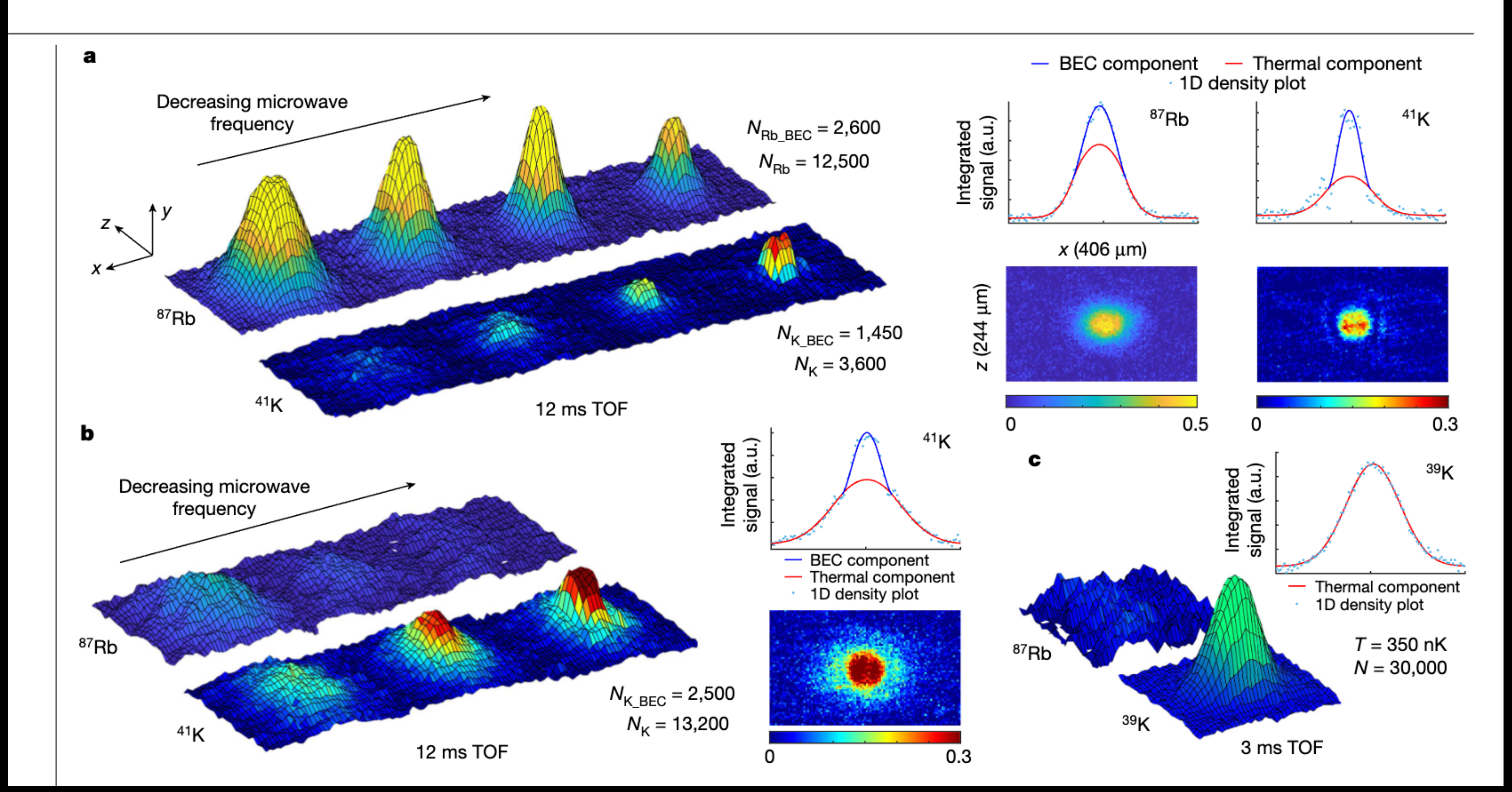

A space-based quantum gas laboratory at picokelvin energy scales

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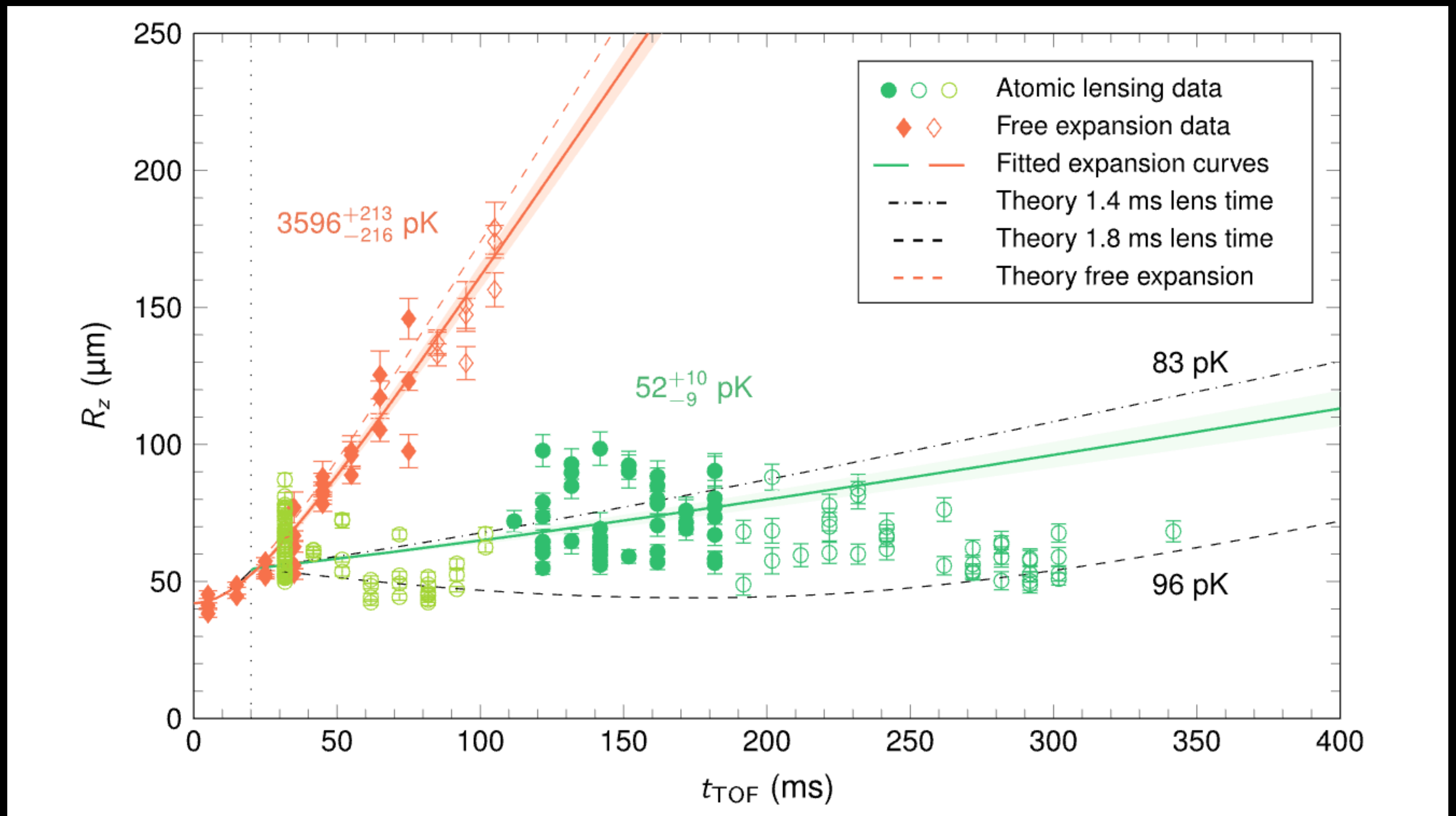
Check for updates

Naceur Gaaloul[1,12], Matthias Meister[2,12], Robin Corgier[1,3,11], Annie Pichery[1,3], Patrick Boegel[4], Waldemar Herr[5], Holger Ahlers[1,5], Eric Charron[3], Jason R. Williams[6], Robert J. Thompson[6], Wolfgang P. Schleich[2,4,7,8,9], Ernst M. Rasel[1] & Nicholas P. Bigelow[10]



- Ongoing work aboard CAL
- Fundamental physics looking at Einstein Equivalence, but also technology development for precision measurement of gravity, rotation, new physics…
- *"Very low energy scales in physical systems enable quantum physicists to explore new states of matter, observe phase transitions and accurately measure fundamental physical quantities."*

Key context (new physics in general)

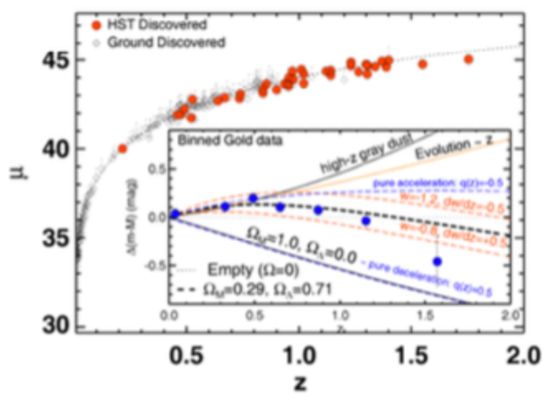
- Fundamental ideas in physics are testable with precision clocks (quantum sensors in general)

Fundamental Physics

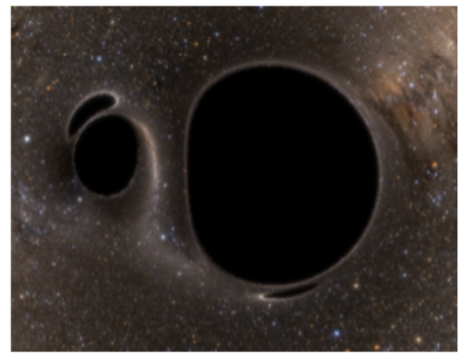
The Ingredients

Matter?

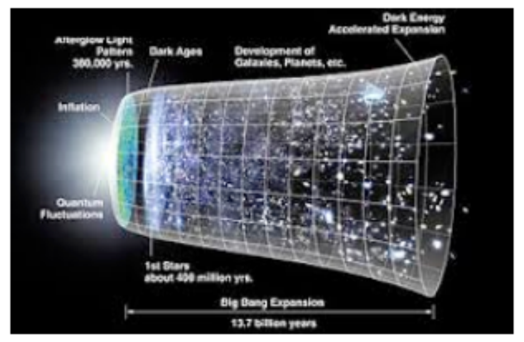
Dark Matter



Dark Energy

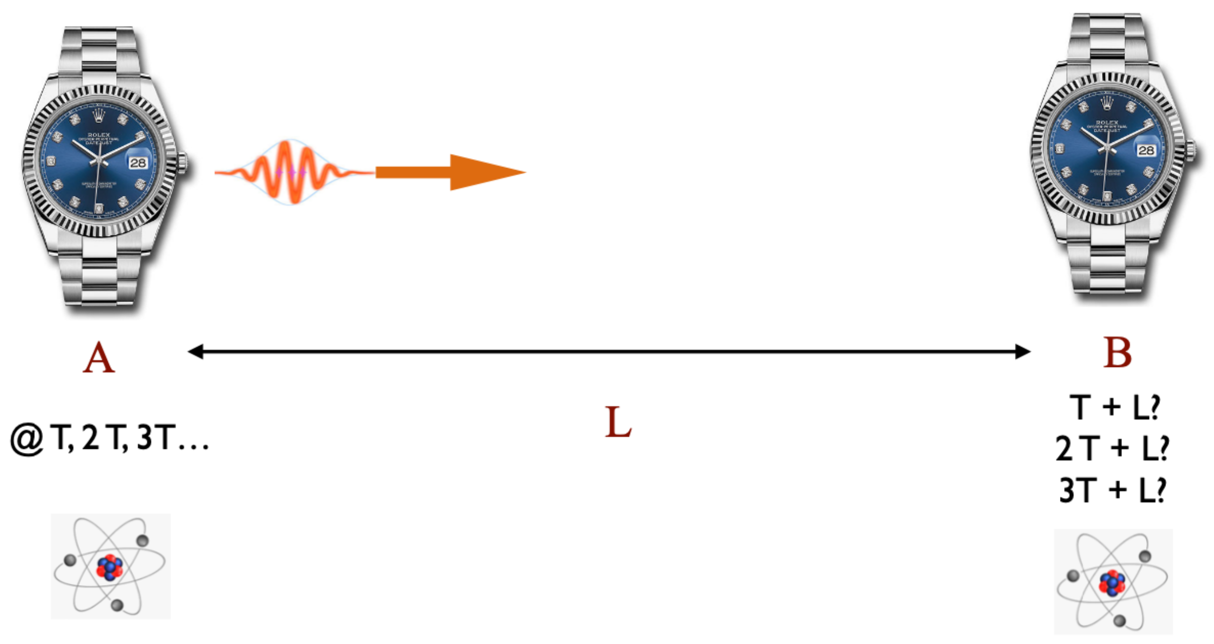


Black Holes



Big Bang

Clock Comparison



Differential Acceleration over Baseline

Gravitational waves

Dark matter

Modern research methods in atomic, molecular and optical (AMO) physics laboratories allow unprecedented access to quantum mechanical phenomena

- Low temperatures
- Slow gas particles
- Long coherence times
- Programmable entanglement
- Encoded quantum information

ALL OF THESE ARE BUILDING BLOCKS FOR PRECISION TIME / FORCE MEASUREMENT

Opportunities and challenges (BECCAL)

Quantum gas research in space
High-priority science applications and microgravity justifications

1. Atom interferometry
   - Unlimited time in free-fall & stationary near objects; greater sensitivity
2. Coherent atom optics
   - Monochromatic matter waves and constant (even very small) velocity
3. Scalar Bose-Einstein gases
   - No gravity to distort trapping potentials
4. Spinor Bose-Einstein gases and gas mixtures
   - Gravity eliminated for all elements/isotopes/states; 3D & box traps.
5. Strongly interacting gases and molecules
   - Access extremely low densities and homogeneous gases
6. Quantum information
   - Target of opportunity in "quantum space race"

BECCAL Science Definition Team
GER-SDT: Dennis Becker, Markus Krutzik, Ersnt Rasel, Wolfgang Schleich (Chair)
US-SDT: Nathan Lundblad, Holger Müller, Dan Stamper-Kurn (Chair), Ben Stuhl

Sunsetting / changes

- CAL is preparing for final round of hardware upgrades and extended science campaigns through next ~2 years
- General results are a set of understood capabilities and continued progress in space-based ultracold atomic physic capabilities, as well as key results across multiple PI groups
- BECCAL launching ~2027+ to push beyond limits of CAL
- Post-ISS need for microgravity quantum-science capabilities
- **Terrestrial drop-tower (Einstein Elevator) is a key partner in advancing this science**
- CAL/BECCAL hardware is capable of significant discovery science focused on the pristine microgravity environment of ISS; likely in the area of quantum on curved manifolds, quantum sensing in space, and ultimate temperature-limit / tests of quantum-physics work.
- New hardware is needed to explore the dark-matter / dark energy conundrum

Opportunities and challenges (beyond)

1. PFAST approach (decadal)
2. DSQL (deep space quantum link, other panelist)
3. Q-SPACE : LEO atom interferometer?
4. QGG instrument?
5. general free flyer
6. LEO / CLD

Other ideas likely in conception stage!

Can we leverage the high-quality vacuum of wake-shielded LEO or even lunar surface/orbit to do interesting open-question physics?

Can we balance the non-astronaut-maintained nature of CLD/LEO with the simpler logistics of a small multi-user / swap-in philosophy?

What will the role and effect of the Chinese space station and their planned/ongoing ultracold atomic physics / quantum experiments be?

Check for updates

The deep space quantum link: prospective fundamental physics experiments using long-baseline quantum optics

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Abstract

The National Aeronautics and Space Administration's Deep Space Quantum Link mission concept enables a unique set of science experiments by establishing robust quantum optical links across extremely long baselines. Potential mission configurations include establishing a quantum link between the Lunar Gateway moon-orbiting space station and nodes on or near the Earth. This publication summarizes the principal experimental goals of the Deep Space Quantum Link. These goals, identified through a multi-year design study conducted by the authors, include long-range teleportation, tests of gravitational coupling to quantum states, and advanced tests of quantum nonlocality.

Keywords: Quantum optics; Foundational quantum mechanics; General relativity

Quantum gravity gradiometry for future mass change science

Ben Stray[1], Xavier Bosch-Lluis[1], Robert Thompson[1], Clayton Okino[1], Nan Yu[1], Norman Lay[1], Brian Muirhead[1], Jason Hyon[1], Holly Leopardi[2], Peter Brereton[2], Anand Mylapore[2], Bryant Loomis[2], Scott Luthcke[2], Parminder Ghuman[2], Srinivas Bettadpur[3], Maike Diana Lachmann[4], Thomas Stolz[4], Christopher Kuehl[4], Dennis Weise[7], Holger Ahlers[5], Christian Schubert[5], Ahmad Bawamia[6] and Sheng-wey Chiow[1*]

Opportunities and challenges (FUNPAG)

Fundamental Physics Analysis Group :

“…To realize such a research campaign to discover new physics, the community urges NASA to establish a broad-based, ground R&D program to develop space-ready key quantum technologies such as atomic clocks, atom interferometers, quantum optics capabilities, and other AMO-based quantum sensors.

Such development of space-qualified quantum sensors cannot be supported by any other agency. Funding is necessary for proof-of-concept experiments that integrate individual technological components into a single experimental apparatus necessary for the science goal.

Strong NASA support for the development of quantum technologies in space will engage the strong US AMO community toward this goal and to succeed in the global quantum space race.”

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- David Aveline + Matteo Sbroscia (JPL)

CAL science

- Nick Bigelow (Rochester) + Naceur Gaaloul (Hannover)
- Cass Sackett (UVA), Maren Mossman (USD), Peter Engels (UW), Jose D’Incao (UMB)
- CAL team at JPL (Ethan Elliott, many others)

Contributors to presentation

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