Fundamental Physics Program

Status, Planning, Research Findings, Challenges

Presentation to:

Committee on Biological and Physical Sciences in Space

Sponsoring Org/Office Code:
SLPSRA/HQs, OZ/JSC, OB/JSC
Name of Forum: *National Research Council*
Date: *Nov 1, 2017*

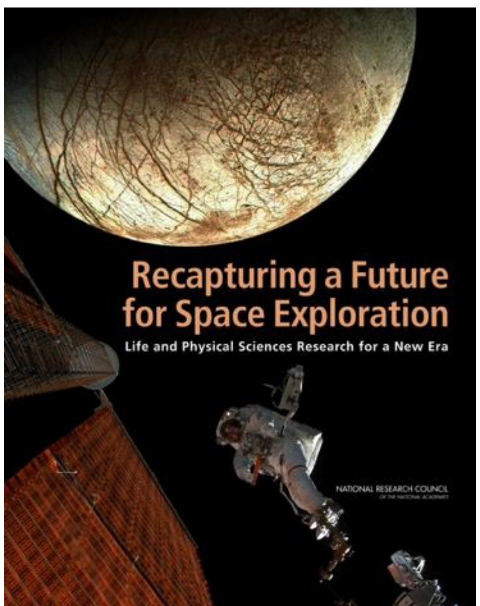
Presenter's Name: *Mark Lee, NASA Headquarters)*

JPL FP/ISS Research Project Overview Status

Element	Cost	Sched	Tech	Mgmt	Comments
	11/1/2017				
Program	G	G	G	G	*BECCAL SDT Selection process completed 4 selections.*
DECLIC ALI	G	G	G	G	***Hahn PI:*** *ALI-R launched Aug 13 on SpaceX12; investigation planned to start in Jan 2018.*
ACES	G	Y	G	G	*ACES LRD deferred to 2019. MWL delivery deferred to mid 2018.* ***Yu PI:*** Micro Wave Link at JPL, data analysis support (JPL) ***Gibble PI:*** *Reduce overall error bars. (Penn State University)* ***Hollberg PI:*** *Improved link to ground. (Stanford University)* ***Oates PI:*** *Micro Wave Link at NIST, data analysis support. (NIST, Boulder)*
SOC	G	G	G	G	***Diddams PI:*** *Micro optical comb support for ESA SOC study. (NIST, Boulder)* ***Oates PI:*** *Yb optical clock support for ESA SOC study. (NIST, Boulder)*
QWEP	G	G	G	G	***Mueller PI:*** *Experiment and theory Support to ESA study.*
PK4 Dusty Plasma (Columbus Module)	G	G	G	G	***Goree PI:*** Nonlinear wave experiments in dusty plasmas (University of Iowa) ***Konopka PI:*** Complex Plasma under Microgravity (Auburn University) ***Liu PI:*** Three-dimensional dusty plasma experiments (University of Iowa) ***Gangoli PI:*** Understanding the Frequency Synchronization Physics in PK-4 Experiment (NRL) *Bellan PI:* Laser Induced Fluorescence Diagnostic for PK4 (Caltech) *Hyde PI:* PK-4: Self-Ordering of Interacting Complex Plasma Particles in Microgravity (Baylor University)
Microscope	G	G	G	G	***Turyshev PI:*** Orbit determination through Laser Ranging from Table Mountain. Starts Sept. 2017.
BECCAL	Y	Y	Y	Y	*BECCAL SDT Selection process completed 4 selections*. SCRR schedule TBR.
CAL	X	X	X	X	Final dash to FHA Dec 11 and launch TBD (Early 2018)

NASA Decadal Review Recommendations

2011 NRC decadal Survey on Microgravity Science in Space: *Recapturing a Future for Space Exploration*

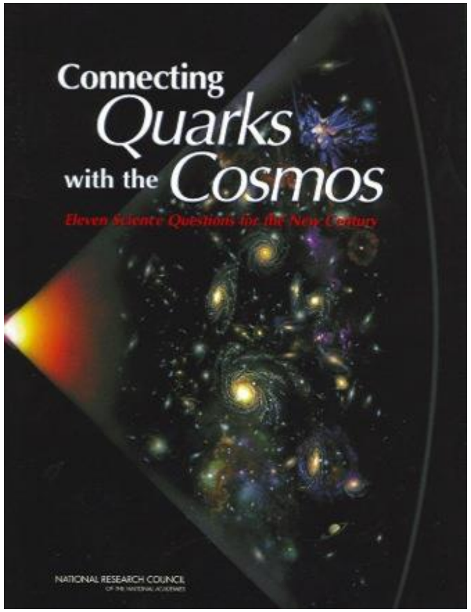


PF2: "Space offers unique conditions to address important questions about the fundamental laws of nature, with sensitivity beyond that of ground-based experiments in many areas."

FP3: "Research related to the Physics and Applications of Quantum Gases. Space Environment enables many investigations, not feasible on earth, of the remarkable unusual properties of quantum gases and degenerate Fermi gases"

ISS Space Laboratory for Fundamental Physics Exploration

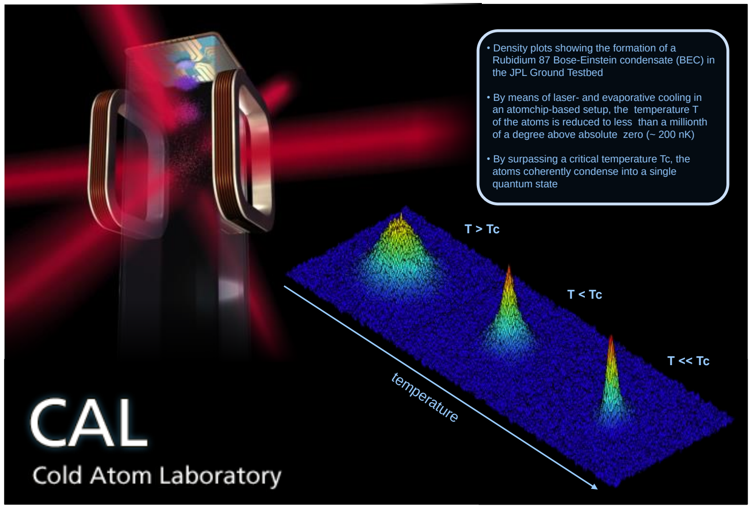
Overall program theme, guided by NCR Decadal Survey, ISS is being utilized as enabling space laboratory for **high precision measurements** to explore matter, space, time, and quantum mechanics.



Precision measurements enabled by ISS platform will help search for answers for some of the 11 important physics questions in the new century (NRC report)

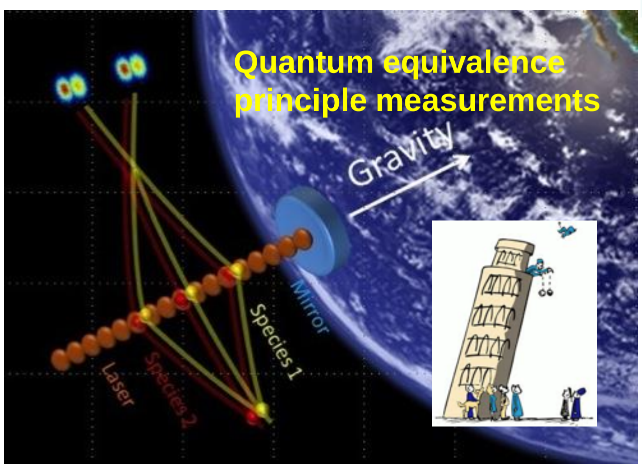
- **What is the dark matter?**
- **What is the nature of the dark energy?**
- **How did the Universe begin?**
- **Did Einstein have the last word on gravity?**
- **What are the masses of neutrinos and how have they shaped the evolution of the Universe?**
- **How do cosmic accelerators work and what are they accelerating?**
- **Are protons unstable?**
- **Are there new states of matter at exceedingly high density and temperature?**
- **Are there additional space time dimensions?**
- **How were the elements from iron to uranium made?**
- **Is a new theory of matter and light needed at the highest energies?**

Precision Measurements Will Showcase the Full Capability and Benefit of ISS Space Laboratory and Microgravity Science



Microgravity –

- Remove “large” gravity force for ultra-cold atoms
- Allow long interaction time with cold free fall atoms for extraordinary precision
- Enable gravity direction reversal for the necessary systematic reduction
- Help producing ultra-cold atom sources
- Confine experimental physical size for manageable environmental control
- Facilitate generation of large macroscopic quantum state



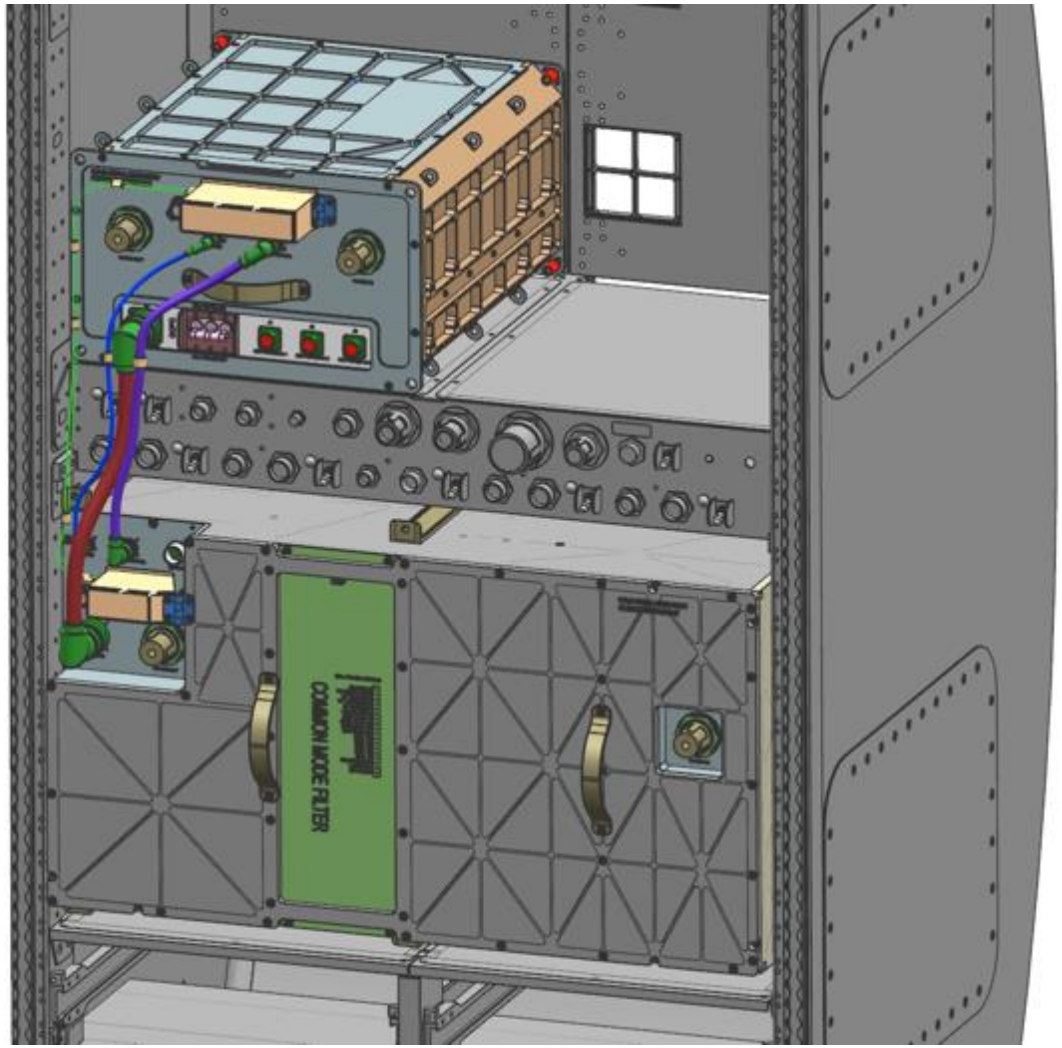
ISS on orbit –

- Large change in gravitational effects
- Velocity and directional changes and modulations
    - Seek a breakdown of fundamental symmetries
    - Search for dark energy and dark matter effects

NASA Cold Atom Laboratory Configuration

Fundamental Physics

Power Electronics
& Rack infrastructure
(5th Locker)



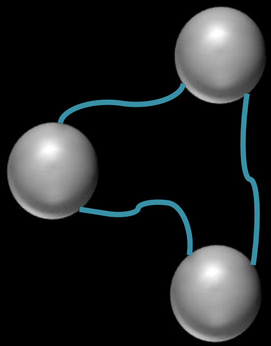
Science Instrument
(Quad Locker)

- Science Module
- Science support functions
- Rack infrastructure

Cooling Cycles

- **Magneto-optical trapping – laser cooling to ~100 microkelvins**
- **2-D magnetic trap created by atom chip**
- **Evaporation cooling with radio frequency knife to eject anti-magnetically polarized atoms from the trap (magnetic insensitive or Zeeman or hyperfine untrapable atom states forming BEC at ~1/10th of microkelvin**
- **Further cooling using adiabatic expansion in weakened or turned-off magnetic trap under microgravity environment**
- **Delta kick cooling by turning off the magnetic trap for specific length of time allowing further adiabatic expansion cooling then pulsing the magnetic trap back on to stop the expansion with no loss of atoms achieving possibly 3 order of magnitude lower temperature to 100 picokelvins**

CAL science: Studies of few-body physics in microgravity



Searching for universal features in the behavior of quantum collisions between a few particles might shed light into how complexity can arise from simple underlying physics

CAL will make precise measurements of so-called Efimov States and explore their universality, yielding new insights into how complexity can emerge from simple underlying physics

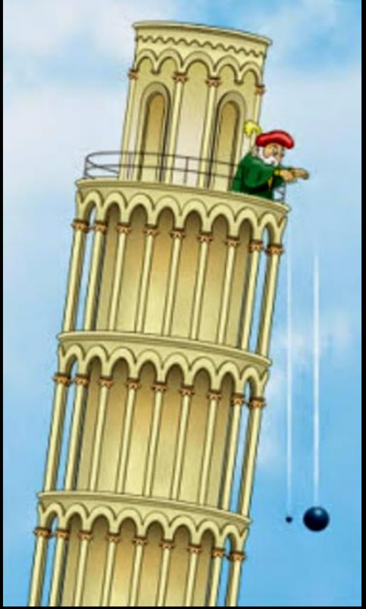
Requirements: Species: K39 (Rb87 used as coolant); 20 weeks on orbit

Eric Cornell, JILA

Peter Engels. WSU

Co-I Debbie Jin, JILA

In Memoriam, 1968-2016

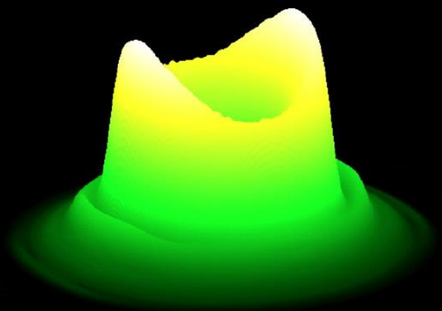


CAL science: Testing Einstein

Will a potassium atom and a rubidium atom fall at precisely the same rate? Once upgraded with AI capability CAL will perform a quantum test of Einstein's Equivalence principle

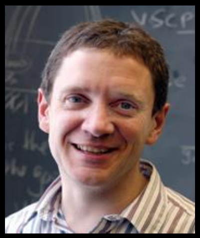
This team will also demonstrate a space based atom laser, a source of coherent matter waves, using the CAL-1 science module

Requirements: Rb-87 for non-AI experiment (Rb +K needed for AI) 15 weeks on orbit for non-AI Experiments



Space Atom Laser

CO-I H. Mueller,
UC Berkeley



Co PI N. Bigelow
U. Rochester

Co PI W. Ketterle
MIT

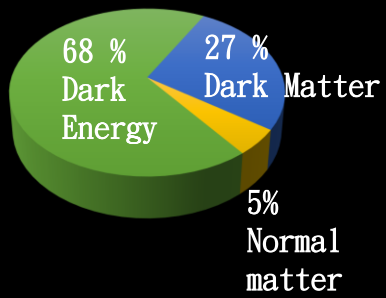
Co-I Bill Phillips
JQI

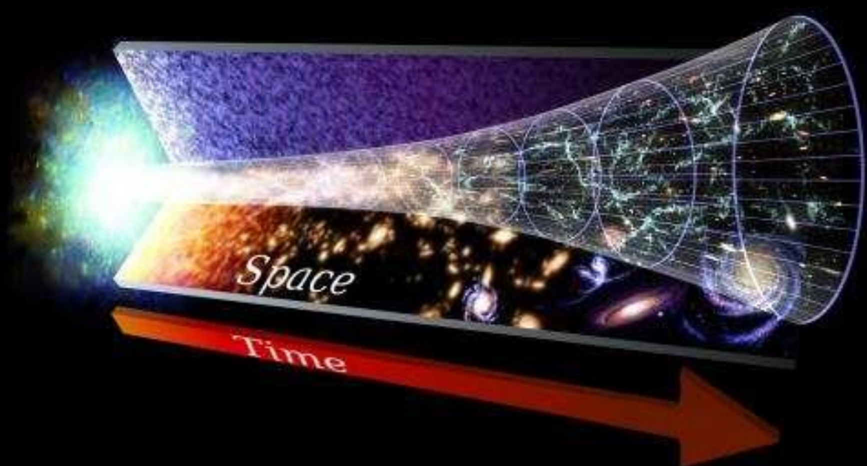
Detection of Dark Energy

Searching for Chameleon forces of dark energy fields

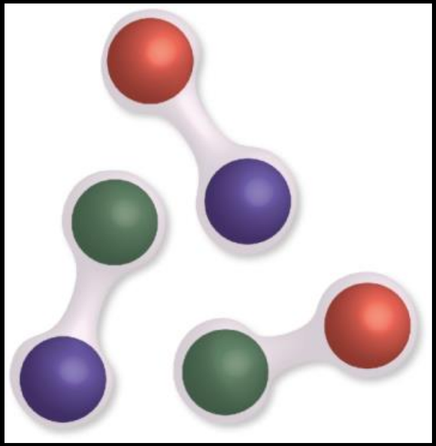
Seek to answer the question "What is the nature of dark energy"

- Chameleon field is one of the promising candidates for dark energy as scaler field
- Environmental screening effort must exist for a dark energy field to be consistent with all observations
- Atomic particles are not screened, providing a great opportunity for detecting Chameleon field
- ISS experiment or on another space platform can detect the dark energy field if exists or rule it out gaining valuable understanding





Quantum Halo Molecules



Quantum Halo molecules are the most weakly bound of any diatomic molecules, and have the largest spatial extent. Their size in facts extends far beyond the range of the classical potential of the atoms

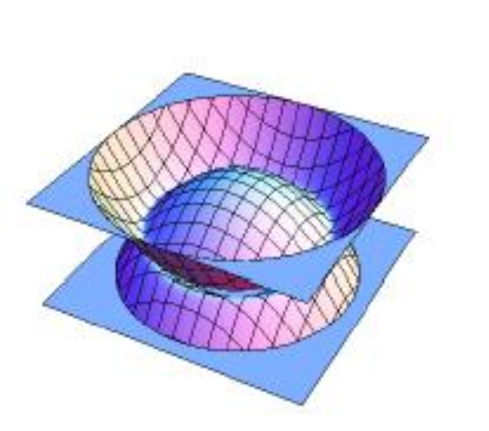
CAL will study the formation of these novel molecules in a new temperature regime and explore their utility for future space based tests of Einstein's equivalence principle

PI also has experiments which require AI

Requirements: Rb-87 and K-41; 4 weeks on orbit for non-AI experiments

PI Jason Williams, JPL

Quantum bubbles

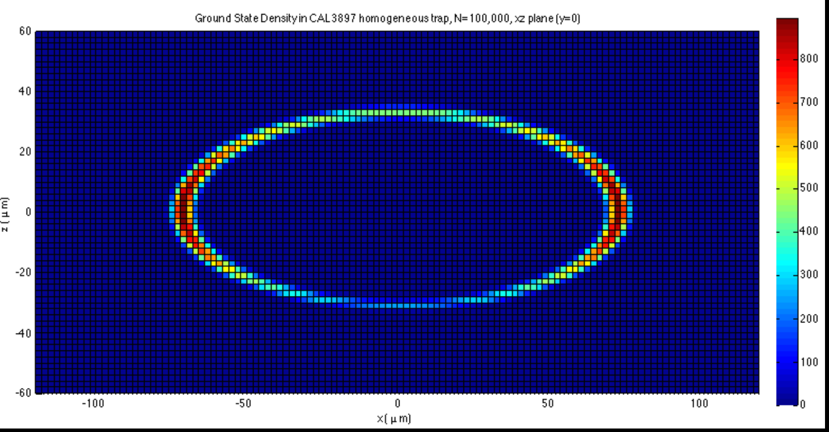


Adiabatic potential for bubble geometry

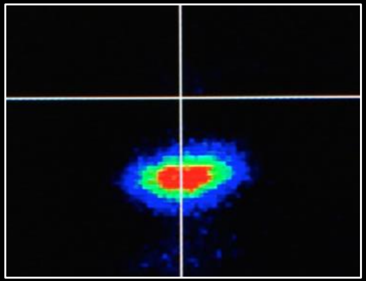
Microgravity allows us to study “bubble” quantum states that can’t be observed on earth

CAL will demonstrate this novel topology and explore features such as excitation spectra and interference effects

Requires: Species Rb-87; 12 weeks of CAL on-orbit time



On orbit, bubble shaped topologies can be demonstrated for the first time



On ground, atoms fall to bottom of potential

PI N. Lundblad
Bates College

Co-I Dave Aveline
JPL

Studies of Adiabatic expansion

CAL will test novel techniques to employ adiabatic expansion to achieve extremely low temperatures in microgravity

In a separate experiment this team will develop a novel cold atom rotation sensor and use it to compare to measured ISS rotations

Requirements: Species Rb 87 and K41 or K-39; 6 weeks on orbit

Adiabatic cooling: let gas expand into very weak trap. As it expands it steadily cools, just as an aerosol can cools as you spray it

PI Cass Sackett, U. Va.

CAL Ground based Research

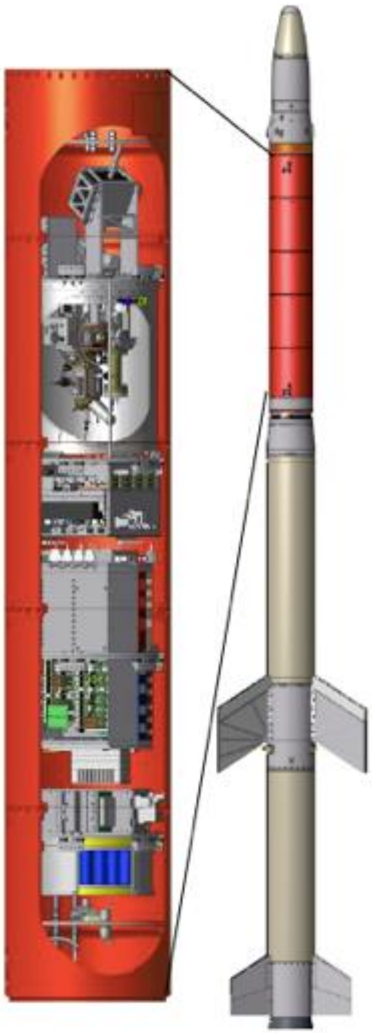
Studies of Magnon Interferometry and Cooling (Dan Stamper-Kern, UC Berkeley): A magnon is a collective excitation of the spin structure of atoms in an optical lattice. This proposal will study how they can be used to make ultra-high precision atom interferometers and to achieve extremely low-entropy states.

This experiment could be performed in an upgraded version of CAL

High Precision Microwave Spectroscopy of Long-Lived Circular-State Rydberg Atoms in Microgravity (Georg Raithel, U. Michigan) This experiment is aimed at precision measurement of fundamental constants such as the Rydberg constant in microgravity. A microgravity version of this experiment could resolve such fundamental questions as the size of the proton, currently a controversial subject in particle physics hinting at physics beyond the standard model

This experiment could be a potential follow-on to CAL

Constraints: MAIUS + CAL = BECCAL

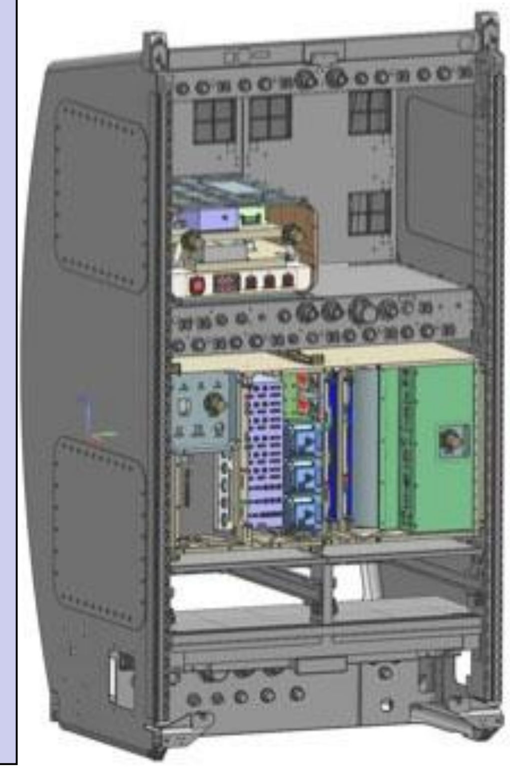


DLR
MAIUS-1
2016-2019

- 315 kg
- 300 W
- 0.55 m^3
  - 0.5 m dia
  - 2.8 m tall
- Limited access to ug

NASA
CAL-1
2017-2020

- 362 kg
- 900 W
- 0.38 m^3
  - 5/8 of Exp Rack
- Limited rack availability



BECCAL

Re-use CAL infrastructure to extent possible

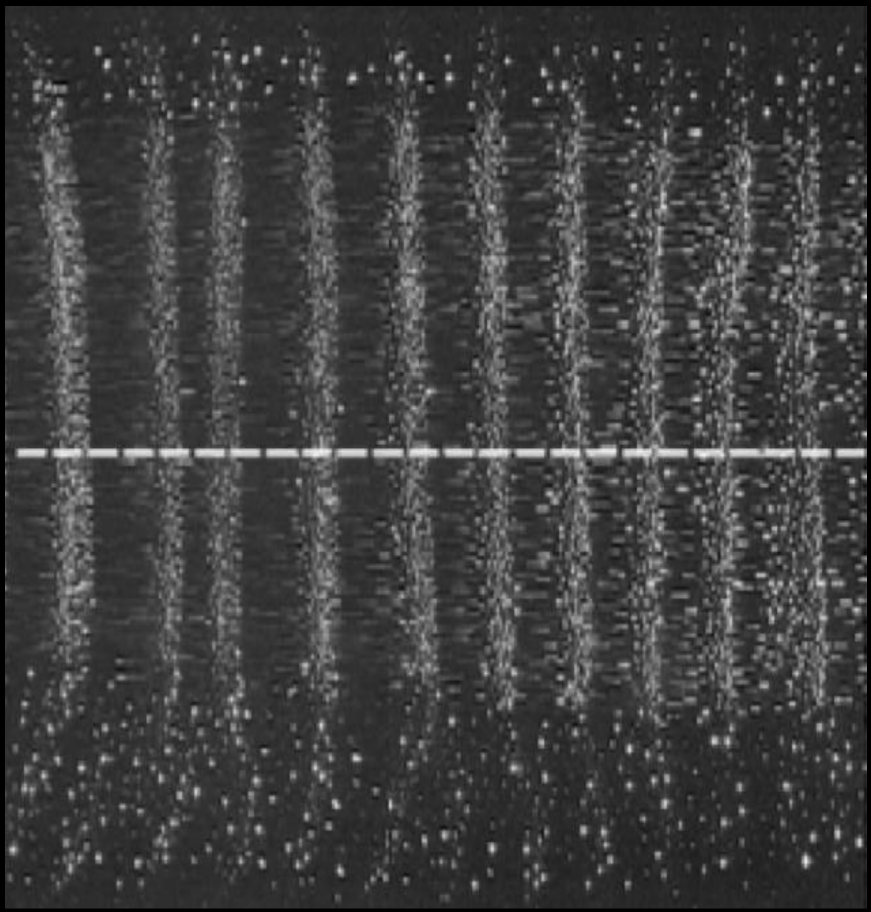
BEC-CAL as CAL Follow-up mission

NASA-DLR bilateral collaborations

Provide an unique space facility for investigation opportunities

- Understanding quantum systems of atom optics, degenerate gases and their mixtures (*new and different capabilities from CAL*)
- Testing the universality of free fall (*More precise measurements than CAL*)
- Methods and phenomena for Bose-Einstein condensation, atomic mixtures, delta-kick collimation and coherent manipulation by light pulses (*Improvements over CAL*)
- Quantum phases (miscibility studies, spinor physics, etc.) in the vicinity of the transition thresholds (*Enhanced from CAL*)
- Few body and many body scaling and behaviors (*Similar to CAL*)
- Atom interferometer demonstration (*improved from CAL*)
- Satellite-based geodetic applications and Earth observation (*New from CAL*)

PK-4: Non-linear Wave Phenomena

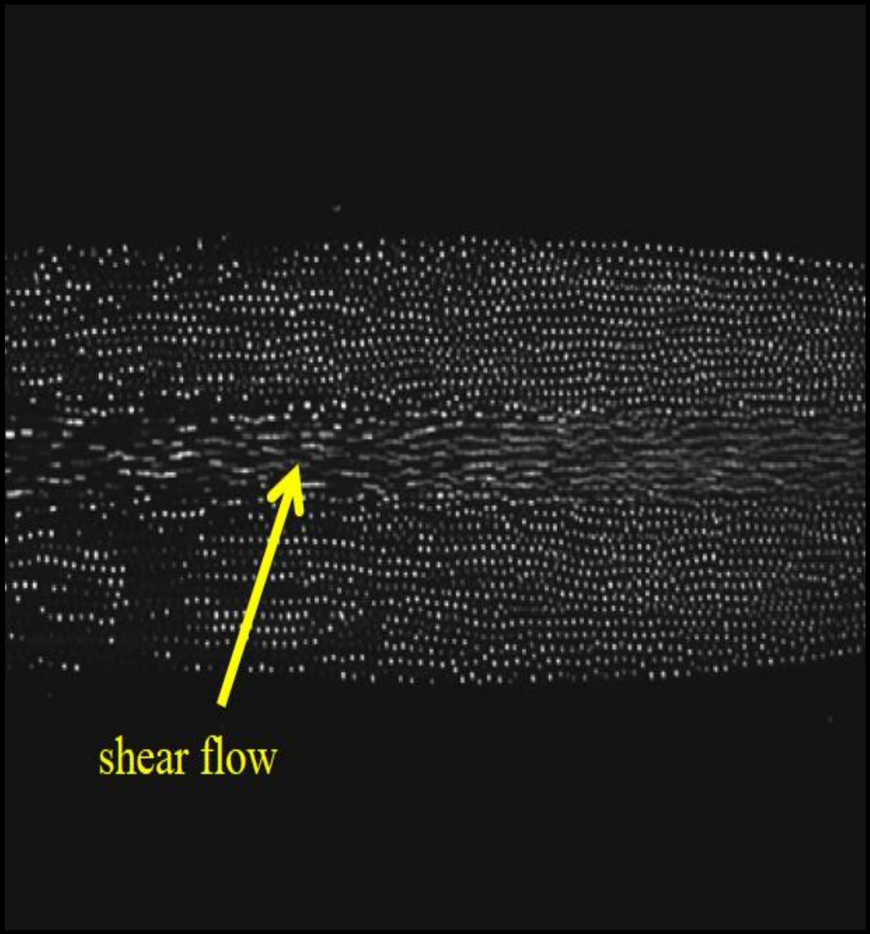


Can we extend the physical understanding of non-linear dust acoustic wave phenomena by modulating the ion density?

A team of scientists will investigate the physics of wave synchronization using dusty plasma. Dust plasmas are suitable for the study because they meet essential requirements, self-excited, nonlinearity, ease of modulation, diagnostics for wave motion.

PI: J. Goree (Univ. of Iowa)
Co-I: B. Liu (Univ. of Iowa)
Co-I: G. Ganguli (NRL)
Co-I: A. Melzer (Univ. Grefswald)

PK-4: Condensed Matter Analog



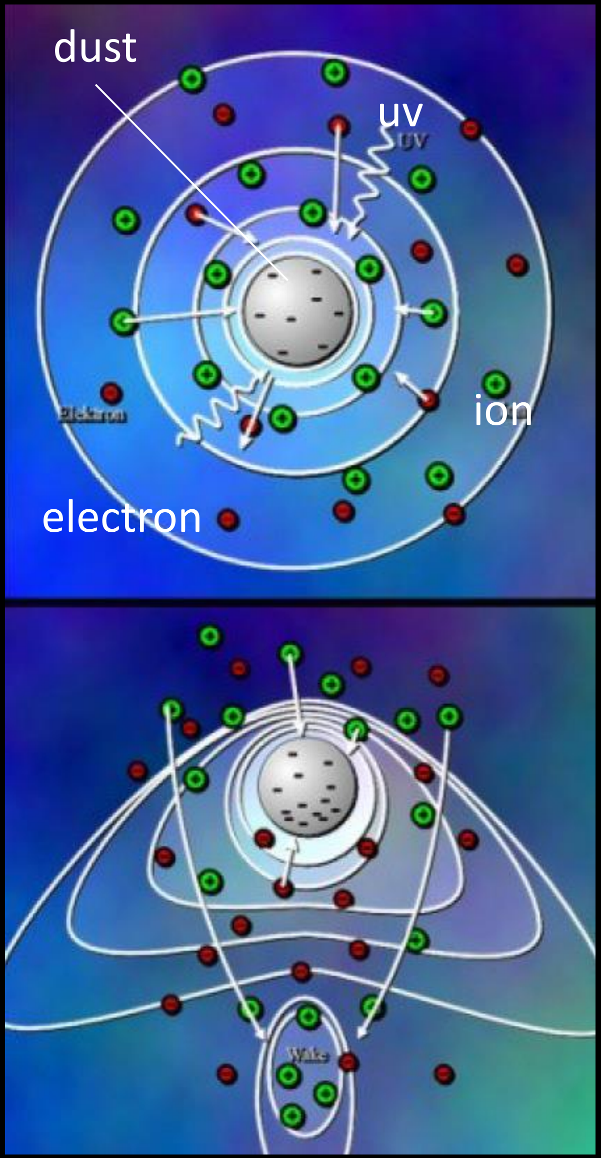
Can we exploit unique properties of dusty plasma to verify the theoretical prediction of viscous heating?

Does a 3D dusty plasma exhibits stick-slip motion during plastic deformation induced by laser shear force?

A team of scientists will investigate he physics of liquids and fluids, soft condensed matter, and non-equilibrium statistical mechanics.

PI: B. Liu(Univ. of Iowa)
Co-I: J. Goree (Univ. of Iowa)

PK-4: Charging, Interactions, Kinetics



Can we determine charges on the dust more accurately?

What is the role of directed ions currents on the particle interaction?

Can we use the dusty plasma to understand a diverse range of physical phenomena, including fluid mechanics, wave properties at the kinetic level

A team of scientists will use PK-4 apparatus to understand the charging, interactions of micro-particles, and kinetics

PI:U. Konopka (Auburn Univ.), Co-I: E. Thomas (Auburn Univ.), Co-I:J. Williams (Wittenberg Univ.)

PK-4: Theory of non-linear wave: Synchronization

Synchronization of non-linear waves are ubiquitous in nature.

Can we theoretically understand the synchronization phenomena of the dust acoustic wave in the PK-4 plasma?

A team of theorists will investigate the properties of non-linear waves.

PI: G. Ganguli (NRL)
Co-I: C. Crabtree (NRL)

DECLIC ALI-R : Scaling, Universality, and RG

Is the scaling hypothesis ultimately valid near the critical point?

Are the Nobel prize winning RG (Renormalization Theory) predictions still valid near extremely close to the critical point?

Are the current classical-to-critical crossover theories valid in the simple fluid systems?

DECLIC ALI-R will make the most precise measurements of light attenuation property of a simple fluid near its liquid-gas critical point, which is not possible on the ground.

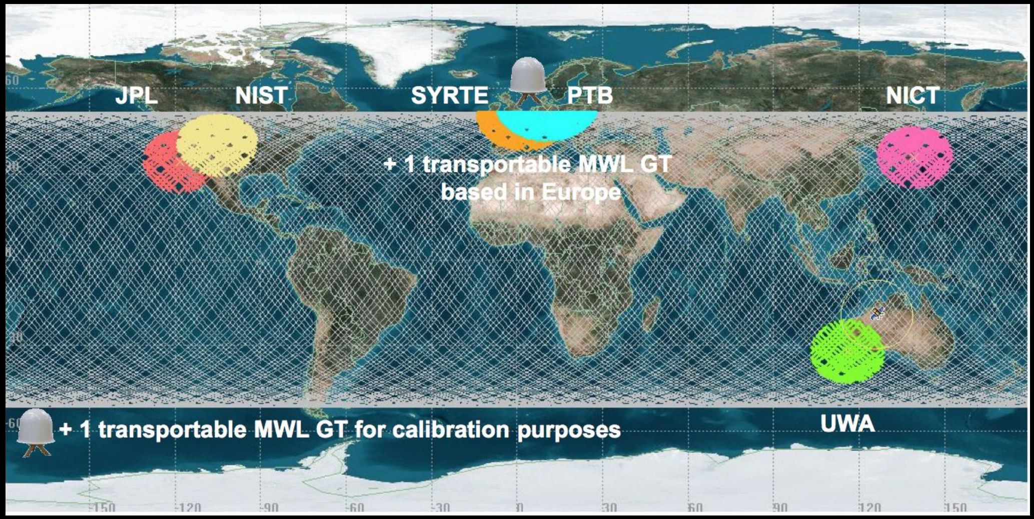
U.S. PI: I. Hahn (JPL, US), CNES PI: Y. Garrabos (Univ. Bordeaux, France)

US Collaboration in the ESA ACES Mission

Atomic Clock Ensemble in Space (ACES) – an ESA ISS Experiment (2019 Launch)

US Participation: ESA deliver two ground stations in US (JPL and NIST) for the overall ACES global clock comparison network.

- **Demonstrate and validate a new generation of cold atom clocks in space**
- **Demonstrate the capability to compare ground clocks on a world-wide basis at high state of the art precisions.**
- **Test fundamental laws of physics to high accuracy (gravitational Red-shift, change of fine structure constant, and anisotropy of light.)**
- **Detect possible dark energy signatures**



MICROSCOPE: Test of Einstein

Galileo on ground

MICROSCOPE in space

JPL TMO

Is Einstein's equivalence principle valid to one part in 10^{15} or beyond?

A team of scientists will enhance the test precisions by determining the orbit of the satellite using the state-of-the-art laser ranging technique.

PI: S. Turyshev (JPL)

MICROSCOPE Accomplishments

Turyshev (JPL)

- The new laser ranging facility on the JPL's Table Mountain Observatory (TMO) is entering the final stage of development: Laser ranging equipment is on TMO with laser ranging efforts to start in Sep 2017.

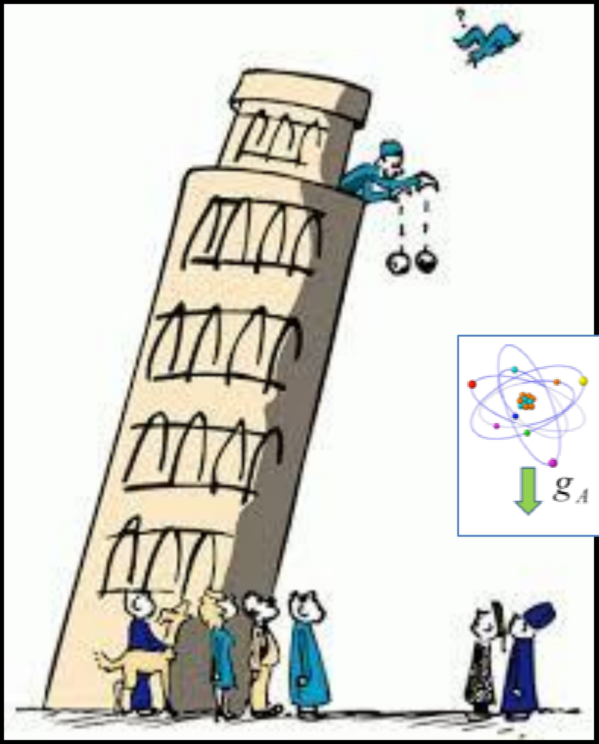
- The new set of M4-M7 mirrors is expected at JPL in Sep. 2017. They will be installed on OCTL in Oct 2017. Full scale of laser ranging operations to geodetic spacecraft will begin by the end of Oct 2017.

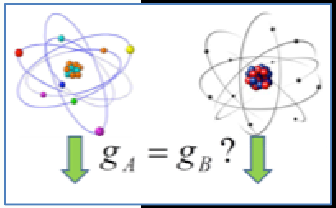
- The CNES and Microscope team is getting ready to complete the primary science phase. We negotiate on the beginning of ranging operations to the Microscope spacecraft to be initiated in Nov 2017. We are working on obtaining their approval to range the spacecraft. We are working on a physics paper describing observables and anticipated results.

Einstein Equivalence Principle

ESA QWEP collaboration and NASA QTEST Study

- Improve the limit on violation of universality of free fall
- Look for evidence for ultra-light particles for dark matter/dark energy
- Test Space-Time dependence of quantum state
- Search for spin-gravity coupling
- Test of Quantum Electrodynamics and explore inner structure of electron at LHC energy scale and Planck Scale

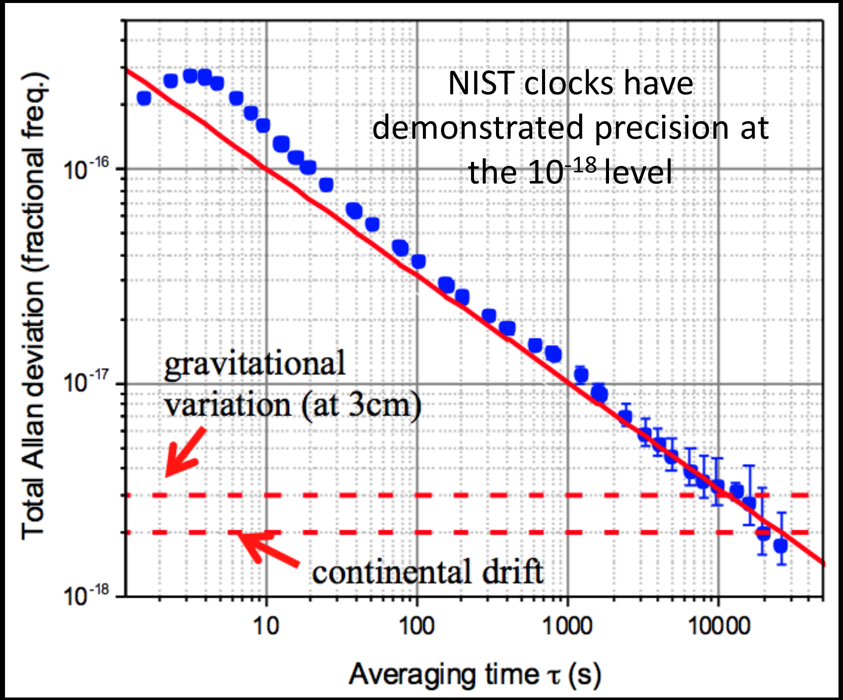


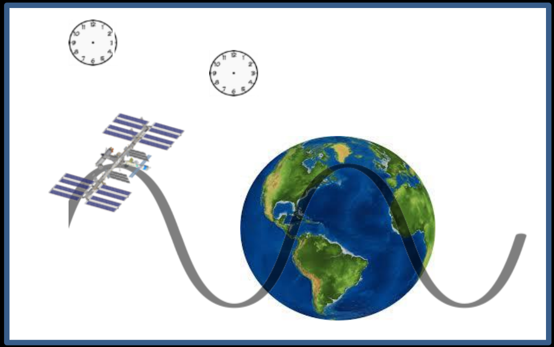


Space Optical Clock (SOC)

US participation and JPL optical clock capability development

- Tests of Einstein Theories of Gravity
  - Gravitational red-shift: light relativistic frequency shift
  - Lense-Thirring effect: Gravity frame drag effect
  - Newton's inverse square law at long distances
- Test Local Lorentz invariance
  - Isotropy of the speed of light
  - Constancy of the speed of light
  - Time dilation experiments
- Tests of Local Position Invariance
  - Universality of the gravitational red-shift
  - Time variations of fundamental constants
- Detection of Dark Matter Fields
  - Ultra-light dark matter waves, clumps, or stochastic backgrounds





clocks for dark matter detection

Summary

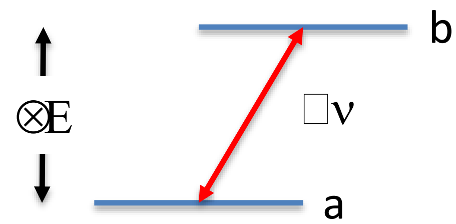
- ISS with the microgravity environment is an enabling space laboratory for exploring fundamental physics through precision measurements
- A fundamental physics research plan has been presented to realize the grand vision of conducting highly impactful science on ISS, answering some of the most fundamental physics questions, as well as leading the new technologies.
- The current program is centered on the CAL development, with strong forward-looking ground research activities. There also exists a healthy set of flight research activities with international collaborations (BECCAL, ACES, QWEP, PK-X).
- Short term goal is to complete CAL and CAL Upgrade while developing concepts of future fundamental physics experiments.
- Long term goal is to use ISS as a space laboratory for exquisite precision measurements using atom interferometer and with an accuracy within the realms of Planck physics.

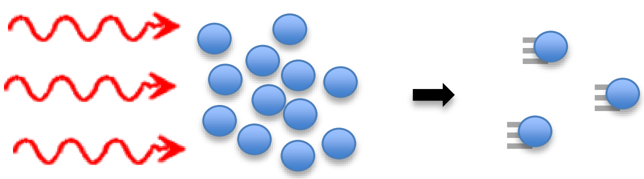
Atom Interferometer
π-Pulse Review

Two-Level System Coupled With Resonant Light

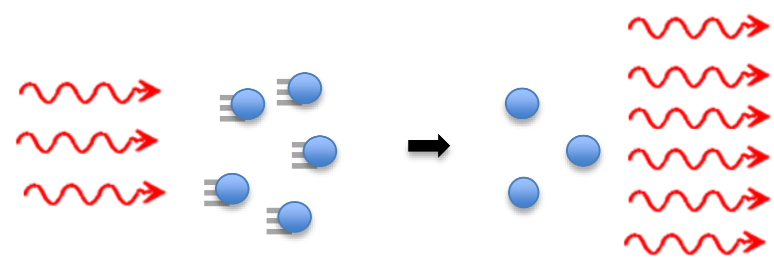
- For simplicity, first consider atoms in a pure two-level system |a> and |b> separated in energy by ΔE.

Resonant light (□ν = ⊗E) drives atoms from the ground to excited state (a->b), which absorb a photon in the process.



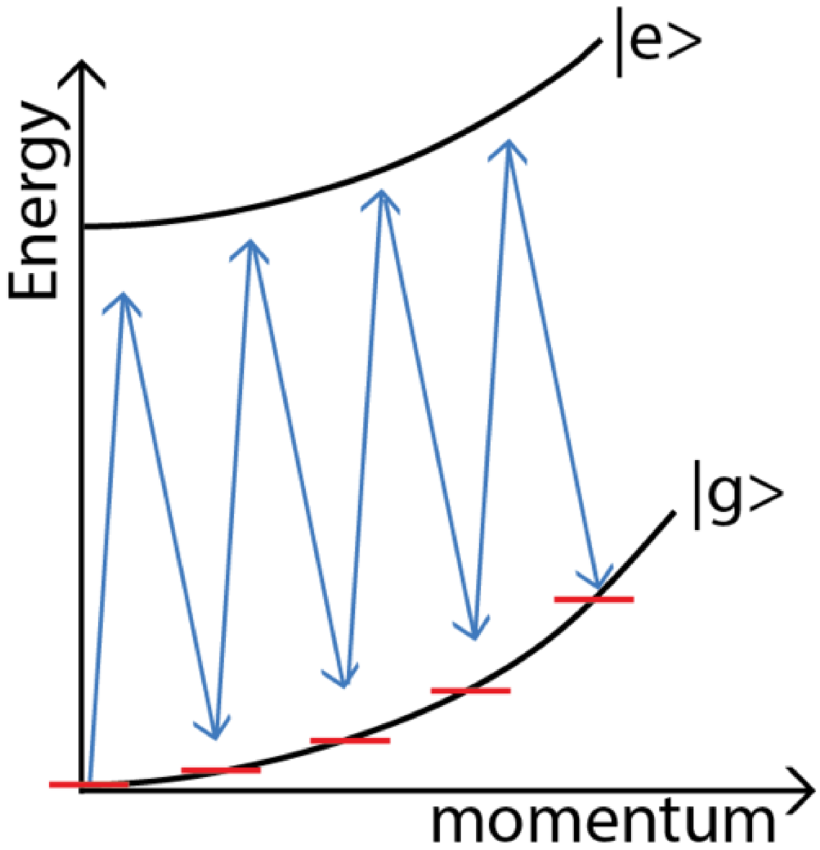


Ground-state atoms absorbing photons from a laser receive momentum kicks (m*v = photon momentum) along the direction of the laser beam.



Atoms in the excited state release a photon and receive a kick that returns them to the zero-momentum (stopped) state via stimulated emission.

Bragg Transition



In a Bragg transition, two counter-propagating beams are detuned so that transferring a specific number of photon momenta is resonant. In this diagram, the atom absorbs the momentum of 8 photons, though a different detuning would transfer a different number of photon momenta. The atom remains in the ground electronic state, but gains kinetic energy.

Raman Transition

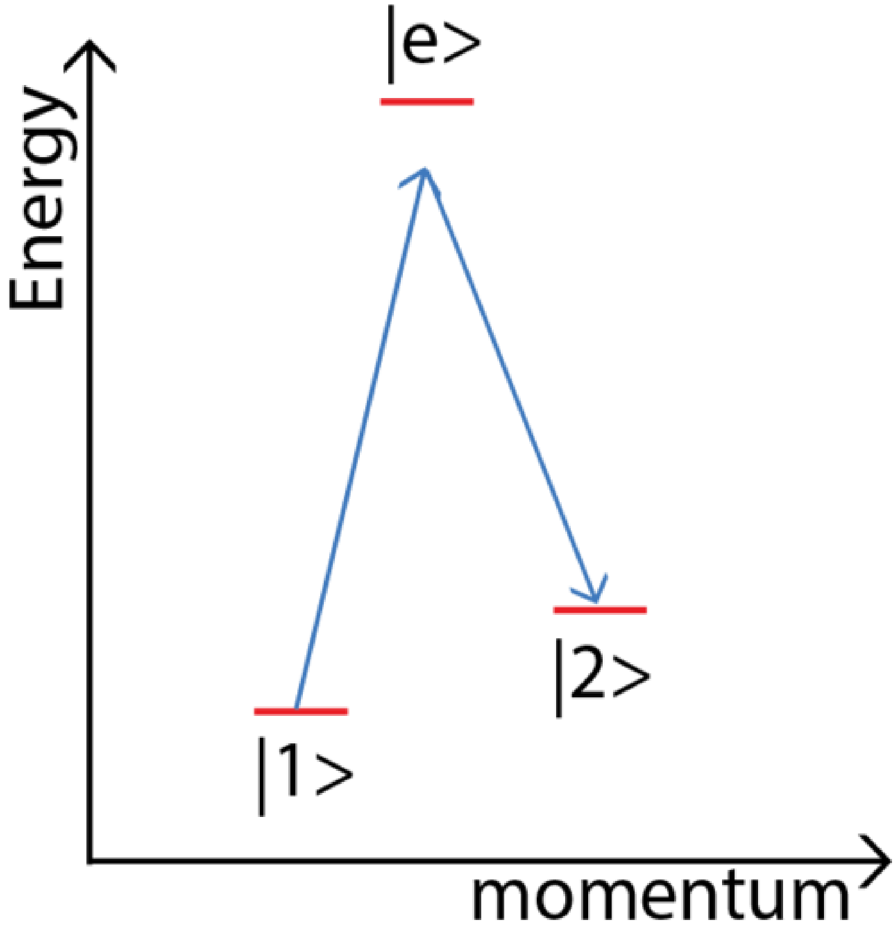


Figure 2: In a stimulated Raman transition, the atom is illuminated with counter-propagating laser beams. The atom absorbs a photon from one beam and emits a photon into a beam moving the opposite direction. The result is a net kick of 2 photon momenta. In this type of transition, the atom changes both its kinetic energy and its internal state.

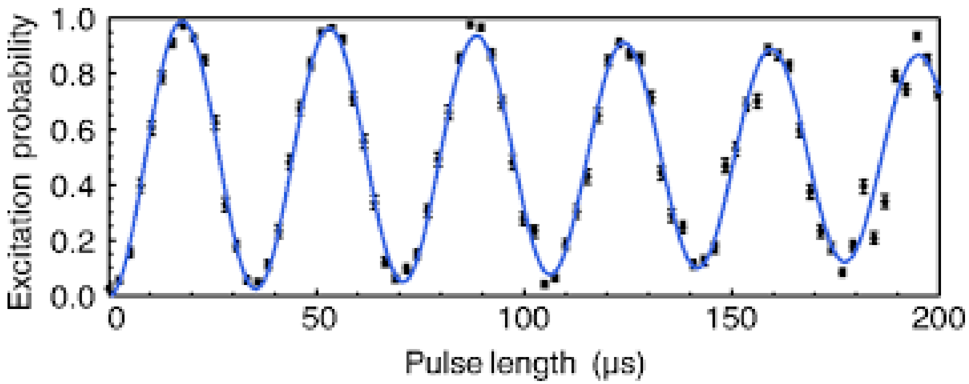
Rabi Frequency

- Bragg and Raman transitions induced by tuned/detuned laser pulses
- Oscillation frequency between ground and excited state ~100 microseconds (Rabi frequency)
- Continuously shine atoms with **$\pi/2$** pulses lasting

  ~25 microseconds will convert 50% of atom to excited state to start moving
- Continuously shine atoms with **π** pulses lasting 50 microseconds will stop the moving atoms and move the stationary atoms

Bloch Sphere Representation of Rabi Oscillation

- In the absence of spontaneous emission, the atoms coherently oscillate between states |a> and |b> at the so-called Rabi frequency (Ω_R), which scales with the intensity of the laser and otherwise on static quantities (transition matrix elements).

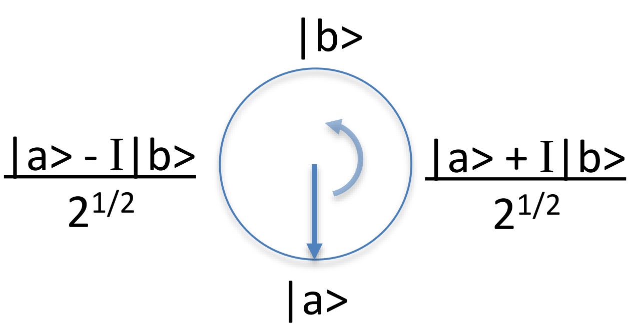


Representative data showing atoms Rabi-flopping between two states when continuously irradiated with a resonant laser.

The excitation probability is given by

$$\frac{\text{\# of atoms in state } |b>}{\text{\# of atoms in state } |a>}$$

- In the Bloch-vector representation, atomic states oscillate on a sphere with all atoms in the ground state at the bottom, excited state at the top, and coherent superpositions of states in the middle:



- $\pi/2$ pulse rotates Bloch vector by 90 degrees, e.g. from ground to 50-50 superposition state.
- π pulse flips population by 180 degrees, e.g. from ground to excited state and vice-versa.

Light-pulse MZ Atom Interferometers

- Measurement based on an ensemble of effective 2-level systems, coupled with light pulses with opposite **k**-vectors (Doppler sensitive spectroscopy).
  - Here, the two photons allow transitions between ground and long-lived excited states.
  - Raman pulses couple two electronic and momentum levels, $g_1 \neq g_2$, $k_{eff} = 2k$
  - Bragg pulses couple two momentum levels, same electronic, $g_1 = g_2$, $k_{eff} = 2nk$

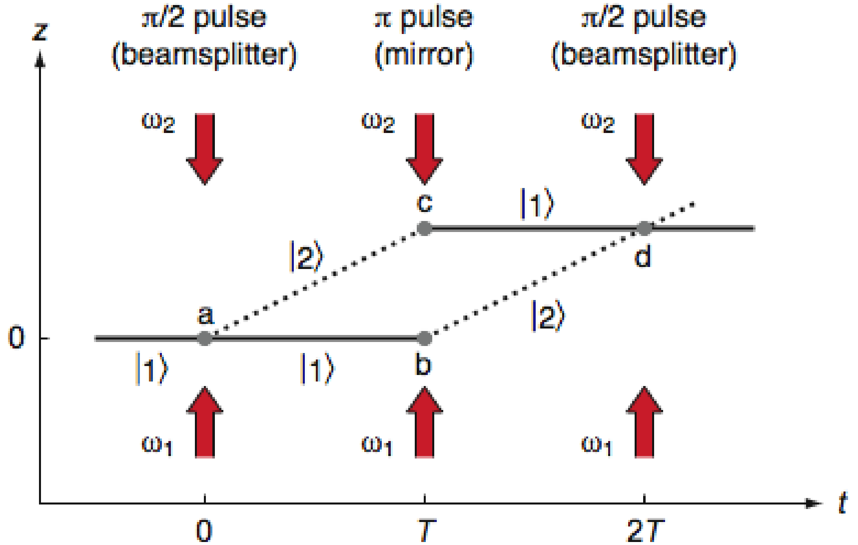
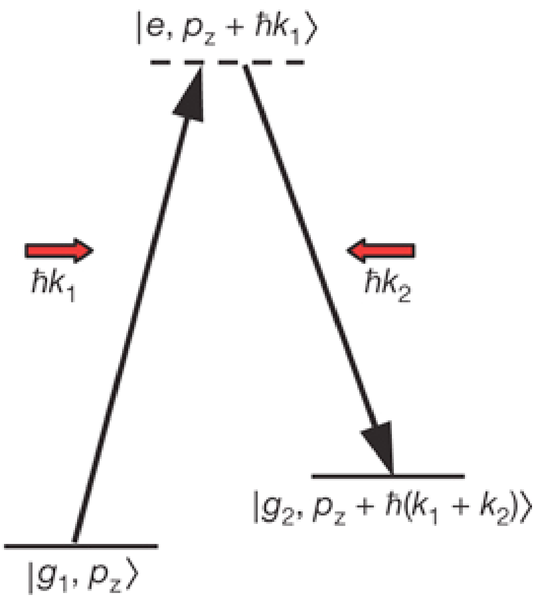
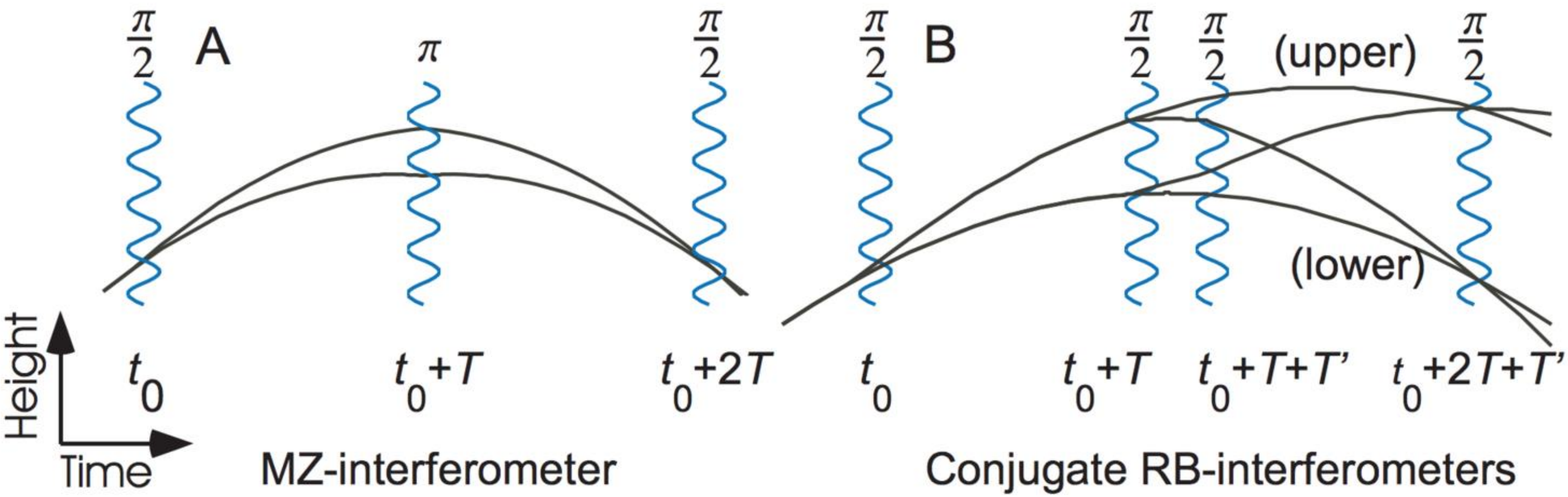


Fig. 1. Light-pulse atom interferometer diagram



Two discrete energy and/or momentum states coupled with 2-photon transitions



Spacetime trajectories of matterwave interferometers where (A) is a Mach-Zender geometry and (B) is a pair of conjugate Ramsey Bordé interferometers. The vertical motion of atoms as a function of time (black) is manipulated by the effects of fast light pulses (blue).

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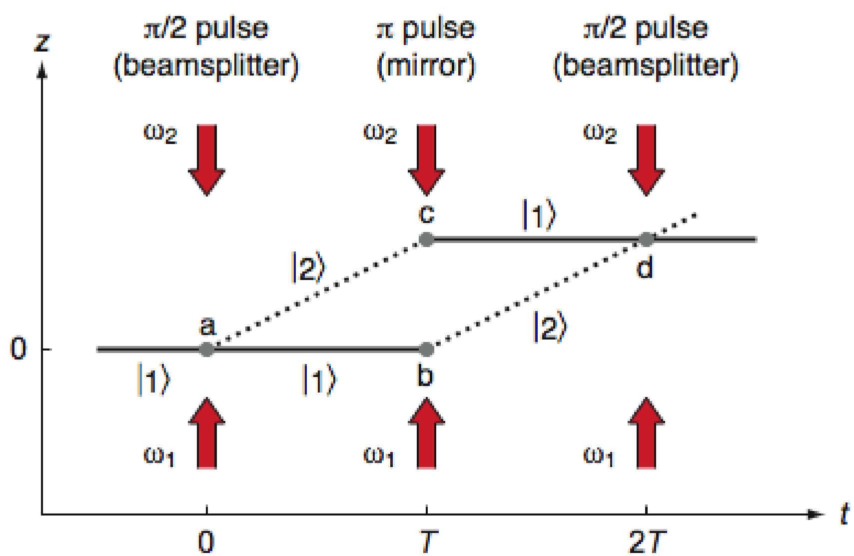

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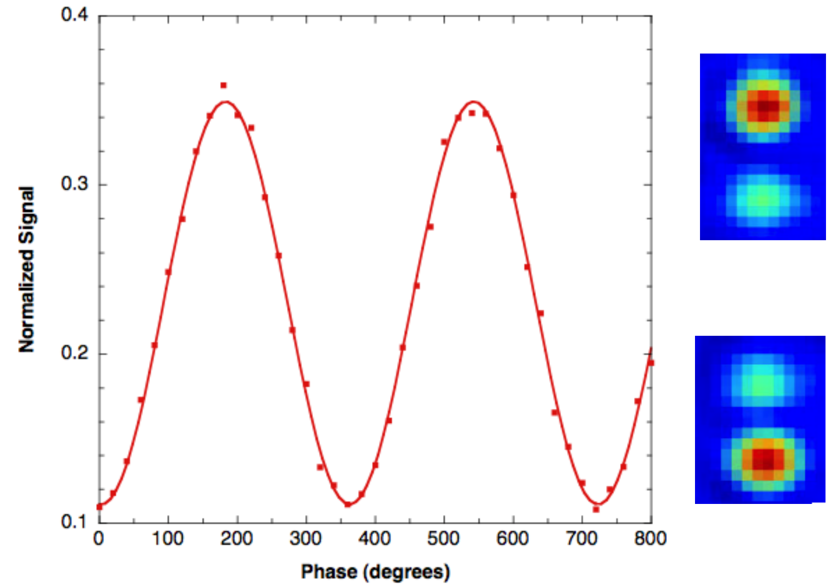


Fig. 2. Atom interferometer fringes as observed in our laboratory prototype instrument [6]. The phase of the final Raman p/2 pulse was scanned to generate the characteristic interferometer fringe.

Sensitive to inertial forces and rotations

$$\Delta\Phi_a = \mathrm{k_{eff}} \cdot aT^2$$

$$\Delta\Phi_{rot} = 2\mathrm{m}(\Omega \cdot \mathrm{A})/\hbar$$

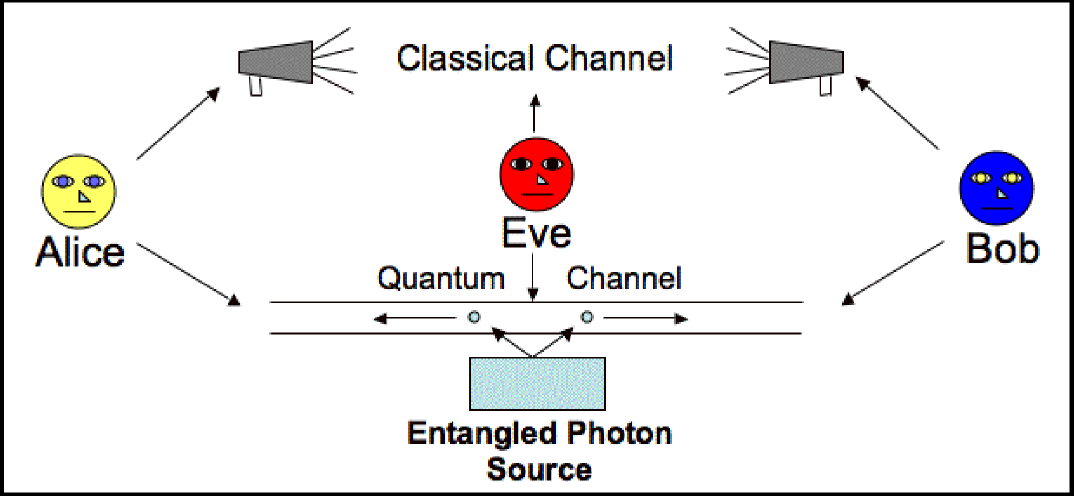
Simple phase readout from final atomic states:

$$P = \frac{1}{2}(1 - \cos(\Delta\Phi))$$

Enabling Quantum Communications in Space

Entangled photon source and quantum network

- Ultimate communication security through quantum key distributions
- Quantum-limited reception and detections for communication efficiency and sensor precision
- Quantum system behavior in large gravity variation environment



Quantum Key Distribution (QKD)

Alice's random bit	0	1	1	0	1	0	0	1
Alice's random sending basis	+	+	×	+	×	×	×	+
Photon polarization Alice sends	↑	→	↘	↑	↘	↗	↗	→
Bob's random measuring basis	+	×	×	×	+	×	+	+
Photon polarization Bob measures	↑	↗	↘	↗	→	↗	→	→
PUBLIC DISCUSSION OF BASIS								
Shared secret key	0		1			0		1