Fundamental Physics Program
Fundamental Physics Deep Dive

National Aeronautics and Space Administration

Presentation to the Committee on Biological and Physical Sciences in Space
October 14, 2021

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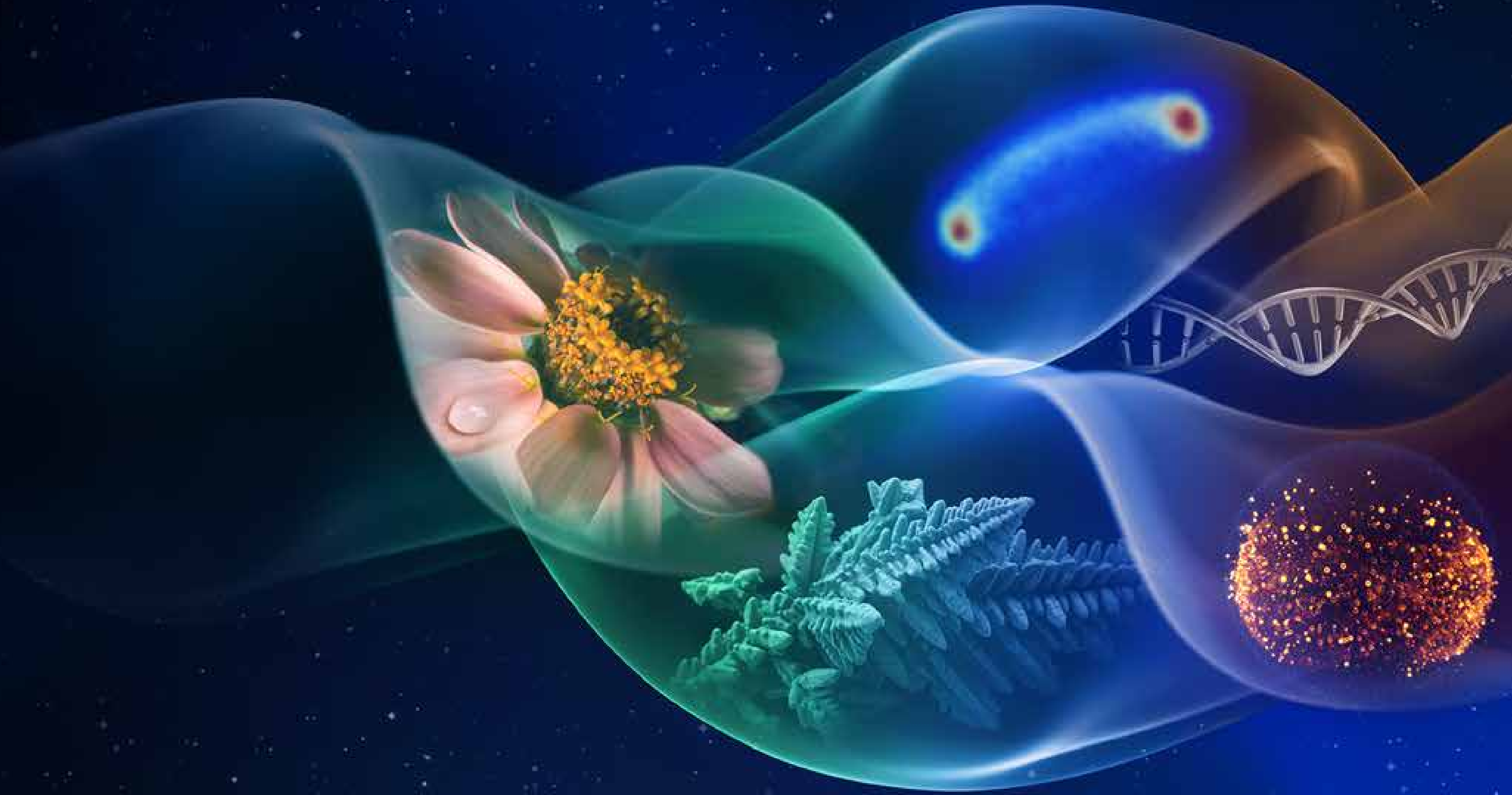
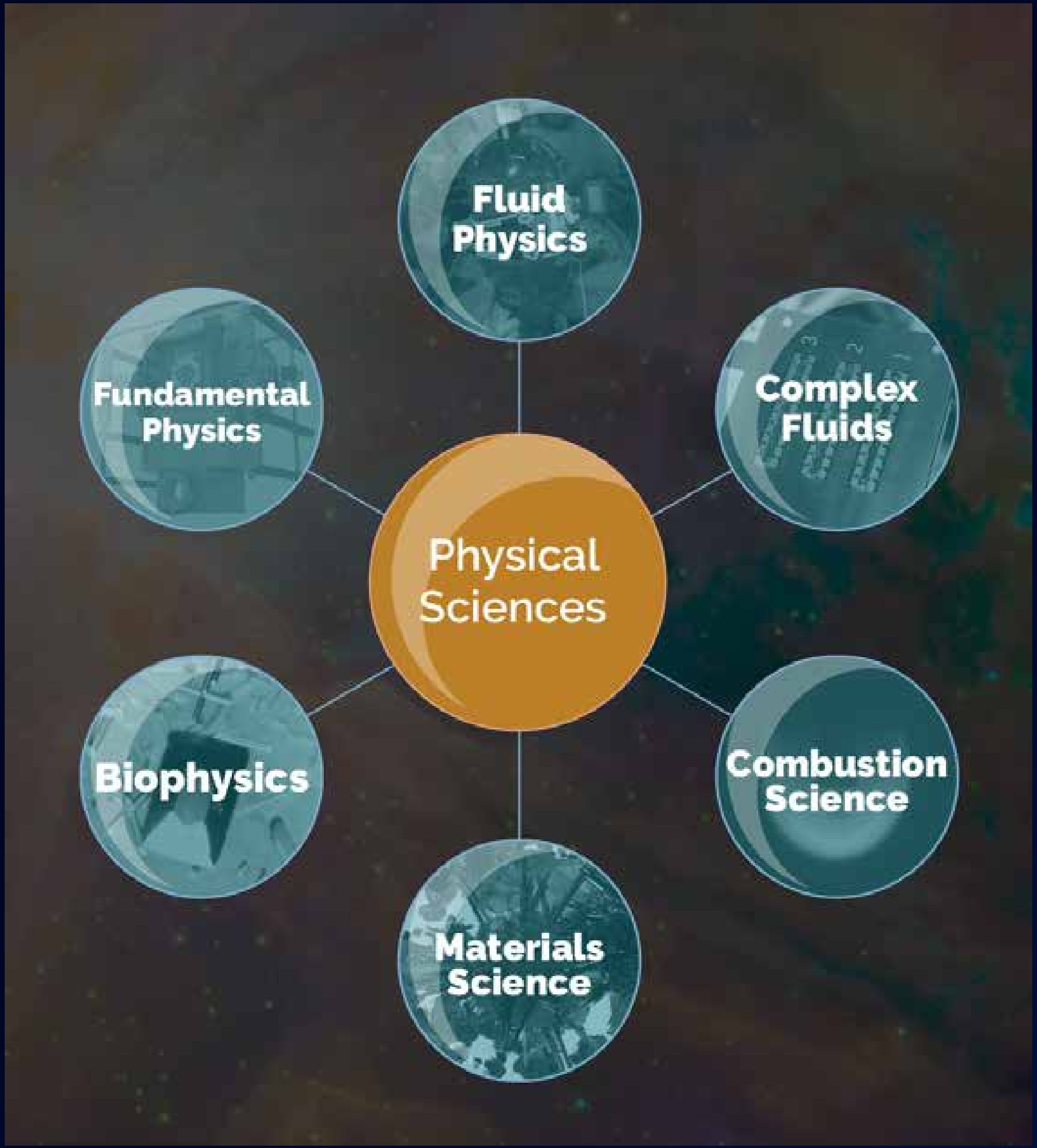
Fundamental Physics Program Scientist

Outline – Fundamental Physics Program

- Overview of current program
- Changes in last 5 years
- In what areas can the program conduct the most transformative science?

Overview





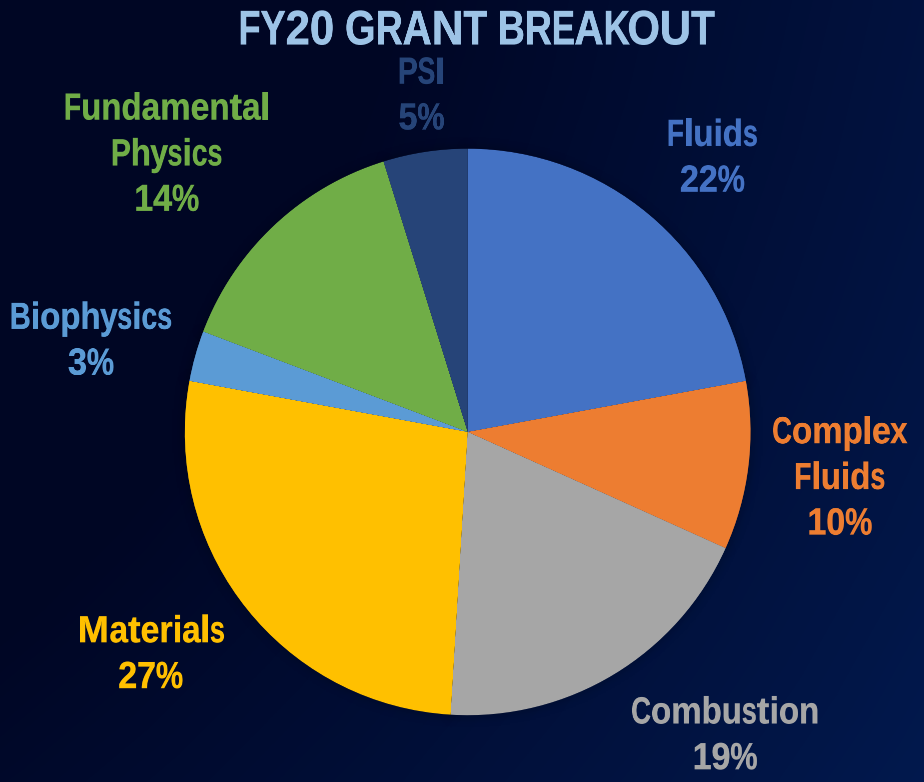
Objectives

- **Investigate** <u>fundamental laws</u> **of physics and physical processes, often using either microgravity or interplanetary distances as research tools**
- **Provide a** <u>mechanistic understanding</u> **of processes underlying space exploration technologies such as power generation and storage, space propulsion, life support systems, and environmental monitoring and control**
- **Develop cutting-edge** <u>technologies</u> **to facilitate spaceflight research**
- **Promote** <u>open science</u> **through Physical Science Informatics**
- **Support the transfer of knowledge and technology of space-based research to terrestrial systems to** <u>benefit life on Earth</u>

Database

- **Physical Sciences Informatics (psi.nasa.gov)**

Physical Sciences Content



Total PS FY20 Grants	104
Flight	64
Ground	40

Number Directed vs Competed	
Directed	10
Competed	94

Fundamental Physics Research 2021

Atomic Clock Ensemble in Space – ESA project, NASA providing technical support and ground links. 1E-16 clock measures gravitational red shift – 3 PIs

Plasma Kristall 4 – ESA-DLR/Russian project, NASA funding PIs. Continuing a series of experiments on dusty plasmas – 5 PIs

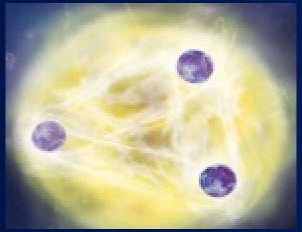
Direct Detection of Dark Energy – Einstein Elevator Experiment – NASA/DLR collaboration, using new DLR drop facility. Search for departures from Newtonian gravitational attraction at small length scales as predicted by modified gravity theories of Dark Energy – 1 PI, directed study

Cold Atom Laboratory – NASA project, first cold atom research facility in orbit. Launched 2018, still working toward full capabilities. Results so far include Bose-Einstein condensates in bubble geometries and picokelvin temperatures in Rb. K capabilities coming with installation of new electronics – 5 PI teams

See back-up for additional details

CAL Flight Investigations

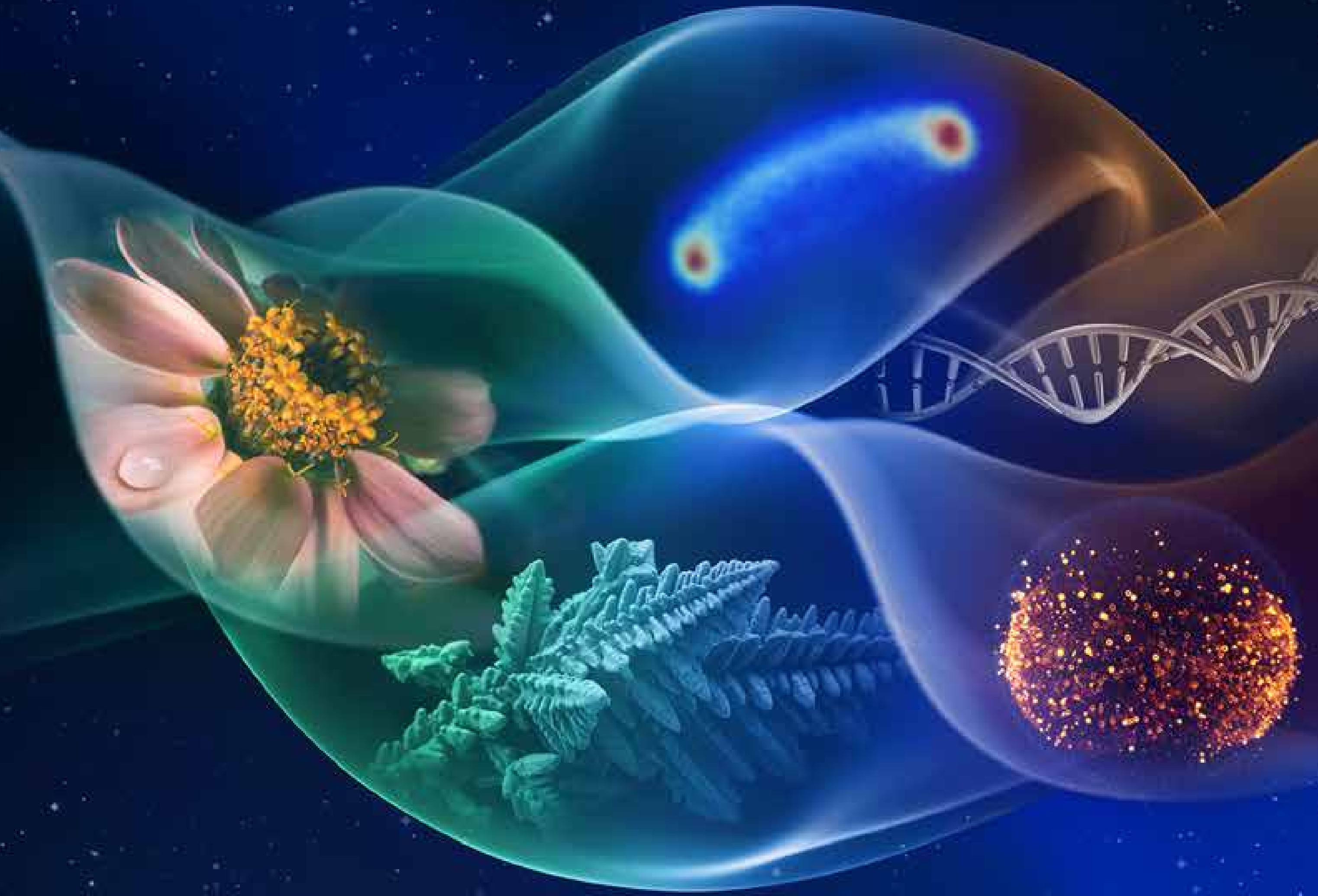
- Zero-G Studies of Few and Many Body Physics (**PI E. Cornell**)
- Atom interferometry Will Pave the Way for Definitive Space-based Tests of Einstein's Theory of General Relativity (**PI N. Bigelow, Co-PI W. Ketterle, Co-PI W. Phillips**)
- Microgravity dynamics of bubble-geometry Bose-Einstein condensates (**PI Nathan Lundblad**)
- Fundamental Interactions of Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment (**PI Jason Williams**)
- Development of Atom Interferometry Experiments for the International Space Station's Cold Atom Laboratory (**PI Cass Sackett**)



Efimov states – three-body self-similar molecules

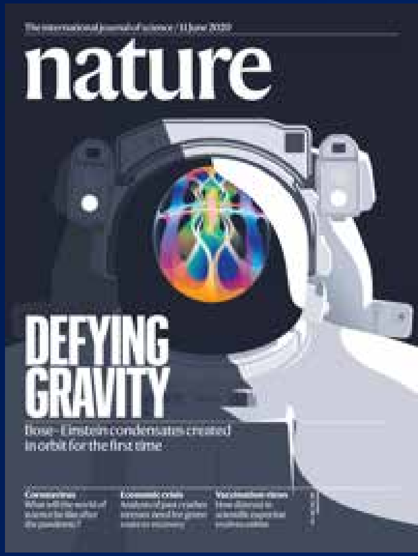
An astronaut tries Galileo's test of the universality of free-fall

Recent Changes

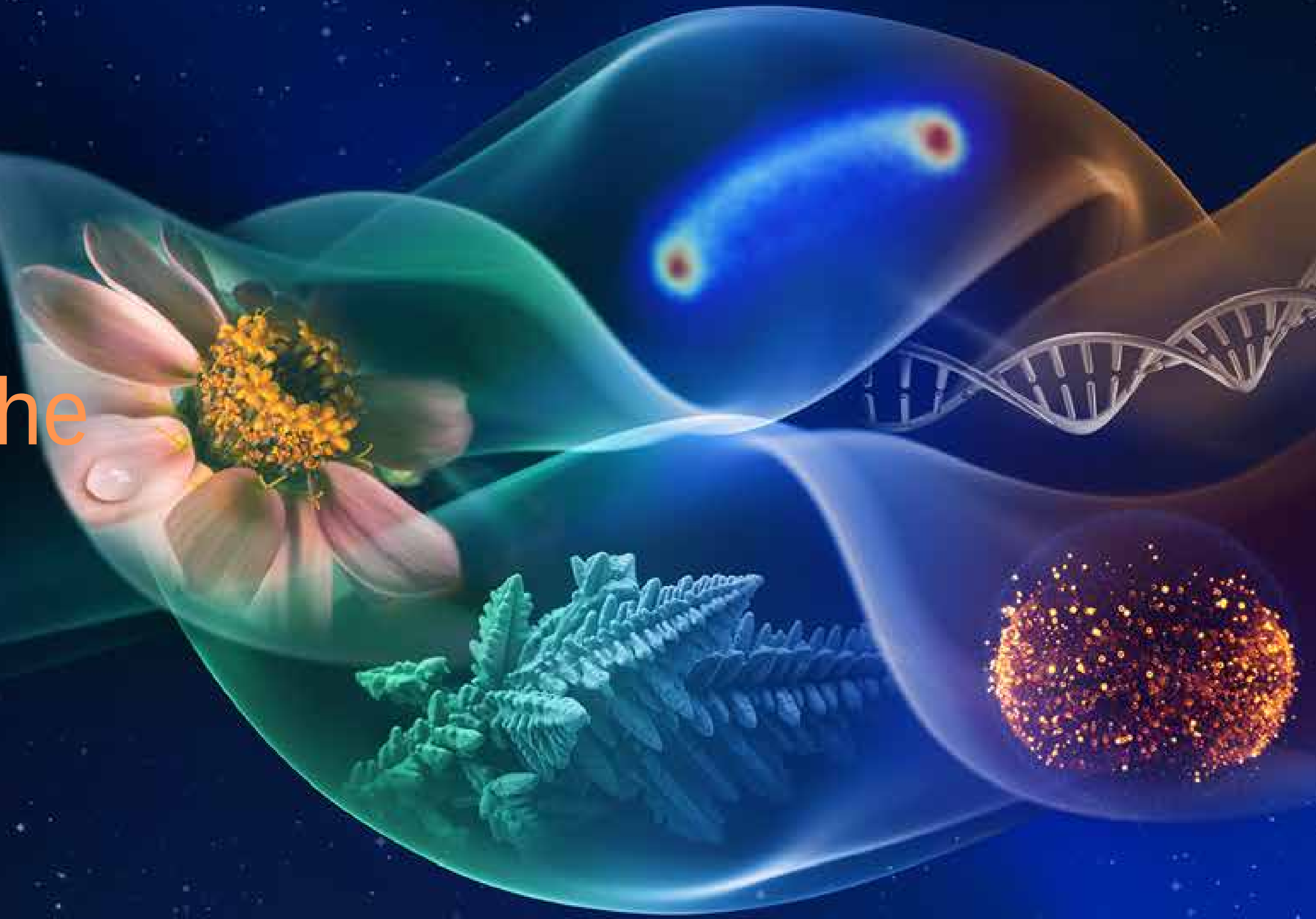


Biggest Changes in Past 5 Years

- 2017 Chinese scientists publish results of Quantum Key Distribution from satellite
- 2018 NASA-DLR agreement for Bose-Einstein Condensate Cold Atom Laboratory (BECCAL) Cooperation. DLR will build the facility, NASA to accommodate on ISS. Scientists from both agencies to define requirements
- 2018 CAL in orbit. First generation instrument with initial capabilities to produce BECs.
- 2018 National Quantum Initiative Act. Major effort across Federal R&D coordinated by White House
- 2020 Atom Interferometry Module installed in CAL. First space-based atom interferometer
- 2020 BPS moves to Science Mission Directorate. Increased focus on transformative science



Looking Forward to the Decadal Survey



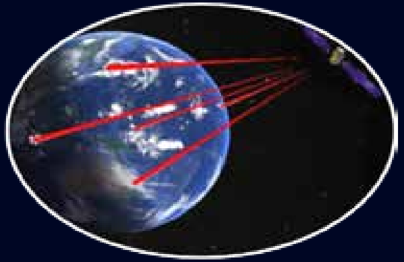
In what areas can the program conduct the most transformative science?

- Quantum Matter – the physics of few- to many-body quantum systems
- General Relativity – precision metrology exploring the limits of GR
- Dark Matter and Dark Energy – quantum mechanics applied to search for signatures of DM and DE
- Quantum Mechanics – Entanglement in relativistic systems; Entanglement and decoherence tested over solar system-scale distances

Quantum Science Decadal Keystone Mission Candidates

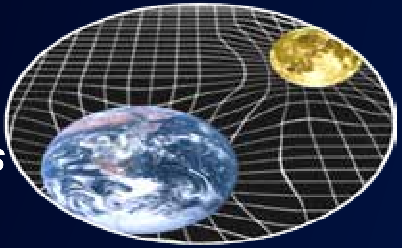
Research on Free Flyers

Gravitation and Dark Matter



Fund Physics with Optical Clock Orbiting in Space (FOCOS)

Quantum/ Gravitation Correlations



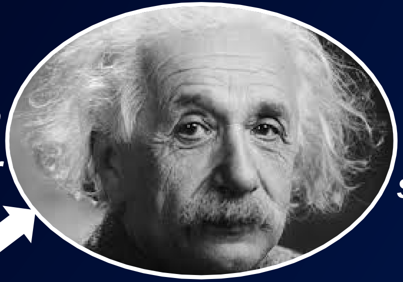
Space Experiments Exploring Quantum Entanglement and Relativity(SEEQER)

Gravitation and Dark Energy

Gravity Observation and Dark Energy Detection Explorer in the Solar System (GODDESS)

Research on crewed platforms (ISS, Gateway, etc.)

Gravitation with Quantum Matter

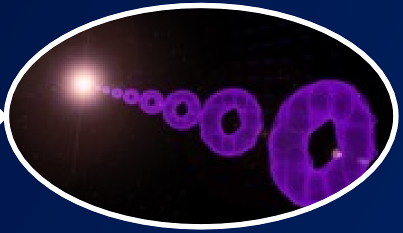


Quantum Test of Equivalence and Space Time (QTEST)

Quantum Matter

CAL SM4

BECCAL (DLR)



Quantum Explorer (QUEX)

ISS/Gateway Keystone Mission Candidate - Quantum Explorer

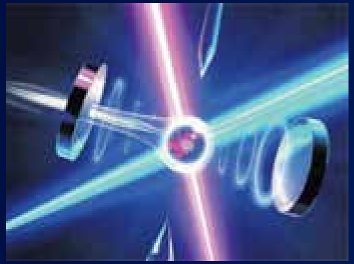
Objectives
- Investigations of the Nature of the Quantum Vacuum
- Explorations of Quantum Chaos and Pattern Formation
- Atom lasers and matter-wave holography
- Matter-wave localization
- Quantum simulation of the early universe, black holes, neutron stars, etc

Heritage
- ISS Cold Atom Laboratory multi-user facility.
- BECCAL multi-user facility

Relevance/Impact.
- 2011 Decadal FP3: Physics and applications of quantum gases
- Demonstrate pathfinder cold atom technology for future missions

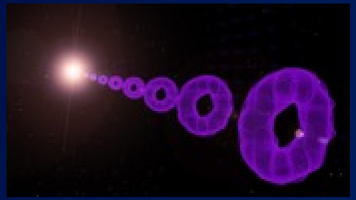
Approach
- Highly reconfigurable open design
- ISS Express Rack implementation
- Utilize astronauts or commercially-flown PIs as space-based quantum scientists
- Customized, PI driven, design of science modules
- Select flight PIs through ROSES NRA

Astronaut installation of CAL SM3



Cold atoms in optical cavities will allow the study of effect of the vacuum on the motion of atoms

Mixtures of quantum gases will allow new insights into quantum chaos



BEC's in expanding traps can simulate aspect of early universe

Free Flyer Keystone Mission Candidate - SEEQER
Space Experiments Exploring Quantum Entanglement and Relativity

Objectives

Understand quantum system behavior and test the influence of gravity and relativistic effects on quantum mechanics using photon entanglement separated by light-second distances

- Long baseline Bell tests with entangled photons exposed to different reference frames
- Test theories of gravitationally induced decoherence
- Test the strong form of Einstein's Equivalence Principle
- Probe the influence on human decision making on quantum systems

Experimental Approach & Heritage

- Mission configurations under study for Lunar Gateway to ISS/Earth baseline.
- Work closely with partners to validate and refine SEEQER architecture through participation in planned SCAN, CSA, Singapore, DLR, and ESA experiments in Low Earth Orbit.
- Leverage heritage from deep space optical communications

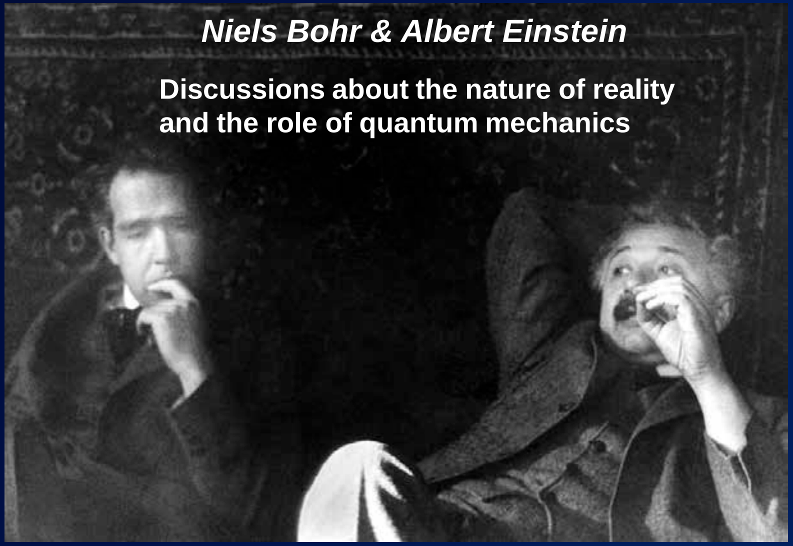
Relevance/Impact

- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2017 Fundamental Physics Standing Review Board (FPSRB) White Paper
- A violation of Einstein's theories or of quantum mechanics at any level will require rewriting physics textbooks.
- Contribute to establishing a grand unified theory of physics that includes gravitation.
- Pioneer development of infrastructure for a space quantum network.

Project Development Approach

- Use science definition team to finalize science objectives, science envelope requirements, mission concept, and technology tall poles.
- Perform technology maturation of critical elements, including entangled photon source, detector, and timing architecture
- Select investigators through ROSES NRA.

Artist Rendition of SEEQER



Niels Bohr & Albert Einstein

Discussions about the nature of reality and the role of quantum mechanics

Free Flyer Keystone Mission Candidate - GODDESS
Gravity Observer for Detection of Dark Energy in Solar System

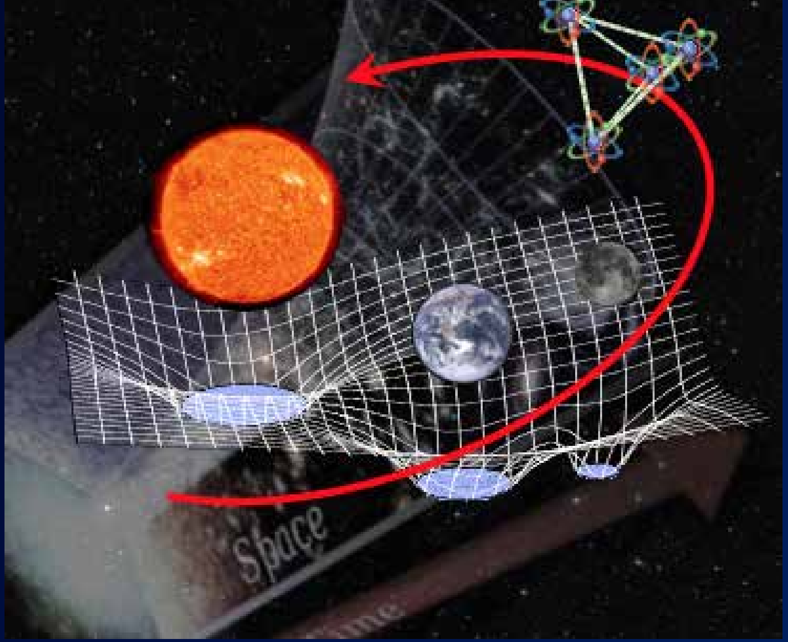
Objective
- Use atom interferometry to seek direct evidence of a class of proposed scalar-field dark energy candidate particles screened near regular matter
  - Chameleon, Symmetron, Galileon
- Search for ultra-light (<< 1 eV) dark matter candidates
- Search for deviations from General Relativity
- Provide more stringent limits of Cosmological Constant
- Detect Gravitational waves, including their direction in frequency band between LIGO and LISA

Experimental Approach & Heritage
- Search for Chameleon and Symmetron in University of Hannover Einstein Elevator drop tube.
- Use a tetrahedral space mission configuration of atomic drag-free sensors ~ 1 au from the Sun.
- Link sensors using laser ranging.
- NIAC Phase 1 study completed. Phase II study on-going.

Relevance/Impact
- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2003 Quantum to Cosmos (Q2C) NRC Report & 2017 FPSRB White Paper
- Discovering what the nature of dark energy is would be ground-breaking as would finding deviations to General Relativity and identifying the dark matter particle.
- Enormous discovery potential with mid-band directional GW detection.

Project Development Approach
- Complete Einstein Elevator developmental project in 2026.
- Use NIAC phase II activity to mature concept.
- Select investigators through ROSES NRA

Artist Rendition of Goddess



Free Flyer Keystone Mission Candidate - FOCOS

Fundamental physics with Optical Clock Orbiting in Space

Objective

- Perform high-resolution tests of fundamental physics with 10^{-18} accuracy optical clocks in space
  - Red-shift and local position Invariance of general relativity by ~ 3 orders of magnitude
  - Search for time variations in the fine structure constant.
  - Search for ultra-light (<1eV) dark matter candidate particles.
- Enable geodesy to mm precision & demonstrate global time transfer to 10^{-18}

Heritage

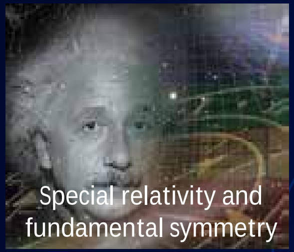
- 2004: PDR for NASA's Primary Atomic Reference Clock in Space (PARCS); Neil Ashby, NIST
- 2006: Study Complete for Rubidium Atomic Clock Experiment (RACE); Kurt Gibble, Penn State
- 2010 & 2014 ESA Cosmic Vision M4 proposals (SAGAS & STE-QUEST)
- 2017: Completion of 2 NRA investigations to support ESA's Space Optical Clock Study (NIST)
- 2019: SDT team selected by NASA to evaluate objectives for Optical Clock in Space.
- 4 NRA investigators participating in ESA's 2021 Atomic Clock Experiment in Space (ACES)

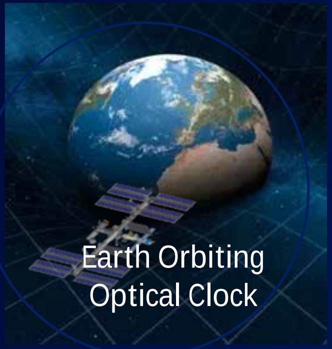
Relevance/Impact

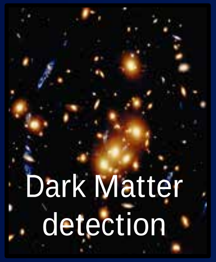
- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2003 Q2C NRC Report & 2017 FPSRB White Paper
- A violation of Einstein's theories at any level will require a re-write of physics.
- Discovery of dark matter particle or reduction of possible candidates is ground-breaking
- Pathfinder for Global clock network for science and exploration

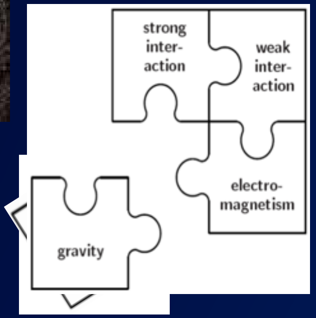
Approach

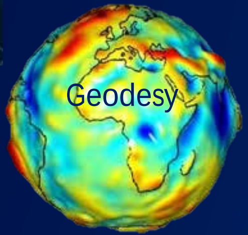
- Use science definition team to finalize science objectives, requirements, and concept.
- Perform technology maturation of critical elements, including time/frequency link
- Select investigators through ROSES NRA.
- Partner with NIST and engage potential international partners with goal to cost share.











ISS/DSG Keystone Mission Candidate - QTEST

Quantum Test of Equivalence and Space Time

Objective

- Use atom interferometry to probe with a factor of 10^{+4} higher resolution than currently if Einstein's Equivalence Principle holds for quantum test particles. (more than x10 better than MicroSCOPE)
- Improve testing of the standard model of particle physics by x10 (fine structure constant).
- Search for ultra-light dark matter candidates with improved precision.

Heritage

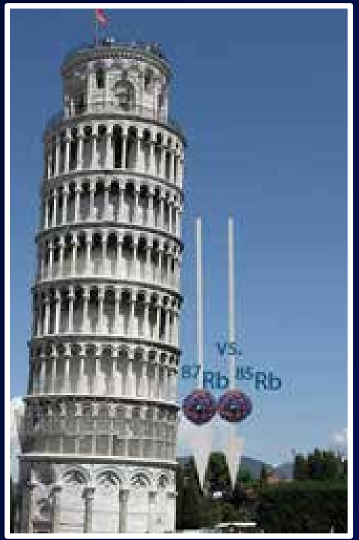
- 2006: Completed 5-year flight study "Quantum Interferometer Experiment (QuItE) " (Kasevich, Stanford).
- 2014: ESA M4 STE-QUEST Mission proposal
- 2017: Completed study of ESA's Quantum Weak Equivalence Principle (QWEP). (Mueller, Stanford)
- 2017: Completion of Quantum test of Equivalence (QTEST) Mission study, with JPL Team X evaluation.
- 2020: CAL demonstrates atom interferometry in space

Relevance/Impact

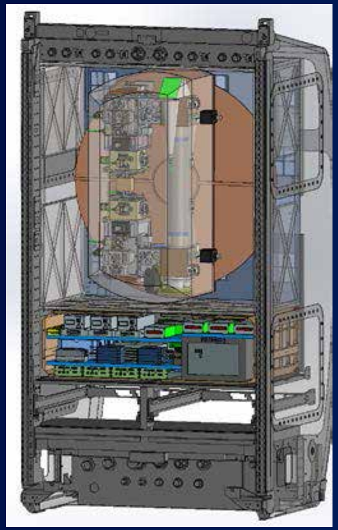
- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2003 Q2C NRC Report & 2017 FPSRB White Paper
- A violation of Equivalence Principle at any level will require rewriting physics textbooks.
- Discovery of dark matter particle or reduction of possible candidates is ground-breaking
- Extend the EEP test to particle wave packets and wave function under gravity.

Approach

- Use high-flux Rb85 and Rb87 ultra-cold atom sources as test masses
- Gravity direction modulation
- Perform technology maturation of critical elements to TRL 5-6 by end of FY24 (PDR)
- Select flight investigators through ROSES NRA
- Seek international collaboration with ESA, DLR and CNES (MicroSCOPE)



Caption

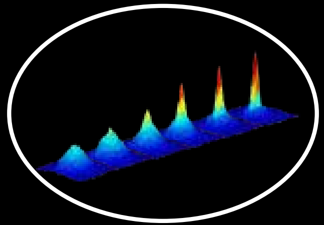


ISS QTEST payload

Making Quantum Leaps in Quantum Science by

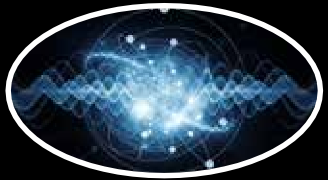
Seeking answers to today's most intriguing questions

Exploring the Quantum Realm



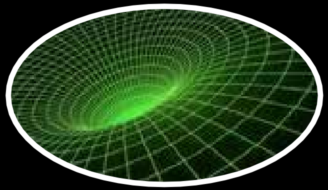
- What are the Quantum Properties of atoms and molecules?

- How is Quantum Entanglement influenced by gravity?

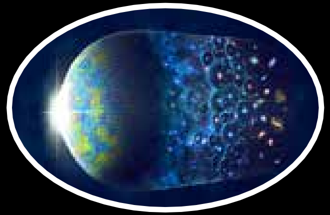


- How does complexity & order arise from Quantum interactions?

New Physics with Quantum Tools



- Is Einstein's General Relativity valid under all experimental conditions?



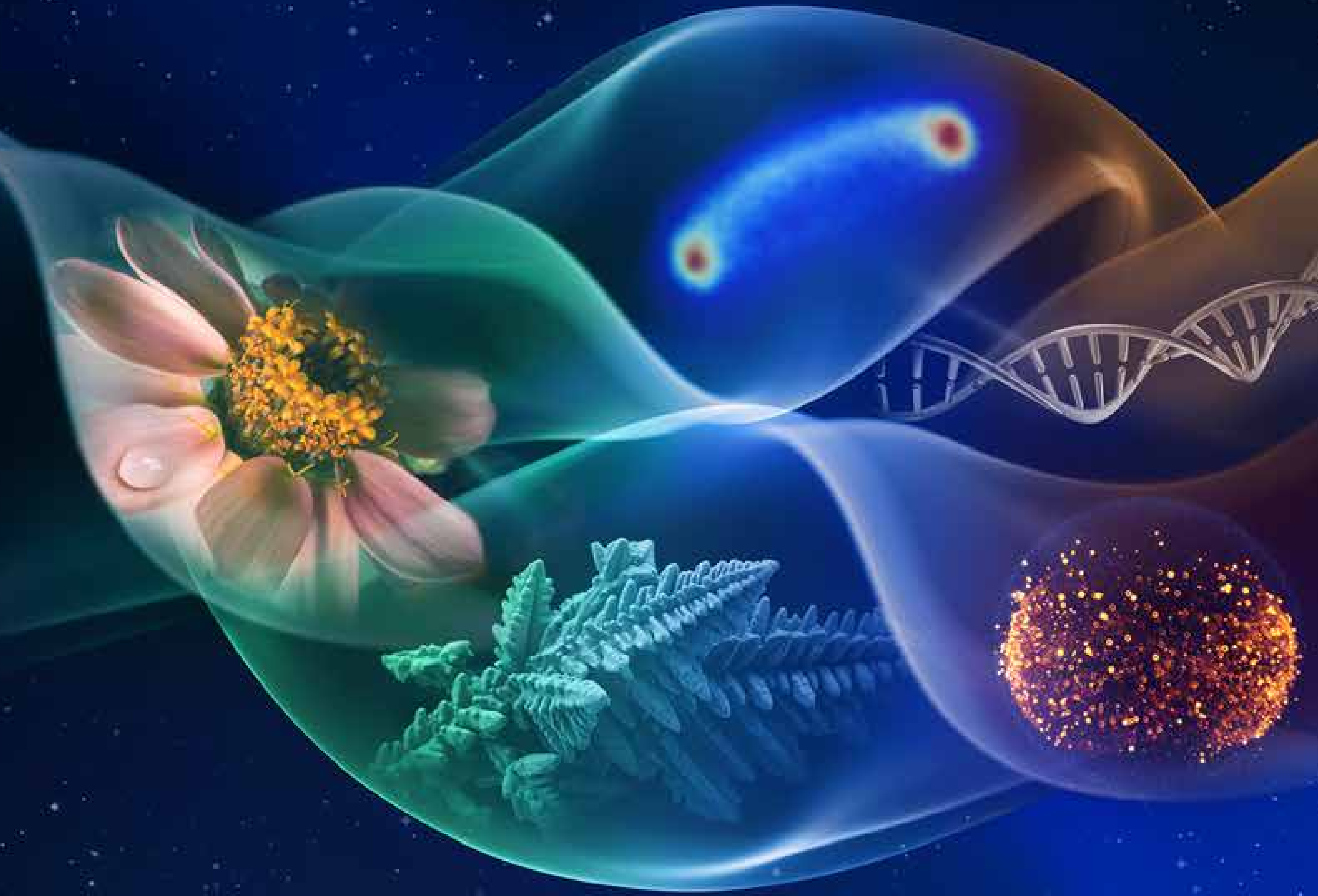
- What is the true nature of Dark Energy?

- Is Dark Matter an ultra-light field?

In pursuit of these questions, we will

- Transform our understanding of matter, space, and time
- Develop new technologies that enable Space & Earth commercial opportunities
- Inspire students to continue the pursuit of new NASA discoveries

Deep Dive



Deep Dive Outline – Program Needs, Concerns, Issues

Program Needs

Program Issues and Concerns

Quantum Science Roadmap

Research Objectives

- Quantum Matter
- Quantum/Gravitation Correlations
- General Relativity and Dark Energy
- General Relativity and Dark Matter
- General Relativity and Quantum Matter
- Current Research Projects

Program Needs

1. ~~Regular solicitations supporting research that explores and refines new research concepts, and builds context for current flight projects~~ Done! Expect annual solicitations starting FY2022
2. ~~Advisory connection with the research community~~ Done! BPS advisory committee in work
3. Innovative approaches to developing space-qualified instrumentation. DLR university-based institutes are a potential model.
4. Program stability to allow (1) to build a pipeline of exploratory research, technology development, and flight investigations pursuing the biggest questions in physics

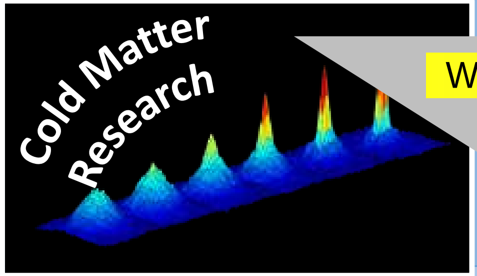
Program Issues and Concerns

1. We're underinvesting in new areas of science – We need to balance funding between current areas of flight research and new science areas like interaction between gravity and quantum mechanics. What does a critical mass look like for new areas of research?
2. It's exciting to be at the edge of discovery in science, but many areas of fundamental physics are controversial and should be approached with care. Controversy shouldn't be avoided, but it needs to be handled intelligently. We need a strong theory program and healthy discussion to shed light on open questions. How to effectively stimulate discussion between theory and experiment?
3. Leaving room for discovery - science advances through both well-planned, fully analyzed steps and chance observations. How to leave space for the unexpected result?

Quantum Science Roadmap

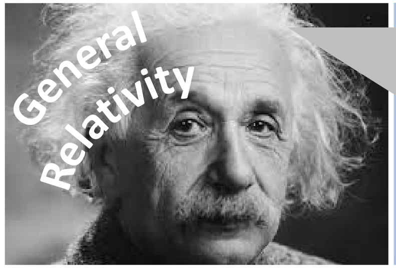
Present	Near Term	Formative	Visionary

Cold Matter Research



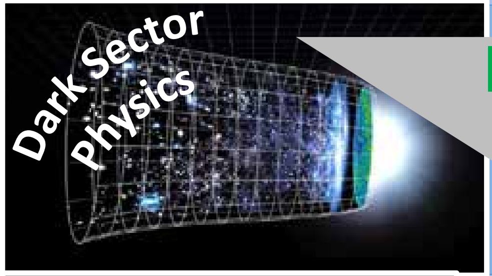
- What are the properties of quantum systems of atoms and molecules?
- How can we design useful science systems and sensors using quantum properties?
- How does complexity & order arise from Quantum interactions?

General Relativity



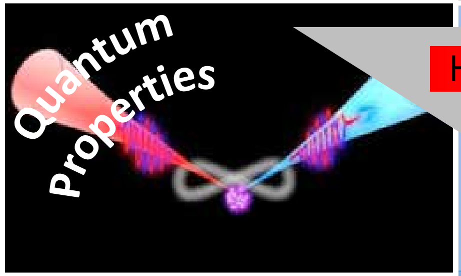
- Is Einstein's theory of General Relativity valid under all experimental conditions?
- Under what conditions will Einstein's Weak Equivalence Principle be violated?
- How can General Relativity be unified with Quantum Mechanics?

Dark Sector Physics



- Is the Chameleon or Symmetron fields Dark Energy?
- Are ultra-light scalar fields responsible for Dark Matter?
- Are scalar fields responsible for Dark Energy?

Quantum Properties

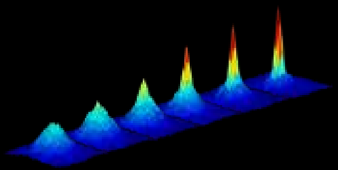


- How does complexity & order arise from Quantum interactions?
- What is the role of free will in quantum mechanics?
- Is there quantum interference from curved spacetime?
- Is Quantum Mechanics locally real?

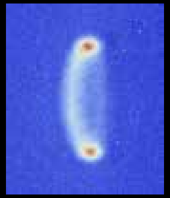
Missions

Phase	Partners	Mission	Research
Present	DLR	CAL-SM3	CMR/QP
Present	DLR	D3E3	DSP
Near Term	DLR NSF	CAL-SM4	CMR/QP
Near Term	ESA NIST CNES DLR	ACES	GR
Formative	DLR NSF	BECCAL	CMR/QP
Formative	DLR	QTEST4	GR/DS
Formative	DLR SCAN	SEEQER	QP/GR
Visionary	DLR NSF	Quantum Explorer	CMR/QP
Visionary	NIST DLR	FOCOS	GR/DS
Visionary	TBD	GODDESS	DS/GR

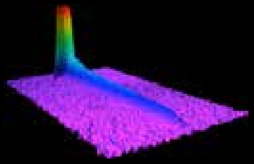
Quantum Matter Research Objectives



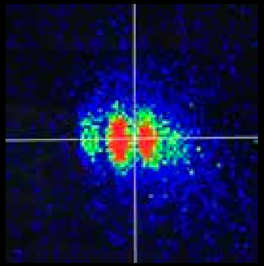
Study scalar and spinor Bose-Einstein gases and mixtures.



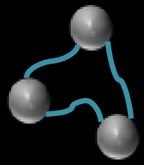
Explore quantum bubbles and rings.



Research Atom Lasers.



Study atom interference and achieve pico-K temps

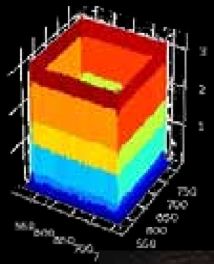


Search for universal features in few particles quantum collisions

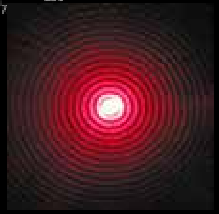
Research quantum halo molecules.

Testing Einstein with Atom Interferometry.

Develop cold atom technology for science, exploration, and commercial benefit

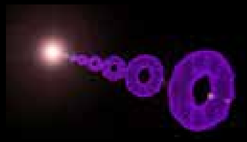


Study atoms trapped in box potentials

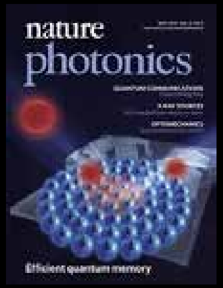


Explore quantum diffraction and reflection in matter waves

Research strongly interacting quantum gases and molecules



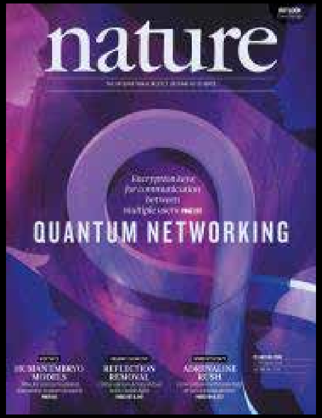
Perform Quantum simulations



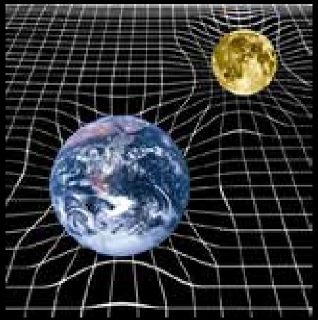
Research quantum memories

Quantum/ Gravitation Correlations: Research Objectives

Test local realism of quantum mechanics and place upper bounds on the speed of wavefunction collapse.

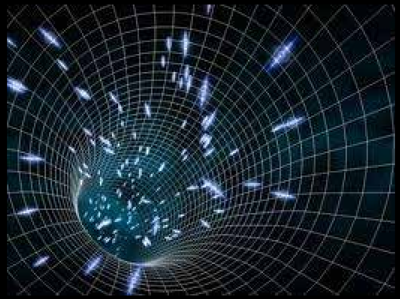


Evaluate the time ordering paradox and the role of free will in quantum mechanics.



Study special and general relativistic effects with entangled photons and search for quantum interference due to curved spacetime.

Develop technology to enable quantum teleportation, quantum key distribution and a space quantum network.

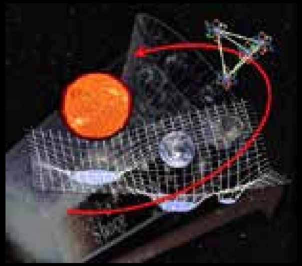


Seek evidence of decoherence by probing quantum entanglement in accelerating reference frames.

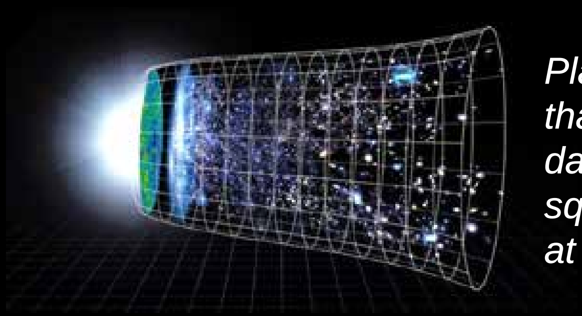
General Relativity and Dark Energy: Research Objectives

Search for dark energy scalar field candidates screened by local mass densities with atom interferometry in Einstein Elevator.

Determine exact origin of gravitational waves in 0.03 to 3Hz band using formation flying satellites

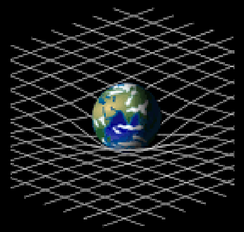


Search for direct detection of the galileon dark energy scalar field in the Vainshtein screening model using free space atom interferometry and formation flying satellites.

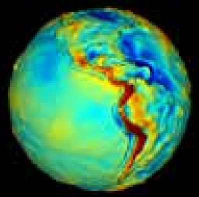


Place bounds on the likelihood that cosmological constant is dark energy and test inverse square law with high precision at 0.1 AU scale.

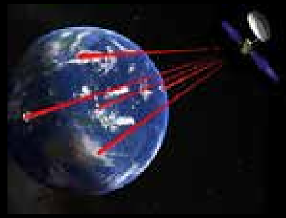
General Relativity and Dark Matter: Research Objectives



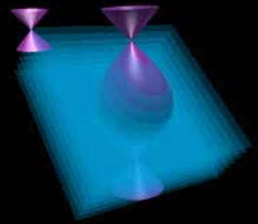
Perform a high resolution test of metric theories of gravity.



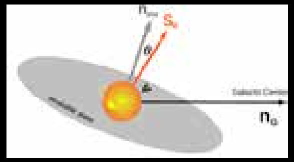
Study relativistic geodesy of the Earth with sub- cm precision.



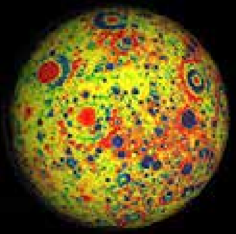
Establish an Optical Master Clock in space to serve as time keeper for Earth.



Perform a high resolution test of Local Lorentz Invariance.

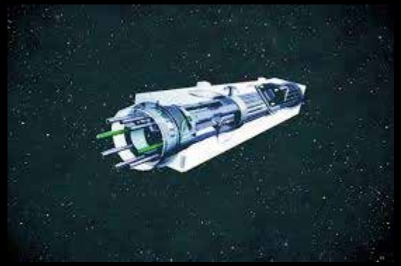


Perform a high resolution test of Local Position Invariance.



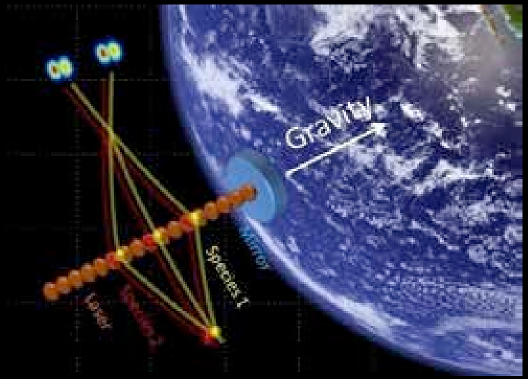
Enable studies of geodesy of the Moon and planets with unprecedented precision.

Seek direct evidence of scalar field dark matter particles.

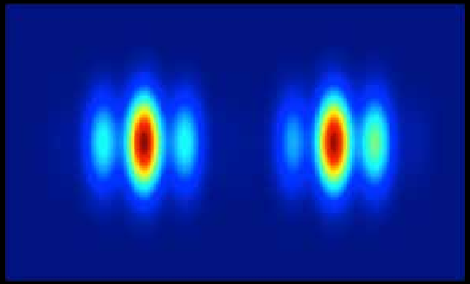


Establish an Optical Master Clock in space to serve as Solar System time keeper.

General Relativity with Quantum Matter: Research Objectives

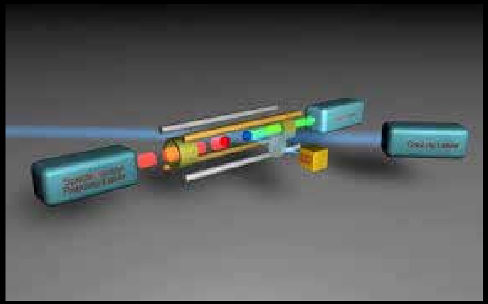


Test Einstein's weak equivalence principle to better then 10^-16 using atom interferometry and quantum particles.



Test Space-Time dependence of quantum states including red-shift and coupling of spin to gravity.

Seek evidence for low mass dark matter particles using atom interferometry and quantum particles.



Measure photon recoil with high precision to allow improved measurement of fine structure constant and tests of quantum electrodynamics.

Reference Material

Current Research

- Atomic Clock Ensemble in Space (ACES)
- Plasma Kristall- 4 (PK-4)
- Atom Interferometry and Dark Energy Detection
- Cold Atom Laboratory (CAL)

Atomic Clock Ensemble in Space (ACES)

ESA ISS external mission with CNES developed Cs Atom clock.
Principal Investigator: Christophe Salomon, Ecole Normale Superieure, France
NASA Project Manager & Project Scientist: Dr. Nan Yu, JPL
NASA Pis: Nan Yu, JPL; Kurt Gibble, Penn State; Chris Oates, NIST; and Leo Hollberg, Stanford
Customers/Adopters (Push): Decadal Review FP2. NASA Science Mission Directorate. NASA Communications and Navigation Roadmap & NASA SCAN office: Time Keeping and Time Distribution. Optical and Quantum Communication.

Objective:

- Validate cold atom space clock technology to the 10^-16 level
- Perform time and frequency transfer to the Earth
- Test general and special relativity to high precision
- Use relativistic geodesy to map the Earth’s gravitational potential.

Experimental Approach:

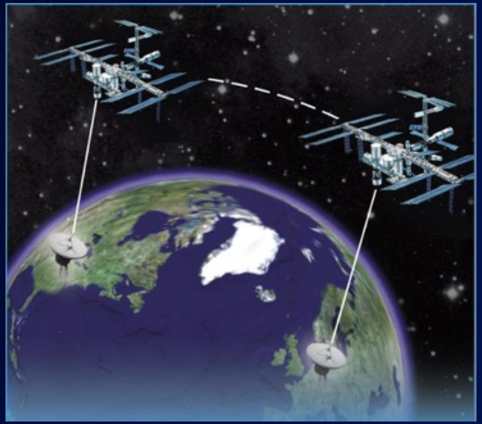
- Cesium laser cooled atomic fountain clock.
- Hydrogen maser flywheel oscillator provide accurate short time stability.
- Microwave and Optical time transfer from ACES to a constellation of ground clocks for clock comparison activity.

Relevance/Impact:

- Decadal FP2: – Einstein’s Equivalence Principle is the foundation of Einstein’s General Theory of Relativity. Uncovering a violation would indicate additional forces beyond the 4 currently known and require modifications to the Standard Model of Physics.
- Global and National time & frequency reference, relativistic geodesy.
- LOP-G: Verify laser ranging technique

Project Development Approach:

- CNES provides Pharao Cs Clock.
- ESA is mission implementer using EADs Astrium.
- ESA to deliver MWL to NIST and JPL teams for use in global frequency co



ISS Resource Requirements

Accommodation (carrier)	External to Columbus Module
Upmass (kg) (w/o packing factor)	227
Volume (m^3) (w/o packing factor)	1.0
Power (kw) (peak)	0.45
Crew Time (hrs) (installation/operations)	Installation only
Autonomous Operation	18 months
Launch	Spring 2022 (TBD)

Award	SCR	RDR	PDR	CDR	FHA	Ops
Jun 2012	N/A	N/A	N/A	N/A	Feb 2022	6/22– 12/23

Plasma Kristall-4 (PK-4)

ESA/ROSCOSMOS/DLR Project installed in the ISS Columbus Module
German Lead Scientist: Dr. Hubertus Thomas, MPE, Garching, Germany
Russian Lead Scientist: Dr. Andrey Lipaev, JIHT, Moscow, Russia
ESA Coordinator: Astrid Orr, ESTEC, Netherlands
PK4 Facility Science Team Chair: Prof. John A. Goree, Univ. of Iowa
NASA PIs: J Goree & B Liu, University of Iowa; U Konopka, Auburn University; G Ganguli, NRL; NSF Pis: P Bellan, Caltech; T Hyde, Baylor University.
PS/PM: Dr. Inseob Hahn, JPL

Customers/Adopters (Push): Decadal Review: TSES4; FP1; AP4; AP5; Need listed on 5 of 38 Exploration Quantifiable Capabilities quad charts; HRP Exploration Rmap has 1 major dust health risk and 5 dust knowledge gaps; NASA Technology Roadmap 7.6 Sub goal: Manage particulate contamination; Human Health, Life Support, Habitation Roadmap 6: Dust mitigation in 6 key technology areas.

Objective:
- Study of the liquid phase of complex plasma such as flow phenomena
- Study of non-Gaussian statistics of particle motion, diffusion, viscosity.

Experimental Approach:
- Control variables: Particle size, plasma gas, DC discharge field.
- Diagnostics: High speed camera.

Relevance/Impact:
- NASA's decadal survey recommendation for FP in microgravity: dusty plasma, condensed matter physics analog.
- Understanding astrophysics phenomena
- Dust mitigation physics needed for exploration
- Earth Based applications in Semiconductor, Manufacturing, and Clinical Industries.

Project Development Approach:
- Hardware built by DLR contractor OHB System AG (Kayser-Threde
- PK4 is the culmination of a sequence of prior flight experiments with the collaborating partners starting on the Russian MIR station.

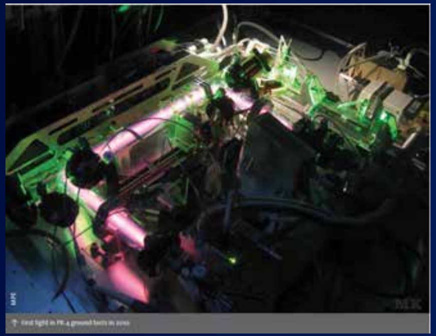


Image Credit: +European Space Agency, ESA / +ROSCOSMOS RUSSIA)

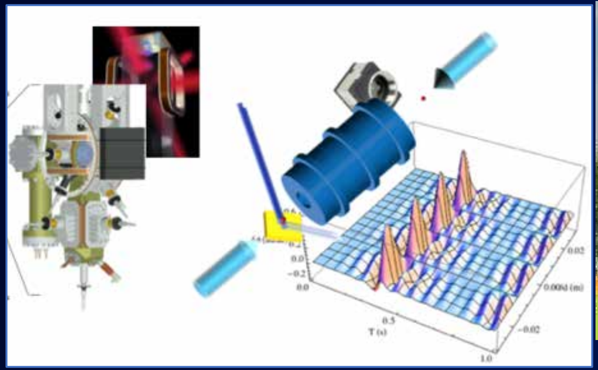
ISS Resource Requirements

Accommodation (carrier)	ISS Columbus Module
Upmass (kg) (w/o packing factor)	25
Volume (m^3) (w/o packing factor)	0.24
Power (kw) (peak)	0.3
Crew Time (hrs) (installation/operations)	TBD
Autonomous Operation	6 years, not continuous
Launch	10/2014

Award	SCR	RDR	PDR	CDR	FHA	Ops
4/1/2017	N/A	N/A	N/A	N/A	Jul 2014	1/15 – 9/22

Atom Interferometry and Dark Energy Detection

NASA Project Manager: Ulf Israelsson, JPL
NASA Project Scientist: Nan Yu, JPL
NASA Principal Investigator: Dr, Sheng-Wey Chiow, JPL
External Co-I: Prof. Holger Mueller, UC Berkeley
German collaborator: Prof. Wolfgang Ertmer, Prof. Ernst Rasel
Customers/Adopters (Push/Pull): Decadal Review FP2. NSF. NASA Science Instruments Roadmap (Quantum Interferometry). Technology applicable to 5 of 38 Exploration quantifiable capabilities quad charts.



Objective:
- To conclusively verify or refute if the chameleon field is responsible for the dark energy which represents 68% of the energy content in the Universe.
- Demonstrate AI precision measurements in micro gravity

Experimental Approach:
- Reuse the MAIUS cold atom module through collaboration with Germans
- Use specially designed periodic dark energy source mass for environment gravity interference and systematic reduction
- Perform multiple atom Interferometers with repeated drop experiment runs afforded by the Hannover Einstein Elevator

Relevance/Impact:
- Address important science question of the century
- Use and demonstrate precision measurement tools in microgravity
- Mature atom interferometer technology and science measurement concepts for future space experiments

Project Development Approach:
- Build on BPS funded dark energy study and results already published.
- Establish collaborations with DLR and German science foundation
- Initiate a joint Phase A implementation feasibility study for reusing MAIUS
- JPL build and evaluate the dark energy source mass structure and its integration interface.
- German team integrates the experiment drop payload and operate experiments
- US and German scientists share data and perform joint analysis and investigate science

Resource Requirements

Accommodation (carrier)	Ground based
Upmass (kg) (w/o packing factor)	N/A
Volume (m^3) (w/o packing factor)	N/A
Power (kw) (peak)	N/A
Crew Time (hrs) (installation/operations)	N/A
Operation	1 year
Launch	N/A

Award	SCR	RDR	PDR	CDR	FHA	Ops
Jun 2019	N/A	N/A	N/A	N/A	N/A	2024

Cold Atom Laboratory (CAL)

NASA Project Manager: Kamal Oudrhiri, JPL
NASA Project Scientist: Rob Thompson, JPL
Flight Pis: Nick Bigelow, Rochester, Jason Williams, JPL, Cass Sackett, U Virginia, Nathan Lundblad, Bates College, Eric Cornell, U Colorado/JILA.
Customers/Adopters (Push): Decadal Review FP3 & FP2. NSF. NASA Science Instruments Roadmap (Quantum Interferometry). Technology applicable to 5 of 38 Exploration quantifiable capabilities quad charts.

Objective:

- Establish ultra-cold atomic physics in space and provide a cutting edge research facility for the NASA science community.

Experimental Approach:

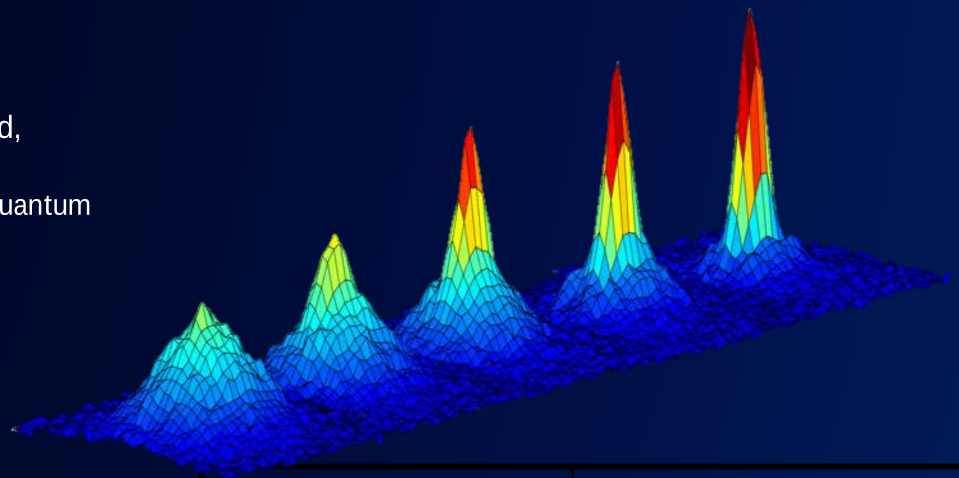
- Study evaporatively cooled atomic samples of 87Rb, 39K, and 41K
- Provide researchers with a state of the art suite of tools for ultra-cold atom studies including advanced state selection; Feshbach control of atom interactions and precision atom interferometry

Relevance/Impact:

- First multi-user research facility in space
- Exceptionally diverse and prestigious team of PI 's including 3 Nobel Laurates
- Decadal FP3: Cold Atom Research & FP2: Fundamental Forces, EEP violation, Stand. Model extension.
- Science Instruments Roadmap: Quantum Interferometry.
- Identified need in 5 of 38 exploration quantifiable capabilities quad charts, including precision landing, GW detection, and In-situ resource utilization (detection).

Project Development Approach:

- JPL continues remote operation of CAL and maintains testbeds
- Continue science module 3 operations through end of mission in Sep 2022.
- Complete installation of slice 7b and perform K science through end of mission in Sep, 2022
- Separate quantum science package includes CAL SM4 development, PI extensions until SM4 is ops ready, extension of CAL operations through FY26, and CAL closeout in FY27.



ISS Resource Requirements

Accommodation (carrier)	US Module Express Rack
Upmass (kg) (w/o packing factor)	300
Volume (m^3) (w/o packing factor)	0.4
Power (kw) (peak)	.85
Crew Time (hrs) (installation/operations)	TBD
Autonomous Operation	3 years
Launch	May 2018

Project start	CDR	Launch	Sci Ops Start	SM3 launch	Slice 7B launch	Final Report
Sep-12	Feb-15	May-18	Oct-18	Dec-19	Jun-21	Sep-23