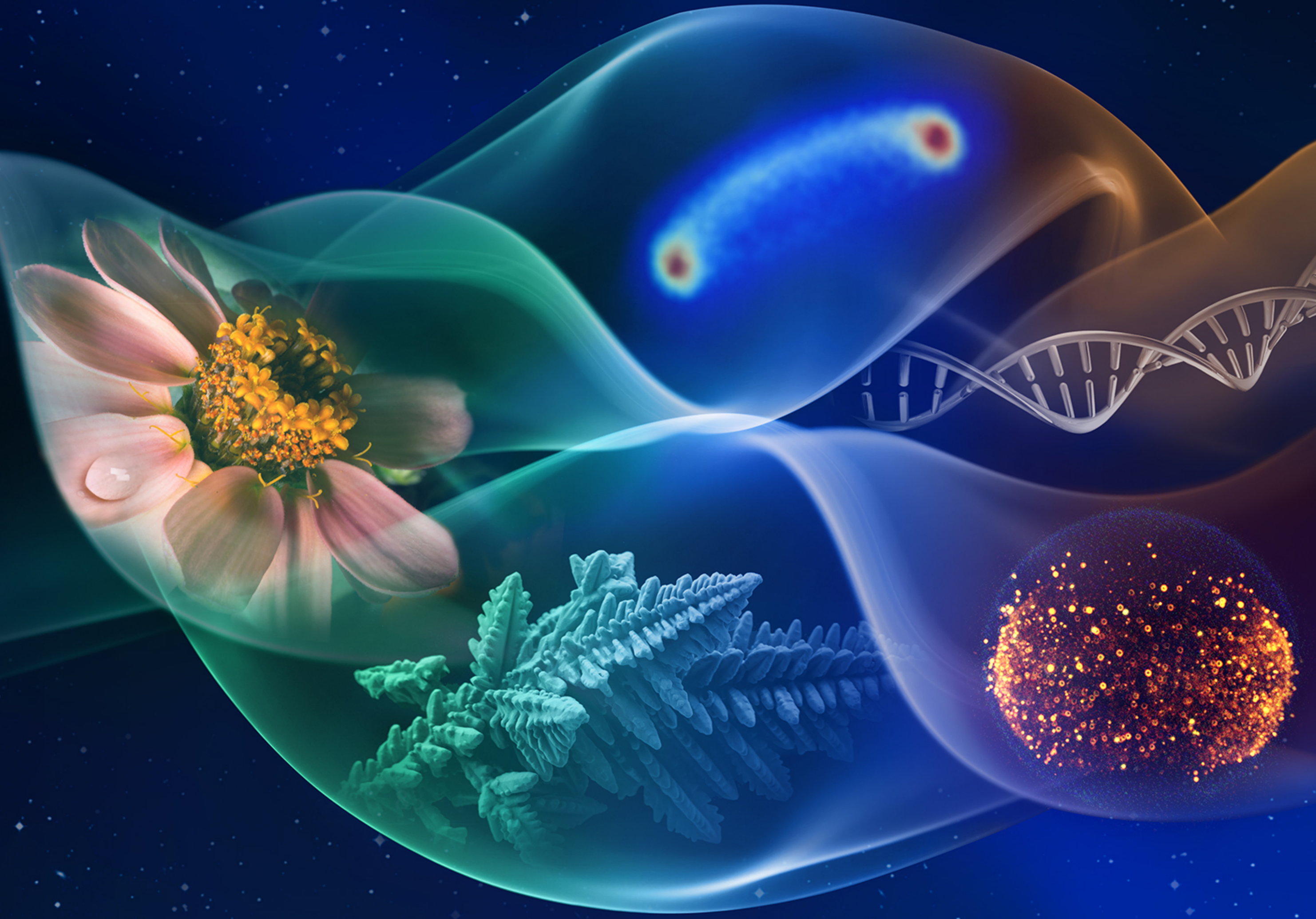
National Aeronautics and
Space Administration

# Biological and Physical Sciences

## Physical Sciences Focus Areas

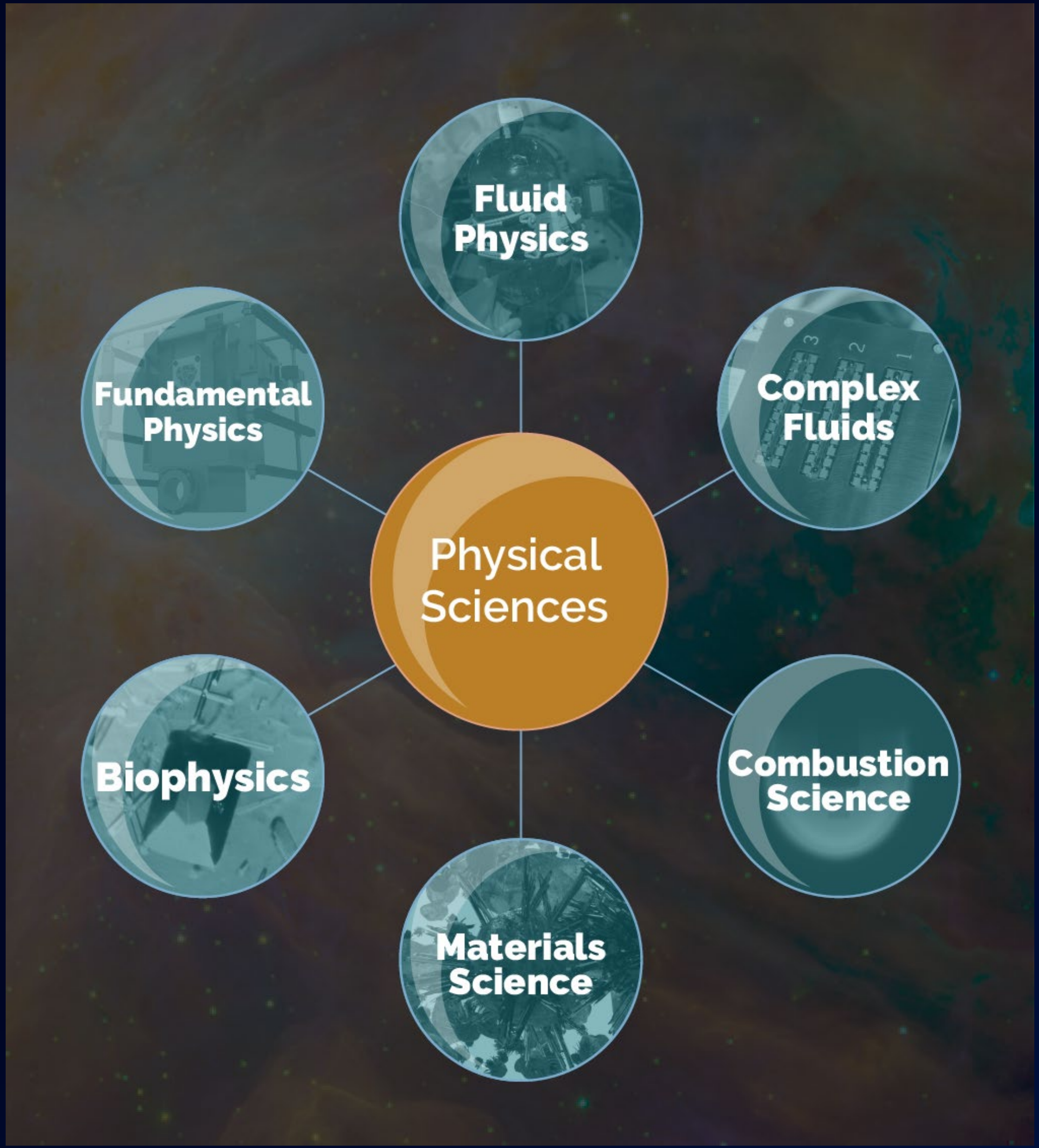


BPS Decadal Survey Panel Meeting #2
January 24, 2022

Brad Carpenter
Program Scientist

# Outline

- Overview of current program
- Soft Matter Focus
- Quantum Science Focus



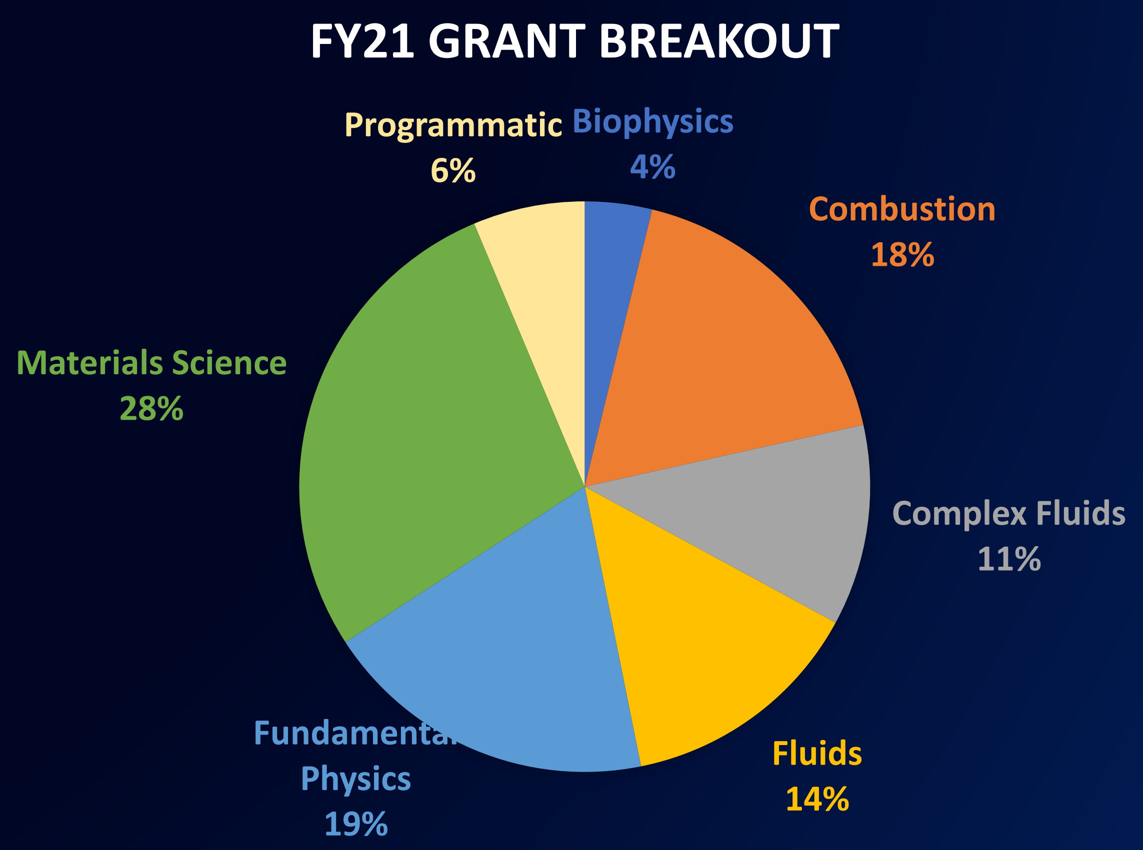

## Objectives

- Investigate **fundamental laws** of physics and physical processes, often using either microgravity or interplanetary distances as research tools
- Provide a **mechanistic understanding** 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 **technologies** to facilitate spaceflight research
- Promote **open science** through Physical Science Informatics
- Support the transfer of knowledge and technology of space-based research to terrestrial systems to **benefit life on Earth**

## Database

- Physical Sciences Informatics (psi.nasa.gov)

# Physical Sciences Content




| Total PS FY21 Grants | 99 |
|---|---|
| Flight | 66 |
| Ground | 33 |

| Number Directed vs Competed | |
|---|---|
| Directed | 2 |
| Competed | 97 |

taskbook.nasaprs.com

National Aeronautics and Space Administration

BPS
BIOLOGICAL AND PHYSICAL SCIENCES

# Physical Science Focus Areas

## Soft Matter

2011 Decadal Recommendation FP1, Research on Complex Fluids and Soft Matter

## Quantum Science

2011 Decadal Recommendation FP2, Research that Tests and Expands Our Understanding of the Fundamental Forces and Symmetries of Nature

2011 Decadal Recommendation FP3, Research Related to the Physics and Applications of Quantum Gases

# What is Soft Matter?

"Soft materials consist of basic units that are significantly larger than an atom but much smaller than the overall dimensions of the sample. …Soft matter is dissipative, disordered, far-from-equilibrium, non-linear, thermal and entropic, slow, observable, gravity-affected, patterned, non-local, interfacially elastic, memory-forming and active.

...

It is often a comfort to hide behind obscurity and complexity; *soft matter cannot take that road!" –Nagel, Experimental soft-matter science, Rev. Mod. Phys. 2017* *https://arxiv.org/pdf/1610.10013.pdf*

Other sources for the NASA Soft Matter plan:

Grand Challenges in Soft Matter Science: Prospects for Microgravity Research report (NASA/CP-20205010493)

Frontiers of Materials Research: A Decadal Survey (2019) http://nap.edu/25244

Plasma Science: Enabling Technology, Sustainability, Security, and Exploration (2020) http://nap.edu/25802

# NASA Soft Matter Heritage

1976 First granular media mechanics flight project – Stein Sture (Shuttle experiments 1990's-2000's)

1987 First colloids research grant - Bill Russel

1992 First flight projects selected - Dave Weitz, Paul Chaikin – hard sphere colloids phase diagram experiments on Shuttle, Mir

1990's Magnetorheological fluids – Alice Gast/Eric Furst (first flight ~2003)
- Extensional rheology - Gareth McKinley (first flight 2008)
- Liquid crystal flight project – Noel Clark (first flight 2015)
- Dusty Plasma experiments – John Goree and others (first flight 2001, DLR/RSA hardware)

2010-2021 Second generation colloid physics
- Structured materials – Ali Mohraz bijel experiments
- Directed Assembly – David Marr Janus particle experiments
- Entropically driven phase behavior – Khusid/Chaikin, Arjun Yodh, Dave Weitz experiments

# Current and Future International Soft Matter

FOAM – Foam Optics and Mechanics (ESA) U.S. PI Doug Durian

PASTA – Particle Stabilized Emulsions and Foams (ESA) U.S. PI James Ferri

Plasma Krystal-4 – (ESA/DLR/RSA) U.S. PIs John Goree, Uwe Konopka, Truell Hyde (NSF-funded)

COMplex PlAsma faCiliTy for ISS (COMPACT) – Development Phase B., with DLR developing hardware.  DLR, NASA, and NSF to provide investigators

# Elements of the Soft Matter Initiative

### Ground-Based Research

- ✓ Ground-based microgravity facilities
- ✓ Modelling
- ✓ Annual Funding Opportunities

### Space-Flight Research

- ✓ Physical Science microscope on ISS
- ✓ Use IP and commercial hardware available on ISS
- ✓ Proposal call every 3 years

### Soft Matter facility (*post-decadal)*

- ✓ Low earth orbit
- ✓ Beyond low earth orbit

### AI/ML/Big data platform

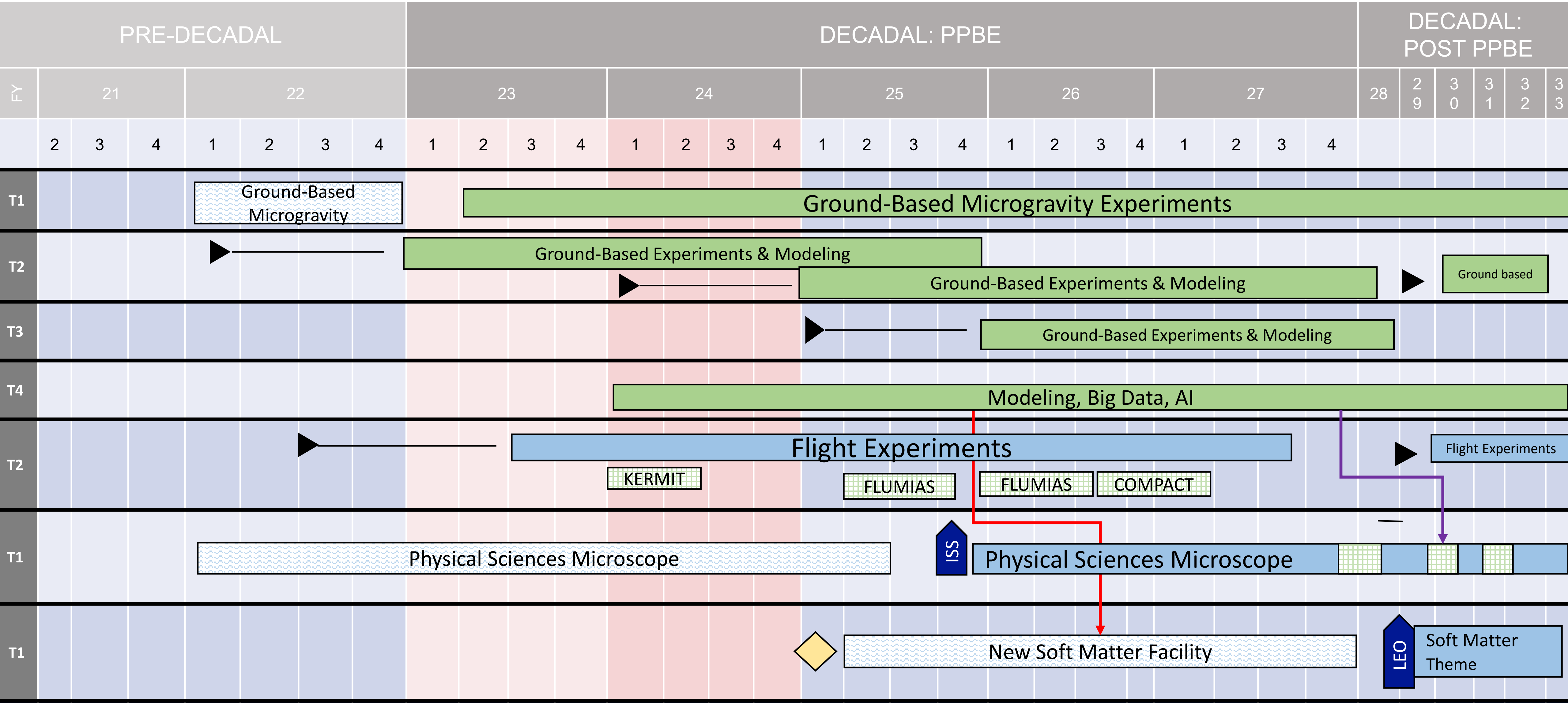
- ✓ Improved computation
- ✓ Better experimentation, imaging, and data analysis

Soft Matter Dynamics aims to improve the understanding of nonequilibrium phenomena to enable the *control and use* complex soft matter dynamical systems

Decadal guidance will shape the future of this initiative

# Dynamics of Soft Matter Hardware Roadmap

**Advance the understanding of nonequilibrium phenomena from nano- to large- scale systems to understand, control, and use complex soft matter dynamical systems**



# Quantum Science – A burgeoning field

- **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**


# Current Quantum Science Research

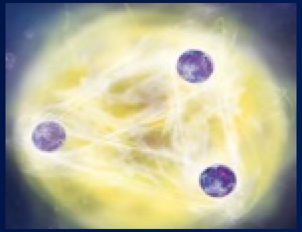
Atomic Clock Ensemble in Space – ESA project, NASA providing technical support and ground links. 1E-16 clock measures gravitational red shift – 3 PIs

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 Ru. K capabilities coming with installation of new electronics – 5 PI teams

# 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

# Quantum Science Mission Concept Areas

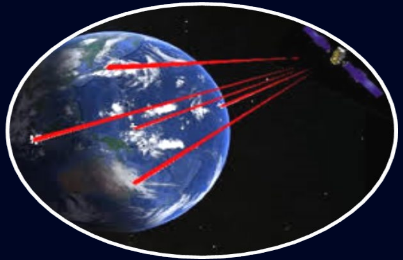
- **Quantum Matter – the physics of few- to many-body quantum systems**
- **General Relativity – precision metrology exploring the limits of GR**
- **Dark Matter and Dark Energy – quantum mechanics applied to search for signatures of DM and DE**
- **Quantum Mechanics – Entanglement in relativistic systems;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

Future BPS investment in these concept areas will be guided by Decadal priorities

# Quantum Science Decadal Keystone Mission Candidates

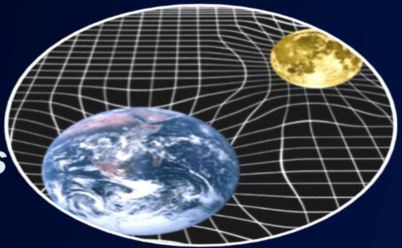
## Research on Free Flyers

Gravitation and Dark Matter



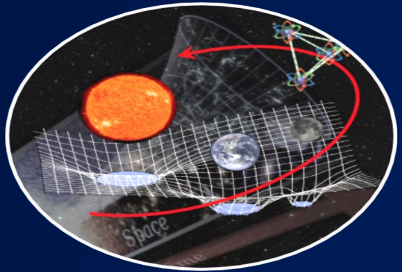
Fund Physics with Optical Clock Orbiting in Space (FOCOS)

Quantum/ Gravitation Correlations



Space Experiments Exploring Quantum Entanglement and Relativity(SEEQER)

Gravitation and Dark Energy

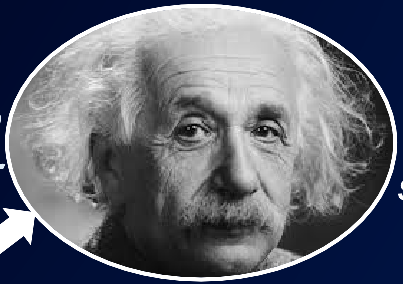



Gravity Observation and Dark Energy Detection Explorer in the Solar System (GODDESS)

---

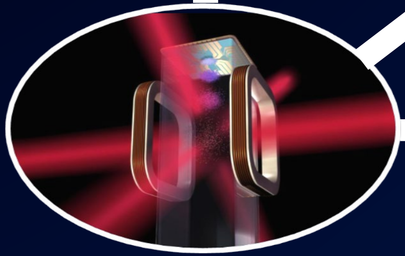
## Research on crewed platforms (ISS, Gateway, etc.)

Gravitation with Quantum Matter



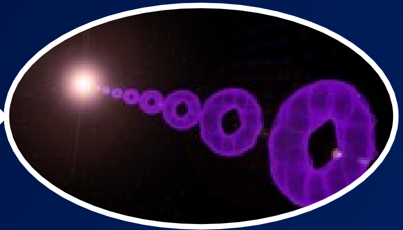
Quantum Test of Equivalence and Space Time (QTEST)

Quantum Matter



CAL SM4

BECCAL (DLR)



Quantum Explorer (QUEX)

# ISS/Gateway Keystone Mission Candidate - Quantum Explorer

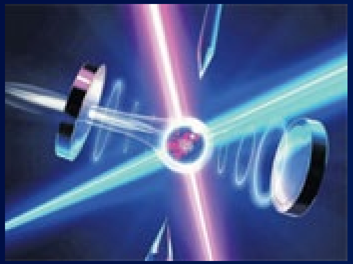
## Objectives
- Investigations of the Nature of the Quantum Vacuum
- Explorations of Quantum Chaos and Pattern Formation
- Atom lasers and matter-wave holography
- Matter-wave localization
- Quantum simulation of the early universe, black holes, neutron stars, etc

## 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

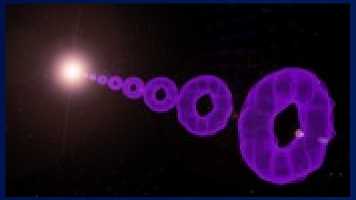
## Approach
- Highly reconfigurable open design
- ISS Express Rack implementation
- Utilize astronauts or commercially-flown PIs as space-based quantum scientists
- Customized, PI driven, design of science modules
- Select flight PIs through ROSES NRA

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

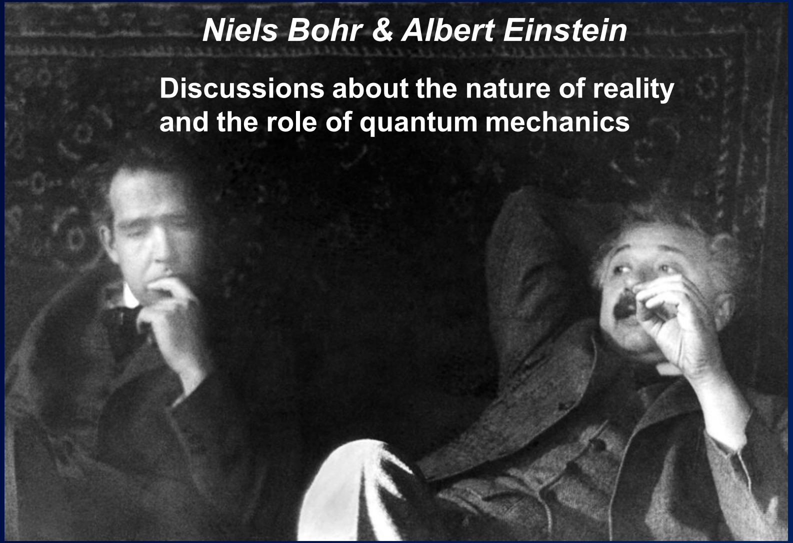
### Relevance/Impact

- 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

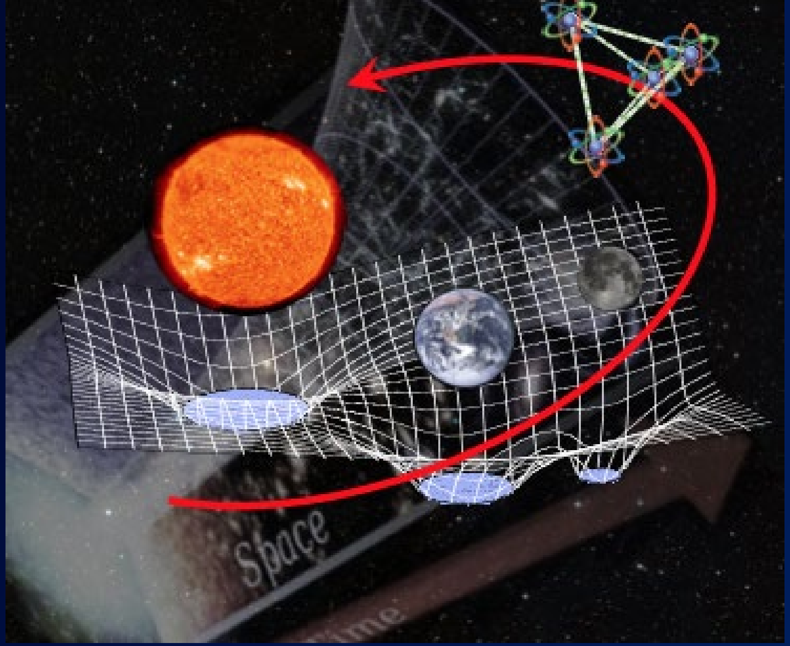
**Objective**
- Use atom interferometry to seek direct evidence of a class of proposed scalar-field dark energy candidate particles screened near regular matter
  - Chameleon, Symmetron, Galileon
- Search for ultra-light (<< 1 eV) dark matter candidates
- Search for deviations from General Relativity
- 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

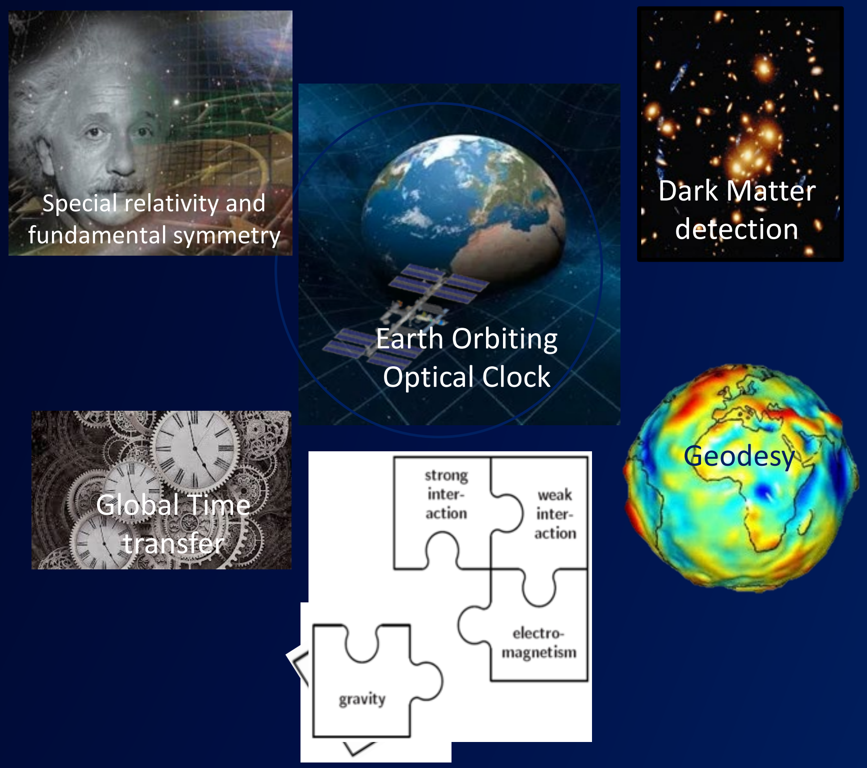
- 2004: PDR for NASA's Primary Atomic Reference Clock in Space (PARCS); Neil Ashby, NIST
- 2006: Study Complete for Rubidium Atomic Clock Experiment (RACE); Kurt Gibble, Penn State
- 2010 & 2014 ESA Cosmic Vision M4 proposals (SAGAS & STE-QUEST)
- 2017: Completion of 2 NRA investigations to support ESA's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



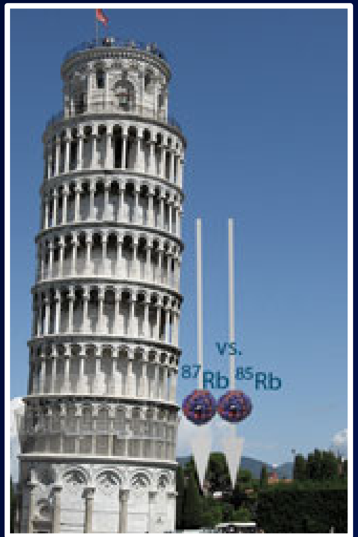
# ISS/DSG Keystone Mission Candidate - QTEST
## Quantum Test of Equivalence and Space Time

### 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.

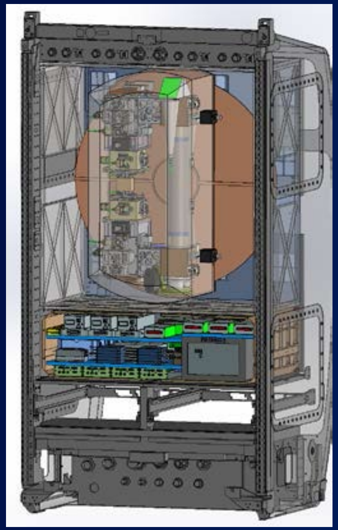
### Heritage
- 2006: Completed 5-year flight study "Quantum Interferometer Experiment (QuItE) " (Kasevich, Stanford).
- 2014: ESA M4 STE-QUEST Mission proposal
- 2017: Completed study of ESA's Quantum Weak Equivalence Principle (QWEP). (Mueller, Berkeley)
- 2017: Completion of Quantum test of Equivalence (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)

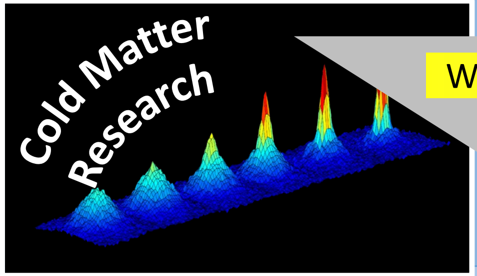


Pisa

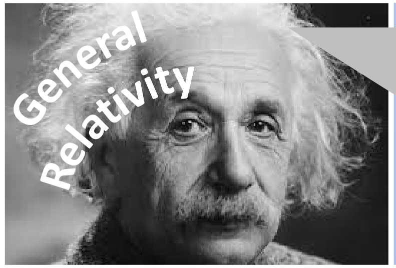

ISS QTEST payload

Quantum Science Roadmap

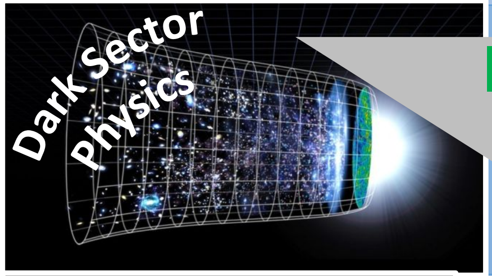
| Present | Near Term | Formative | Visionary |
|---|---|---|---|



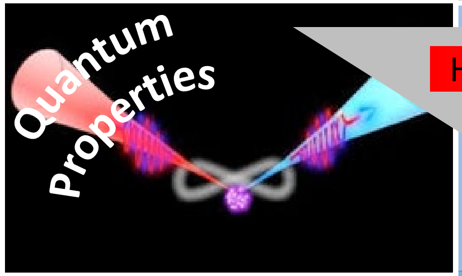

- What are the properties of quantum systems of atoms and molecules?
- How can we design useful science systems and sensors using quantum properties?
- How does complexity & order arise from Quantum interactions?




- 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?




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




- 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?

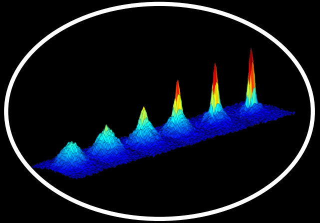
Missions

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

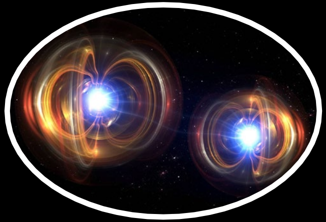
# Making Quantum Leaps in Quantum Science by

*Seeking answers to today's most intriguing questions*

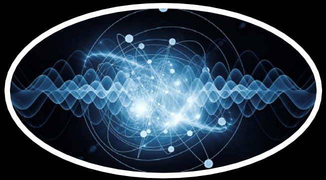
## Exploring the Quantum Realm



- What are the Quantum Properties of atoms and molecules?

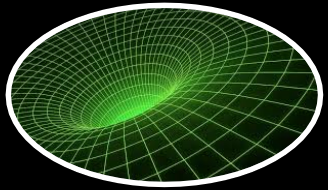


- How is Quantum Entanglement influenced by gravity?

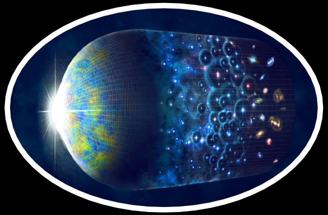


- How does complexity & order arise from Quantum interactions?

## 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