*Fundamental Physics Research in Space**

ISS Research Academy Briefing

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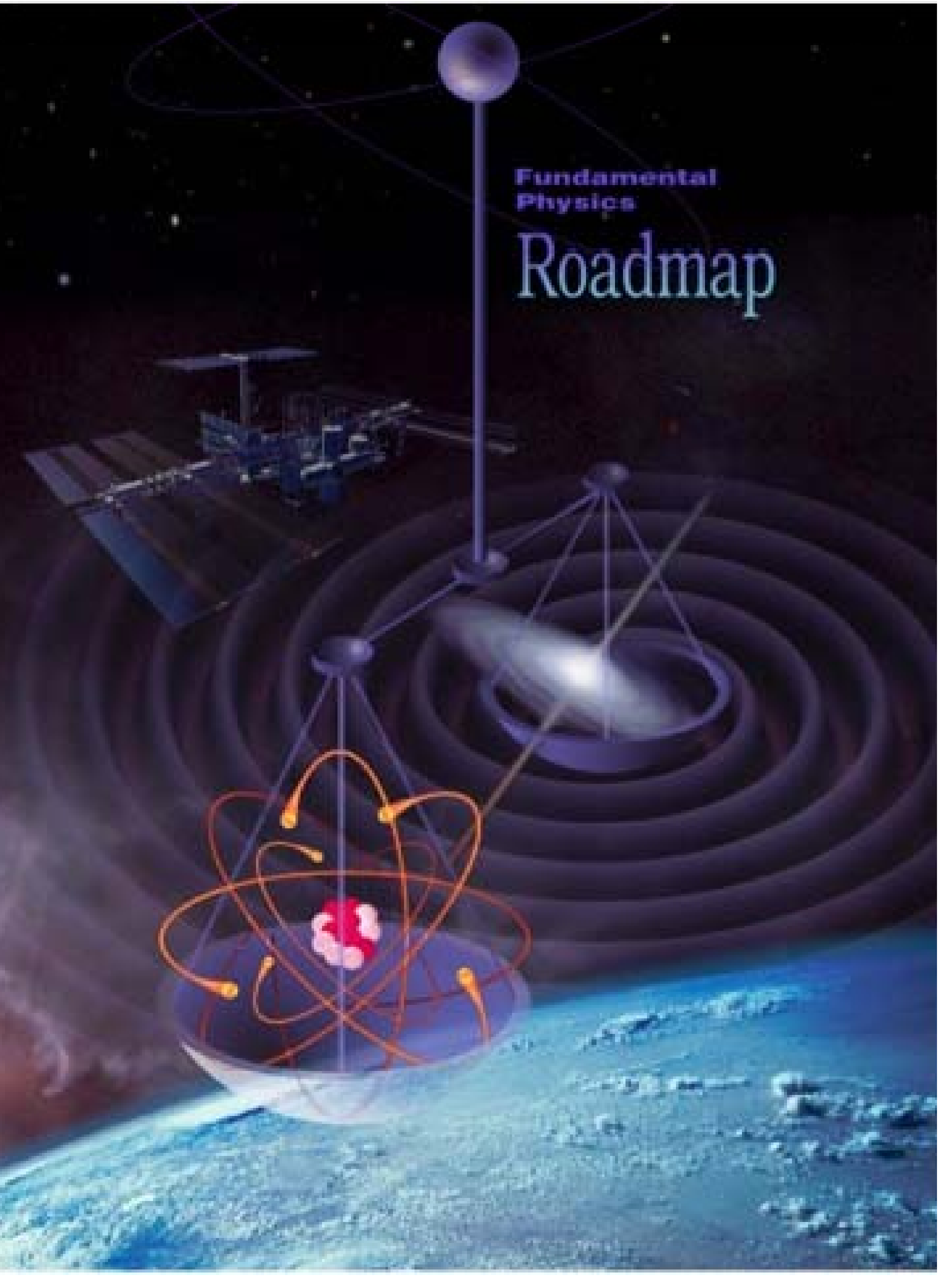
Fundamental Physics Research in Space

AGENDA

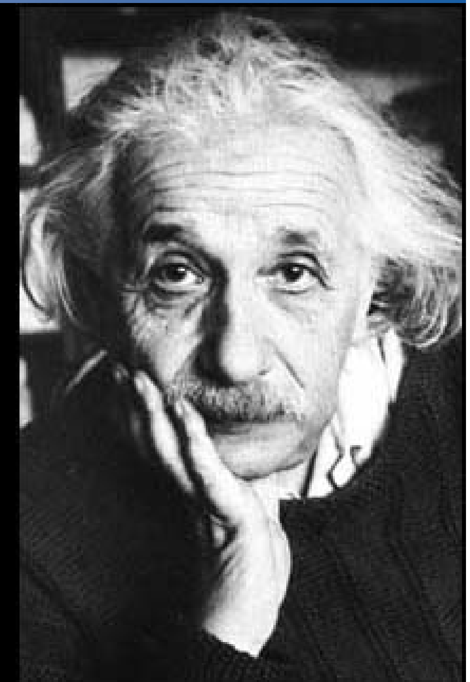
- **Physics in the 21st Century**
- **Laboratory versus Observational Physics**
- **Benefits of Space Experimentation**
- **Planned experiments and activities**
- **Advanced Technology**
- **Conclusions**



Context: Fundamental Physics in the 21st Century

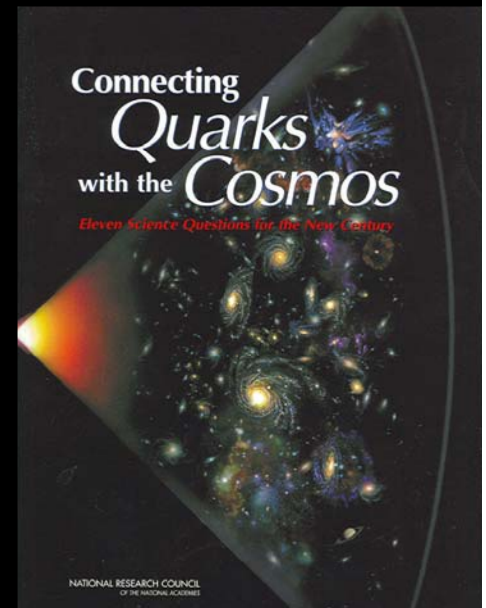
- **Physics is standing at the threshold of major discovery**
  - **Our two foundational descriptions of nature, quantum mechanics and general relativity, are incompatible with each other.**
  - **When this conflict is resolved, a different view of reality may emerge that unifies matter, space, and time.**

- **Cosmological observations are providing additional clues that our understanding of reality is in need of drastic modification.**
  - **Only 4% of the Universe energy content is known.**
  - **23% is in the form of some unknown dark matter**
  - **73% is in the form of an unknown dark energy that is accelerating the expansion of the Universe**



Quarks to Cosmos - 11 questions for the new century

- **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?**



NSF
NIST
DOE
NASA SMD
NASA SOMD

Laboratory versus Observational Physics

OBSERVATIONAL PHYSICS - SMD

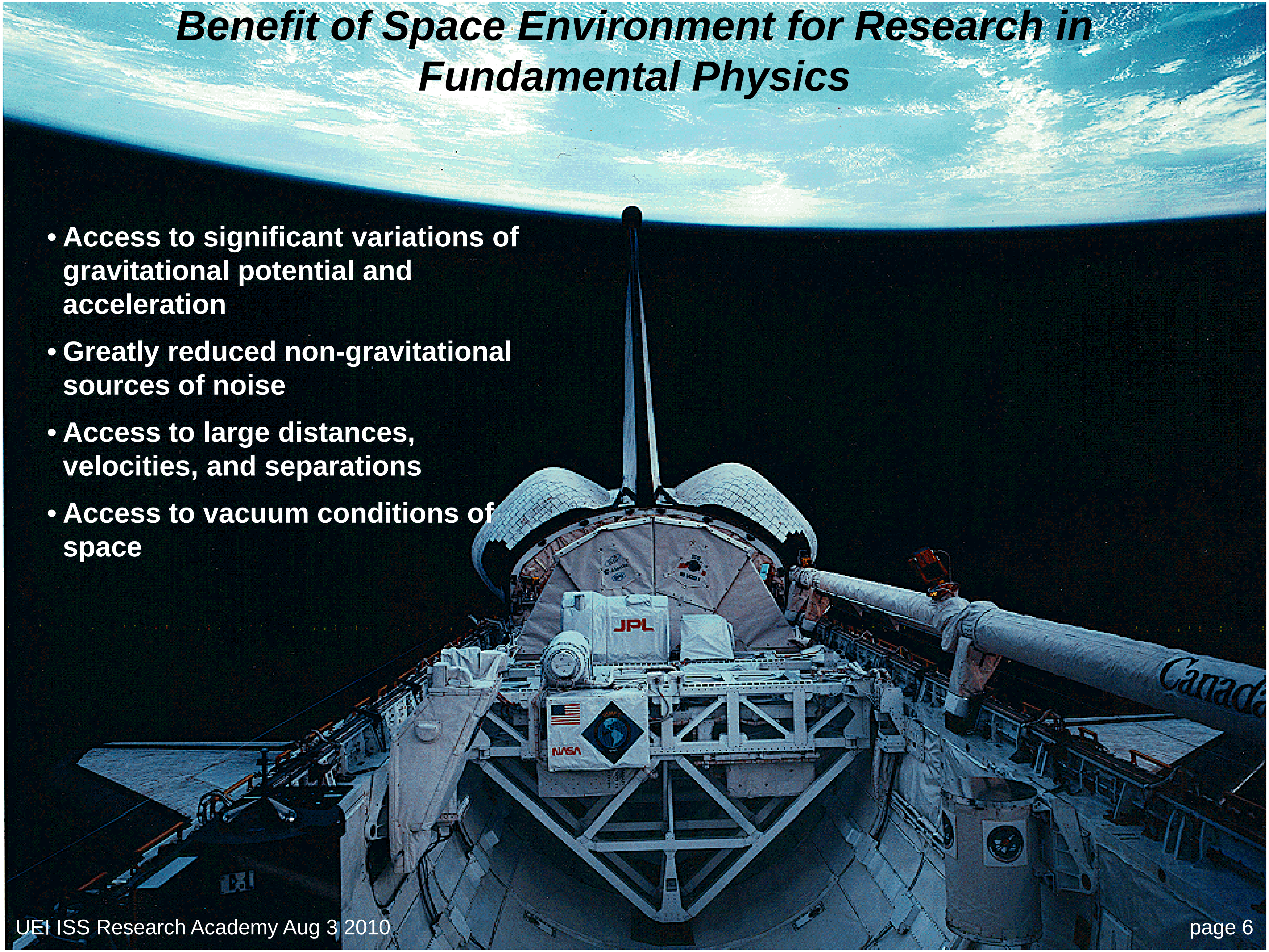
- **Studies are exclusively <u>observational</u> in nature with signals emanating beyond the solar system.**
- **Understanding the source and location of the signals is crucial.**
- **Domain of the current Beyond Einstein program**
    - **Gravity waves, strong gravity tests of GR, dark energy surveys, dark matter searches, CMB measurements, high energy cosmic rays.**

LABORATORY PHYSICS – ESMD/SOMD

- **Studies of matter, space, and time using space laboratories.**
- **Test mass or specimen under study resides in the laboratory**
- **Gravitational Physics, Critical phenomena, Physics beyond the Standard model.**

Benefit of Space Environment for Research in Fundamental Physics

- **Access to significant variations of gravitational potential and acceleration**
- **Greatly reduced non-gravitational sources of noise**
- **Access to large distances, velocities, and separations**
- **Access to vacuum conditions of space**



Laboratory Fundamental Physics Quests

and Explore
tal Physical
Law g Matter,
Spa ime

Discover and
Organizin
Nature fr ructure
and C y Emerge

In Pursuing ou Quests we will:

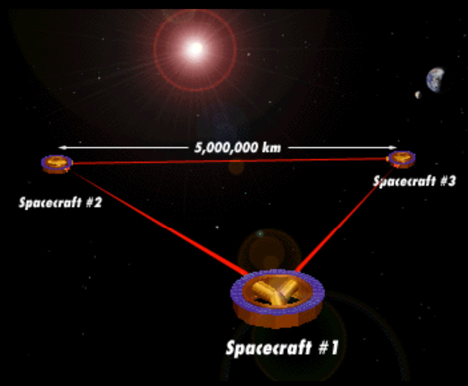
d

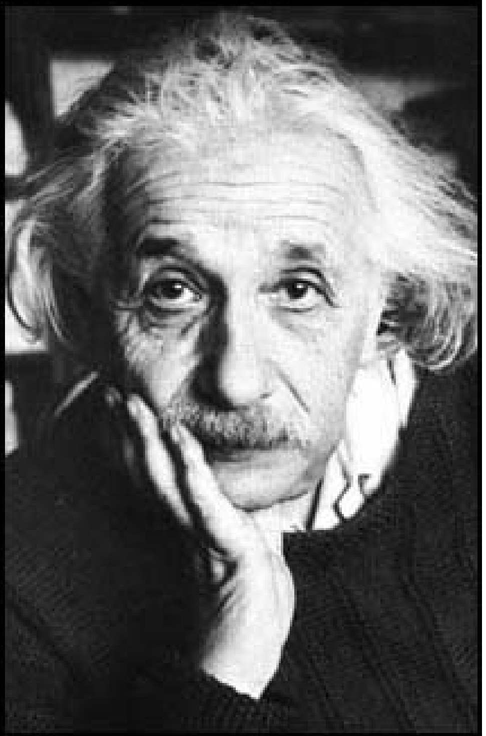
Fulfill the Innate Human Desire to Understand our Place in the Universe

Build the Foundation for Tomorrow's Breakthrough Technologies

Solving the mystery of gravity- how can NASA contribute?

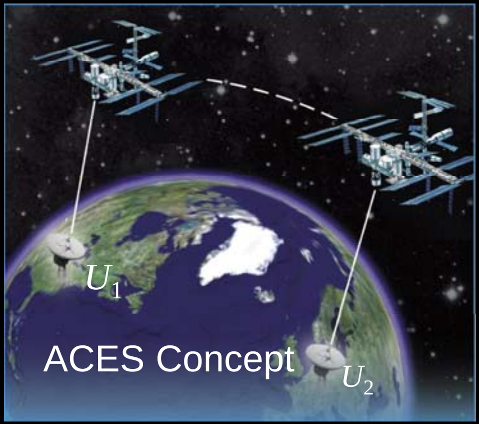
- **Survey and explore the conditions near black holes.**
  - **Observational physics only**
- **Directly detect gravitational radiation from black holes, neutron stars, and other astrophysical sources.**
  - **Observational physics only**
- **Test the inverse square law of gravity at distances from sub-millimeter to planetary scales to search for violations**
  - **Laboratory physics only**
- **Test Einstein's equivalence principle to exquisite precision to uncover new forces**
  - **Laboratory physics only**
- **Perform high precision laboratory tests of General Relativity in the solar system**
  - **Laboratory physics only**

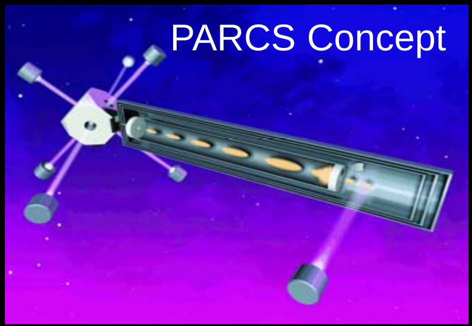




What lies beyond the Standard Model of Physics? – how can NASA contribute?

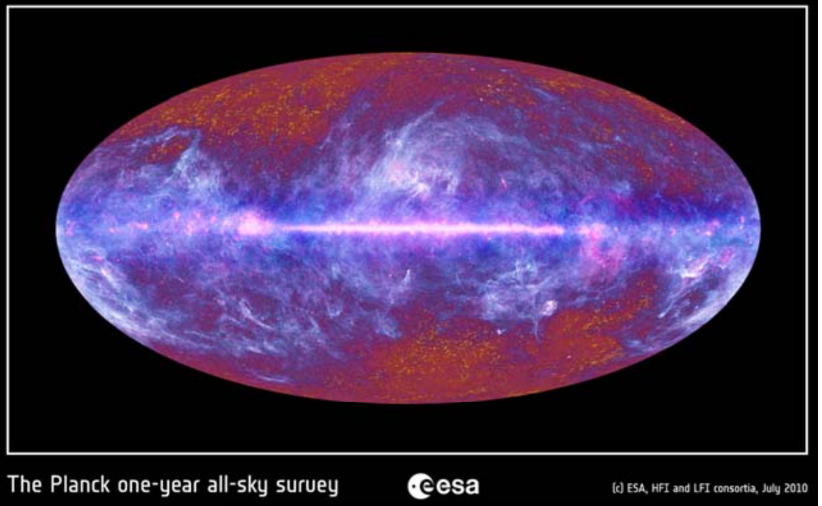
- **Determine the origin and identity of nature's most energetic particles.**
  - **Observational physics only**
- **Detect proton decay to provide crucial information about the unification of forces. - Laboratory physics in space may contribute through:**
  - **Determining the edm of the electron**
- **Is special relativity valid under all conditions? – Clock experiments in space can contribute through:**
  - **Local Position Invariance tests**
- **Are nature's constants really constant? – Clock experiments in space can contribute through**
  - **High resolution measurements of alpha-dot**
  - **Isotropy of the speed of light**
- **Are there compacted unseen dimensions? – Laboratory physics in space can contribute through:**
  - **Sub-mm inverse square law measurements**

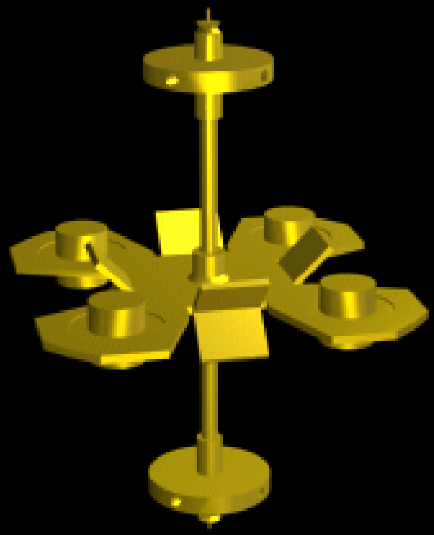




What is the dark matter? – how can NASA contribute?

- **Map the distribution of dark matter in galaxies, clusters of galaxies, and throughout the universe.**
  - **Observational physics only**
- **Identify dark matter particles and measure their properties - Laboratory physics can contribute through:**
  - **Discovery of Newton's force law violations**
  - **Discovery of Equivalence Principle violations**
- **Search for other relics of the Big Bang - Laboratory physics can contribute through:**
  - **Existence proof search for relics**



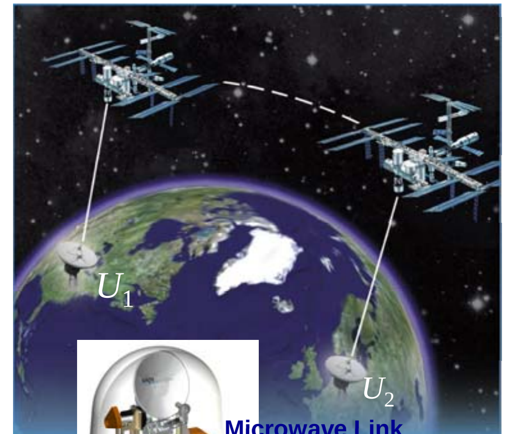


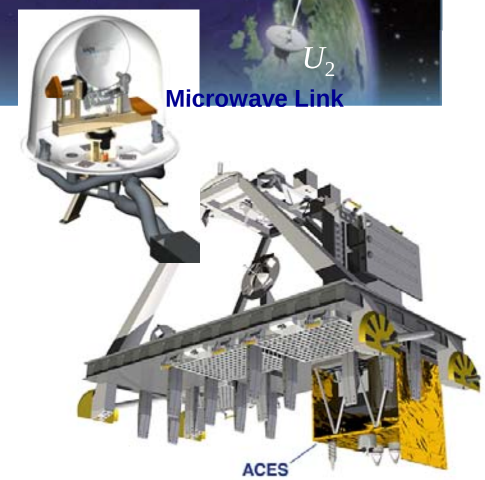
1/r^2 test cell

Atomic Clock Ensemble in Space (ACES) NASA Collaboration

Jet Propulsion Laboratory

U.S. PI: **TBD**
ESA Project Scientist: **Luigi Cacciapuoti, ESTEC**





Objectives:

- Contribute to ESA objectives to validate a space clock to the 10^-16 level; perform frequency transfer to the Earth at the same stability level; and to test general and special relativity to high accuracy.
- Establish an ESA-NASA collaboration on Fundamental Physics in Space

Relevance/Impact:

- Improved knowledge about fundamental laws of nature.
- Improved technology for space science (laser ranging, geodesy) and space exploration applications (autonomous navigation, formation flying)
- Improved technology for applications of societal, commercial, and national security importance (navigation, time-keeping, GPS, metrology).
- High educational and outreach value to validate importance of ISS research and inspire the next generation.

Development Approach:

- ACES flight hardware developed by CNES and European partner nations
- ESA will deliver a microwave ground link to JPL to integrate in frequency standards laboratory
  - Links also at 5 additional locations
- JPL scientists will compare the ACES clock stability aboard the ISS with the JPL Hg-ion clock using the microwave link and participate in data analysis and publications.
- Launch is planned in 2013 followed by a 12-18 month operations phase.

DECLIC ALI NASA/CNES Collaboration

U.S. PI: TBD
CNES Team Coordinator: Daniel Beysens, CEA Grenoble

NASA Objectives and Contributions:

- Study the temperature and density relaxation behavior near the critical point in both single and two-phase region
- Compare the relaxation time measurements with theoretical predictions
- Study of boiling and phase separation behavior of critical fluids under zero-gravity conditions

Relevance/Impact:

- Critical phenomena of fluids is used as a well-defined test bed to understand physical behavior that can be extrapolated to complex systems used in space applications such as two-phase flow system and retention and storage of cryogens.
- Tests the Nobel prize winning theory which is used to predict behavior in a variety of other complex systems.
- Re-establish US role in fundamental physics on the ISS.

Development Approach:

- DECLIC and ALI Hardware developed by CNES
- Hardware launched by NASA. ALI insert just launched.
- Plan to operate early FY11 for about 6 months
- Data analysis and publications for 12 months beyond that

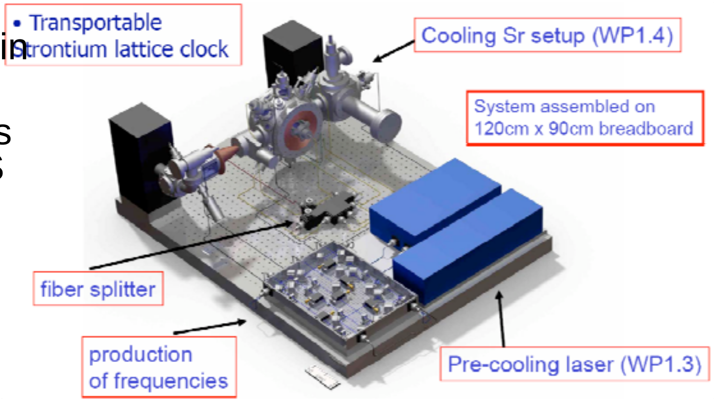
Fundamental Physics NASA Research Announcement

Jet Propulsion Laboratory

Physical Science Program Executive: Dr. Francis Chiaramonte, NASA HQ
Fundamental Physics Element Manager: Dr. Ulf Israelsson, JPL

Objective:

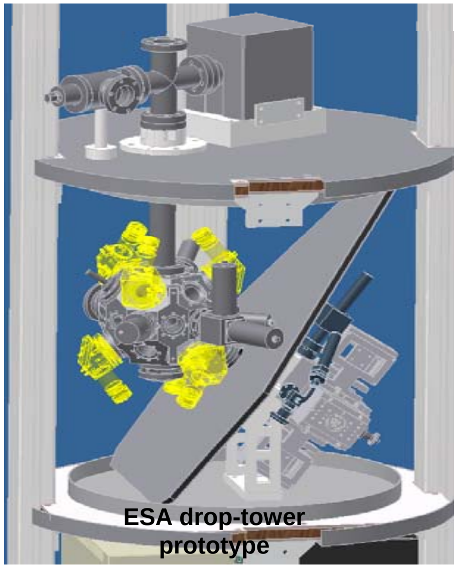
- Develop a fundamental physics 2011 NRA with funding to start in FY12.
- Through a barter agreement with ESA, selected US researchers participate in planned ESA ACES follow-on activities on the ISS
  - ISS Optical Clock stable to 10^-17
  - ISS Atom interferometer



ESA Sr Clock concept

Relevance/Impact:

- Recover U.S. leadership role in these critical space technologies.
- Advanced clocks and atom interferometers are key ingredient in many fundamental physics experiments; benefit space science and space exploration; and have societal, strategic, and commercial importance on Earth.
- Improved inertial technology applications (accelerometers, gradiometers, navigation, etc.) with orders of magnitude better resolution than current devices.
- Draw energetic new scientists and engineers into NASA and inspire the next generation.



Approach:

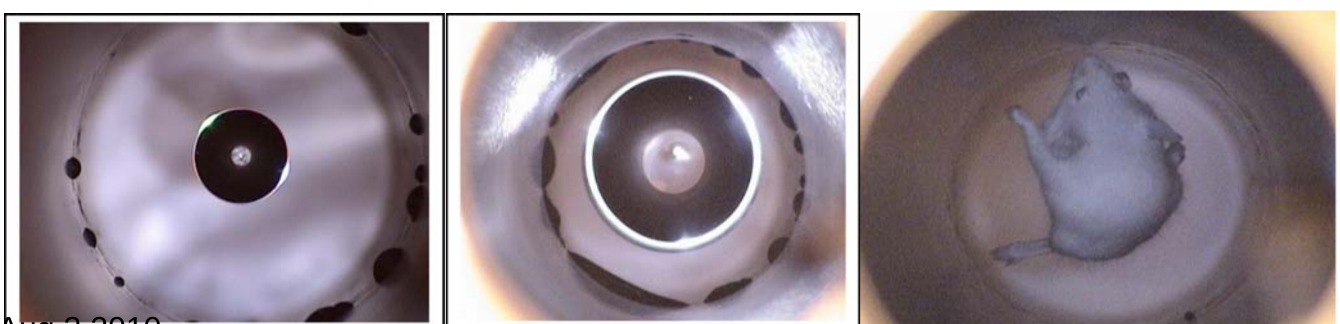
- Hold NRA workshop in FY10, develop and release NRA in FY11, start community funding in FY12.
  - Aug/Sep 2010 “blue-ribbon” workshop planned jointly with Europeans
- Develop barter agreement in FY11.

Relationship between Physics and Technology

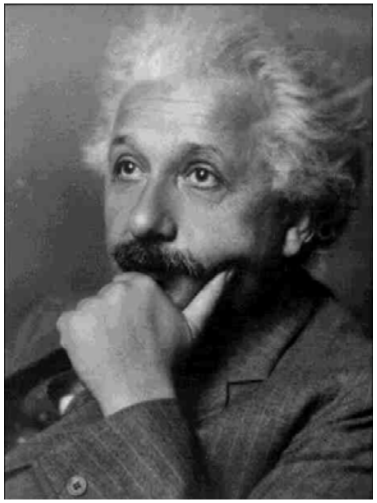
- **Expanding the frontiers of physics requires new improved sensors, approaches, and technologies.**
- **These new technologies invariably find their way into applications that benefit society and US competitiveness**
  - **Laser**
  - **NMR/MRI**
  - **Computer devices, WWW**
  - **Atomic clocks, GPS**
- **New scientific insight can itself also lead to applications – once some behavior of the physical world is understood well enough to be modeled, it can be manipulated to support societal needs.**
  - **Technology examples above started out as new physics.**
  - **Progression from TRL 0 to applications can take decades**
- **Today's physics is the foundation for tomorrow's breakthrough technologies.**

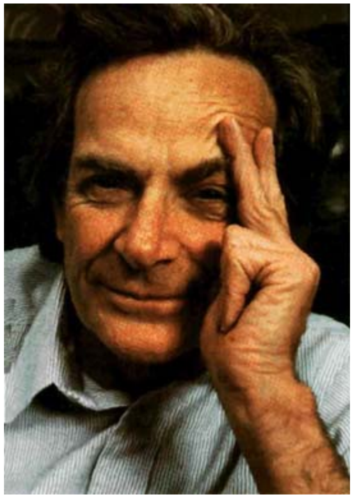
Examples of Physics Technologies

- Atomic clocks stable to one part in 10^17
  - 5 second drift since the Universe was born
- High resolution thermometry accurate to a few parts in 10^11
  - Can in principle detect the cooling of the cosmic microwave background radiation as the Universe expands
- Atom interferometer is intrinsically 10 orders of magnitude more sensitive to an inertial force than light interferometers
  - Do not require cryogenic cooling
  - Microscopic quantum particles
  - Provides drag-free test mass measurements without a drag-free satellite
  - Is 1000 times more sensitive if operated in zero-g.
- Low-gravity simulator developed at JPL provides a tunable gravity environment from 0g to +2g for low-gravity fluid and life science research.



Physics and Exploration





"There are grounds for cautious optimism that we may now be near the end of the search for the ultimate laws of nature."
— Stephen Hawking

"Nature uses only her longest threads to wave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry."
— Richard Feynman

Conclusions

- Performing carefully crafted fundamental physics experiments on the ISS can allow NASA SOMD to answer some of the most challenging questions facing humanity today.
- The insights may profoundly change our view of Nature and our role in it and open up heretofore unimaginable technologies to serve humanity.
- All atoms (of the same kind) are created equal and have built in clocks represented by hyperfine transitions. These atoms can be used as highly sensitive clocks, atom interferometers, and atom lasers with unprecedented accuracy.
- ESA is eager to collaborate with US scientists to validate new technologies and test foundational principles of nature.
- NASA SMD performs observational physics that seeks answers to today's important physics questions.
- Other US agencies (NSF, NIST, and DOE) have complementary ground research programs addressing the same questions.
- Today’s fundamental physics activities provides the foundation for tomorrow’s technologies and can uniquely inspire our next generation.