An Overview of NASA Fundamental Physics

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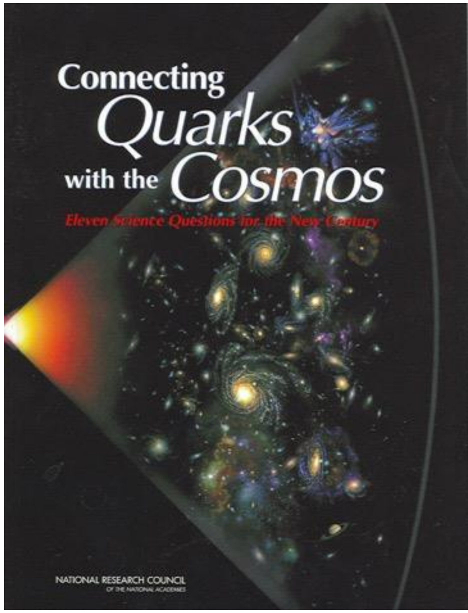
Space Life and Physical Sciences
Research and Applications Division

Committee on Biological and Physical Sciences in Space
Irvine, California
14 December 2016

Today's important physics questions
Quarks to Cosmos - 11 questions for the new century

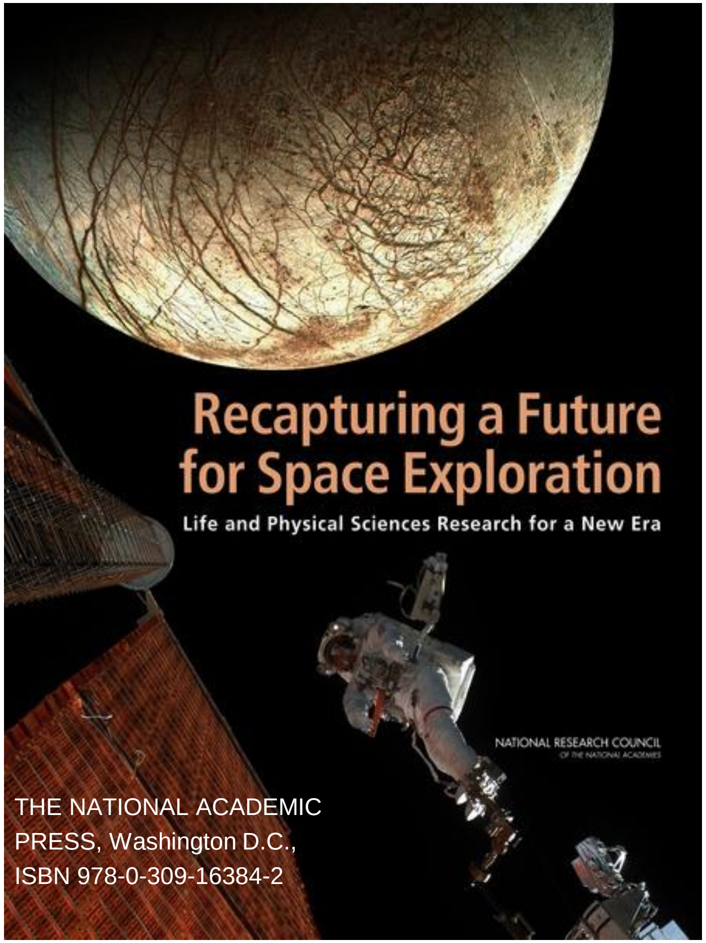
- What is dark matter?
- What is the nature of the dark energy?
- How did the Universe begin?
- Did Einstein have the last word on gravity?
- What are the masses of neutrinos and how have they shaped the evolution of the Universe?
- How do cosmic accelerators work and what are they accelerating?
- Are 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 HEOMD

NRC 2011 Decadal Recommendations to NASA 1/2

- Fundamental Physics Recommendations:
  - Research on Complex Fluids and Soft Matter
    - Complex/Dusty Plasma
    - PK-3, PK-4, PlasmaLab, DECLIC-insert
  - Research That Tests and Expands Understanding of the Fundamental Forces and Symmetries of Nature
    - ACES, SOC, QWEP, QTEST
  - Research Related to the Physics and Applications of Quantum Gases
    - CAL
  - Investigations of Matter in the Vicinity of Critical Points
    - DECLIC



THE NATIONAL ACADEMIC PRESS, Washington D.C., ISBN 978-0-309-16384-2

NRC 2011 Decadal Recommendations to NASA 2/2

Recommendation 1: A successful exploration program in the physical sciences requires a ground-based fundamental physical sciences program. An ongoing ground-based program must be established to support flight commitments in the fundamental physical sciences.

Recommendation 2: Flight experiments and facilities that are available for a rapid return to flight should be peer reviewed for possible return to flight. To justify this the committee points to the numerous existing experiments and supporting facilities that are at an advanced stage of flight readiness.

Recommendation 3: In funding projects, NASA should seek partnerships with other agencies and other nations. Research in fundamental physical science is supported by a range of federal agencies in the United States and is widely supported internationally.

Recommendation 4: NASA should build a program in fundamental physical sciences sufficiently large enough, including flight and ground-based investigators, to attract prominent scientists, create a vibrant ground-based program, and generate potential space-based missions.

Status of implementing Decadal Recommendations

	ISS Fundamental Physics	CY13	CY14	CY15	CY16	CY17	CY18	CY19	CY20	CY21	CY22	CY23	CY24
FP1	Complex Fluids and Soft Matter	PK3		PK4					DECLIC-EVO-Dusty Plasma Insert				
FP2	Fundamental Forces and Symmetries in Nature	SOC, QWEP, QTEST Studies				ACES			SOC, QWEP, QTEST Implementation				
FP3	Physics and Applications of Quantum Gases	CAL Study				CAL			CAL Upgrade and Follow-on				
FP4	Critical Phenomena	DECLIC-ALI				DECLIC-ALI-R		DECLIC-EVO Critical Phenomena Insert					
REC1	Vigorous Ground Based Research program												
REC1	Adequate flight experiment and facility hardware												
REC1	International and Other U.S. Agency Partnerships												
REC1	Adequate size investigator community												

Legend

- Not meeting Decadal Recommendation
- Marginally meeting Decadal Recommendation
- Meeting Decadal Recommendation

The ISS Cold Atom Laboratory – Answering today's critical scientific questions

CAL1 2017 ➔ CAL2 (upgrade) 2019 ➔ CAL3 –Dark Energy 2021 ➔ CAL4 –QTEST? 2023

Unique Space Environment

- Microgravity
- Low vibration
- Large spatial extent
- Large gravitational field variation
- Free from atmospheric interferences
- Inertial frame

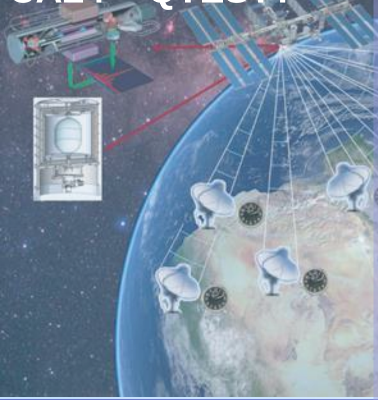
Fundamental Physics and Applications

- Relativity theories
- Standard Model
- Fundamental symmetry
- Equivalence Principle
- Gravity physics
- Cosmology and quantum decoherence
- Cold Atoms
- Bose Einstein Condensation
- Planck-Scale Physics

Technology verification

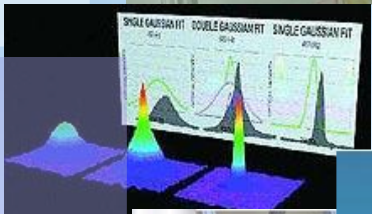
- Ultra-stable clocks
- Ultra-stabilized lasers and optical frequency combs
- Precision time transfer and ranging
- Atom interferometer inertial sensors
- BEC and quantum degenerate gas
- Gravity Wave Atom Interferometry

CAL4 – QTEST?

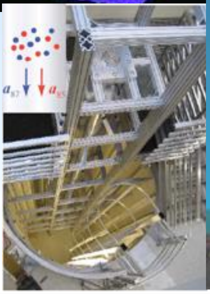


Approach

- Initial low cost effort through international collaborations
- Engaging science and research community
- Modular capability and hardware build-up from science engagement, to instruments, to missions
- Seek multi-agency collaborations with NIST, DoD and DOE

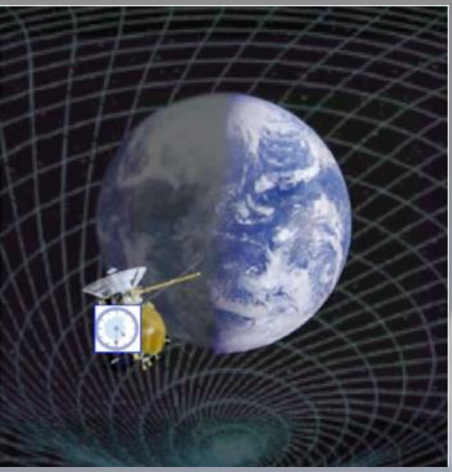


CAL1 & CAL2

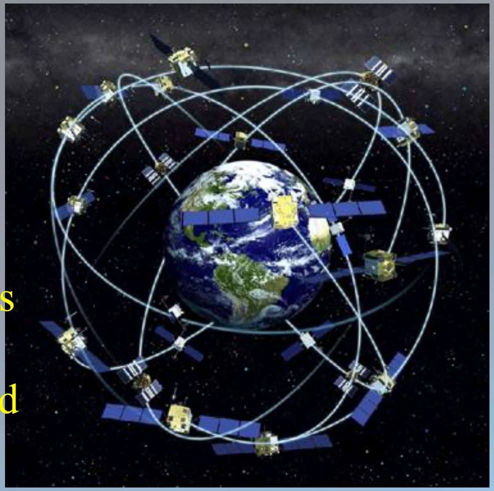


CAL 3- DE

The ISS Cold Atom Laboratory is evolving and translational - from laboratory science, to national security, to GPS guidance in daily life



Fundamental Science
- Einstein's Equivalence Principle
- Variation of fundamental constants
- Einstein relativity theories
- fundamental symmetries
- Understanding gravity and laws of nature
- Testing Weak Signals from Planck-Scale Physics
- AI GW Detection.



Societal Benefits
- Next generation GPS
- Geodesy application
- Global transfer and timekeeping
- Underground resource exploration
- Resource management

Research and Education
1) Inspire next generation scientists
2) Attract top talents into sciences and space exploration
3) Top-notch research result published in prestigious scientific journals

Government Agencies
- Communication and navigation guidance (DoD)
- Synthetic aperture imaging (DoD, NASA)
- Deep Space tracking and navigation (NASA)
- Inertial navigation (DoD, NASA)
- National Primary Standards (DoC/NIST)
- Underground structure detection (DoD, DHS)
- Quantum sensors for readout (DOE, NIST, NASA

Roadmap and Planned Activities

Program	CAL1	CAL2	CAL3	CAL4	CAL5
Mission	Current	DLR Upgrade	New FP	New FP	ISS Extension
Science	Cold Atoms/AI	Cold Atoms/ New species	Cold atoms/Dark Energy	QTEST	SOC
Time	2017	2019	2021	2023	2025
NRA	CAL	2018	2020	2022	2024

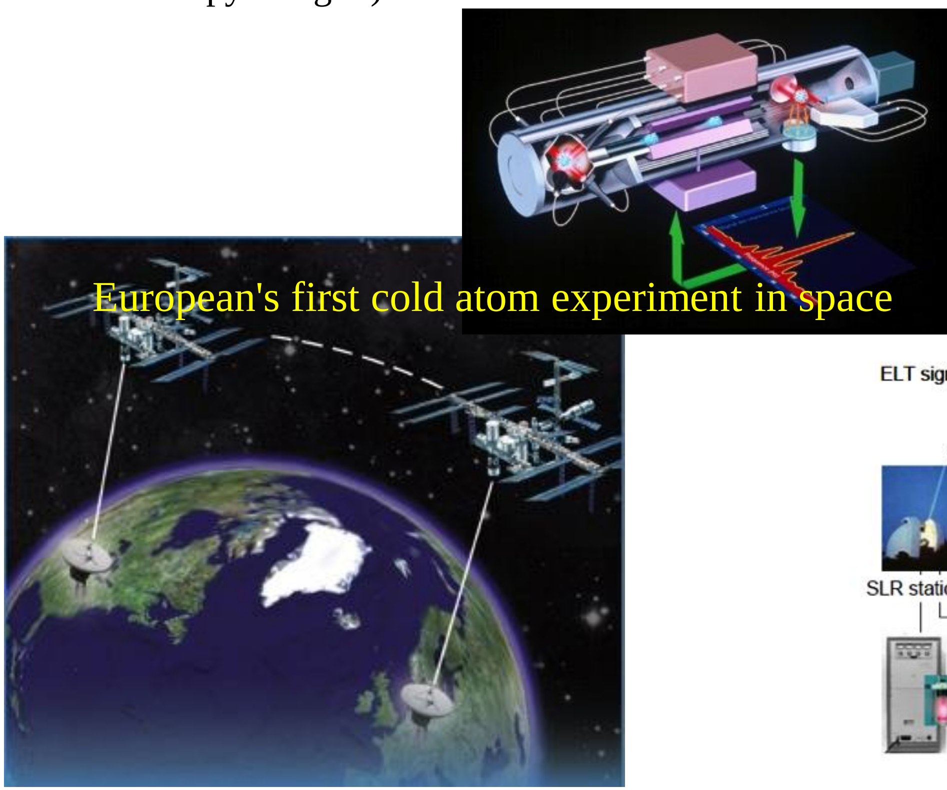
- ACES (+ mission delay supplemental for JPL/NIST)
- DLR funded CAL upgrade to study new species
- Dark Energy Hunting, using CAL upgrade
- Gravity Wave Detection using atom interferometry
- SOC
- QWEP
- QTEST
- Technology Maturation activities
- ISS optical clocks
- Sequence of NRAs starting in 2018

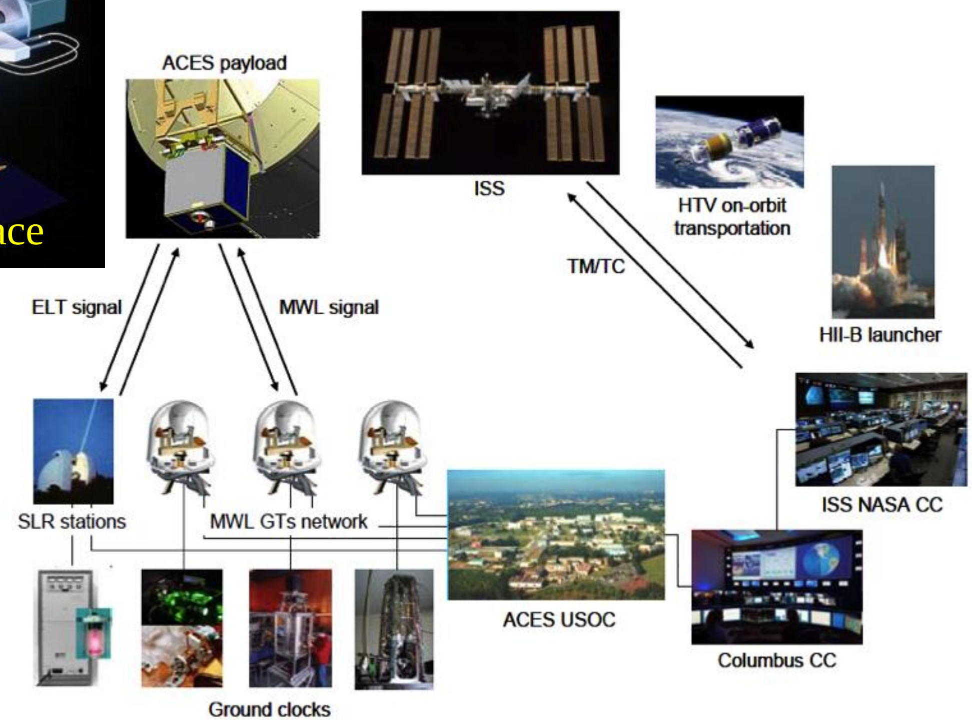
US Collaboration in the ESA ACES Mission (I)

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

Science Objectives:

- Demonstrate validate a new generation of atomic clocks in space (10^{-16} stability and accuracy level)
- Demonstrate the capability to compare ground clocks on a world-wide basis (stability better than 10^{-16})
- Test fundamental laws of physics to high accuracy (gravitational Red-shift, drift of fine structure constant, and anisotropy of light.)





US Collaboration in the ESA ACES Mission (II)

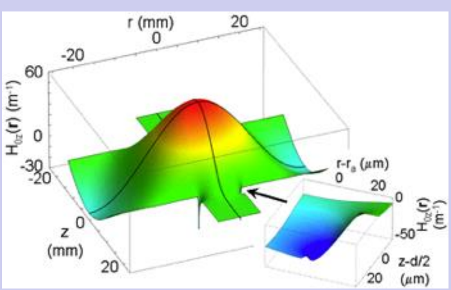
Ground link stations at leading US time and frequency metrology institutions for the critical global coverage

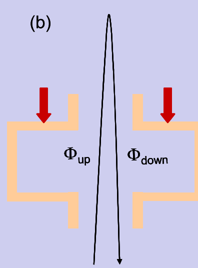
US Collaboration Objectives:

- Contribute to ACES objectives to validate the cold atom space clock; to perform time and frequency transfer to the Earth at the same stability level; and to test general and special relativity to high precision
- To demonstrate US clock capabilities at NIST; validate and characterize the JPL trapped ion mercury clock technology
- Establish an ESA-NASA collaboration on Fundamental Physics in Space

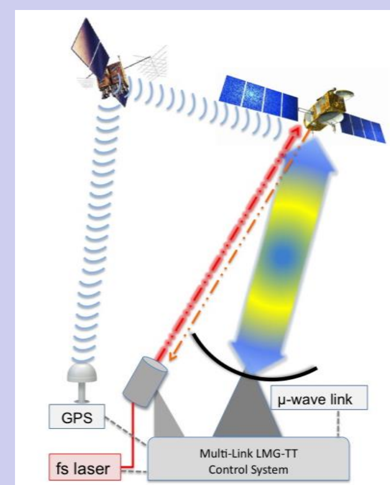
Ground Research supporting ACES clock and time transfer sciences

ACES cold atom clock shift studies:
PI: Prof. K. Gibble, Penn State Univ.

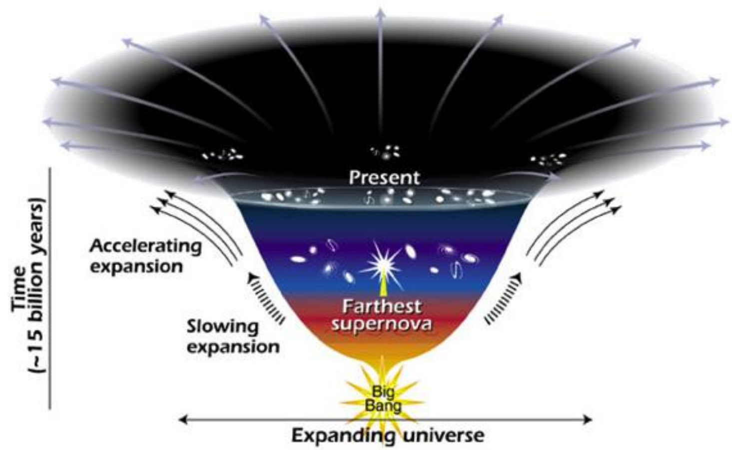




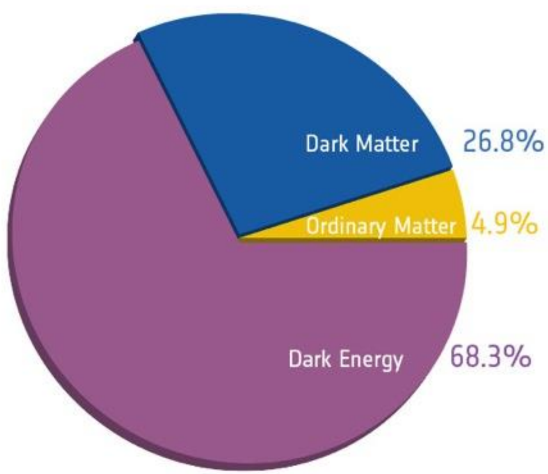
ACES advanced optical frequency transfer and time synchronization:
PI: Prof. L. Hollberg, Stanford University

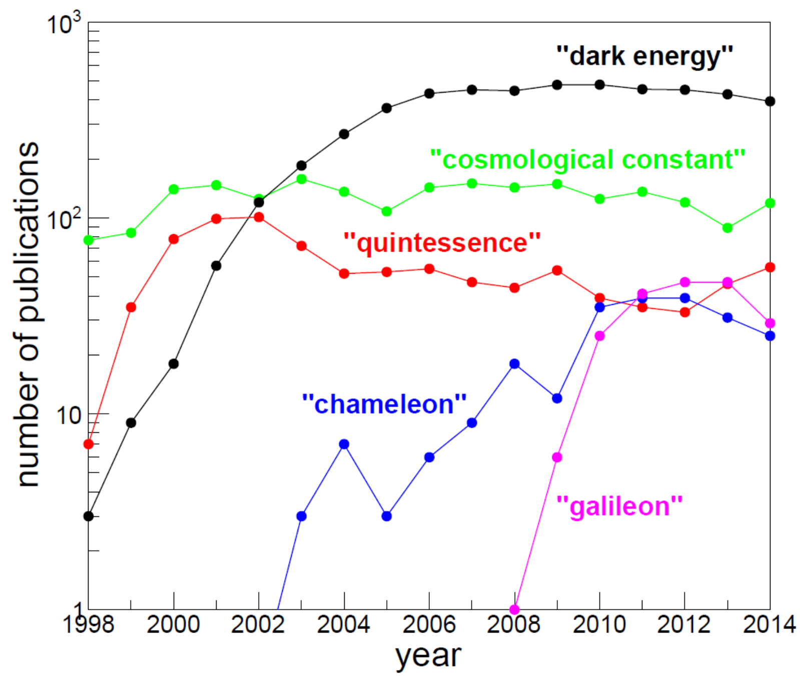


Hunting for Dark Energy in CAL Upgrade (I)



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.





Hunting for Dark Energy in CAL Upgrade (II)

Probe Dark Energy with Atom Interferometers

An experiment

The idea

Probing Dark Energy with Atom Interferometry
C. Burrage, E. J. Copeland, E. A. Hinds
JCAP 1503 (2015) 03, 042

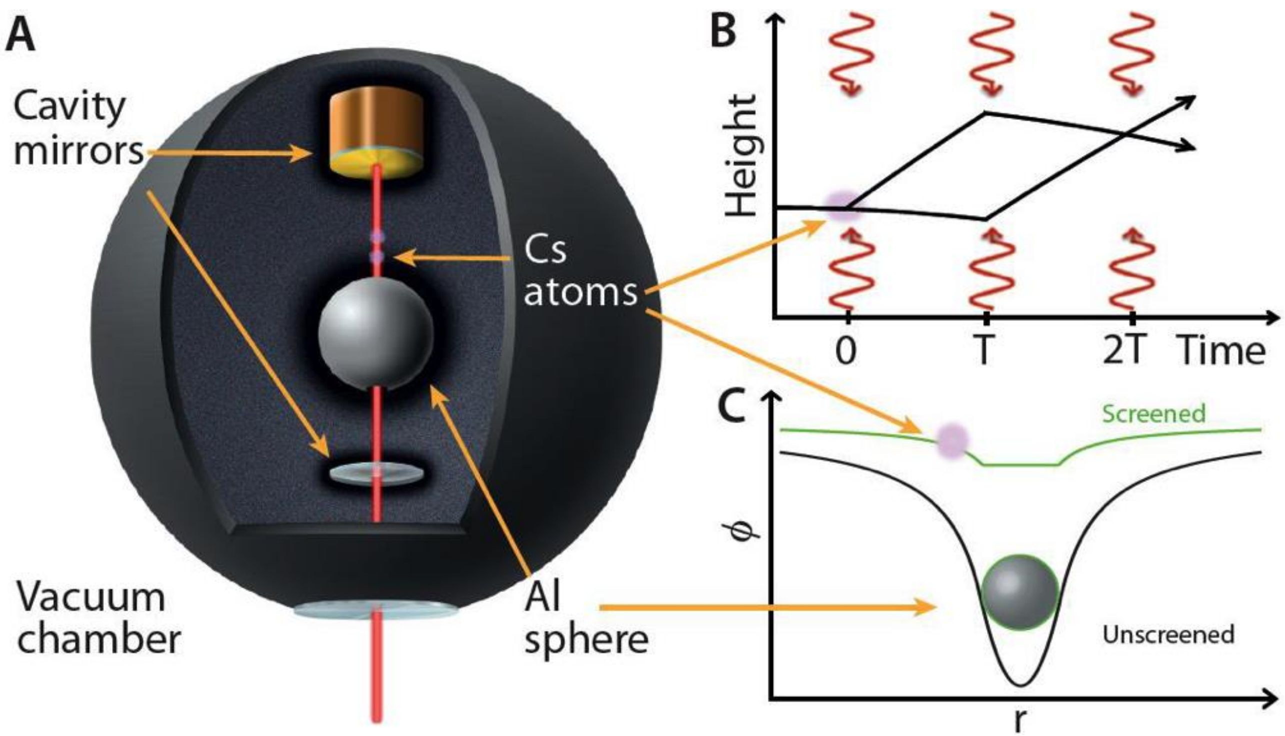
Dark energy / optical cavity interferometer

Realization:
Single atom's small size in ultra high vacuum makes it ideal test mass which evades screening

Atom-interferometry constraints on dark energy. Paul Hamilton, Matt Jaffe, Philipp Haslinger, Quinn Simmons, Holger Müller, and Justin Khoury. Science, 349, 849 (2015) (or abstract and full text). arXiv:1502.03888

Hunting for Dark Energy in CAL Upgrade (III)

Atom Interferometer Chameleons Experiment



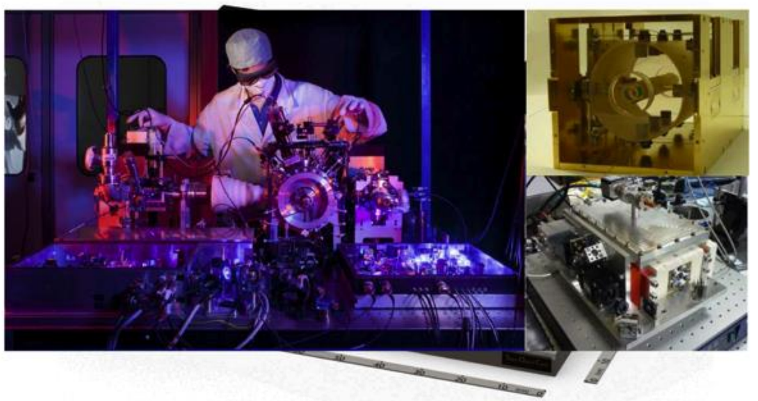
$$a \approx \frac{G m_s}{r^2}\left[1 + 2\lambda_a \lambda_s \left(\frac{M_{\mathrm{Pl}}}{M}\right)^2\right]$$

- Aluminum sphere source mass for scalar field
- Atoms act as test masses for force sensing
- Final state probability $\propto \vec{k} \cdot \vec{a}\, T^2$

Opportunity for International Collaborations

Transportable Sr lattice clock

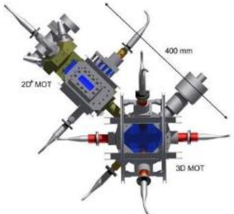
Sr clock prototyping activities started by ESA are now continuing under EC funding

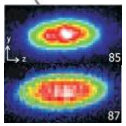


- Way forward:
  - SOC transportable prototype to be used in the frame of the ACES mission for geodesy studies
  - Phase A study for the SOC mission to be started in 2015

Quantum Test of WEP

- Scientific Objective: Perform a WEP test on quantum objects by measuring the Eötvös parameter to better than 10^{-14}
- Instrument: Dual atom interferometer measuring the differential acceleration between two freely-falling samples of ultra-cold ^{85}Rb and ^{87}Rb atoms
  - Long interrogation times (T~1-10 s)
  - 10^7 rejection ratio of common mode acceleration noise (drag and mechanical vibration)
  - Absolute sensor with precisely known scale factor
  - Measurements performed in a small size vacuum system: simplified control of external perturbations (magnetic, thermal, etc)





- There is a number of difficulties in the frontier between QM and GR due to the absence of a quantum theory of gravitation that call for experiments like a quantum test of WEP

- Q-WEP Experiment Scientific Requirements (ESR) defined by the Science Team
- Q-WEP accommodation on-board the ISS studied in two competitive industrial activities that positively concluded on mission feasibility

Cacciapuoti, 2014 NASA FP PI Workshop

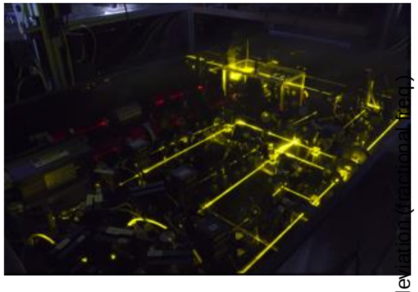
ESA ISS Fundamental Physics Program just updated its Roadmap by the Fundamental Physics Roadmap Advisory Team

discussed in that document as well as the final recommendations remain very actual. Today, we intend to revisit the document produced by FPR-AT in 2010 and update it in the light of the recent progress in the field. The document specifically addresses three major topics:

- *Testing the foundations of gravitational physics with clocks in space;*
- *Atom interferometry tests of the Weak Equivalence Principle;*
- *Ultra-high energy research from space.*

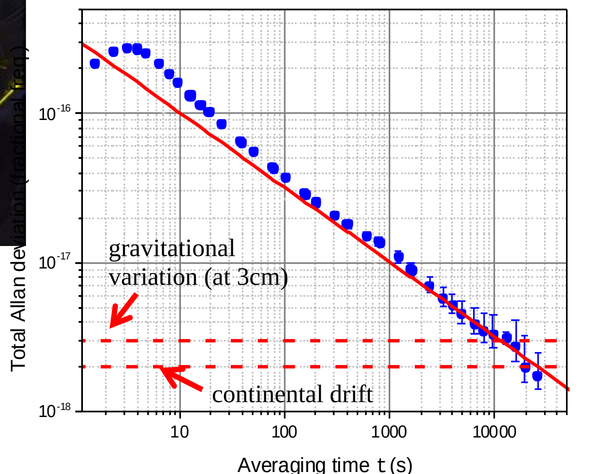
Optical Clocks in Space

Mission concept: Toward ultimate accuracy probing into the Planck scale physics at 10^-26m for testing Einstein gravity theory and fundamental symmetries



High impact science:

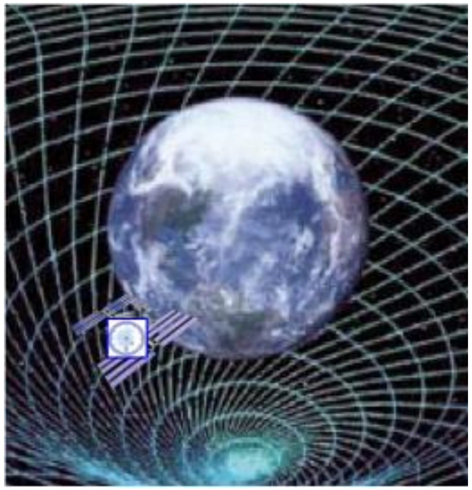
- tests of Metric Theories of Gravity
  - Gravitational red-shift: by a factor of 10^3;
  - Lense-Thirring effect: by a factor of over 10^2;
  - Gravitoelectric perigee advance: by a factor of 10
  - 1/r^2-Newton's law at long distances: by a factor of 10
- Test Local Lorentz invariance
  - Isotropy of the speed of light: by a factor of 10^4;
  - Constancy of the speed of light: by a factor of over 10^3;
  - Time dilation experiments: by a factor of 10^3.
- tests of Local Position Invariance
  - Universality of the gravitational red-shift: by a factor of 10^3;
  - Time variations of fundamental constants: by a factor of over 10^2



Recent breakthroughs in earth-based optical atomic clocks have demonstrated precision at the 10^{-18} level

Beneficial technology:

- Future primary clocks may have to be in space
  - Mitigate local gravity effect
- Relativistic geodesy
  - Fluctuations in the earth gravity field via the gravitational redshift effect
- Global scale time keeping system
  - Mitigate Limitations in earth-based time transfer capabilities
- Links out to interplanetary space

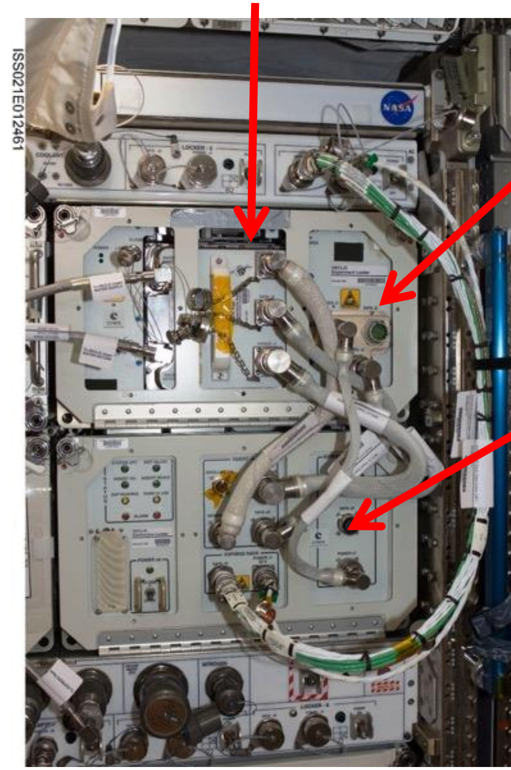


DECLIC International Collaboration

- DECLIC facility is a joint CNES/NASA project
  - Following ~10 years of development, the DECLIC multi-user/multi-discipline facility was launched in Aug, 2009.
  - CNES finances the development of the instrument. NASA covers the costs of launch and operations.

- Overall science objectives
  - Physical principles governing microstructure formation : Material Science (DSI insert)
  - Supercritical water property : Fluid Management (HTI insert)
  - Boiling phenomena, Critical Phenomena: Fundamental Physics (ALI insert)

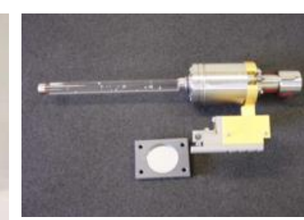
- NASA portion of science: fundamental physics
  - One US PI in collaboration with CNES scientists
  - Studying equation-of-state, phase transition phenomena and two-phase fluid behavior in microgravity



DECLIC on board ISS

ALI insert

HTI cell

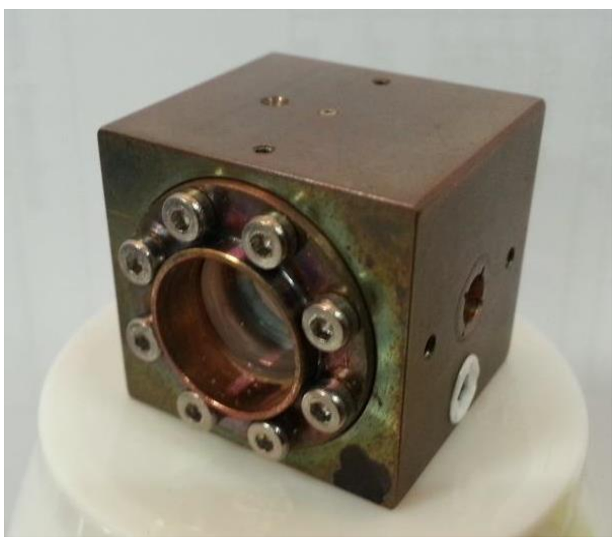


DSI cell

DECLIC ALI-R Experiment

- Turbidity increase was measured nearly 1000 times closer to the critical point than previously possible.

- Re-flight of the ALI experiment with a new cell is planned for launch in late 2016.



RAPID COMMUNICATIONS

PHYSICAL REVIEW E **91**, 060101(R) (2015)

Weightless experiments to probe universality of fluid critical behavior

C. Lecoutre,[1,2,*] R. Guillaumont,[1,2] S. Marre,[1,2] Y. Garrabos,[1,2] D. Beysens,[3,4] and I. Hahn[5]

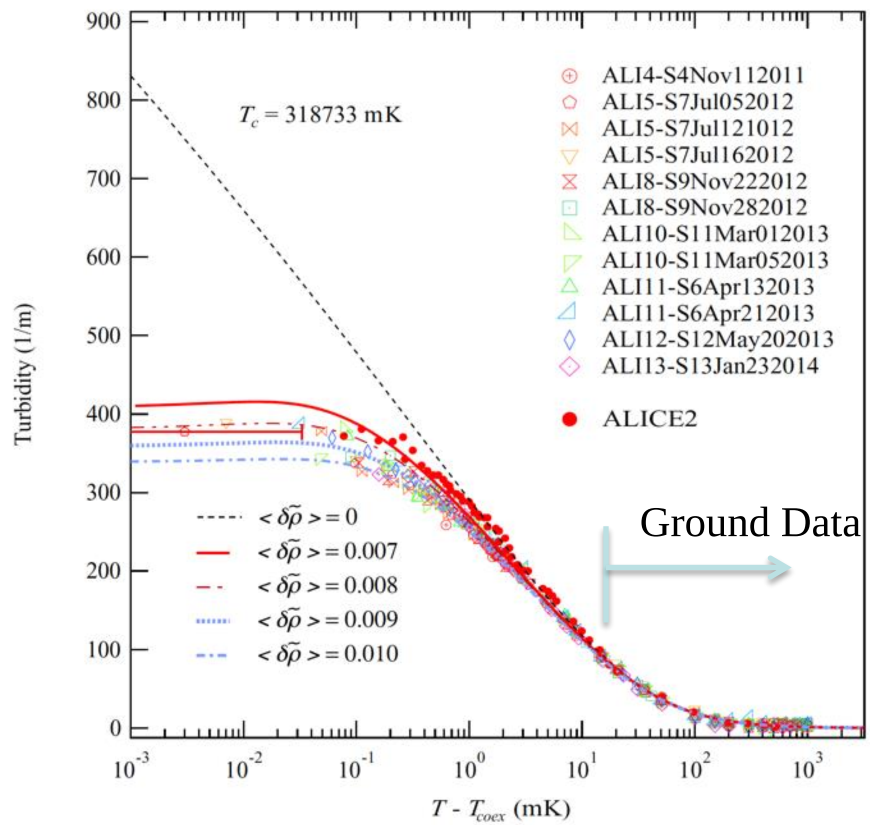
[1]*CNRS, ICMCB, ESEME, UPR 9048, F-33600 Pessac, France*

[2]*Université Bordeaux, ICMCB, UPR 9048, F-33600 Pessac, France*

[3]*Physique et Mécanique des Milieux Hétérogènes, UMR 7636 CNRS - ESPCI - Université Pierre et Marie Curie - Université Paris Diderot, 10 rue Vauquelin, 75005 Paris, France*

[4]*Service des Basses Températures, CEA-Grenoble & Université Joseph Fourier, F-38000 Grenoble, France*

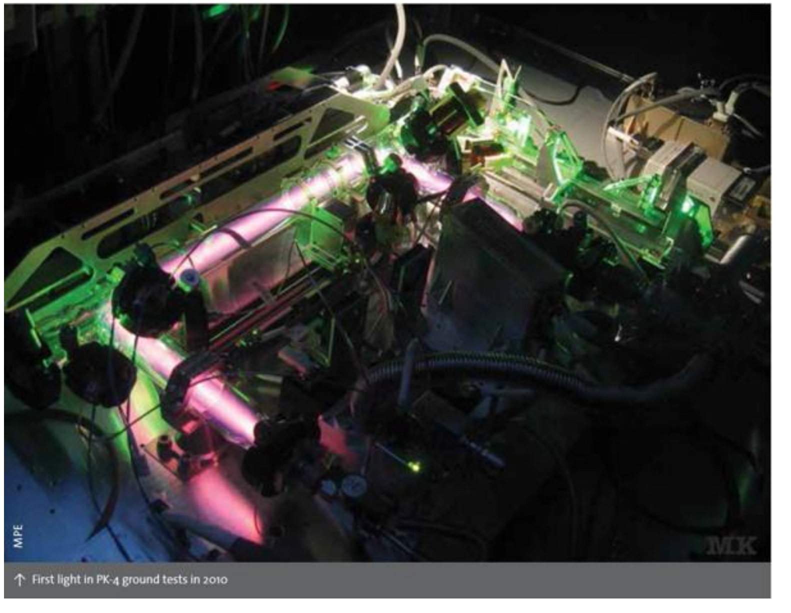
[5]*Jet Propulsion Laboratory, California Institute of Technology, California 91109, USA*



PK-4 (Plasma Krystal -4)
International Collaboration

- PK-4 instrument is an ESA/Roscosmos mission
  - Led by CPRG/DLR/Germany, JHIT/Russia
  - Following 9 years of development, the PK4 multi-user facility is on orbit since Nov, 2014.
  - ESA has invited U.S. scientists and other nations to participate in PK-4
- Overall science objectives
  - Study of the liquid phase of complex plasma such as flow phenomena
  - Study of non-Gaussian statistics of particle motion, diffusion, viscosity.
- NASA portion of science
  - To support multiple U.S. scientists for PK-4 science collaboration

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



NASA/NSF Joint Solicitation (PK-4 research)

- SLPS is currently supporting 3 researchers (Univ. Iowa, Auburn Univ., UCSD)
- Completed a draft NRA titled "NASA/NSF Partnership on Science of Dusty Plasmas utilizing PK-4 facility on board International Space Station"
- Agreement between NSF and NASA regarding cooperation in support of "ISS/PK-4" Research was signed by Gerstenmeier Jan 11, 2016.

INTERAGENCY AGREEMENT

BETWEEN

THE NATIONAL SCIENCE FOUNDATION

AND

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

REGARDING

COOPERATION IN SUPPORT OF "ISS/PK-4" RESEARCH

ARTICLE 1. AUTHORITY AND PARTIES

The National Aeronautics and Space Administration, Space Life and Physical Sciences (SLPS) Physics Program located at 300 E Street SW, Washington, DC 20546 (hereinafter referred to as "NASA") enters into this Interagency Agreement (hereinafter referred to as "IAA") in accordance with the National Aeronautics and Space Act, 51 U.S.C. § 20113. The National Science Foundation, Directorate for Mathematical and Physical Sciences (MPS) and Geosciences (GEO) located at 4201 Wilson Blvd, Arlington, VA 22230 (hereinafter referred to as "NSF"), enters into this IAA in accordance with the National Science Foundation Act of 1950, as amended 42 U.S.C. 1861 et seq. NASA and NSF may be individually referred to as a "Party" and collectively referred to as the "Parties." This IAA furthers the goals articulated in the Memorandum of Agreement between the National Science Foundation and the National Aeronautics and Space Administration on Space, Earth, and Biological Sciences Cooperative Activities dated August 1, 2008.

ARTICLE 19. SIGNATORY AUTHORITY

Approved and authorized on behalf of each Party by:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
William H. Gerstenmaier, Associate Administrator for Human Exploration and Operations Mission Directorate

BY: Willi H Gerstenmaier

DATE: 11 Jan 2016

NATIONAL SCIENCE FOUNDATION
DIRECTORATE FOR MATHEMATICAL AND PHYSICAL SCIENCES

BY: F. Fleming Crim

DATE: 12/8/15

NATIONAL SCIENCE FOUNDATION
DIRECTORATE FOR GEOSCIENCES

BY:

DATE: 12/11/15