Fundamental Physics in the ESA Programme

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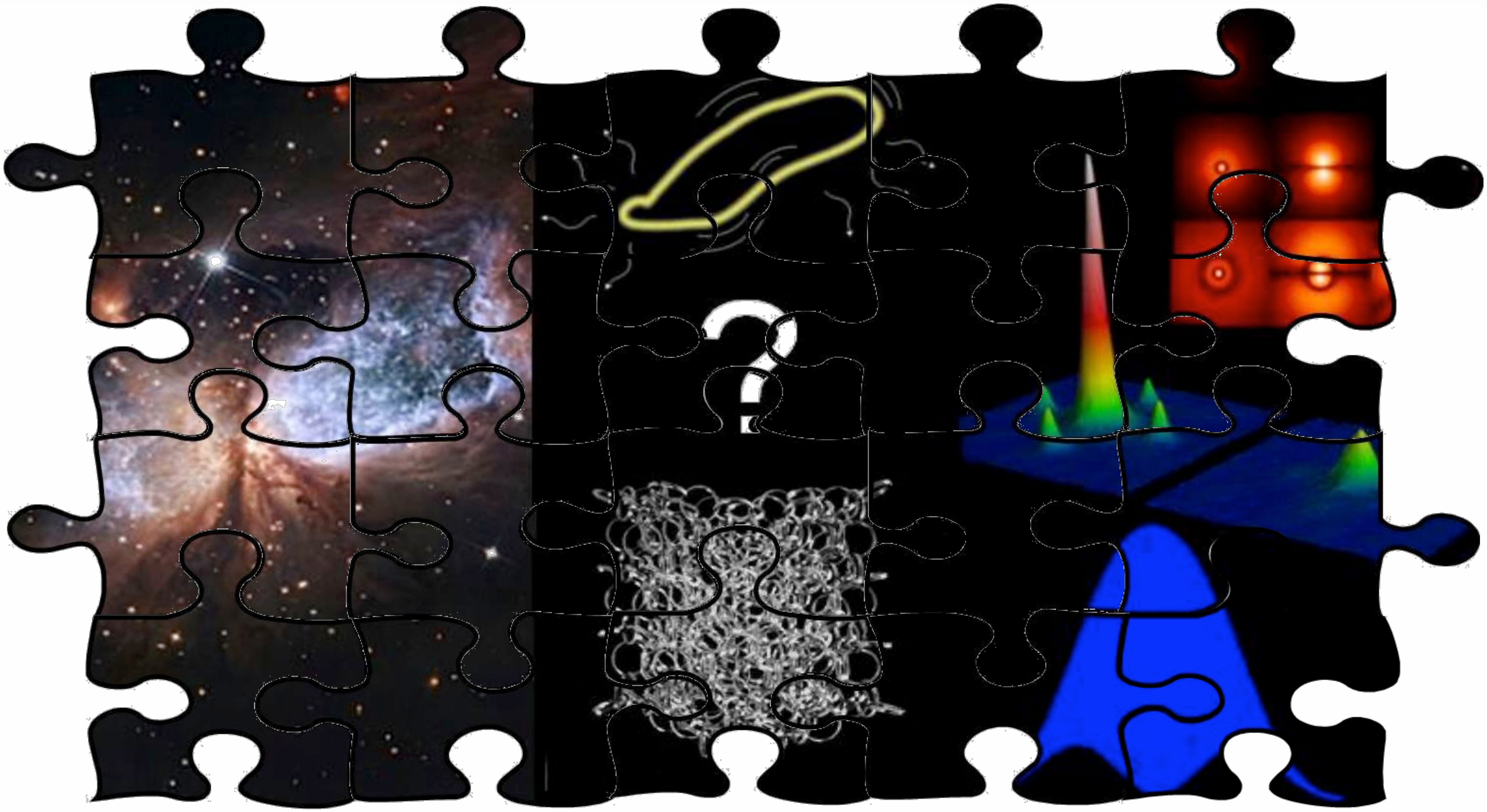
European Space Agency

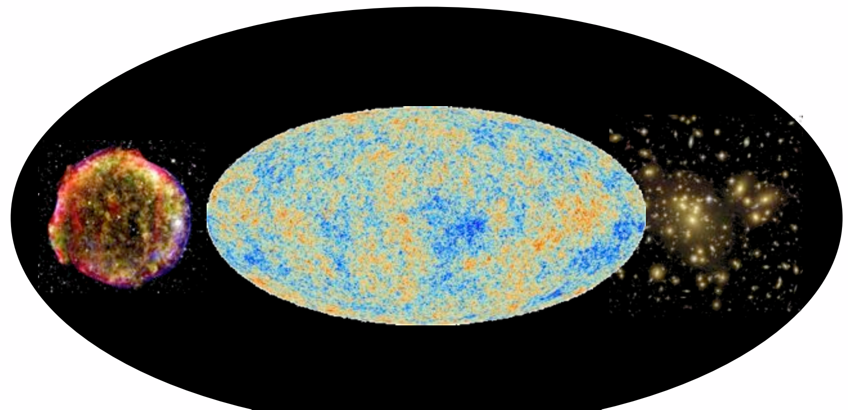
General Relativity and Quantum Mechanics



- General Relativity: Describes space-time and matter on cosmologically large distances and of very dense compact astrophysical objects.
- Quantum Mechanics: Describes the behaviour of matter at small scales; quantum mechanics, together with special relativity, leads to the Standard Model of strong and electroweak interactions which accounts for all the observable known forms of matter.

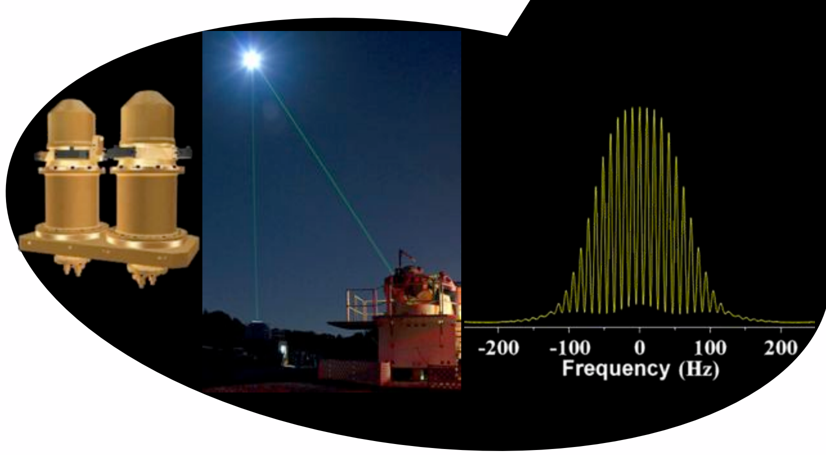
The Challenge

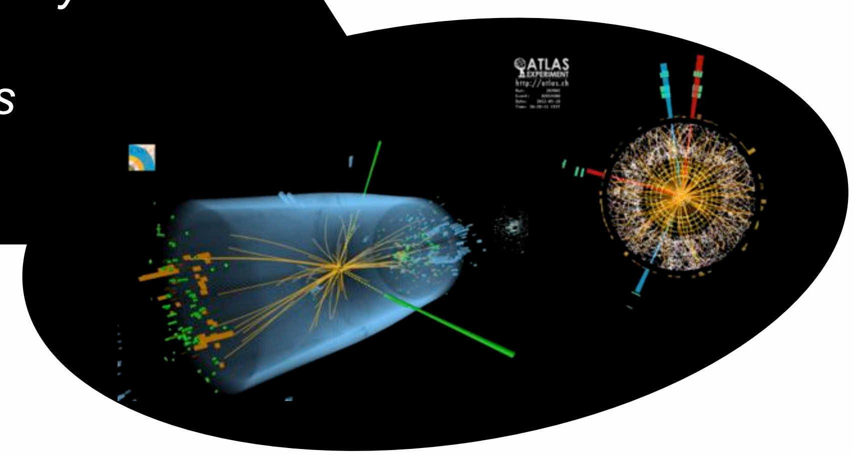
Astronomy & Cosmology
(*CMB, Planck, EUCLID*, …)



Quantum-Gravity
Unification

Strings
Superstrings
Supersymmetry
Loop Quantum Gravity
M-theory
Brane scenarios
…





Low Energy
(LLR, lab tests, ACES, μ–SCOPE, …)

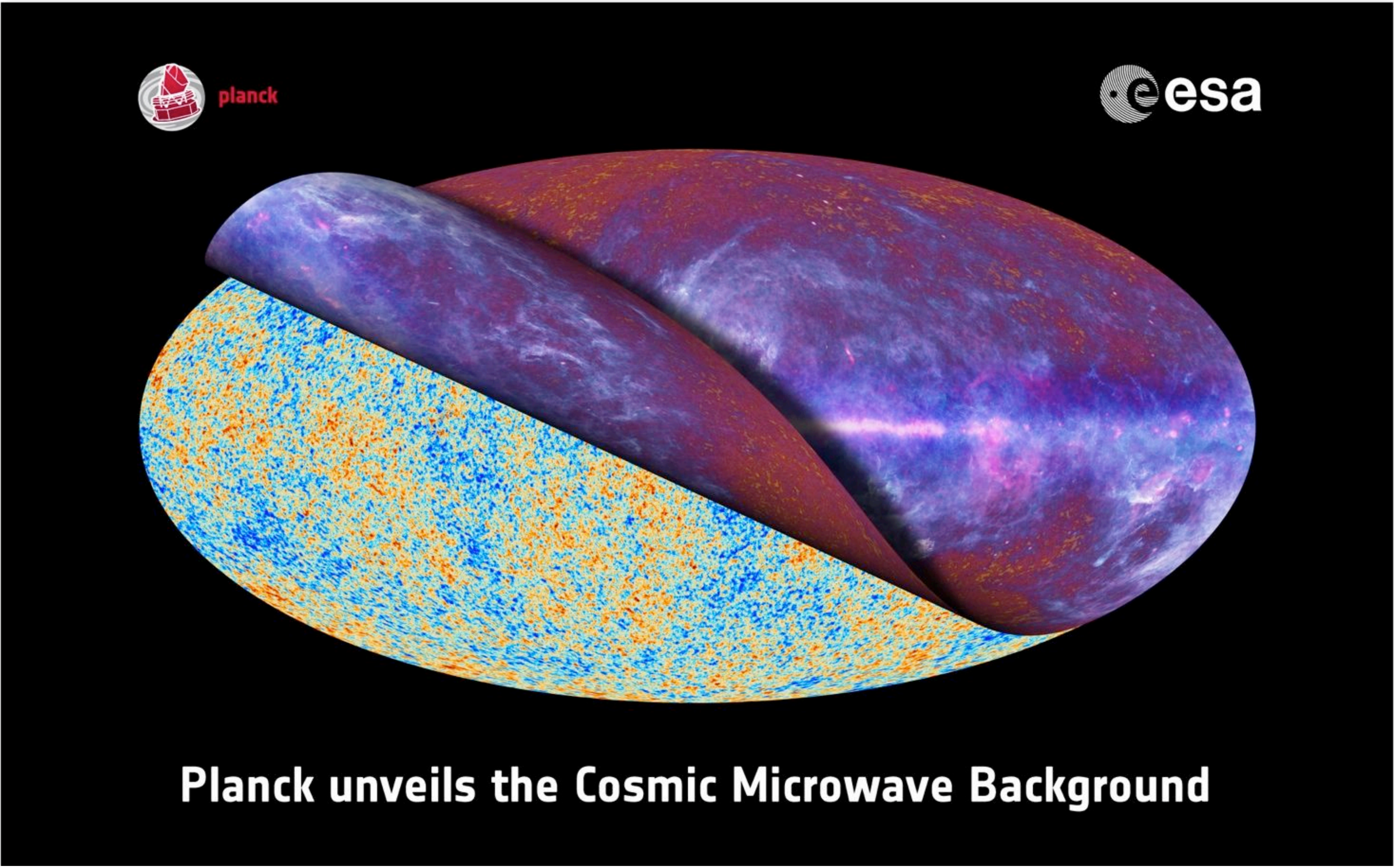
High Energy
(CERN-LHC, Fermilab, DESY, …)

Fundamental Physics in the ESA program

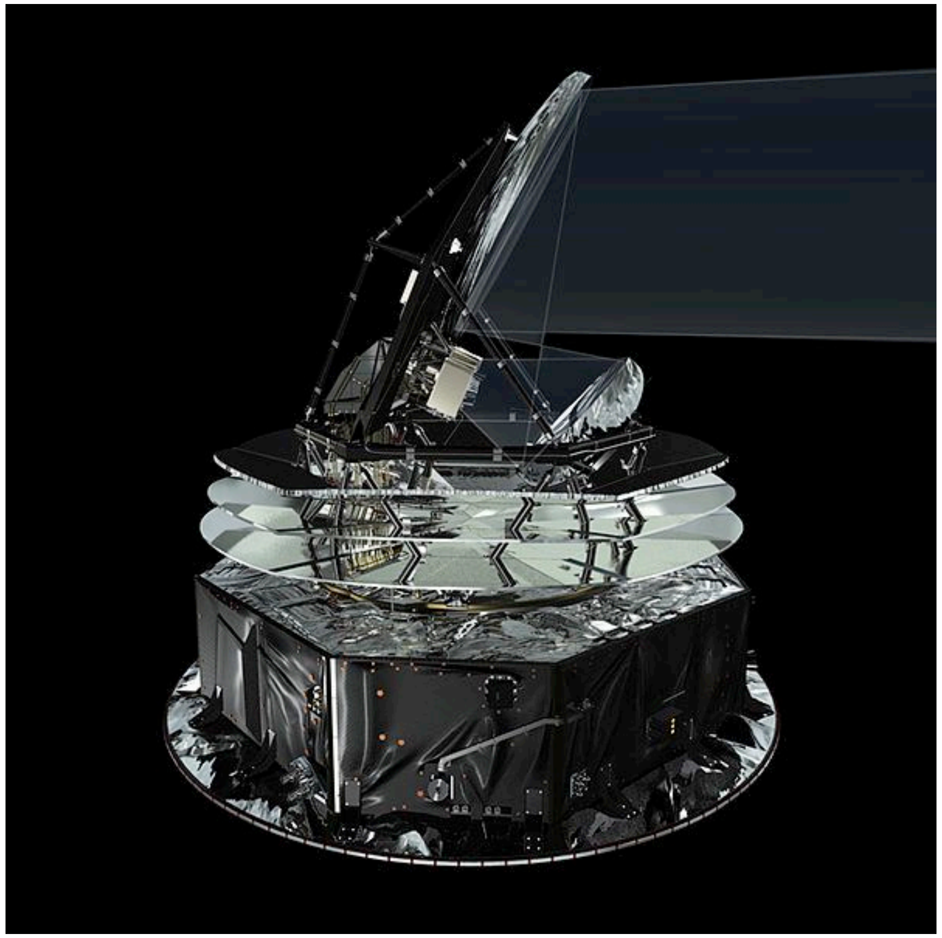
- Astronomy and cosmology
  - Planck
  - Euclid
  - GAIA
- Precision measurements for fundamental physics tests in space
  - BepiColombo
  - LISA-PF
  - Microscope
  - ACES

  …under assessment
  - SOC
  - Q-WEP

Planck


planck
esa
Planck unveils the Cosmic Microwave Background

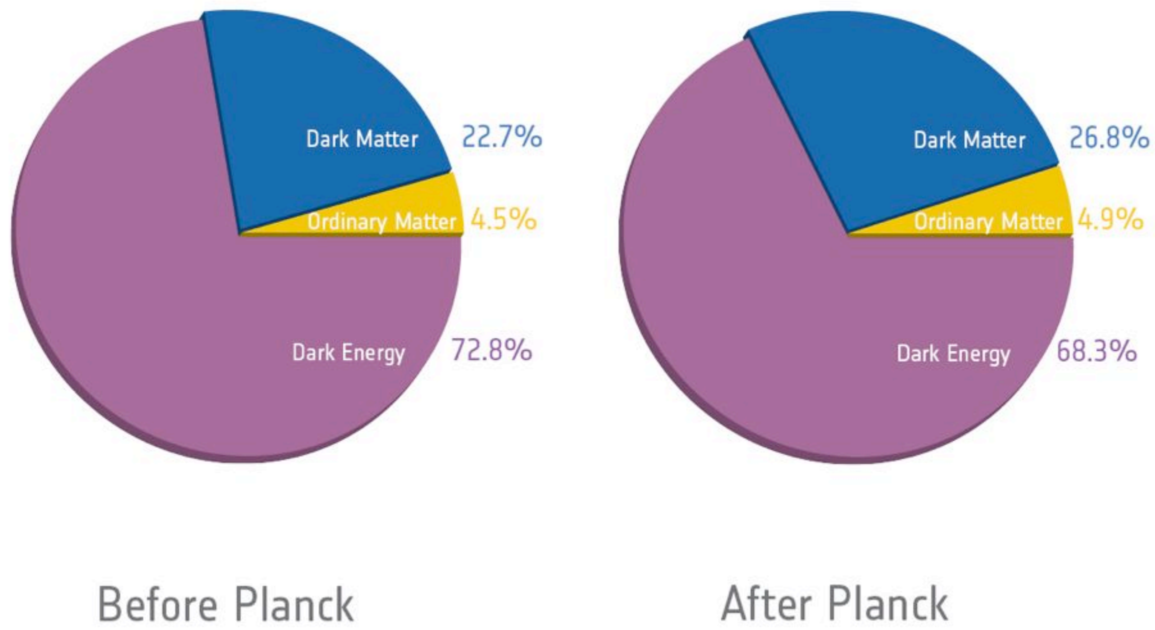
The Planck Mission

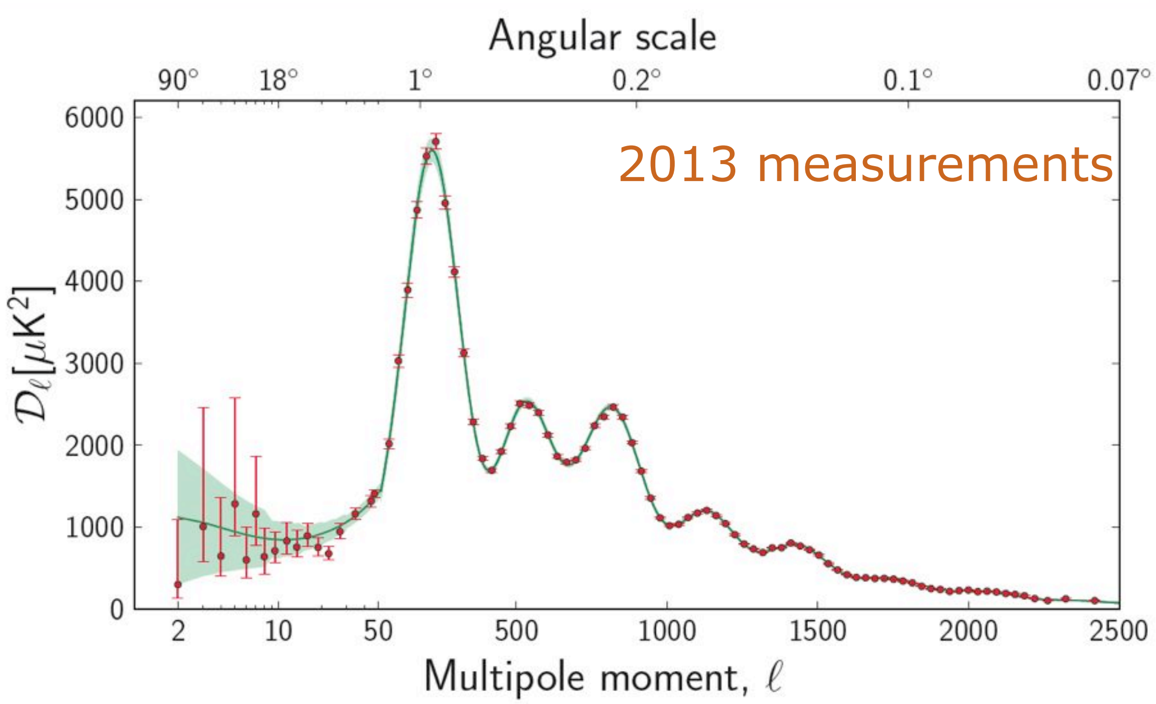


- Planck is a satellite designed, built and operated by the European Space Agency, whose objective is to map the anisotropies of the Cosmic Microwave Background over the whole sky, in temperature and polarization.
- Planck carries a payload including:
  - A 1.5 m offset Gregorian telescope
  - An array of HEMT-based receivers cooled to 20 K and operating between 30 and 70 GHz
  - An array of bolometers cooled to 0.1 K and operating between 100 and 857 GHz
- Planck was launched in May 2009 and has been surveying the sky uninterruptedly since August 2009
  - It covered the full sky five times with the full payload
  - It covered the full sky an additional three times with the low-frequency receivers.
- Planck released in March 2013 its first maps and cosmological results, based on the first 15.5 months of observations
- Planck stopped operating in October 2013.
- The next major data release is planned for October 2014.

Summary of CMB Results

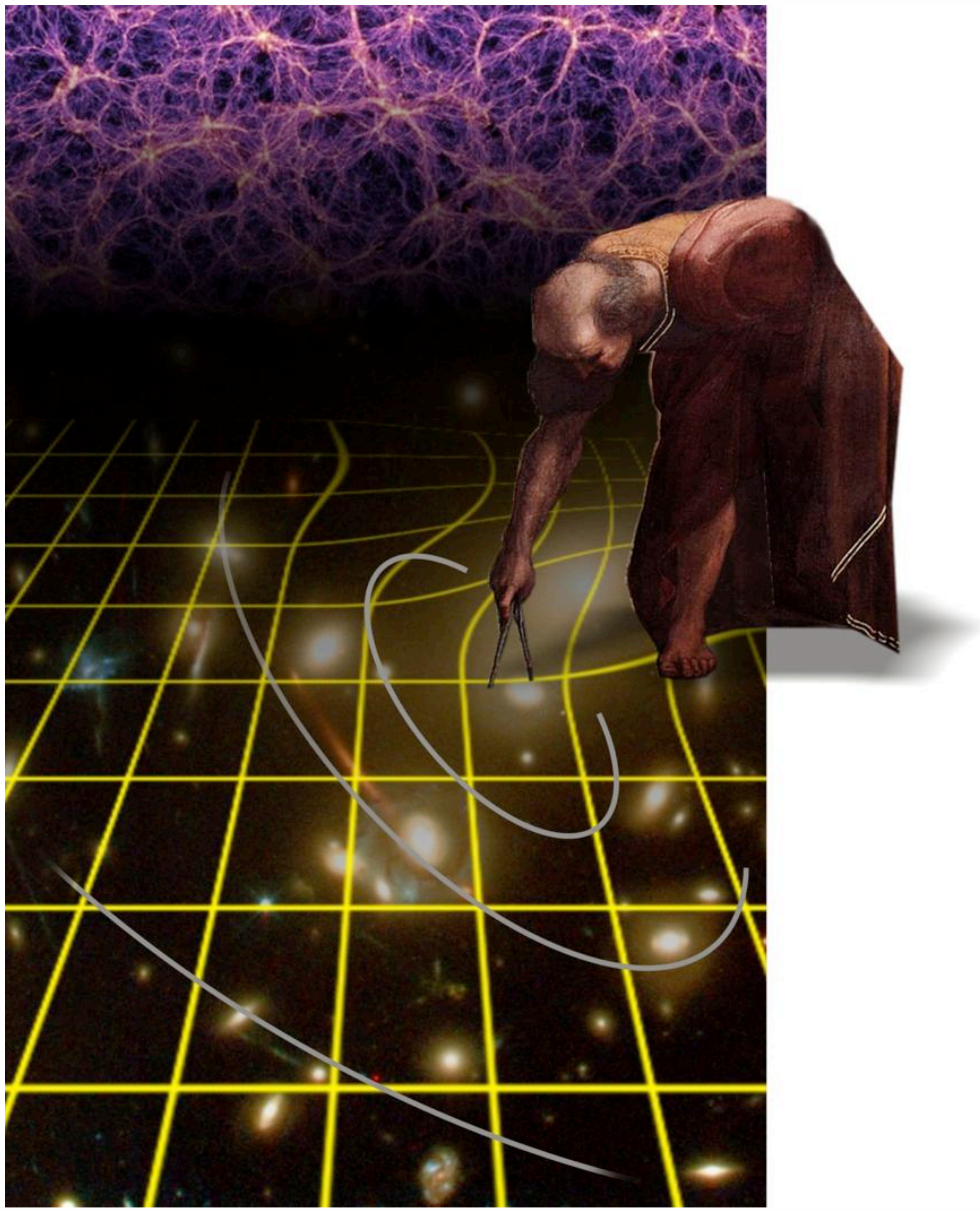
- The ΛCDM model fits the data quite well
- The estimated parameters are different than previously
  - More matter, less dark energy
  - Hubble constant lower than expected
  - Curvature very tightly constrained
- No significant evidence for more than 3 types of neutrinos
- No evidence for non-gaussianity in the statistics of CMB anisotropies
- New constraints for inflationary models: single-field slow-roll inflation is preferred
- Confirmation of WMAP anomalies; deficit of power at large angular scales
- High-significance measurement of CMB lensing and CMB-CIB cross-correlation





Euclid will explore the dark Universe:

Accurate determination of the accelerated expansion of the Universe and the properties of dark matter



The signature of the acceleration is locked up in:

- The geometry of the Universe: Distance as a function of redshift
- Growth of density perturbations: Evolution of structure as a function of cosmic time, growth rate

Probes used by Euclid

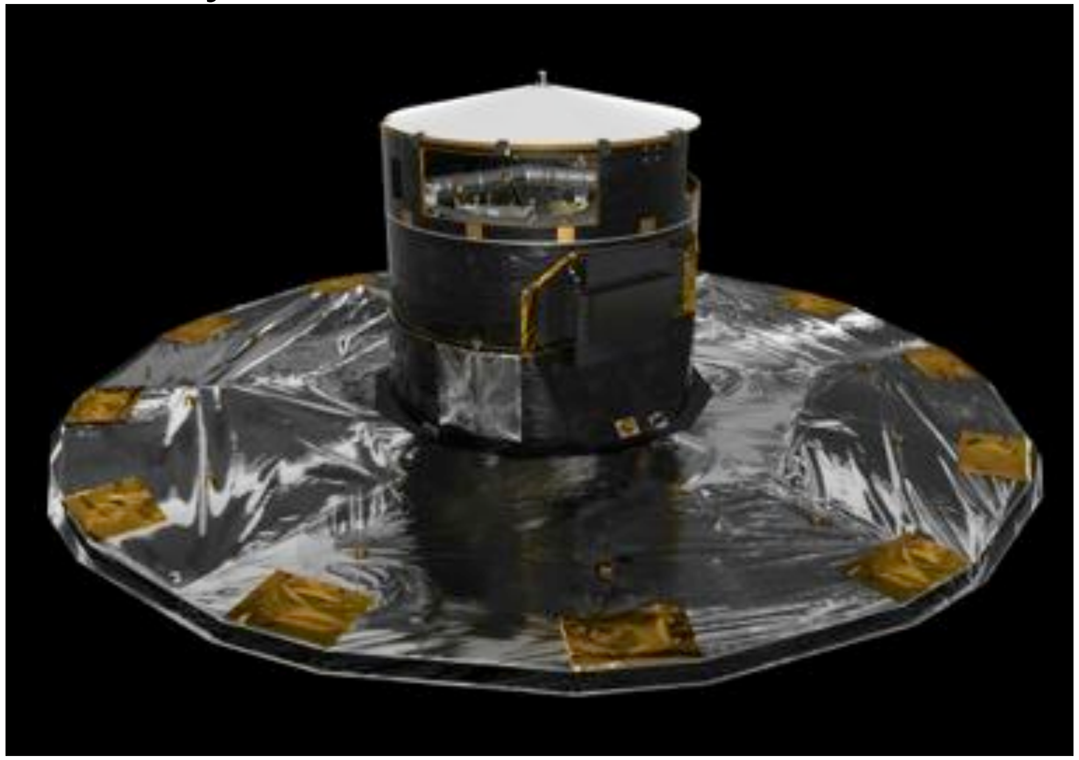
- Galaxy Clustering: VIS imager + NIR imaging-photometer to measure distribution and redshifts of galaxies over a large volume of space
- Weak Gravitational Lensing: NIR slitless spectrometer to measure the distortion (or shear) of galaxies due to (dark) matter along the line of sight

Euclid Scientific Objectives

Issue	Euclid Targets
What is Dark Energy: w	Measure the DE equation of state parameters w_p (acceleration) and w_a (variation in acceleration) to a precision of 2% and 10%.
Beyond Einstein's Gravity: γ	Distinguish General Relativity from modified-gravity theories, by measuring the growth rate exponent γ with a precision of 2%.
The nature of dark matter: m_ν	Test the Cold Dark Matter paradigm for structure formation, and measure the sum of the neutrino masses to a precision better than 0.04eV when combined with Planck.
The seeds of cosmic structure: f_{NL}	Improve by a factor of 20 the determination of the initial condition parameters compared to Planck alone: n (spectral index), σ_8 (power spectrum amplitude), f_{NL} (non-gaussianity)

GAIA

- ESA astrometry mission: It will determine positions, proper motions, and parallaxes for all objects, with end-of-mission precision of 7 μas (at G = 8 mag) and 300 μas (at G = 20 mag) for all point sources in the range G=6-20 mag ($1 \cdot 10^9$ objects).
  - Astrometry and (Spectro)photometry 6-20 mag for 1 billion objects
  - Radial Velocity Spectrometer 6-17 mag for 150 million objects
  - Unbiased full sky survey
- GAIA was launched on 19 December 2013 and currently in its commissioning phase
- Subsystems successfully operated: focal plane with all 106 CCDs fully functional
  - Commissioning is expected to be completed by the end of May
- Scientific objectives
  - Structure and dynamics of the Galaxy
  - The star formation history of the Galaxy
  - Stellar astrophysics
  - Binaries and multiple stars
  - Brown dwarfs and planetary systems
  - Solar system
  - Galaxies, Quasars and the Reference Frame
  - Fundamental physics: General relativity tests



GAIA and Fundamental Physics

- At the μas level, many “relativistic corrections” for the observable become detectable
- A full relativistic model needs to be implemented in the global fit to interpret GAIA data
- In the PPN formalism:

$$ds^2 = [(1-2M_{Sun}/r+2\beta(M_{Sun}/r)^2)]c^2 dt^2 + [1+\gamma 2 M_{Sun}/r][dr^2 + r^2(d\vartheta^2 + \sin^2\vartheta d\varphi^2)]$$

- Test of PPN parameters
  - γ measurement to at the 10^{-6} level
  - β measurement from precession of perihelion of eccentric asteroids
  - Light deflection by Jupiter quadrupole moment
  - Time variations of G

Fundamental Physics in the ESA program

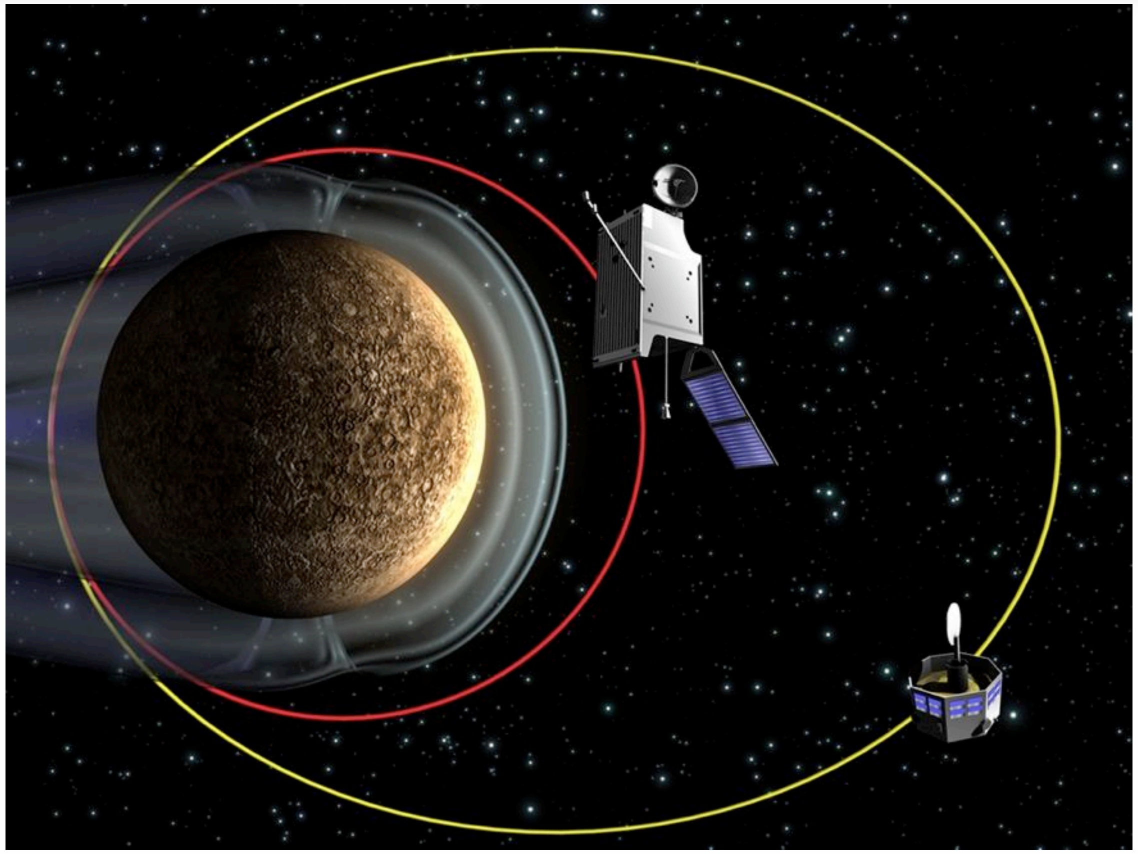
- Astronomy and cosmology
  - Planck
  - Euclid
  - GAIA
- Precision measurements for fundamental physics tests in space
  - BepiColombo
  - LISA-PF
  - Microscope
  - ACES

  …under assessment
  - SOC
  - Q-WEP

BepiColombo

Dual spacecraft mission

- Mercury Planetary Orbiter (MPO)
  - Polar orbit optimized to study the planet itself: 480x1500 km, 2.3 h period
- Mercury Magnetospheric Orbiter (MMO)
  - Polar orbit optimized for study of the magnetosphere: 590x11640 km, 9.2 h period



Scientific Objectives

- Planetary sciences
  - Origin and evolution of a planet close to its star
  - Planet interior, structure, geology, composition and craters
  - Mercury's exosphere composition and dynamics
  - Mercury's magnetized envelope (magnetosphere): structure and dynamics
  - Origin of Mercury's magnetic field
- Fundamental physics: Testing Einstein's theory of general relativity

Why Mercury for fundamental physics tests?

- Mercury lays deeper in the solar gravitational field and moves faster than any other major solar system body
- The relativistic effects are significantly larger on its orbit
- Far from the asteroid belt, Mercury is less affected by unknown gravitational perturbations

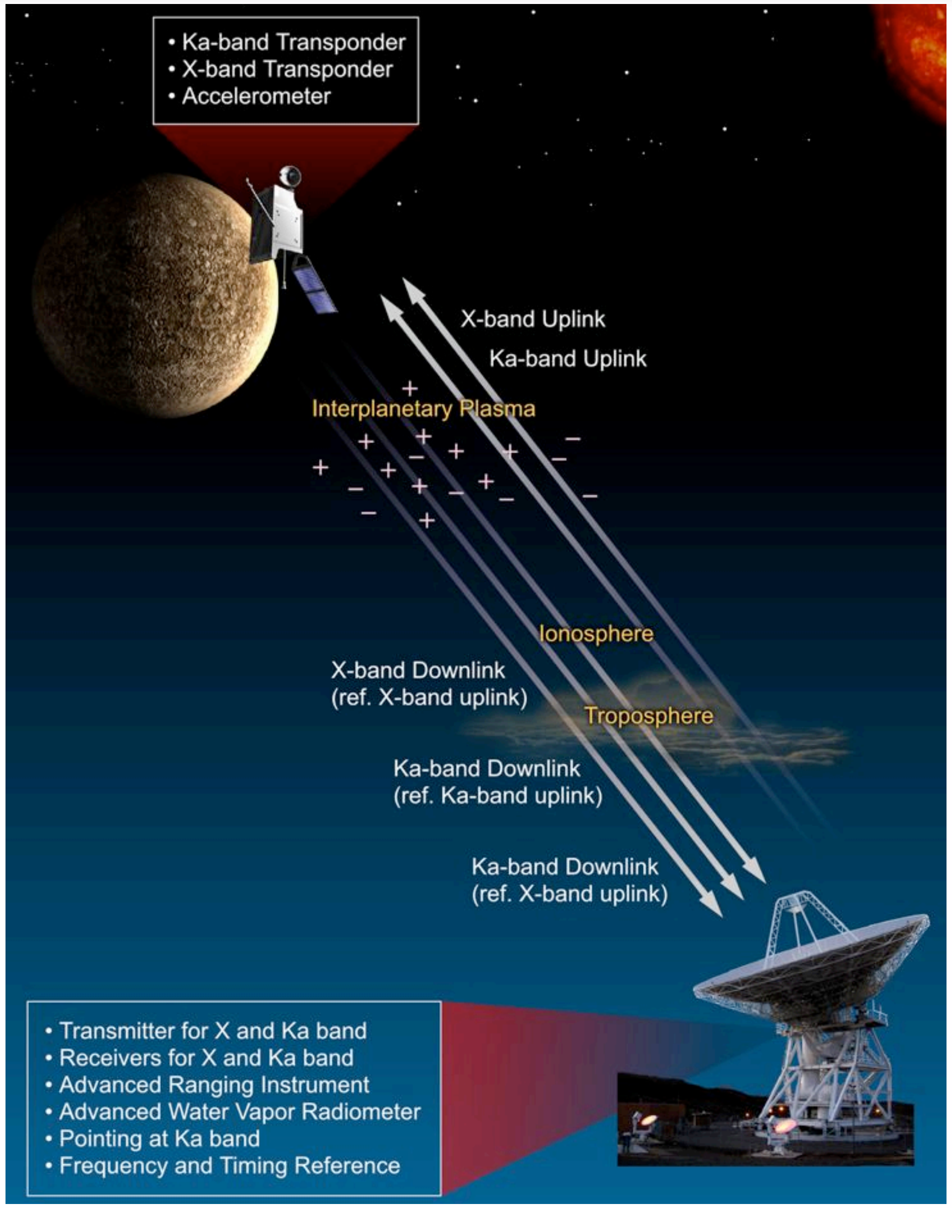
BepiColombo and Fundamental Science

PI	*Instrument*		*Measurements*
V. Iafolla, I	Italian Spring Accelerometer	ISA	Non-gravitational accelerations of MPO
L. Iess, I	Mercury Orbiter Radio Science Experiment	MORE	Core and mantle structure, Mercury orbit, fundamental science, gravity field

Science goals relevant for fundamental physics

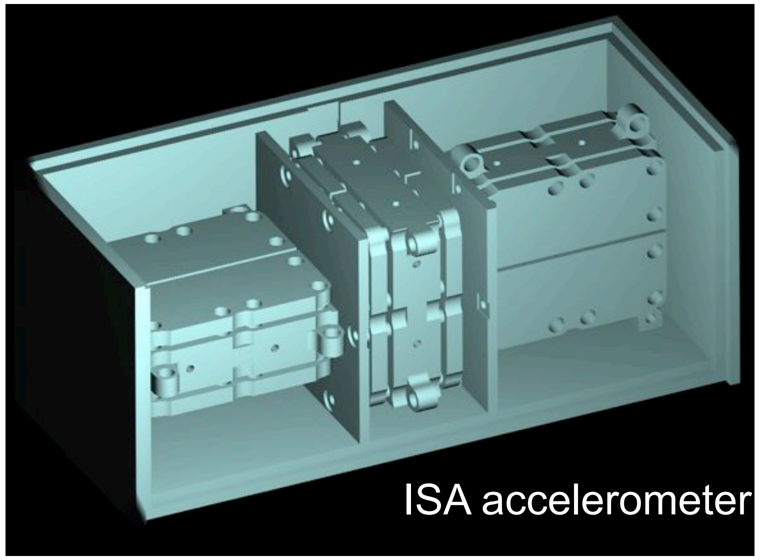
- Test metric theories of gravitation through a measurement of the PPN parameters:
  - Determine γ to an accuracy of $2.5 \cdot 10^{-6}$
  - Determine β to an accuracy of $5 \cdot 10^{-4}$
  - Determine η to an accuracy of $5 \cdot 10^{-4}$
- Determine the solar oblateness to an accuracy of $1 \cdot 10^{-7}$
- Test of time variations of the Newtonian gravitational constant G to an accuracy of $1 \cdot 10^{-12}$ per year

ISA and MORE on-board MPO



Multi-frequency link in X and Ka band

- Range and range rate between the ground stations and the spacecraft after removal of propagation delays
- Propagation delays of ionosphere, troposphere, and plasma
- Expected link stability: $\sigma_y = 1{\cdot}10^{-14}$ between 10^3 and 10^4 s of integration time, corresponding to a 1-way range rate of 1.5 μm/s and to a 1-way displacement of 1.5 mm
- Expected range accuracy: 10 cm

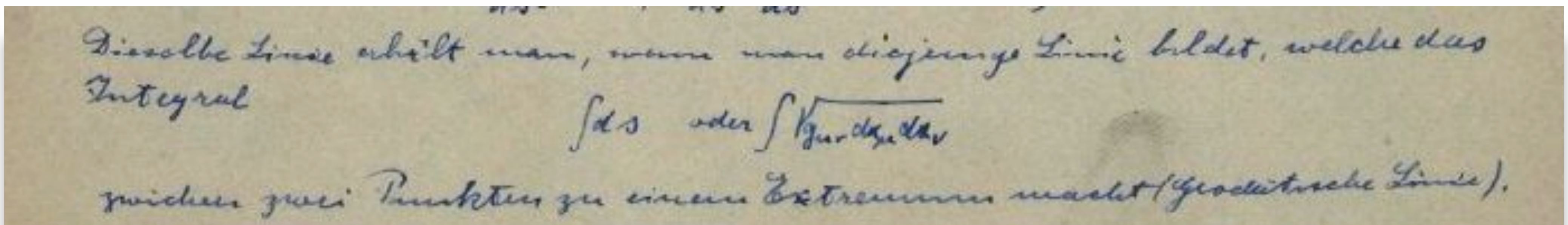


Spring accelerometer

- Accuracy in the along-track orbit reconstruction of about 1 m over one orbital revolution of MPO around Mercury (8355 s).
- The requested accuracy corresponds to an along-track acceleration of about 10^{-8} m/s^2/$\sqrt{\text{Hz}}$ for 10^{-4} Hz$<\nu<10^{-3}$ Hz

LISA PathFinder

- The most basic assumption of General Relativity is that free-particles follow geodesics unless acted upon by an unbalanced force


Dieselbe Linie erhält man, wenn man diejenige Linie bildet, welche das Integral

$$\int ds \quad \text{oder} \quad \int \sqrt{g_{\mu\nu} dx_\mu dx_\nu}$$

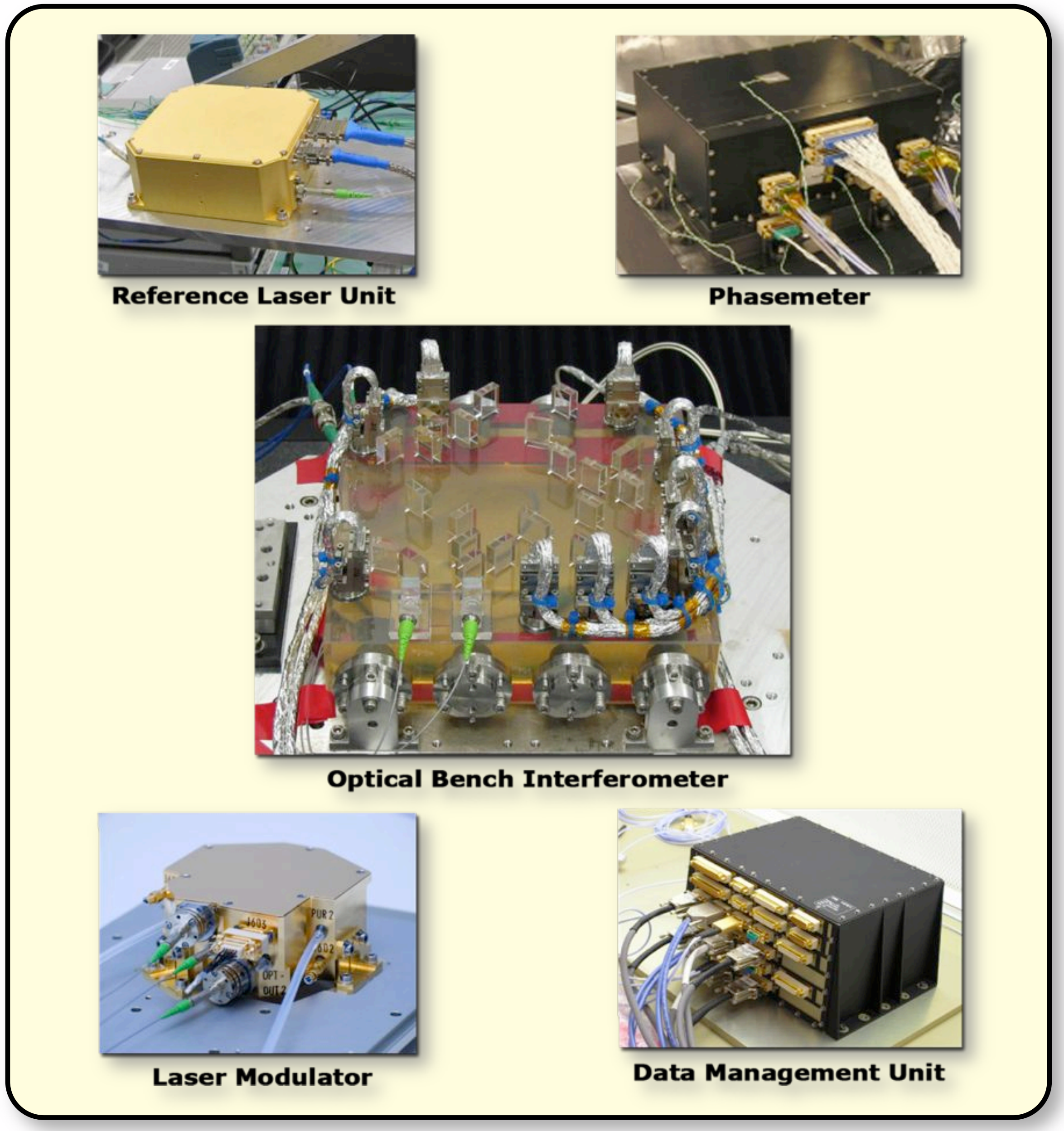
zwischen zwei Punkten zu einem Extremum macht (Geodätische Linie).

The definition of geodesics in Einstein's "The Meaning of Relativity"

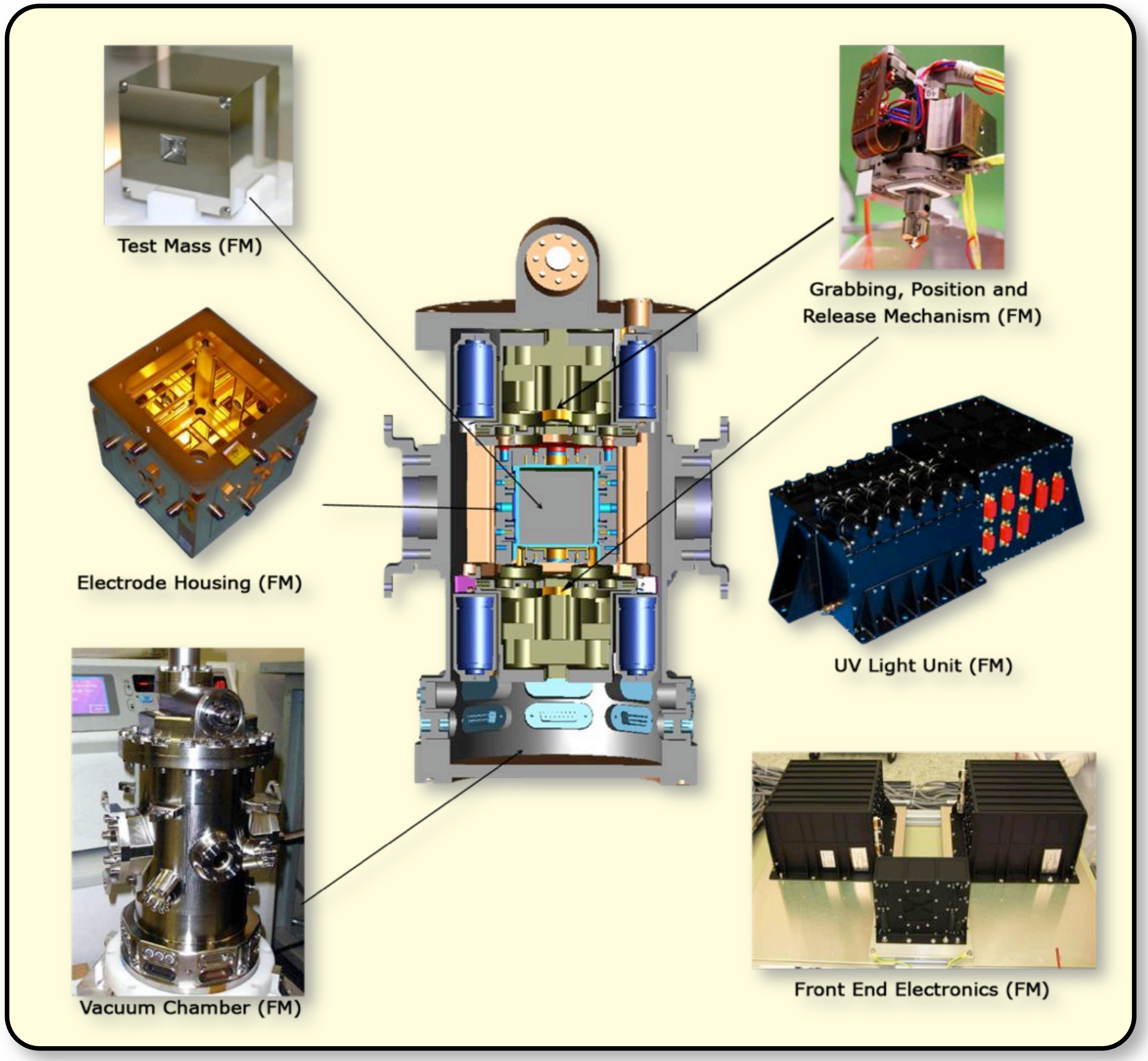
- ALL missions aimed at demonstrating an aspect of GR rely on geodesics
  - LISA Pathfinder will be the first mission to demonstrate that free particles follow geodesics at such an unprecedented level
- An LPF-like satellite provides a near-perfect platform for fundamental physics experiments
  - Spacecraft jitter (w.r.t. inertial frame) is less than 2nm/√Hz at 1mHz

LISA Technology Package

- Two Au:Pt test masses housed in separate vacuum enclosures
- Relative position of test masses read-out by
  - Heterodyne laser interferometry on sensitive axis
  - Capacitive sensing on all degrees of freedom

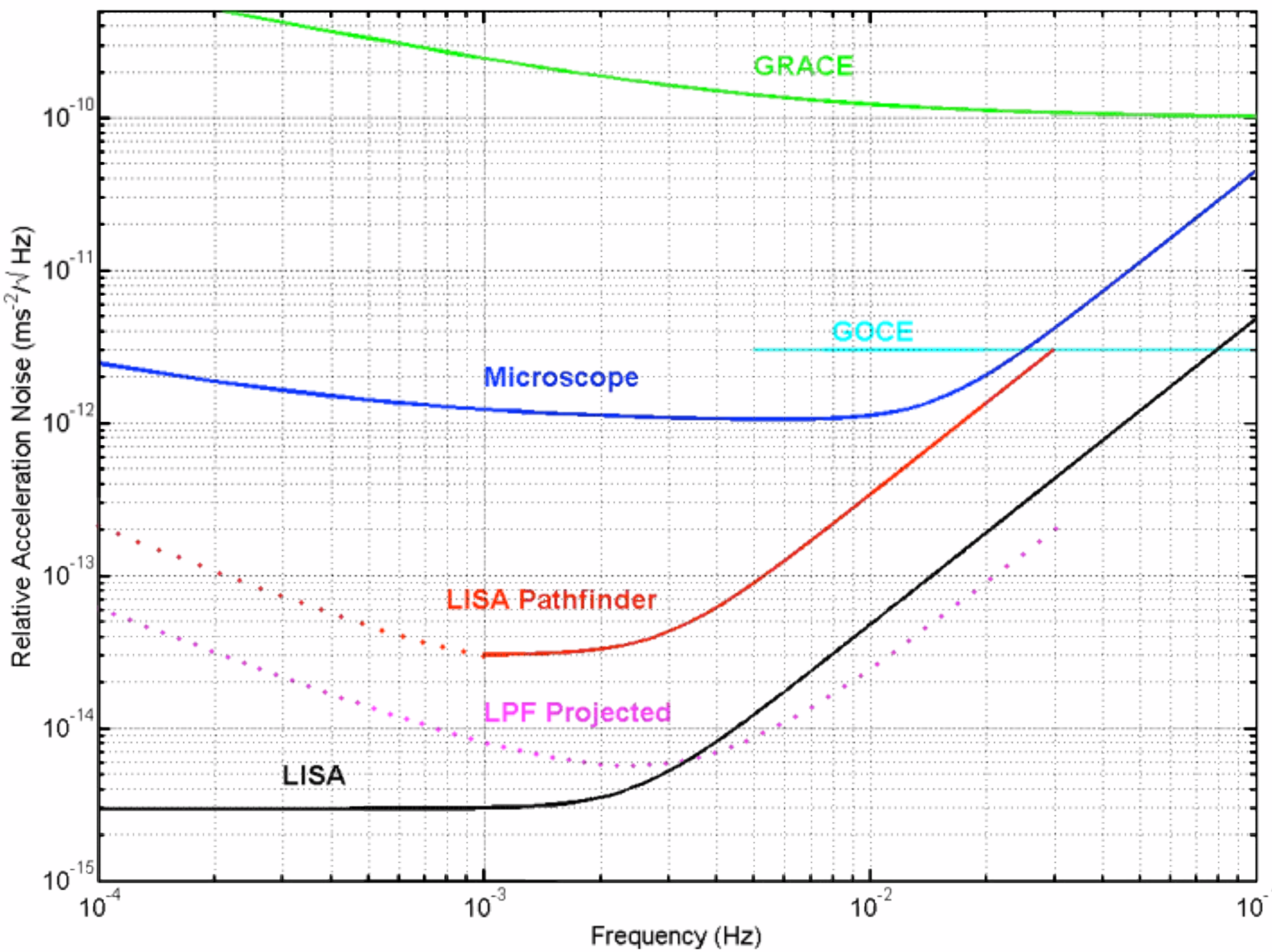


Optical Metrology Subsystem



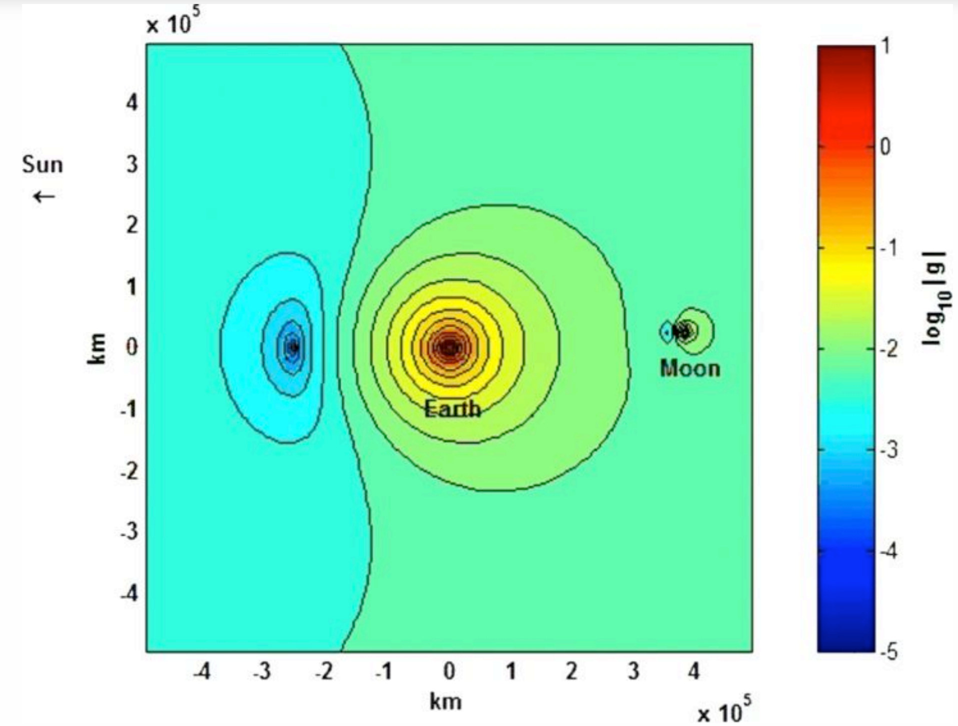
Inertial Sensor Subsystem

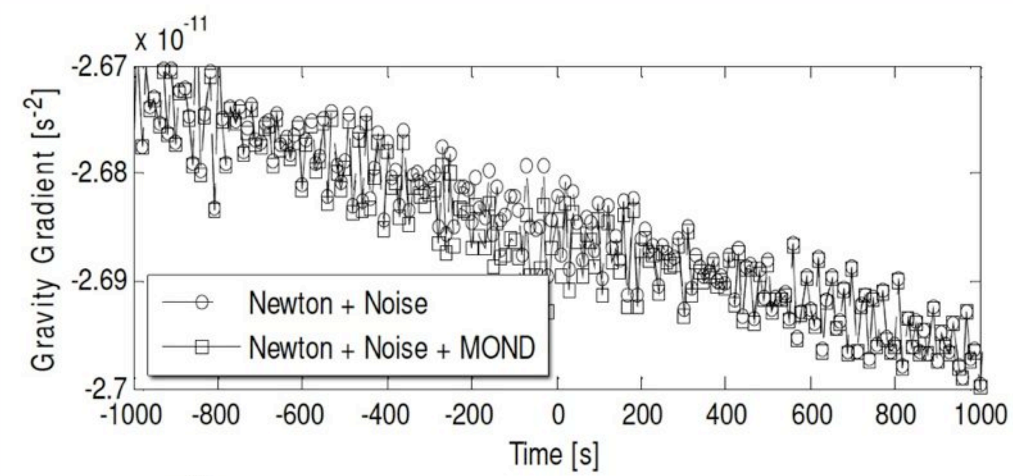
LPF Performance

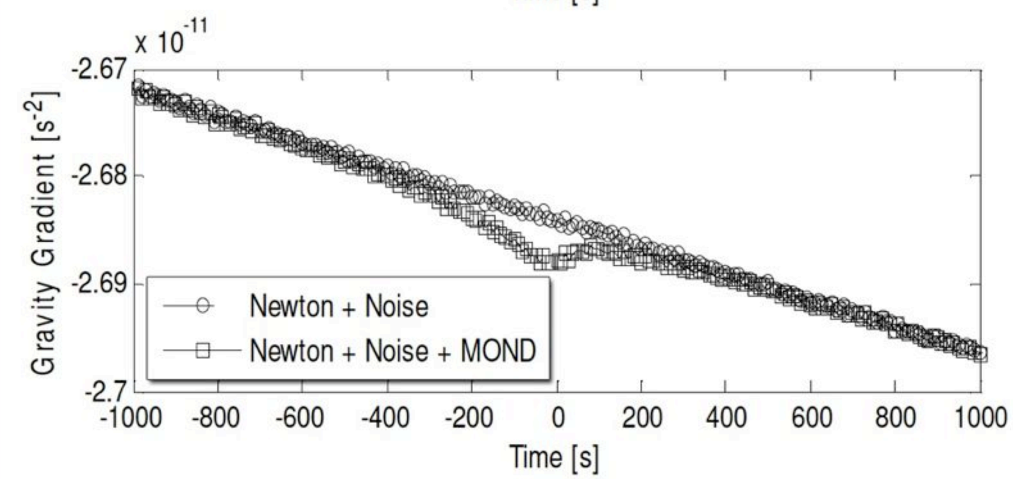


LPF to Test Alternative Theories of Gravity

- Observations of galactic rotation curves do not agree with Newtonian predictions: Rotation curves are *flat* (Tully-Fischer)
- Conventional explanation is that galaxies are surrounded by a halo of dark matter
- Alternative explanation is that Newtonian dynamics breaks down when the background gravitational field falls below a threshold ($a_o \sim 10^{-10} ms^{-2}$)
  - Modified Newtonian Dynamics (MOND) proposed by Millegrom in 1983
  - Relativistic theory (TeVeS) developed by Bekenstein with MOND as the non-relativistic limit
- Saddle Points offer the opportunity to test alternative gravity theories in the local solar system e.g. at the Sun-Earth saddle point
- LPT monitors Newtonian gravity gradient as measured by the drag-free test masses: Any deviation from Newtonian theory will be evident in the test-mass position as they pass through the bubble

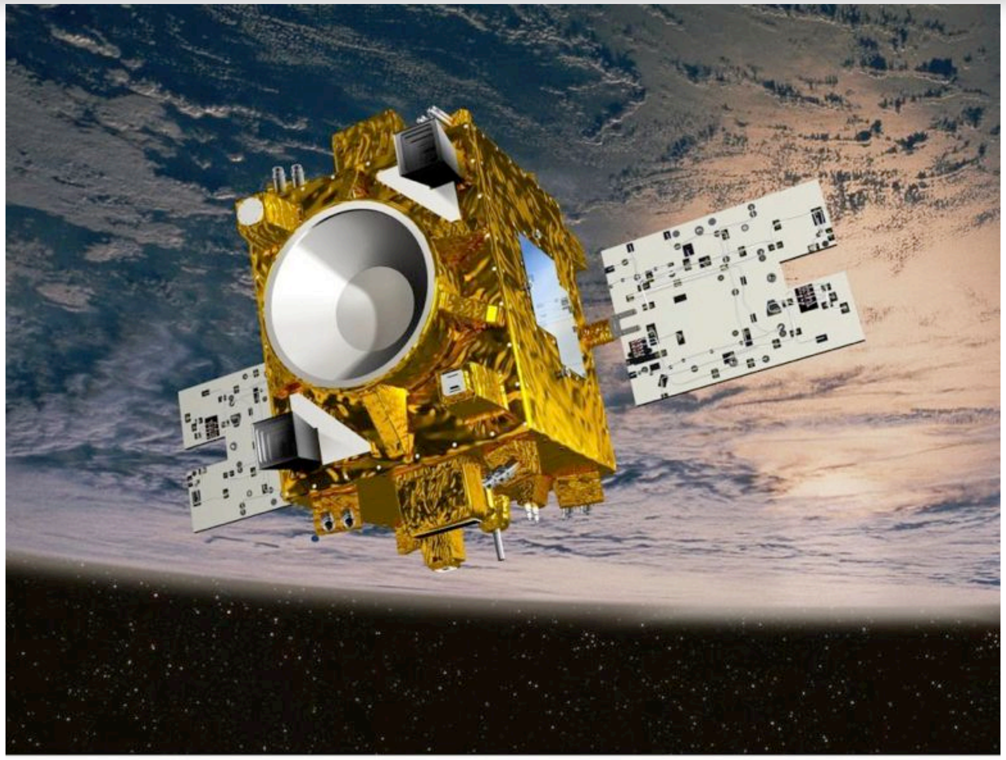






Microscope

Scientific Objective: Weak Equivalence Principle test with a relative accuracy of 10^{-15} (i.e. 2 orders of magnitude better than present tests)



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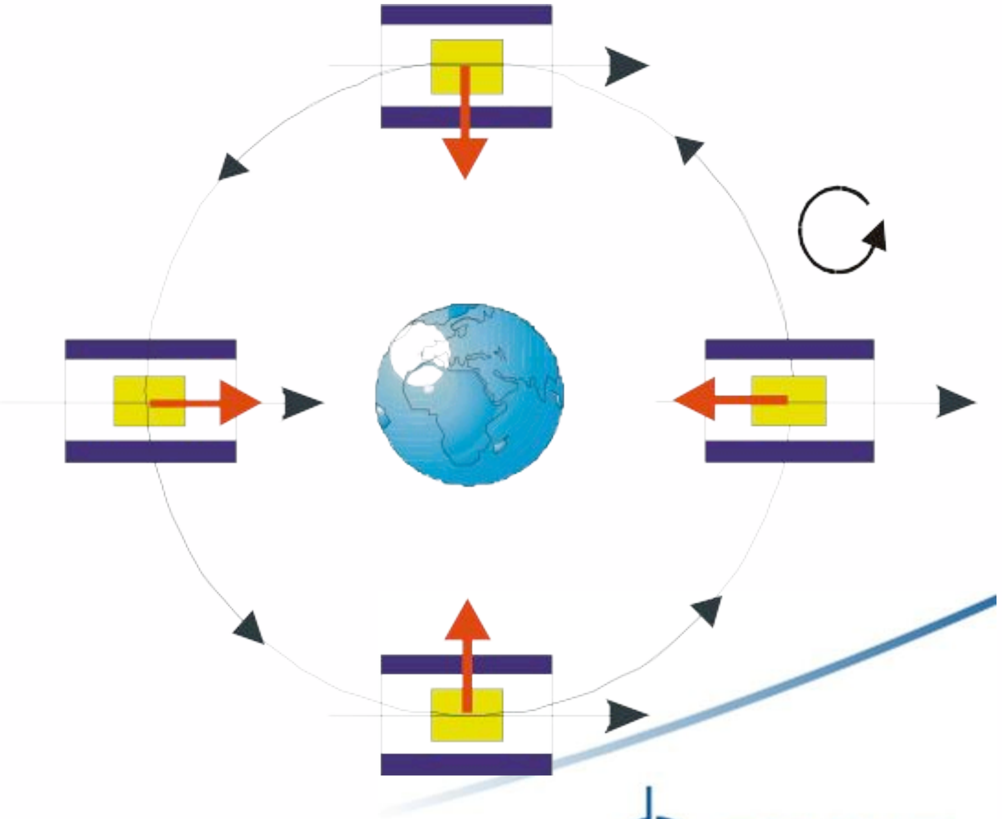
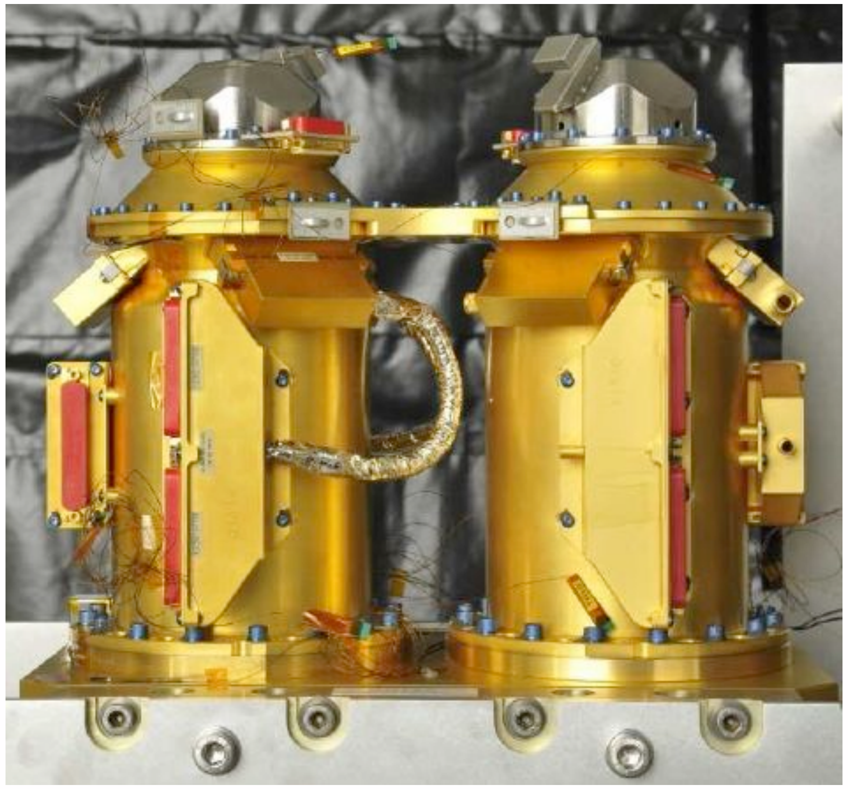
Mission profile:

- CNES mission with ESA contribution
- Orbit: Dawn-dusk sun-synchronous orbit with 700 km altitude and $<5 \cdot 10^{-3}$ eccentricity
- WEP test in
  - Inertial mode (120 orbits): $\nu_{WEP} = \nu_{Orbit}$
  - Spin mode (20 orbits): $\nu_{WEP} = \nu_{Orbit} + \nu_{Spin}$
- Spacecraft
  - Myriade product line platform
  - Volume: 1.360 m x 1.040 m x 1.500 m
  - Mass: 330 Kg
  - Power: 140 W
- Launch scenario: ASAP SOYUZ with Sentinel 1B



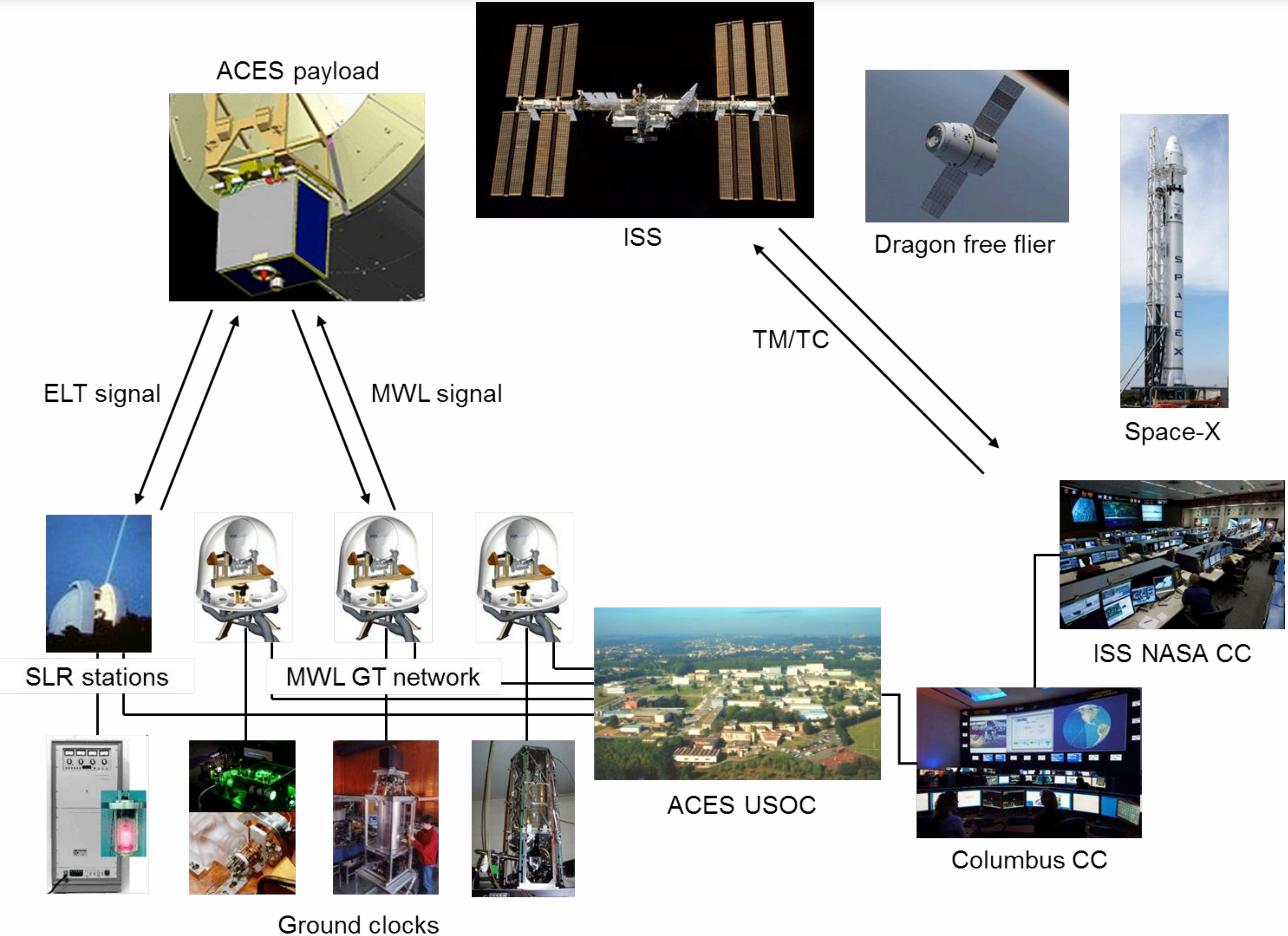
Microscope Payload

- Differential accelerometer developed by ONERA
  - 2 sensor units composed of two concentric test masses each: Pt:Rh/Pt:Rh and Ti/Pt:Rh
  - 3 electrodes to control axial, radial and spin degrees of freedom
  - Performance: $2{\cdot}10^{-12}$ m/($s^2{\cdot}\sqrt{Hz}$) in the 10^{-3}-10^{-2} Hz frequency range

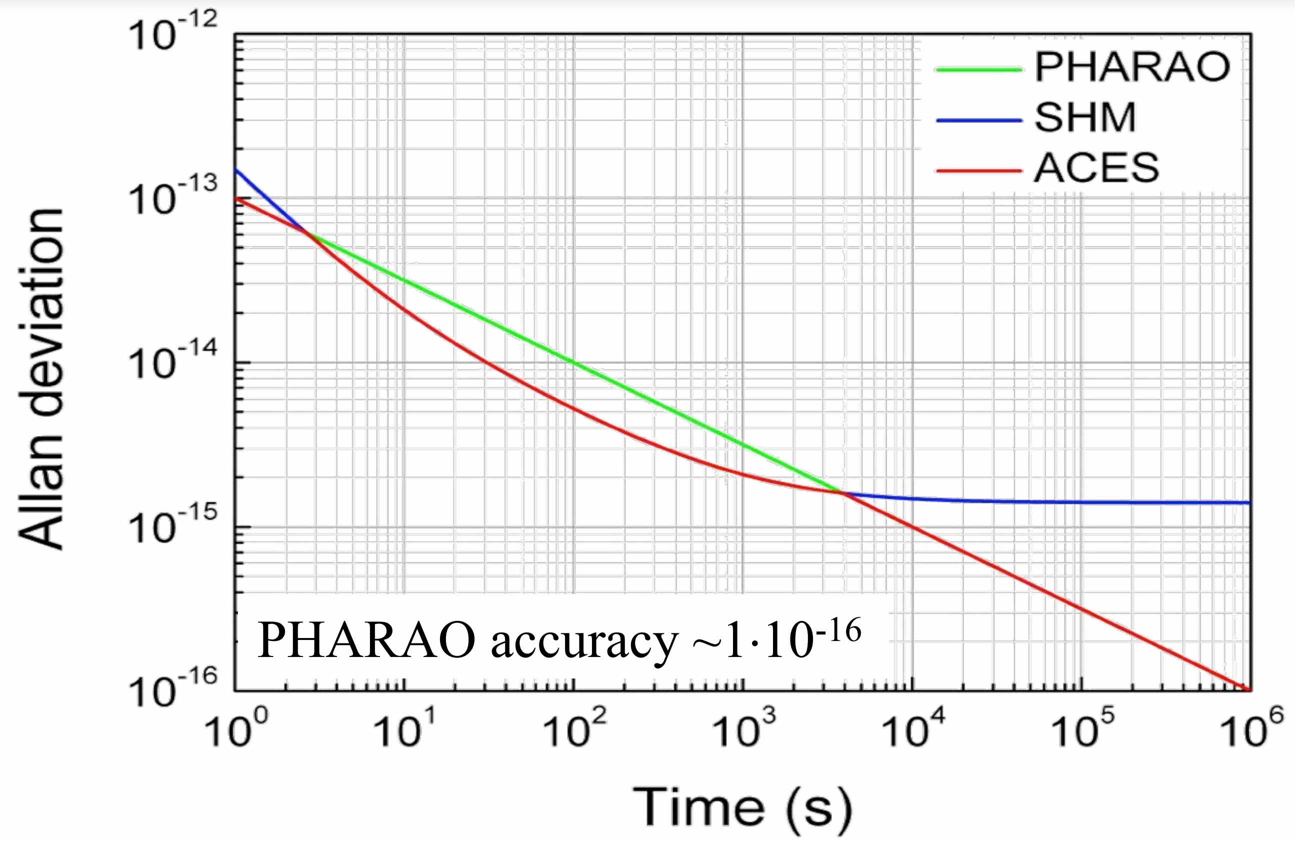


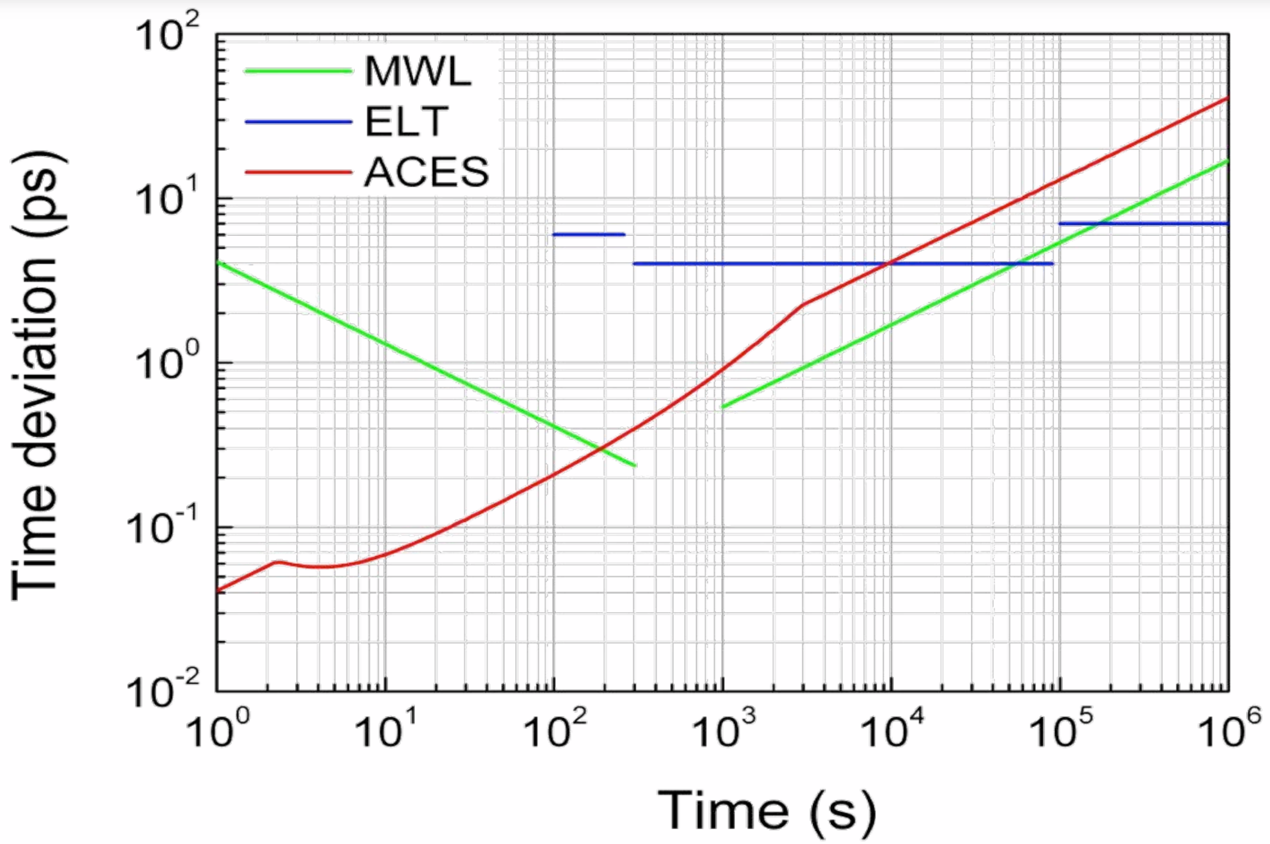
- Cold-gas propulsion system based on Gaia provided by ESA:
  - Electronic Control Module (ECM)
  - 2 x 4 micro-thrusters + redundancy: 1 to 300 µN thrust, 0.2 µN resolution
  - 2 x 3 thanks of N_2
  - Mission lifetime limited by the cold-gas propulsion system

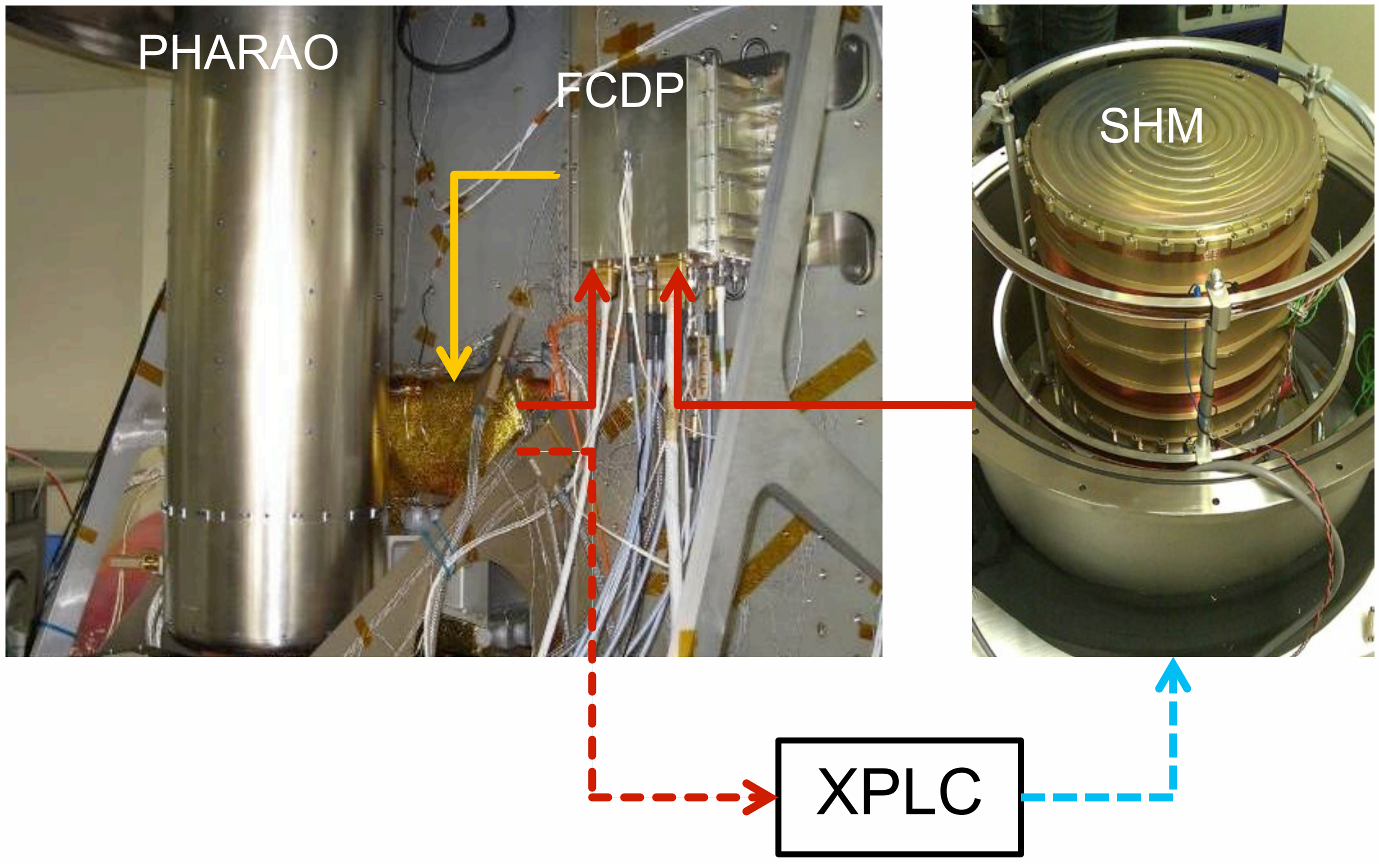
Atomic Clock Ensemble in Space

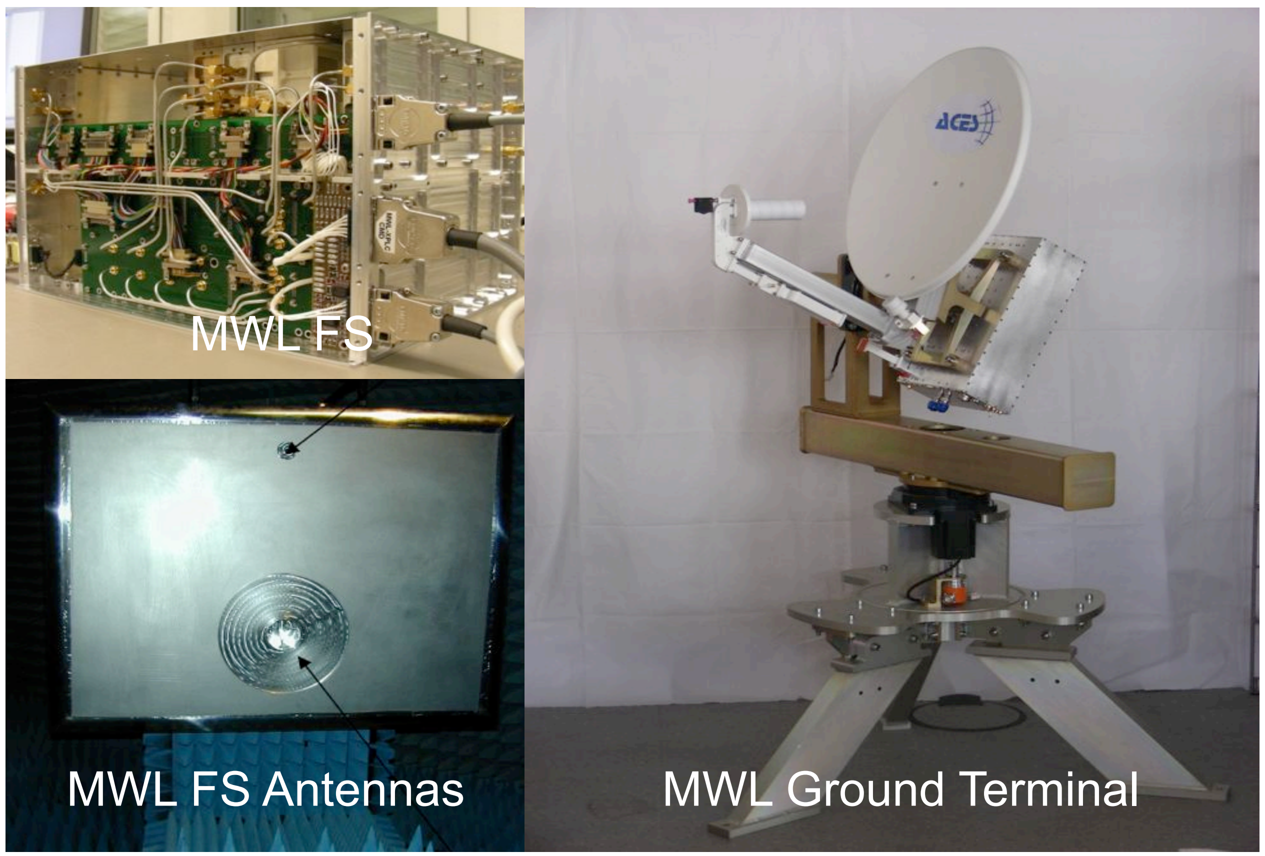


ACES Clocks and Links Performance

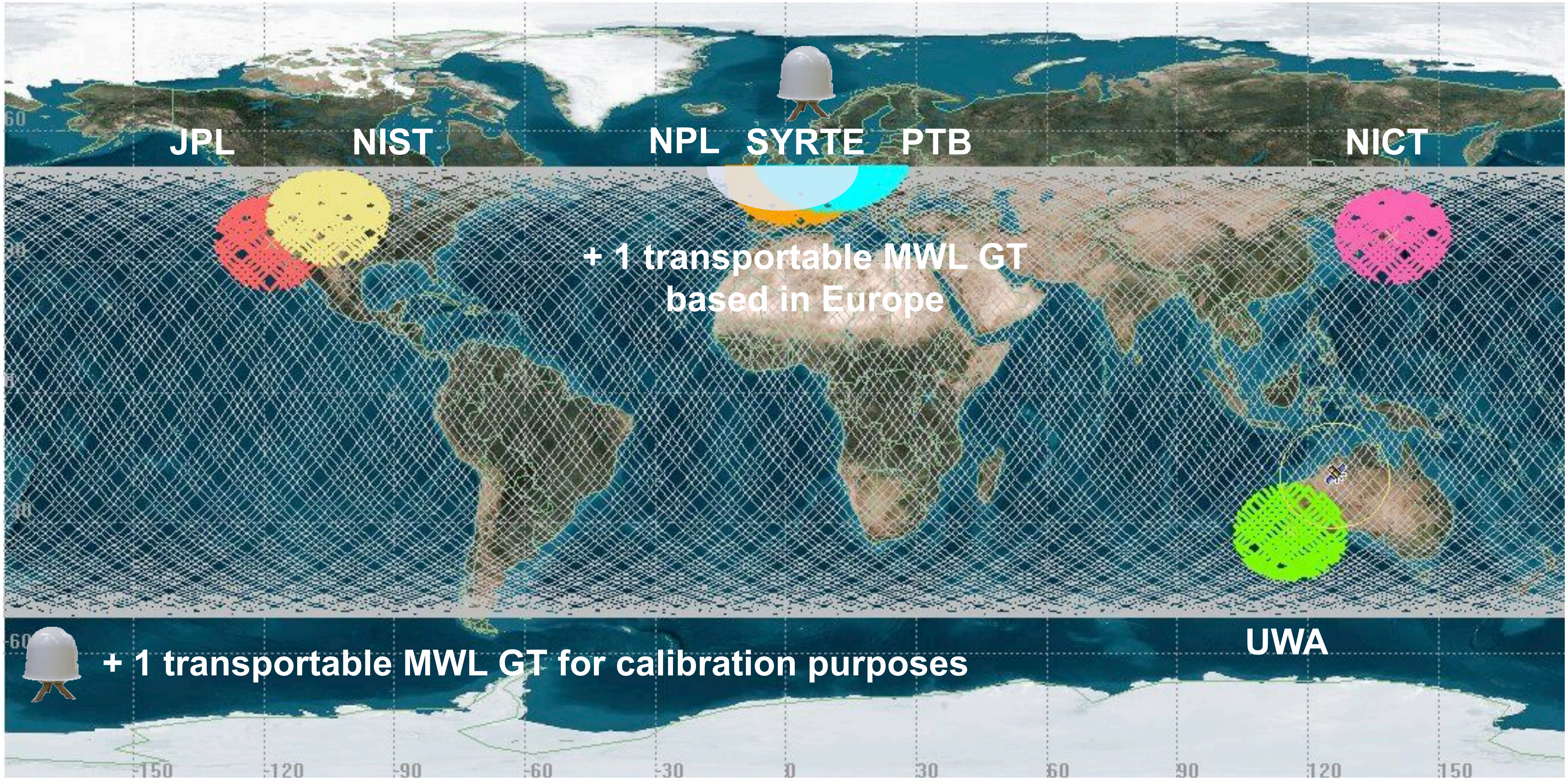








Core Network of MWL GTs



+ METAS (CH) + Wettzell (DE)

ACES and Fundamental Physics Tests

ACES Mission Objectives	ACES performances	Scientific background and recent results
Fundamental physics tests		
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at an uncertainty level $< 50 \cdot 10^{-6}$ after 300 s and $< 2 \cdot 10^{-6}$ after 10 days of integration time.	Space-to-ground clock comparison at the 10^{-16} level, will yield a factor 35 improvement on previous measurements (GPA experiment).
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1 \cdot 10^{-17}$ year $^{-1}$ down to $3 \cdot 10^{-18}$ year $^{-1}$ in case of a mission duration of 3 years	Optical clocks progress will allow clock-to-clock comparisons below the 10^{-17} level. Crossed comparisons of clocks based on different atomic elements will impose strong constraints on the time drifts of α, m_e / Λ_{QCD} , and m_u / Λ_{QCD} .
Search for violations of special relativity	Search for anisotropies of the speed of light at the level $\delta c / c < 10^{-10}$.	ACES results will improve present limits on the RMS parameter α based on fast ions spectroscopy and GPS satellites by one and two orders of magnitudes respectively.

Space Optical Clocks

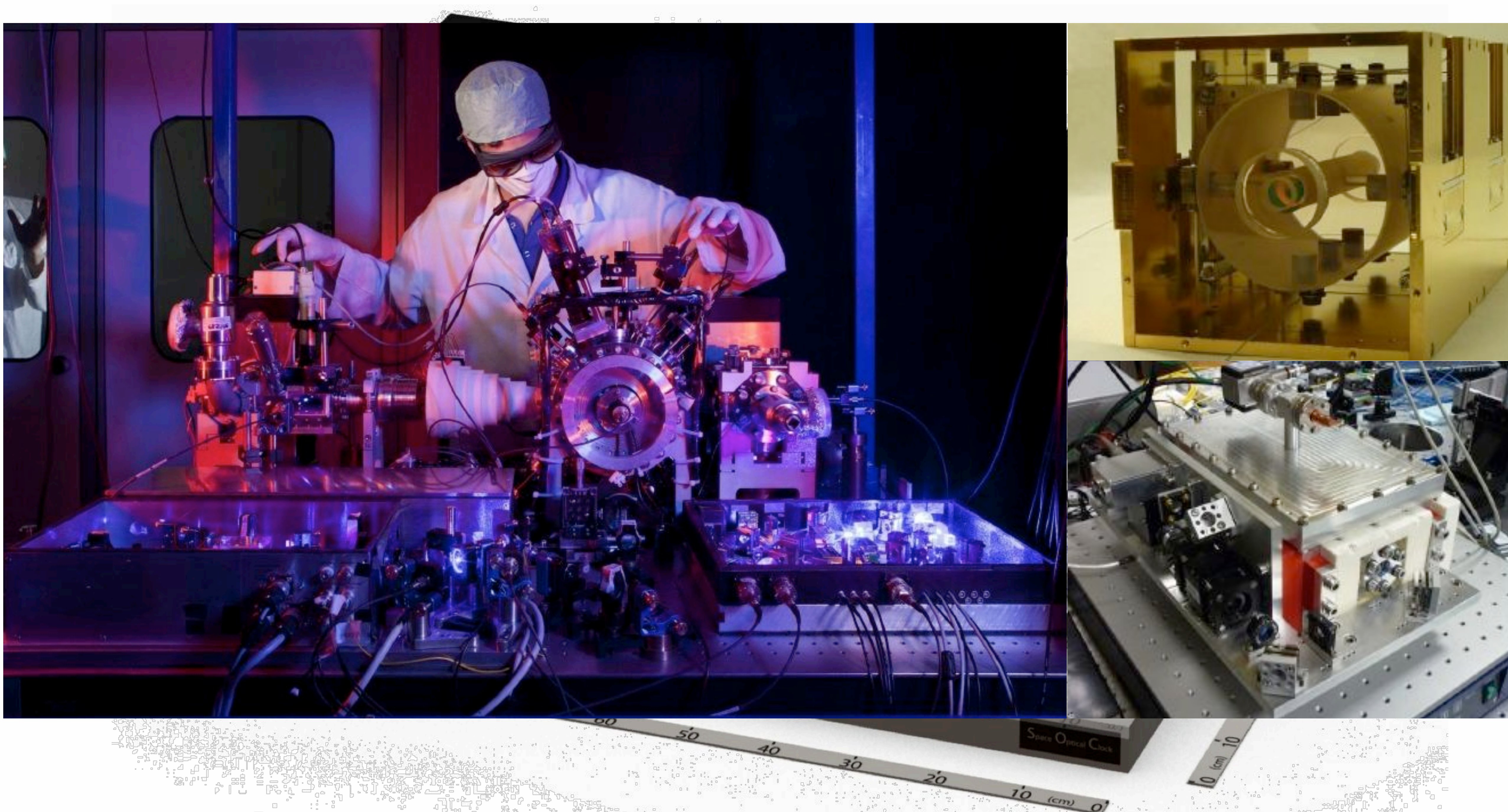
- Atomic clock fractional frequency instability at the quantum projection noise limit: $\sigma_y(\tau) = \frac{1}{\pi}\frac{\Delta\nu}{\nu_0}\frac{1}{\sqrt{N_{at}}}\sqrt{T_c/\tau}$
  - $\Delta\nu \sim$ 1Hz, limited by the interaction time
  - $N_{at} \sim 10^6$, limited by cooling and trapping techniques, collisions, etc.
- From the microwave to the optical domain
  - Frequency instability is inversely proportional to ν_0: optical transitions show a potential increase of almost 5 orders of magnitude
    - Microwave fountain clocks: $\sigma_y(\tau) = 10^{-14}\,\tau^{-1/2}$
    - Optical clock: $\sigma_y(\tau) = 10^{-18}\,\tau^{-1/2}$
  - Accuracy: 10^{-18}
- Technical issues and solutions
  - Measurements of optical frequencies $\rightarrow$ fs frequency-comb generator
  - Recoil and Doppler effect $\rightarrow$ trapped ion clock or lattice clock
  - Reference oscillator noise $\rightarrow$ better clock lasers and reference cavities

SOC as ACES follow-on mission

Sr lattice clock with $1\cdot10^{-17}$ fractional frequency instability and inaccuracy

Transportable Sr lattice clock

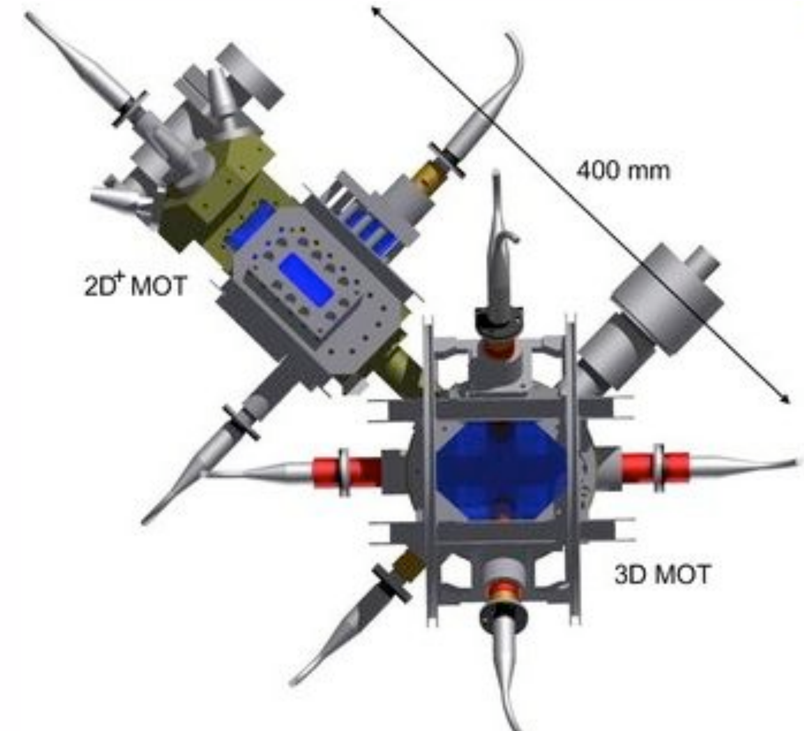
Sr clock prototyping activities started by ESA are now continuing under EC funding



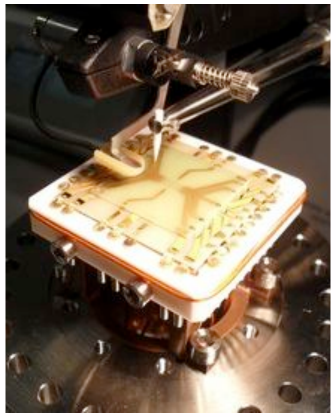
SOC Status

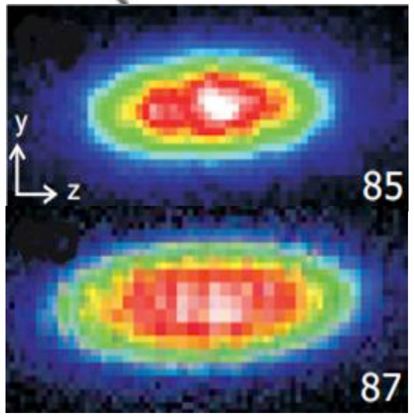
- Results to date:
  - First transportable laser system for clock interrogation (laser locked on a high-finesse cavity) demonstrated - *Appl. Phys. B* **104**, 741 (2011)
  - First-generation Sr clock physics package completed and presently under test
  - Second-generation Sr clock physics package being completed
  - ^{88}Sr clock transition detected with < 10 Hz linewidth
  - Characterization of Sr clocks at SYRTE and PTB at the $1{\cdot}10^{-16}$ level - *Metrologia* **48,** 399 (2011)
- 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 the second half of 2014

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)





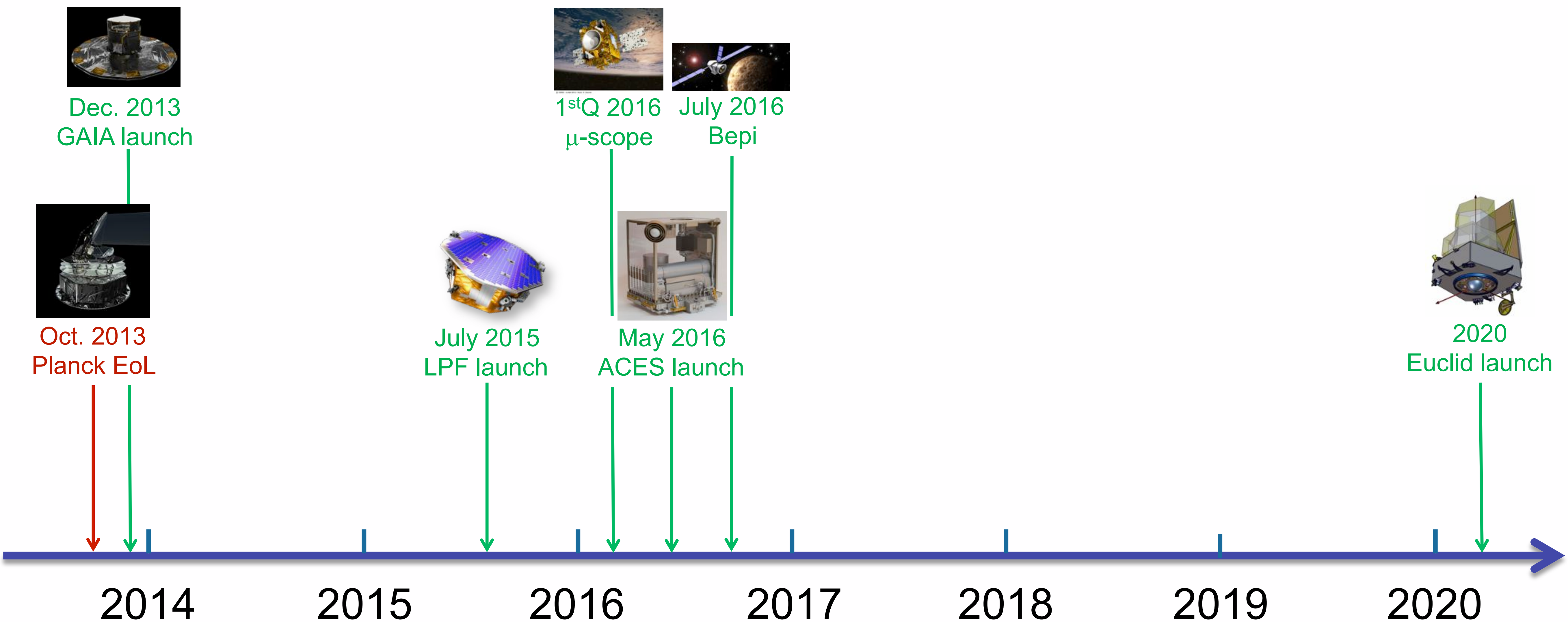
- There is a number of difficulties in the frontier between QM and GR due to the absence of a quantum theory of gravitation that call for experiments like a quantum test of WEP

Q-WEP Status

e

- Detection of inertial effects with atom interferometry during parabolic flights
- Atom interferometry with BEC in the microgravity environment of the Bremen drop tower
- SAI sensor assembly and tests completed: towards the implementation of a BEC source
- Q-WEP Experiment Scientific Requirements (ESR) delivered by the Science Team (US scientists included)
- Q-WEP accommodation on-board the ISS studied in two competitive industrial activities that positively concluded on mission feasibility

Fundamental Physics in Space



Next Milestones in the ESA CV Programme

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- Medium-class missions
  - M1: *Solar Orbiter* → launch 2017
  - M2: *Euclid* → launch 2020
  - M3: *Plato* → launch 2024
  - M4: ESA Executive will present plans for M4 call at the next SPC; this means that any release of an AO for M4 will not be before June 2014.
- Large-class missions
  - L1: JUICE → launch 2022
  - L2: *The Hot and Energetic Universe* science theme was selected as L2 for a launch opportunity in 2028
    - Based on the stated interest of NASA and ISAS/JAXA to participate in the mission, ESA intends to include US and Japanese scientists in the Study Team.
    - AO for payload and science ground segment elements will likely be released in early 2015 with Phase A completing at the end of 2016.
    - Mission adoption (final approval) is expected around the end of 2018.
  - L3: *The Gravitational Wave Universe* science theme was selected as L3 for a launch opportunity in 2034
    - ESA intents to appoint an advisory team to recommend on the best scientific and technical approaches for a gravitational wave observatory: work is likely to start in June 2014 and be completed by October.
    - Given NASA's stated interest, ESA intends to invite NASA participation in the advisory team and in the subsequent technology assessment studies.

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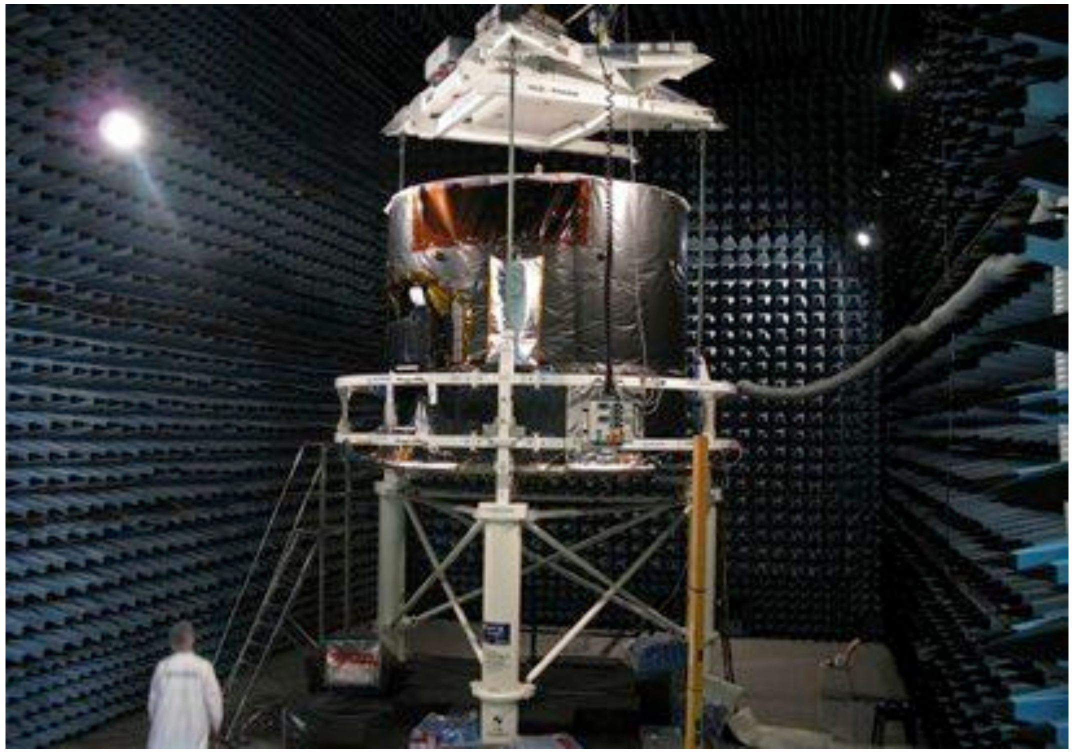
GAIA Status

- Gaia was launched on 19 December 2013 and currently in its commissioning phase
- All subsystems have been successfully operated. Focal plane is fully functional with all 106 CCDs operational
- Commissioning is expected to be completed by the end of May
- Performance tests have been started; issue with stray light being addressed
- Routine science phase expected to start in June/July
- First GAIA data release in 2016



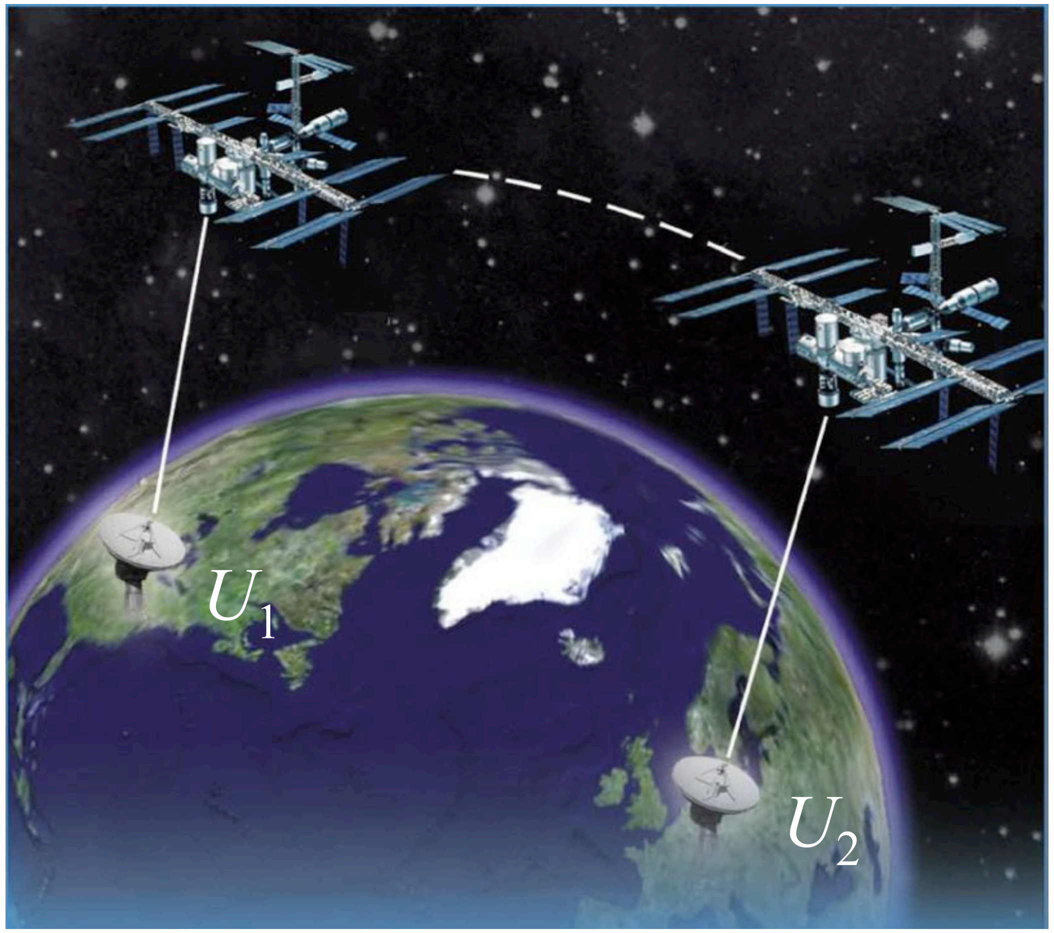
BepiColombo Status

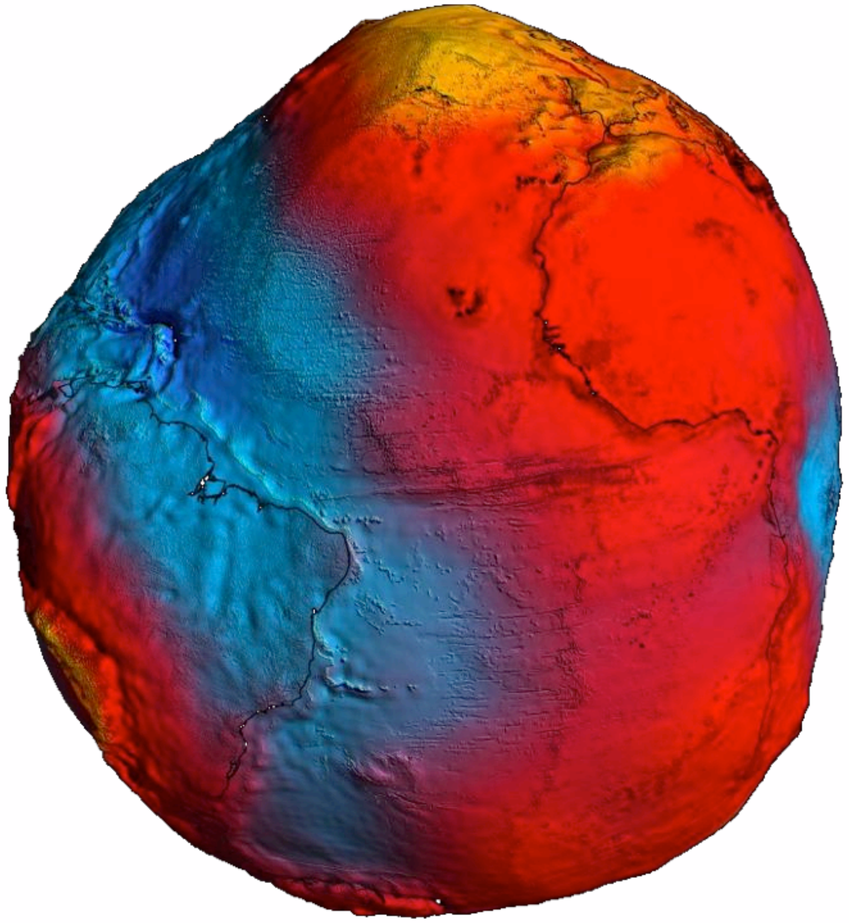
- MPO PFM unit and payload final integration in Torino (Italy)
- The MTM PFM integration for thermal and chemical propulsion hardware is on-going
- MMO FM integration and functional verification completed
- The mission and science operations preparation activities proceed as planned
- Launch date: July 2016

LPF Status

- LISA Pathfinder is well on its way to validate the technologies required by future spaceborne GW detectors
- The first set of environmental tests have been successfully completed
- Results from the OSTT demonstrate performance better than requirements
- Cold Gas Thrusters are now the baseline for the mission
- The project is in hibernation awaiting the delivery of LTP Core Assembly (optical bench and inertial sensors), scheduled for December 2014
- Launch is scheduled for July 31st 2015

Relativistic Geodesy with ACES



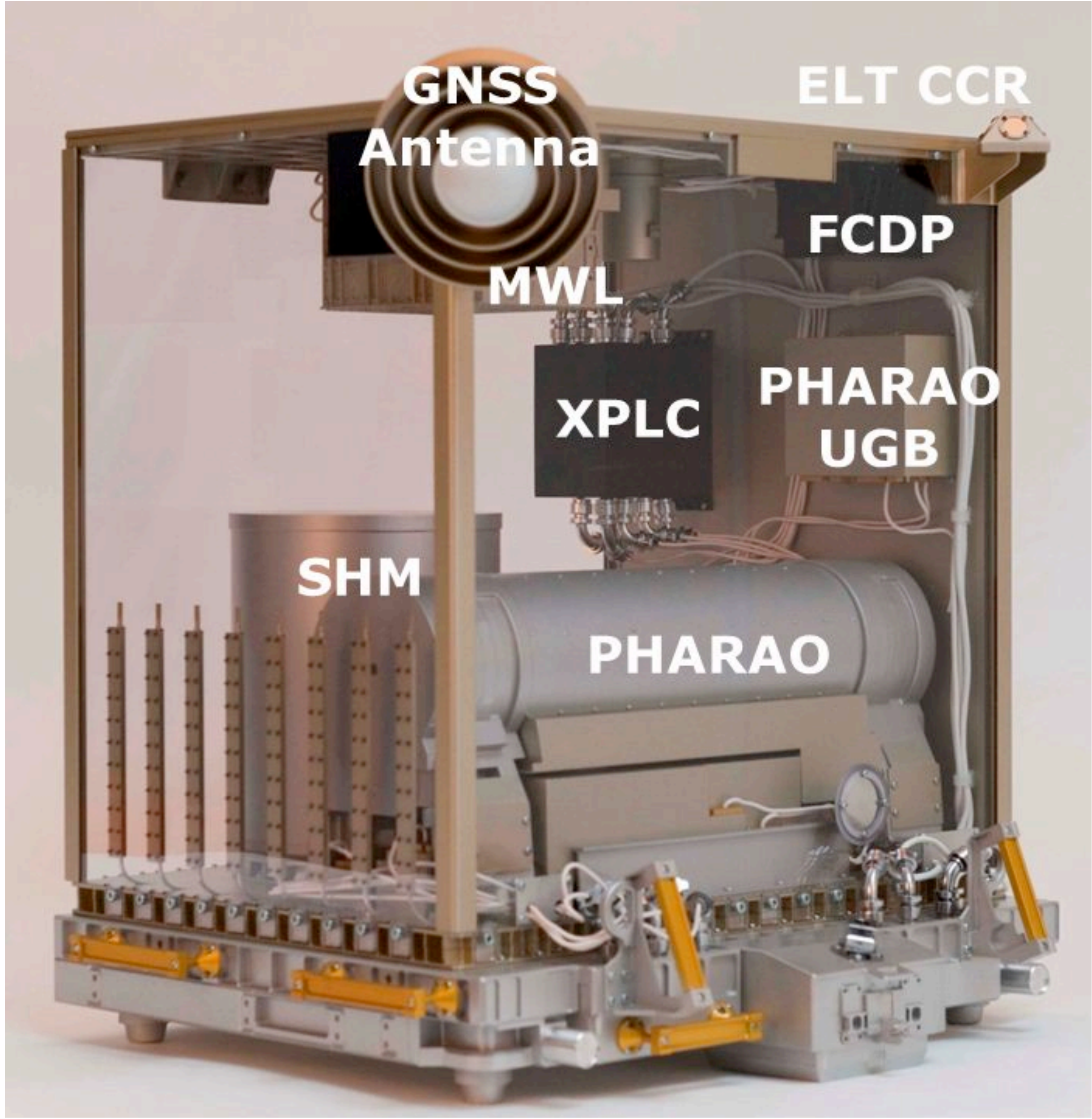


Relativistic geodesy: mapping of the Earth gravitational potential based on the precision measurement of the red-shift experienced by two clocks at two different locations

- ACES will perform intercontinental comparisons of optical clocks at the 10^{-17} level after 1 week of integration time, measuring the local height of the geoid at the 10 cm level.
- The global coverage offered by ACES will complement the results of the CHAMP, GRACE, and GOCE missions.

The ACES Payload

- PHARAO (CNES): Atomic clock based on laser cooled Cs atoms
- SHM (ESA): Active hydrogen maser
- FCDP (ESA): Clocks comparison and distribution
- MWL (ESA): T&F transfer link
- GNSS receiver (ESA)
- ELT (ESA): Optical link
- Support subsystems (ESA)
  - XPLC: External PL computer
  - PDU: Power distribution unit,
  - Mechanical, thermal subsystems
  - CEPA: Columbus External PL Adapter (ESA-NASA)



Volume: 1172x867x1246 mm^3
Mass: 227 kg
Power: 450 W

AIRBUS DEFENCE & SPACE

ACES Status

- SHM and PHARAO FM delivery in 2014
- ACES PFM system tests to be completed by mid 2015
- Deployment of MWL GTs at the selected Institutes in 2015
- ACES launch NET May 2016

Why Quantum?

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- The variety of quantum states is much larger than that of classical ones: it appears plausible that quantum tests may ultimately be able to see deeper details of couplings between matter and gravity than classical ones.
- When considering non-standard couplings of matter to gravity, there might be a difference between how the wave packet center is moving and how it is deforming: in a sense the quantum motion of the particle is non-universal as the evolution of the associated wave packet (width) depends on *m.*
- The intrinsic spin of quantum probes has no classical equivalent: the procedure to couple a quantum field to gravity is much more complex and more fundamental (tetrads).
- The absence of a quantum theory of gravitation is not a reason not to perform experiments at the interface between GR and QM; on the contrary it provides the stimulus to investigate this unexplored domain with new experiments.
- Atom interferometry promises outstanding sensitivity in the measurement of differential accelerations, while still having possibilities for future improvements.

STE-QUEST

STE-QUEST **Space-Time Explorer and QUantum Equivalence Principle Space Test**	
Theme	What are the fundamental physical laws of the Universe?
Primary Goal	To test the Einstein's Equivalence Principle to high precision and search for new fundamental constituents and interactions in the Universe.
Observables	• Differential acceleration measurements of freely falling atoms; • Clock redshift measurements.
On-board Instruments	Single spacecraft carrying: • A differential atom interferometer operating on the two rubidium isotopes; • Time and frequency transfer link in the microwave for comparing atomic clocks on ground.
Orbit	Highly elliptical orbit around the Earth.
Lifetime	5 years.
Type	M-class mission.

STE-QUEST Science Investigations

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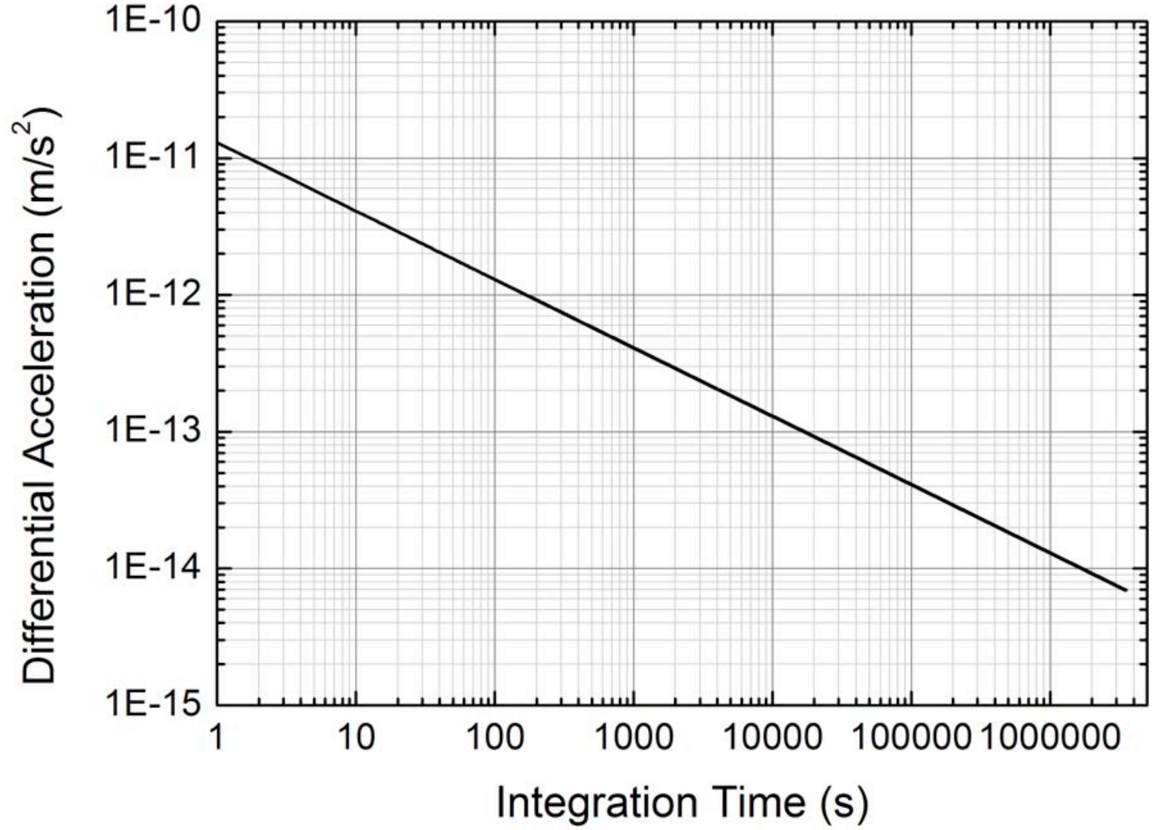
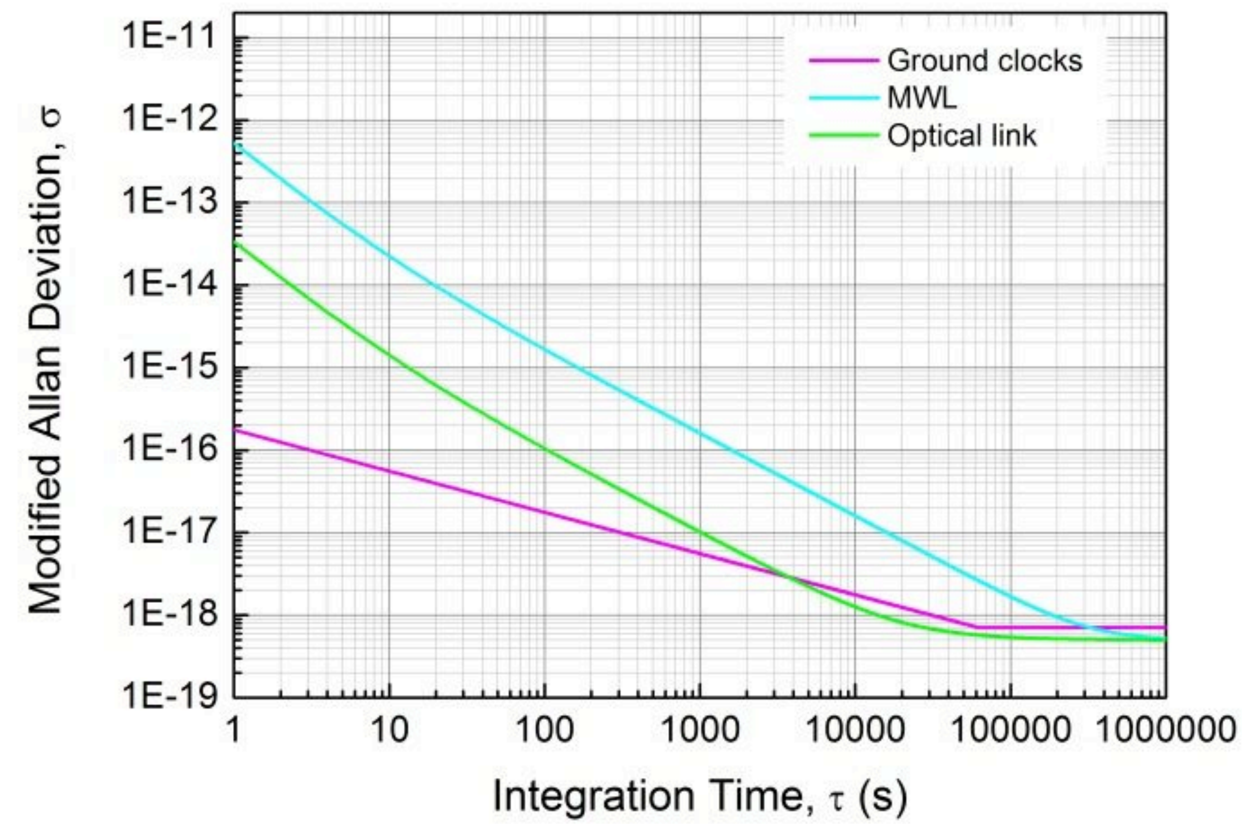
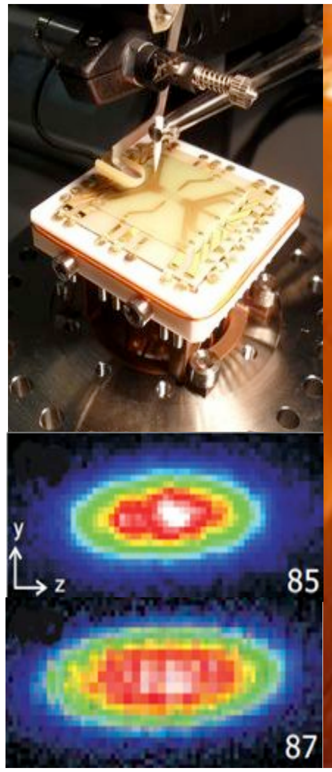
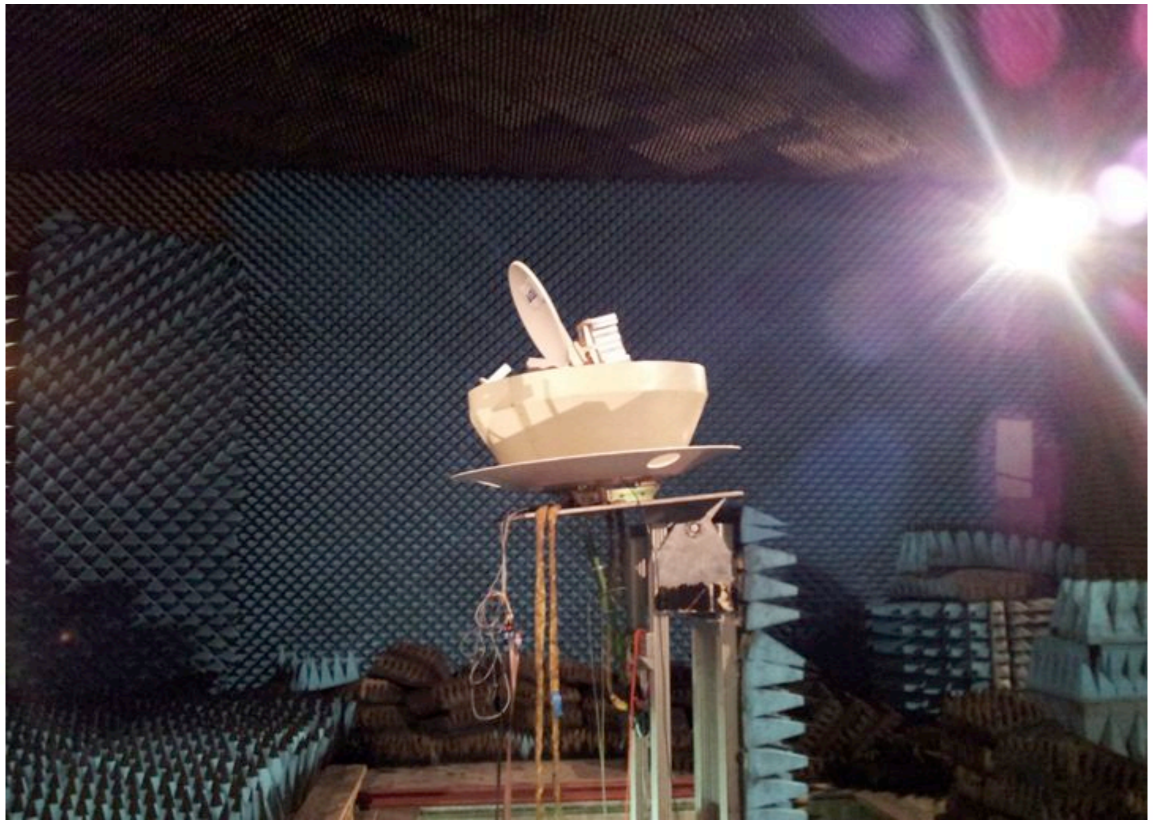
Science Investigation	Measurement Requirement
Weak Equivalence Principle Tests	
Free fall of matter-waves	Test of the universality of free fall of matter waves to an uncertainty the Eötvös ratio lower than $2{\cdot}10^{-15}$.
Gravitational Red-shift Tests	
Sun field	Sun gravitational red-shift measurement to a fractional uncertainty of $2{\cdot}10^{-6}$, with an ultimate goal of $5{\cdot}10^{-7}$.
Moon field	Moon gravitational red-shift measurement to a fractional uncertainty of $4{\cdot}10^{-4}$, with an ultimate goal of $9{\cdot}10^{-5}$.

STE-QUEST Instruments Performance









Atom Interferometry Test of WEP

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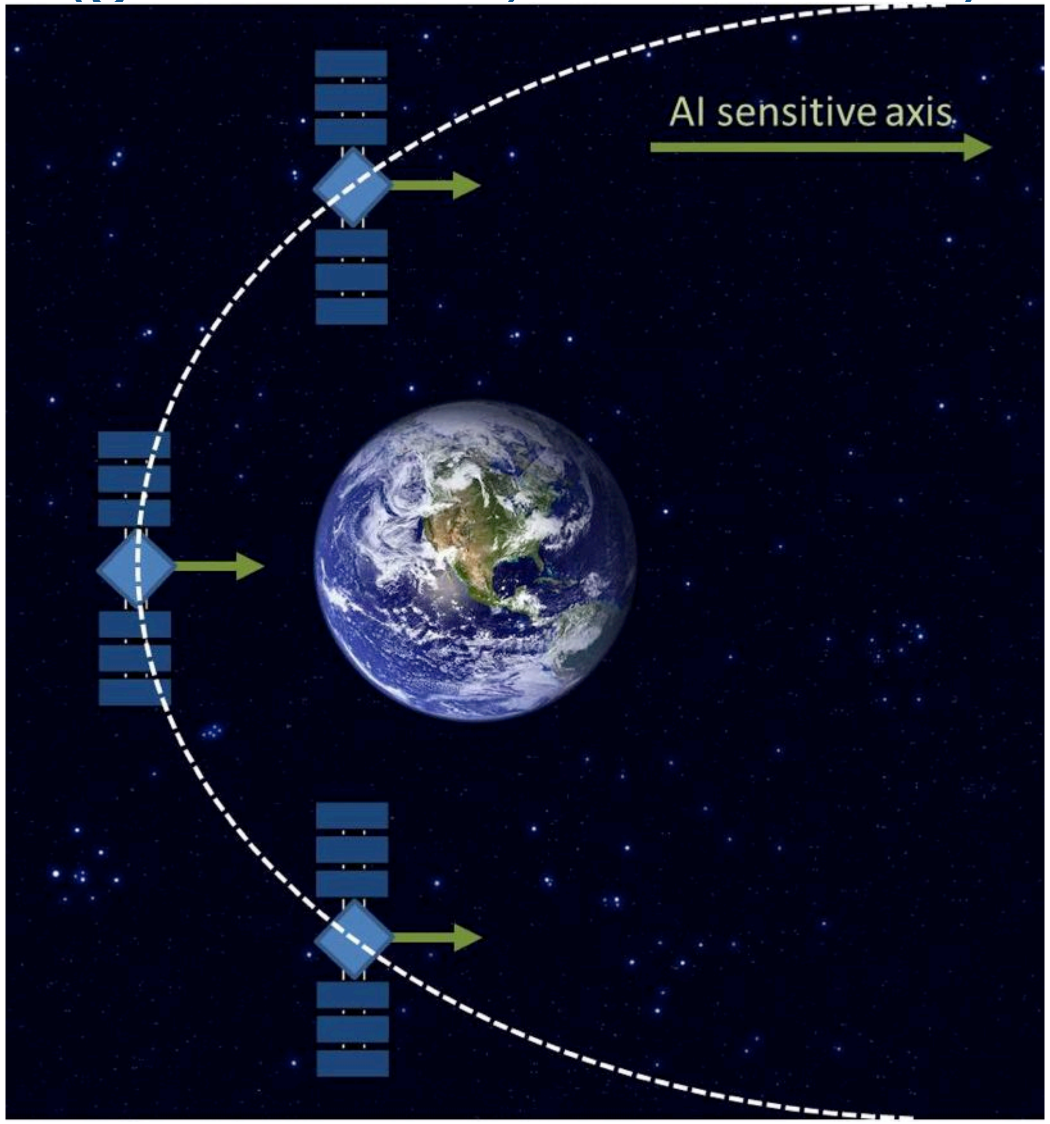
Eötvös ratio: $\eta = 2 \cdot \frac{(m_g/m_i)_A - (m_g/m_i)_B}{(m_g/m_i)_A + (m_g/m_i)_B}$

Atom interferometry measurement of the differential acceleration between ultra-cold atomic samples of ^{85}Rb and ^{87}Rb

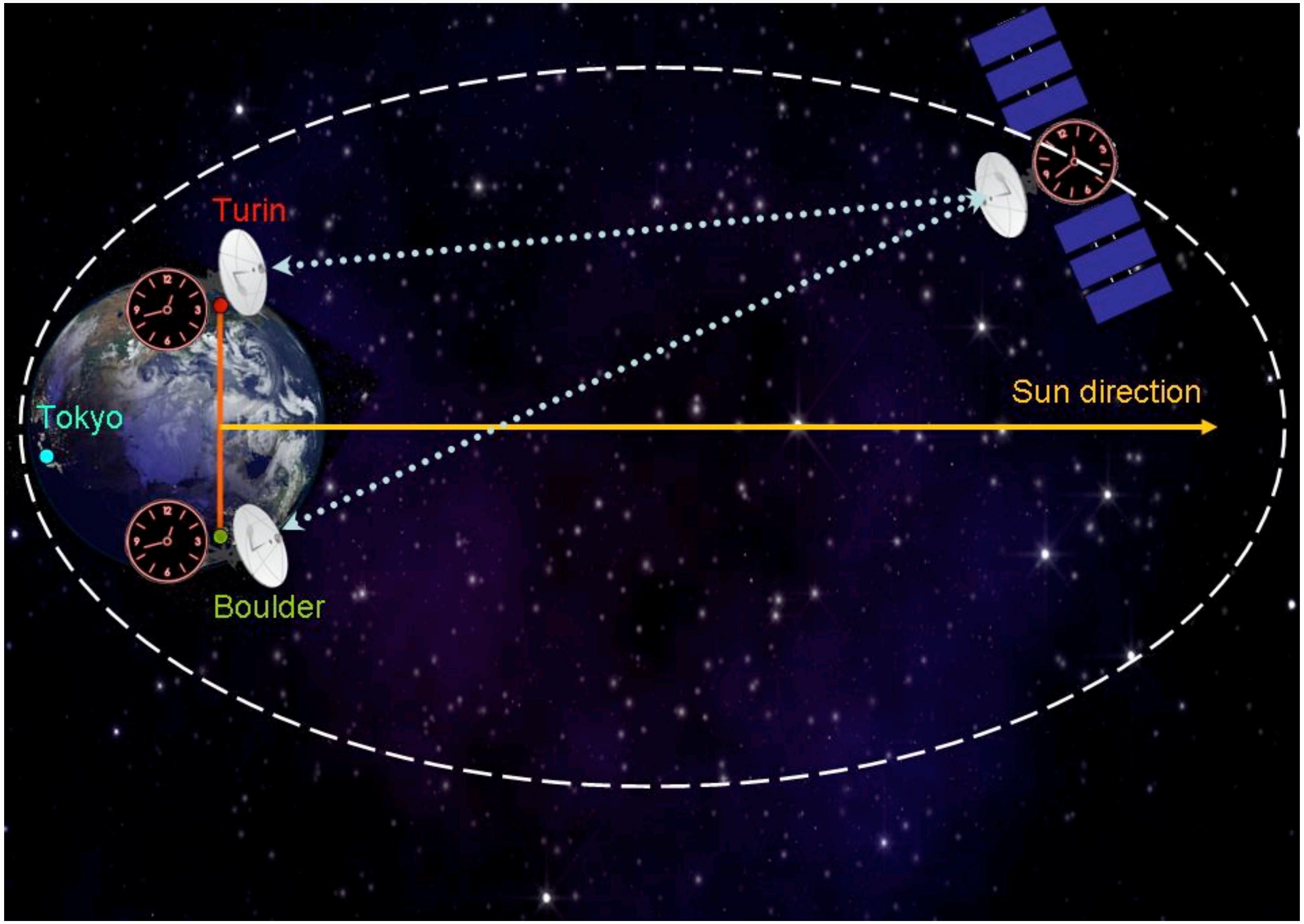
Spacecraft with fixed orientation around perigee (g > 4.5 m/s2, h < 3000 km)



Measurement performance:

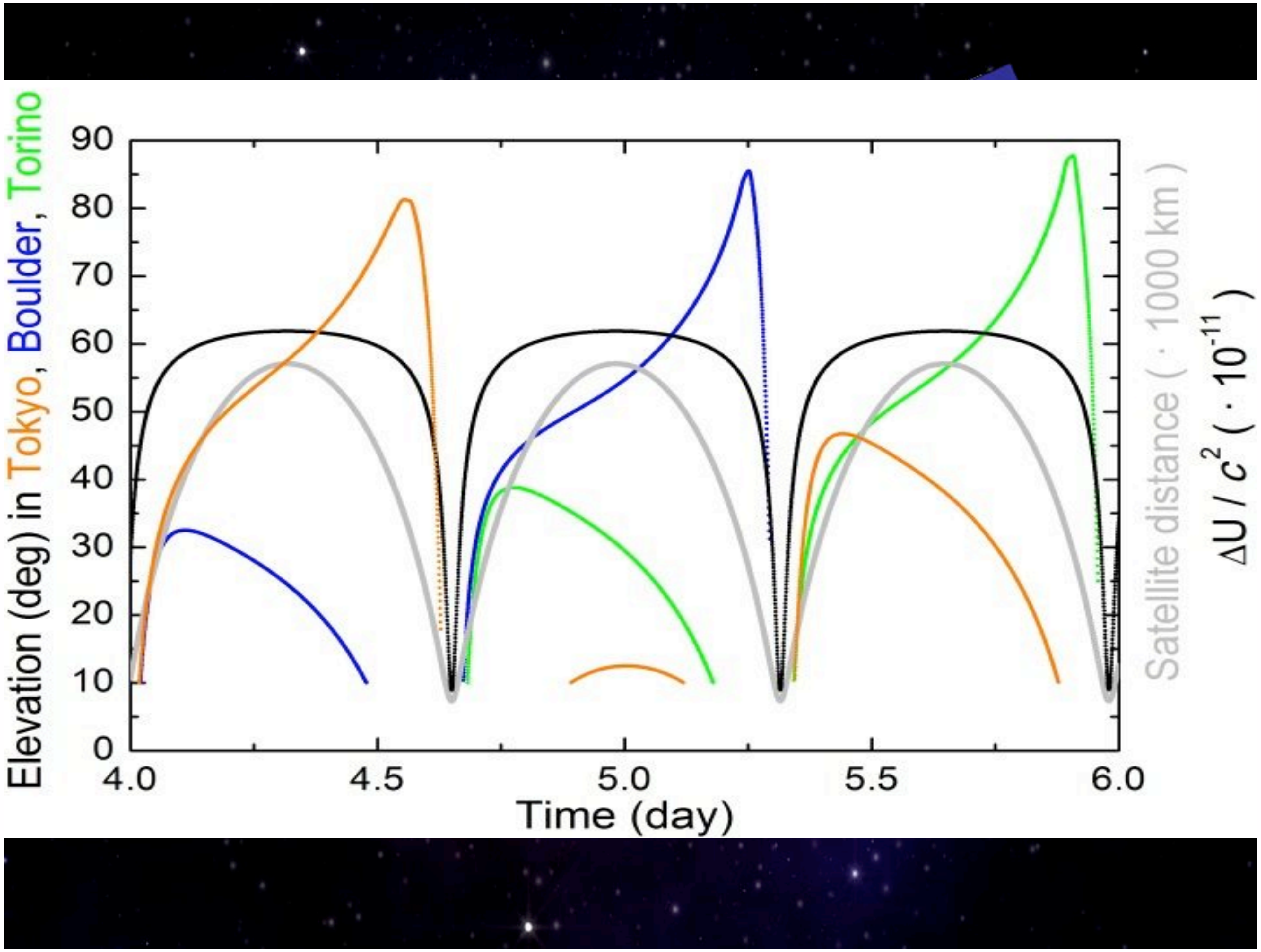
- Single-shot sensitivity: $\sigma_\eta = \sigma_{\Delta a}/g(r) \cdot \cos(\nu)$
- $\sigma_{\Delta a}$ (~ $3 \cdot 10^{-11}$ m/s^2, 20 s measurement cycle duration) depending on gravity gradients through the atom interferometer fringe contrast
- Sensitivity per orbit between $5.0 \cdot 10^{-14}$ (700 km perigee) and $5.3 \cdot 10^{-14}$ (2200 km perigee)
- $2 \cdot 10^{-15}$ accuracy level reached after 1.5 years of measurement duration

Sun/Moon Red-shift Measurement



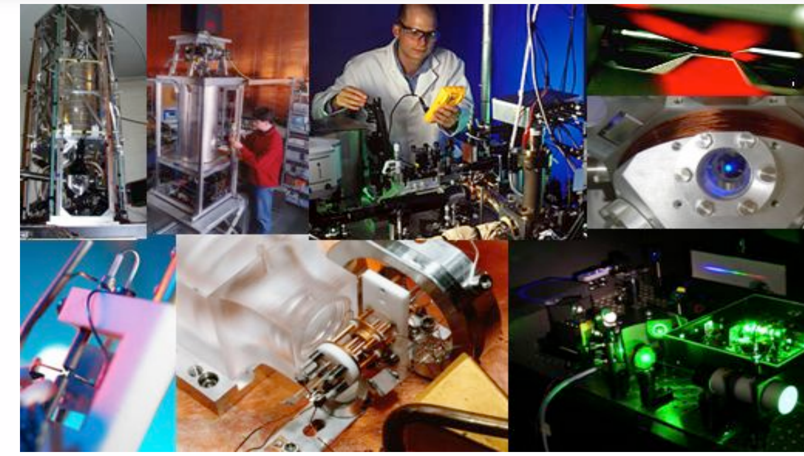
	Measurement resolution	
	After 2 days	After 4 years
Sun red-shift	$6 \cdot 10^{-5}$	$2 \cdot 10^{-6}$
Moon red-shift	$1 \cdot 10^{-2}$	$4 \cdot 10^{-4}$

Ground Clock Comparisons

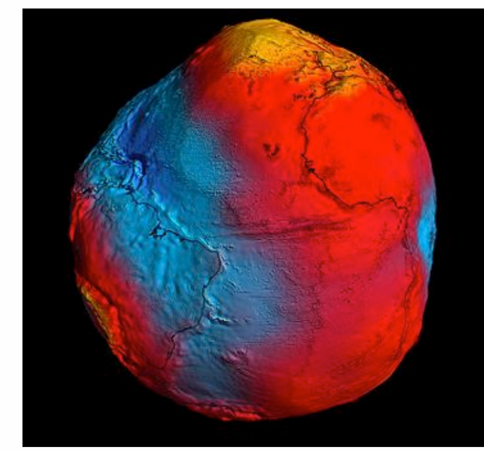


Legacy Science

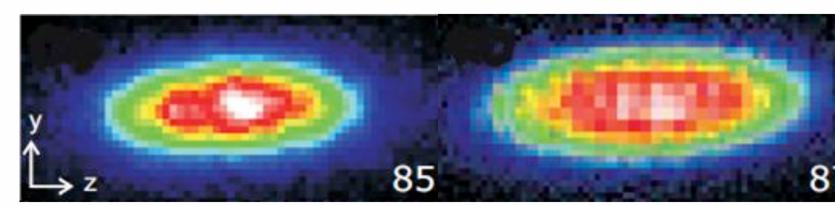
Time and frequency metrology: STE-QUEST will connect atomic clocks on ground in a worldwide network, bringing important contributions to the generation of atomic time scales and to the synchronization of clocks.



Relativistic geodesy: The comparison of clocks on Earth will give access, via the red-shift formula, to differential geopotential measurements on the Earth's surface. A resolution at the level of 1 centimetre on the differential geoid height can be achieved by STE-QUEST.



Cold-atom and matter wave physics in conditions of weightlessness: STE-QUEST will study the evolution of ultra-cold atomic samples in an environment free from perturbations and over long free-propagation times.



Optical and microwave ranging (optional): The optical and microwave links will allow the cross-comparison of different ranging techniques and the measurement of differential atmospheric propagation delays (optical vs microwave).

Cosmic Vision Planning Cycle

Tentative planning for mission calls:

a.	M1, M2, L1	done, done, done
b.	M3, M4, L2	done, 2014, 2014
c.	M5, M6, L3	2018, 2020, 2020

Tentative planning for mission launches:

a.	M1, M2, L1	2017, 2020, 2022
b.	M3, M4, L2	2024, 2026, 2028
c.	M5, M6, L3	2030, 2032, 2034
d.	M7	2035