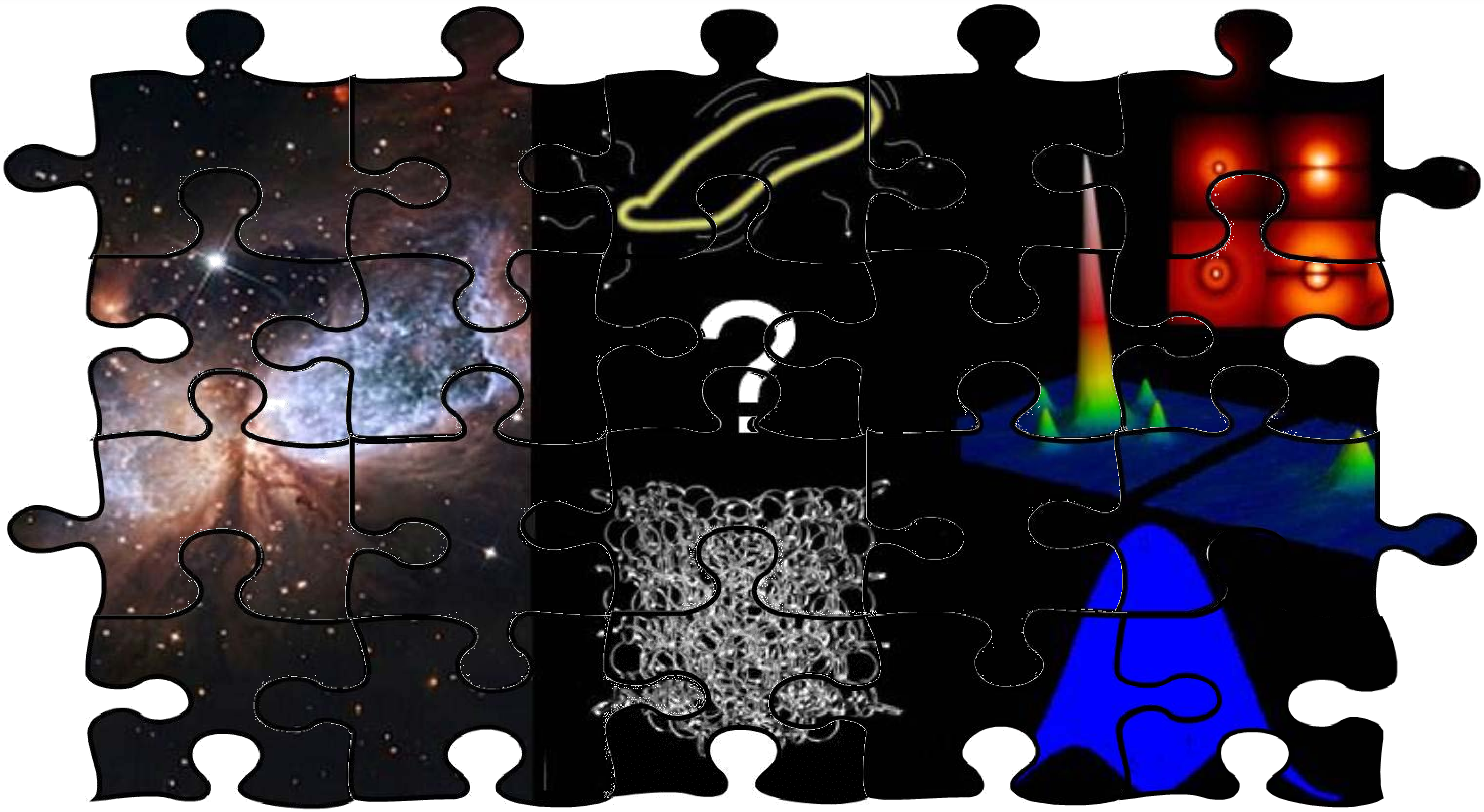
Fundamental Physics in the ESA Programme

L. Cacciapuoti

European Space Agency

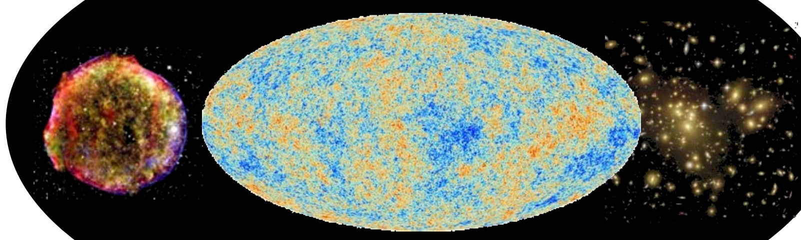
General Relativity and Quantum Mechanics



- 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 so-called Standard Model of strong and electroweak interactions which accounts for all the observable known forms of matter.

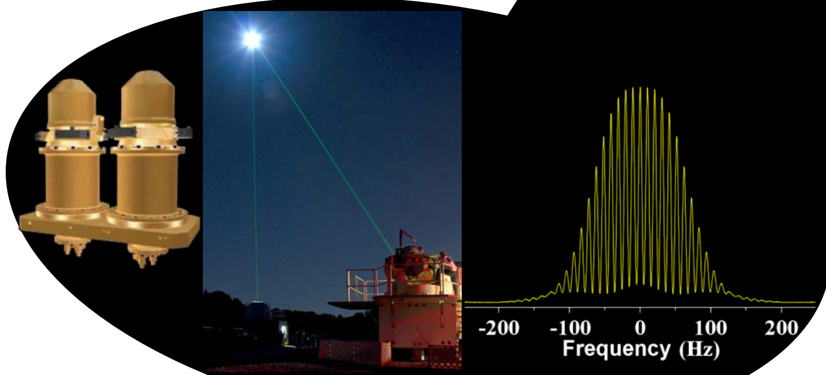
The Challenge

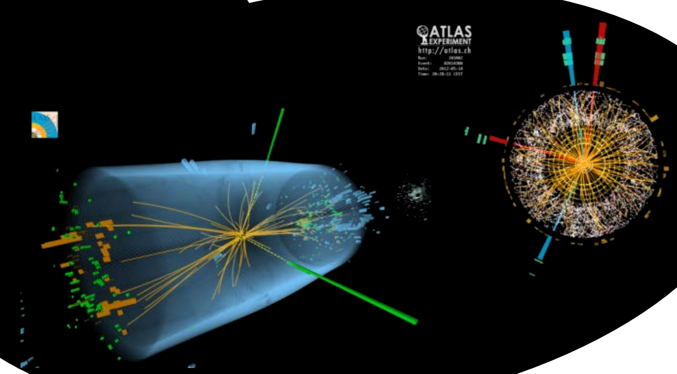
Astronomy & Cosmology
(CMB, Planck, EUCLID, …)



Quantum-Gravity
Unification

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





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

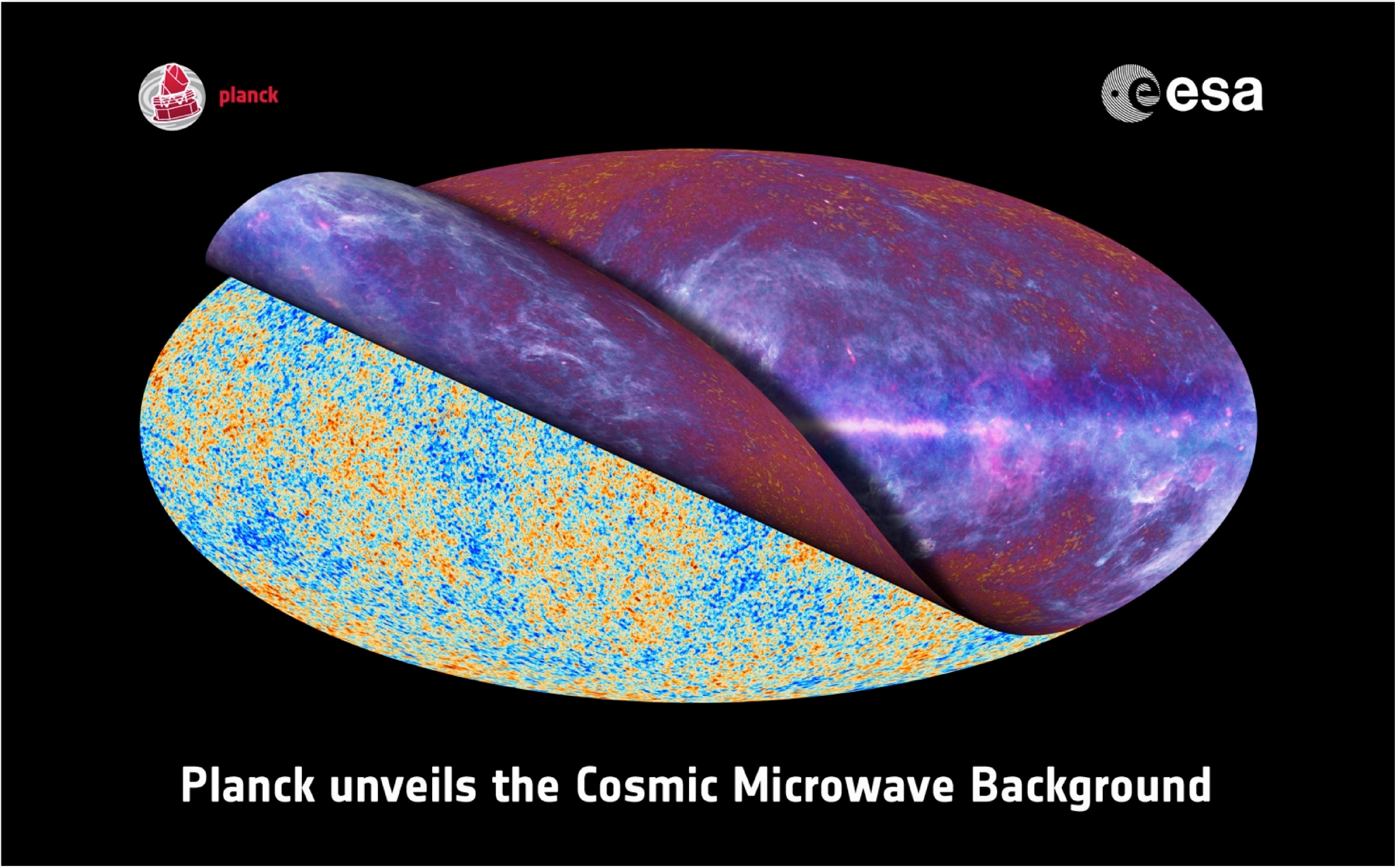
High Energy
(CERN-LHC, Fermilab, DESY, …)

Fundamental Physics in the ESA program

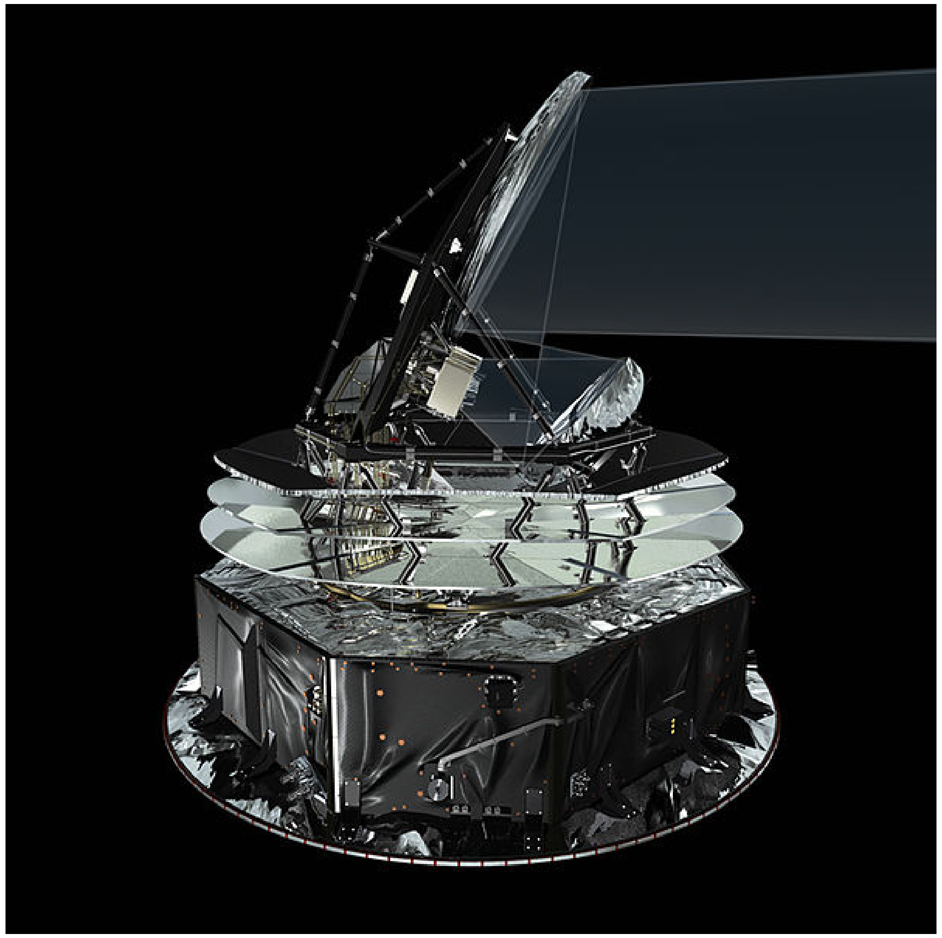
- Astronomy and cosmology
  - PLANCK
  - EUCLID
  - GAIA
- Precision measurements for fundamental physics tests in space
  - Bepi-Colombo
  - LISA-PF
  - MICROSCOPE
  - ACES

  …under assessment
  - SOC
  - STE-QUEST

Planck


planck
esa
Planck unveils the Cosmic Microwave Background

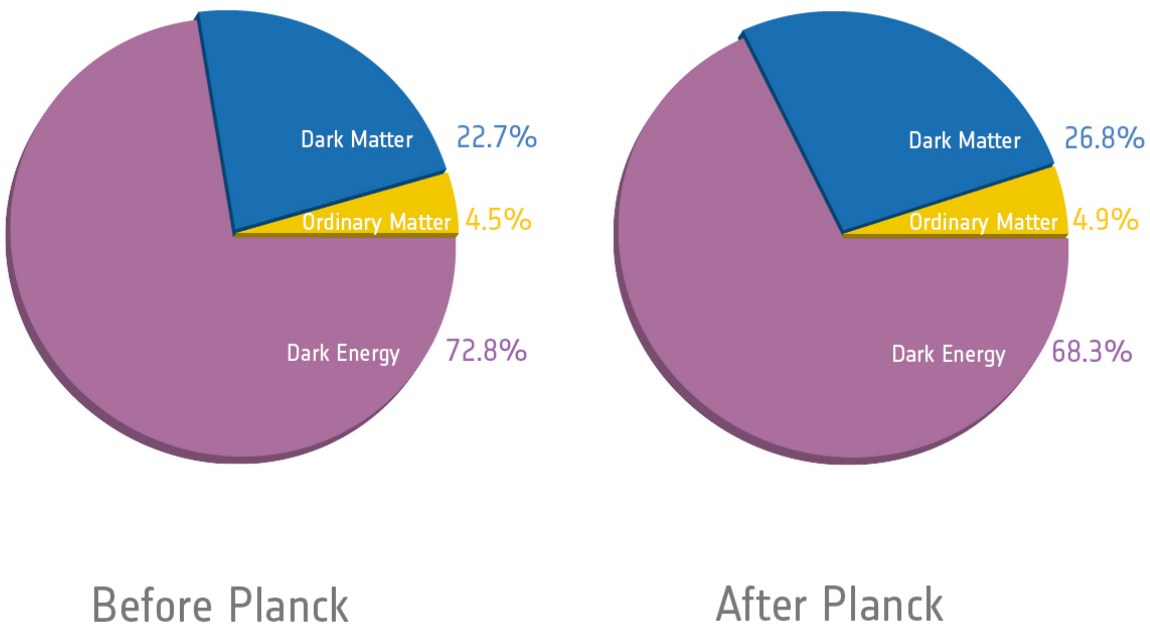
The Planck Mission

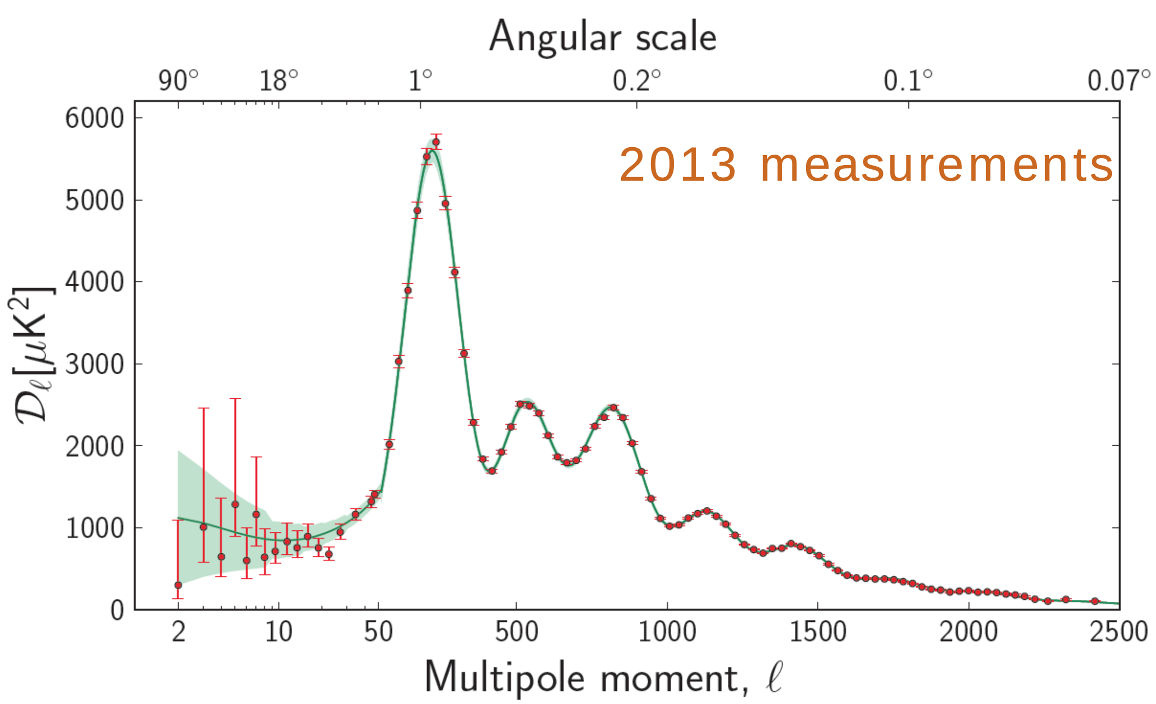


- Planck is a satellite designed, built and operated by the European Space Agency, whose objective is to map the anisotropies of the Cosmic Microwave Background over the whole sky, in temperature and polarisation.
- Planck carries a payload including:
  - A 1.5 m offset Gregorian telescope
  - An array 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 will stop operating in October 2013. The next major data release is planned for mid-2014.

Summary of CMB Results

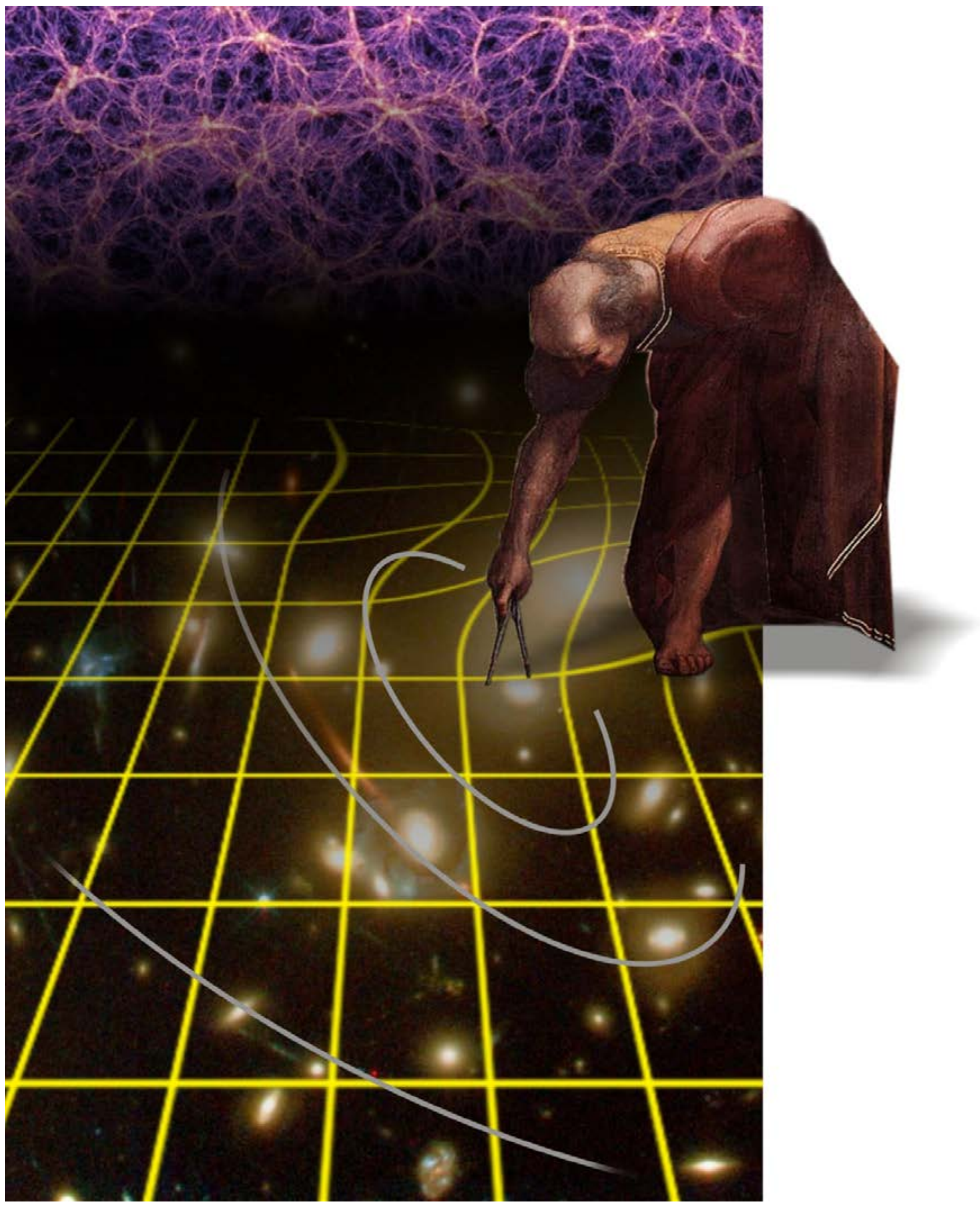
- The ΛCDM model fits the data quite well
- The estimated parameters are different than previously
  - More matter, less dark energy
  - Hubble constant lower than expected
  - Curvature very tightly constrained
- No evidence for more than 3 types of neutrinos
- No evidence for non-gaussianity
- New 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 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

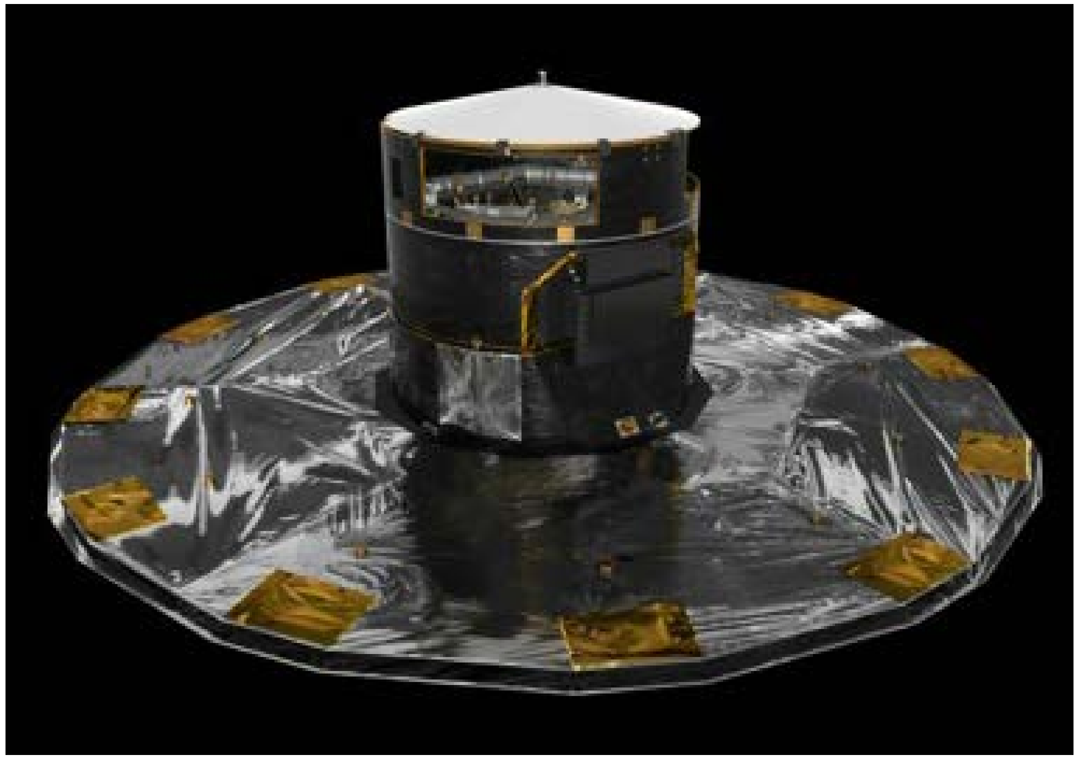
Euclid Scientific Objectives

Issue	Euclid's 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 V = 8 mag) and 300 µas (at V = 20 mag) for all point sources in the range V=6-20 mag (1.5×10^9 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

- 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:

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

- Test of PPN parameters
  - γ measurement to $2 \cdot 10^{-6}$
  - β measurement
  - Light deflection by Jupiter quadrupole moment
  - Time variations of G

Fundamental Physics in the ESA program

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  - PLANCK
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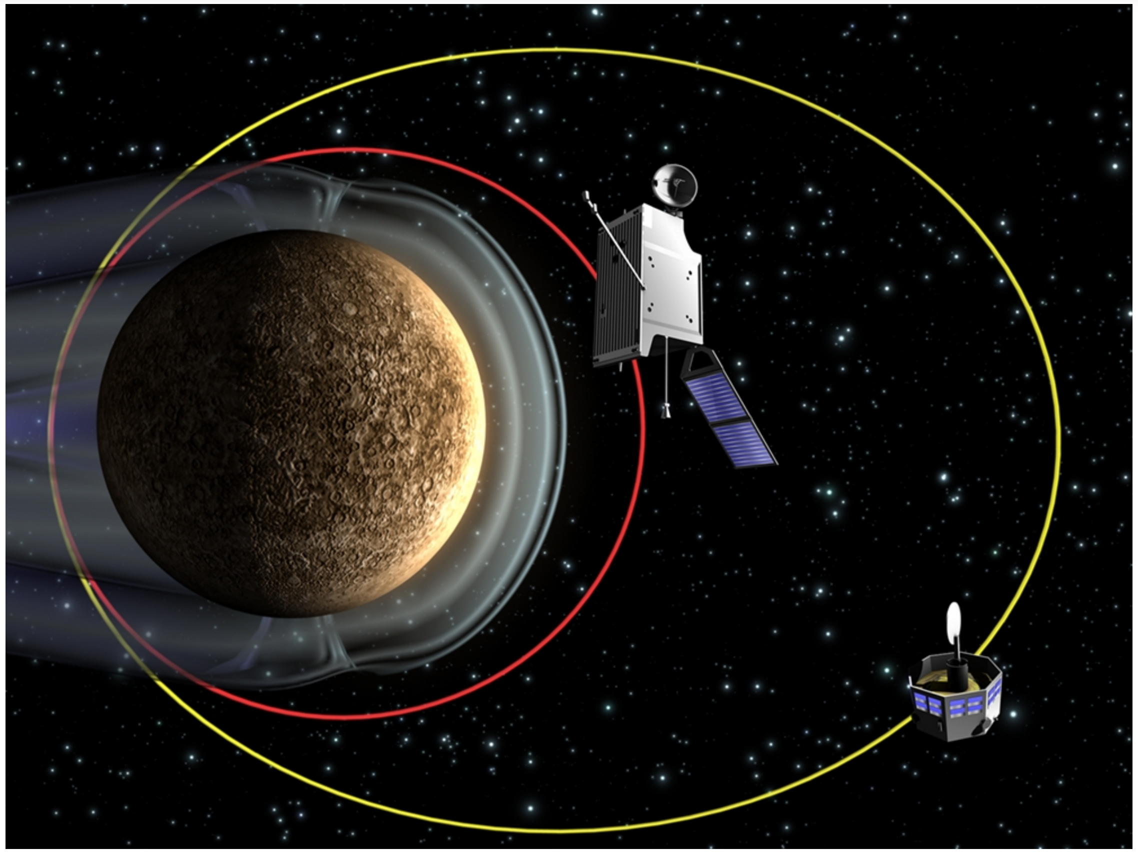
  - BepiColombo
  - LISA-PF
  - MICROSCOPE
  - ACES

  …under assessment
  - SOC
  - STE-QUEST

BepiColombo

Dual spacecraft mission

- Mercury Planetary Orbiter (MPO)
  - Polar orbit optimized to study the planet itself: 400x1500 km, 2.3 h period
- Mercury Magnetospheric Orbiter (MMO)
  - Polar orbit optimized for study of the magnetosphere: 400x12000 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

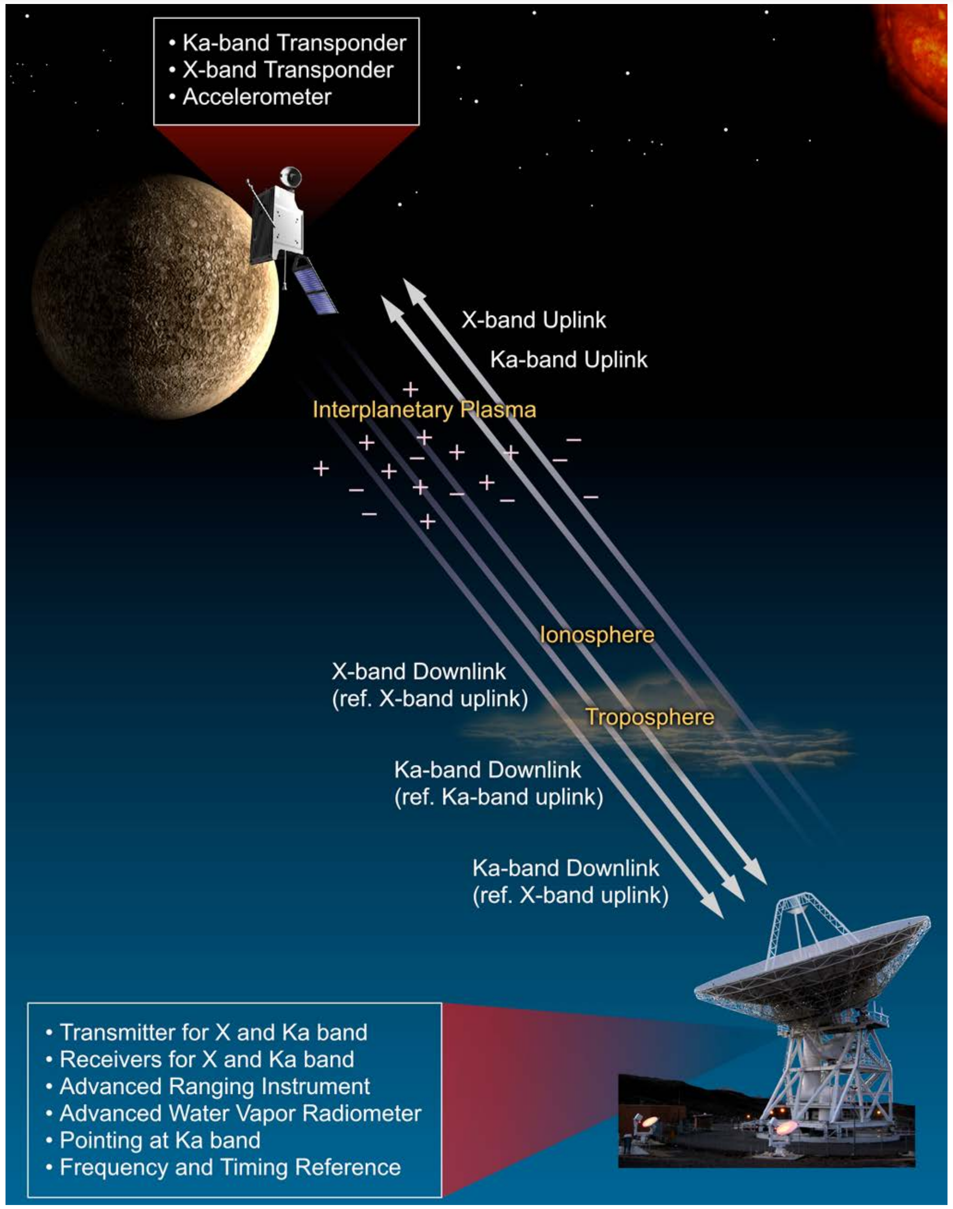
BepiColombo and Fundamental Science

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

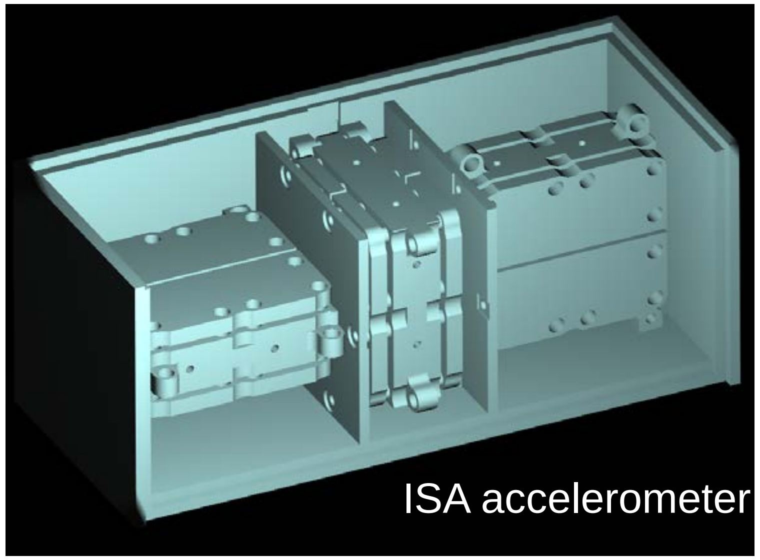
- Test metric theories of gravitation through a measurement of the PPN parameters:
  - Determine γ to an accuracy of $2 \cdot 10^{-6}$
  - Determine β to an accuracy of $3 \cdot 10^{-5}$
  - Determine η to an accuracy of $1 \cdot 10^{-4}$
  - Determine α_1 to an accuracy of $7 \cdot 10^{-6}$
- Determine the solar oblateness to an accuracy of $4.8 \cdot 10^{-9}$
- Test of time variations of the Newtonian gravitational constant G to an accuracy of $3 \cdot 10^{-13}$ 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

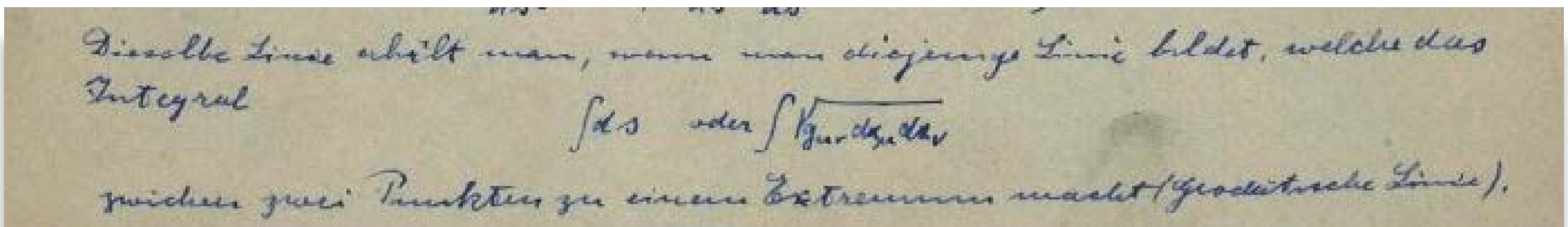


Spring accelerometer

- 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

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

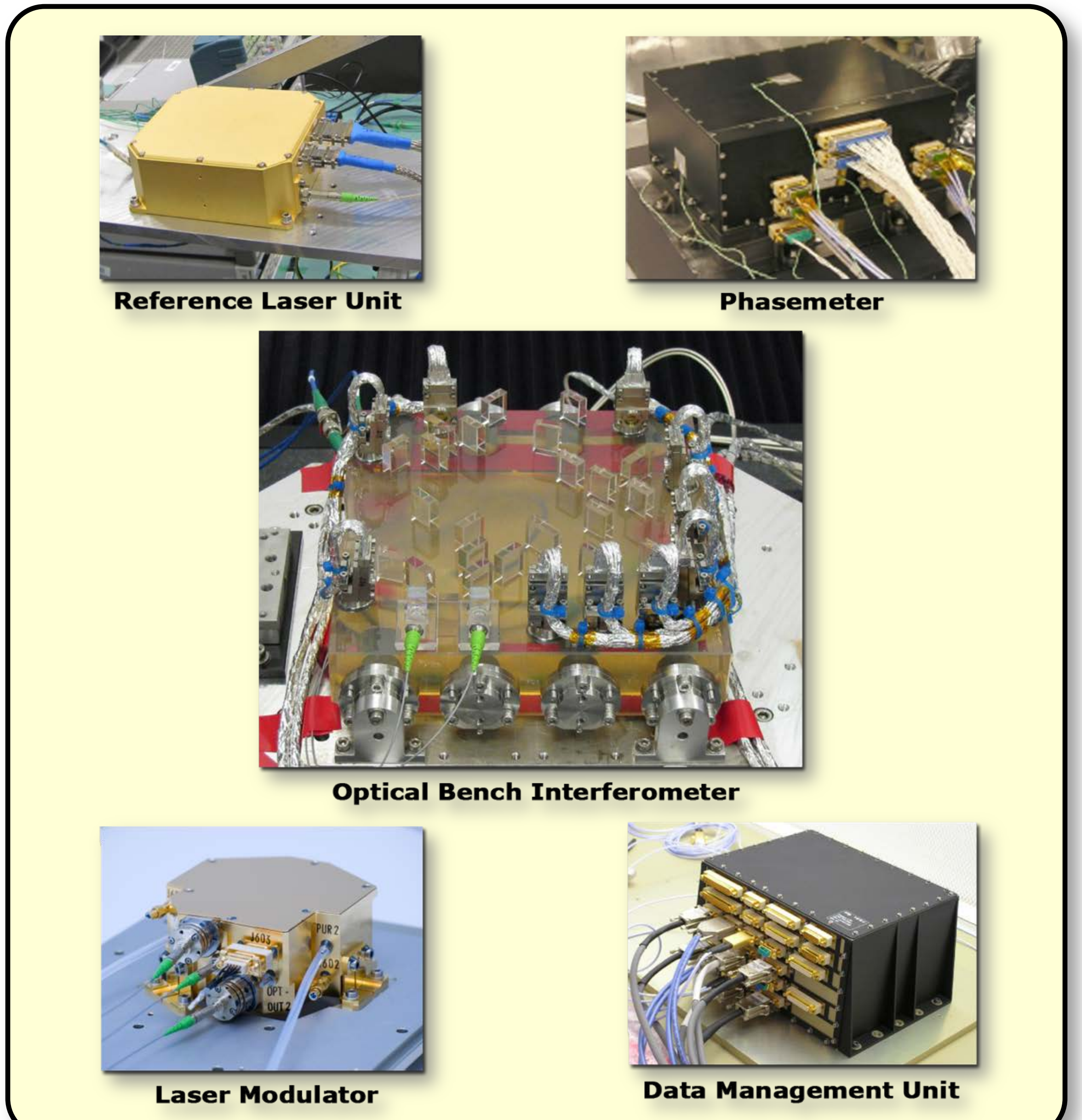
zwischen zwei Punkten zu einem Extremum macht (Geodätische Linie).

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

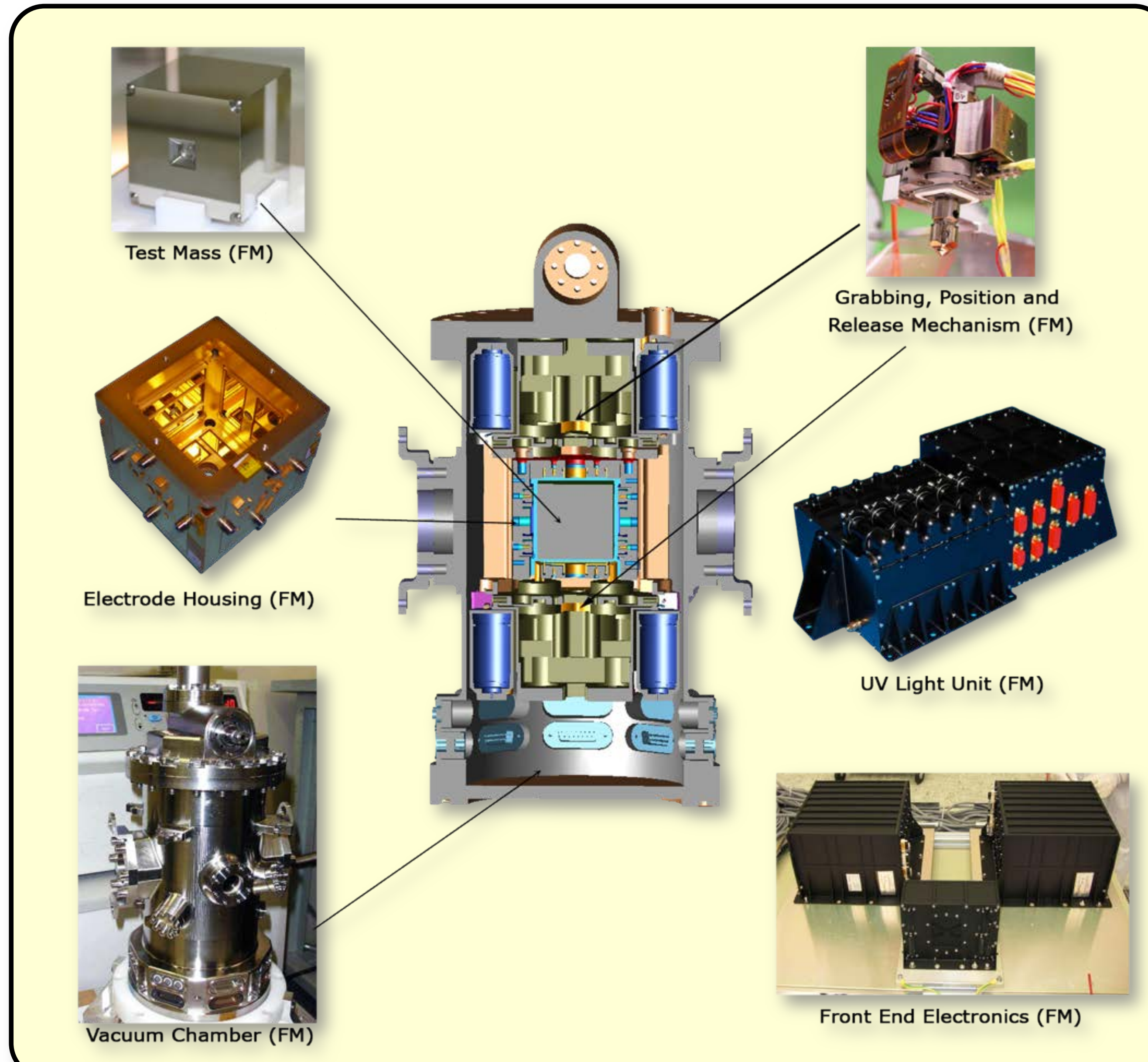
- ALL missions aimed at demonstrating an aspect of GR rely on geodesics
  - LISA Pathfinder will be the first mission to demonstrate that free particles follow geodesics at such an unprecedented level
- An LPF-like satellite provides a near-perfect platform for fundamental physics experiments
  - Spacecraft 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

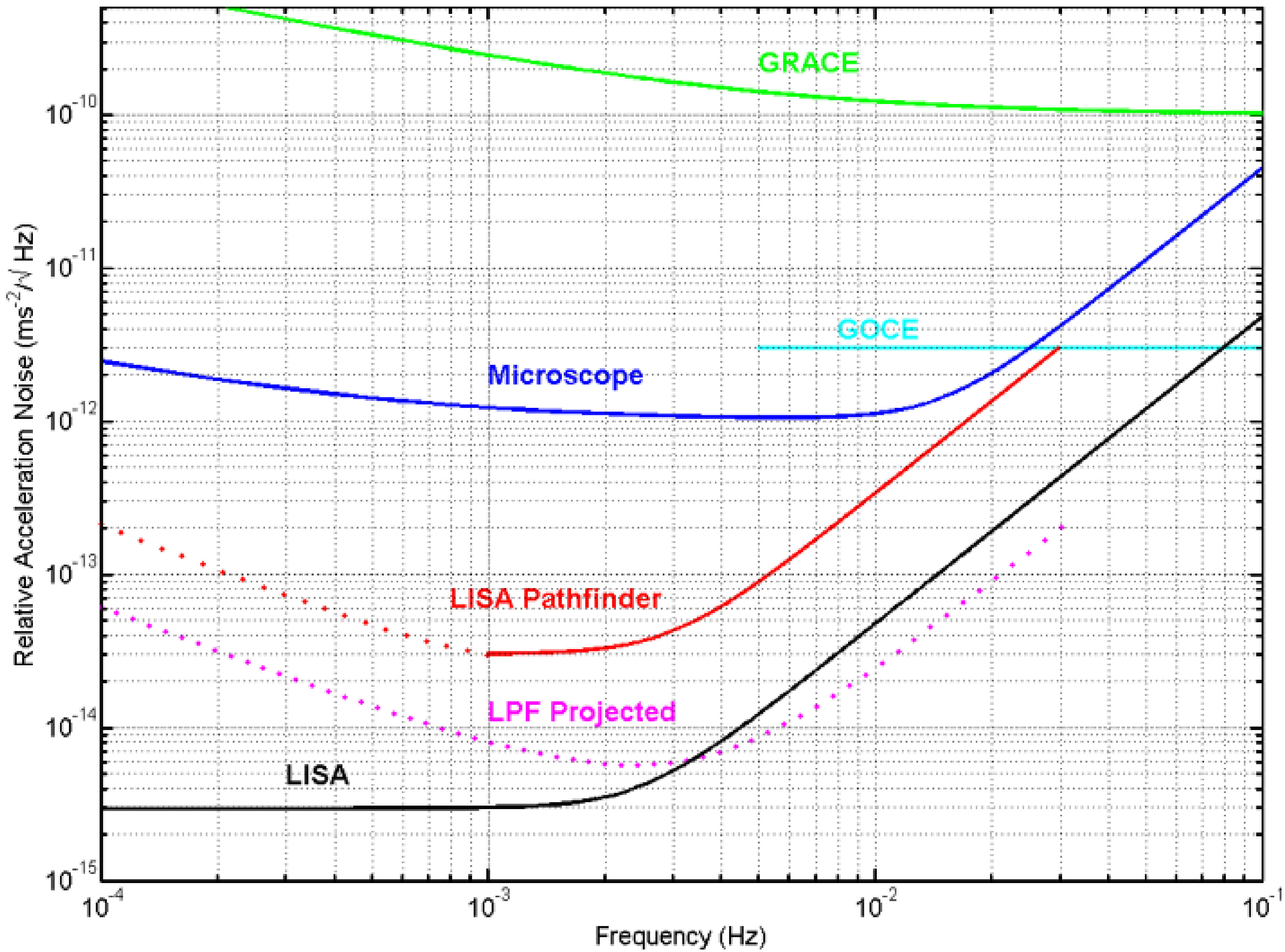


Optical Metrology Subsystem



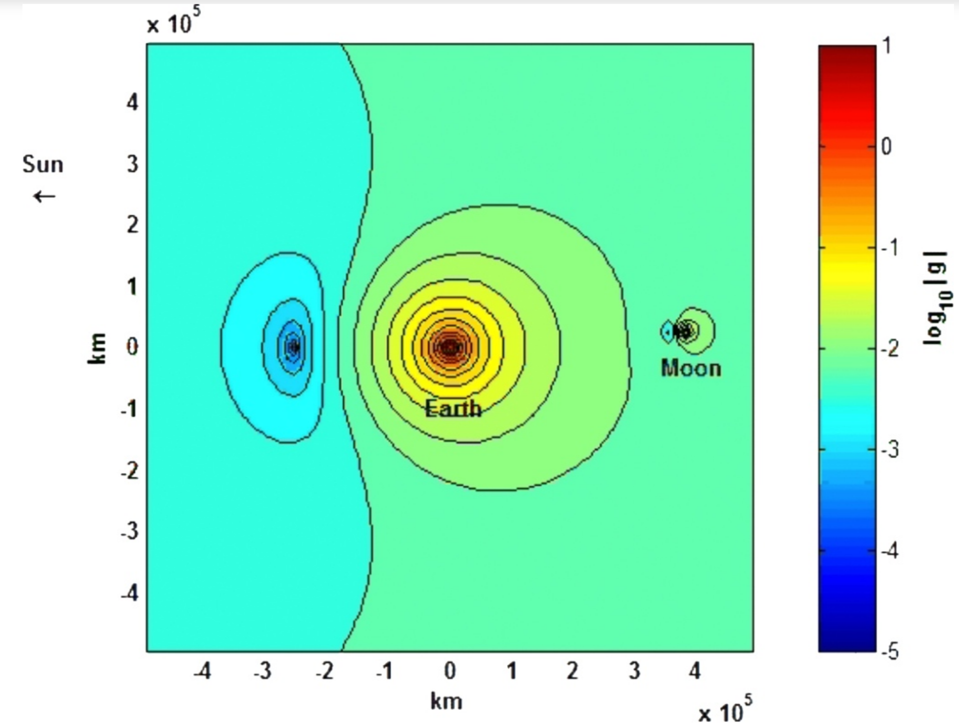
Inertial Sensor Subsystem

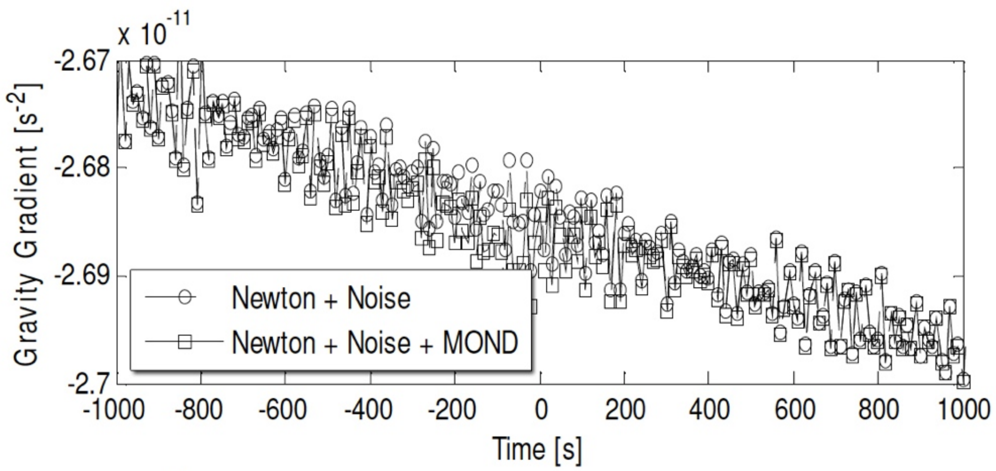
LPF Performance

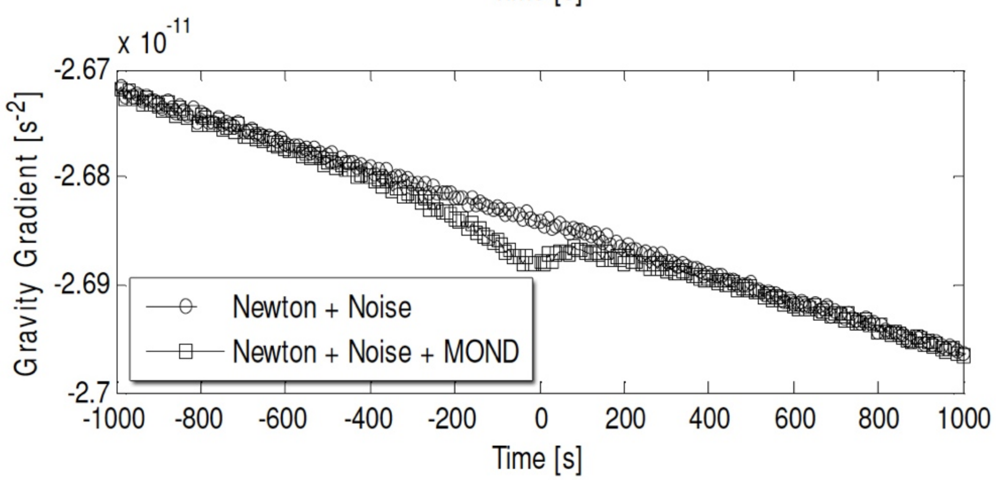


LPF to Test Alternative Theories of Gravity

- 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

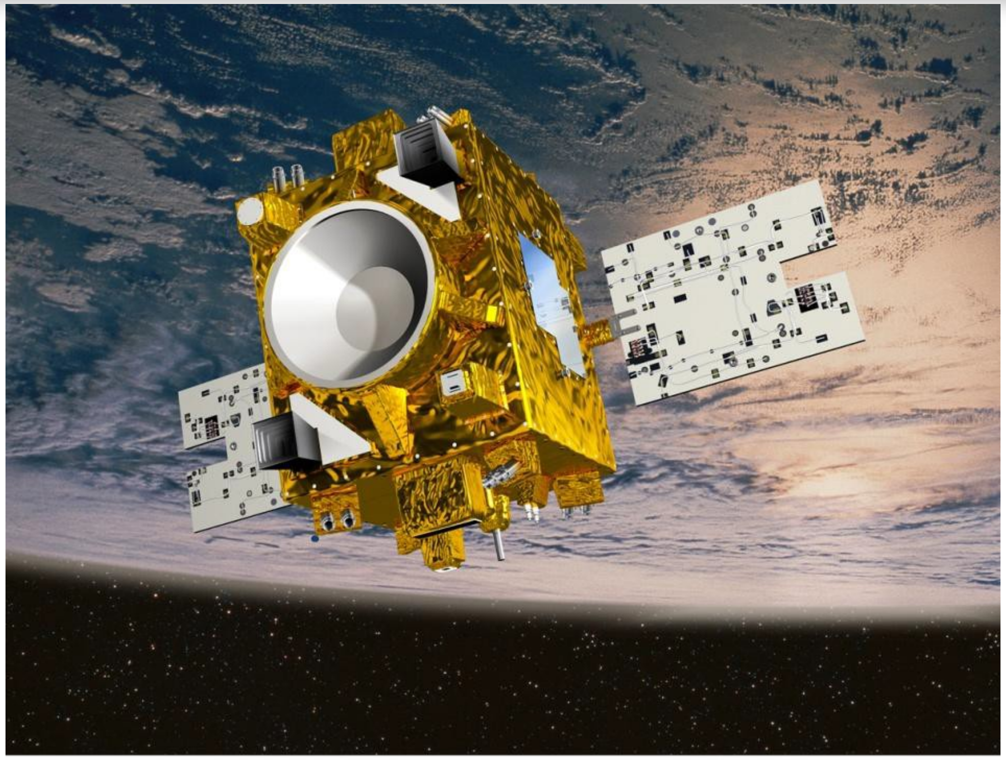






MICROSCOPE

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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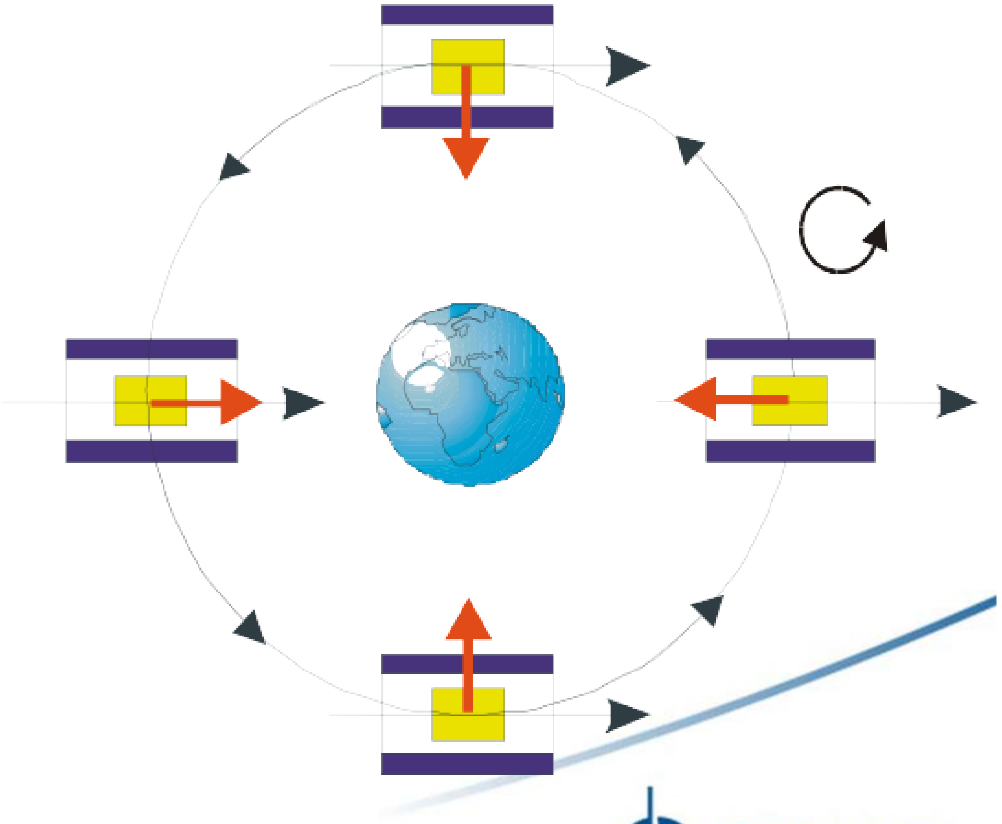
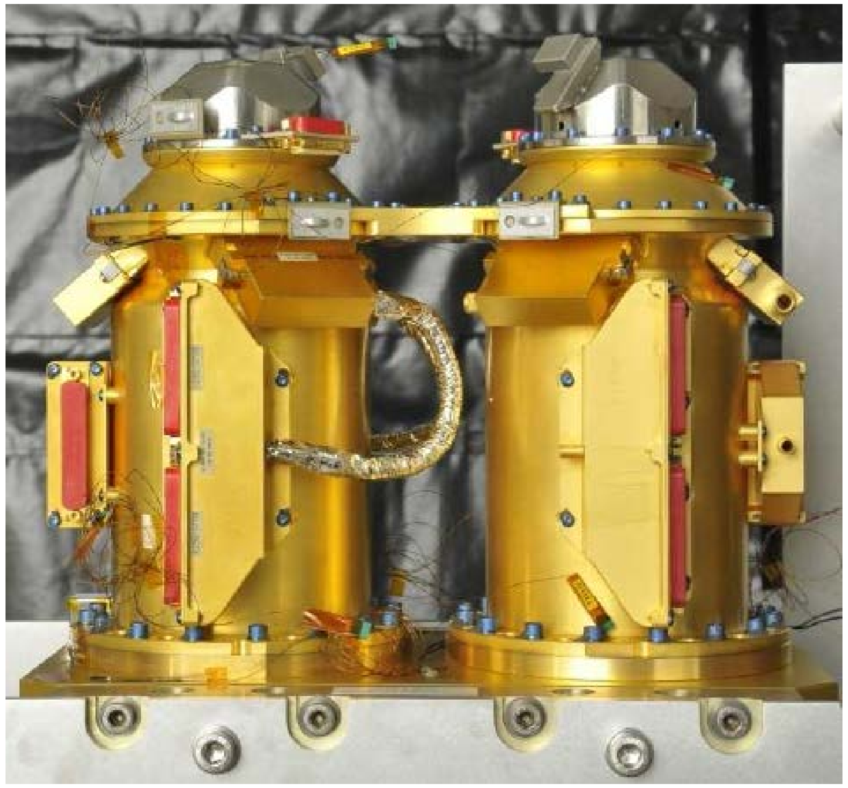
Mission profile:

- 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

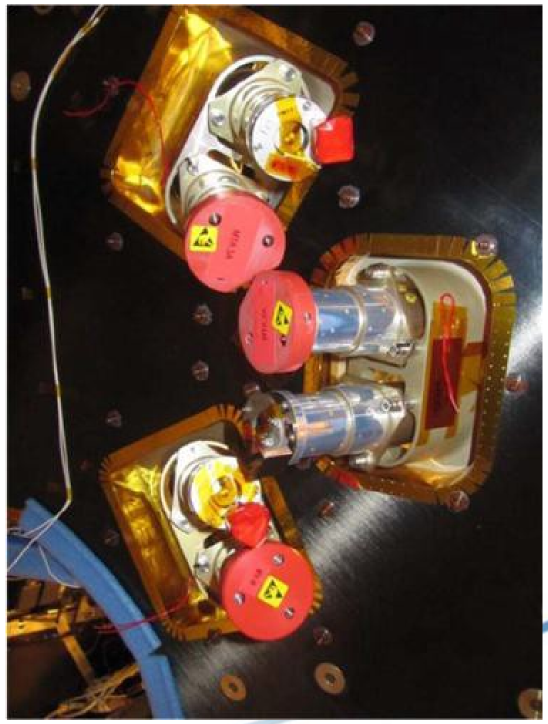


MICROSCOPE Payload

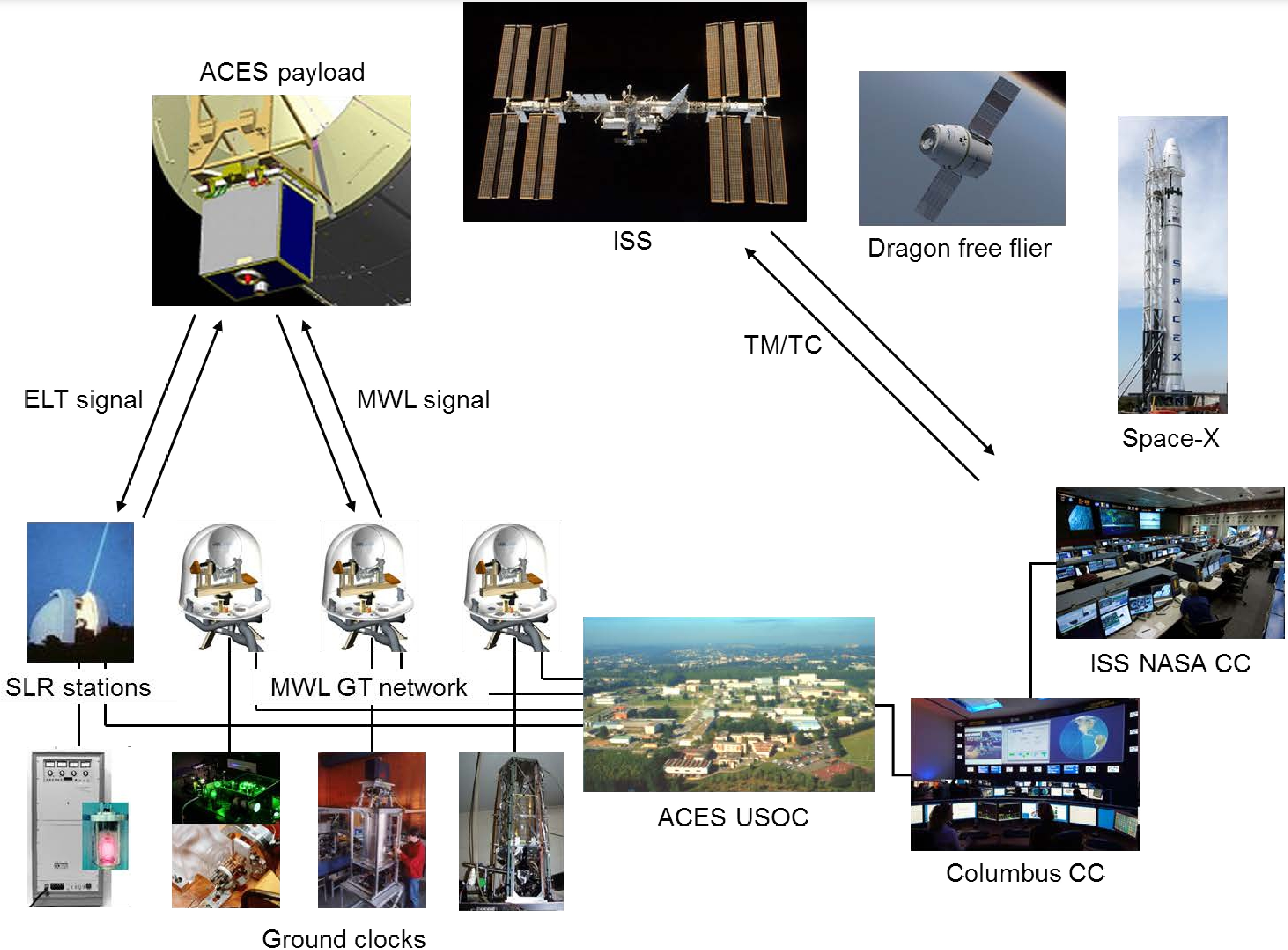
- Differential accelerometer developed by ONERA
  - 2 sensor units composed of two concentric test masses each: Pt:Rh/Pt:Rh and Ti/Pt:Rh
  - 3 electrodes to control axial, radial and spin degrees of freedom
  - Performance: $2{\cdot}10^{-12}$ m/($s^2{\cdot}\sqrt{Hz}$) in the 10^{-3}-10^{-2} Hz frequency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

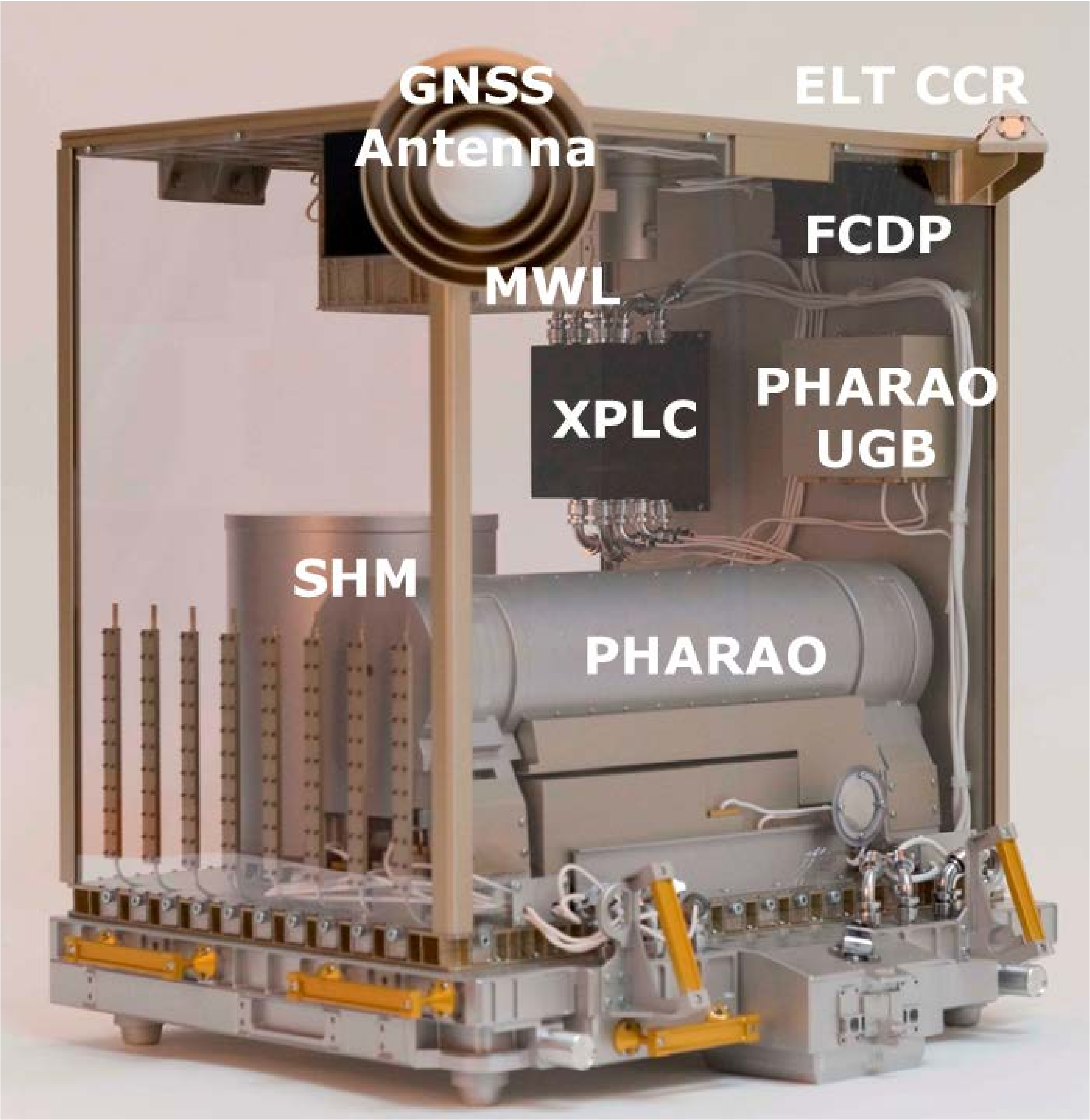


Atomic Clock Ensemble in Space



The ACES Payload

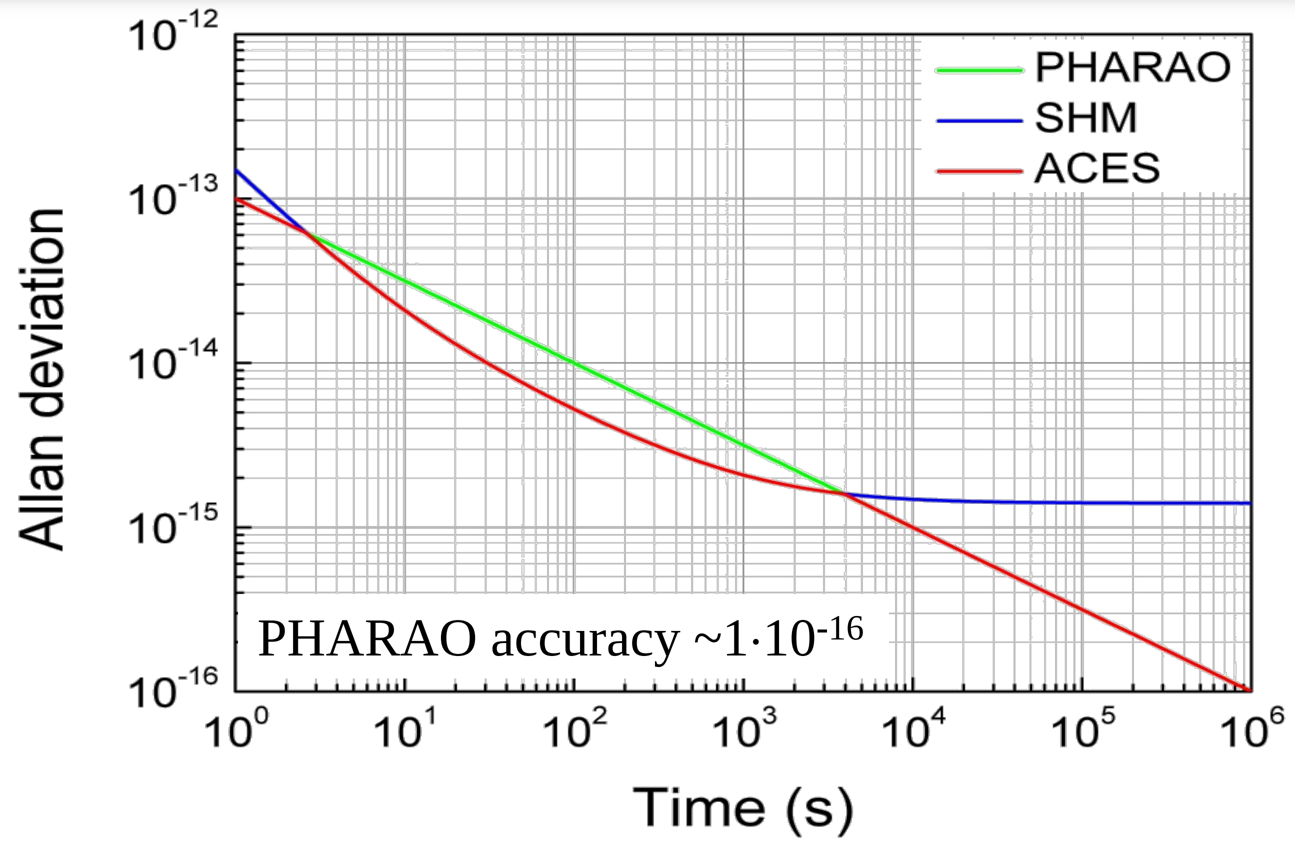
- PHARAO (CNES): Atomic clock based on laser cooled Cs atoms
- SHM (ESA): Active hydrogen maser
- FCDP (ESA): Clocks comparison and distribution
- MWL (ESA): T&F transfer link
- GNSS receiver (ESA)
- ELT (ESA): Optical link
- Support subsystems (ESA)
  - XPLC: External PL computer
  - PDU: Power distribution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

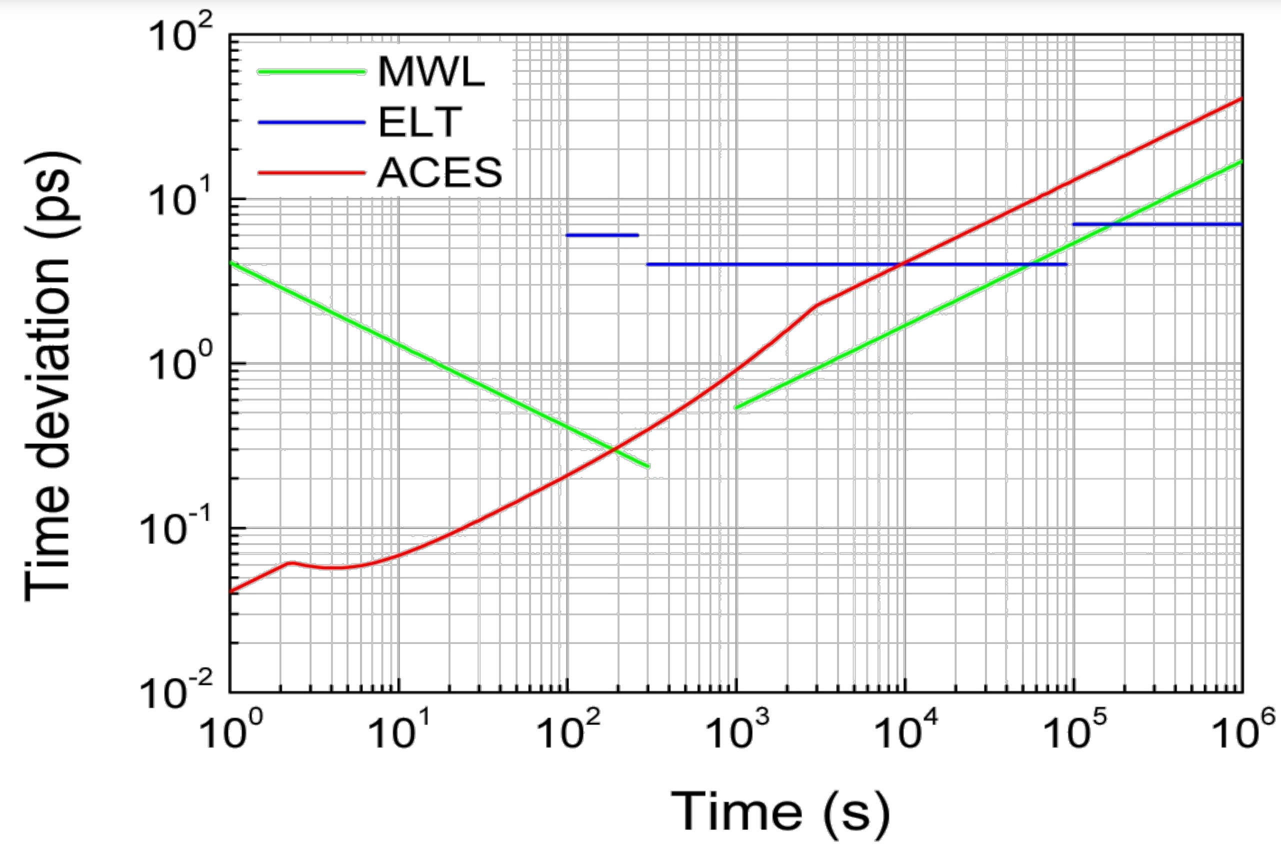


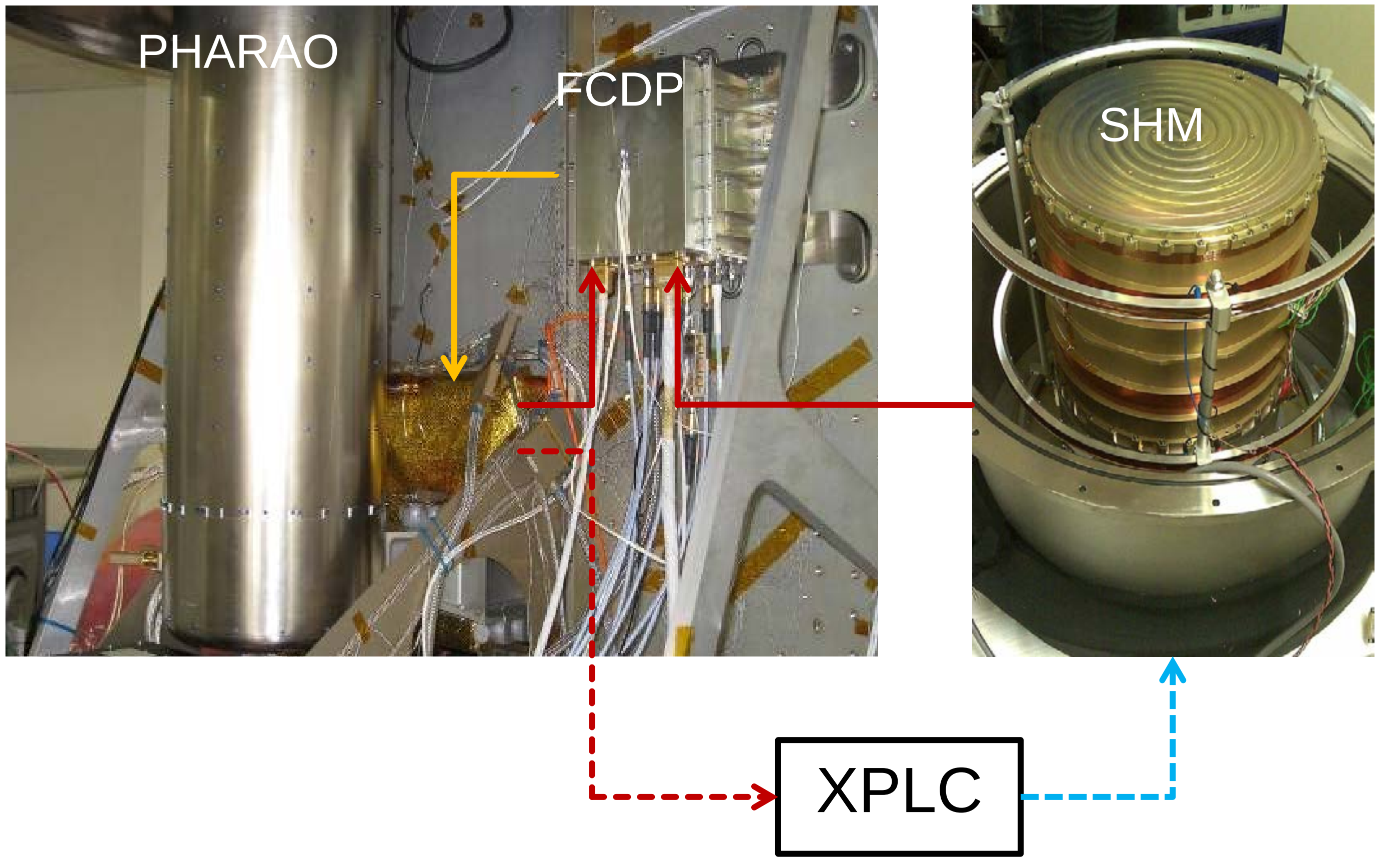
Volume: 1172x867x1246 mm^3
Mass: 227 kg
Power: 450 W

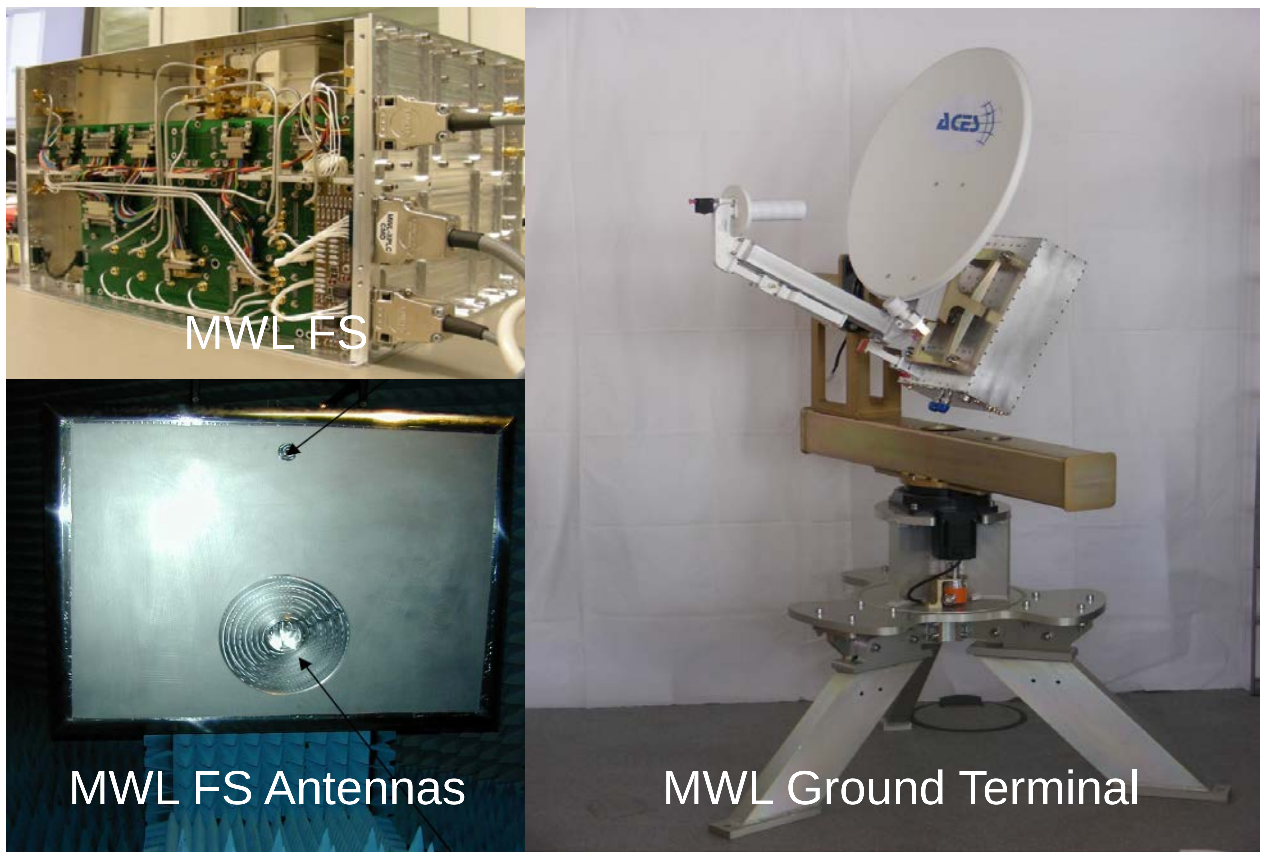
ASTRIUM

ACES Clocks and Links Performance

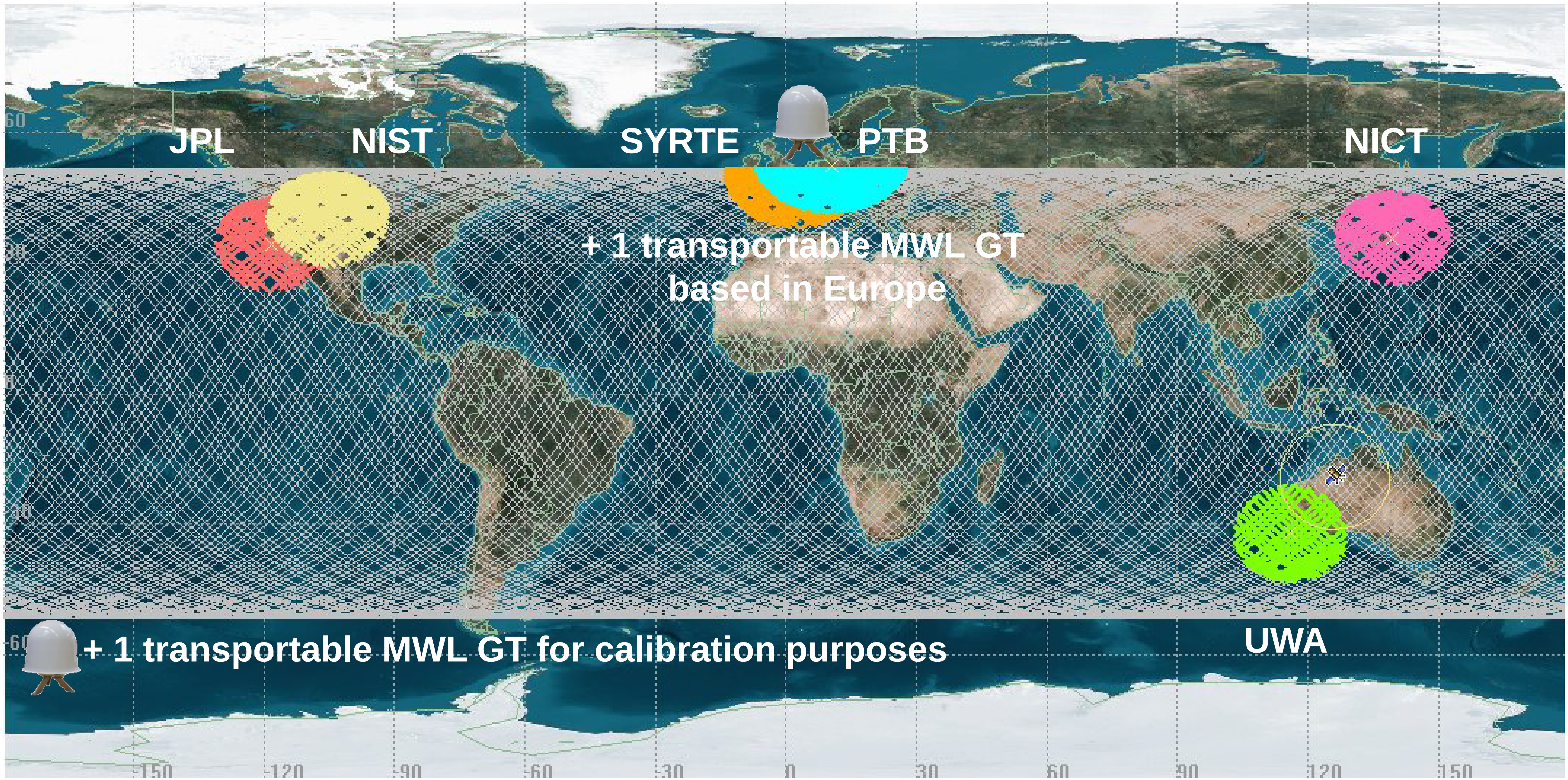








Core Network of MWL GTs



+ NPL (UK) + METAS (CH)

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: $\sigma_y(\tau) = \frac{1}{\pi}\frac{\Delta\nu}{\nu_0}\frac{1}{\sqrt{N_{at}}}\sqrt{\frac{T_c}{\tau}}$
  - $\Delta\nu \sim$ 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: 4 to 5 orders of magnitude improvement is possible $\rightarrow$ optical transition 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}

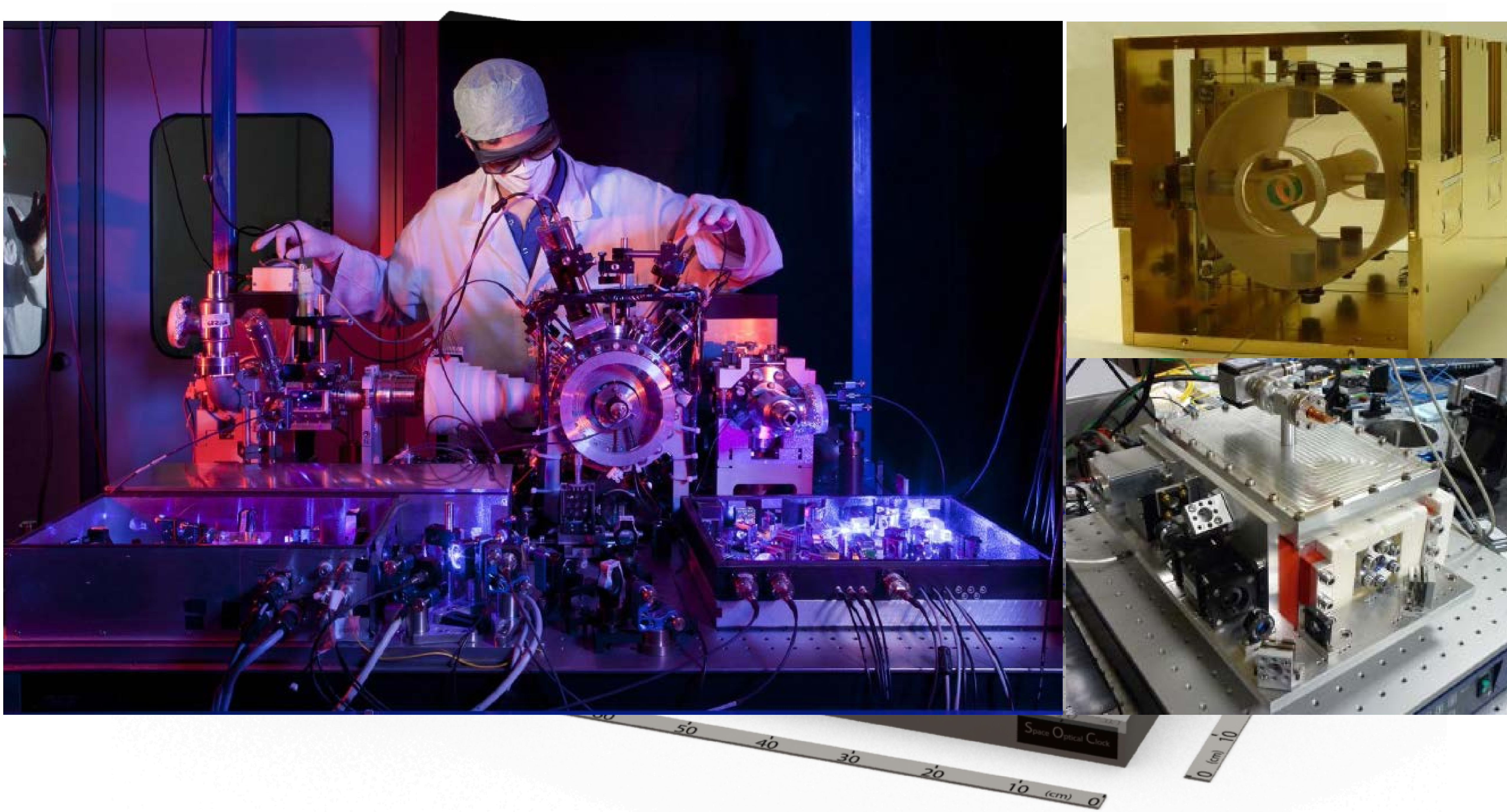
SOC as ACES follow-on mission

$\downarrow$

Sr lattice clock with $1 \cdot 10^{-17}$ fractional frequency instability and inaccuracy

Transportable Sr lattice clock

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



SOC Status

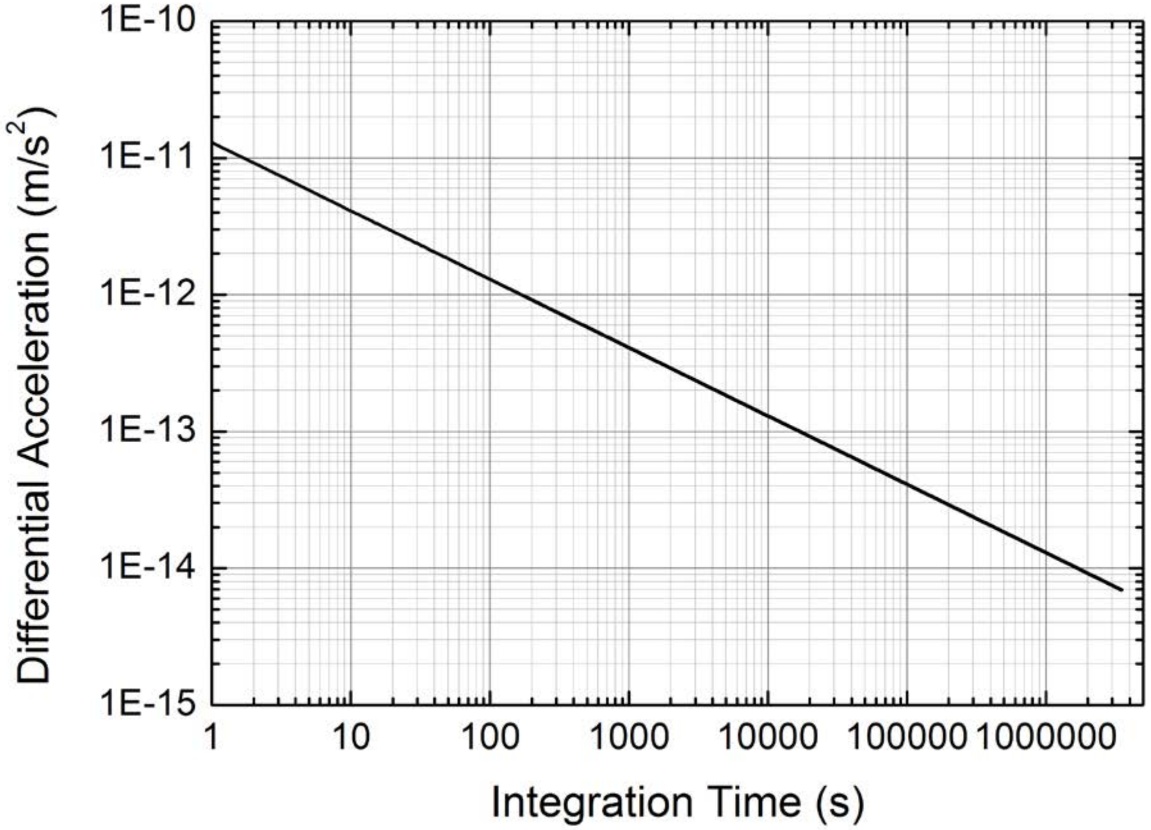
- Results to date:
  - Transportable Sr physics package completed and now under test
  - First transportable laser system for clock interrogation (laser locked on a high-finesse cavity) demonstrated - *Appl. Phys. B* **104**, 741 (2011)
  - ^{88}Sr clock transition detected with < 10 Hz linewidth
  - 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 2014

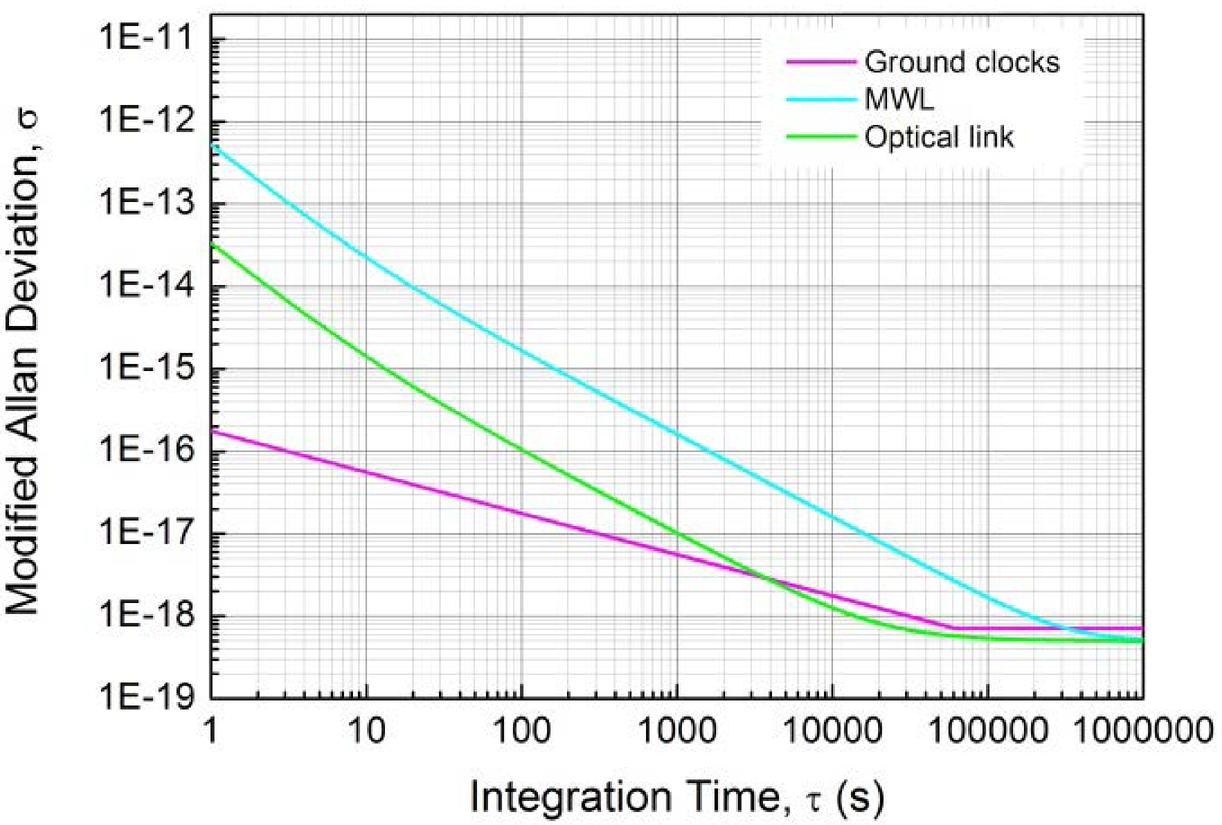
STE-QUEST Space-Time Explorer and QUantum Equivalence Principle Space Test	
Theme	What are the fundamental physical laws of the Universe?
Primary Goal	To test the Einstein's Equivalence Principle to high precision and search for new fundamental constituents and interactions in the Universe.
Observables	• 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.

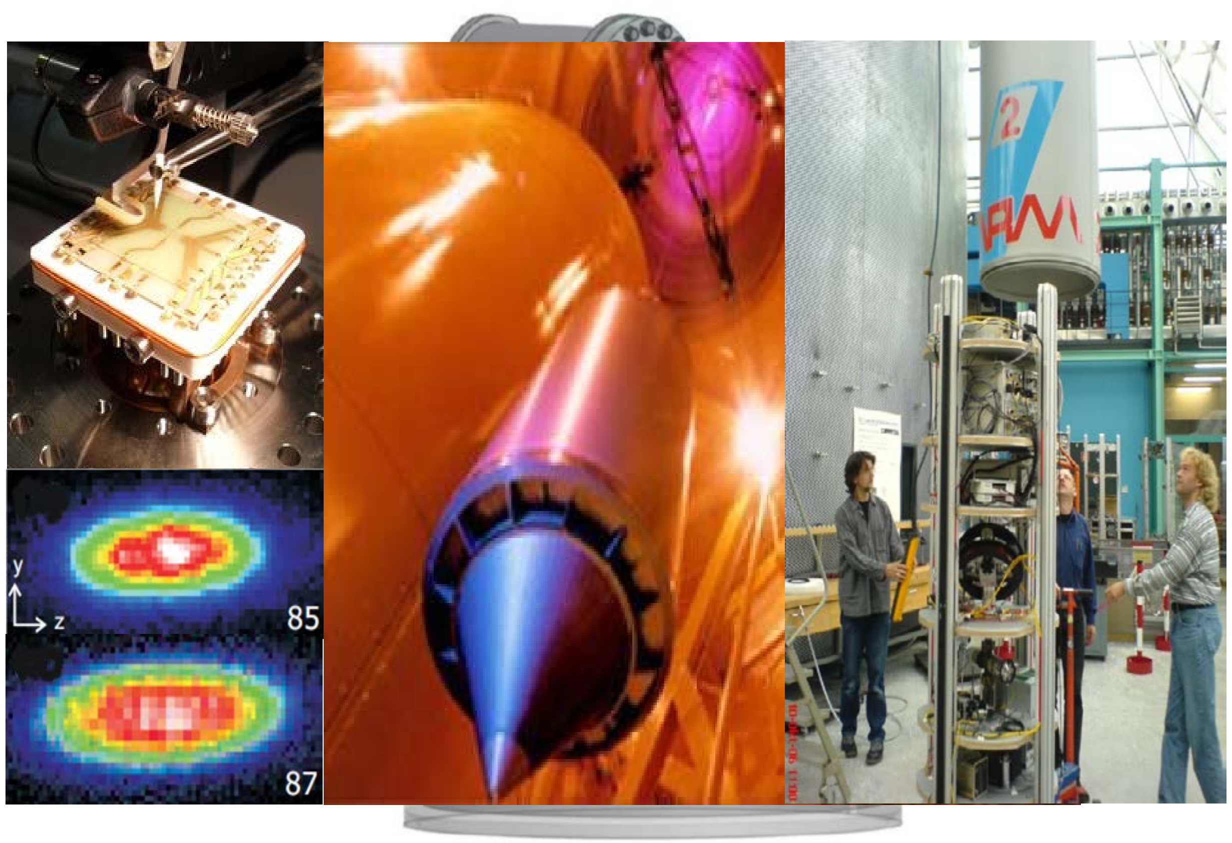
STE-QUEST Science Investigations

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 $9 \cdot 10^{-5}$.

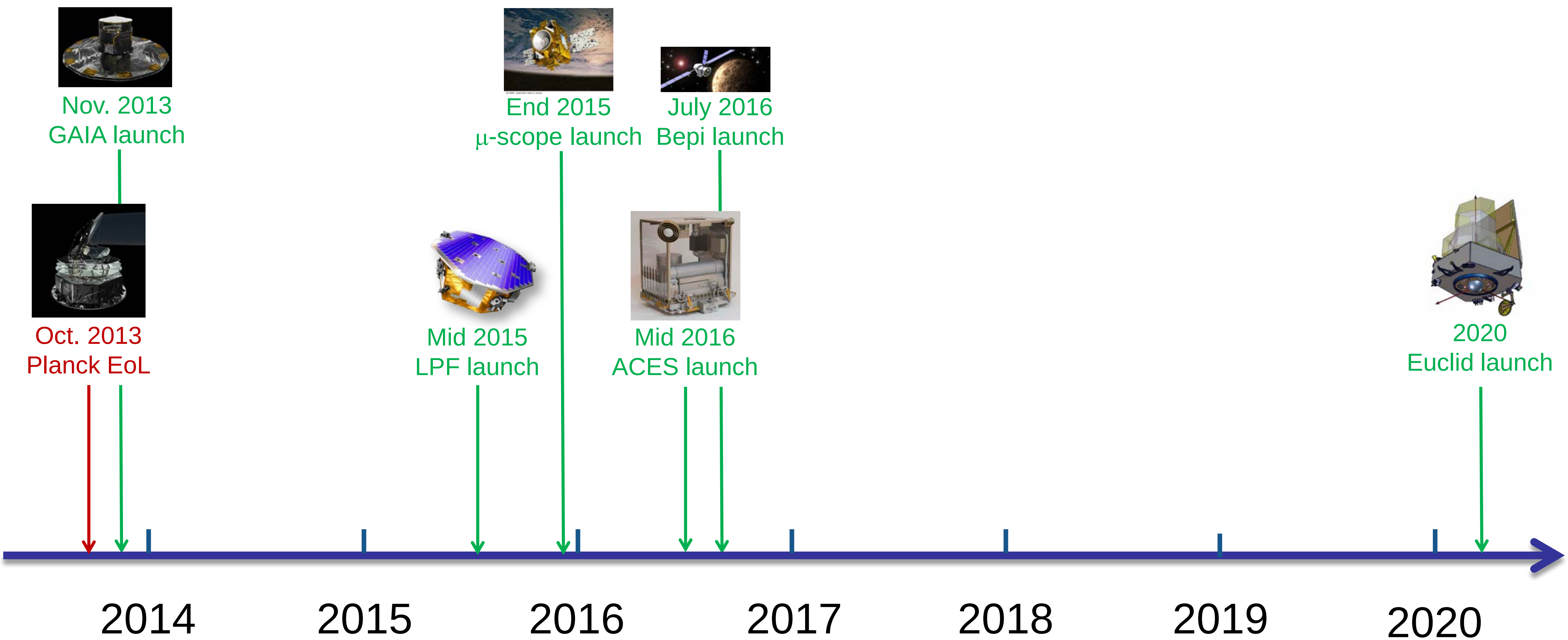
STE-QUEST Instruments Performance







Fundamental Physics in Space



Next Milestones in the ESA Sci Programme

- L2/L3 science theme call
  - 32 White Papers received covering a wide range of topics in astronomy, space science and fundamental physics.
  - Open workshop held on 3-4 September
  - In October, the SSC is expected to recommend on the two science themes that should be implemented as L2 and L3.
  - Based on the SSC recommendation, D/SRE will make a proposal to the SPC.
  - Selection of science themes for L2 and L3 will be at the 13-14 November 2013 SPC meeting.
- Call for the L2 mission is expected in 2014, with the L3 call around the end of the decade.
- M3 mission selection: Echo, Loft, MarcoPolo-R, STE-QUEST + Plato
  - Open workshop to present the M3 mission candidates on 21 January 2014 in Paris followed by Working Group meetings.
  - SSAC will meet directly after WGs and they will be invited to make a single recommendation which will go to the SPC for their decision at their 19/20 February 2014 meeting.
- Call for the M4 mission is expected in mid 2014