Fundamental physics in space:

overview and perspectives

focus on the French programme

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Space and fundamental physics

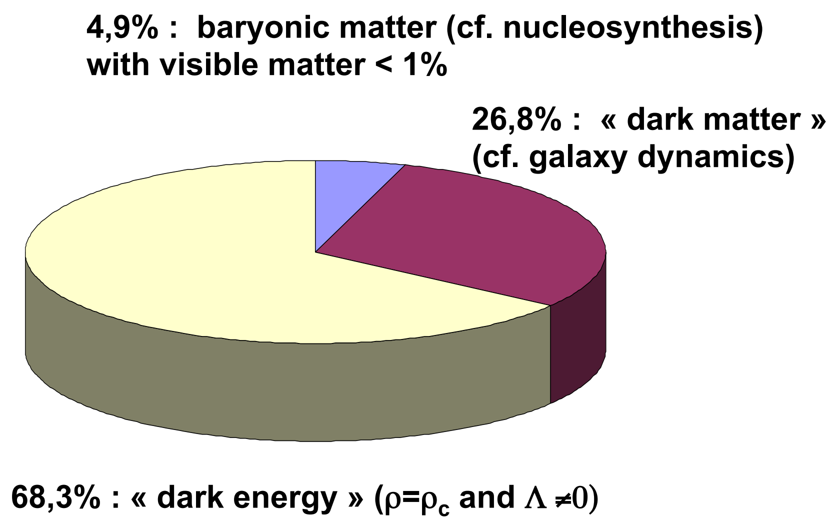
- astrophysics and particle physics tend to join together through various problems linked to
  - the unification of the fundamental interactions of nature ...
  - … and the specificity of gravity with respect to the other interactions (weak, electromagnetic, strong)
  - search of new fields / particles predicted by the unification theories

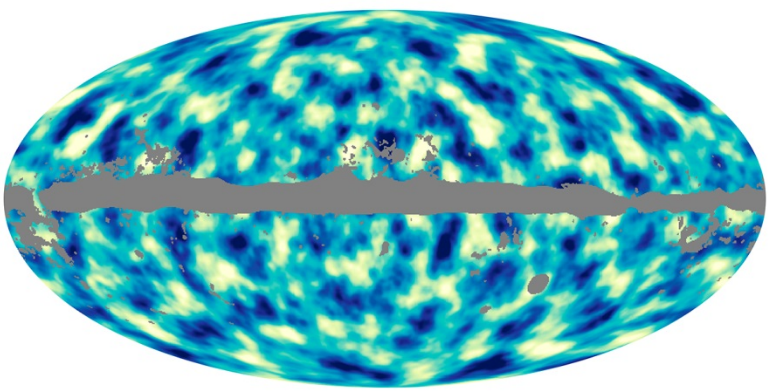
- ultimate goal : a new physics beyond General Relativity and the Standard Model of particle physics

The origin (and fate ?) of the universe

Findings:

- at large scale, the universe has a flat geometry
- less than 5% of its content is made of «ordinary» matter
- expansion tends to re-accelerate



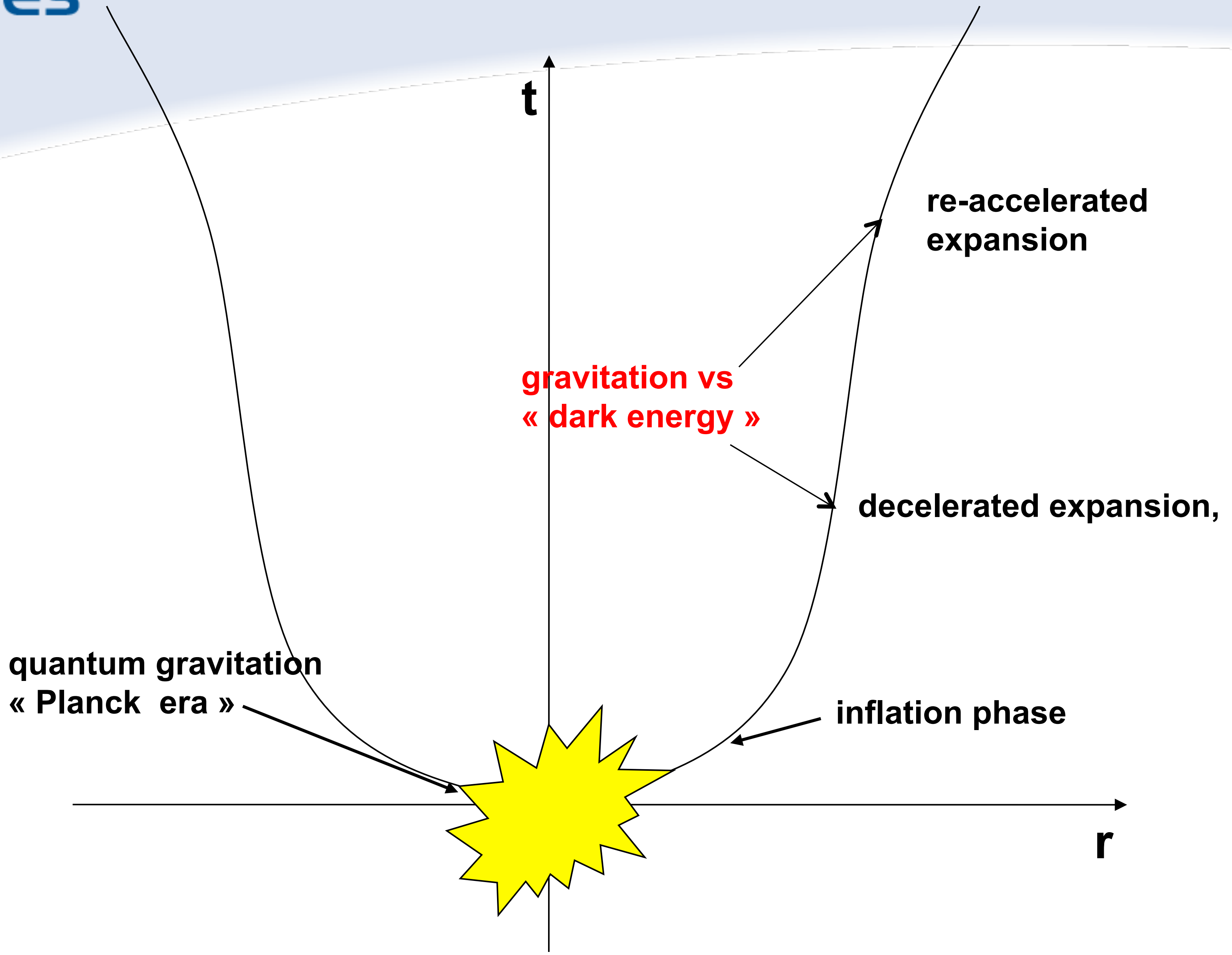


All-sky map of dark matter distribution in the universe (Credit: ESA and the Planck collaboration)

Question:

- what is the nature of dark matter and dark energy ?

[do they exist ?]


t
re-accelerated
expansion
gravitation vs
« dark energy »
decelerated expansion,
quantum gravitation
« Planck era »
inflation phase
r

The picture of physics today

⇨ **2 theories very different in nature and structure:**

⇨ **at large scale, General Relativity (GR)**

- a geometrical, non quantum theory of gravitation

⇨ **at atomic and subatomic scale, the « Standard Model » of particle physics**

- quantum field theories
  - electromagnetic interaction
  - weak interaction
  - strong interaction

General Relativity

⇨ **frame : the global Lorentz invariance of special relativity becomes a local invariance (RG as a gauge symmetry)**

$$R = G \,.\, T + \Lambda$$

R : space-time curvature

G : gravitational constant

T : mass-energy density

Λ : « cosmological constant »

⇨ **now, in spite of its successes, GR cannot be the ultimate theory of gravitation, e.g.:**

- **it exhibits an embarrassing singularity at t=0**
- **it does not take into account the quantum effects, predominant in the primordial universe (« Planck era » : t <10^{-43}s), nor the subsequent inflation phase**
- **significance of the cosmological constant Λ ?**

The « Standard Model » of particle physics

frame : special relativity + local invariances under gauge symmetry groups G (e.g. U(1) group for electromagnetism)

those G symmetries are suppposed to account for the bestiary of fields and particles of ordinary matter

⇨standard scheme: SU(3)xSU(2)xU(1) + Higgs-Englert mechanism

⇨it accounts for the known interactions and the number and type of known elementary particles …

⇨… but not for the mass of the particles and the coupling constants (set of free parameters)

⇨it does not explain everything

- e.g. matter- antimatter dissymmetry

A multiple and coherent approach

- **probing the early universe**
  - the CMB
  - a dark matter probe

- **probing the violent universe**
  - the space observatories
  - a gravitational wave observatories

- **space as a laboratory**
  - probing GR in the near-by space
  - testing the EP
  - space and time metrology

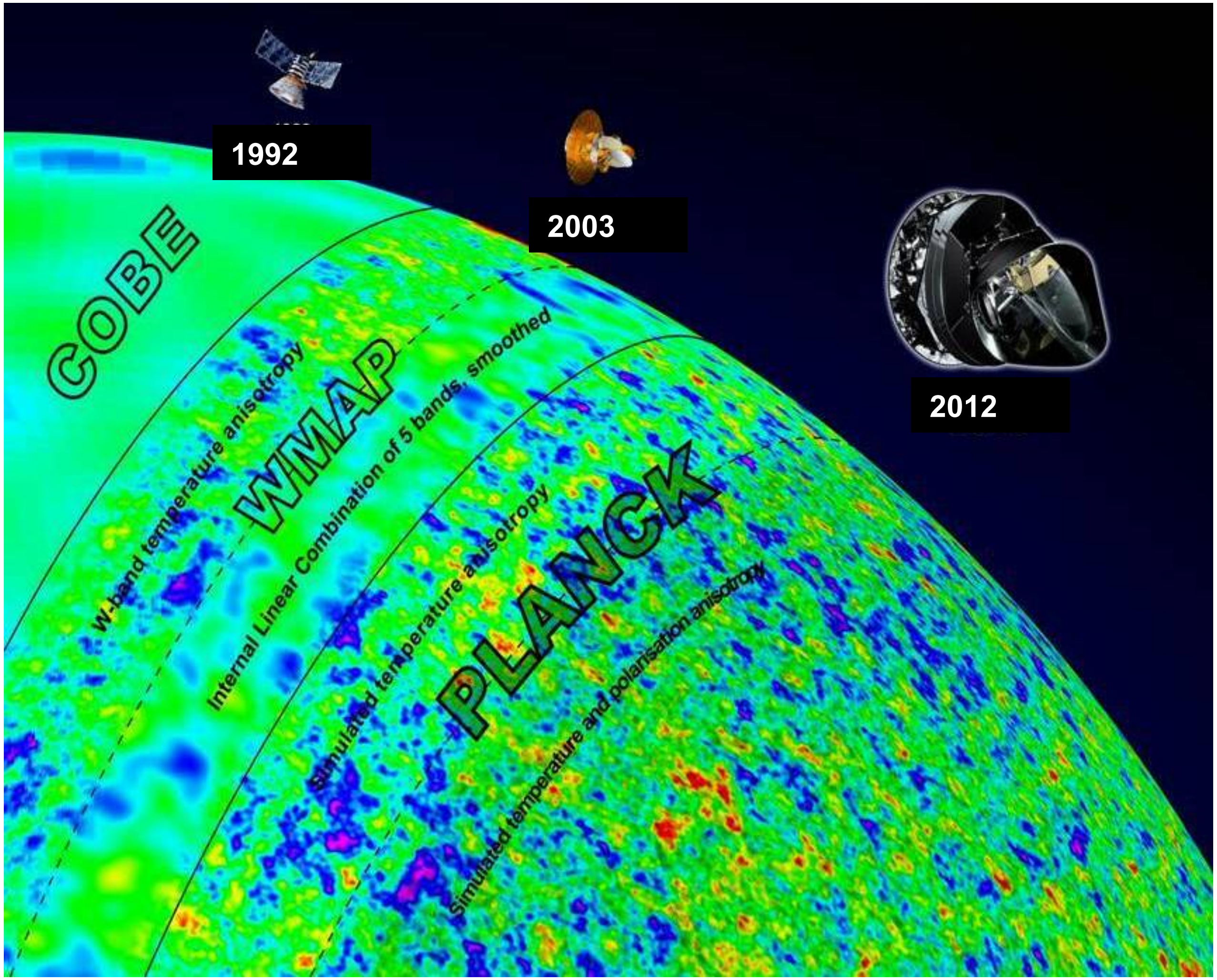
Probing the early universe: the CMB

- the primordial universe ; fine study of the cosmological background radiation (CMB)
- probing the geometry and content of the universe
- precise measurement of the cosmological parameters ($\Omega = \rho / \rho_c$, Λ , H)
  - balloons : BOOMERANG, ARCHEOPS
  - satellites : COBE, WMAP, PLANCK

- COBE : evidence of the inhomogeneities of the CMB at a level of 10^{-6}
- WMAP
- PLANCK
- future mission ? : PRISM (traces of the primordial gravitational waves in the CMB polarization)

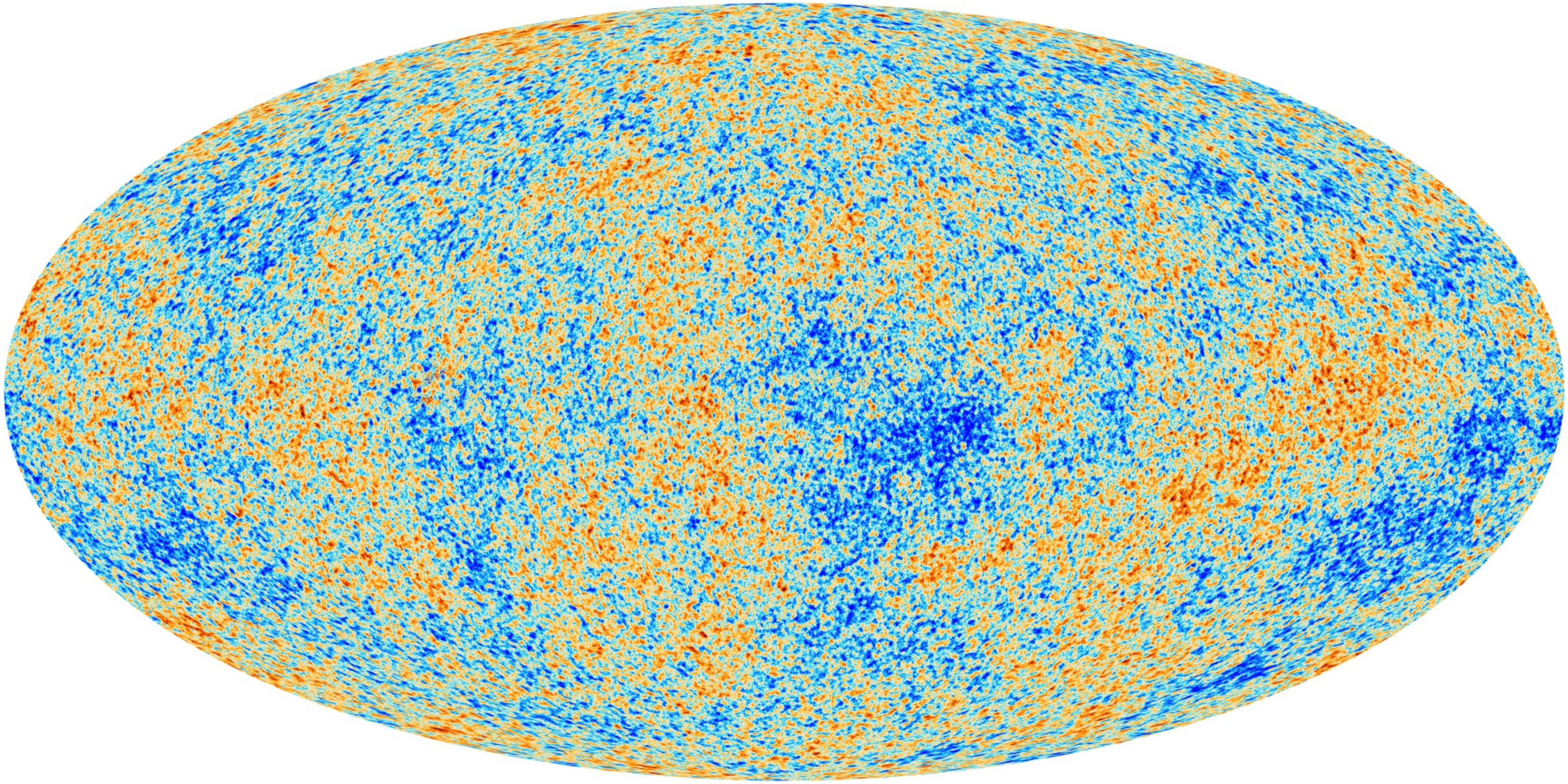
Cosmology as an observational science

The Cosmic Microwave Background seen by Cobe, WMAP, Planck



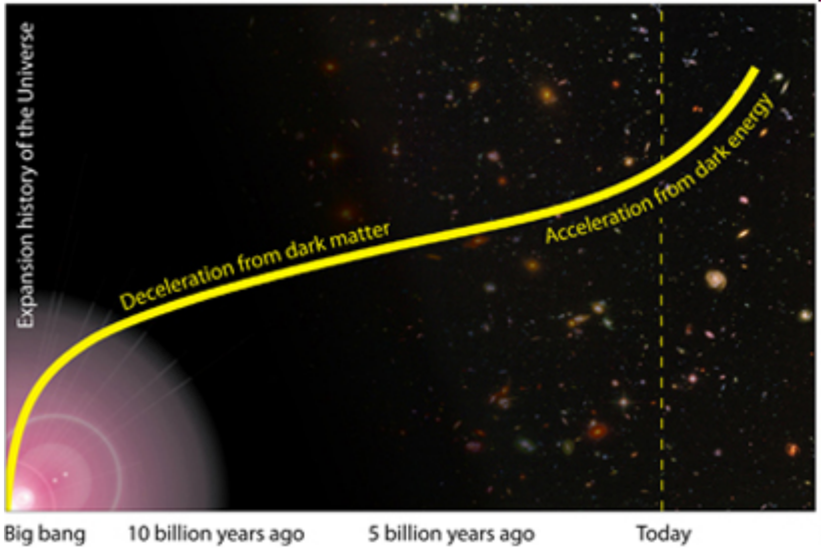
PLANCK cosmological results (April 2013)

(credit: ESA / Planck collaboration
HFI PI: JL Puget, IAS, Orsay, France;
LFI PI: N Mandolesi, ITSRE, Bologne, Italy)

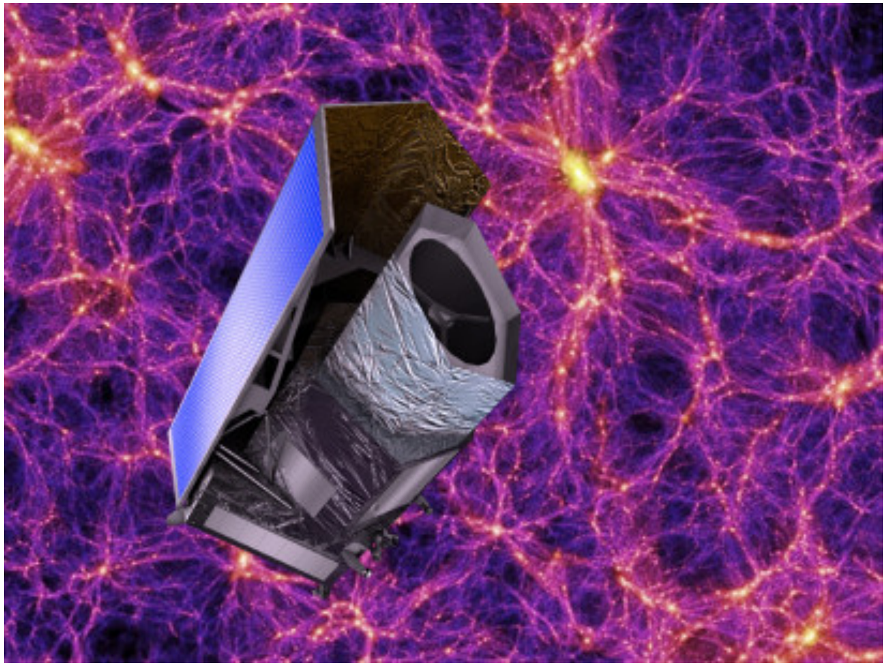


Probing the early universe: Euclid (ESA, 2019)

Objective: to understand the nature of dark energy through accurate measurement of the accelerated expansion of the universe



Expansion history of the universe



Euclid satellite artist's view (credit: ESA)

Probing the early universe : the space observatories

- very distant (i.e. young) objects (z>10) : first stars and early galaxy formation
- muti wavelength approach :

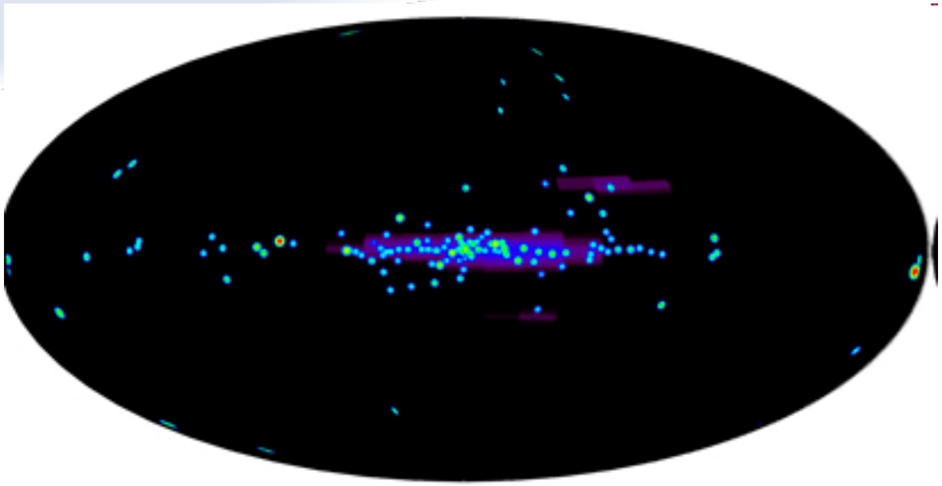
observations in all the frequency ranges of the electromagnetic spectrum

- FIR / submm : HERSCHEL, [SPICA]
- visible / NIR : HST, JWST
- X : CHANDRA, XMM-NEWTON, [ATHENA?]

The cold universe (FIR, submm)

Herschel image of the Eagle Nebula, using the PACS (Photodetector Array Camera) and the SPIRE (Spectral and Photometric Imaging Receiver) instruments
(credit: ESA / HERSCHEL / PACS & SPIRE)

Probing the violent universe : the space observatories



The hard X-ray sky at energies between 50 and 100 keV
(credit: ESA / INTEGRAL / SPI)

SPI is a gamma ray spectrometer developed by IRAP (CNRS & Toulouse university) and CNES for ESA's Integral mission

goal: study the sources of intense and/or rapidly variable gravitational fields

compact objects: AGN, neutron stars, black holes
INTEGRAL, CHANDRA, XMM-NEWTON

violent transient phenomena: gamma-ray bursts
SWIFT, SVOM

Probing the violent universe: a gravitational wave observatory

- gravitational waves: a new window for astrophysics

- e-LISA (ex NGO) will survey for the first time the low-frequency gravitational wave band (about 0.1 mHz to 1 Hz), with sufficient sensitivity to detect interesting individual astrophysical sources out to z = 15

- e-LISA will study a variety of cosmic events and systems e.g. coalescence of massive black holes, black hole consuming smaller compact companion; binary compact objects

The unification theories

most unification theories include common ingredients:

- **extra dimensions (4d → 10d)**
- **larger symmetries**

⇨ **those ingredients assume or imply new features which would appear as hypothetical extra fields / particles**

⇨ **can they account for dark matter and/or dark energy?**

The unification theories

- if those extra fields interact in a different way with leptons and baryons, their coupling with matter depends on the chemical composition, which results in a violation of the Equivalence Principle (EP) beyond a certain degree of accuracy

- if the extra fields get a mass through some mechanism then the laws of gravitation will appear modified below some scale

⇨ the predictions of those theoretical elaborations shall be confronted with experiment, which allows to eliminate or to constrain certain models

Consequences

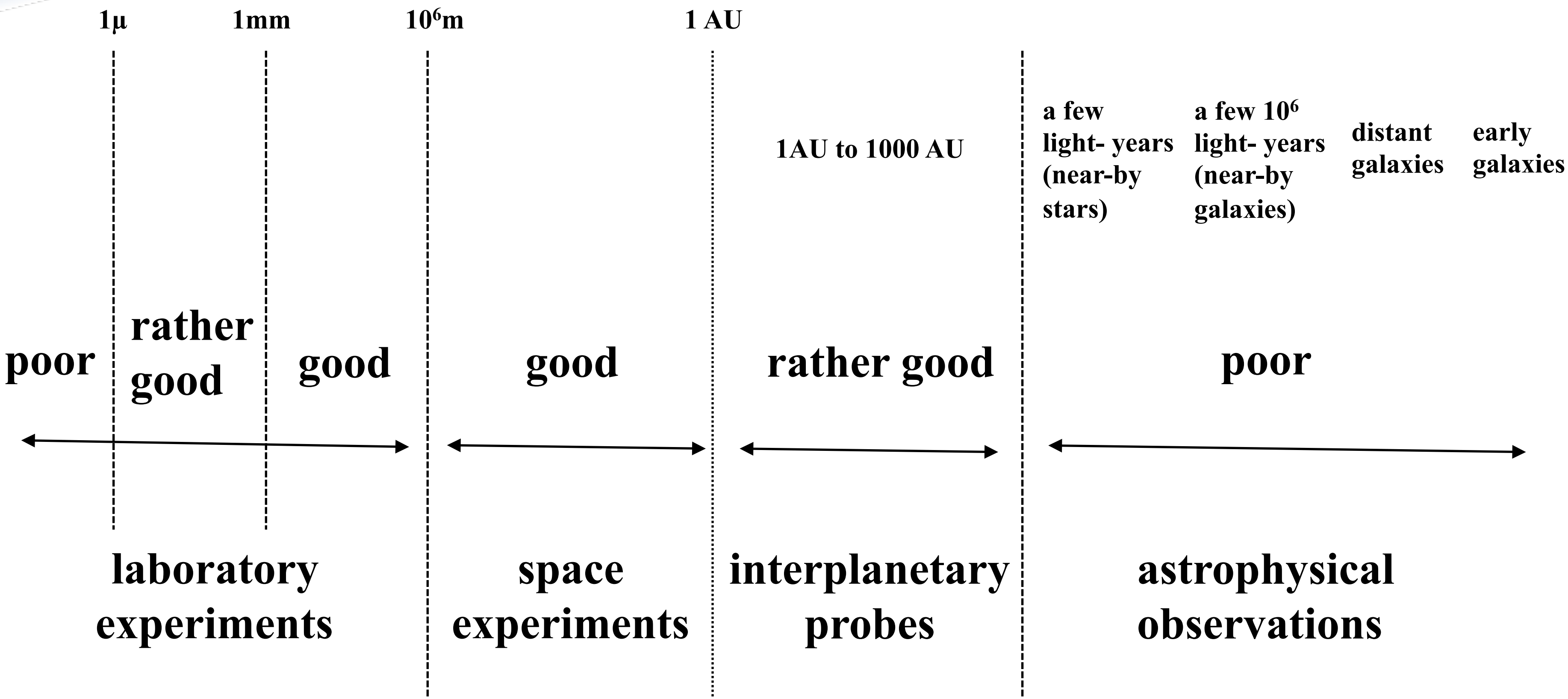
⇨ **accurate testing of the gravitation laws at various scales, in particular tests of GR in the solar system and in the near-by space :**

- **accurate metrology of time and space**
- **accurate measurement of the post-newtonian parameters**

❑ **test the observable consequences of the unification theories, e.g. test the Equivalence Principle**

❑ **the space assets will be an essential tool for testing the observable consequences of the unification theories**

Testing the laws of gravitation at different scales



Probing GR in the near-by space

- several effects predicted by GR have been accurately verified in the solar system and in the vicinity of the Earth
- gravitational redshift (Einstein effect); frequency shift of clocks in a gravitational field
  - experiment GP - A (Vessot, 1976)
  - project T2L2(2003), PHARAO / ACES (2015)
  - GNSS signals: GPS, Galileo
- time-delay (Shapiro effect)
  - interplanetary probes : Voyager (1991) : $|\gamma - 1| < 2.10^{-3}$
- deflection of light by a massive body
  - VLBI, Hipparcos, Gaia
  - Hipparcos data (1995) : $|\gamma - 1| < 10^{-3}$
- frame dragging, geodetic precesssion
  - GP-B (Everitt, 2004)

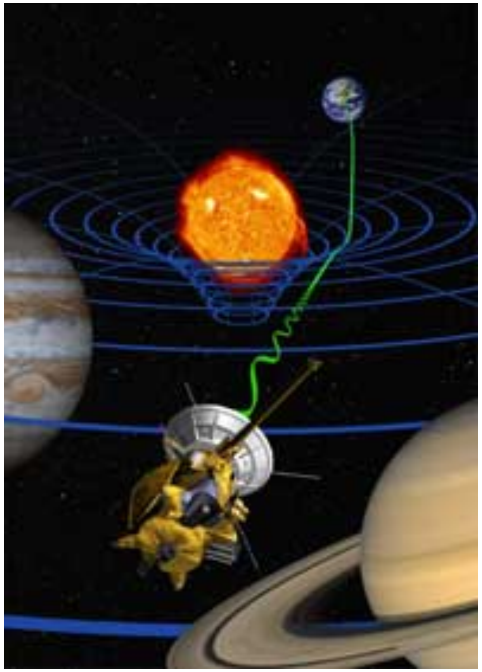
Probing GR in the near-by space

- **Earth-Moon distance measured by laser ranging**
  - **EP test (eventual polarisation toward the Sun of the Moon's orbit around the Earth) « effect Nordvedt »**
  - **measurement of the PPN** $\beta - 1 = (12 \pm 11) \times 10^{-5}$

  [J.G. Williams, S.G. Turyshev, D.H. Boggs, IJMPD 18, 1129 (2009)]

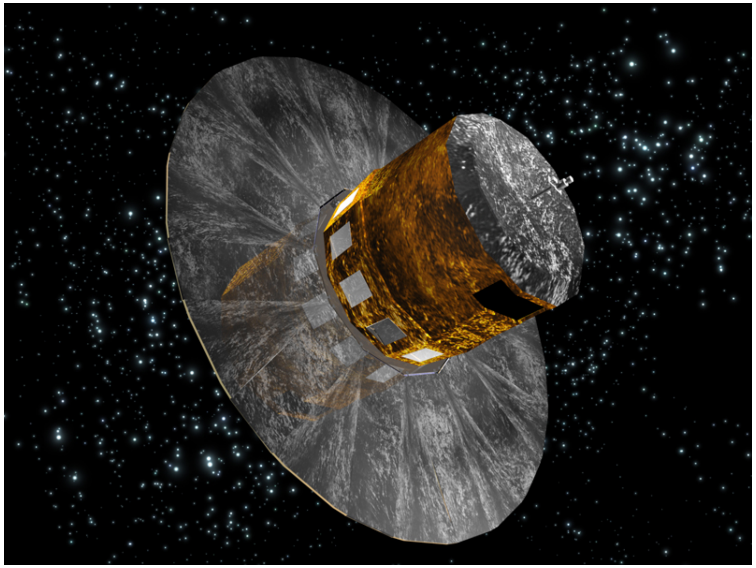
- **radio-science experiments / tracking data analysis of the interplanetary probes:**
  - **Pioneer, Voyager, Cassini, Juice (3GM, PRIDE)**
  - **best measurement of γ today: Cassini**
    - **Doppler tracking during the Earth to Saturn cruise**
    - **accurate radio tracking at the 2002 solar conjunction**

$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$$



GAIA

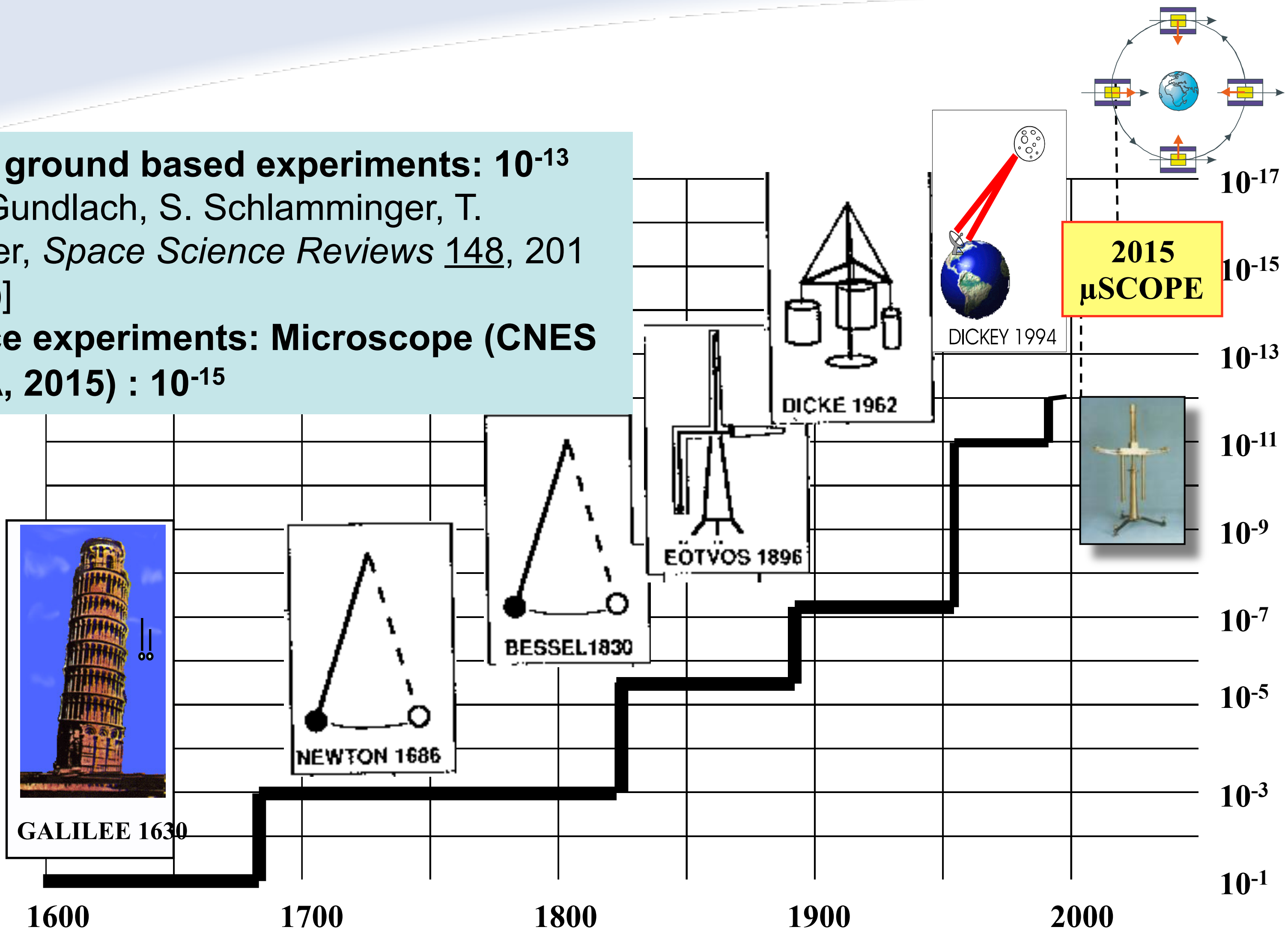
- a census of 1 billion stars of our galaxy during its 5-year mission
  - the primary goal of the Gaia mission is to study the composition, formation and evolution of our galaxy. Gaia will perform an all sky survey and will map the 3-d position and velocity of all objects down to 20th magnitude
  - stellar evolution
  - small bodies of the solar system
  - exoplanets
- launch: November 20th, 2013



- **dark matter: Gaia measurements will precisely identify the gravitational disturbance traces due to the dark matter, thus enabling to refine the knowledge of its distribution**
- **fundamental physics: the bending of light due to the gravitational effect will be measured with an unprecedented precision, enabling to refine the PPN parameters**

Testing the Equivalence Principle

- best ground based experiments: 10^{-13} [J.H. Gundlach, S. Schlamminger, T. Wagner, *Space Science Reviews* 148, 201 (2009)]
- space experiments: Microscope (CNES + ESA, 2015) : 10^{-15}



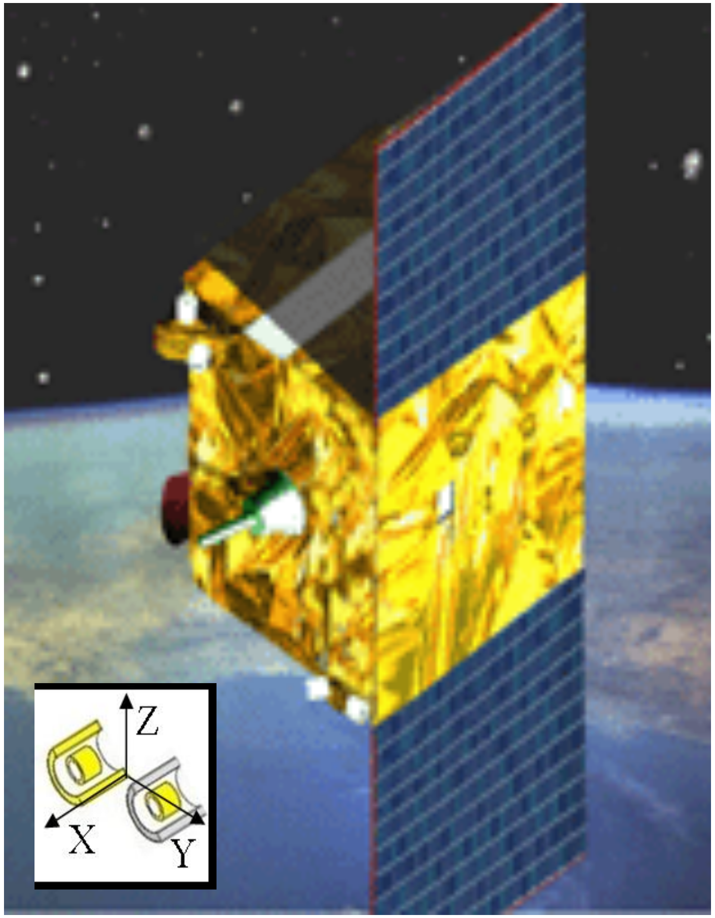
Space as a fundamental physics lab: the Microscope project

objective: test of the Equivalence Principle between inertial mass and gravitational mass at 10^{-15} , i.e. 2 to 3 orders of magnitude better than the best tests on ground

- **principle : comparison of the motion of 2 test-masses made of different materials free-falling in the Earth's gravitational field**
- **they are installed inside a drag-free satellite in order to compensate the effect of the non gravitational forces (residual atmosphere, radiation pressure)**

Space as a fundamental physics lab: the Microscope project

- **description :**
  - a drag-free microsatellite (CNES Myriad family)
  - 2 ultrasensitive differential accelerometers with capacitive detection by ONERA, France
  - a set of cold gas thrusters
  - contributions from Germany (ZARM funded by DLR, and PTB) and ESA (cold gas μ-thrusters)
- **P.I. P. Touboul (ONERA)**
- **launch planned in 2016**
- **mission parameters**
  - Sun synchronous orbit 700 km, 6h/18h (9 months without eclipse)
  - Excentricity : 5×10^{-3}, inclination : 95°
  - Nominal mission: 1 year



Microscope, a microsatellite of CNES's Myriad family *(artist's view, credit: CNES)*

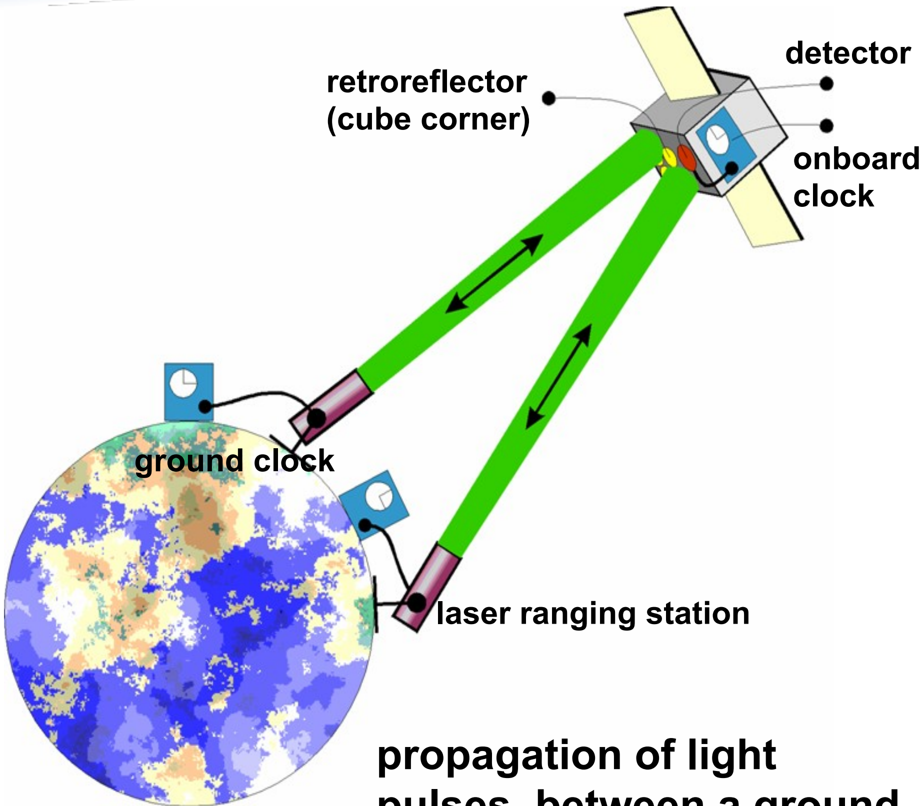
Space as a fundamental physics lab: PHARAO / ACES onboard the ISS

- PHARAO is an ultra stable (10^{-16} / day) and ultra precise (10^{-16}) Cs cold atom space clock
- PI: C. Salomon (ENS/LKB), co-PI : P. Laurent (Obs. de Paris/SYRTE)
- CNES : space hardware development
- PHARAO is part of ACES (Atomic Clock Ensemble in Space)
- ACES will be installed by 2016 on the external balcony of Columbus on the ISS and will include
  - the Cs cold atom clock PHARAO
  - an active Hydrogen maser (Switzerland)
  - a frequency comparator and a board-to-ground µ-wave link (ESA)
- applications :
  - fundamental physics experiment tests
  - time & frequency metrology, time distribution
  - future generations of positioning and navigation systems
  - future cold atom devices , e.g. STE-QUEST: accelerometers, gyrometers, interferometers

ACES on the ISS
(artist's view, credit: ESA)

Space as a fundamental physics lab: time metrology

- time metrology : T2L2 (Time Transfer by Laser Link)
  - high performance 2-way time transfer and comparison between remote ultra-stable ground clocks
  - comparison of various techniques of optical and micro-wave time transfer (GPS, TWSTFT, ACES, GALILEO)
  - contribution to time scales and time distribution (TAI, UTC)
  - tests of fundamental physics
    - measurement of an eventual variation of the fine structure constant α
    - isotropy check of the speed of light at the level of 2.7×10^{-9} (USO limitation)
  - passenger experiment onboard Jason 2 (launched in 2008)
  - PI: E. Samain, Observatoire de la Côte d'Azur (OCA\GEMINI)



propagation of light pulses between a ground based clock and a space clock

2-way method : measurement of 3 dates (departure, on board arrival, return to Earth)

Stability : 10 ps from 10 to 100s
Accuracy : < 500 ps

Thank you for your attention