The STE-QUEST Mission:

(Space-Time Explorer and Quantum Test of the Equivalence Principle):

Testing General Relativity with a Precision Space-Stationed Clock and an Atom Interferometer

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EMMI Workshop - The ^{229m}Th "Nuclear Isomer Clock„

GSI Darmstadt 25 - 27. 9. 2012

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- The STE-QUEST mission
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- Summary

Activities related to optical frequency metrology

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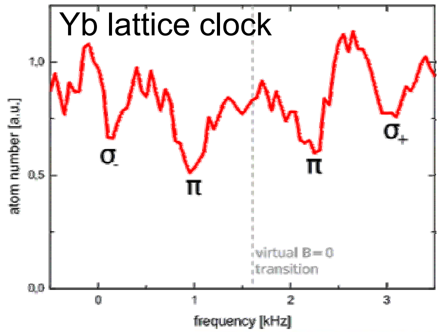
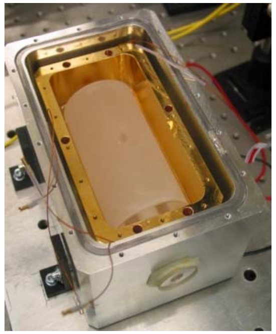
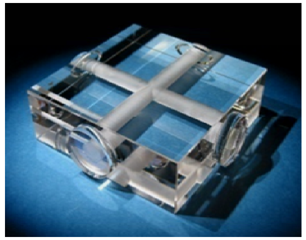
- Optical clocks (with Prof. A. Görlitz)

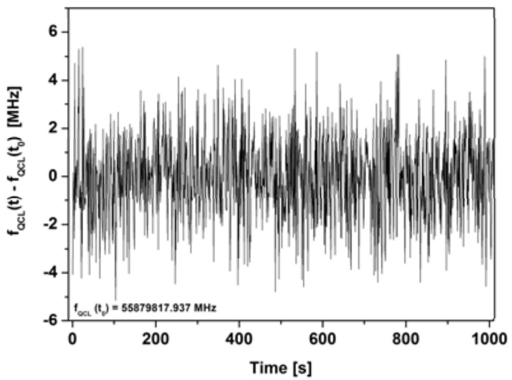


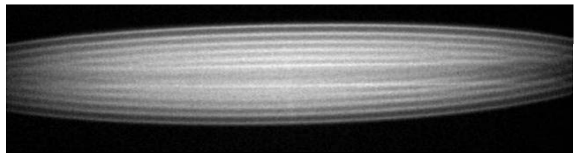
- Ultrastable oscillators based on:
  - Ultrastable cavities (silicon, sapphire, ULE)
  - Rare Earth ions in crystals





- Tests of Lorentz Invariance with cavities (Michelson-Morley-Laser experiment)
- Cold molecular ions (HD^+) and precision spectroscopy for tests of *ab initio* theory
- Frequency metrology in the mid-infrared domain



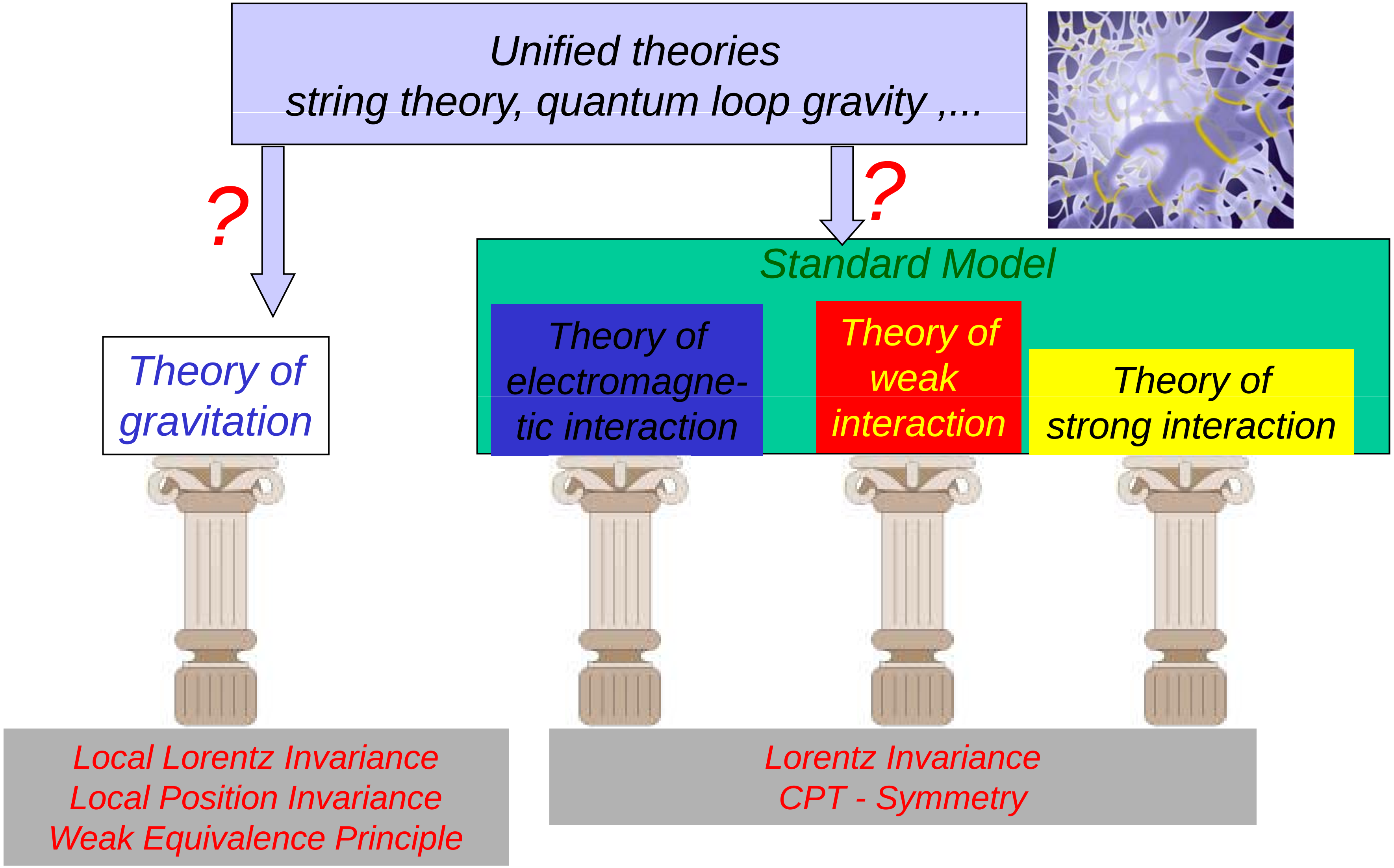


Next - generation clocks: what for ?

- Technical applications (spacecraft navigation in deep space)

- Scientific applications
  - „Physics of clocks“
  - Tests of the Equivalence Principle (on the ground, laboratory experiments)
  - Tests of General Relativity (structure of space-time) → **space missions**
  - Geophysiscs: determination of the geopotential
  - Radio science

Motivation



exactly valid?

The conceptual basis for tests of General Relativity

Gravitational redshift
Lense-Thirring effect
Shapiro delay
Perihelion shift
Schiff effect
Earth & moon free fall
Binaries dynamics
…

General Relativity

Metric theory of gravity

Einstein Equivalence Principle

Universality of Free Fall
(Weak equivalence princip.)

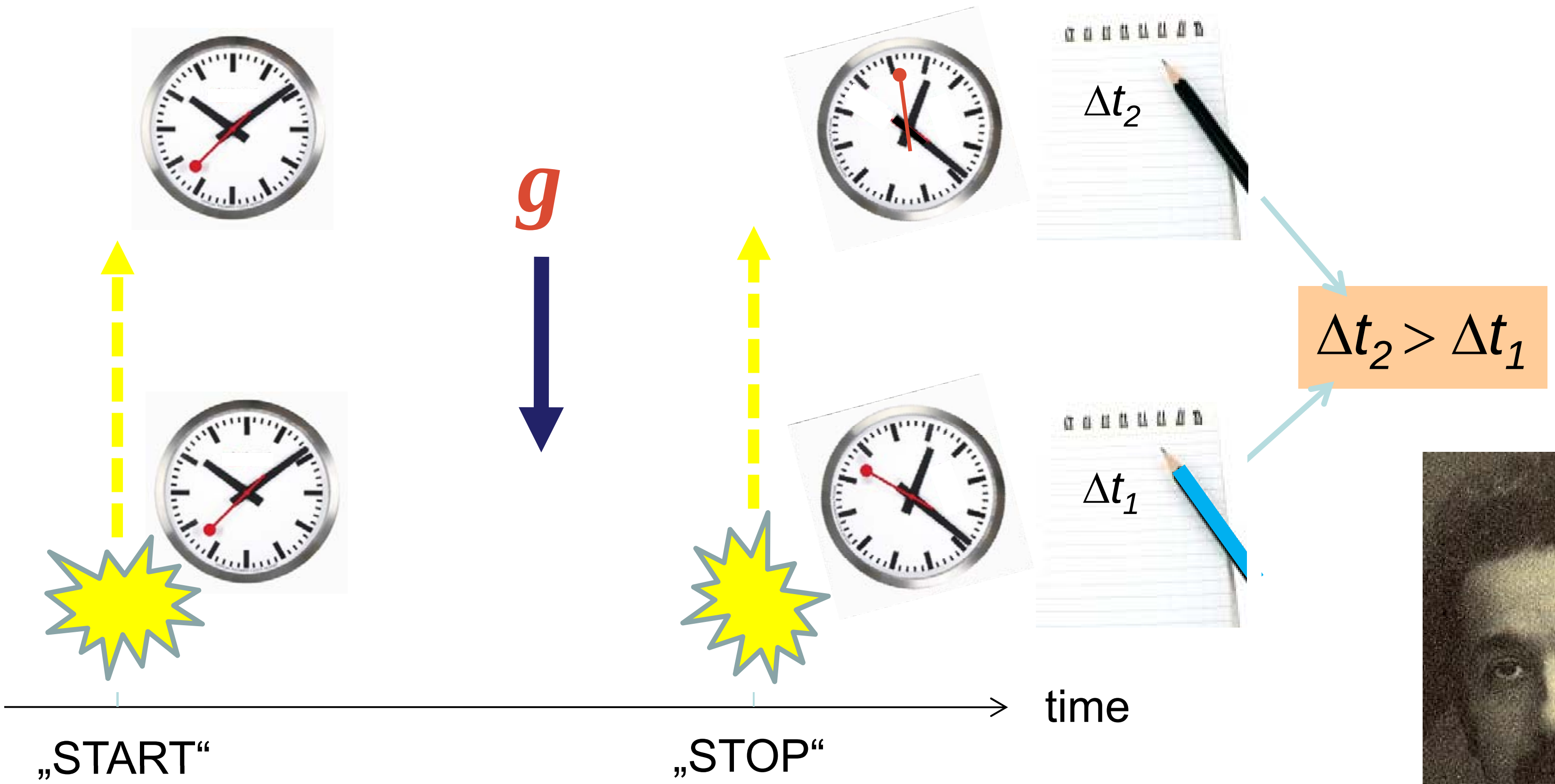
Local Position Invariance
(Universality of grav. Redshift constancy of constants)

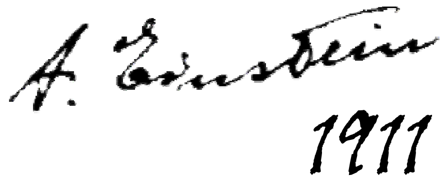
Local Lorentz Invariance
(Special Relativity)

“The trajectory of a point mass in a gravitational field depends only on its initial position and velocity, and is independent of its composition.”

“The result of any local non-gravitational experiment is independent of its location in space and time.”

The gravitational time dilation: gravity modifies time





J. S. Bell, in “Fundamental Symmetries”,
edited by P. Bloch et al. (Plenum, New York, 1987)

The gravitational frequency shift (redshift)

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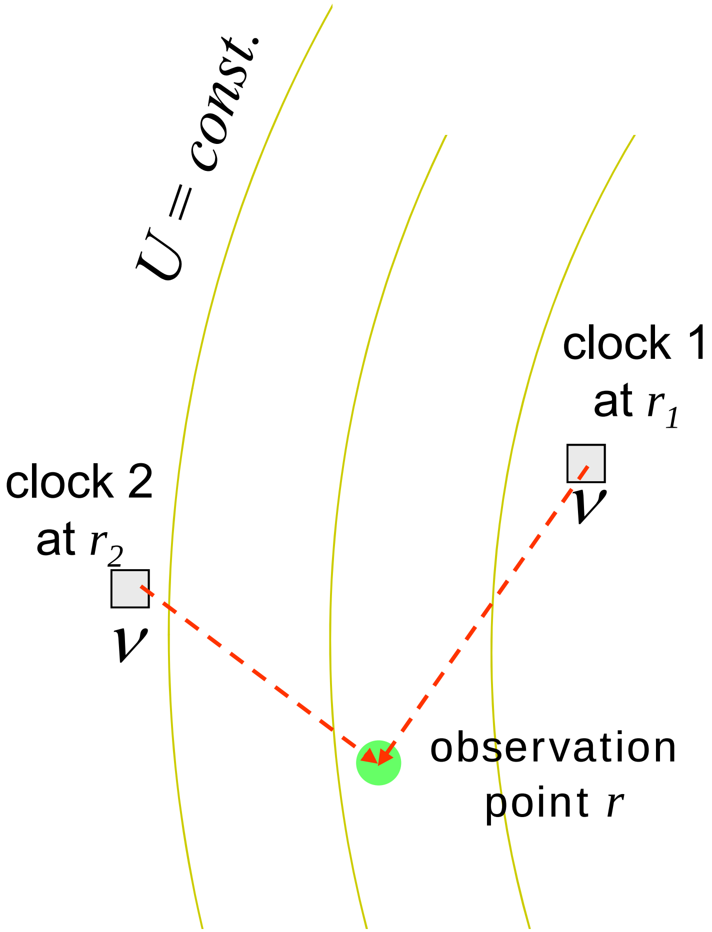
- The comparison of the frequencies stemming from two identical clocks located at different positions yields the nonzero result (if at rest):

$$\frac{\nu_{clock1}(r)}{\nu_{clock2}(r)} \simeq 1 + \frac{U(r_1) - U(r_2)}{c^2}$$



A. Einstein 1911

tat gestattet zunächst folgende Anwendung. Es sei ν_0 die Schwingungszahl eines elementaren Lichterzeugers, gemessen mit einer an demselben Orte gemessenen Uhr U. Diese Schwingungszahl ist dann unabhängig davon, wo der Lichterzeuger samt der Uhr aufgestellt wird. Wir wollen uns beide etwa an der Sonnenoberfläche angeordnet denken (dort befindet sich unser S_2). Von dem dort emittierten Lichte gelangt ein Teil zur Erde (S_1), wo wir mit einer Uhr U von genau gleicher Beschaffenheit als der soeben genannten die Frequenz ν des ankommenden Lichtes messen. Dann ist nach (2a)

$$\nu = \nu_0 \left(1 + \frac{\Phi}{c^2}\right),$$

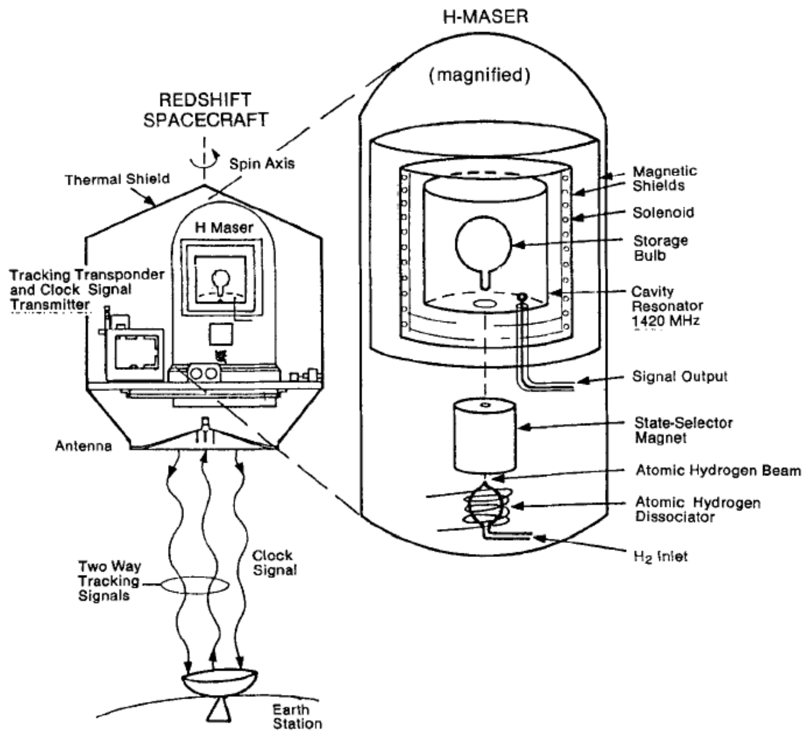
wobei Φ die (negative) Gravitationspotentialdifferenz zwischen Sonnenoberfläche und Erde bedeutet. Nach unserer Auffassung

Space tests I: measurement of gravitational redshift (1976)

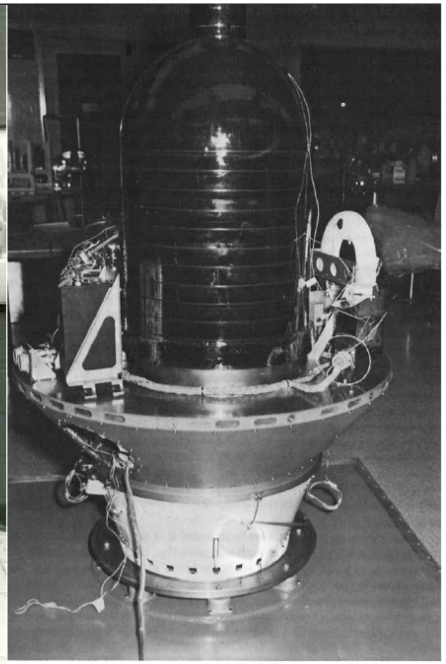
„Gravity Probe A“: Hydrogen maser as atomic clock

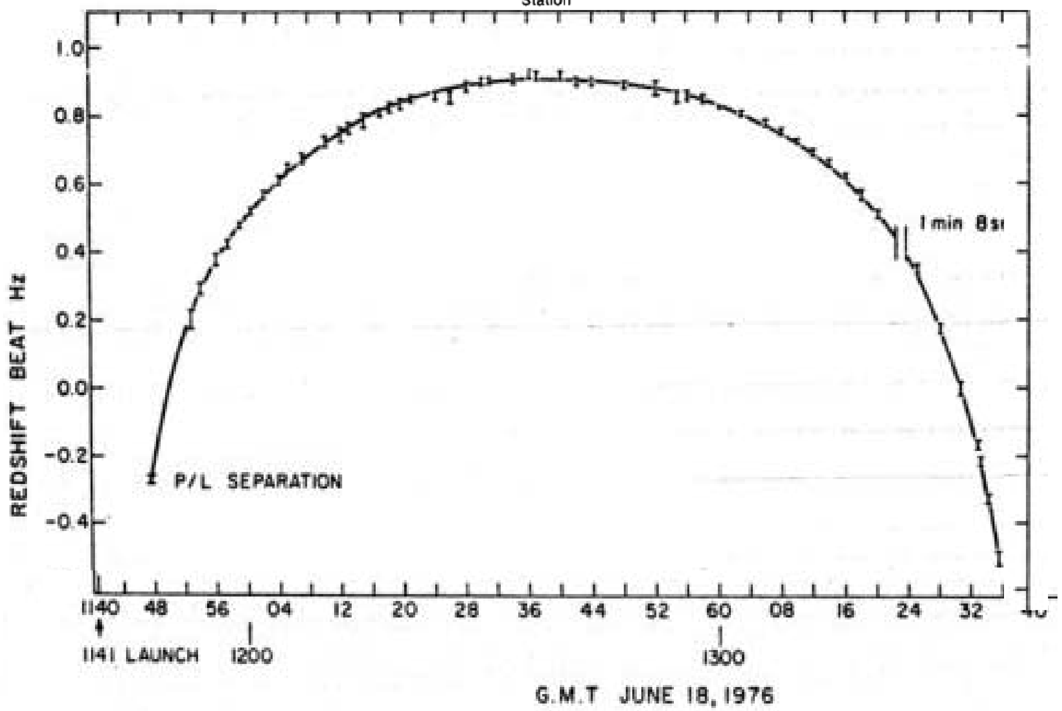
- Rocket flight to 10 000 km altitude

- verified gravitational time dilation with 7×10^{-5} uncertainty (Vessot et al, 1980)



Levine and Vessot



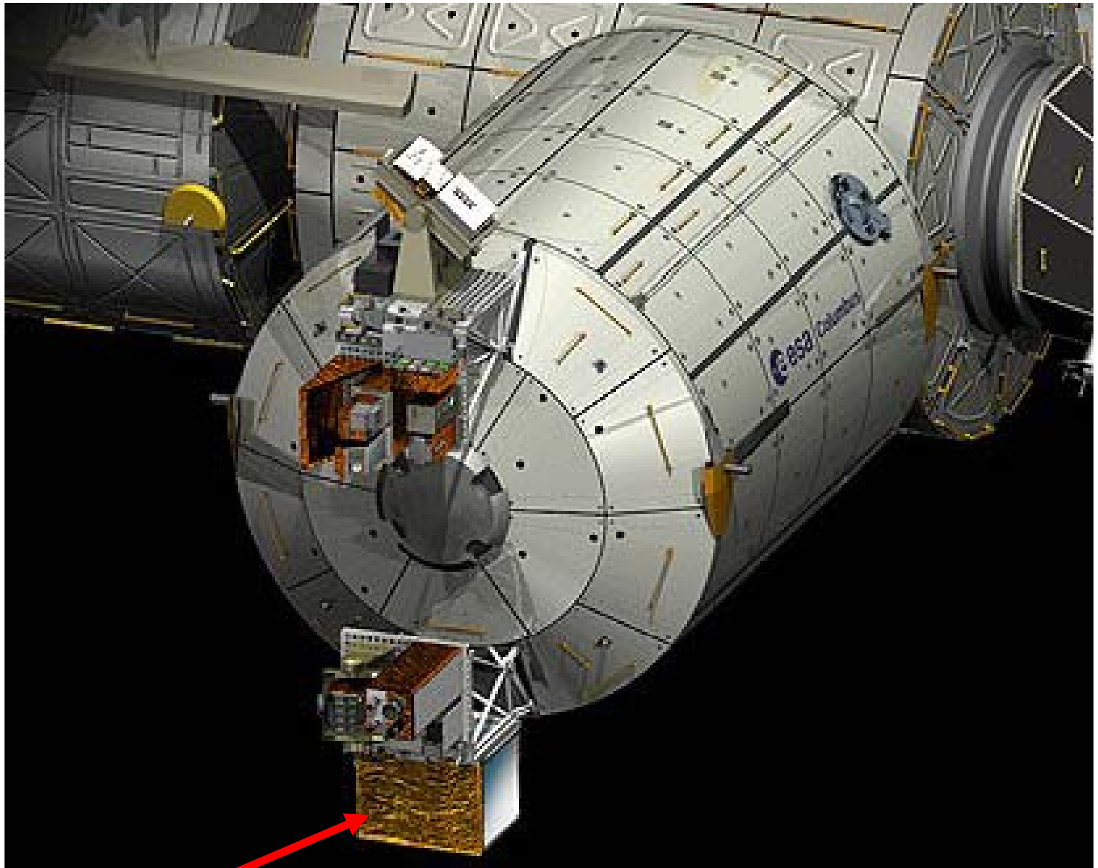


Space tests II: the ACES mission

Columbus module

2/2008

ACES (Atomic Clock Ensemble) on an external platform of the Columbus module



ACES:
Cs cold atom clock
& H-maser

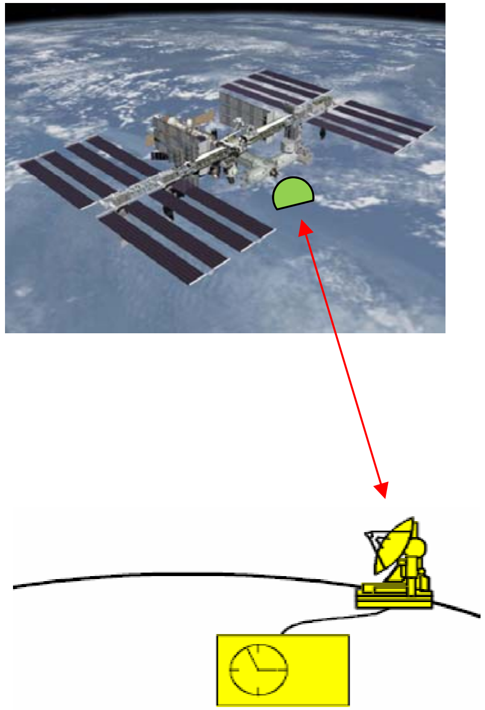
Planned installation year: ~ 2016
Mission duration: 1.5 – 3 years

ACES Mission

- Precision measurement of the gravitational time dilation in the Earth‘s gravitational field
- Comparison of distant clocks on Earth via the ISS clock

$$\frac{\nu_{ISS-clock}(ground)}{\nu_{ground\ clock}} \cong 1+\beta\frac{U(ISS)-U(ground)}{c^2}$$

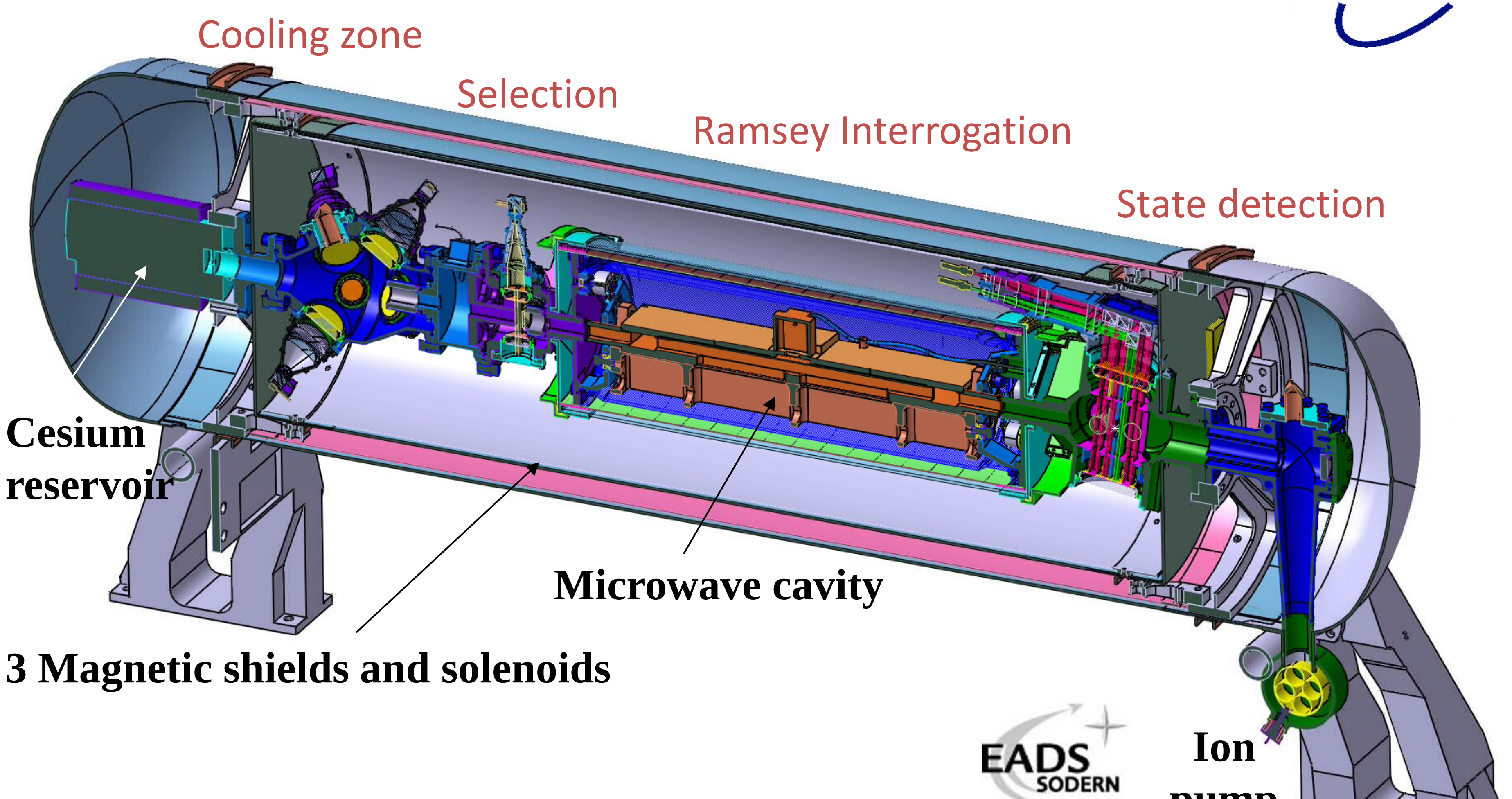
$$\cong 1-\beta c^{-2}\int_{ground}^{ISS}\vec{g}(h)\cdot d\vec{r}$$



- Orbit altitude: ≈ 400 km; effect : ≈ 4 x 10^{-11}
- Atomic clock on ISS has 1 x 10^{-16} uncertainty (goal)
- Ground clocks with < 1 x 10^{-16} uncertainty will be available in 2015
- „Two-way“ - microwave link (< 2 x 10^{-13} s error for 30 000 s integration time)
- U(ISS)-U (ground) must be determined with equivalent height uncertainty of 1 m → need for ISS orbitography
- Goal: determination of β with uncertainty 2.5 x 10^{-6} (~30 times lower than for Gravity Probe A - experiment)

Ground microwave terminal

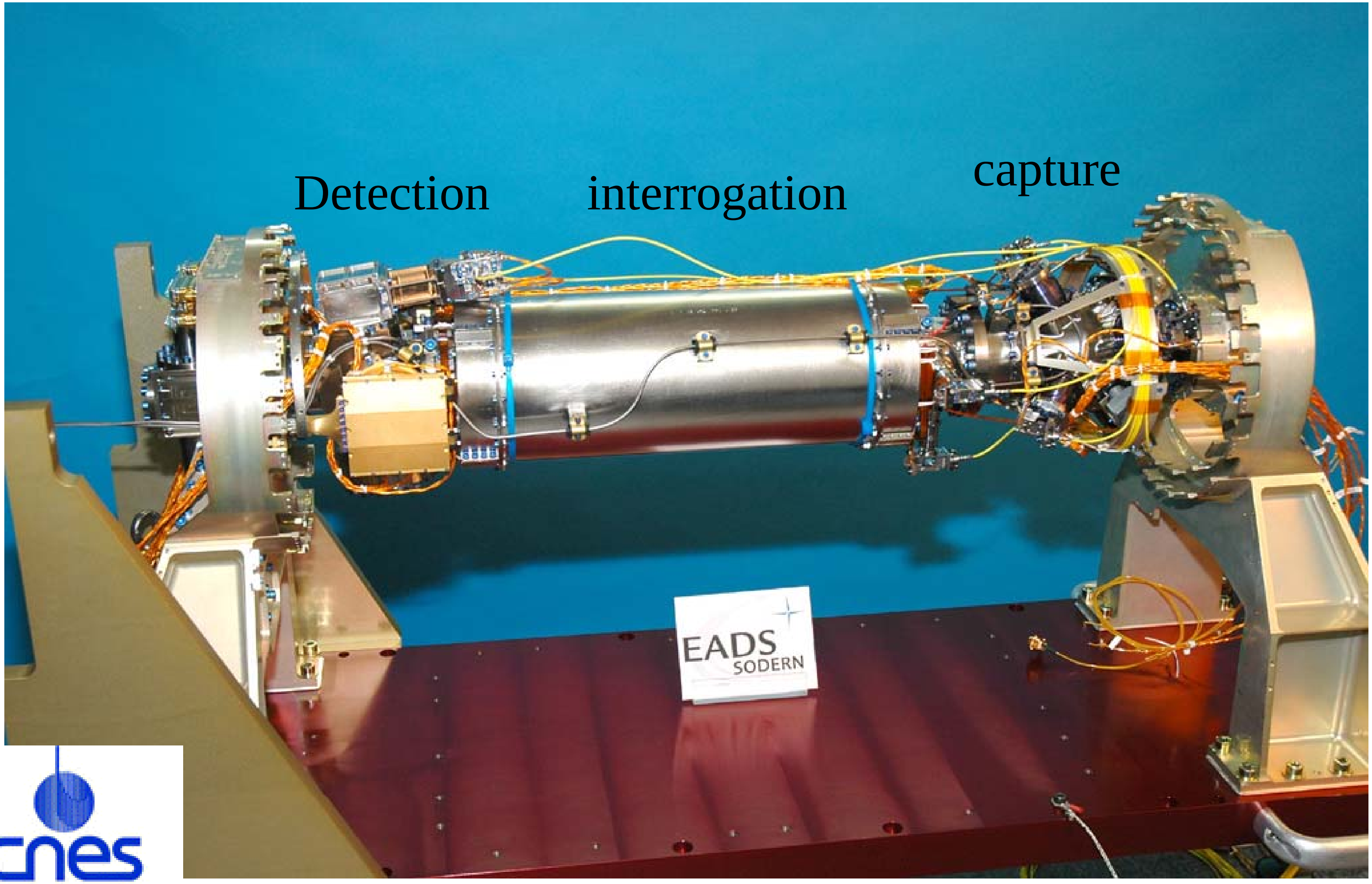
PHARAO: Cold Cs atomic clock



- Terrestrial atomic fountain:
  v = 4 m/s, T = 0.5 s → frequency resolution $\Delta\nu$ = 1 Hz
- PHARAO :
  v = 0.05 m/s, T = 5 s → frequency resolution $\Delta\nu$ = 0.1 Hz

PHARAO atomics package

L=900 mm, M= 45 kg, P= 5 W



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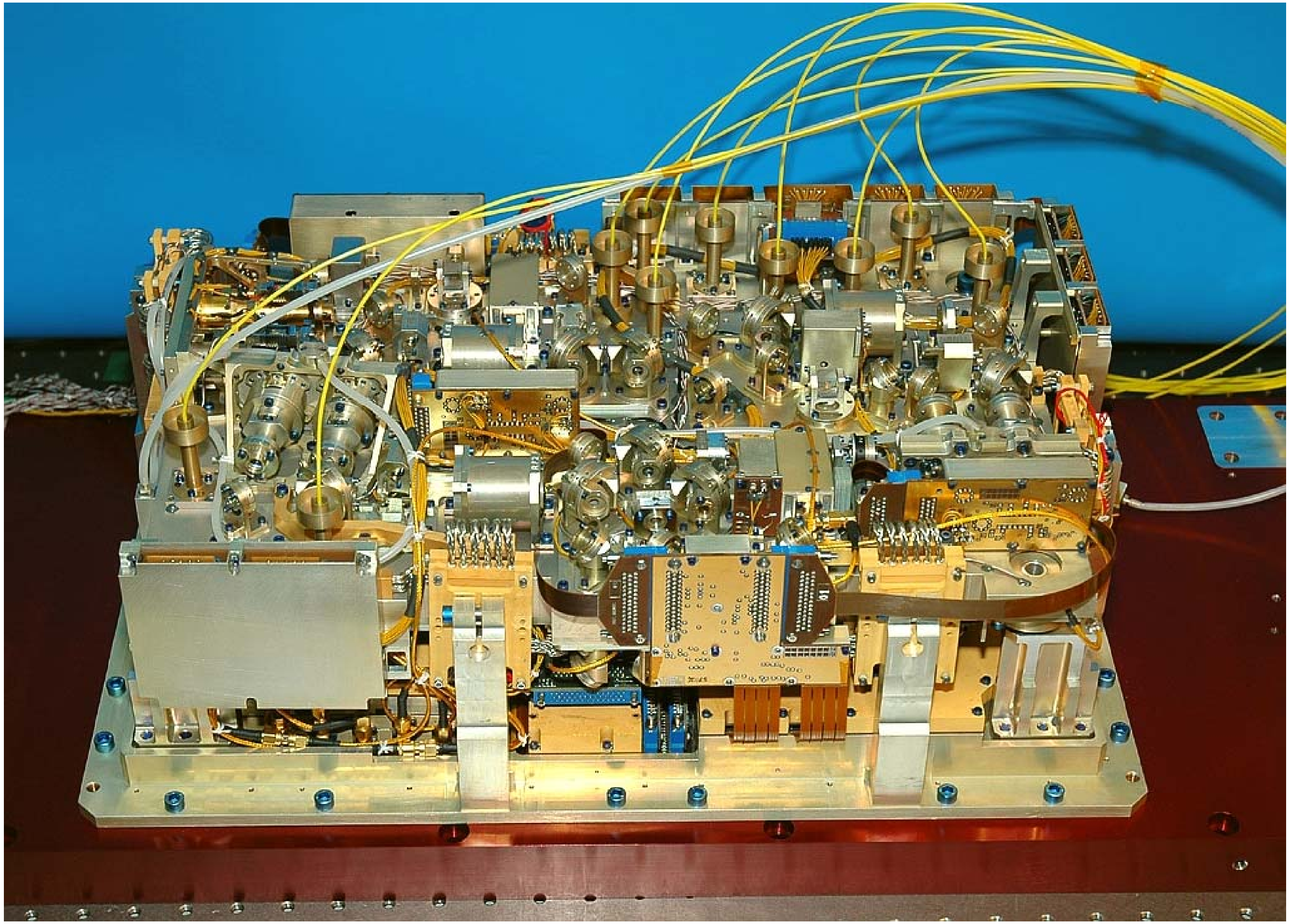
PHARAO laser system

20.054 kg, 36 W, 30 liter

vacuum and air operation, 10 - 35 ^{o}C



cnes

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Main active components:

4 ECDL
4 Diode Laser
6 AOM
30 PZT
11 motors
6 photodiodes
8 Peltier coolers

PHARAO

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PHARAO Engineering Model

- Cold Cesium atoms, interrogated at 9.1 GHz
- Local oscillator: ultrastable quartz

l'Observatoire de Paris — BNM-SYRTE
Bureau National de Métrologie - Systèmes de Référence Temps-Espace
ECOLE NORMALE SUPERIEURE
EADS SODERN
cnes CENTRE NATIONAL D'ÉTUDES SPATIALES
PHARAO
THALES

Concept of the STE-QUEST mission

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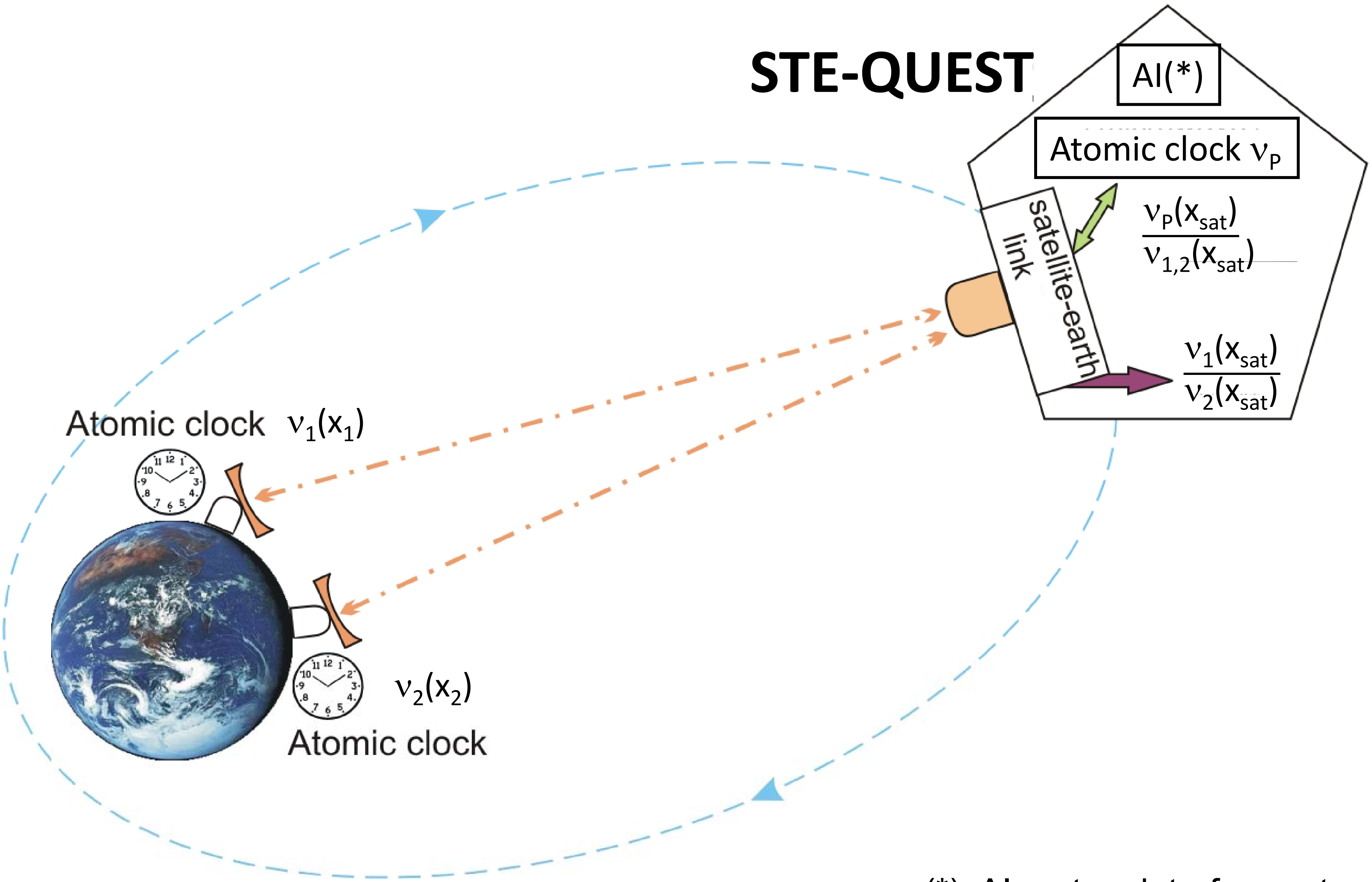

(*): AI = atom interferometer

Mission Overview

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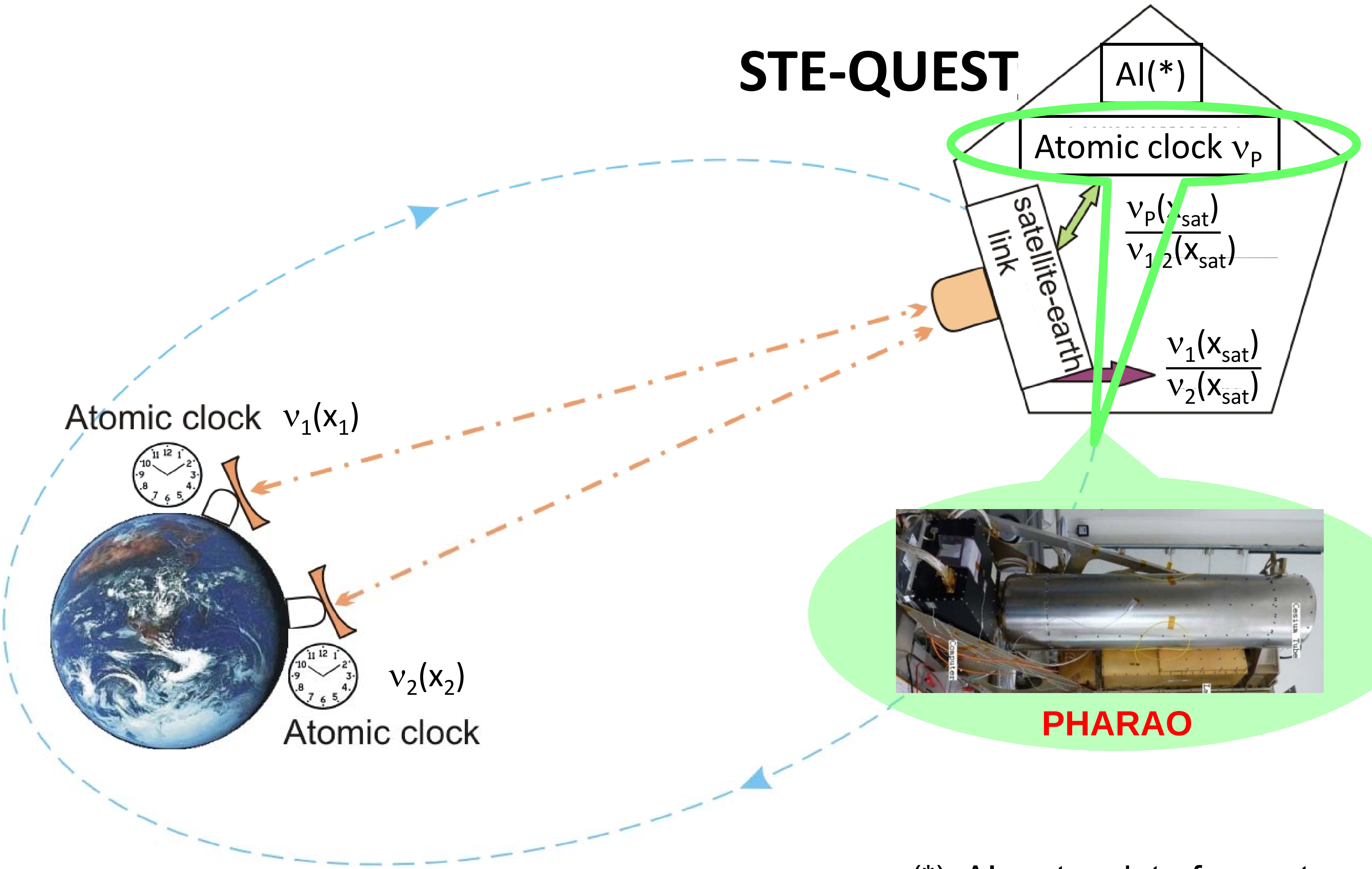
- Science goals:
  Establish more firmly the metric nature of the theory of gravitation, search for Physics beyond the Standard Model plus General Relativity
  - Test the Weak Equivalence Principle for matter waves at level 1.5×10^{-15}
  - Test time dilation in the terrestrial and in the solar gravitational potential, at levels 2×10^{-7} and 2×10^{-6}, resp.
- Application to other fields:
  - master clock in space, distributing time/frequency world-wide
  - Intercomprison of ground clocks
  - mapping of the gravitational potential of the Earth with ultra-high spatial resolution
- STE-QUEST is based on proposals EGE and MWXG [1,2]
- In 2/2011 STE-QUEST was one of four missions recommended by the ESA advisory structure for „slot“ M3 in ESA‘s „Cosmic Vision Program 2015-2025“ and selected for an assessment study.
- „M“ = medium-class mission (cost to ESA < 470 M€; instruments paid by national funds)
- Target take-off date: 2022 or 2024

[1] S. Schiller et al. Exp. Astronomy **23**, 573 (2009)
[2] W. Ertmer et al. Exp. Astronomy **23**, 611 (2009)

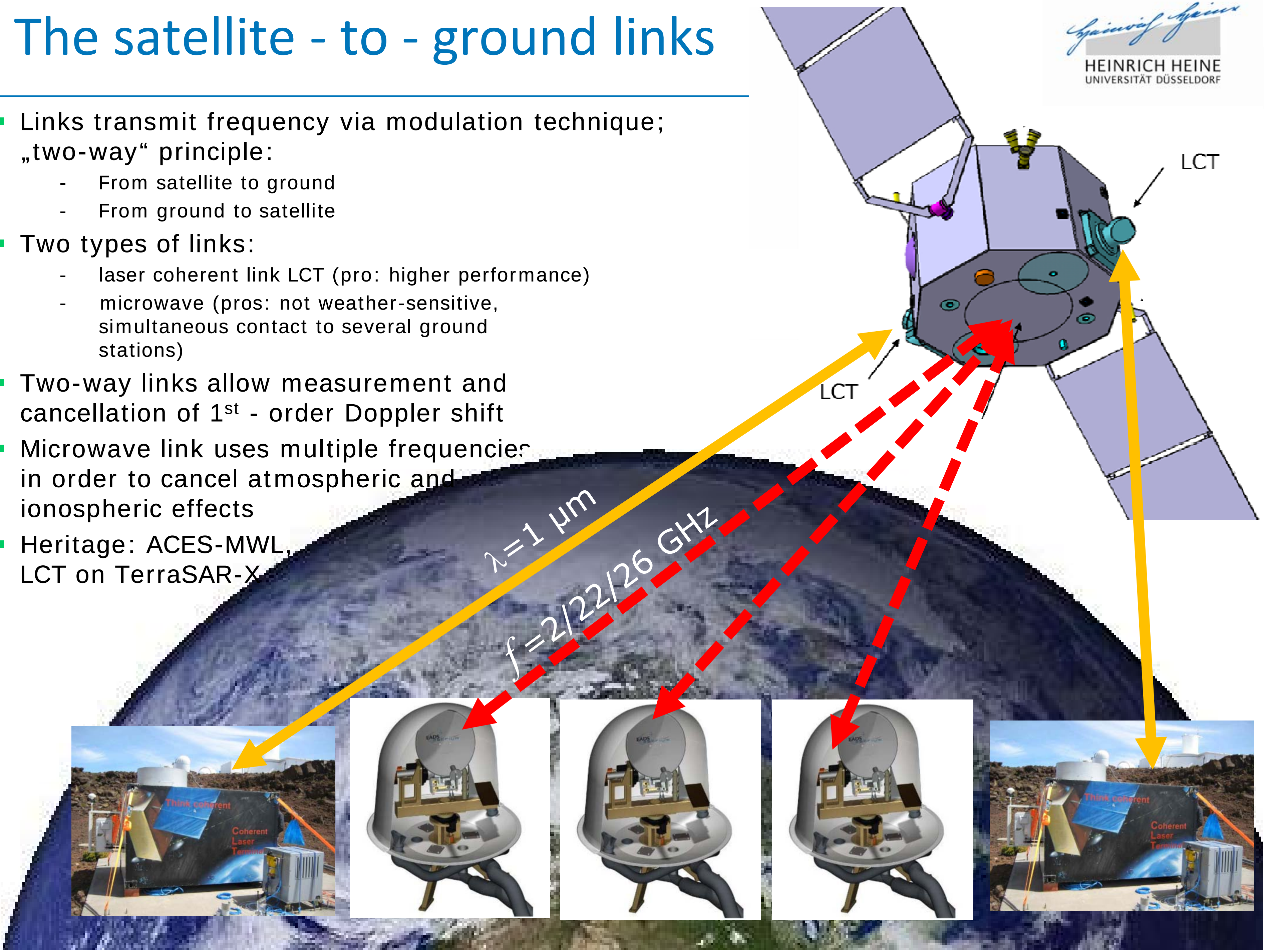
Concept of the STE-QUEST mission



(*): AI = atom interferometer

The satellite - to - ground links

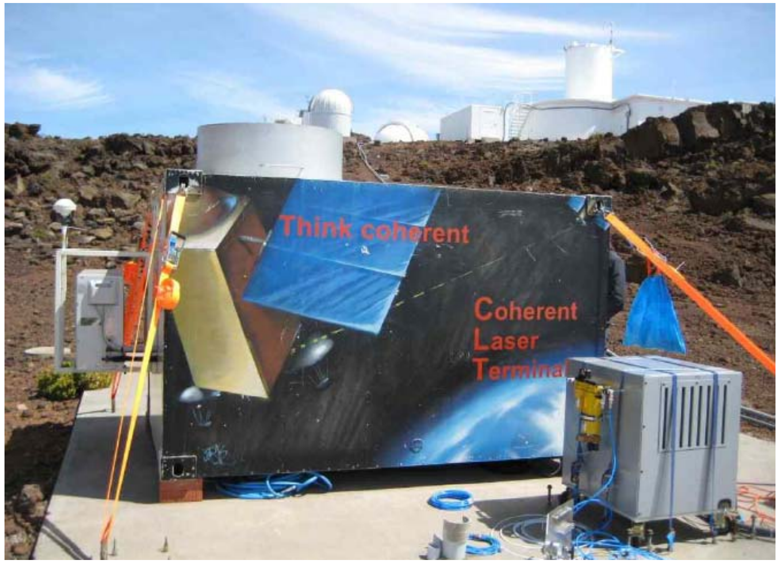
- Links transmit frequency via modulation technique; „two-way“ principle:
  - From satellite to ground
  - From ground to satellite
- Two types of links:
  - laser coherent link LCT (pro: higher performance)
  - microwave (pros: not weather-sensitive, simultaneous contact to several ground stations)
- Two-way links allow measurement and cancellation of 1st - order Doppler shift
- Microwave link uses multiple frequencies in order to cancel atmospheric and ionospheric effects
- Heritage: ACES-MWL, LCT on TerraSAR-X



Ground stations

- 3 MWL ground stations (weather is not an issue): ACES heritage
- 3 LCT ground stations (not necessarily co-located with MWL, need cloud-free sky)
- Ground atomic clocks need not be at same location, but can be connected by fiber-optic link
- Current baseline locations:

Torino/Matera (I), Boulder (USA), Tokyo (J)



LCT ground terminal

MWL ground terminal (2 - 3 m dish)

Testing Earth's gravitational time dilation

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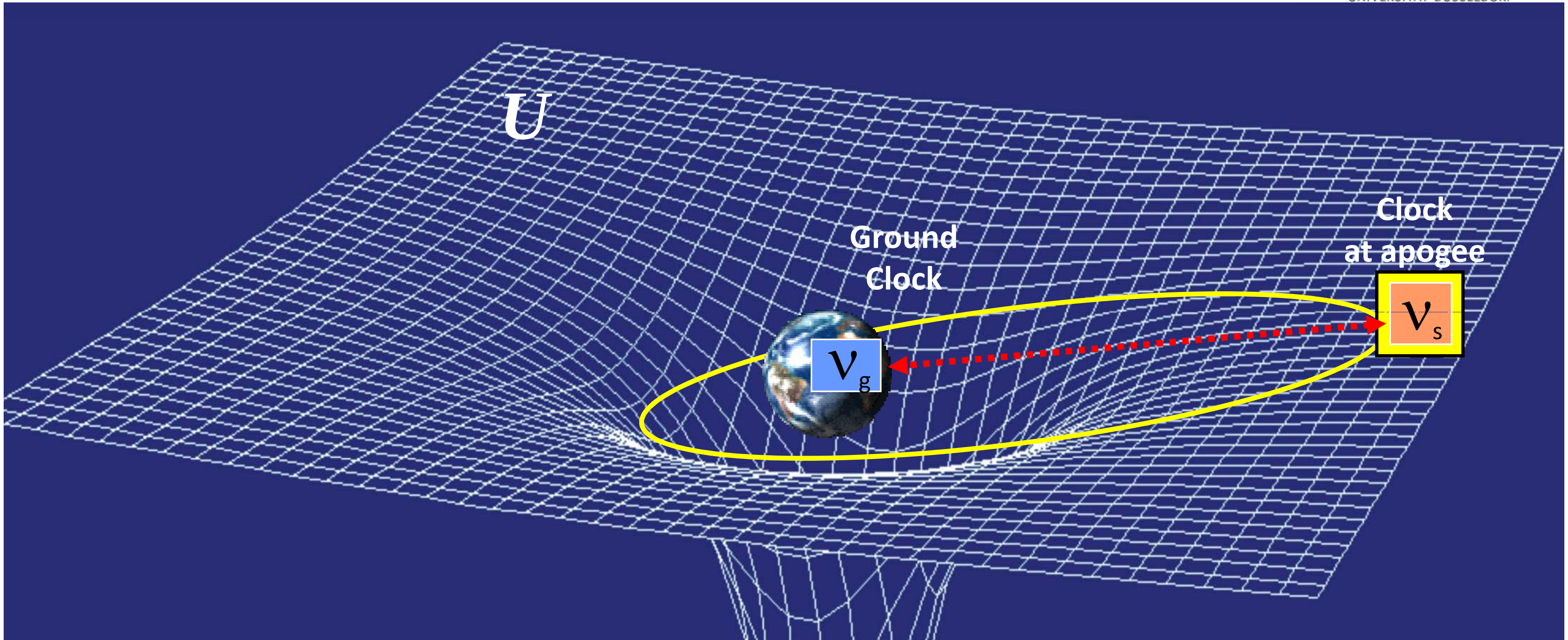

<u>Frequency comparison between ground clock and satellite clock **at apogee**</u>

- in highly elliptic orbit, ΔU(perigee - ground)/c^2 $\approx$ 6 x 10^{-10}
- assume a space clock **inaccuracy** $\cong$ 1 x 10^{-16} (PHARAO with Cs atoms)
- ground clock inaccuracy: negligible
- gravitational potential uncertainty at apogee is not relevant
- gravitational potential at ground clock location must be determined

Testing Earth's gravitational time dilation

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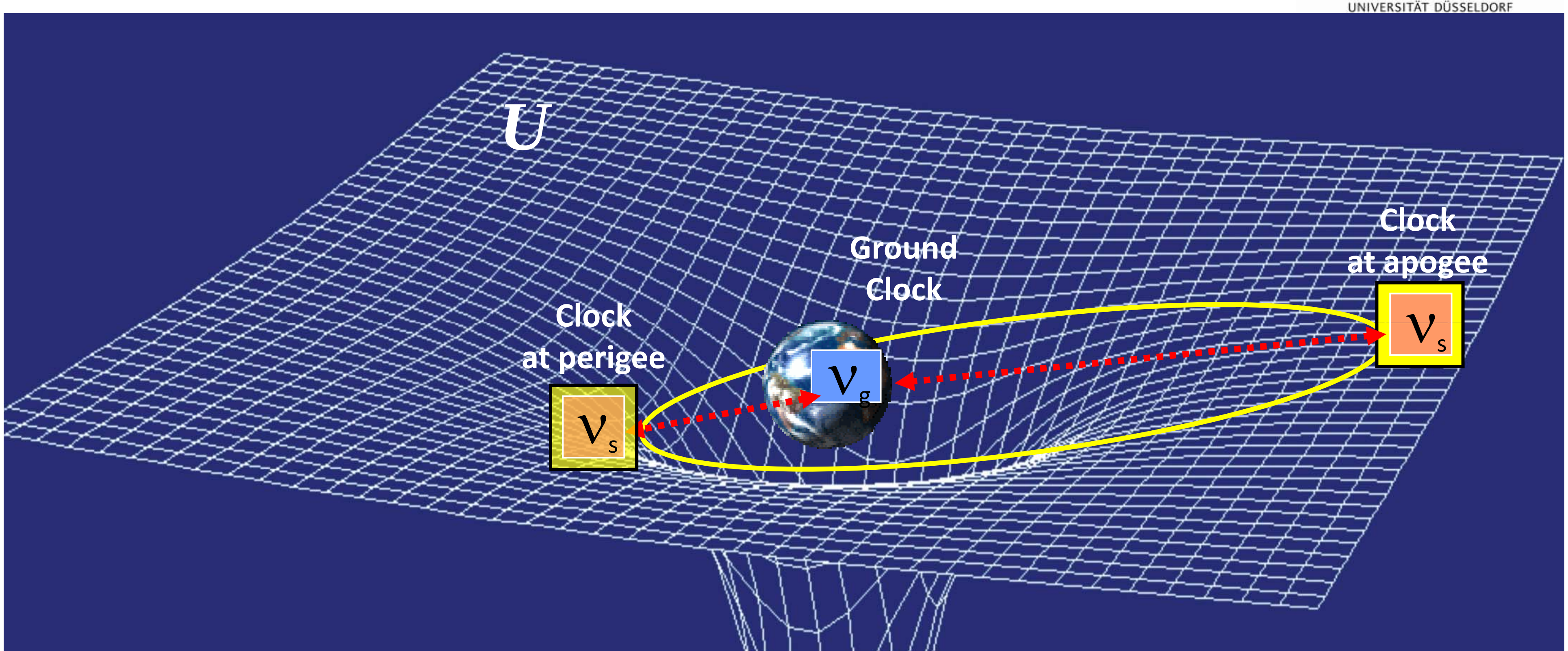
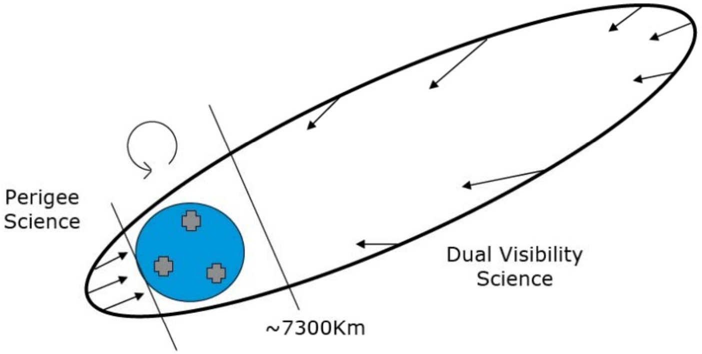


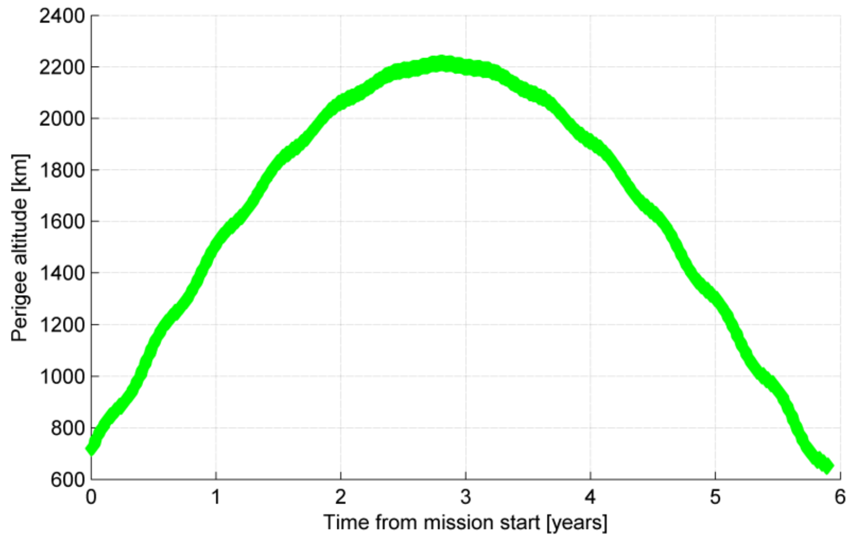
<u>Comparison between ground clock and satellite clock **at perigee and apogee**</u>

- determine: $(\nu_s(\text{apogee}) - \nu_g) - (\nu_s(\text{perigee}) - \nu_g)$
- in highly elliptic orbit, $\Delta U(\text{perigee-apogee})/c^2 \approx 6 \times 10^{-10}$
- assume a space clock **instability** $\cong 1 \times 10^{-16}$ (PHARAO with Cs atoms)
- ground clock instability: negligible
- gravitational potential uncertainties at apogee and at ground clock not relevant

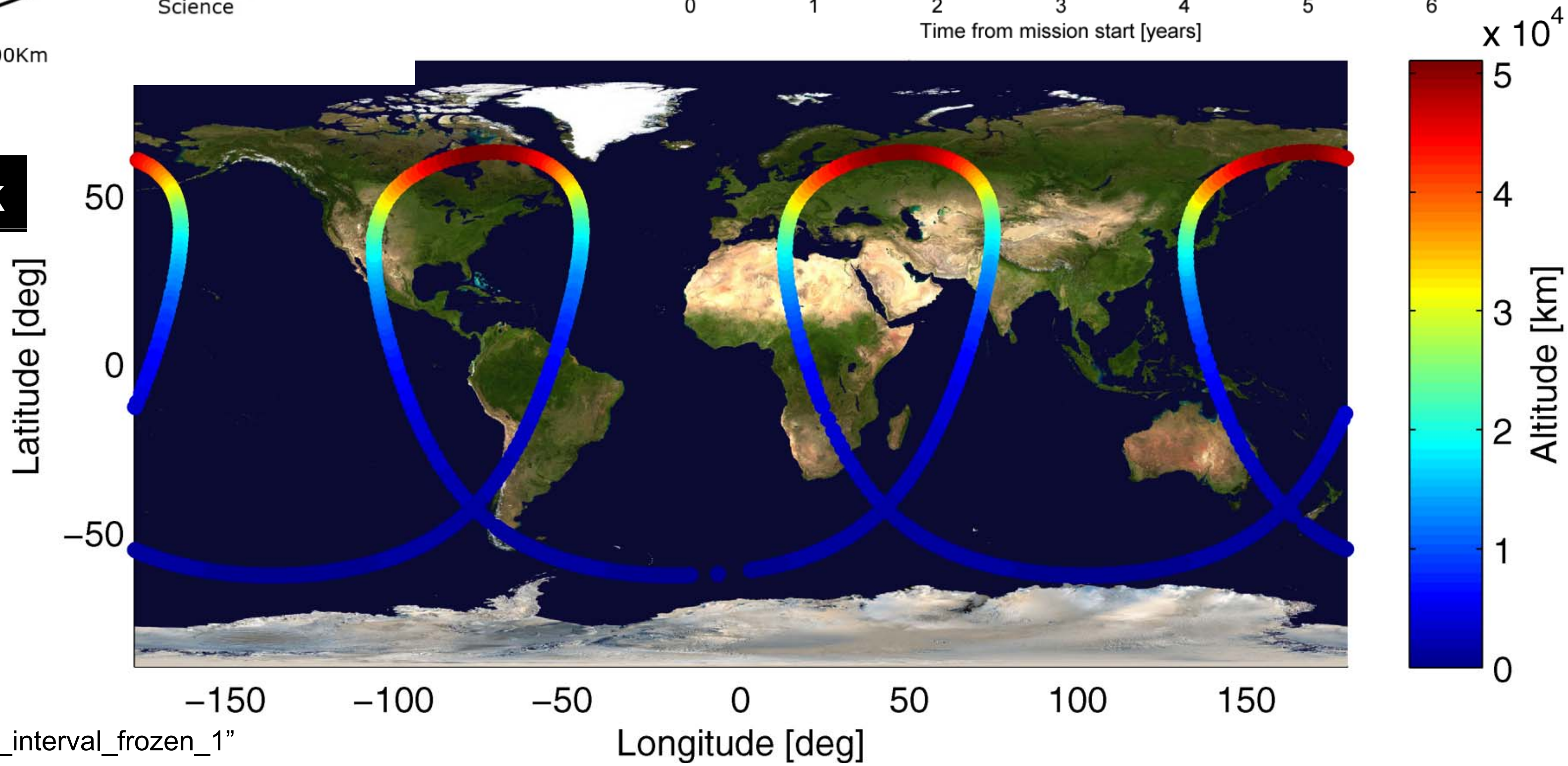
The STE-QUEST orbit

„Frozen orbit“: ground track is constant
- Period: 16 h
- Perigee altitude varies as fct. of time
- Apogee altitude: ≈ 50 000 km





Ground track



“STE_QUEST_elev_data_interval_frozen_1”

Modeling the gravitational frequency shift measurement performance

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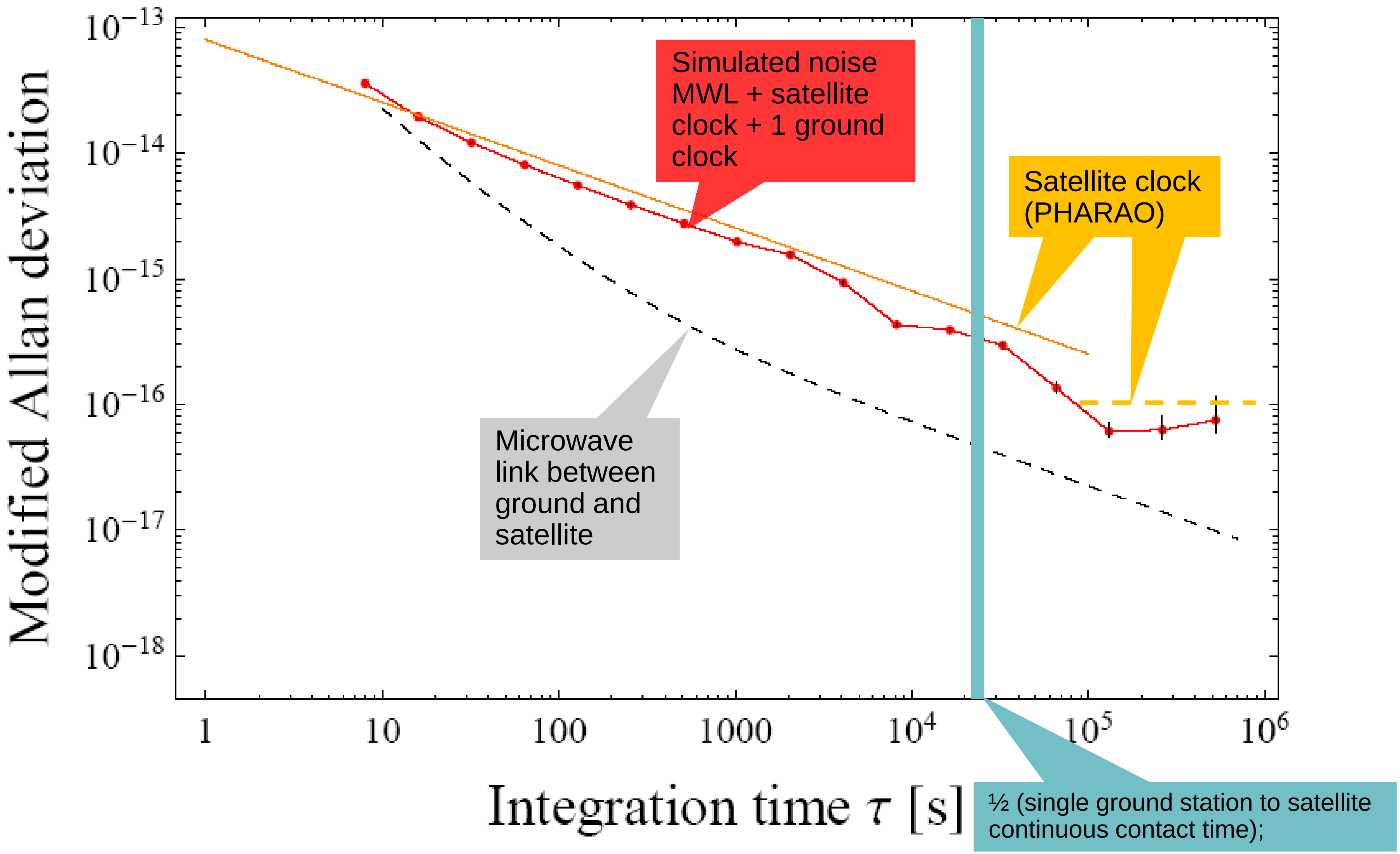
Specifications of clocks and links (acc. to Science Requirement document Issue 1, Rev. 4)



Earth gravitational frequency shift measurement

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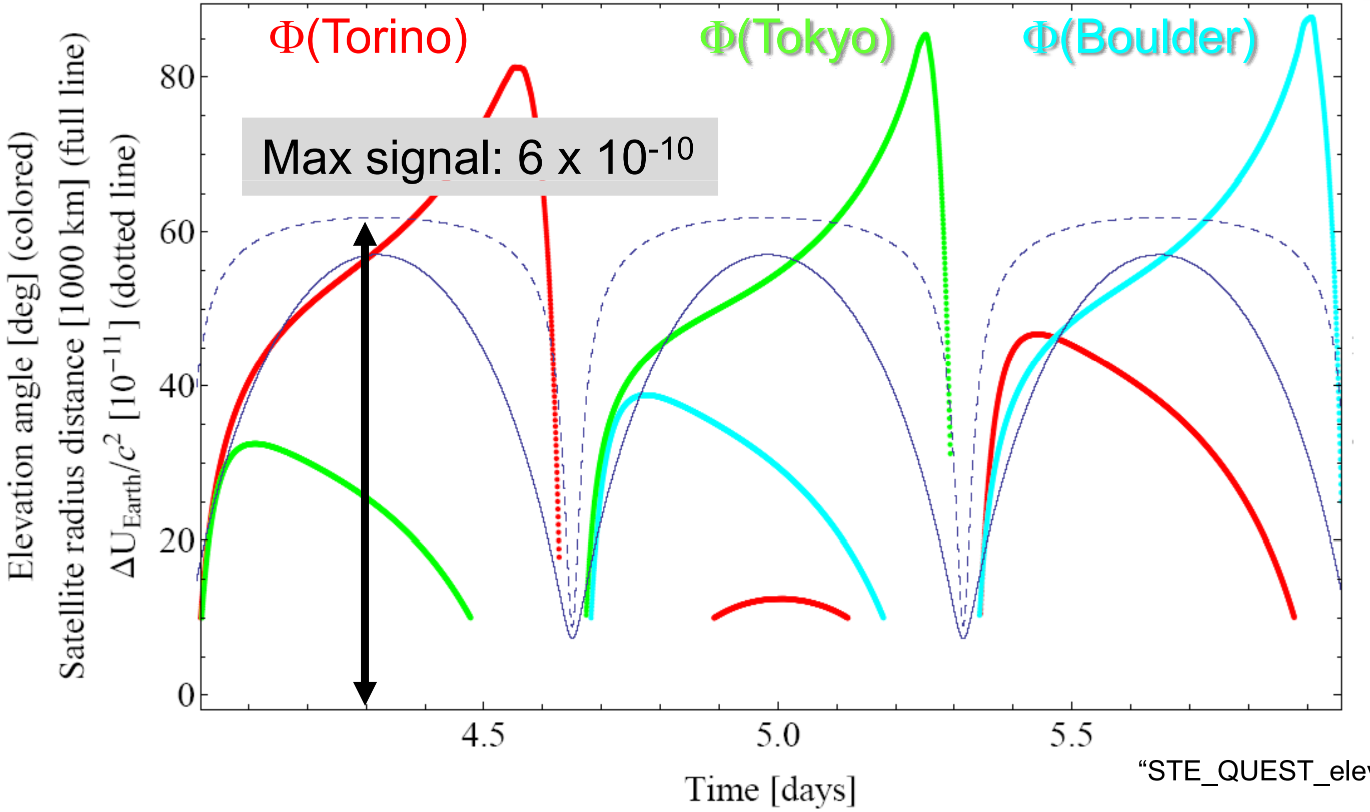

Φ = satellite elevation angle above horizon

3000 – 7000 km altitude intervals are omitted

"STE_QUEST_elev_data_interval_frozen_1"

- Monte Carlo Simulation with synthetic noise (200 noise samples)
- Measurement using 1 ground station over 1⅓ days reaches:
  5 x 10^{-6} (modulation measurement); 4 x 10^{-7} (absolute measurement)
- Need ca. 830 days (6 days) integration (in optimum case) to reach **2 x 10^{-7}** inaccuracy for the modulation (absolute) measurement
- Can only improve the accuracy of the absolute measurement up to the clock accuracy level
- Simultaneous measurements from >1 ground station does not enhance accuracy (since space clock limited) but may compensate down-time

Sun gravitational frequency shift measurement

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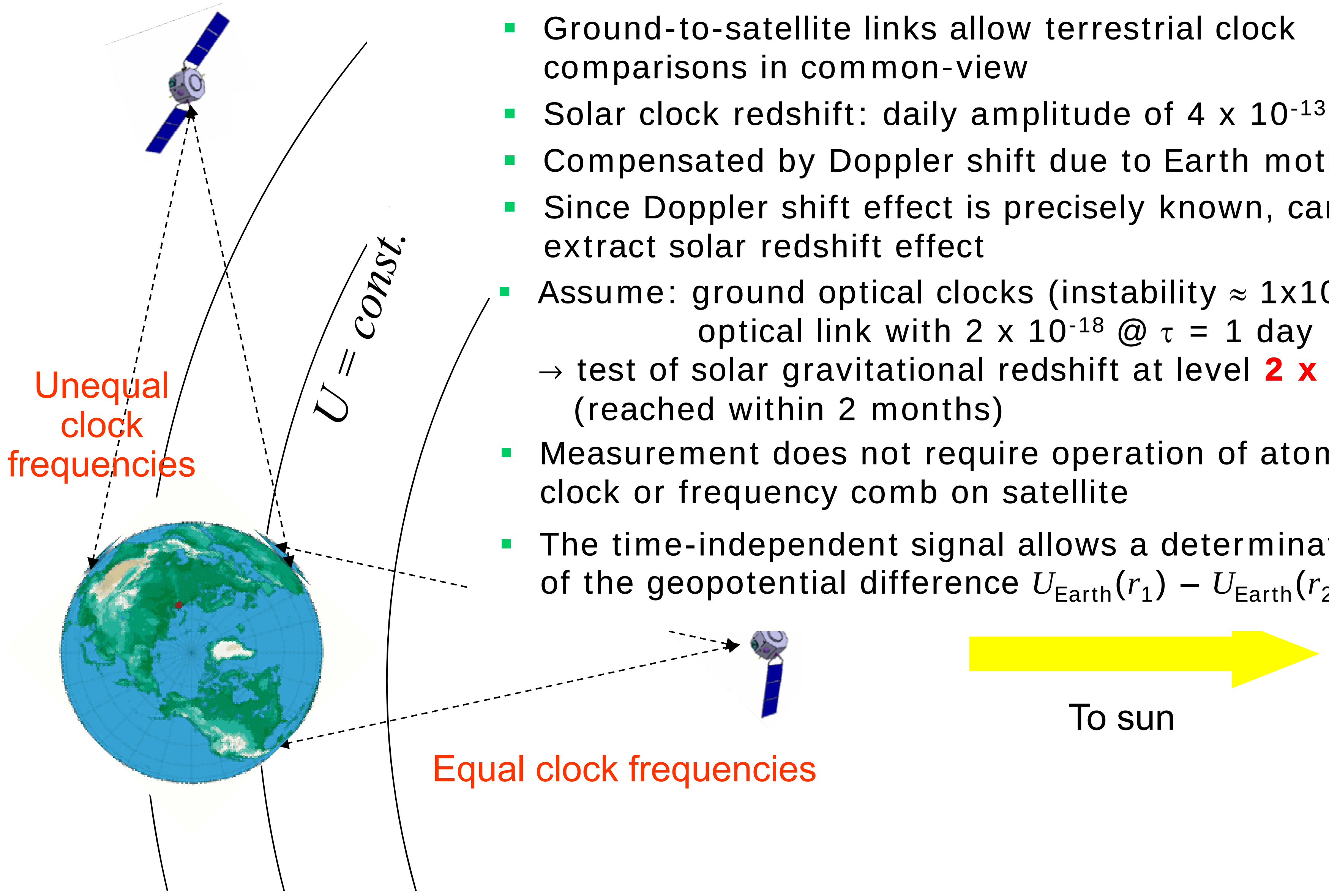
- Precise test of Sun gravitational time dilation

- Ground-to-satellite links allow terrestrial clock comparisons in common-view
- Solar clock redshift: daily amplitude of 4 x 10^{-13}
- Compensated by Doppler shift due to Earth motion
- Since Doppler shift effect is precisely known, can extract solar redshift effect
- Assume: ground optical clocks (instability ≈ 1x10^{-18})
  optical link with 2 x 10^{-18} @ τ = 1 day
  → test of solar gravitational redshift at level **2 x 10^{-6}**, (reached within 2 months)
- Measurement does not require operation of atomic clock or frequency comb on satellite
- The time-independent signal allows a determination of the geopotential difference $U_{\text{Earth}}(r_1) - U_{\text{Earth}}(r_2)$



Weak Equivalence Principle Test

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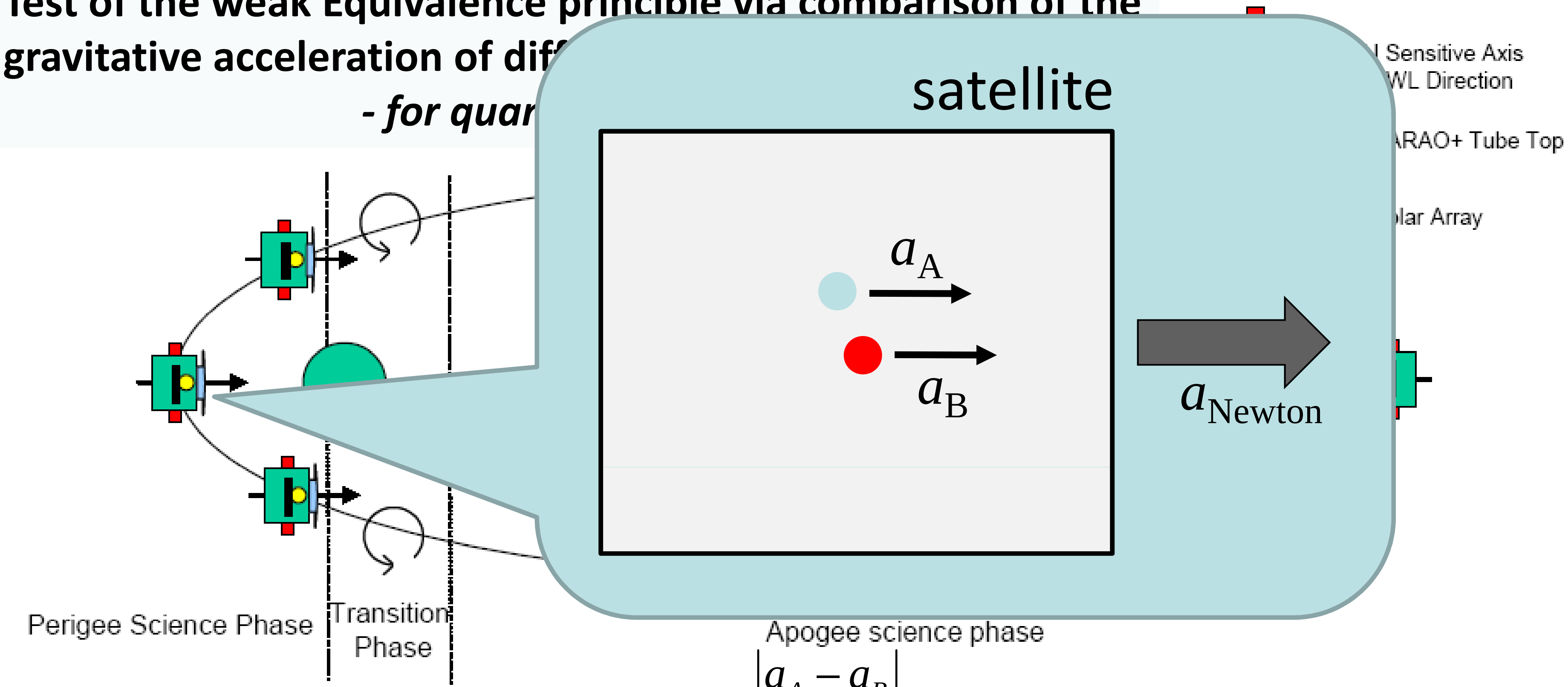
Test of the weak Equivalence principle via comparison of the gravitative acceleration of dif

- for quar

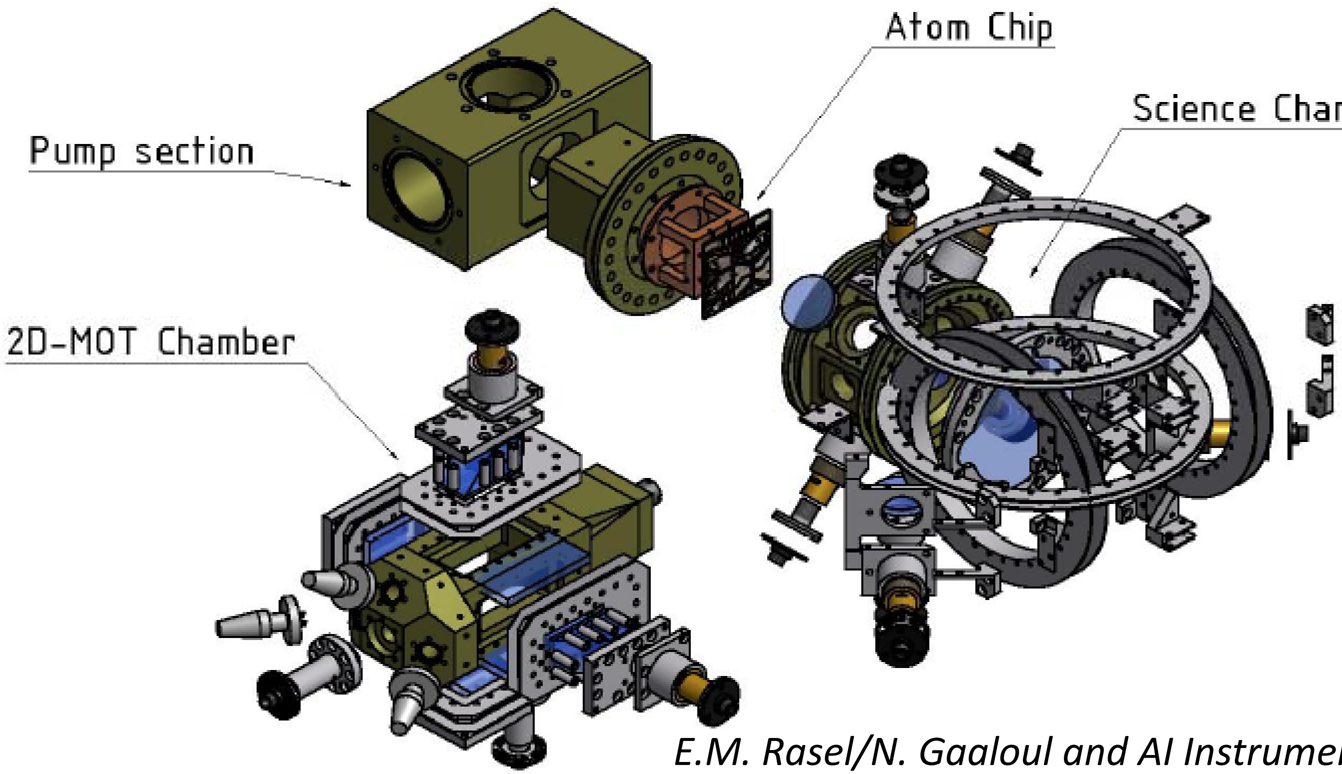


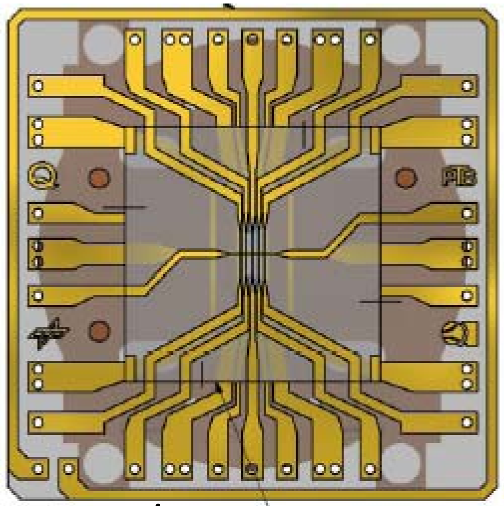
- Determination of the Eötvös ratio $\eta_{AB} = \frac{|a_A - a_B|}{a_{Newton}(r)}$
- Simultaneous observation of two Rubidium isotopes, ^{87}Rb und ^{85}Rb; the differential acceleration is measured
- Measurement is most sensitive near perigee
- Ca. 20 s per single measurement; ca. 100 meas.s near perigee $\rightarrow$ stat. uncertainty $\sigma_\eta \approx 2 \times 10^{-14}$
- Averaging over $\approx$ 1 year $\rightarrow$ reduction to $\sigma_\eta \approx 1 \times 10^{-15}$

On Earth:
$\sigma_\eta \approx 2 \times 10^{-7}$
Fray et al. (2004)

The STE-QUEST dual atom interferometer

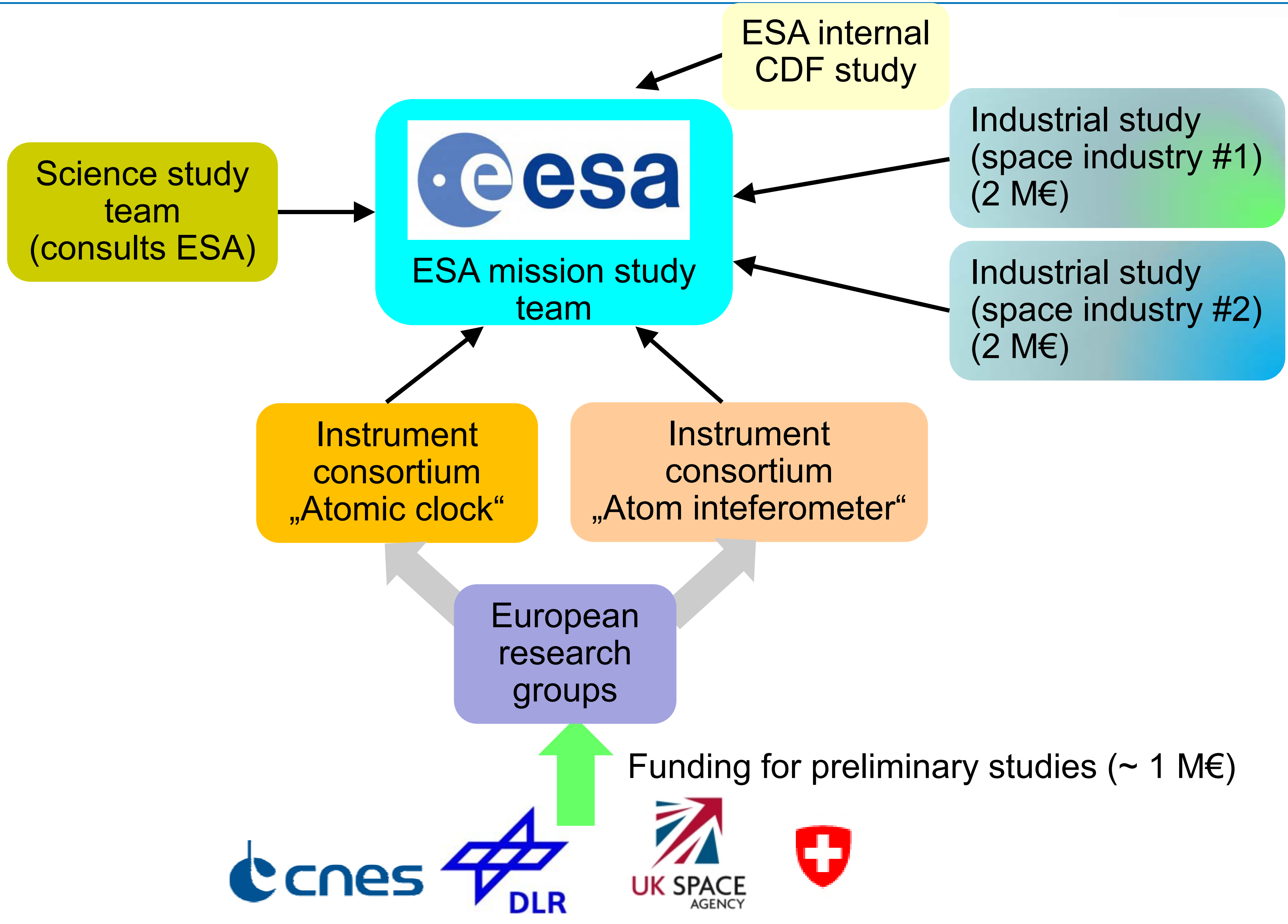
- Ultracold Rubidium atoms
- MOT → optical molasses → magnetic trap → evaporative cooling → optical trap → evaporative cooling → BEC
- Preparation time: 10 s
- 10^6 ^{85}Rb atoms & 10^6 ^{87}Rb atoms in a Bose-Einstein condensate (10 nK)
- Time of free flight: 2 T = 10 s



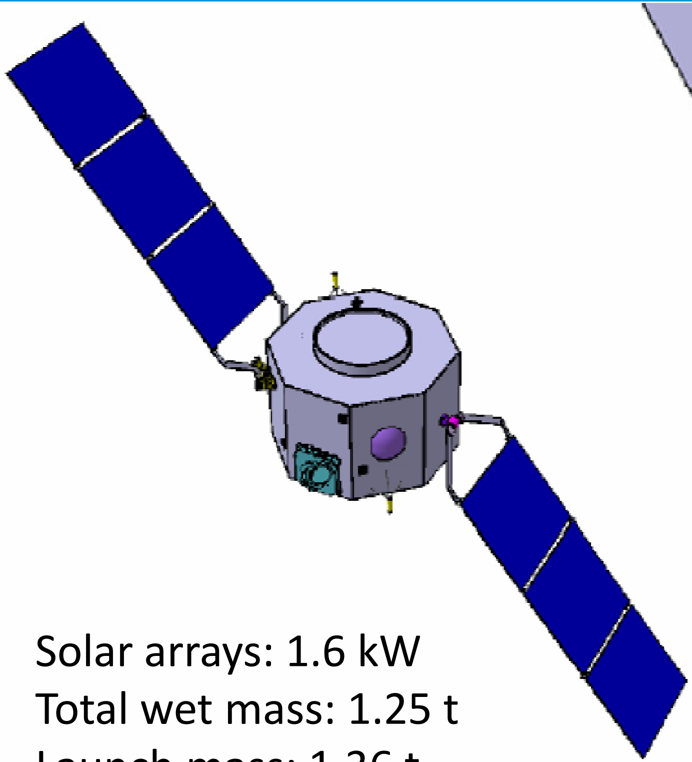


E.M. Rasel/N. Gaaloul and AI Instrument consortium

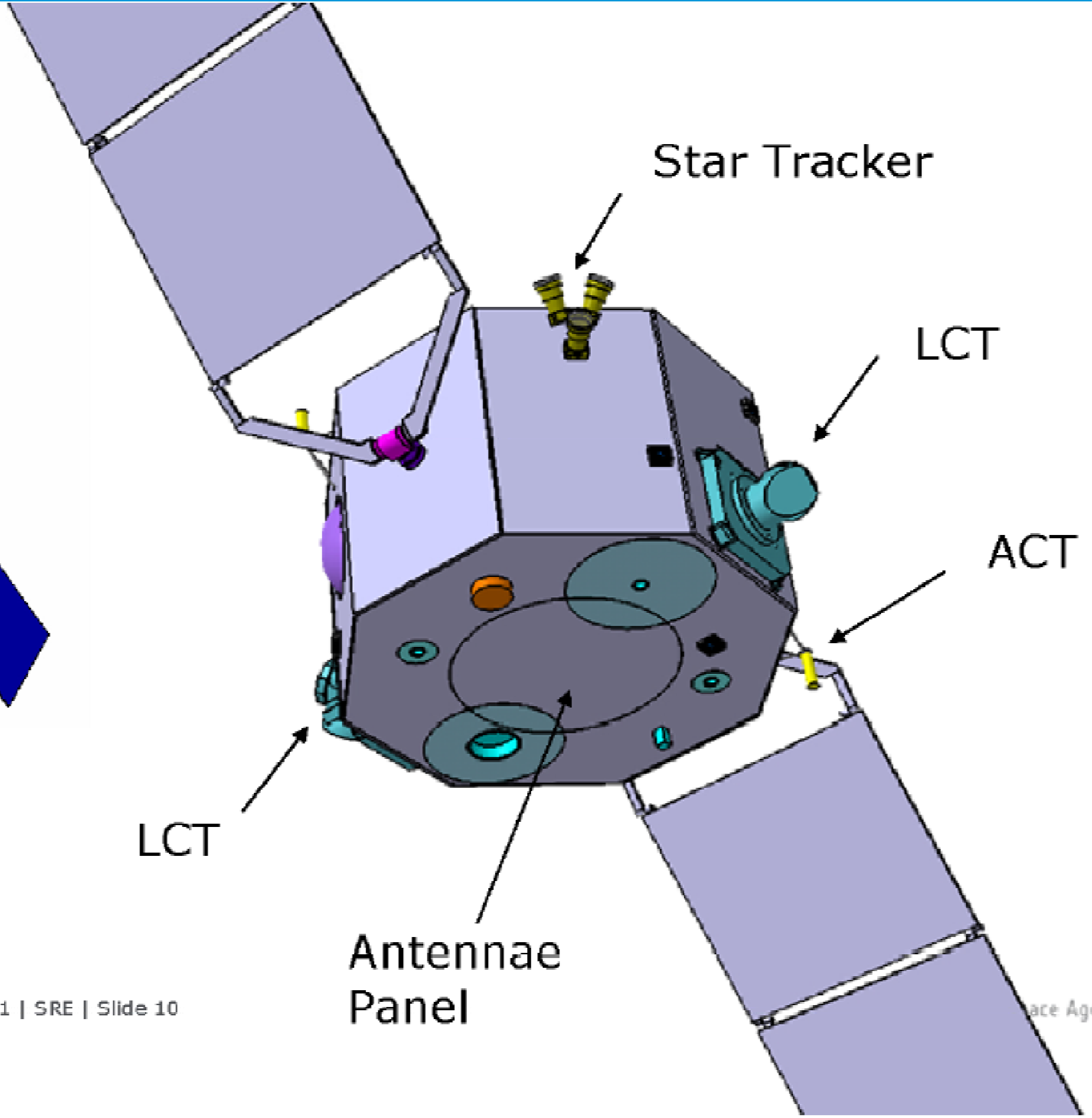
STE-QUEST: organization & activities (2011-13)



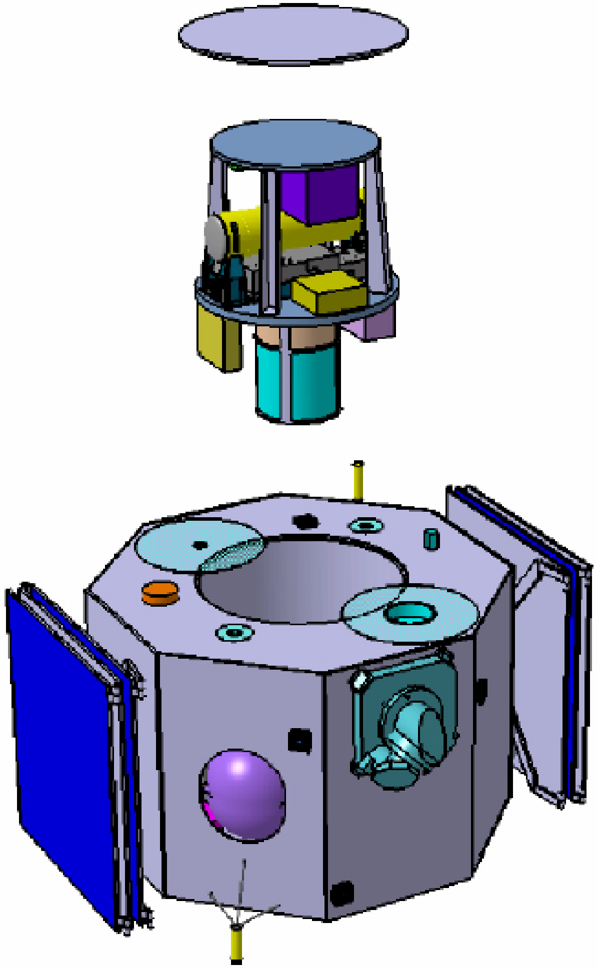
Flight configuration

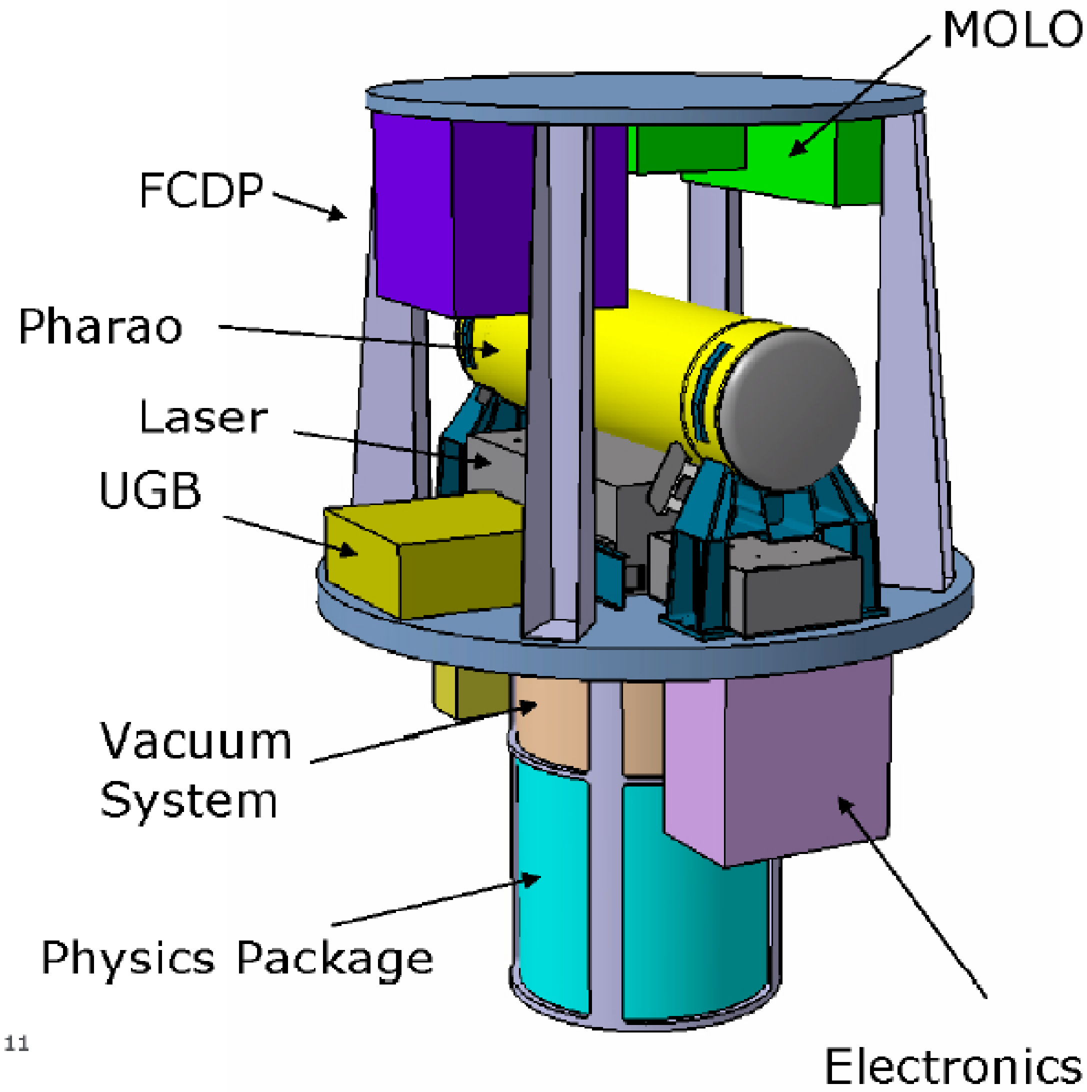


Solar arrays: 1.6 kW
Total wet mass: 1.25 t
Launch mass: 1.36 t
Instruments: 373 kg



Payload Accommodation

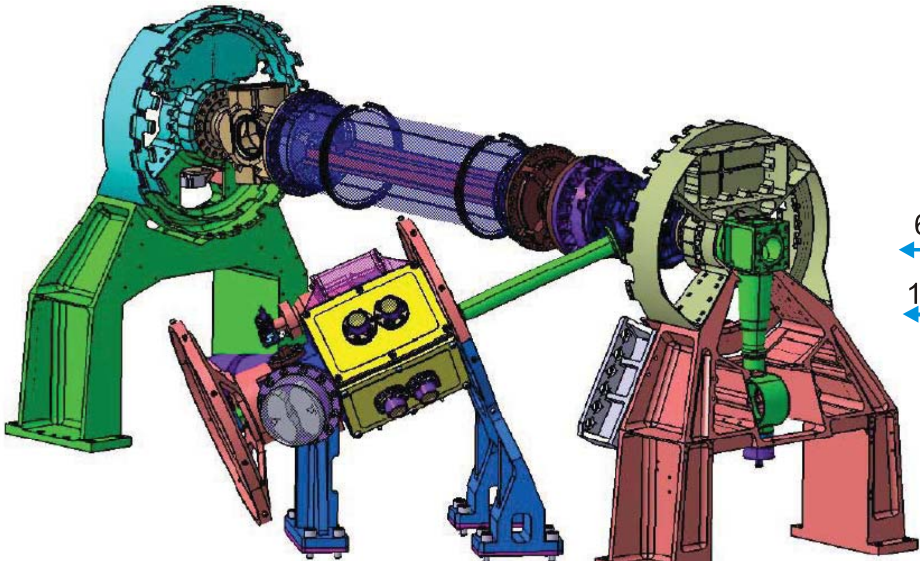




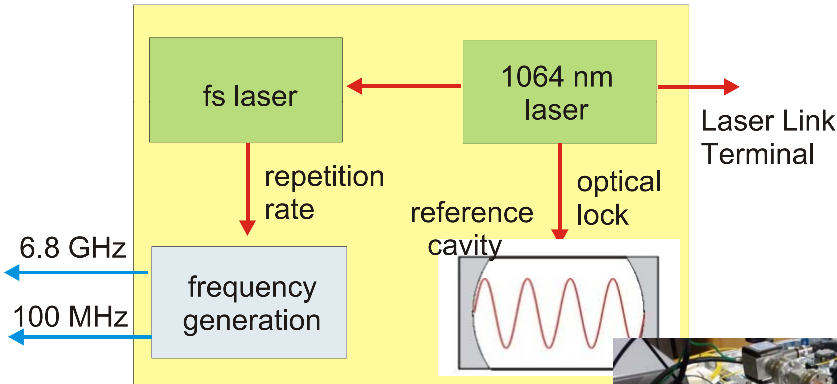
Study of a dedicated STE-QUEST atomic clock

P. Tuckey / Clock Instrument Consortium

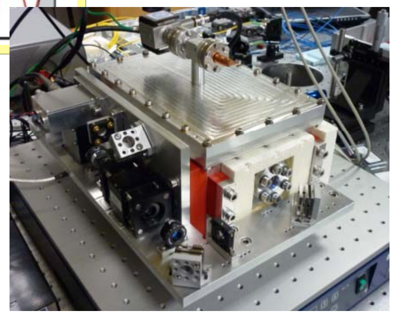
- Evolution of PHARAO (ACES Mission)
- Atom: Rubidium (weaker atom-atom interaction)
- Higher atomic number: 4×10^{8}
- Needs a slow atomic beam (v < 25 m/s) as source → 2D-MOT
- Lower instability: $3 \times 10^{-14}/\tau^{1/2}$, similar to terrestrial fountains, limited by atom number
- Uncertainty < 1×10^{-16}
- Microwave-optical local oscillator (Laser + resonator + frequency comb)



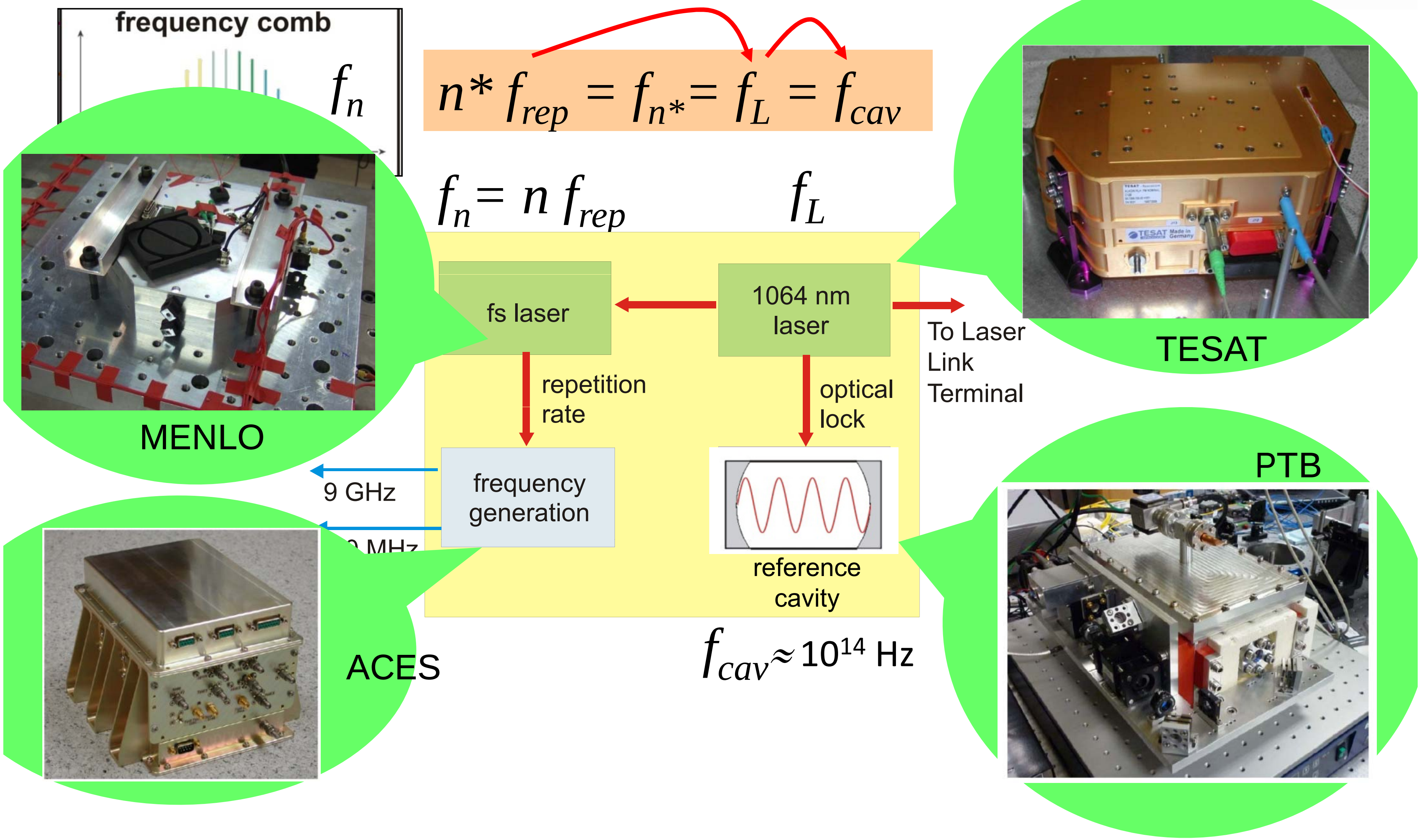
CNES/SODERN



PTB



The microwave-optical local oscillator (MOLO)

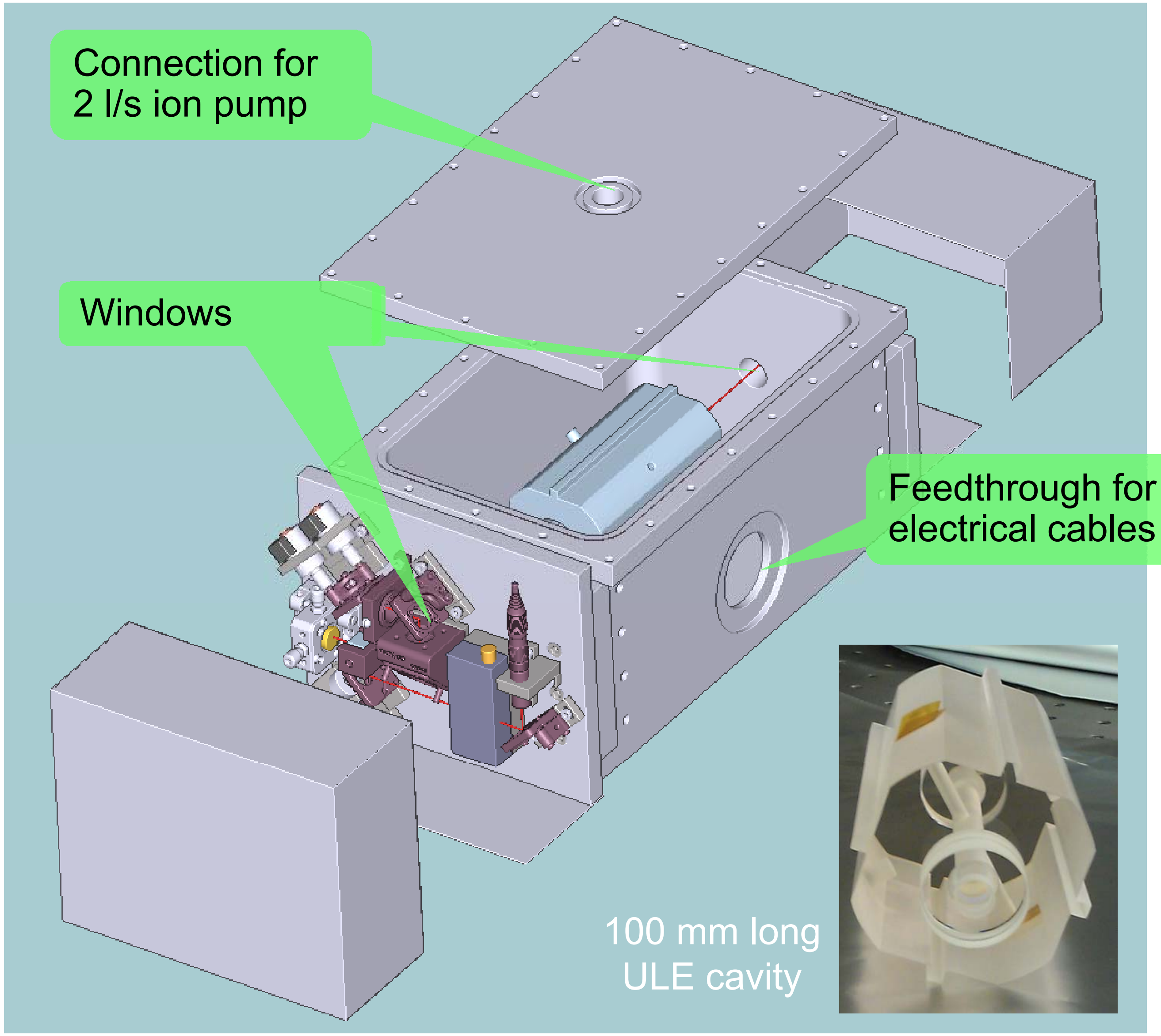


- Will provide a 9 GHz signal with excellent frequency stability (σ = 3.5 x 10^{-15} for τ = 1 – 100 s, after drift removal)

Overall design

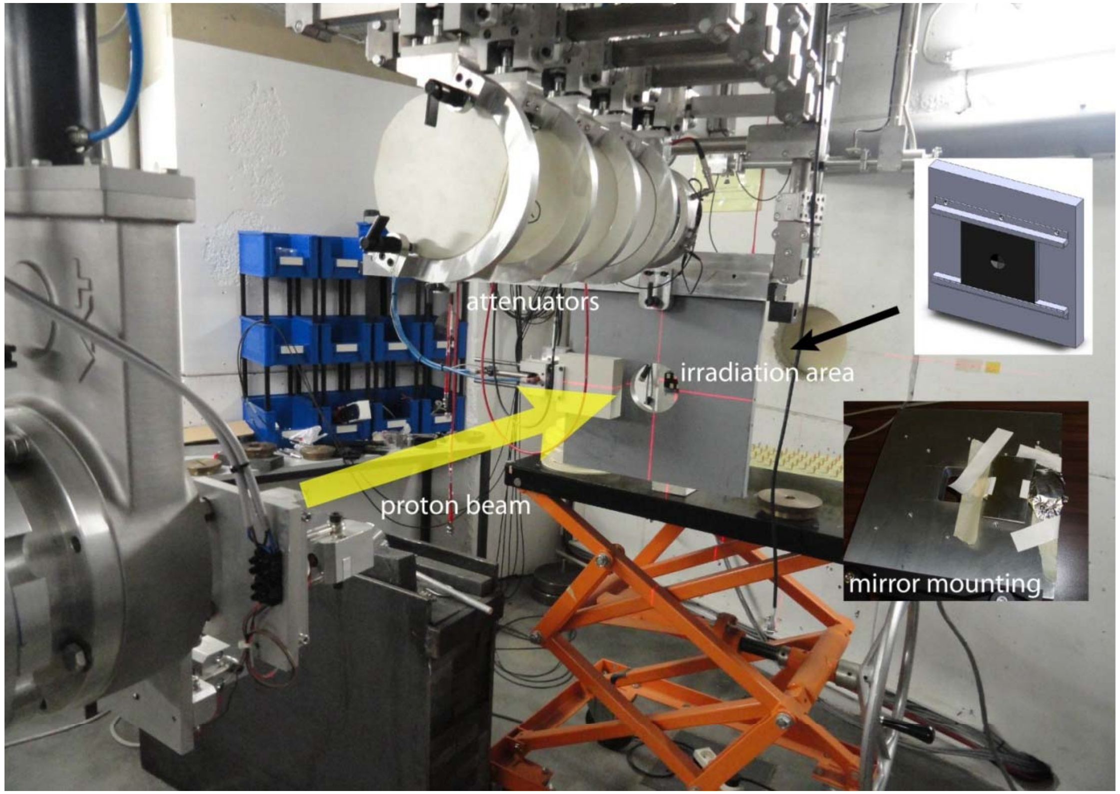
- Evolution of lab designs
- Compact, robust optical subsystem
- Electrically actuated mirrors can compensate for externally induced deformations

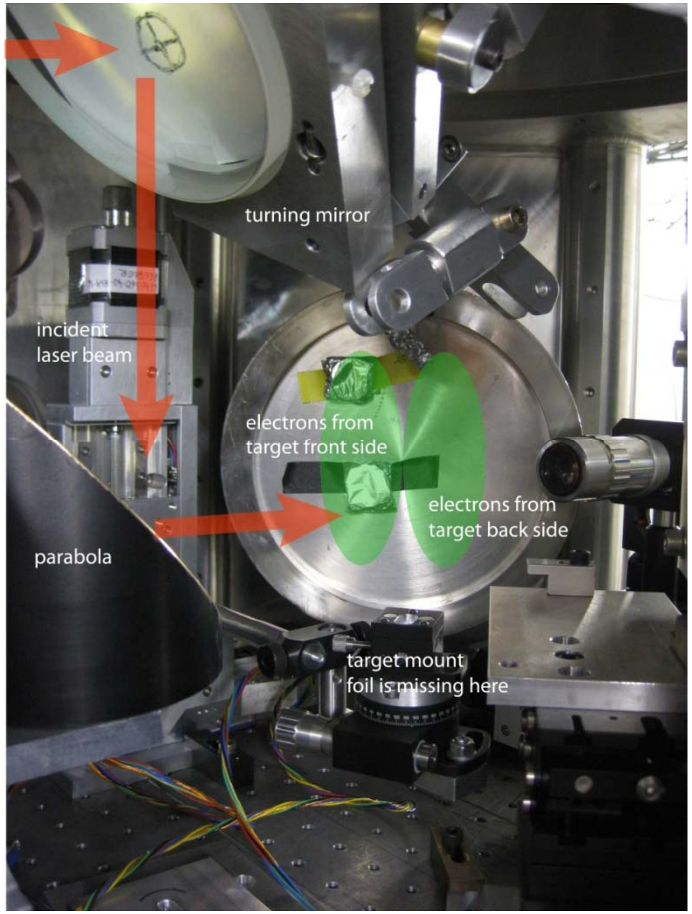
Drawing does not show the cavity mounting frame and thermal shield



Electron and proton irradiation facilities

- Proton irradiation at UCL, Louvain-la-Neuve (Belgium)
- Electron irradiation by pulsed laser generated electrons (ILPP, Düsseldorf; (*O. Karger, T. Königstein, G. Pretzler, B. Hidding*)





Irradiation vacuum chamber

Preliminary results on irradiation test of 1064 nm high-finesse cavity mirrors

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- Irradiation performed by B. Hidding, G. Pretzler and coworkers (Düsseldorf)
- Mirrors protected by thin Al foil to avoid contamination

Irradiation with protons (Light ion irradiation facility at UCL Louvain-la-Neuve, Belgium)

Energy: mirror 1: 14.4 MeV* and mirror 2: 9 MeV* (obtained using an additional 560 µm Al degrader)

Fluence: 2.83×10^{10} /cm^2 each (corresponds to mission fluence for E > 0.7 MeV if 12 mm shield is used)

Influence on cavity linewidth at **10 kHz level or below**

Irradiation with electrons (Laser accelerator @ Düsseldorf)

Energy: roughly thermal distribution, with electron "temperature" $\approx$ 1.5 MeV

Fluence: 2×10^8/cm^2 total over 3 days (realistic level for mission with 12 mm shield)

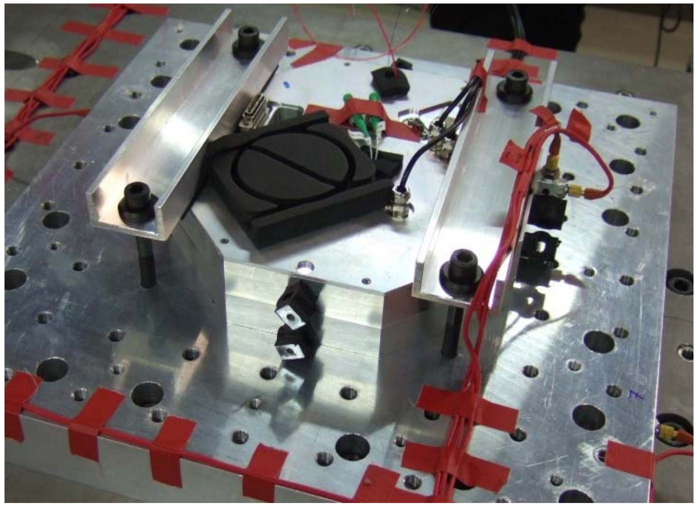
Influence on cavity linewidth at **10 kHz level**

** Beams were not monoenergetic; value is Bragg peak*

Menlo Systems Space Comb

- Demonstration flight on Texus 51 in 4/2013
- Flight model to be delivered for integration in 11/2012

Specifications:
- repetition rate: 100 MHz
- wavelength: 1560 nm
- spectral width: 30 nm
- incl. frequency doubling to 780 nm
- f_{CEO} generation
- 30 cm diameter x 30 cm height incl. electronics
- mass approx. 20 kg incl. electronics
- power requirement < 100 W
- pressurized operation



qualifying vibration test for a TEXUS-mission: vibrations of 8 g RMS for 120 s

Summary

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- <u>Science goals</u>:
  Establish more firmly the metric nature of the theory of gravitation, search for Physics beyond the Standard Model & General Relativity
  - Test the Weak Equivalence Principle with matter waves, goal accuracy : **1.5 x 10^{-15}** (x 10^8 improvement)
  - Test time dilation in the terrestrial and in the solar gravitational potential goal accuracy **2 x 10^{-7}** and **2 x 10^{-6}**, resp. (x 15, x 10^4 improvement)

- <u>Application to other fields</u>:
  - „master clock" in space for precision experiments world-wide, dissemination of time
  - mapping of the gravitational potential of the Earth with high spatial resolution

- <u>Technology:</u>
  - Clock instrument: significant use of existing technology
  - Atom interferometer: novel technology, lower readiness level (drop tower experiments)

- <u>Status</u>:
  - By end 2012, the instrument consortia must present to ESA the preliminary instrument design, provide cost information and convince as many national space agencies as possible to promise funds for eventually building the instruments
  - Mid-2013: downselection by ESA review boards of the 4 candidate M3 missions to a single one

- <u>Message</u>:
  - A set of Thorium clocks (5x10^{-19} unc.) on the ground by 2022 is highly desirable!
  - Support STE-QUEST in person and via your national agencies