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The STE-QUEST Mission: A Test of the Einstein Equivalence Principle and of Time Dilation

S. Schiller

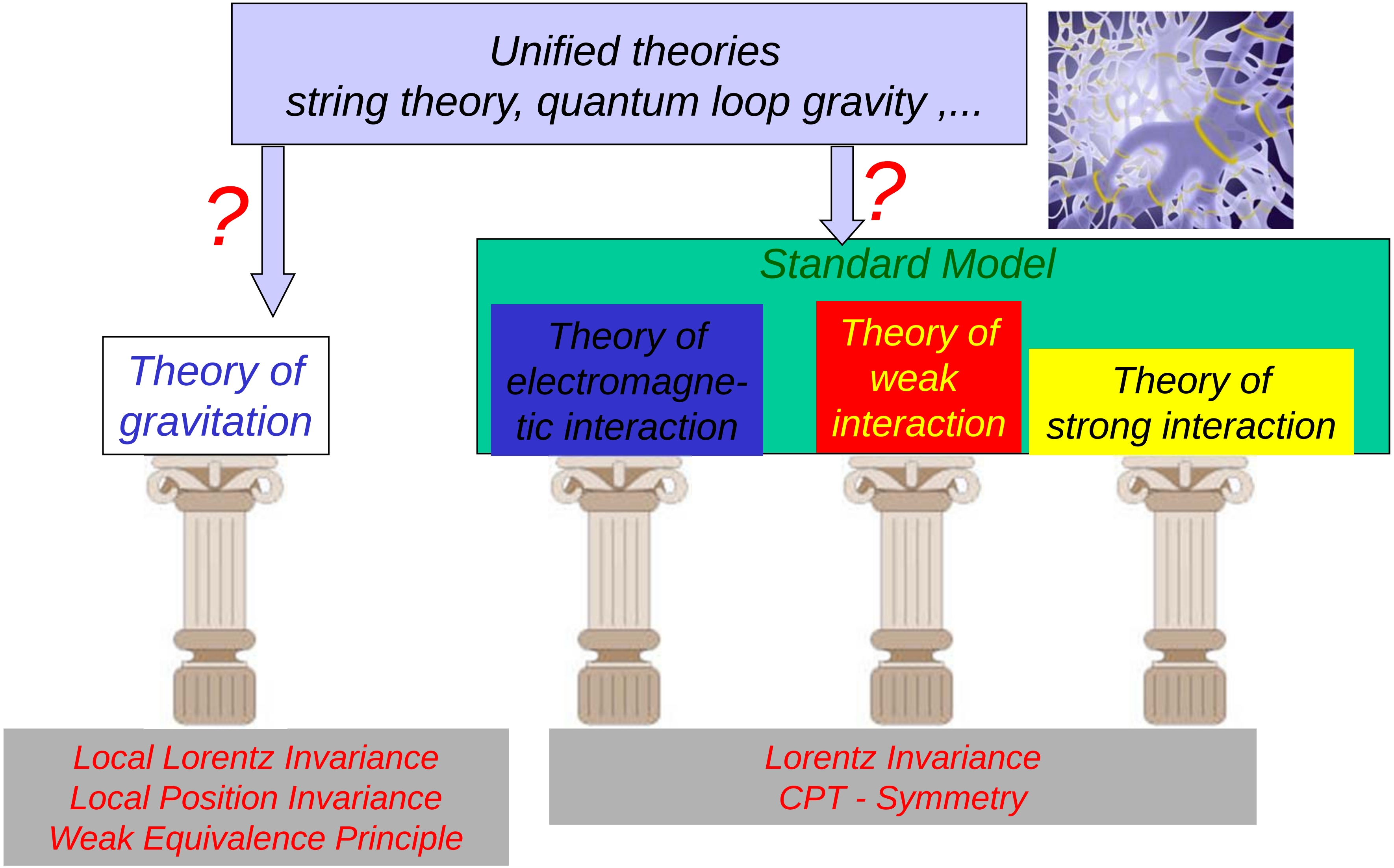
Heinrich-Heine-Universität Düsseldorf

Science Study Team:

K. Bongs (UK), P. Bouyer (F), L. Iess (I), P. Jetzer (CH), A. Landragin (F), E.M. Rasel (D), S. Schiller (D), U. Sterr (D), G.M. Tino (I), P. Tuckey (F), P. Wolf (F)

L. Cacciapuoti (ESTEC Noordwijk), F. Renk (ESOC Darmstadt), M. Gehler (ESTEC Noordwijk)

Motivation



exactly valid?

Scope of the mission

STE-QUEST tests ***fundamental notions of space-time physics:***

- How does the presence of matter modify proper time?

- How does gravity act on matter?

It performs these tests on ***quantum matter***:

- Atomic clocks, in which time is deduced from the energy difference between spin states

- Atoms as matter waves

… and in a model-independent way

The conceptual basis for tests of General Relativity

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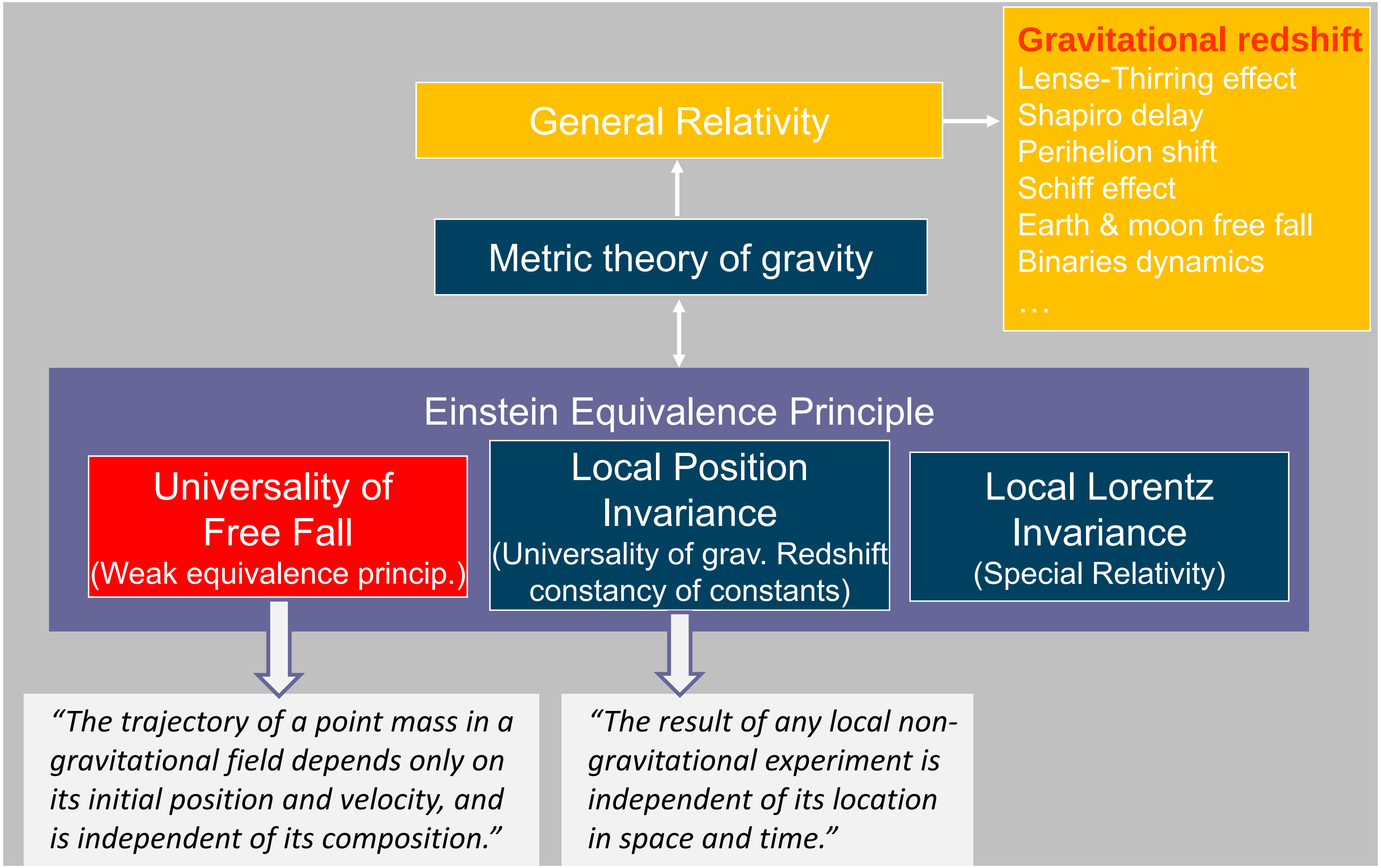
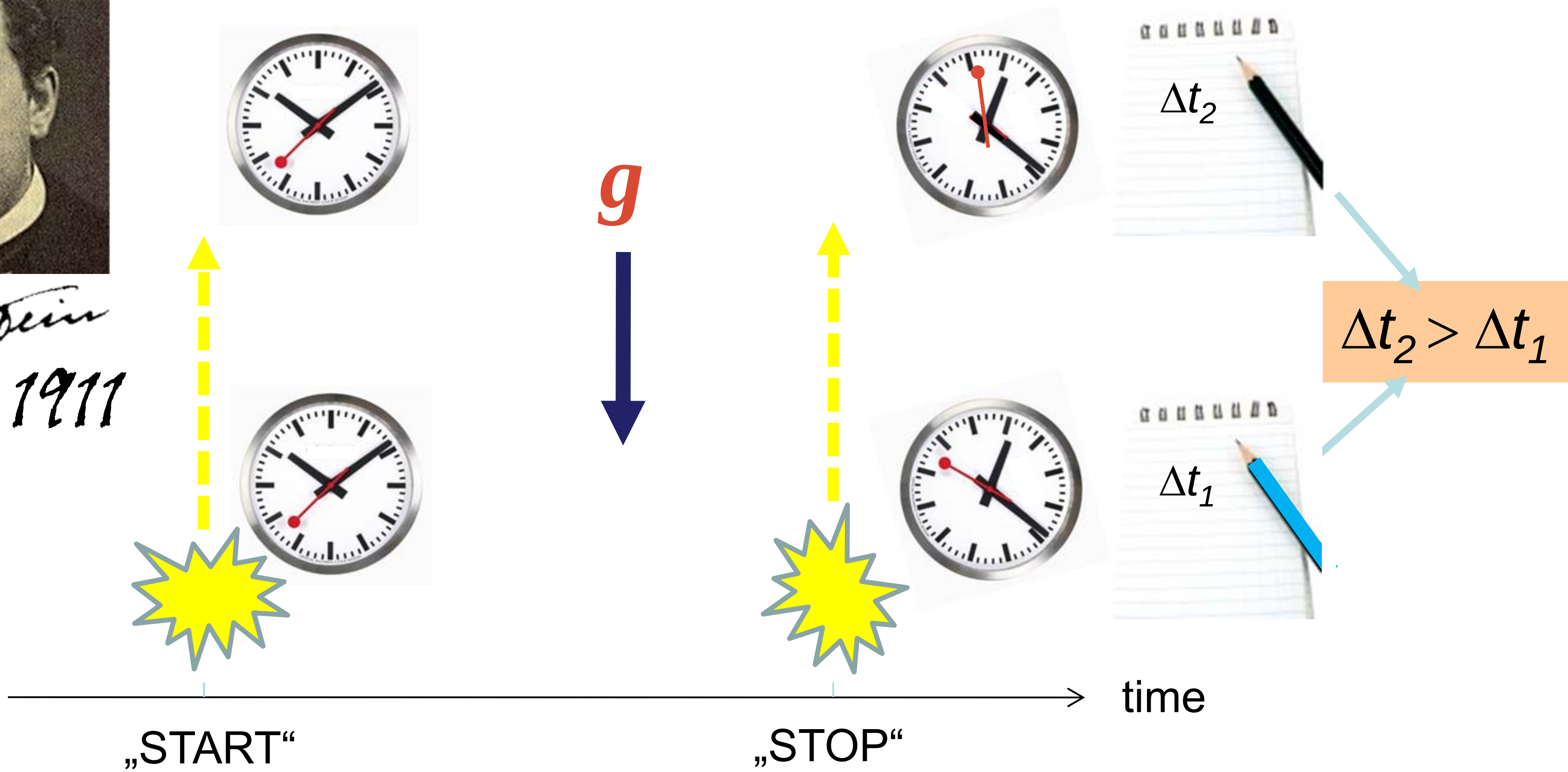


The gravitational time dilation: gravity modifies time



Time dilation measurement
Hafele, Keating (1972): **10% test**
Alley et al. (1976): **1% test**

Frequency shift measurement
Pound and Rebka (1960): **10% test**
Pound and Snider (1965): **1% test**

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

C.O. Alley (1981)

The gravitational frequency shift

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

$$U(r) = -\frac{GM}{r} \quad ?$$

Search for existence of additional scalar fields ϕ emanating from constituents of Earth, Sun, or Moon

- Model $\phi_i(r) \sim S_i/r$

  where S_i may depend on the particle species contained in the massive body, and may depend on the clock type

- Comparison of identical clocks at different locations r_1, r_2 will show an additional frequency shift contribution, which depends on the source type

- STE-QUEST will set limits to S_{EARTH}, S_{SUN}, S_{MOON}

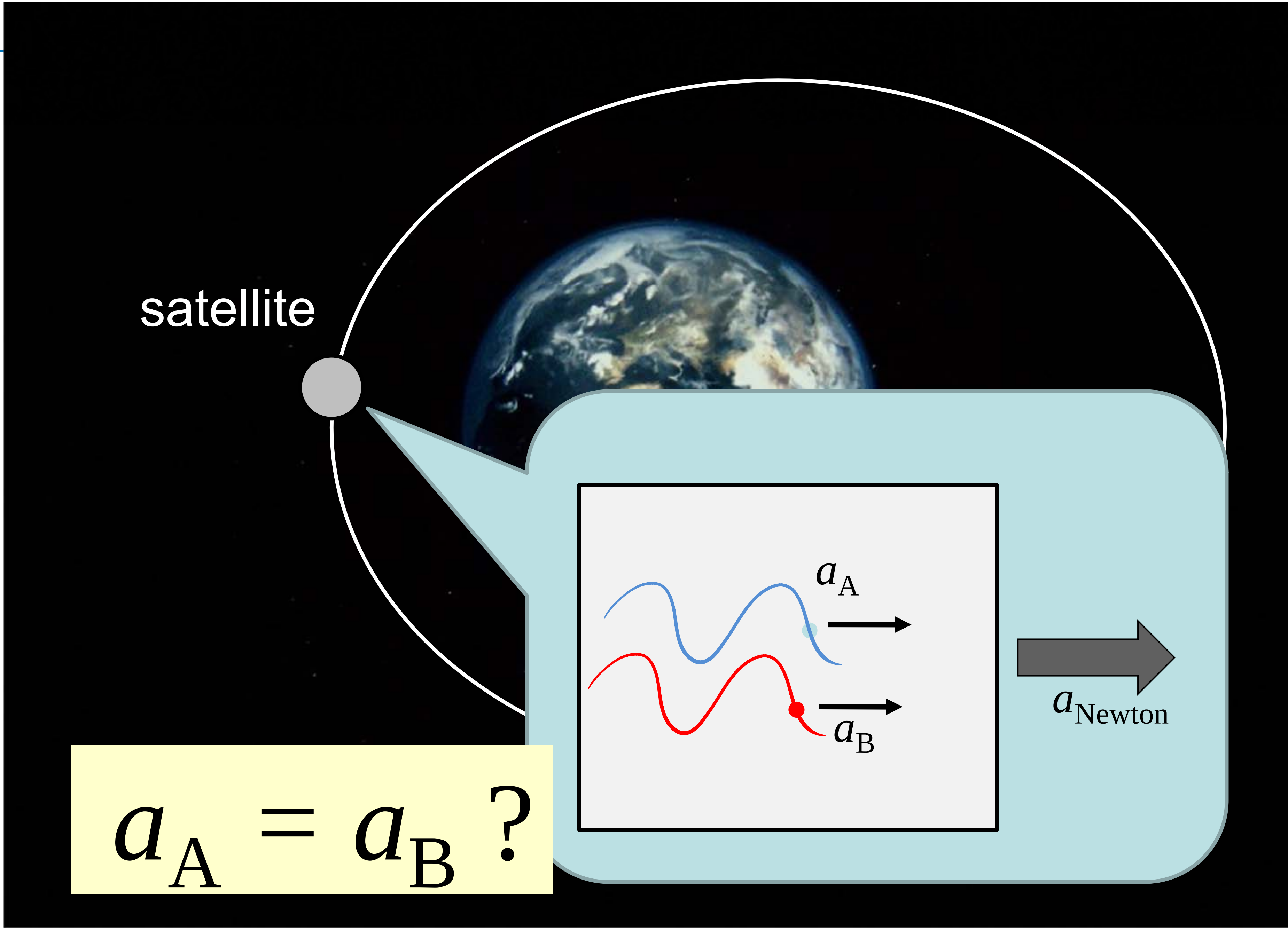
Mass of Sun: protons
Mass of Earth: protons & neutrons

Weak equivalence principle

- **Gravitation** acts on all matter **in the same way**
- Locally, gravitation and acceleration cannot be distinguished

L. Catani, "Galileo performs the experiment of the motion of weights from the Tower of Pisa in the presence of the Grand Duke", Gallery of Modern Art of the Pitti Palace, Florence

Test of universality of gravitational attraction



Experiments context

Numerous experiments:

Universality (clock-type independence) of the gravitational time dilation

Torsion balance experiments

Weak equivalence principle gound-based tests with cold atoms in fountains

Gravitational time dilation in the Sun potential (spectral lines, quartz osc. on s/c)

Laboratory and astronomical searches for space-time-variation of fundamental constants

Laboratory experiments verifyning the time dilation of Special Relativity

Previous and planned tests

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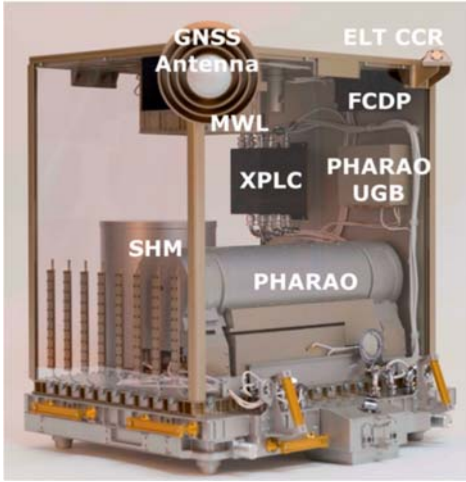
„Gravity Probe A" (1976):
Hydrogen maser as atomic clock

- Rocket flight to 10 000 km altitude
- verified gravitational time dilation with 7×10^{-5} uncertainty (Vessot et al, 1980)

Levine and Vessot

„ACES" (ca. 2016):
Cold Cs microwave clock

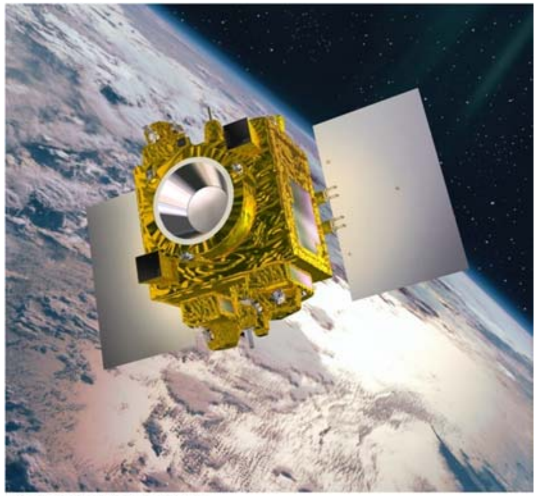
- ISS at 400 km altitude
- goal: verify gravitational time dilation with 2×10^{-6} uncertainty



„MICROSCOPE" (ca. 2016):
Differential accelerometer

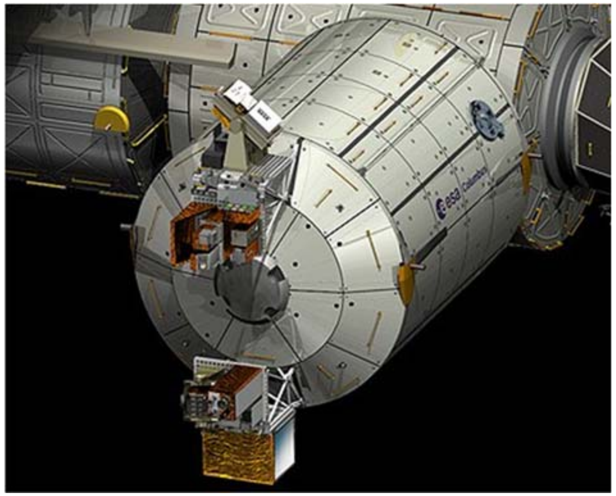
- drag-free spacecraft
- goal: verify equivalence principle with classical test masses at 10^{-15} uncertainty level (x 100 improv.)

MICROSCOPE

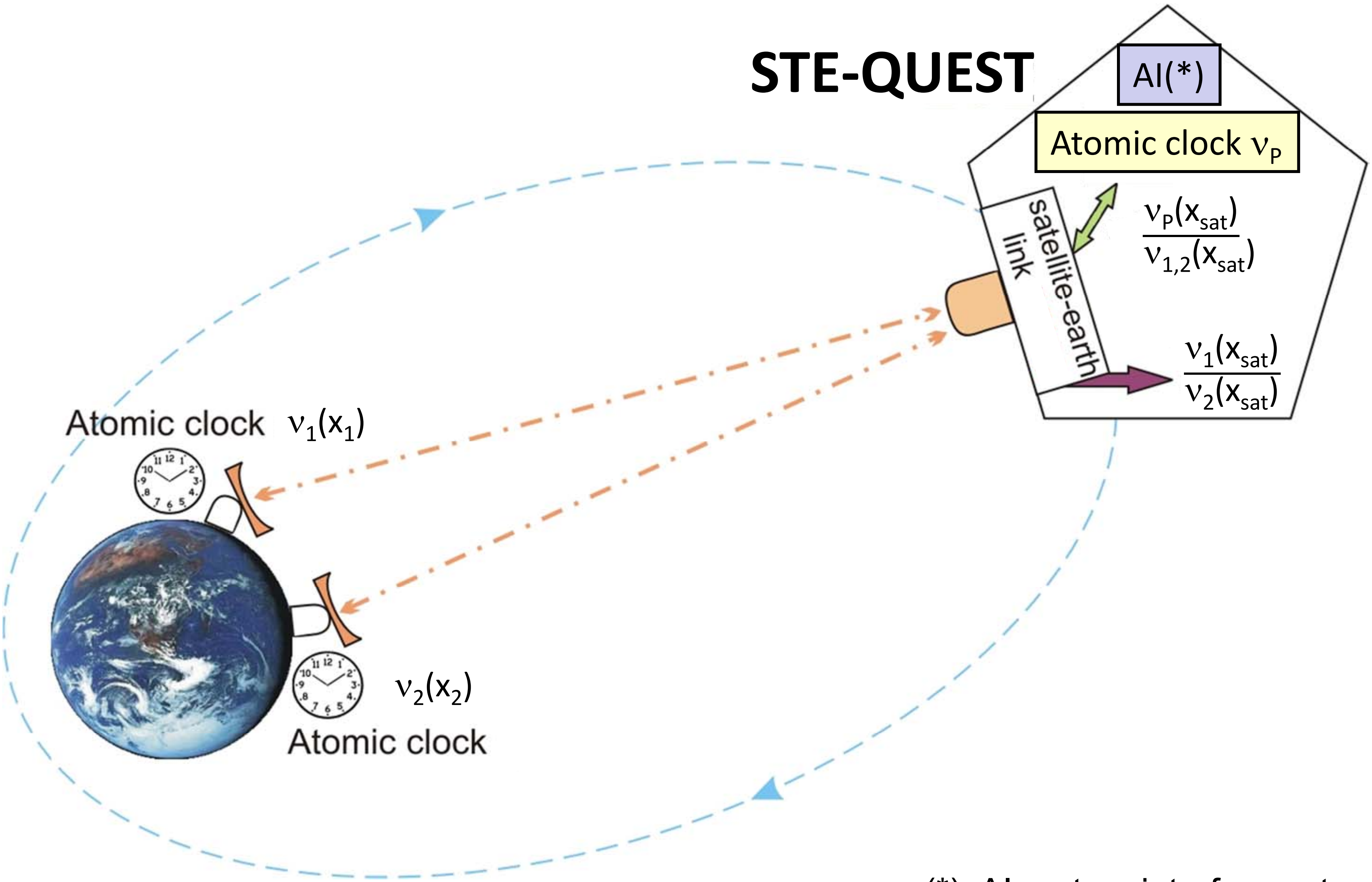


© CNES - Mars 2006/Illust. D. Ducros

Columbus module with ACES



Concept of the STE-QUEST mission



(*): AI = atom interferometer

Mission key points

- **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 2 x 10^{-15}*
  - *Measure time dilation in the terrestrial, in the solar, and in the moon gravitational potentials, at levels 2 x 10^{-7}, 2 x 10^{-6}, and 4 x 10^{-4} , resp.*

- **Secondary goals & application to other fields:**
  - *master clock in space, distributing time/frequency world-wide*
  - *Intercomparison of ground clocks*
  - *mapping of the gravitational potential of the Earth with ultra-high spatial resolution*

- STE-QUEST is based on the earlier proposals EGE and MWXG [1,2] and ESA's CDF study "STE" (2010)
- 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)*

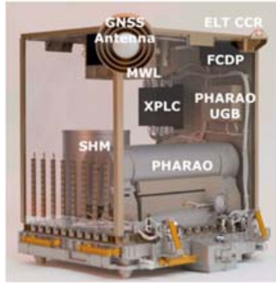
Main issues

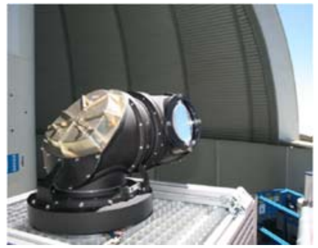
- **Technology readiness**
  - Microwave clock instead of optical clock
  - Optical link and microwave link
  - Optically derived, ultra-stable microwave local oscillator
  - Ultracold matter in drop tower experiments

- **Complexity and cost**
  - Atom inteferometer with two isotopes of the same species
  - Optical link (incl. ground Tx/Rx stations) is a cost driver
  - Mission duration is a less important cost driver

- **A compromise**
  Highly elliptical orbit

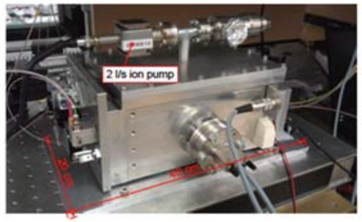
ACES



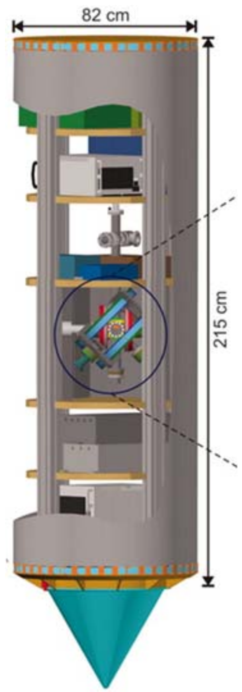


TESAT

MENLO SYS. *et al.*



HHUD, PTB



van Zoest et al (2010)
Müntinga et al (2013)

Testing Earth's gravitational time dilation - I

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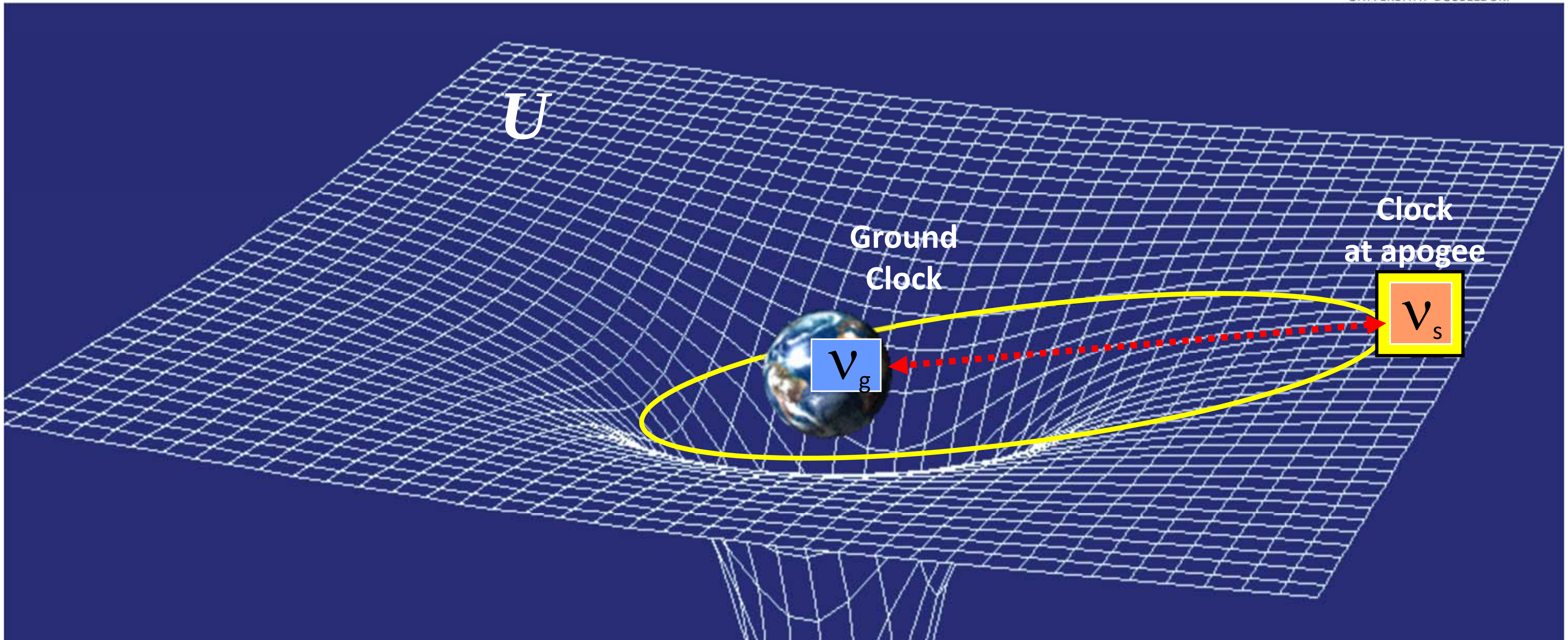

<u>Frequency comparison between ground clock and satellite clock **at apogee**</u>

- in highly elliptic orbit, $\Delta U(\text{perigee - ground})/c^2 \approx 6 \times 10^{-10}$
- assume a space clock **inaccuracy** $\cong 1 \times 10^{-16}$ (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 - II

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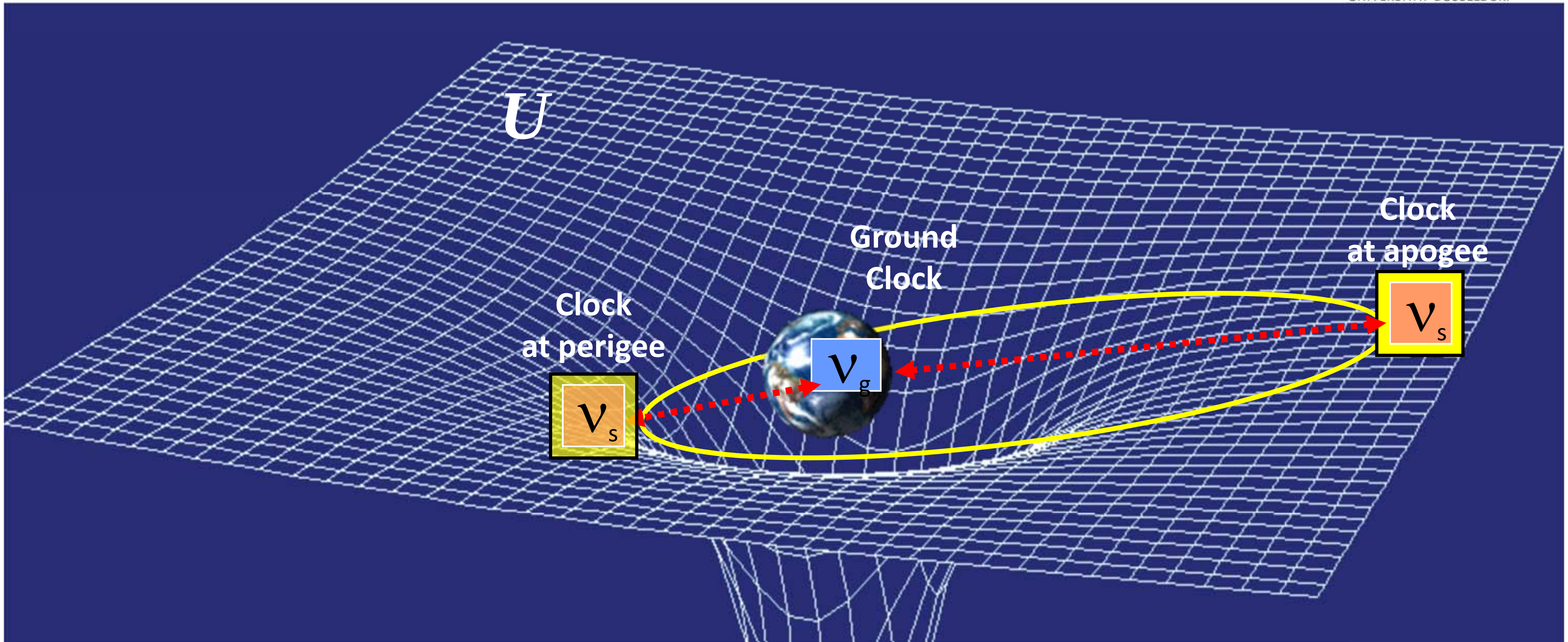
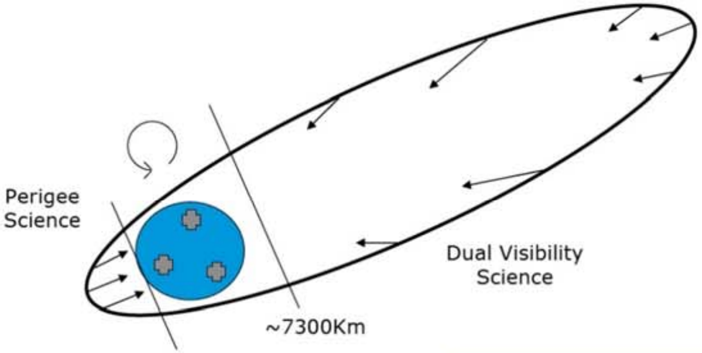


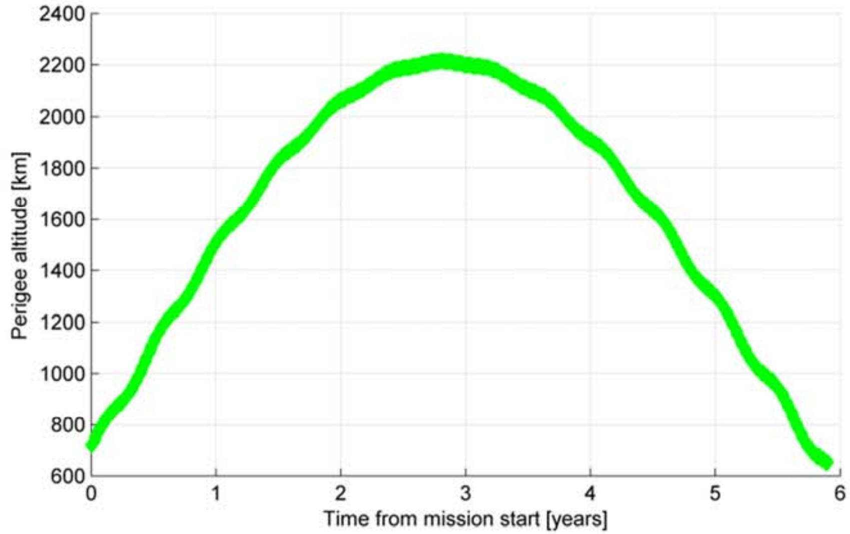
<u>Comparison between ground clock and satellite clock **at perigee and apogee**</u>

- 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

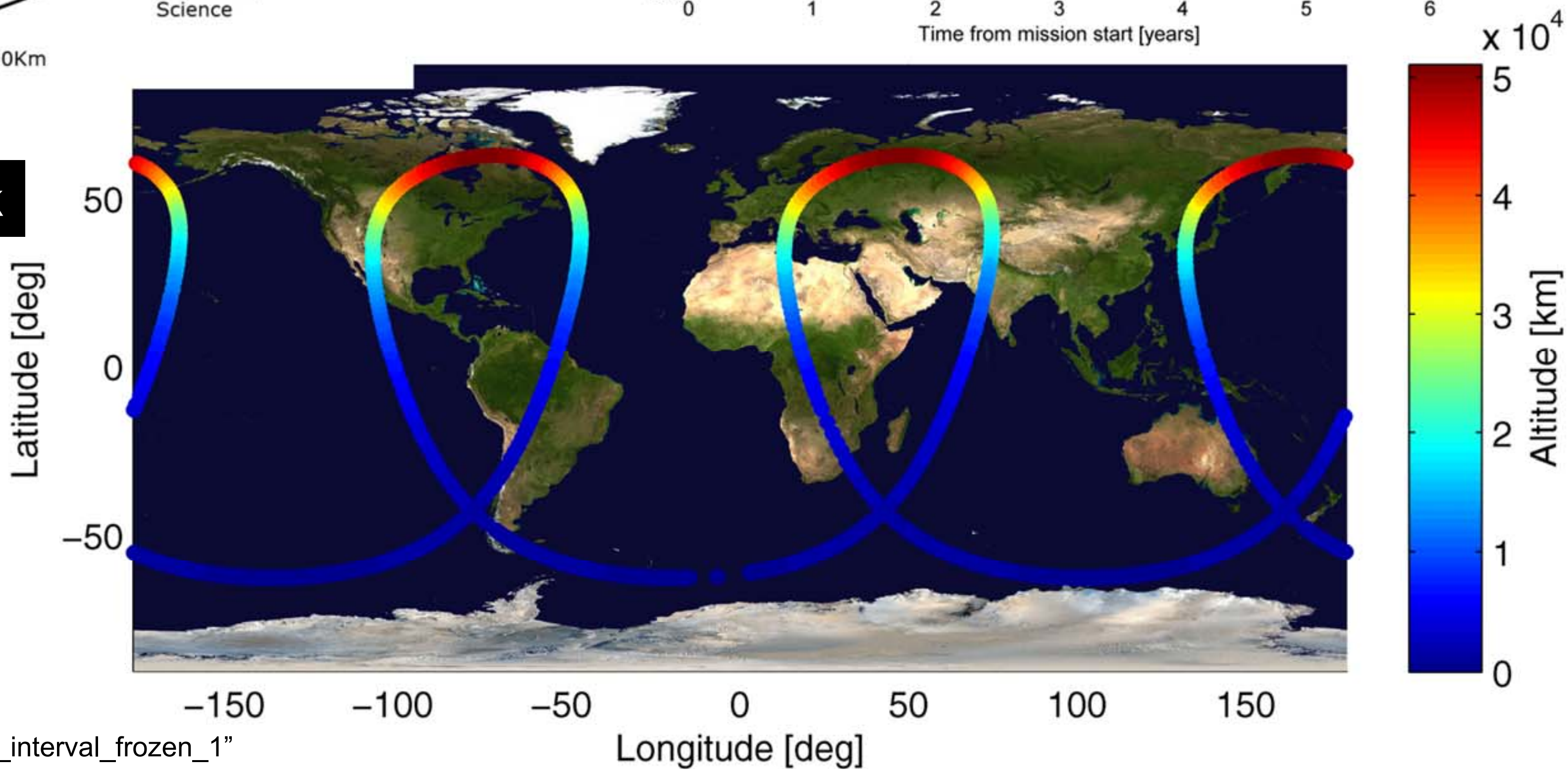
The STE-QUEST orbit

„Frozen orbit“: ground track is constant
- Period: 16 h
- Perigee altitude varies as fct. of time
- Apogee altitude: 51 000 km





Ground track



“STE_QUEST_elev_data_interval_frozen_1”

Earth gravitational frequency shift measurement

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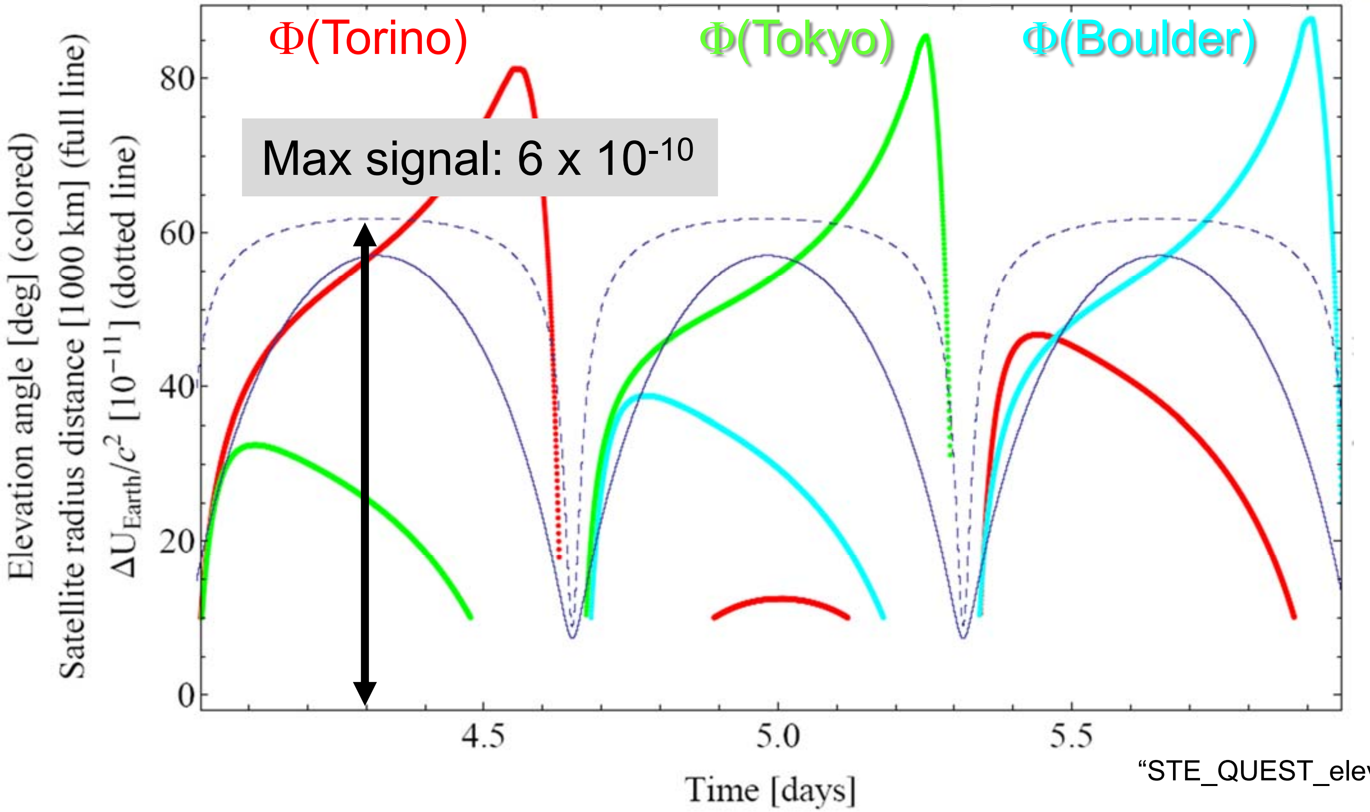

Φ = satellite elevation angle above horizon

3000 – 7000 km altitude intervals are omitted

"STE_QUEST_elev_data_interval_frozen_1"

Modeling the gravitational frequency shift measurement performance

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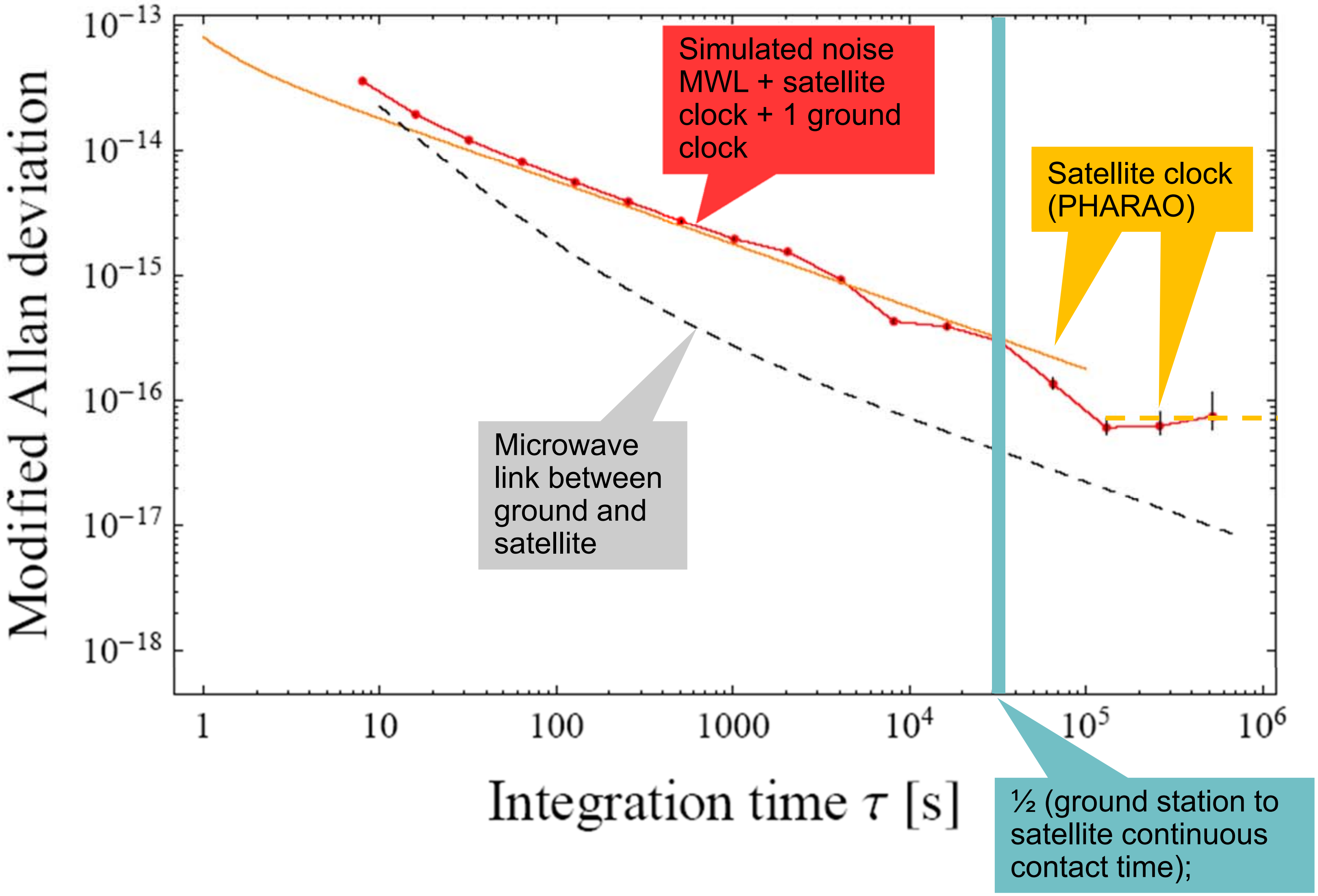
Specifications of clocks and links (acc. to Science Requirement document Issue 1, Rev. 4)



Earth gravitational frequency shift measurement

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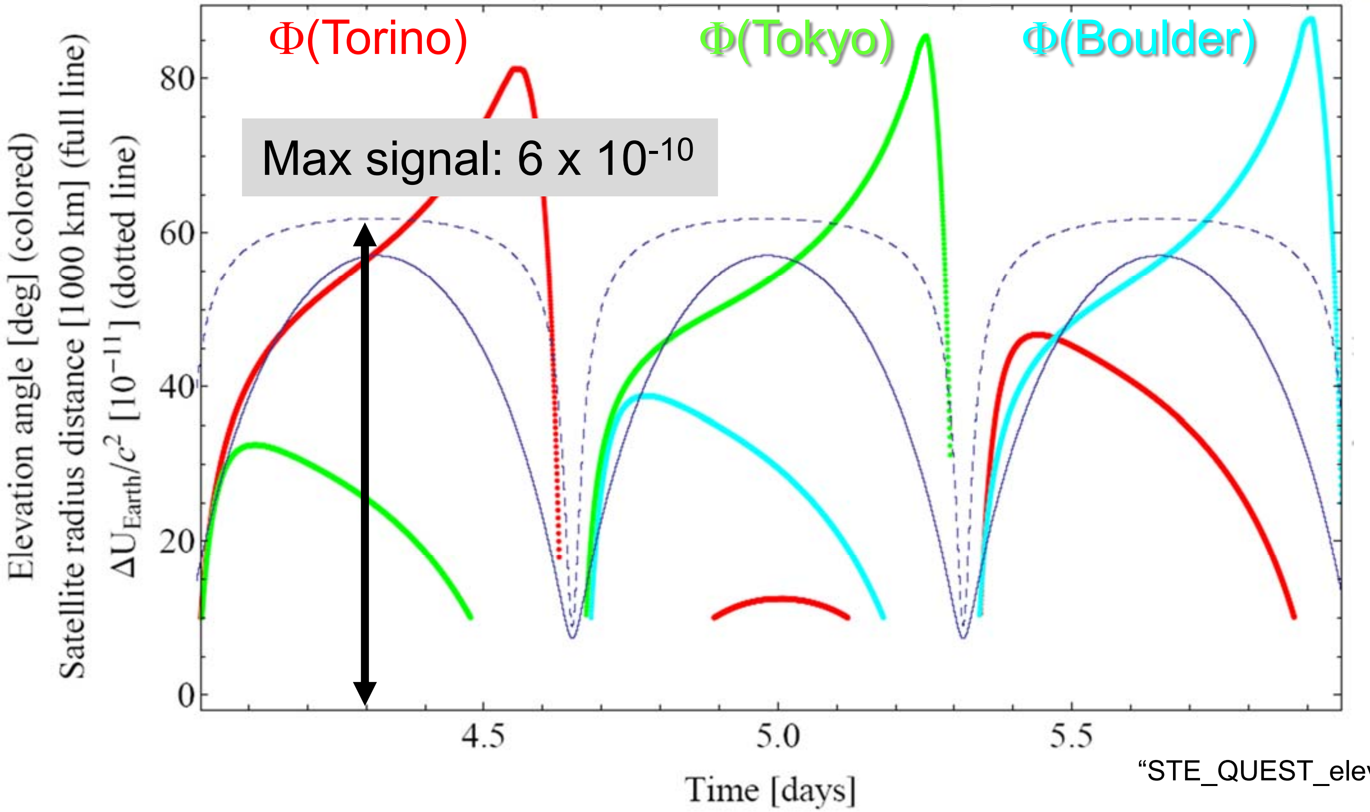

Φ = satellite elevation angle above horizon

3000 – 7000 km altitude intervals are omitted

"STE_QUEST_elev_data_interval_frozen_1"

- Monte Carlo Simulation with synthetic clock + link noise (200 noise samples)
- Measurement using 1 ground station over 1⅓ days reaches:
  5×10^{-6} (modulation measurement); 4×10^{-7} (absolute measurement)
- Need ca. 830 days (6 days) integration (in optimum case) to reach **2×10^{-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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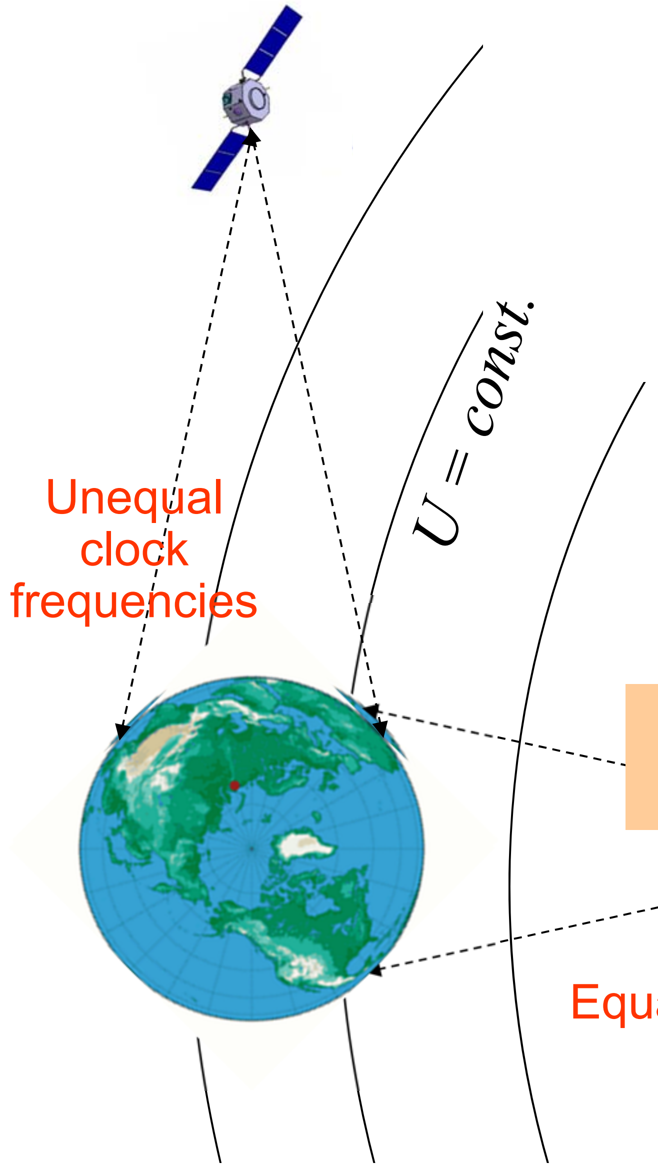

- Precise test of Sun gravitational time dilation

- 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 if $U(r) = GM_{Sun}/r$ *(B. Hoffmann, Phys. Rev. 121, 337 (1961))*
- Since Doppler shift effect is precisely known, one can extract solar time dilation effect
- Assume: ground optical clocks (instability ≈ 1 x 10^{-18})
  optical link with 1 x 10^{-18} @ τ = ½ day
  → test of solar gravitational redshift at level **2 x 10^{-6}**, (reached within 2.5 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 $U_{\text{Earth}}(r_1) - U_{\text{Earth}}(r_2)$

Moon gravitational frequency shift measurement

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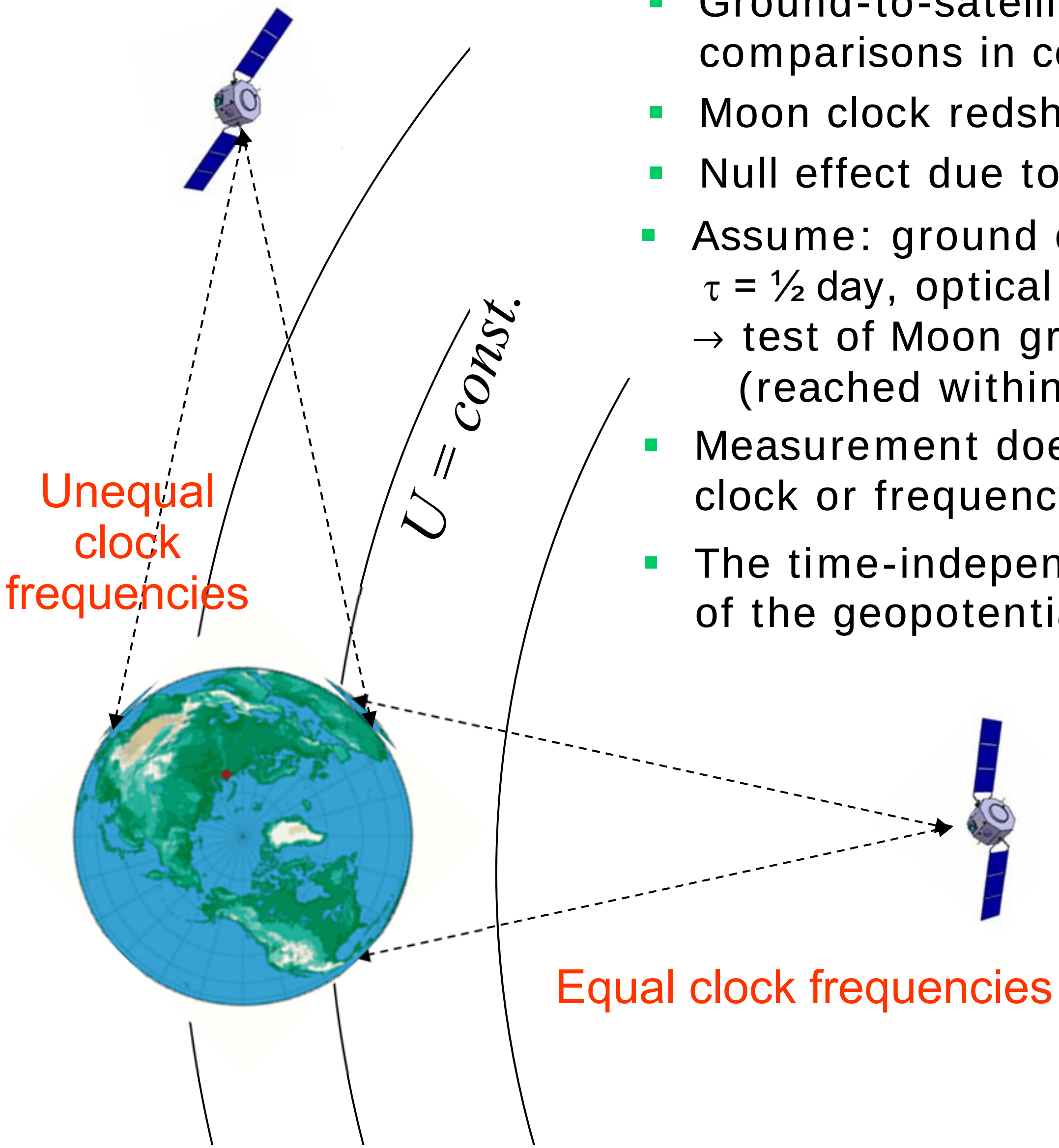
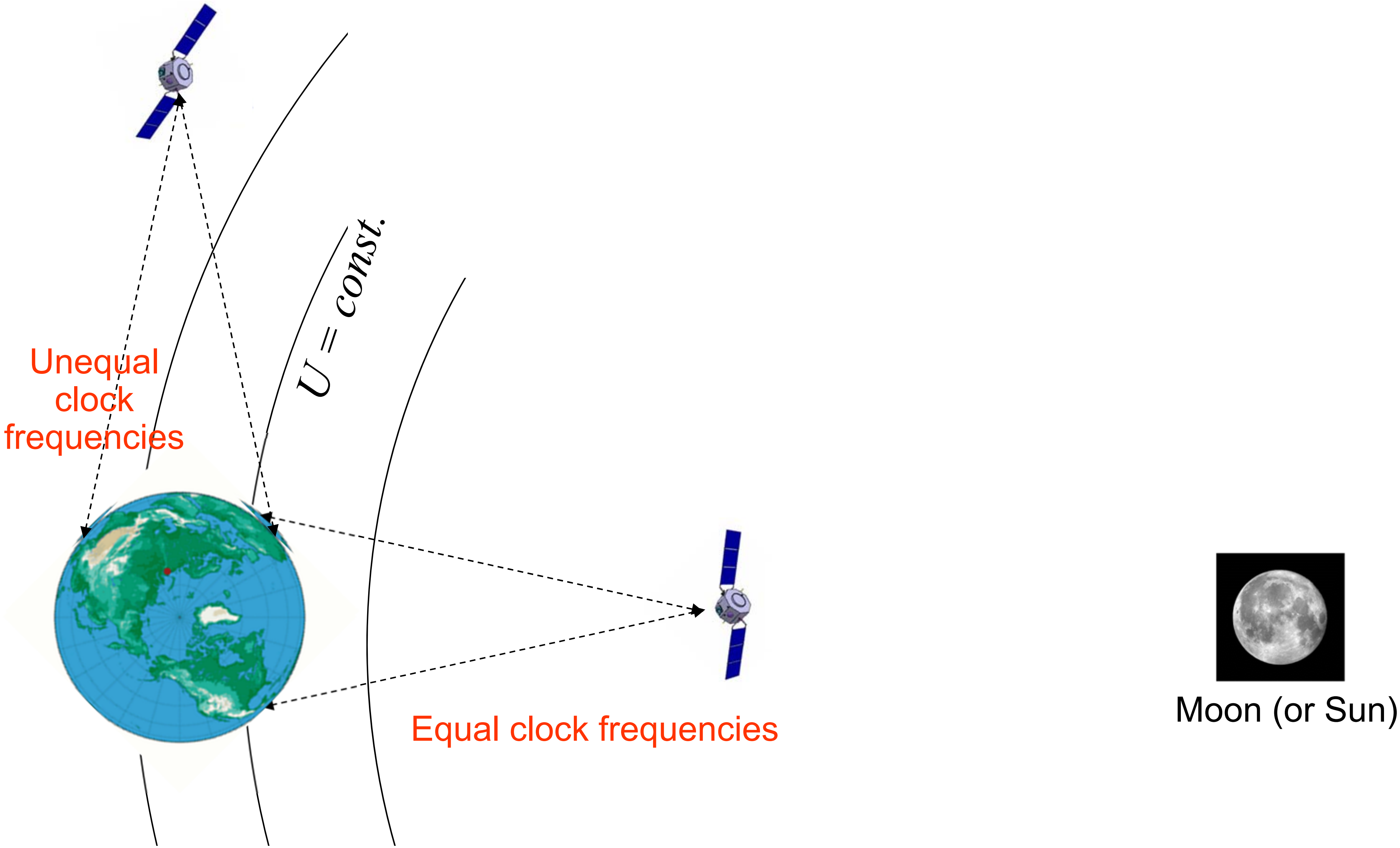
- Precise test of Moon gravitational time dilation

- Ground-to-satellite links allow terrestrial clock comparisons in common-view
- Moon clock redshift: daily amplitude of 6 x 10^{-15}
- Null effect due to Special Relativity contribution
- Assume: ground optical clocks (instability ≈ 1 x 10^{-18} @ τ = ½ day, optical link with 1 x 10^{-18} @ τ = ½ day
  → test of Moon gravitational redshift at level **3.5 x 10^{-4}**, (reached within 2.5 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 $U_{\mathrm{Earth}}(r_1) - U_{\mathrm{Earth}}(r_2)$



Moon

Moon gravitational frequency shift measurement



Tidal effects

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Cancellation between special relativistic and purely gravitational time dilation is only approximate if the clocks are not close

Residual effect is of order $G\, M_{body}\, (R_{Earth})^2 / (d_{Earth\text{-}body})^3$, or

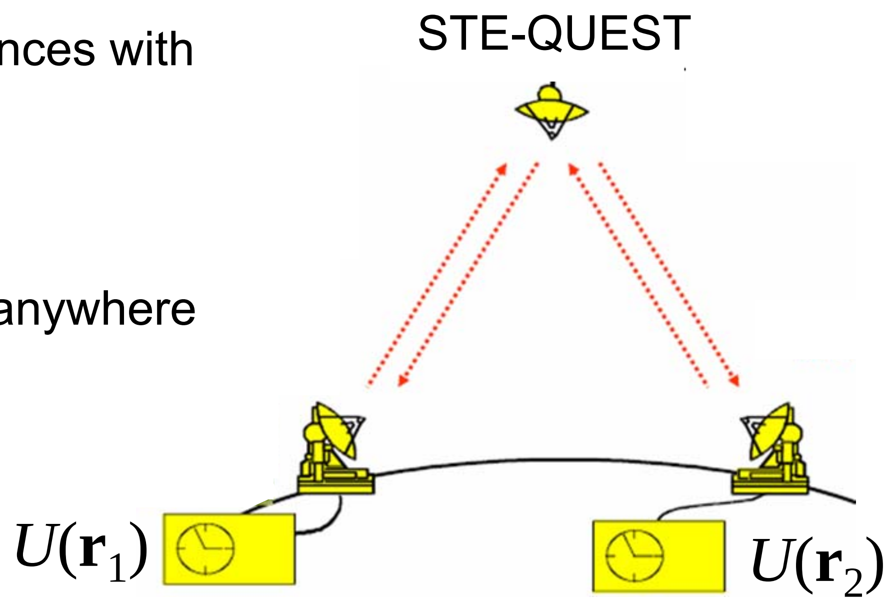
5×10^{-17} for the Moon
1×10^{-17} for the Sun

Comparison of future (1×10^{-18}) distant ground clocks will directly show the gravitational frequency shift caused by Moon and Sun!

(Thomas, Astr. J. **80**, 405 (1975))

Differential measurements of geopotential

- With clocks of accuracy at 1×10^{-18}, it is possible to measure geopotential differences with equivalent height resolution of 1 cm
- Extremely high spatial resolution
- Good time resolution ($\approx$ 1 day)
- Transportable clocks can be positioned anywhere



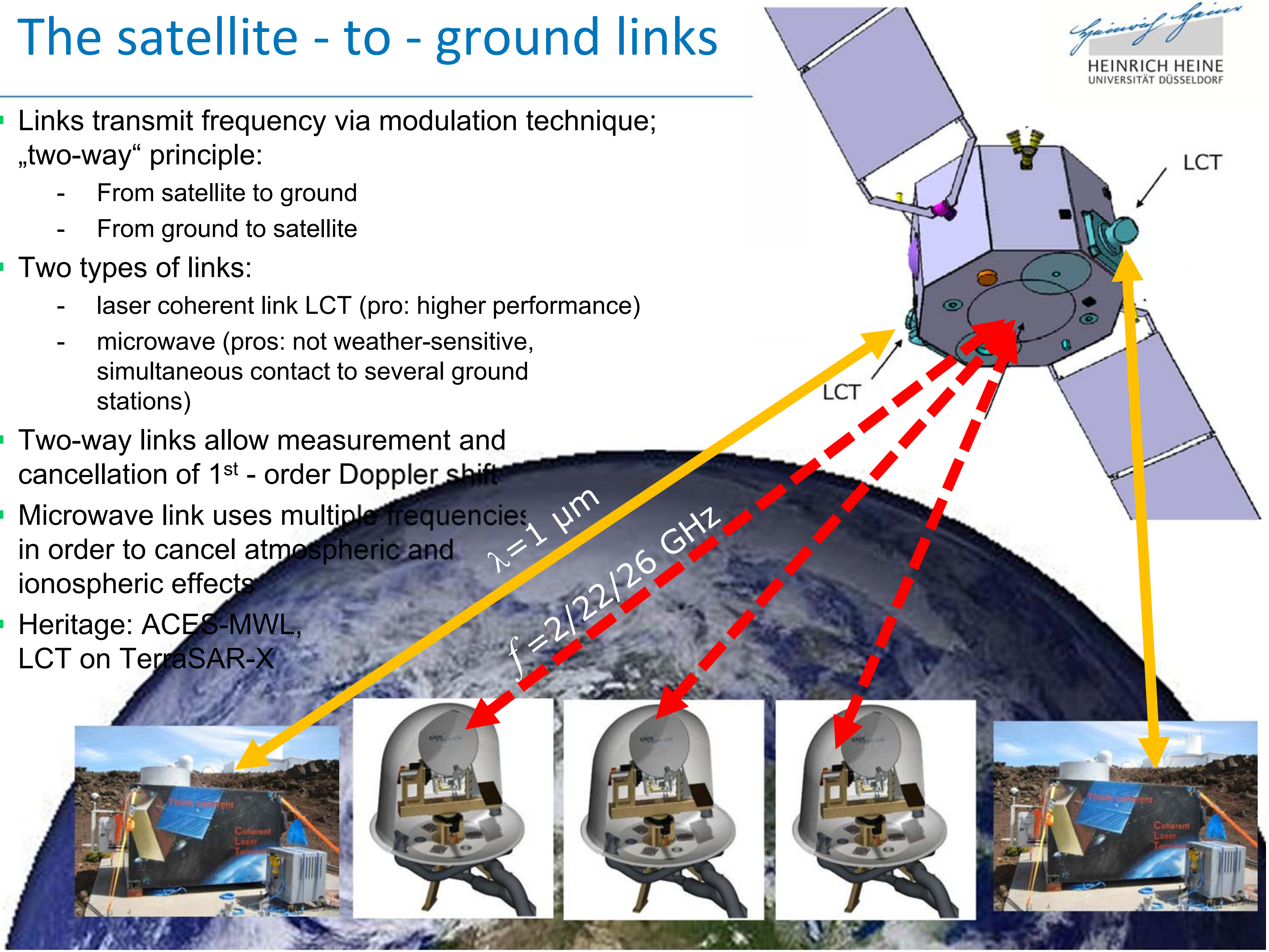
$$\frac{\nu_{clock1}(\mathbf{r})}{\nu_{clock2}(\mathbf{r})} - 1 = \frac{U(\mathbf{r}_1) - U(\mathbf{r}_2)}{c^2} \; *$$

- The onboard atomic clock is not required (only the link)

(*U includes the velocity term)

The satellite - to - ground links

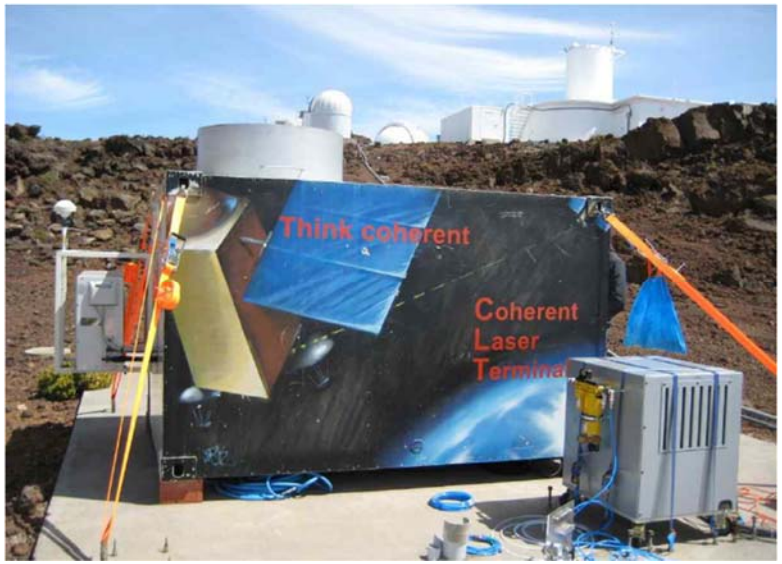
- Links transmit frequency via modulation technique; „two-way“ principle:
  - From satellite to ground
  - From ground to satellite
- Two types of links:
  - laser coherent link LCT (pro: higher performance)
  - microwave (pros: not weather-sensitive, simultaneous contact to several ground stations)
- 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 or Grasse (F), Boulder (USA), Tokyo (J) (t.b.c)



LCT ground terminal

MWL ground terminal (2 - 3 m dish)

Weak Equivalence Principle Test

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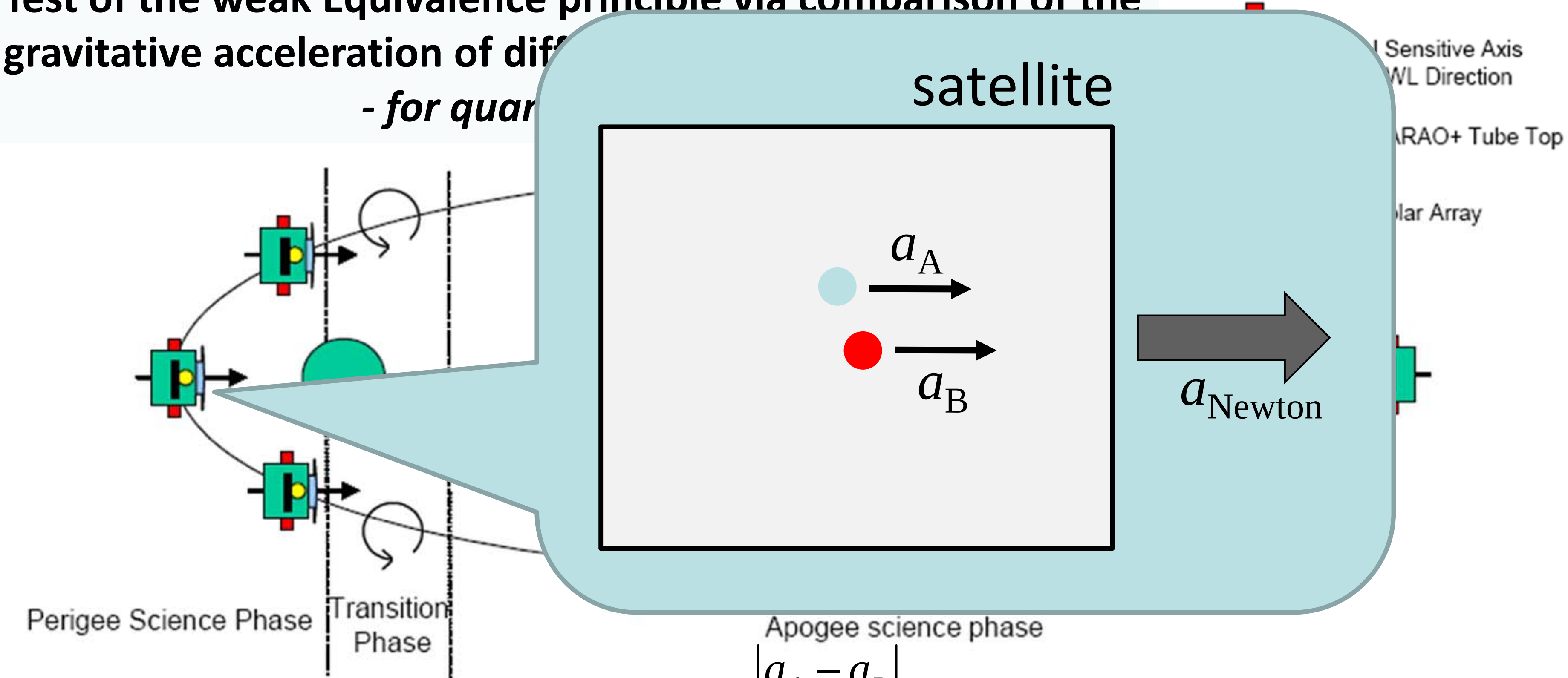
Test of the weak Equivalence principle via comparison of the gravitative acceleration of dif...
- for quan...

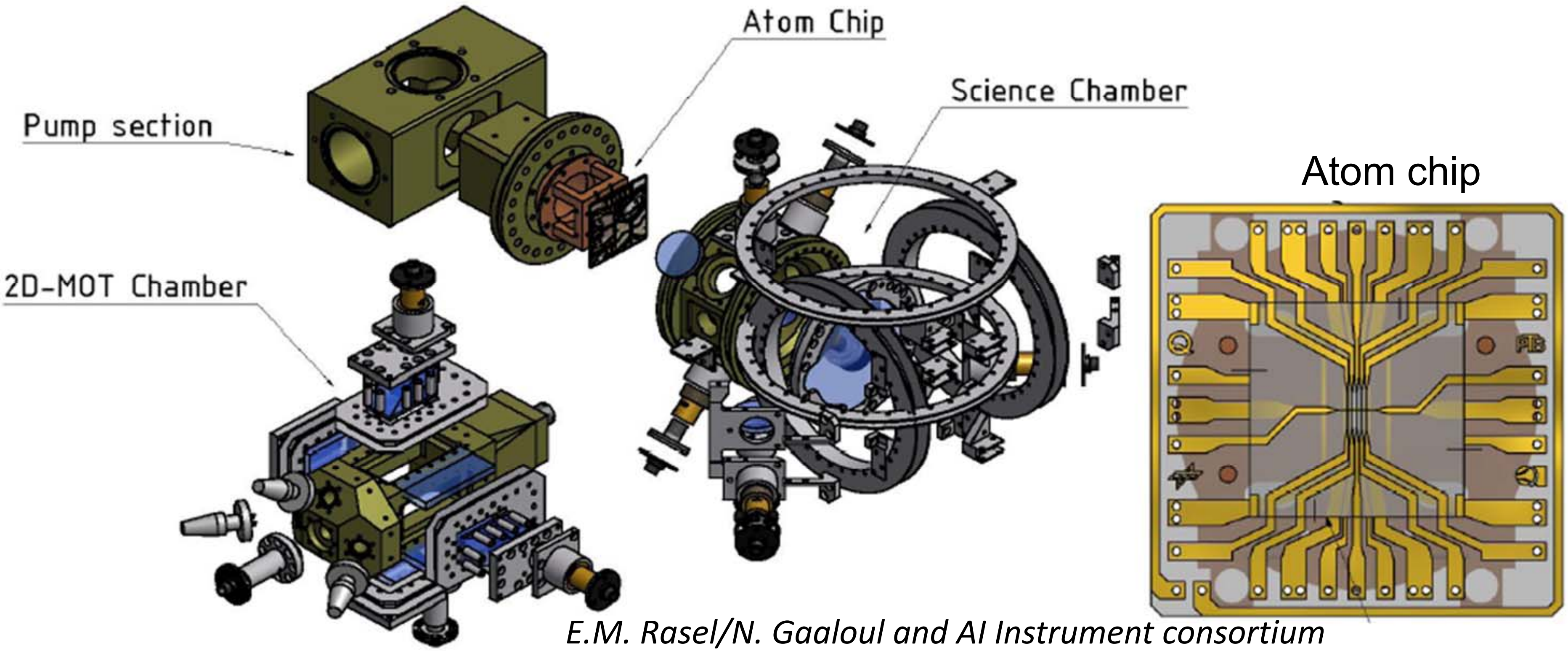


- Determination of the Eötvös ratio $\eta_{AB} = \frac{|a_A - a_B|}{a_{Newton}(r)}$
- Simultaneous observation of two Rubidium isotopes, ^{87}Rb und ^{85}Rb; the differential acceleration is measured
- Measurement is most sensitive near perigee
- Ca. 20 s per single measurement; ca. 100 meas. near perigee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

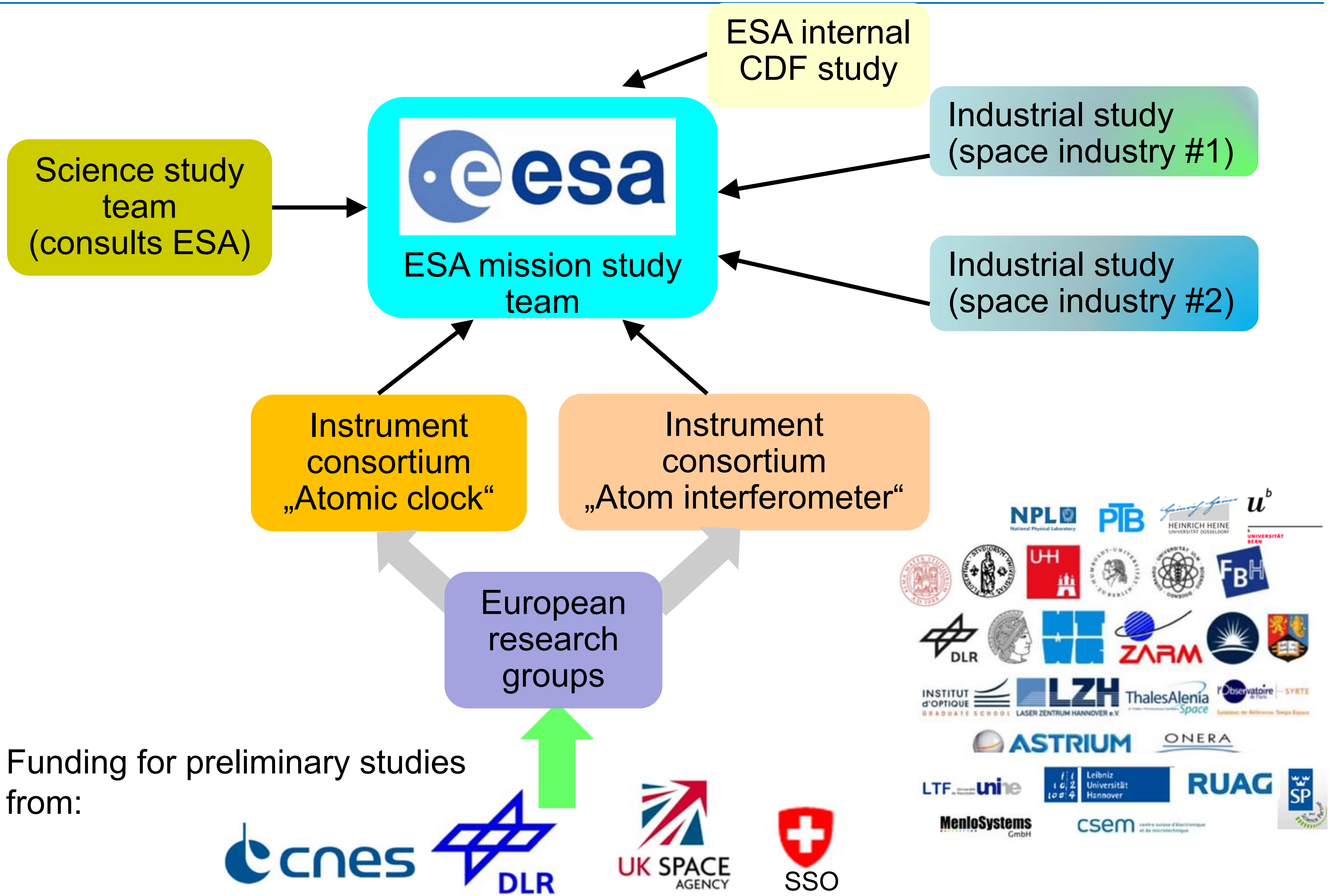
The STE-QUEST two-isotope atom interferometer

- 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

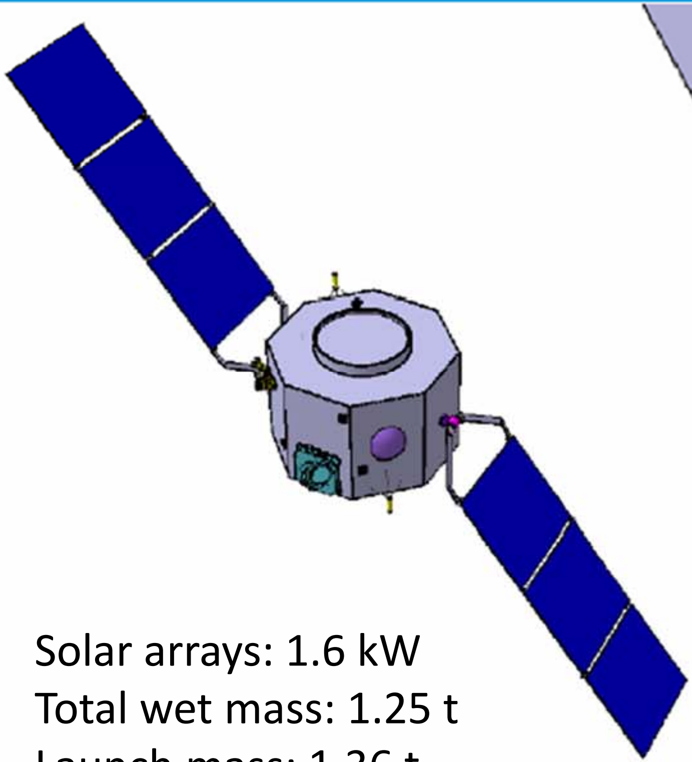
STE-QUEST: organization & activities (2011-13)



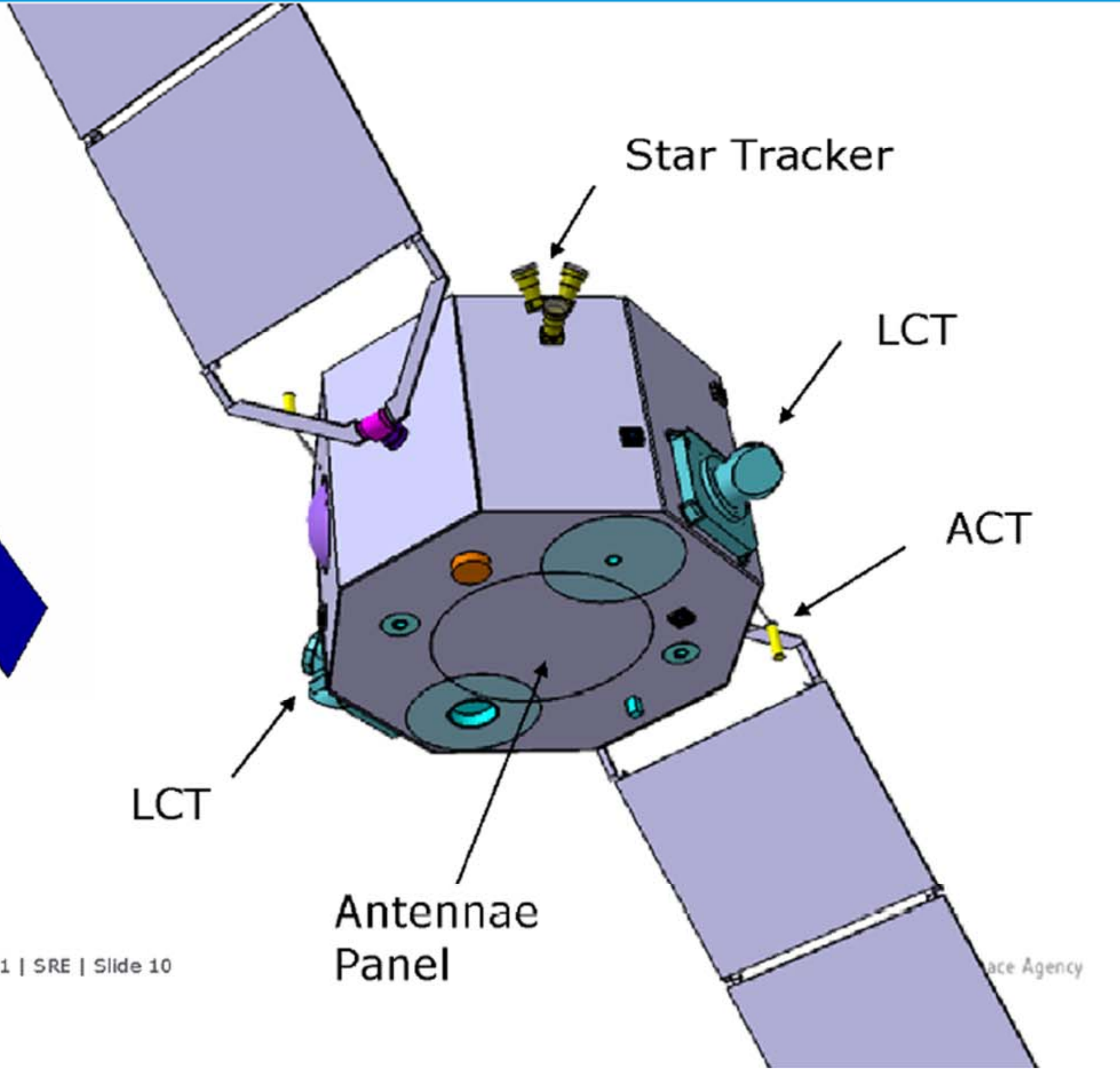
- Instrument consortia:
  - Detailed planning, cost estimations
  - Preliminary studies on robust subsystems (optical cavities, radiation resistance,…)

- Independent development programs (TEXUS flights: FOKUS, QUANTUS,…)

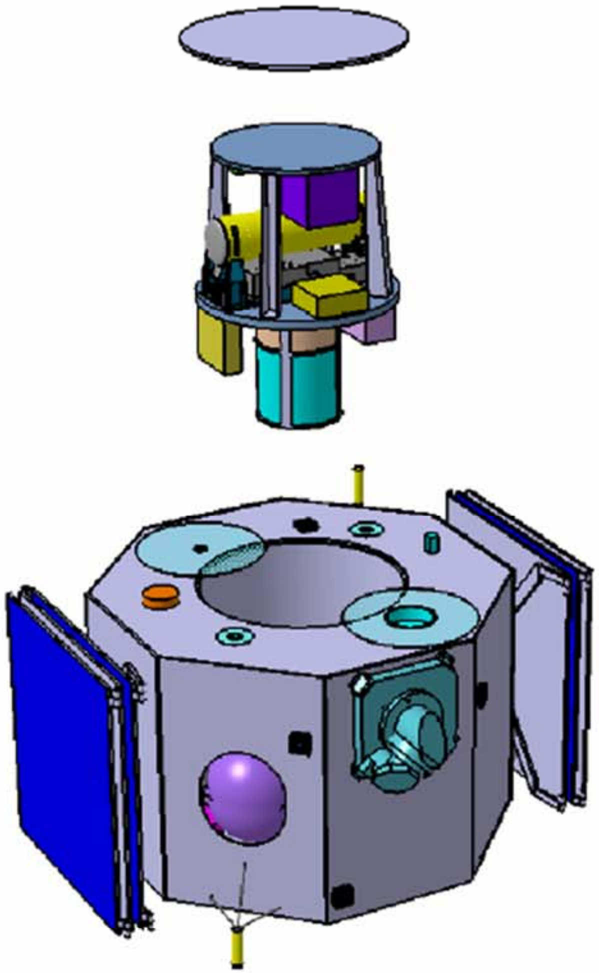
Flight configuration

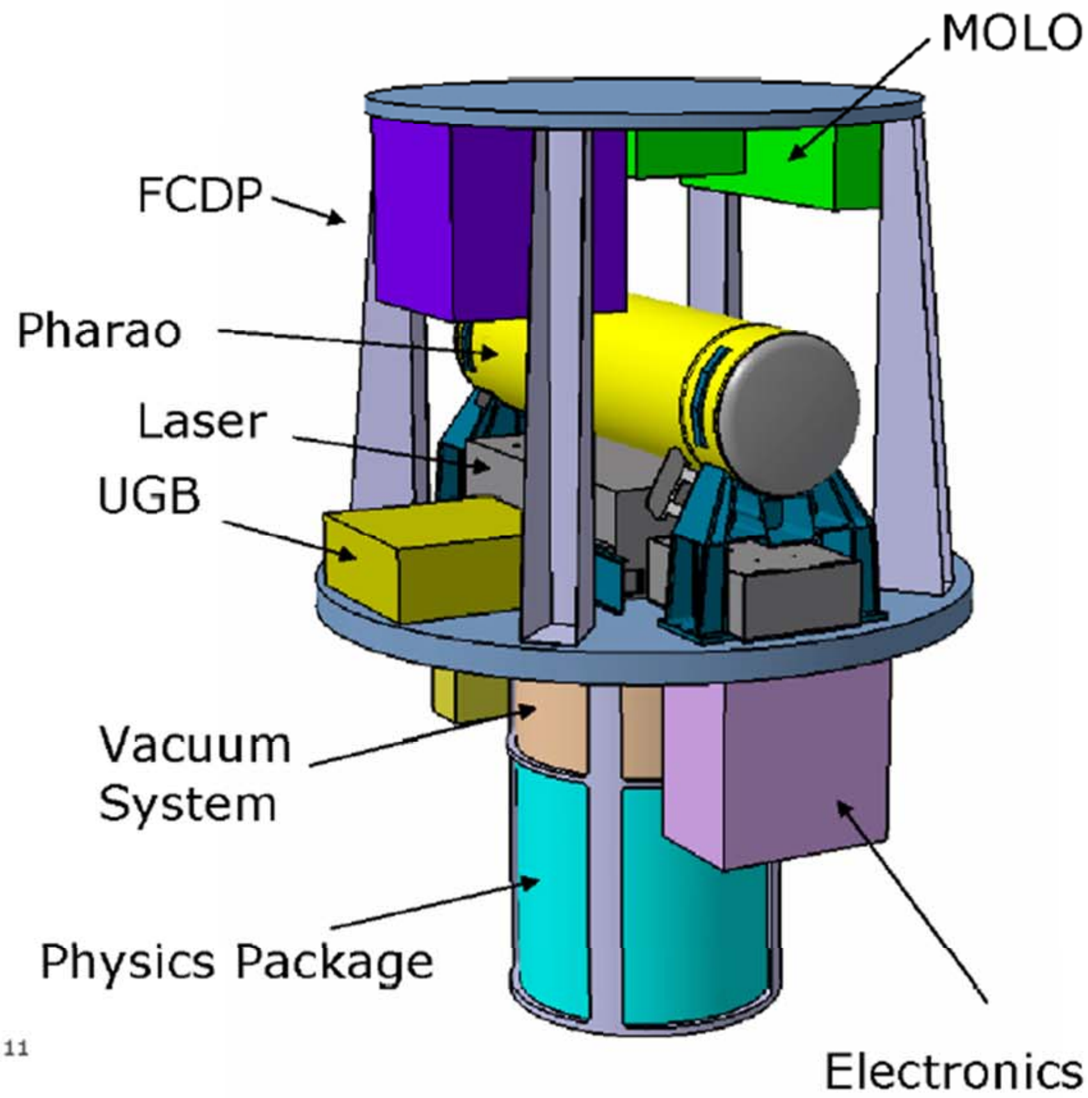


Solar arrays: 1.6 kW
Total wet mass: 1.25 t
Launch mass: 1.36 t
Instruments: 373 kg



Payload Accommodation





Summary

- **Science objectives:**

  Test 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,
    accuracy : **2×10^{-15}** (x 10^8 improvement)
  - Test time dilation in the terrestrial, the solar and the lunar gravitational potential,
    accuracy **2×10^{-7}** , **2×10^{-6}**, **2×10^{-4}** , resp. (x 15, x 10^4, x 10^3 improvement, resp.)

- **Application to other fields:**
  - „master clock" in space for precision experiments world-wide, dissemination of time
  - link and intercompare clocks world-wide
  - mapping of the gravitational potential of the Earth with high spatial resolution

- **Technology:**
  - Clock instrument & links: significant use of existing technology
  - Atom interferometer: novel technology, lower readiness level (drop tower experiments)

- **Challenges:**
  - **Cost of instruments and of optical link**
  - Involvement of additional countries into the mission is important