Fundamental physics with space clocks in highly elliptic orbits

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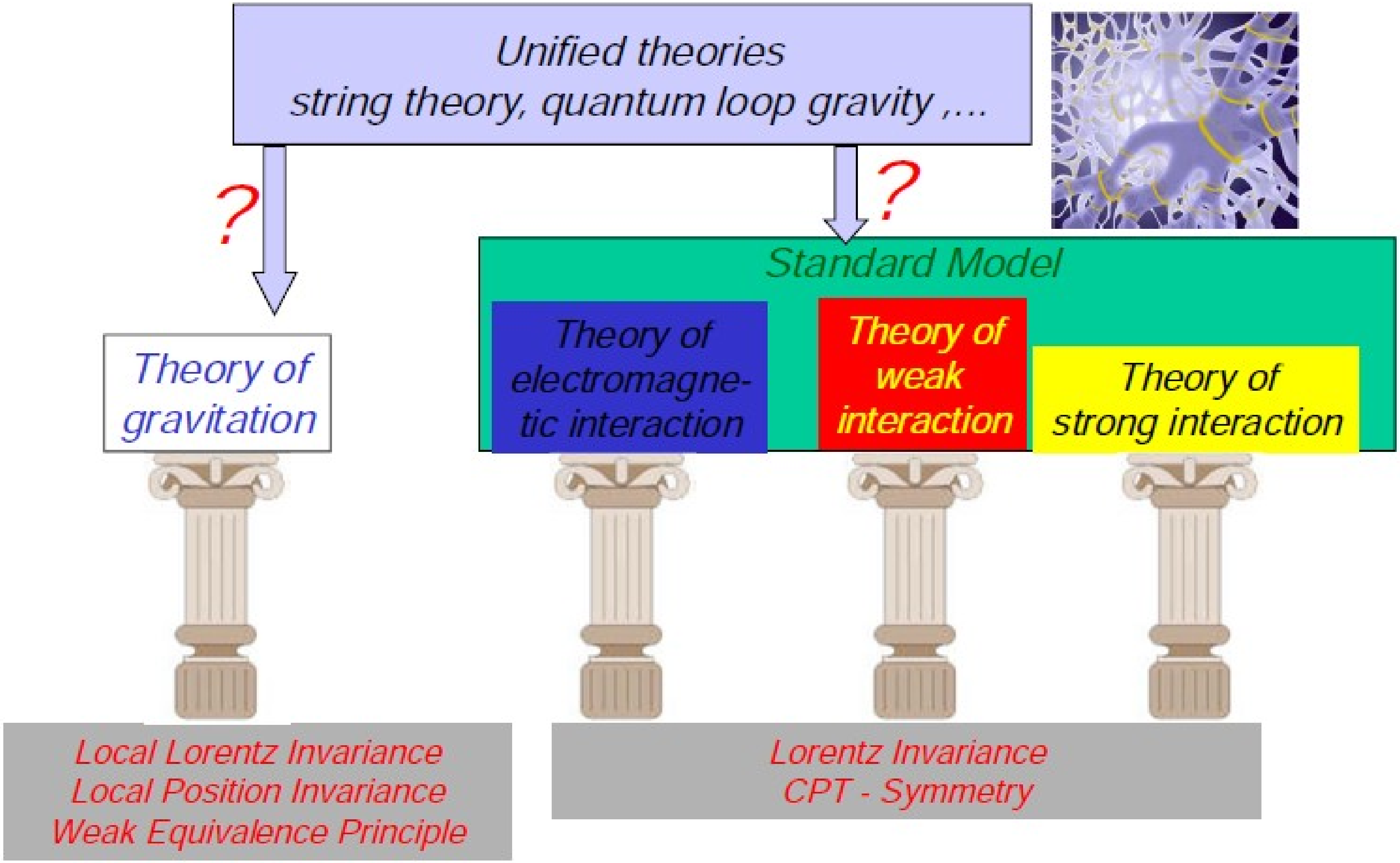
GR 21 Conference, New York , July, 2016

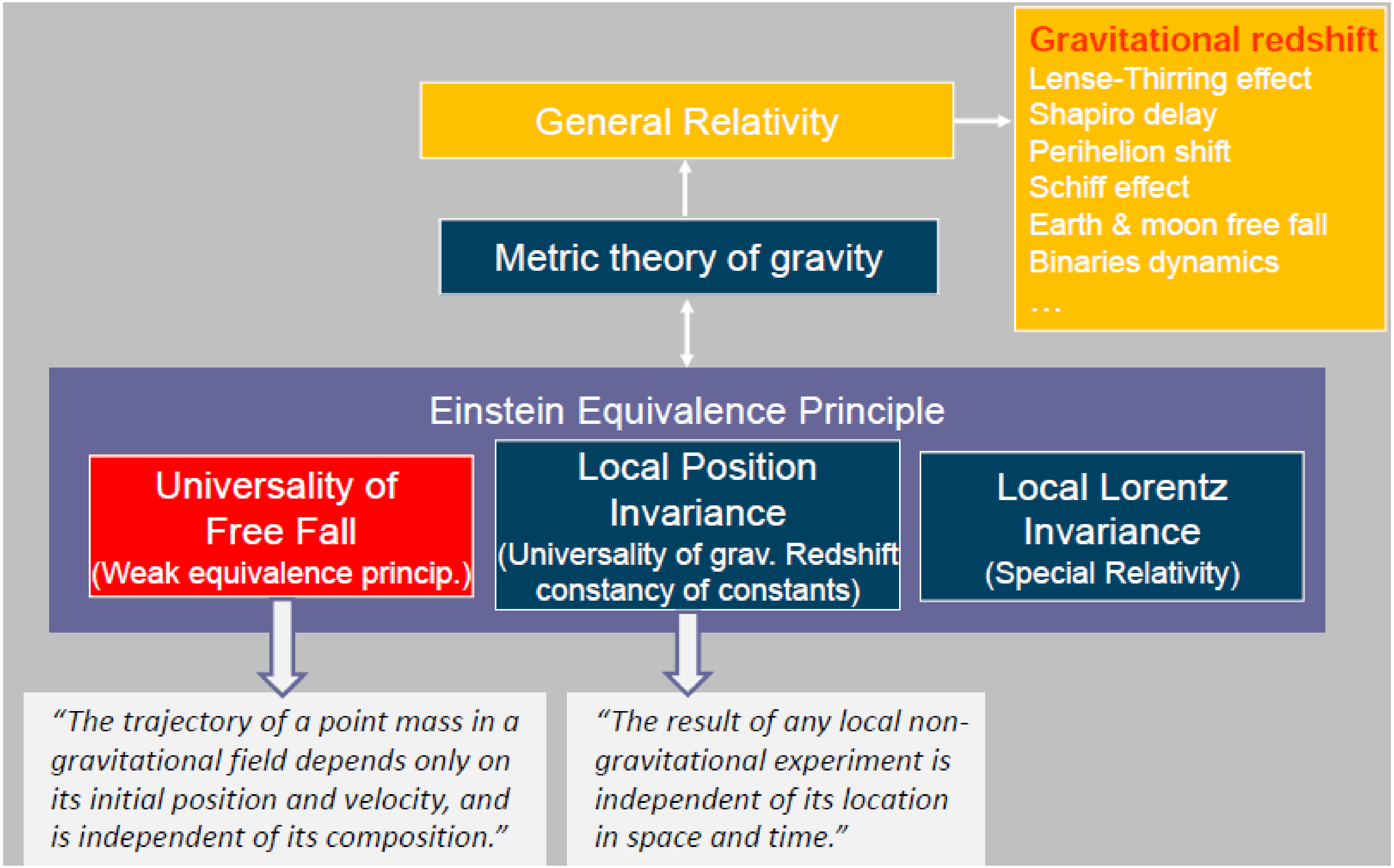
Introduction

- General Relativity is a classical theory, difficult to reconcile with quantum field theory and the standard model of particle physics.
- Most unification models predict modifications of gravitational phenomena at some small (generally unknown) level.
- Dark energy and dark matter may indicate deviations from our known laws of gravitation.
- Many modified gravitational theories and corresponding cosmological models contain long range scalar fields. Higgs boson is the first known fundamental scalar field (short range).
- Low energy tests of fundamental gravitational physics can provide pieces of the puzzle that are complementary to cosmological observation or high energy physics in accelerators (LHC).
- High performance clocks allow very sensitive tests of gravitational physics, and may provide first glimpses into physics beyond general relativity and the standard model of particle physics.

Motivation

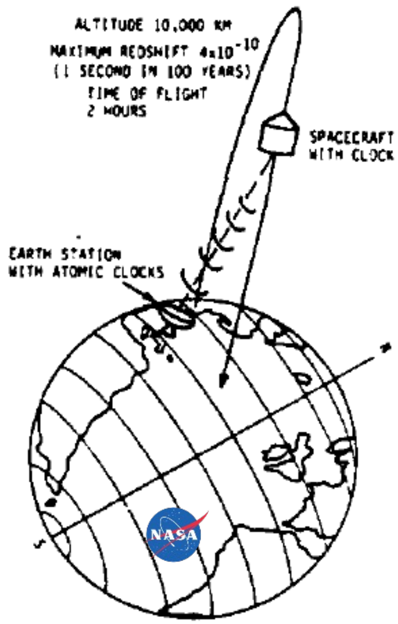


Unified theories
string theory, quantum loop gravity ,...
?
?
Standard Model
Theory of gravitation
Theory of electromagne-tic interaction
Theory of weak interaction
Theory of strong interaction
Local Lorentz Invariance
Local Position Invariance
Weak Equivalence Principle
Lorentz Invariance
CPT - Symmetry



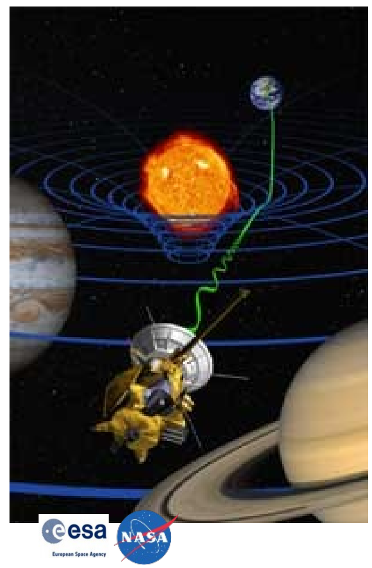
General Relativity
Gravitational redshift
Lense-Thirring effect
Shapiro delay
Perihelion shift
Schiff effect
Earth & moon free fall
Binaries dynamics
…
Metric theory of gravity
Einstein Equivalence Principle
Universality of Free Fall
(Weak equivalence princip.)
Local Position Invariance
(Universality 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."

Fundamental physics in space



Gravity Probe A
1976

Test of gravitational redshift with uncertainty of 1.4×10^{-4}



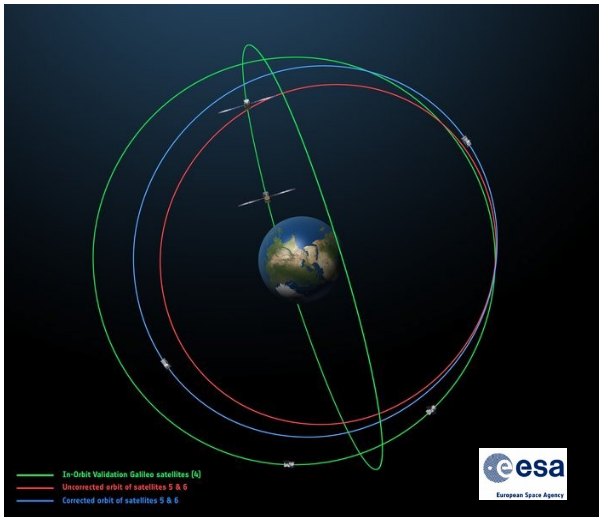
Cassini occultation
2002

Test of Shapiro delay with uncertainty of 2.2×10^{-5}

Gravity Probe B
2004-2005

Test of gravitomagnetic effect at 20% uncertainty. Geodetic precession at 0.3%.

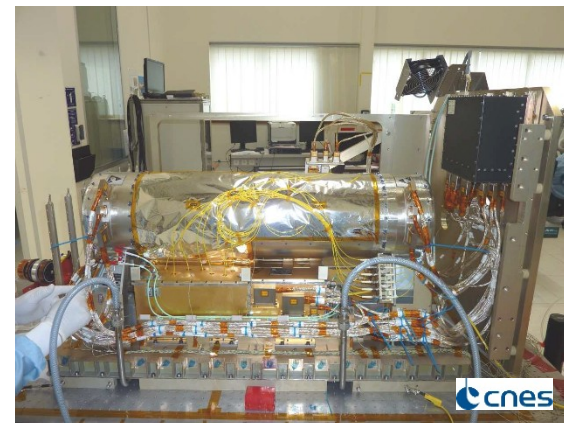
Fundamental physics in space



Galileo 5 & 6
2015 on
Test of gravitational redshift
with uncertainty
of (3-4) x 10^{-5}

Microscope
Launched April 2016

Test of universality of
free fall with uncertainty
of 10^{-15}

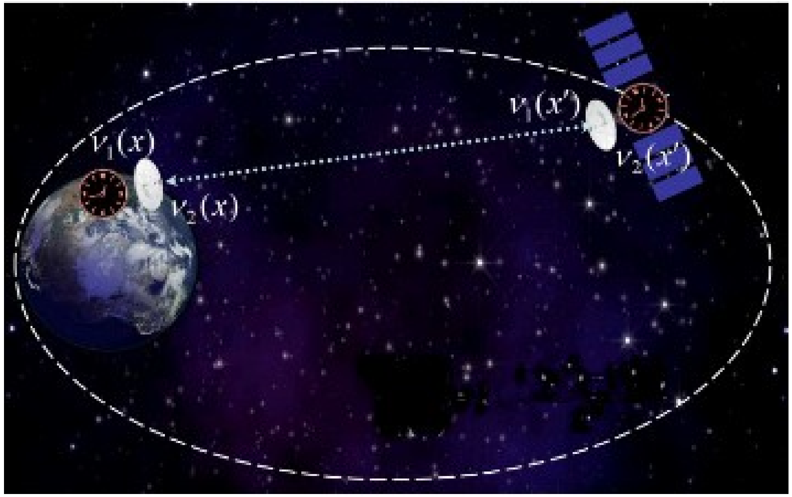


ACES / PHARAO
2018

Test of gravitational redshift
with uncertainty of (2-3)x10^{-6}

E-GRIP Mission Overview

- **Fundamental science goals:**
  Use gravitational redshift measurements with clocks to test:
  - the equivalence principle (local position invariance - LPI) and
  - higher order relativistic effects (orbit precession, Shapiro delay, frame dragging)
- **Geodesy goals:**
  - Intercontinental clock comparison to 1×10^{-17} in fractional frequency
  - Unification of reference frames at cm level
  - Determination of gravitational potential to $< 4\ m^2/s^2$
- **Spacecraft payload:**
  - Space Hydrogen Maser (SHM)
  - Microwave time and frequency link (MWL)
  - GNSS receiver
  - SRL retro-reflector & photon-counting detector
- **Orbit & mission lifetime:**
  - highly eccentric & 2-3 years



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

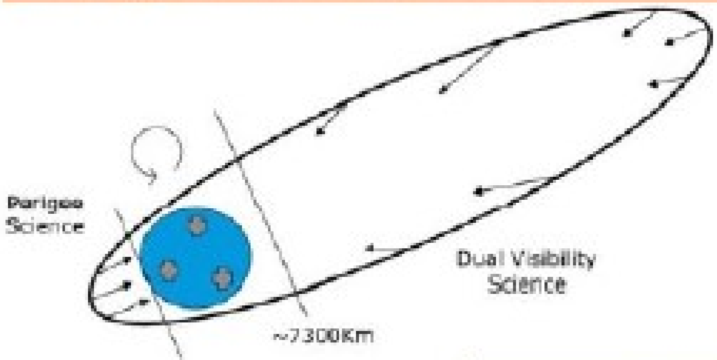
Mass of Sun: protons
Mass of Earth: protons & neutrons

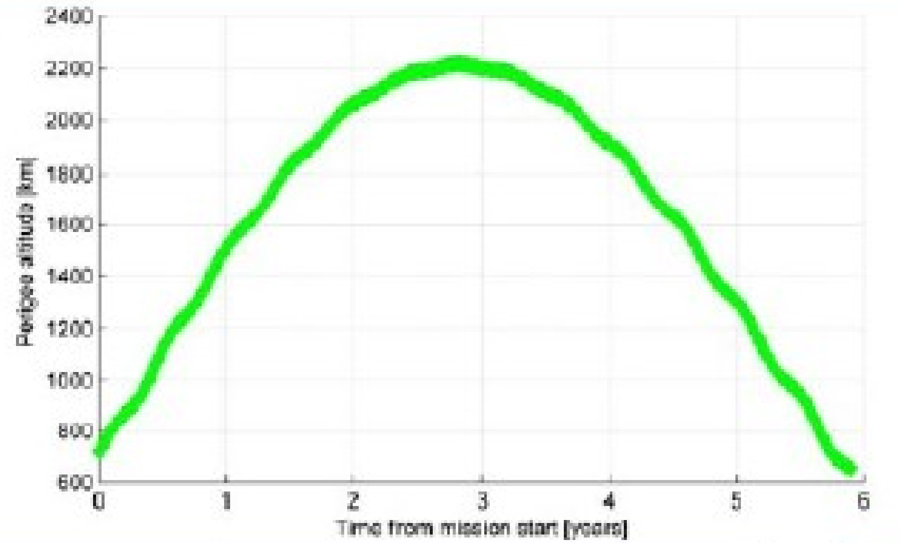
- Comparison of identical clocks at different locations r_1, r_2 will show an additional frequency shift contribution, which depends on the source type

- E-GRIP will set limits to S_{EARTH}, S_{SUN}, S_{MOON}

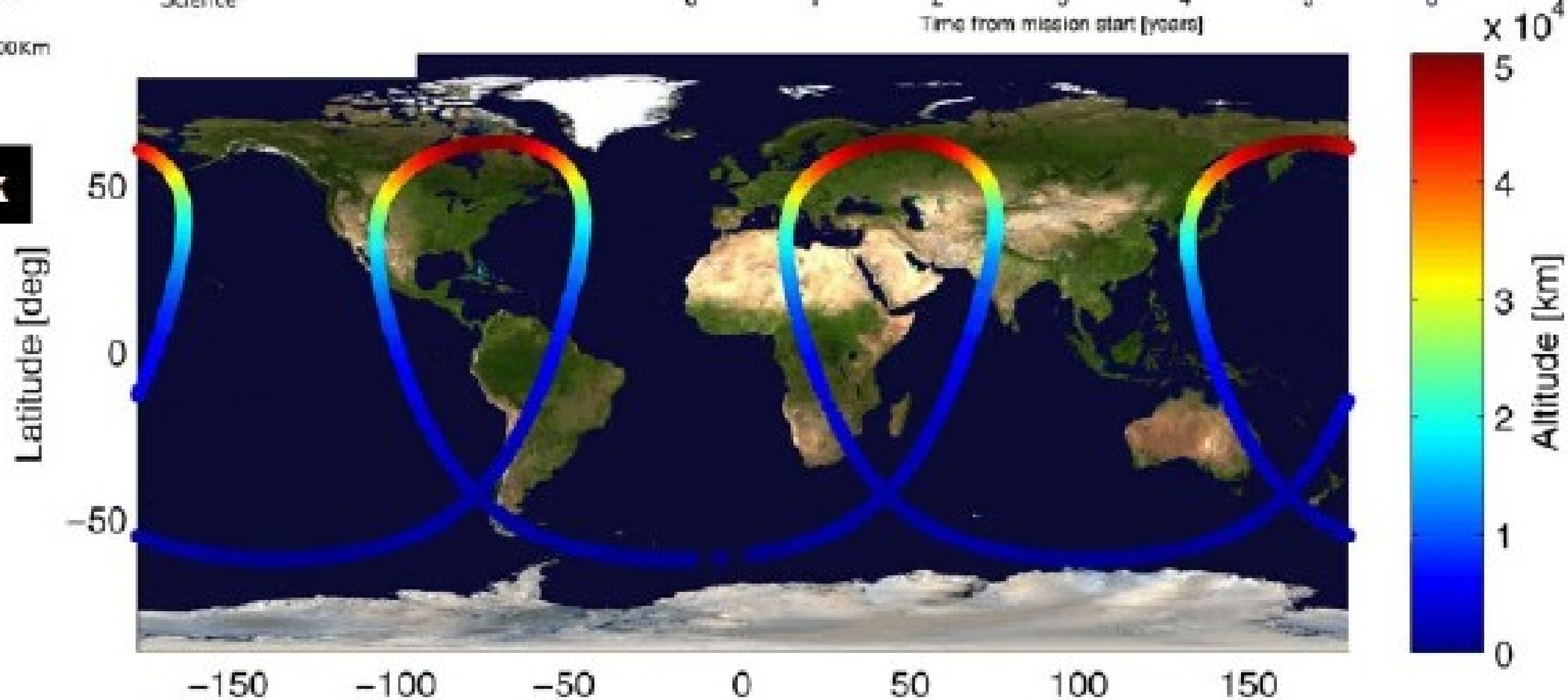
E-GRIP ORBIT

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



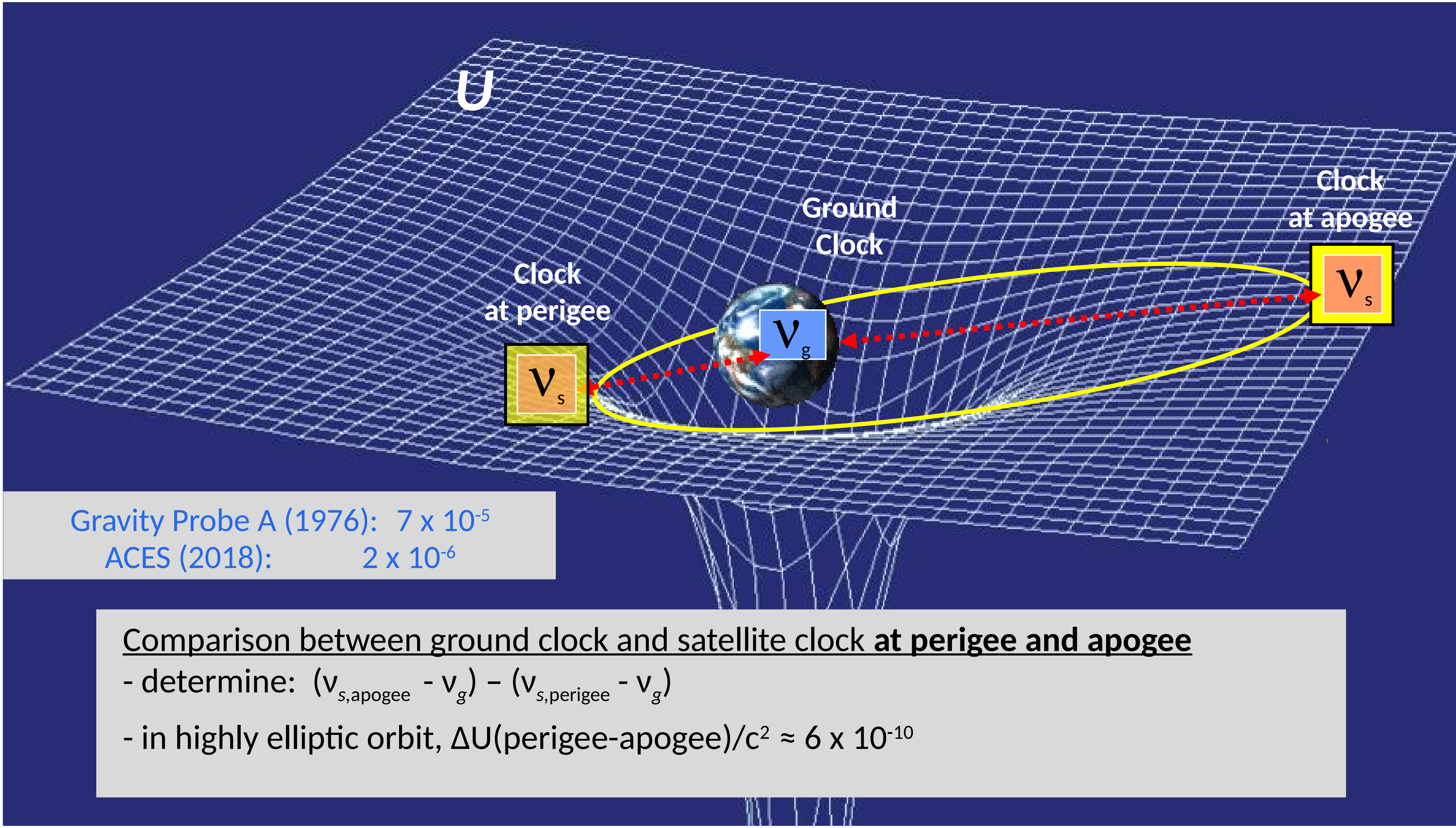


Ground track



"STE_QUEST_elev_data_interval_frozen_1"

Testing Earth's Gravitational Time Dilation



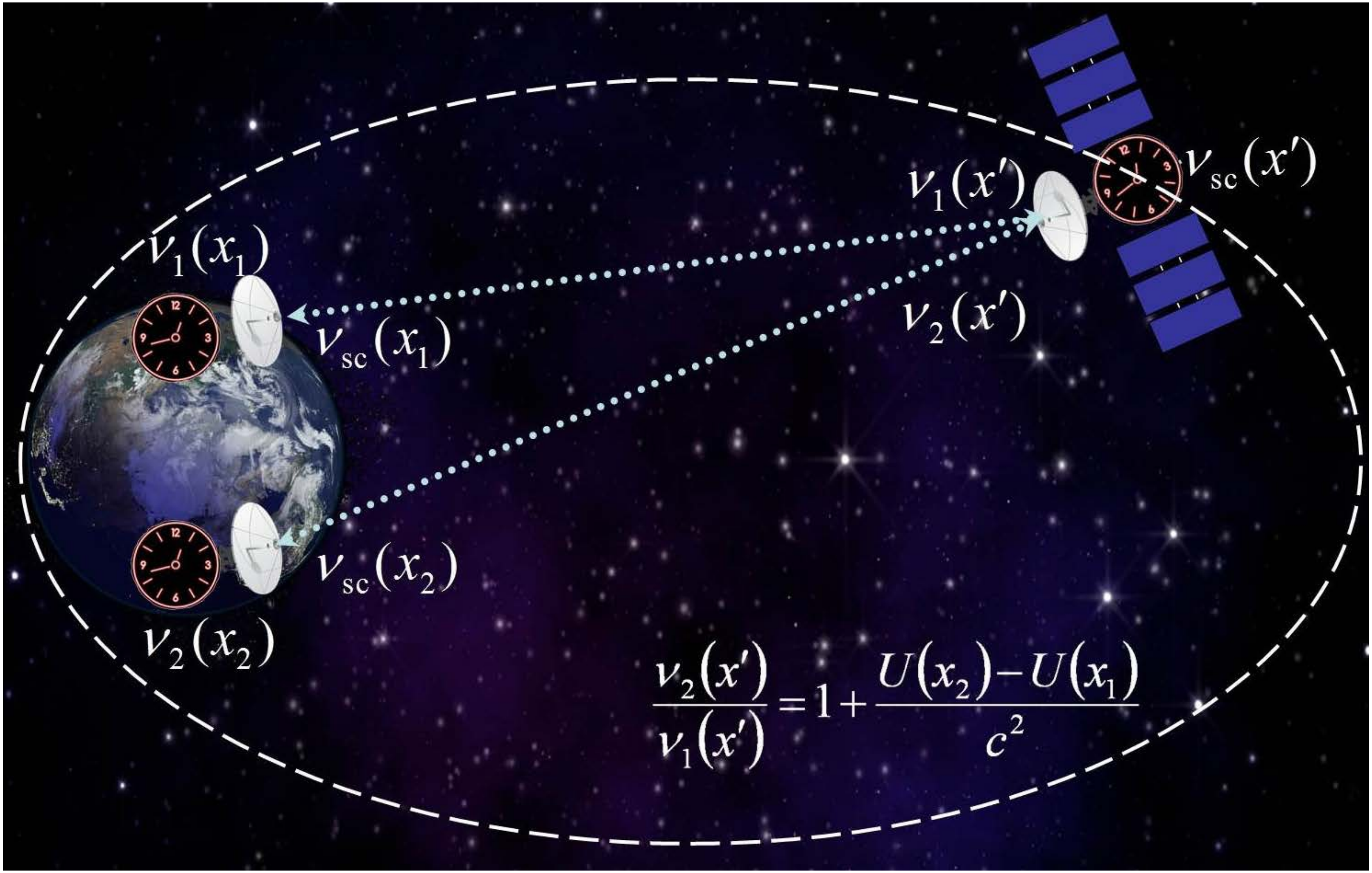
Gravity Probe A (1976): 7×10^{-5}
ACES (2018): 2×10^{-6}

<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, $\Delta U(\text{perigee-apogee})/c^2 \approx 6 \times 10^{-10}$

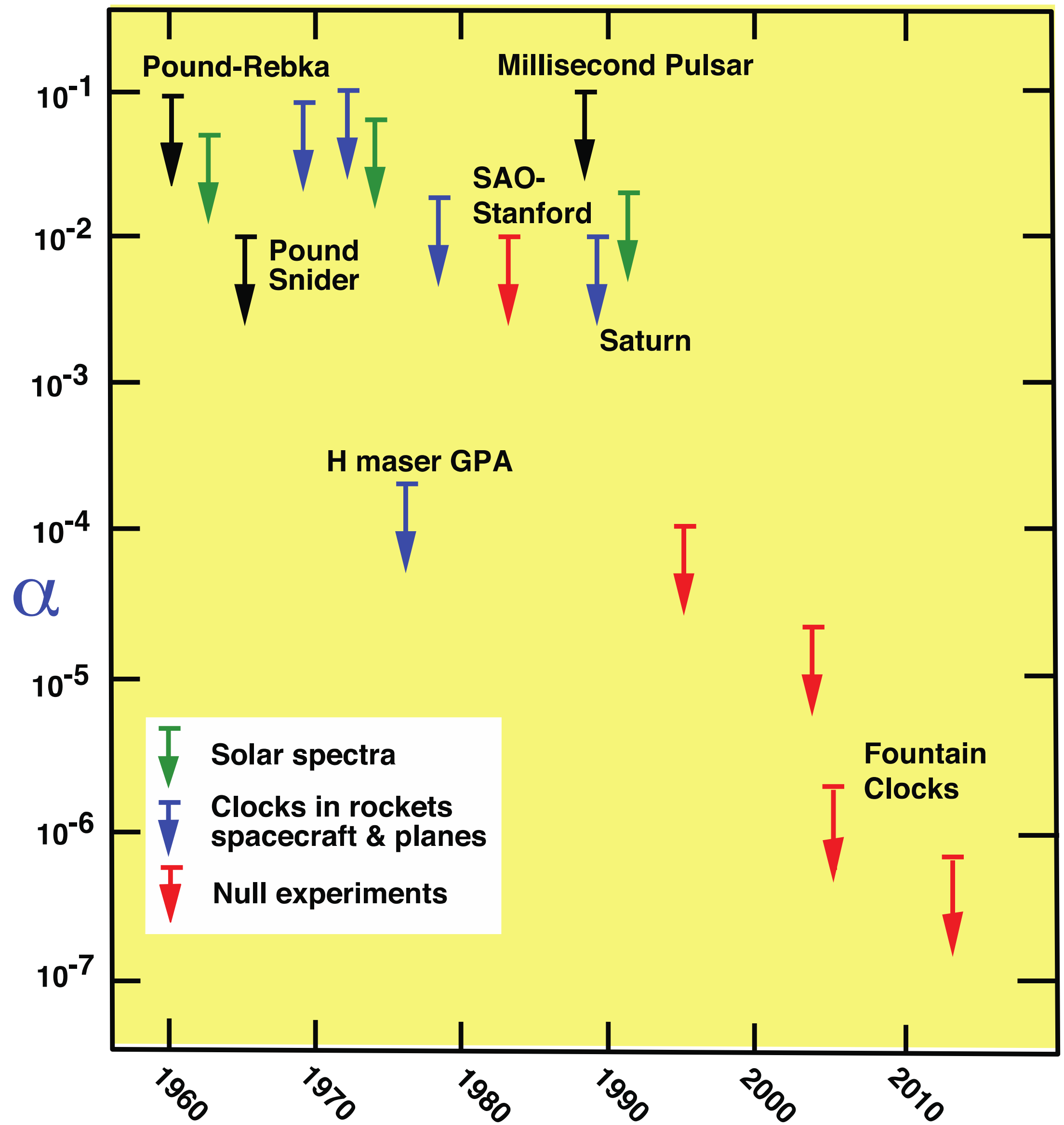
Measurement of time dilation in terrestrial potential with 2×10^{-6} accuracy.
Modulation in the signal due to highly eccentric orbit.

Common-view Comparison



To test Sun and Moon redshift:
A link compares the clock on-board of E-GRIP with two clocks on the ground, allowing a comparison of the received signal with the local clocks at both ends.

Tests of Local Position Invariance



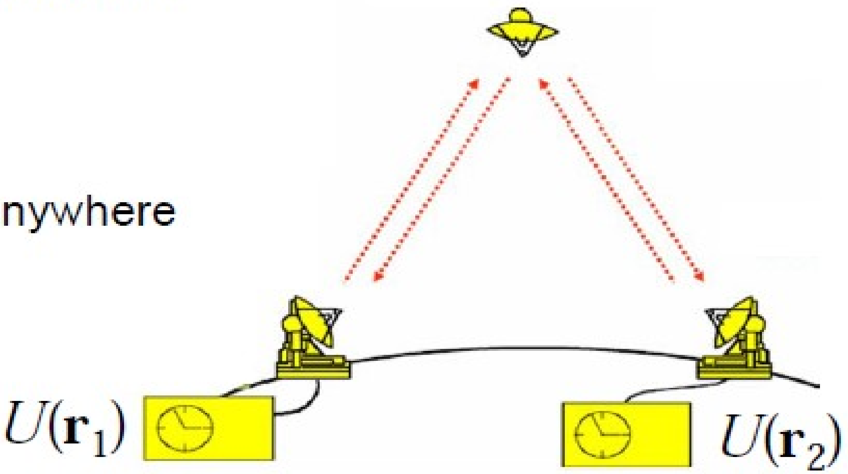
$$\Delta\nu/\nu = (1+\alpha)\Delta U/c^2$$

E-GRIP Tests of LPI	Fractional uncertainty
Earth	2×10^{-6} (goal: 4×10^{-7})
Sun	5×10^{-5}
Moon	1×10^{-2}

Red arrows: “null red-shift measurements” (differences α_i - α_j for two different types of clocks i and j).
Green arrow: best direct LPI tests in the Sun field.
Blue arrow: best direct LPI tests in Earth field.

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)

Conclusions

Future missions like ACES (2018) and proposed ones like E-GRIP
will test EEP with high precision:

- in particular tests of the LPI in the Earth, Sun and Moon gravitational field

- will lead to reference frames improvement and unification

- as well as improve upon relativistic geodesy

The Einstein Equivalence Principle (EEP)

- The EEP is the basis of GR, but also of all metric theories of gravitation.
- It postulates that all types of mass-energy are coupled universally to gravity, i.e. the gravitational interaction is independent of composition, electric charge, flavor, etc…
- This makes gravitation “universal” and allows it to be described as a geometrical phenomenon (curvature of space-time).
- However, this is totally “anomalous” as none of the other known interactions is universal (they all depend on some “charge”).
- So the more natural question is “why is the EEP satisfied” rather than “why should it be violated”!

The Einstein Equivalence Principle (EEP)

- Following Will (1993) the EEP can be divided into three sub-principles:

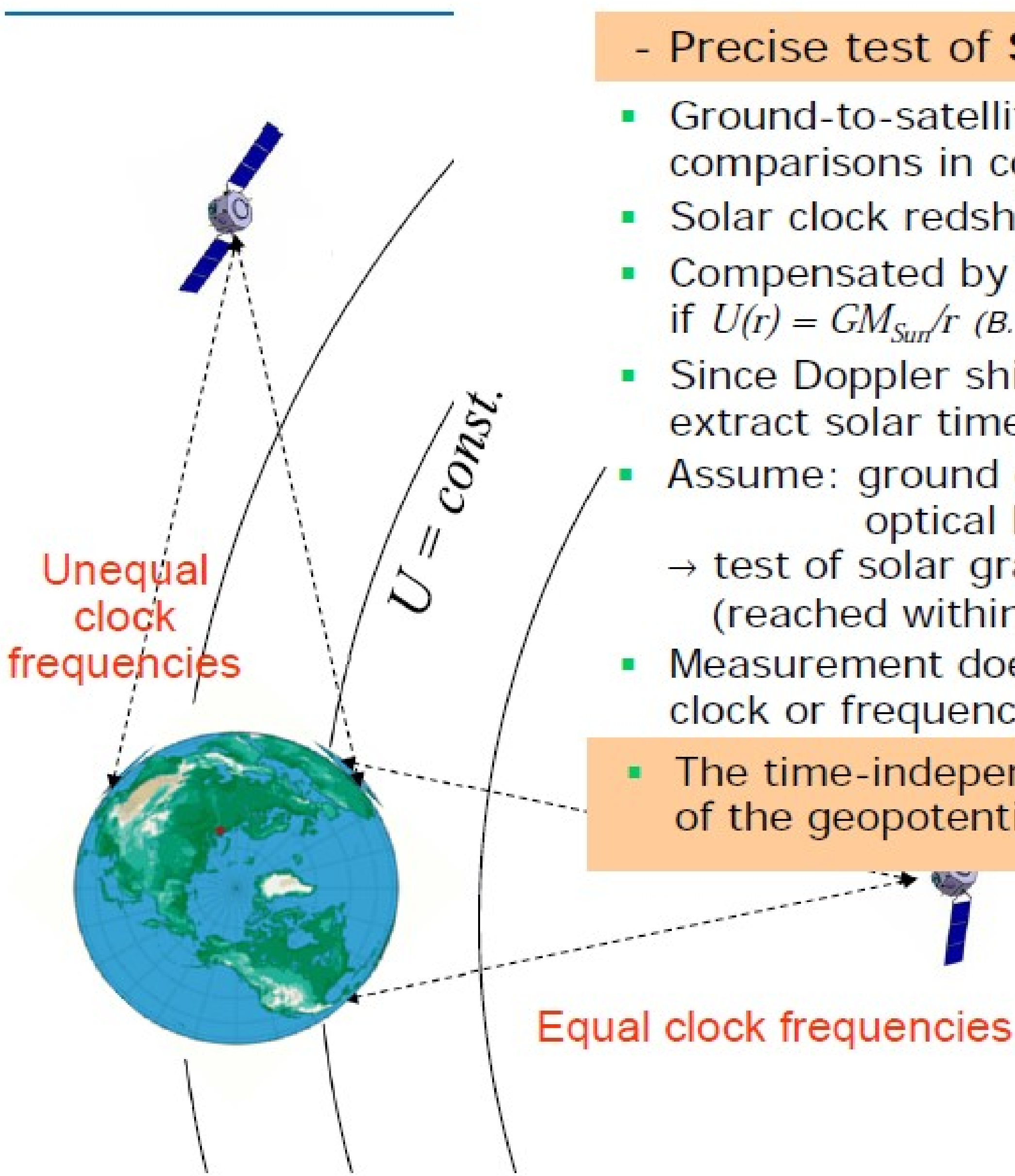
WEP/UFF: *If any uncharged test body is placed at an initial event in space-time and given an initial velocity there, then its subsequent trajectory will be independent of its internal structure and composition.*

LPI/UCR: *The outcome of any local non-gravitational test experiment is independent of where and when in the universe it is performed.*

LLI: *The outcome of any local non-gravitational test experiment is independent of the velocity of the (freely falling) apparatus.*

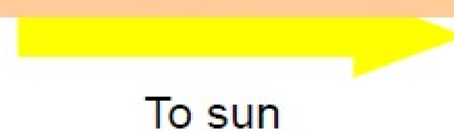
- The three sub-principles are related by Schiff's conjecture (1966), loosely stated: *Any violation of one the subprinciples implies a violation of the other two.* However the quantitative relationship is unknown and depends on the particular model used.

Sun gravitational frequency shift measurement



- Precise test of Sun gravitational time dilation

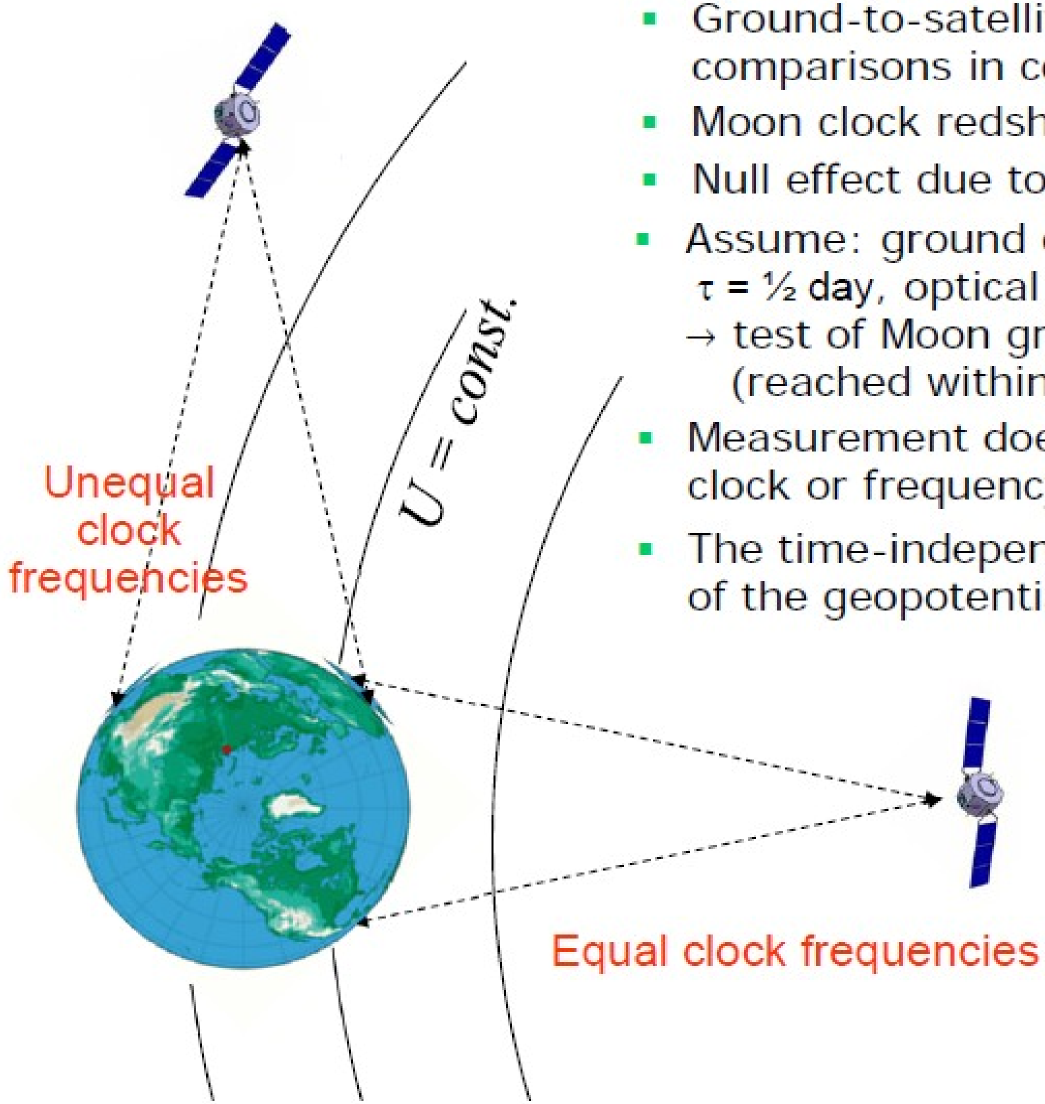
- Ground-to-satellite links allow terrestrial clock comparisons in common-view
- Solar clock redshift: daily amplitude of 4×10^{-13}
- Compensated by Doppler shift due to Earth motion if $U(r) = GM_{Sun}/r$ *(B. Hoffmann, Phys. Rev. 121, 337 (1961))*
- Since Doppler shift effect is precisely known, one can extract solar time dilation effect
- Assume: ground optical clocks (instability $\approx 1 \times 10^{-18}$)
  optical link with 1×10^{-18} @ τ = ½ day
  → test of solar gravitational redshift at level **2×10^{-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

- Precise test of Moon gravitational time dilation

- Ground-to-satellite links allow terrestrial clock comparisons in common-view
- Moon clock redshift: daily amplitude of 6×10^{-15}
- Null effect due to Special Relativity contribution
- Assume: ground optical clocks (instability $\approx 1 \times 10^{-18}$ @ τ = ½ day, optical link with 1×10^{-18} @ τ = ½ day
  → test of Moon gravitational redshift at level **3.5×10^{-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