STE-QUEST Science

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Quantum to Cosmos 6

Nice, 15-17 October, 2013

Contents

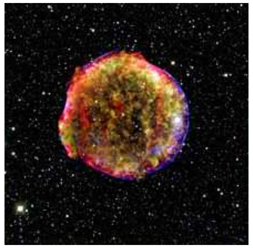
Space Time Explorer and QUantum Equivalence principle Space Test

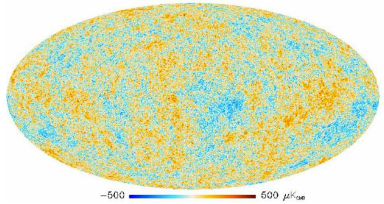
Introduction

- General relativity is a classical theory and difficult to reconcile with quantum mechanics 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 can be seen as deviations from our known laws of gravitation. A small (but non-zero) value of the cosmological constant (Λ-CDM model) is incompatible with quantum field theory (vacuum energy ?).
- Many modified gravitational theories and corresponding cosmological models contain long range scalar fields. BEH (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).

Scientific context

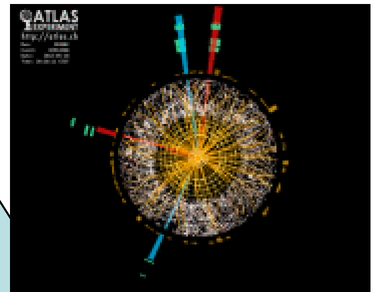
Astronomy & Cosmology
(*Planck, INTEGRAL, EUCLID*, …)





Quantum Gravity
Unification

String theory
Superstrings
Supersymmetry
Loop Quantum Gravity
M-theory
Brane scenarios
etc…

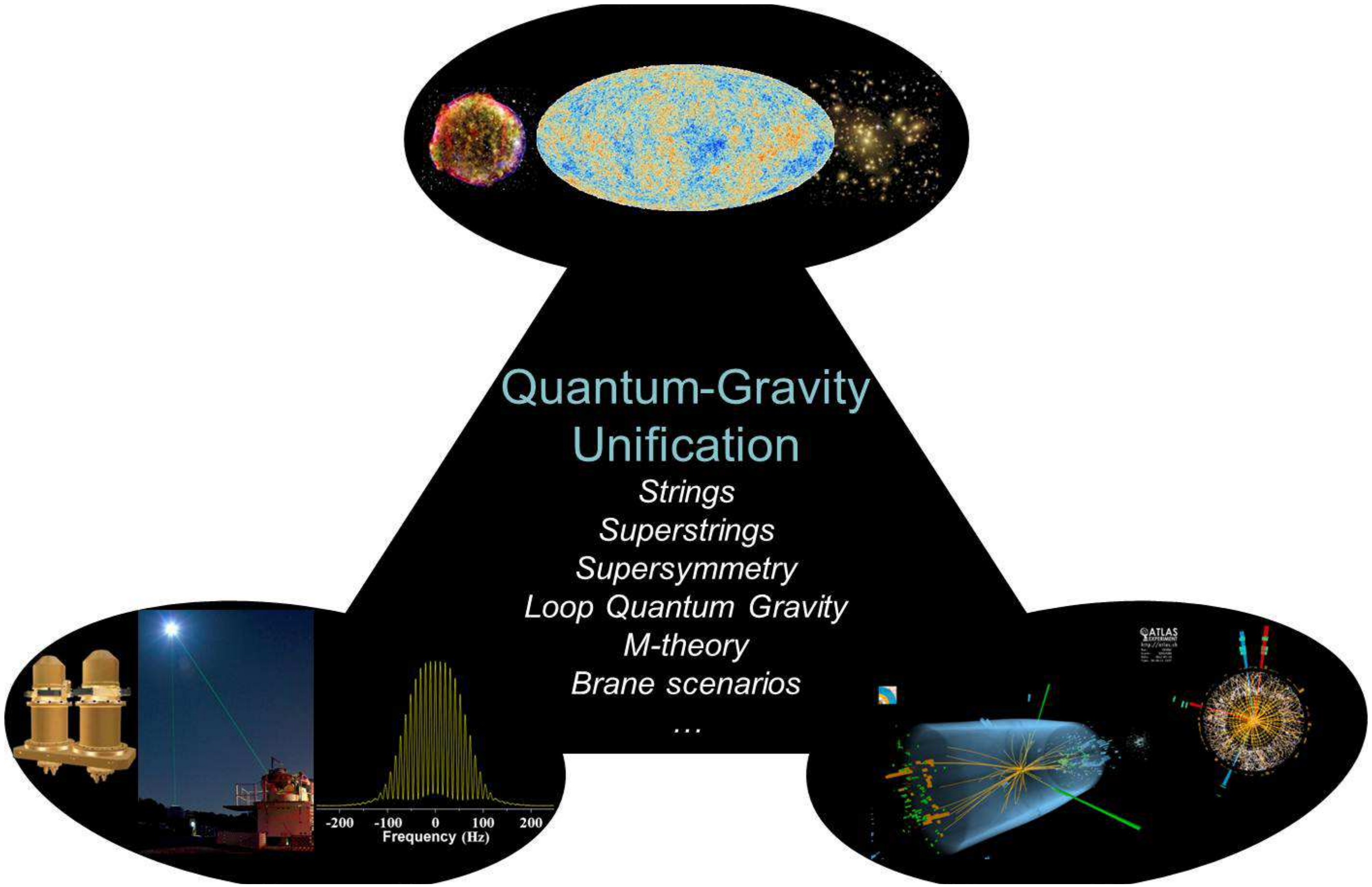


Low energy
(*LLR, lab-tests, ACES, μ-scope, …*)

High energy
(*CERN-LHC, Fermilab, DESY, …*)

Scientific context

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



Low energy
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High energy
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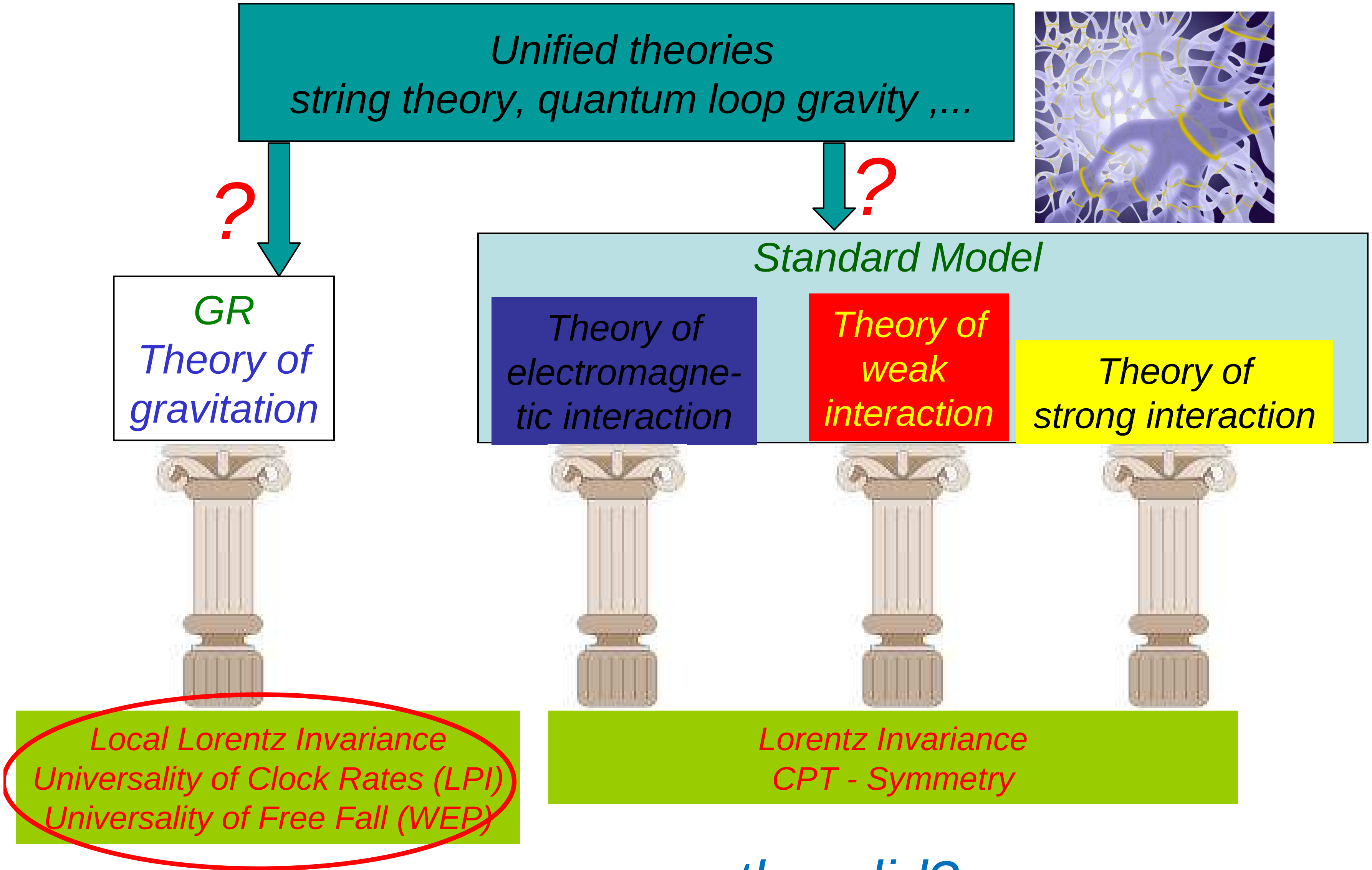
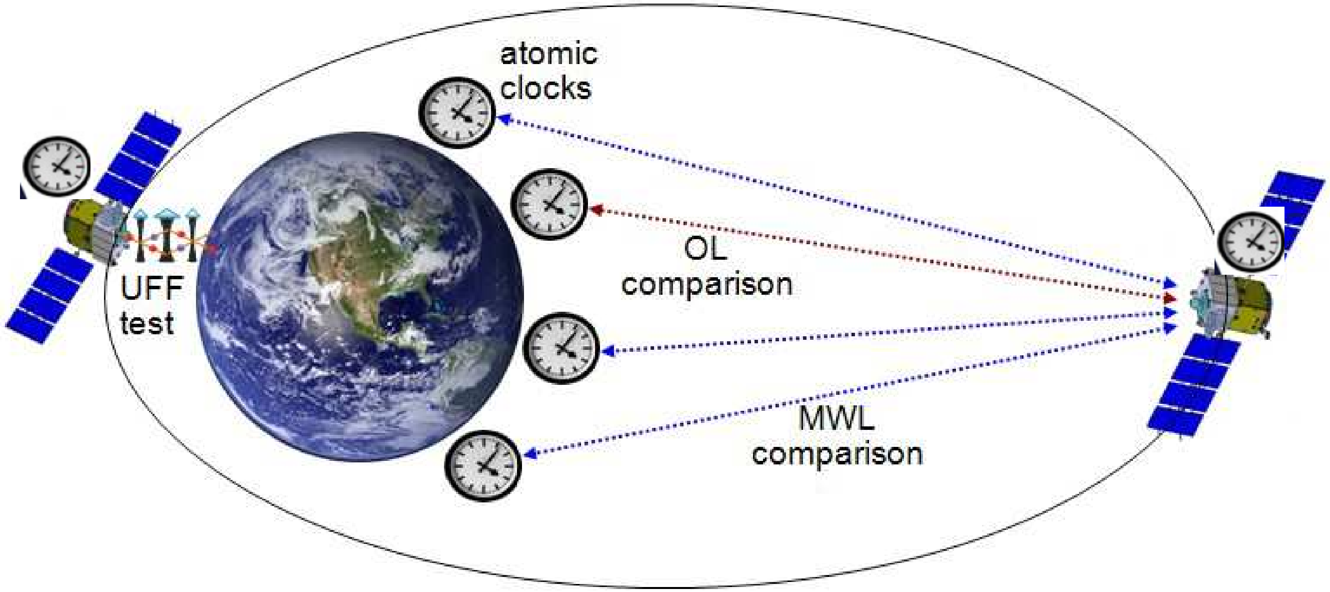


exactly valid?

(courtesy S. Schiller)

STE-QUEST (ESA preselection 2010, launch ≈ 2022)

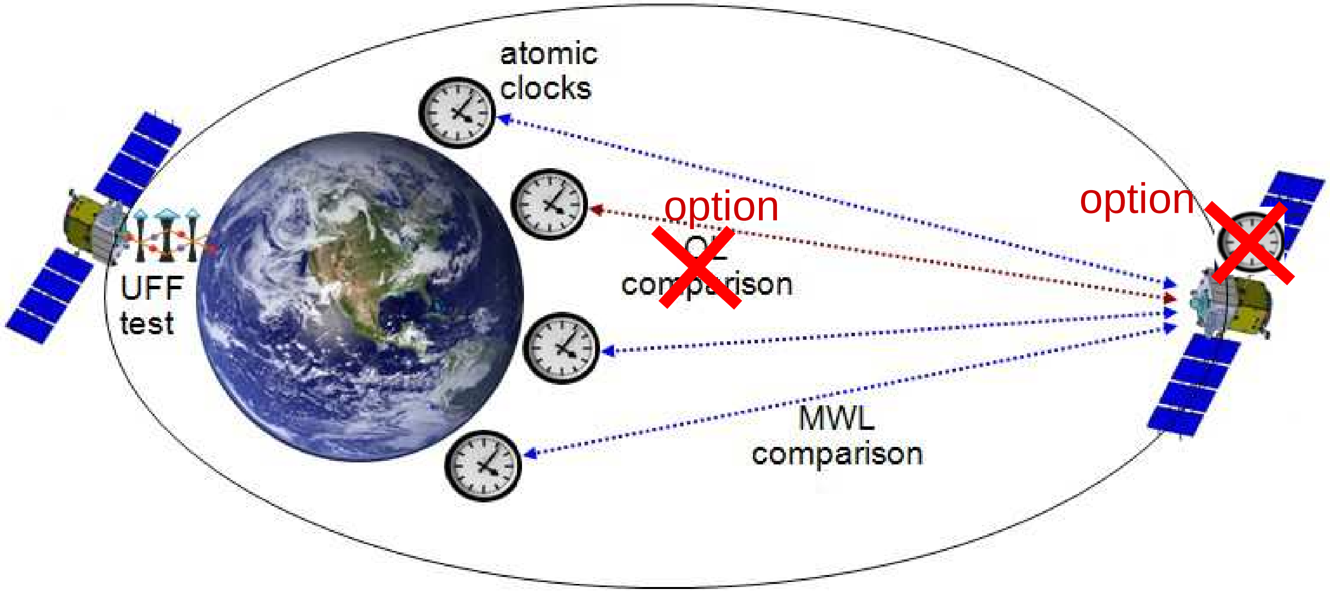


Period: 16 hrs
Apogee: 51000 km
Perigee: 7100 km
Clock (Cs - PHARAO)
Atom interferometer (^{85}Rb-^{87}Rb)
Radio and Optical links

Science Objectives overview:

- UFF/WEP test using ultra cold (BEC) Rb matter waves in differential mode (^{87}Rb et ^{85}Rb) to 2×10^{-15}
- UCR/LPI in Earth field to 2×10^{-7}
- UCR/LPI in Sun and Moon field to 2×10^{-6}(5×10^{-7}) and 4×10^{-4}(9×10^{-5})
- Tests of Lorentz Invariance
- T/F metrology
- Relativistic geodesy

STE-QUEST (present version)



Spacecraft + Links exceed ESA budget

Payload exceeds national agencies budget

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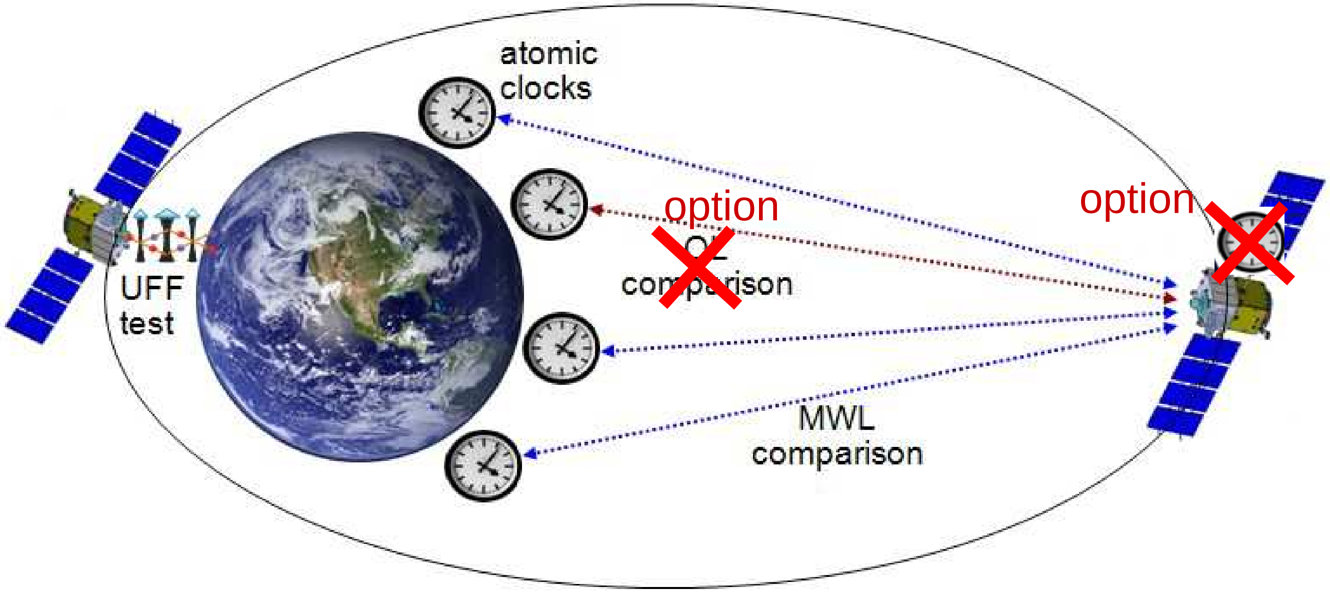

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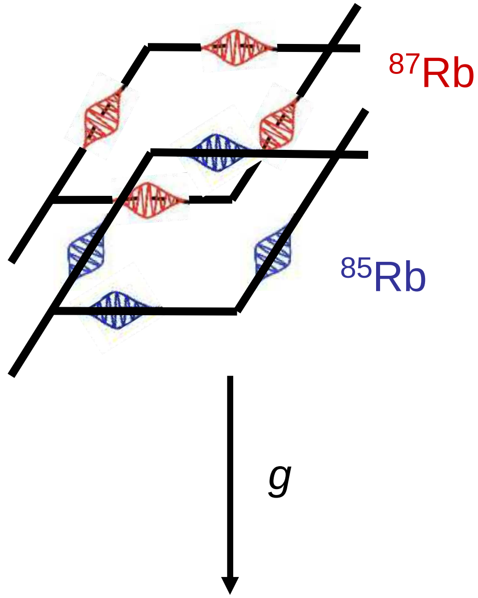
Programmatics:

- Preselected with 4 other candidates in 2010 for 2022/23 Cosmic Vision M3 launch
- Ongoing extensive assessment study for missions and instruments
- Final downselection to one mission in early 2014
- In case of selection → definition study → realization → launch

Universality of Free Fall (UFF/WEP)

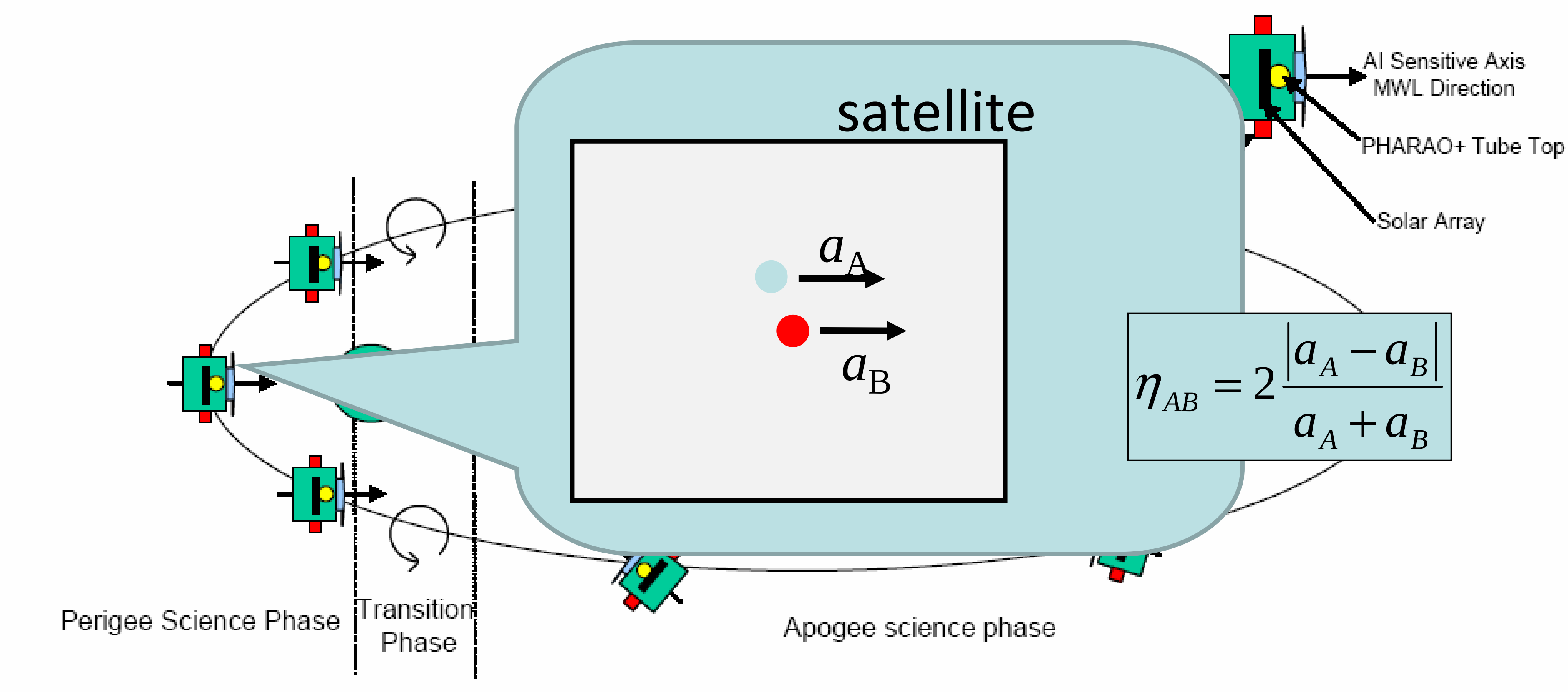
L. Catani, "Galileo performs the experiment of the motion of weights from the Tower of Pisa in the presence of the Grand Duke", Gallery of Modern Art of the Pitti Palace, Florence



"STE-QUEST performs the experiment of the motion of Rb isotopes in a quantum superposition"

STE-QUEST test of UFF/WEP

Violations of UFF/WEP (and UCR/LPI) are generally expected from non-universal couplings of some particle/interaction to gravity eg. due to scalar or tensor fields additional to $g_{\mu\nu}$. This then implies that two "test objects" of different composition fall differently.



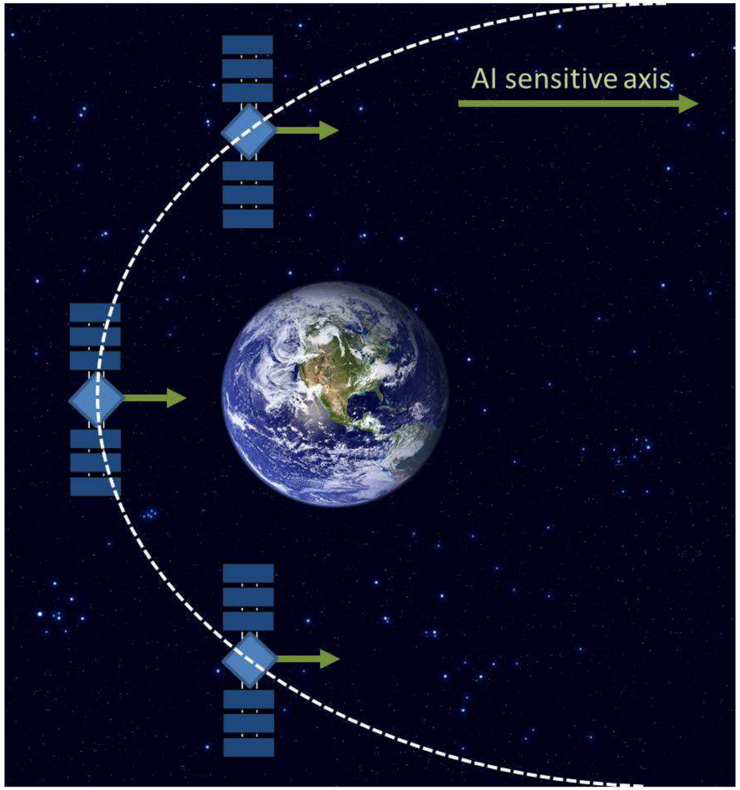
$$\eta_{AB} = 2\frac{|a_A - a_B|}{a_A + a_B}$$

STE-QUEST test of UFF/WEP: performance

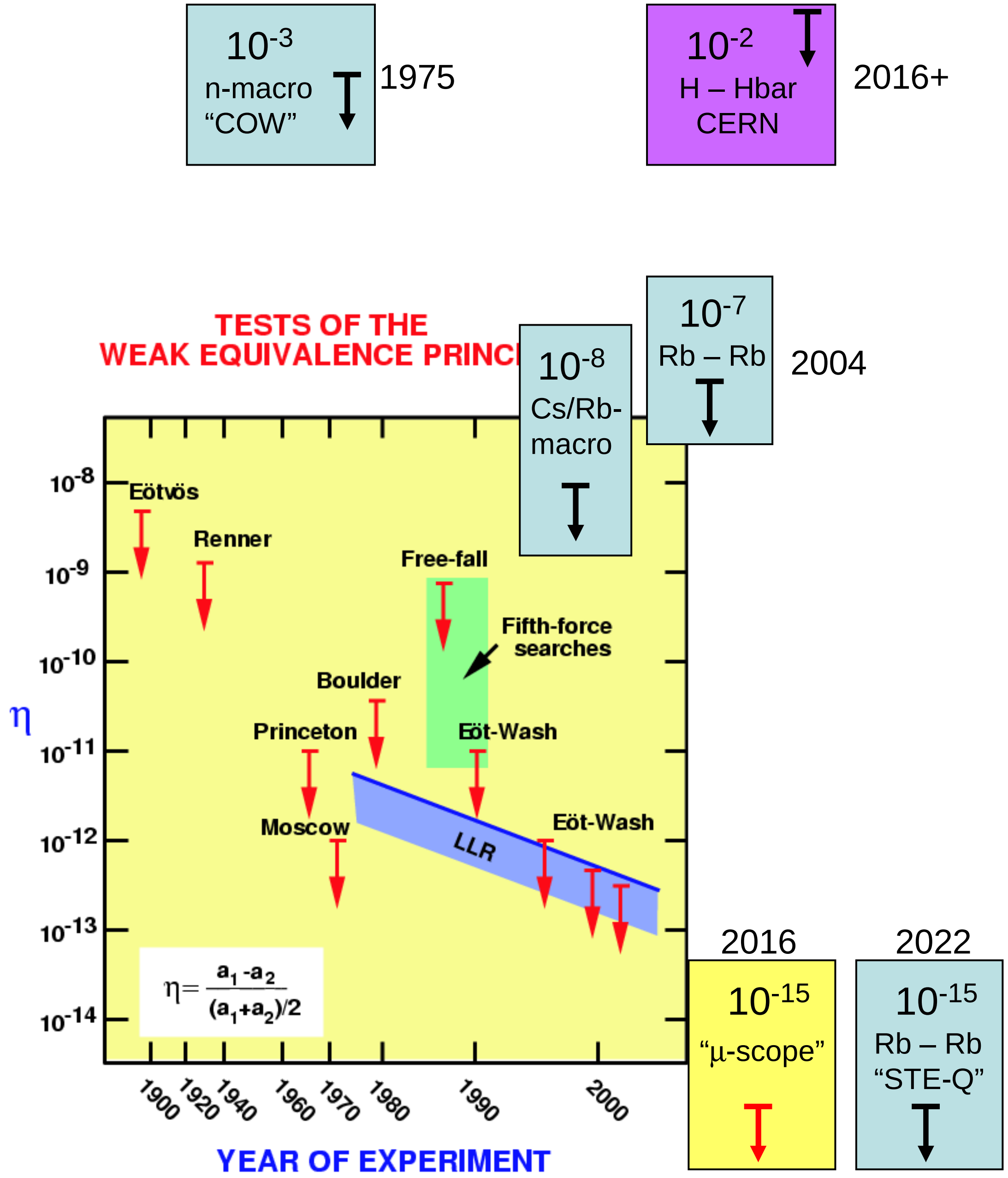
Measure the differential acceleration between two BECs of ^{85}Rb and ^{87}Rb

Statistical uncertainty:
- Uncertainty on Eötvös: $\sigma_\eta = \sigma_{\Delta a}/(g(r)\cos\phi)$
- Single shot (20 s cycle): $\sigma_{\Delta a} \approx 3\times10^{-12}$ m/s^2, depending on gravity gradients through interferometer contrast
- Uncertainty in η per orbit $\approx 5\times10^{-14}$
- 2×10^{-15} level reached after 1.5 years

Systematic uncertainty:
- Gravity and magnetic gradients, Raman laser imperfections, self gravity, …
- Linear maximized sum $\approx 1.4\times10^{-14}$ m/s^2, 4.5 m/s^2 < $g(r)$ < 8 m/s^2 $\rightarrow 2\times10^{-15}$ is reached even in "worst case".
- Systematics can be measured and calibrated during apogee phase or during parts of the perigee passes (5 years mission duration).



STE-QUEST test of UFF/WEP

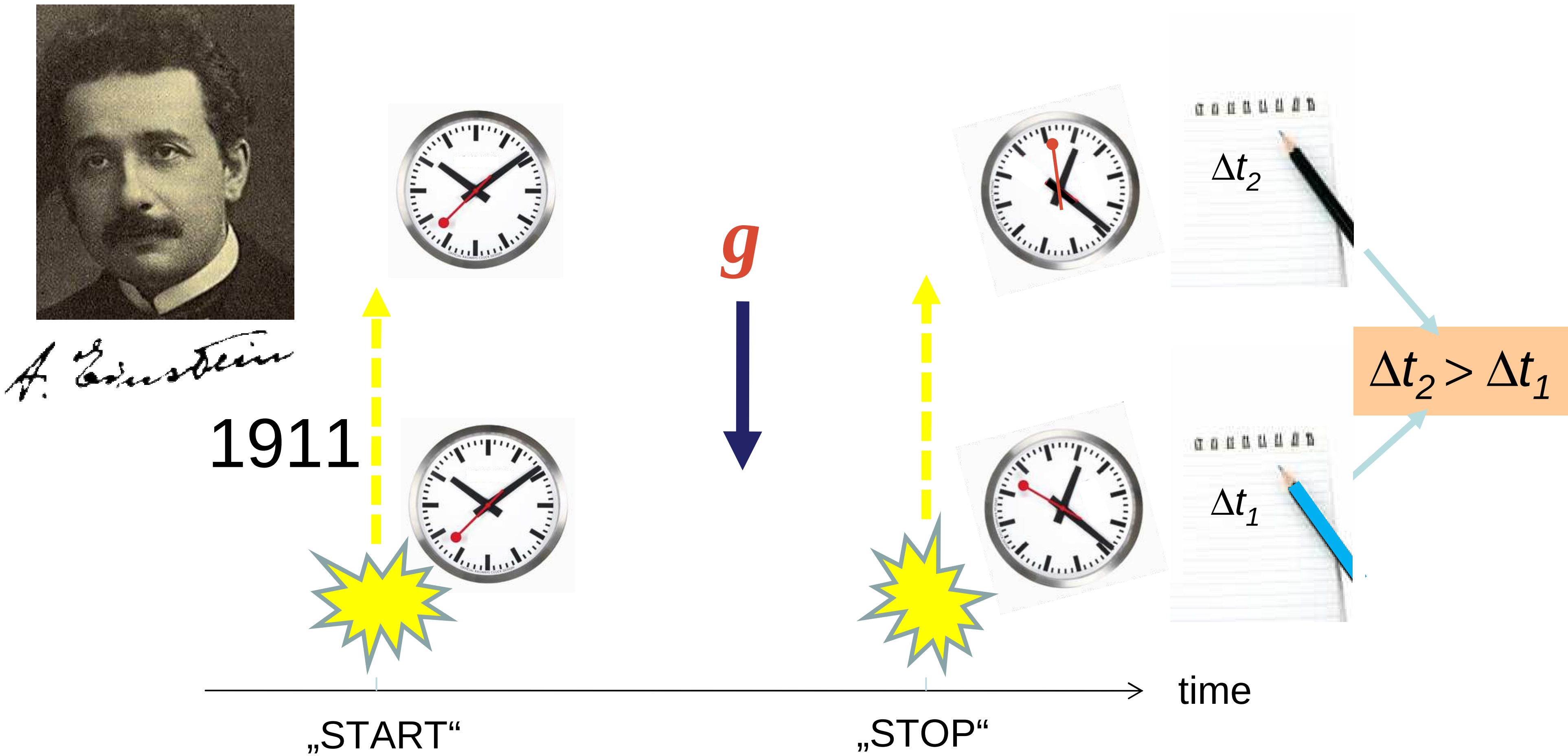


[from Will 2006]

“Macroscopic” vs. “Quantum”

- There exists at present no well established formalism that makes a fundamental distinction between “macroscopic” and “quantum” UFF/WEP tests.
- In some models (eg. Damour & Donoghue, dilaton scenario) ^{85}Rb-^{87}Rb is 5 to 60 times less sensitive than ^{48}Ti - ^{195}Pt (μ-scope)
- From a theoretical point of view quantum tests seem more fundamental (eg. intrinsic spin, tetrads, spinorial derivative, …)
- Quantum description has additional degrees of freedom (wave packet shape vs. only C.o.M.). In the case of STE-Q quantum superposition size >> wave packet size!
- In the absence of Quantum Gravity the description of the gravitational field sourced by a quantum superposition is unclear.
- The absence of a well established formalism does not mean that tests are of no interest (eg. H-Hbar at CERN)
- Fundamentally, and in the absence of a theory of quantum gravity, the interest lies in carrying out experiments that are *phenomenologically* different.

Gravitational Time Dilation (UCR/LPI)



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

Vessot (1980): **0.01% test**
ACES/PHARAO (2016): **10^{-6} test**

(courtesy S. Schiller)

STE-QUEST test of UCR/LPI

Violations of UCR/LPI (and UFF/WEP) are generally expected from non-universal couplings of some particle/interaction to gravity eg. due to scalar or tensor fields additional to $g_{\nu\mu}$. This then implies a dependence on the source eg. Sun (p) vs. Earth (p+n).

Test in the field of the Sun:

- Measure the diurnal frequency variations of two distant Earth clocks using the STE-QUEST links → **2×10^{-6}** (**5×10^{-7}**) after 4y integration.

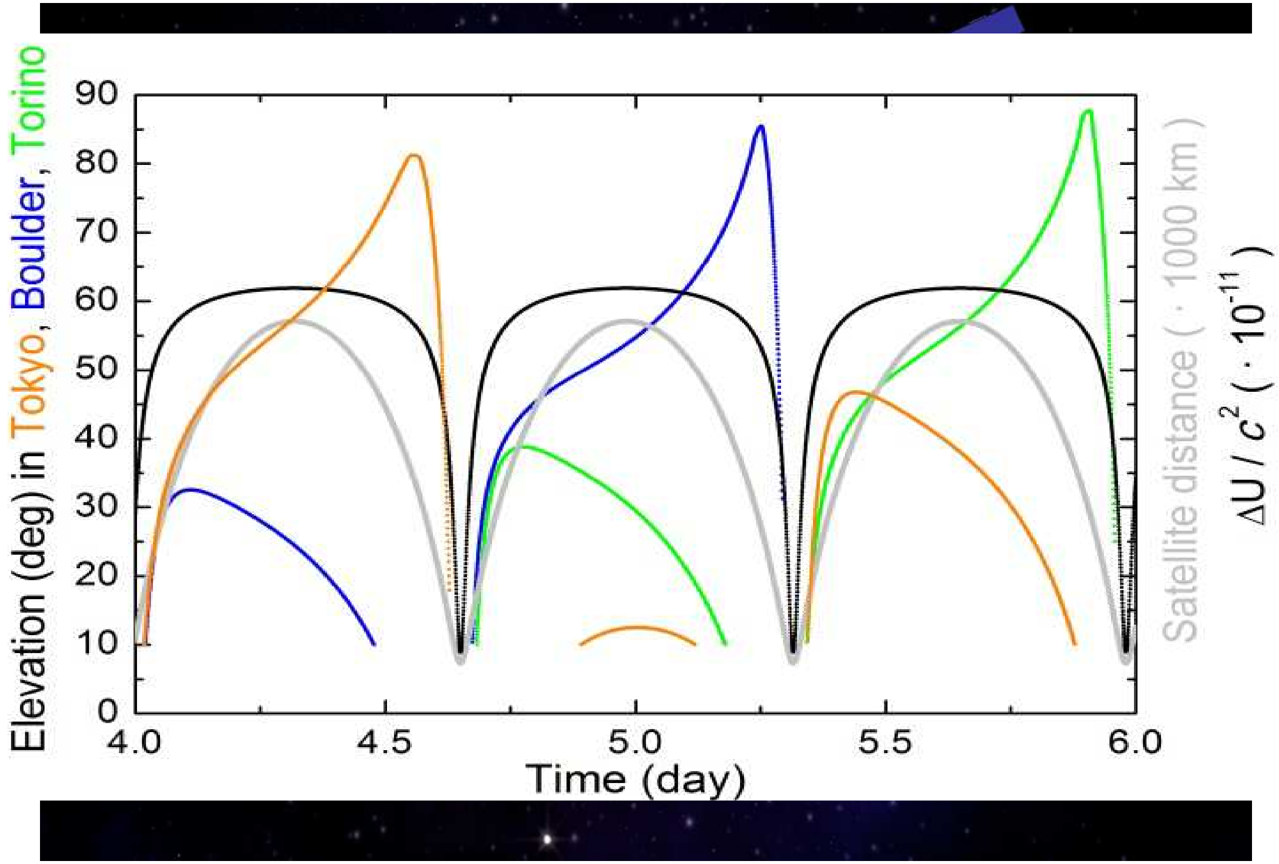
Test in the field of the Moon:

- Measure the ≈diurnal frequency variations of two distant Earth clocks using the STE-QUEST links → **4×10^{-4}** (**9×10^{-5}**) after 4y integration.

Test in the field of the Earth (optional):

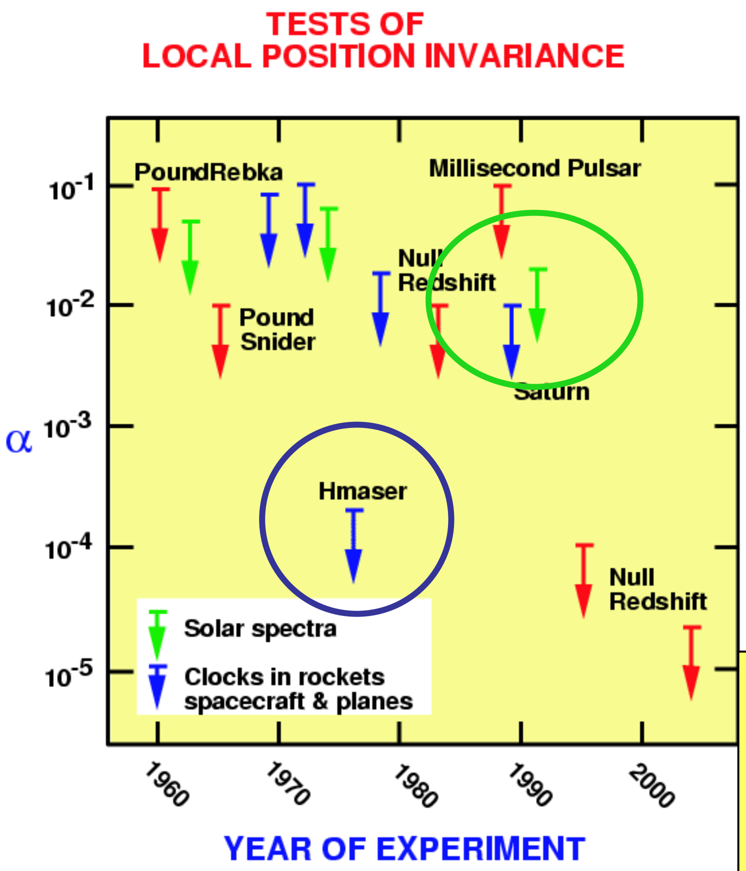
- Measure the absolute frequency difference between ground and space (≈ apogee) → **2×10^{-7}** after 32h integration
- Measure the variation along the elliptic orbit → **2×10^{-7}** after 840d integration (MC simulation results)

Sun/Moon LPI test



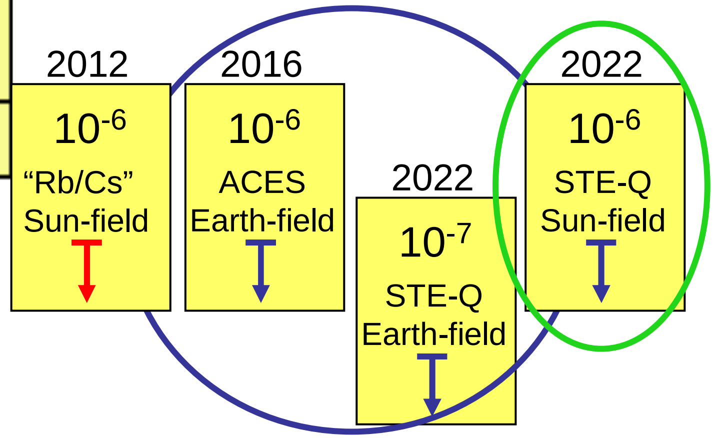
	Measurement resolution	
	After 2 days	**After 4 years**
Sun red-shift	$6 \cdot 10^{-5}$	$2 \cdot 10^{-6}$
Moon red-shift	$1 \cdot 10^{-2}$	$4 \cdot 10^{-4}$

STE-QUEST test of UCR/LPI



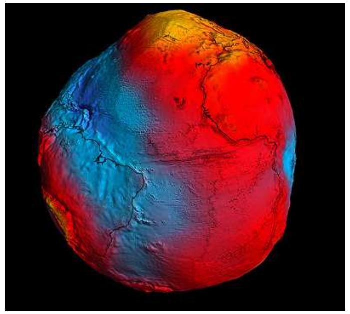
$$\Delta\nu/\nu = (1+\alpha)\Delta U/c^2$$

- In null redshift experiments, the bound is on the *difference* in α between different kinds of clocks.
- No limits in the moon field at present

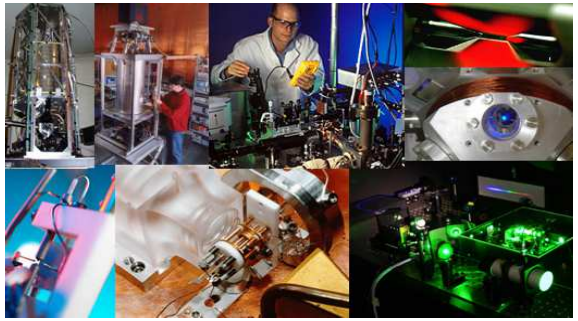


[from Will 2006]

STE-QUEST other science

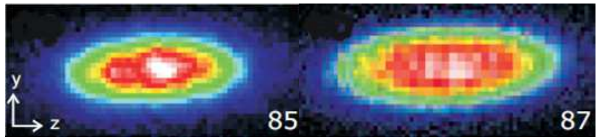


• Tests of Lorentz Invariance (orientation and velocity dependent). Significant improvements, up to 5 orders of magnitude), on a large number of coefficients in the SME.



• Relativistic geodesy: Determine potential difference between distant locations of ground clocks to the cm level. New tool for geodesy and geophysics and related applications.

• High performance comparison of distant clocks for time/frequency metrology, contribution to TAI.



• Cold atom and matter wave physics in microgravity: study evolution and propagation of ultracold samples in absence of perturbations and for long propagation times.

• Microwave vs. Optical link (optional): Compare propagation (atmospheric effects) in the two domains.

Summary of Science Objectives

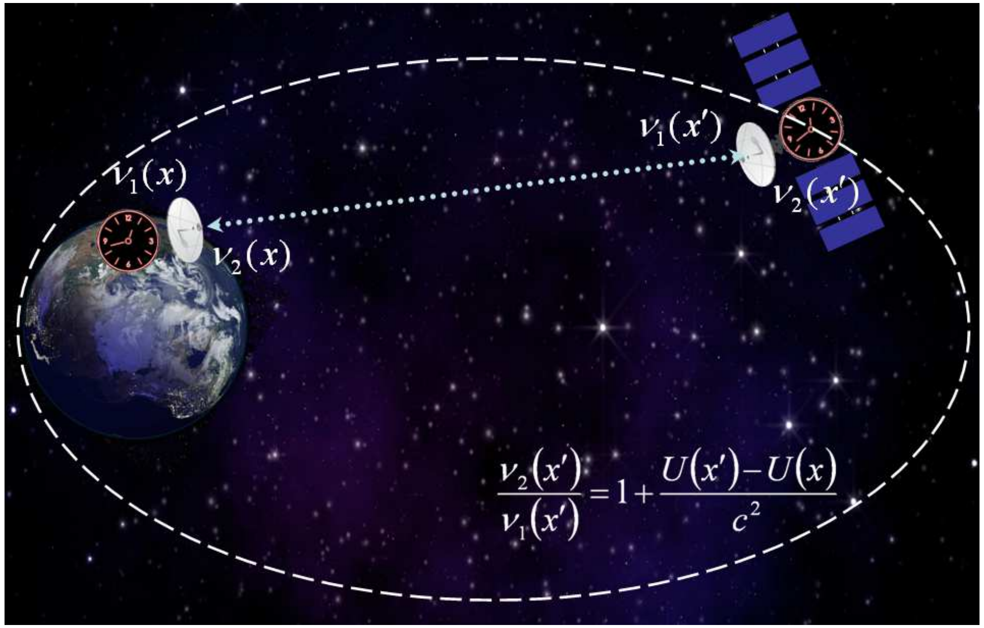
Objective	STE-QUEST	+ options	Other
UFF/WEP	$2x10^{-15}$	$2x10^{-15}$	$2x10^{-7}$ (Fray 2004) $7x10^{-9}$ (Merlet 2010) $2x10^{-13}$ (Eöt-Wash 2008) 10^{-15} (μ-scope 2016)
UCR/LPI Sun	$2x10^{-6}$ ($5x10^{-7}$)	$5x10^{-7}$	10^{-2} (Krisher 1993) $2x10^{-5}$ (ACES 2016)
UCR/LPI Moon	$4x10^{-4}$ ($9x10^{-5}$)	$9x10^{-5}$	$3x10^{-3}$ (ACES 2016)
UCR/LPI Earth	-	$2x10^{-7}$	$7x10^{-5}$ (Vessot 1980) $2x10^{-6}$ (ACES 2016)

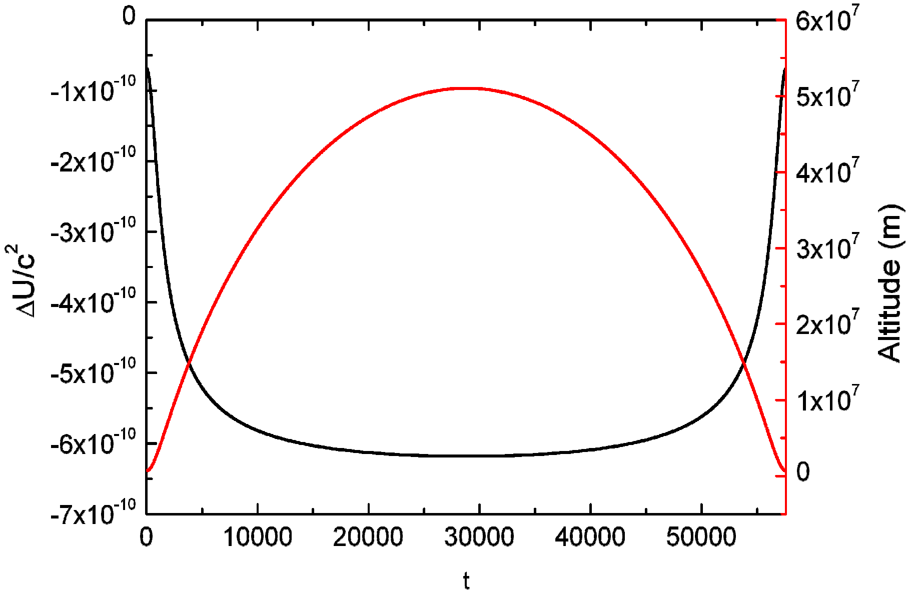
Other science objectives:

- Lorentz Invariance: Improvements by up to 10^5 on several SME parameters.
- Relativistic Geodesy: Improve to cm level: comparable *and complementary* to "classical" geodesy.
- T/F metrology: Distant clock comparisons at 10^{-18} level after a few days integration: Essential for next generation ground clocks (at present $9x10^{-18}$ accuracy, $2x10^{-18}$ stability).
- Cold atom physics in microgravity

THANK YOU

LPI test in Earth field (optional)





- DC measurement:
  - Absolute comparison of the space clocks to clock on the ground
  - Sensitivity: $4{\cdot}10^{-7}$ in 32 hours (2 orbits) over a single ground station; $2{\cdot}10^{-7}$ in 6 days (limited by the specified clock inaccuracy)
- AC measurement:
  - Modulation of the redshift effect between perigee and apogee
  - Sensitivity: $5{\cdot}10^{-6}$ in 32 hours (2 orbits) over a single ground station; of $2{\cdot}10^{-7}$ in 840 days