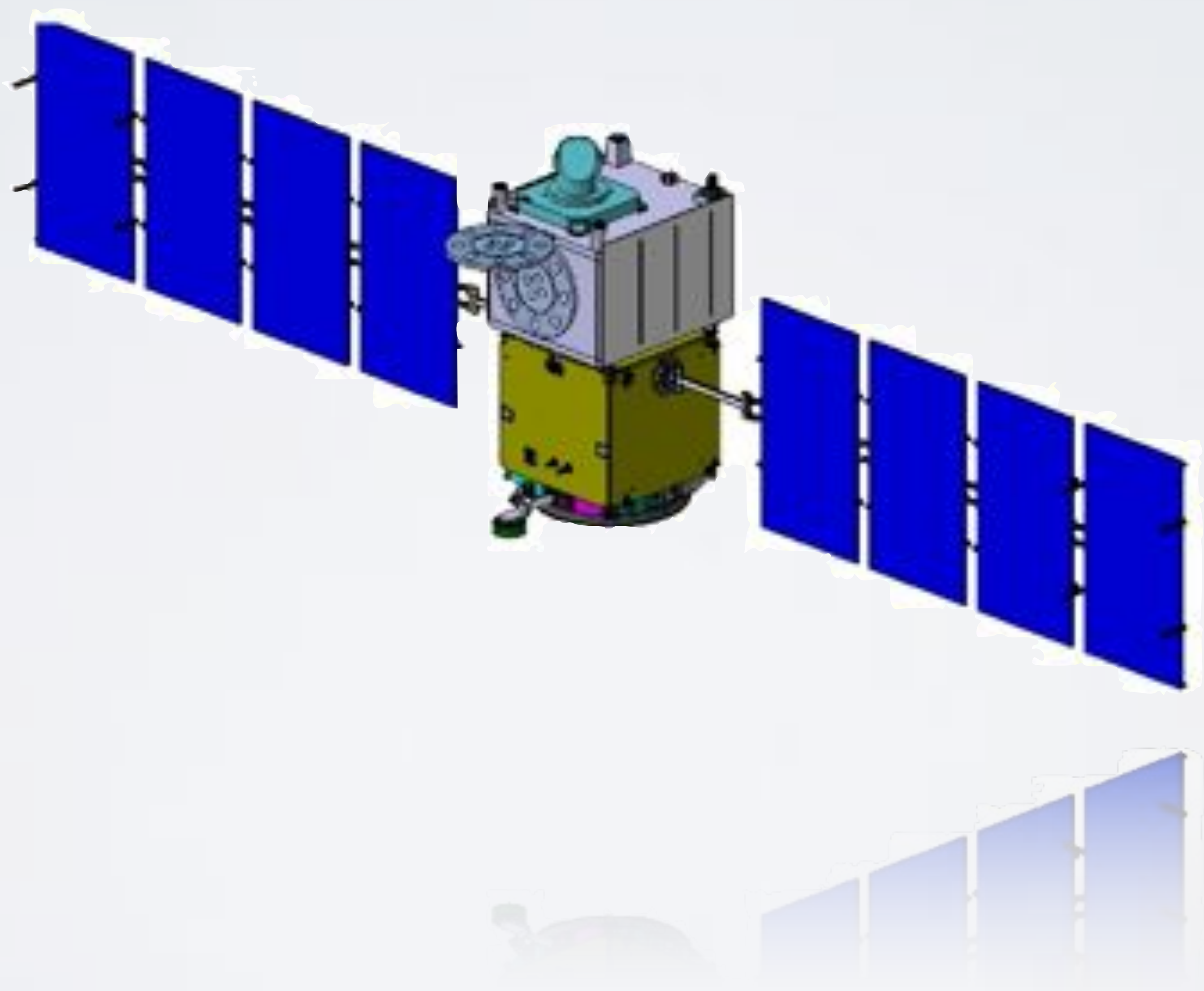
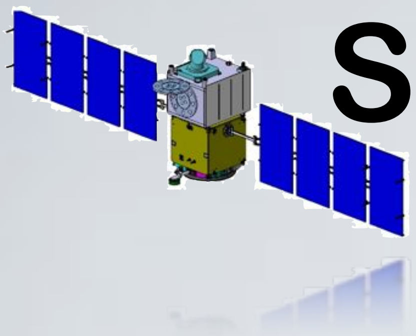
STE - QUEST

Space Time Explorer
&
Quantum Test of the Equivalence principle



A class M mission for cosmic vision 2020-2025



STE - QUEST

A class M mission to test gravitation with light and quantum particles

The Einstein equivalence principle (EEP) is the heart of gravitation theory. It states that :

- Test bodies fall with the same acceleration independently of their internal structure or composition
  - **Weak Equivalence Principle, or WEP**
- The outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed
  - **Local Position Invariance, or LPI**
- The outcome of any local non-gravitational experiment is independent of the velocity of the freely falling reference frame in which it is performed
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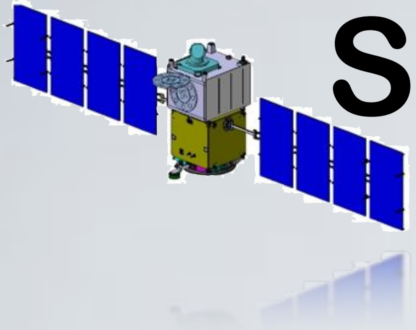

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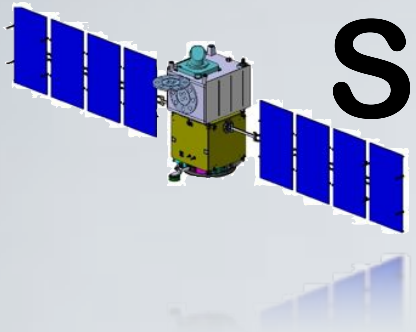

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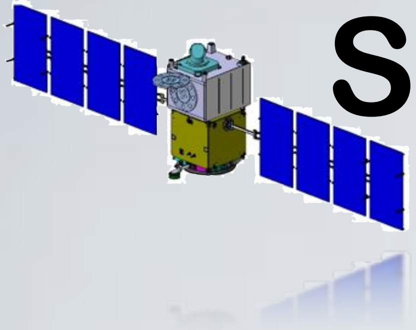

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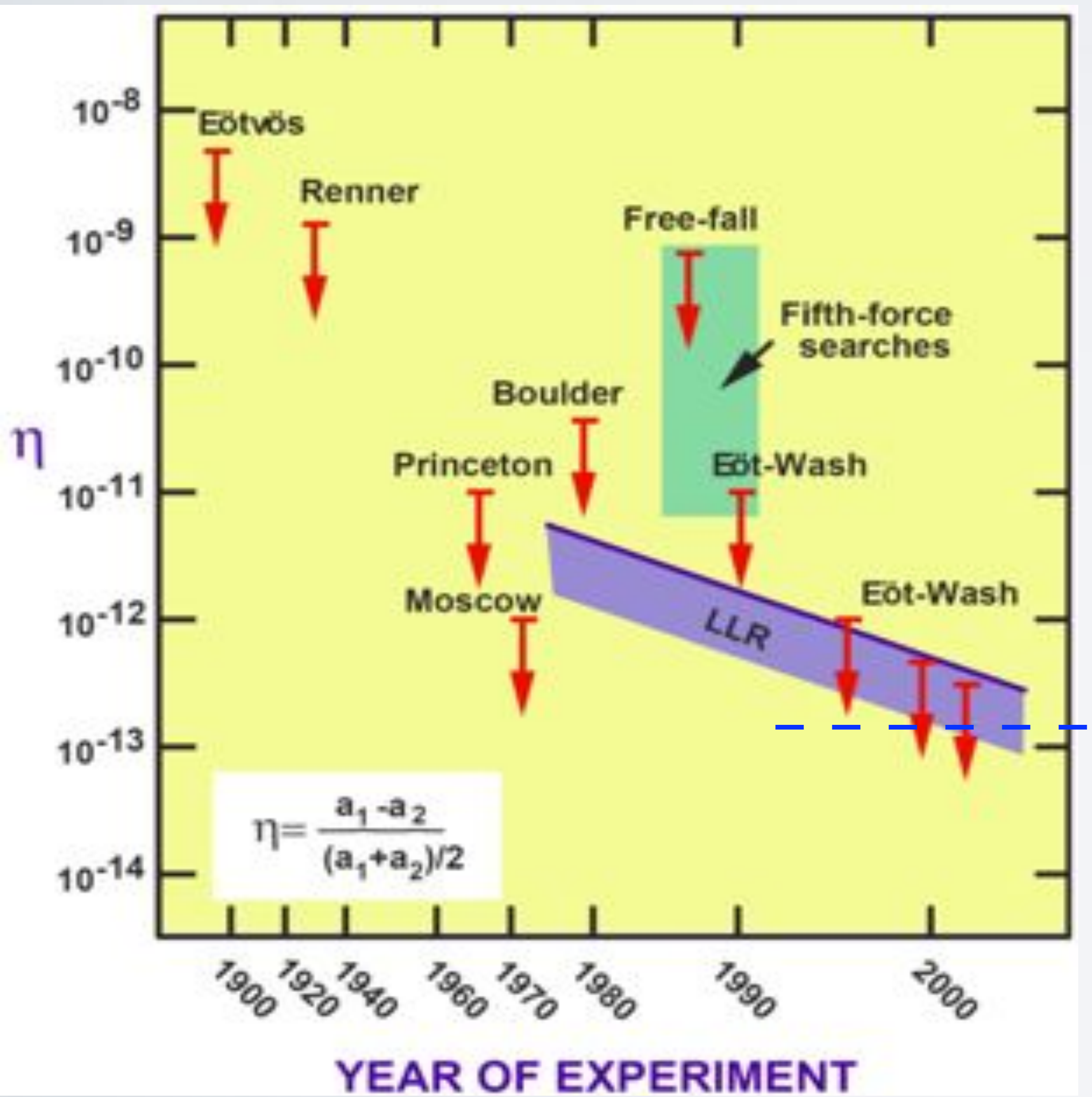
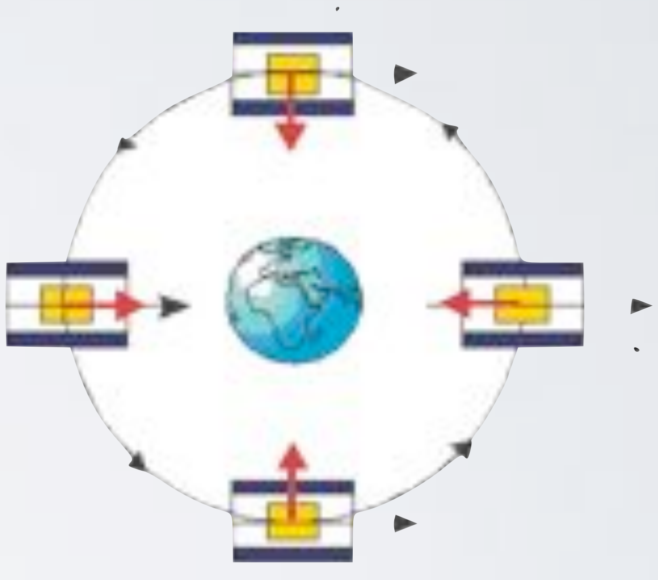
A class M mission to test gravitation with light and quantum particles

Weak Equivalence Principle

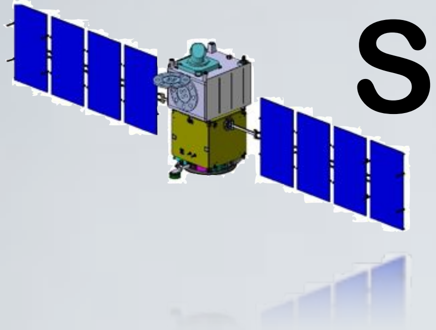


- Macroscopic (MICROSCOPE : 10^{-15})



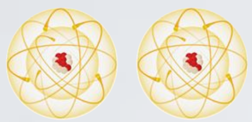
- Microscopic (STE-QUEST : 10^{-15})

$$\begin{cases} \phi_K &= k_K \left(a_K T^2 + X_{\text{mirroir}} \right) \\ \phi_{Rb} &= k_{Rb} \left(a_{Rb} T^2 + X_{\text{mirroir}} \right) \end{cases}$$

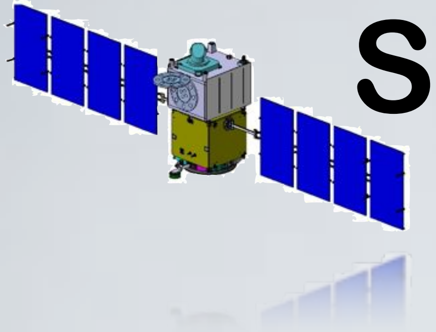


STE - QUEST

A class M mission to test gravitation with light and quantum particles



- Compare the free fall of 2 different atomic species
- Atom interferometry : use a precise ruler to get the position in time



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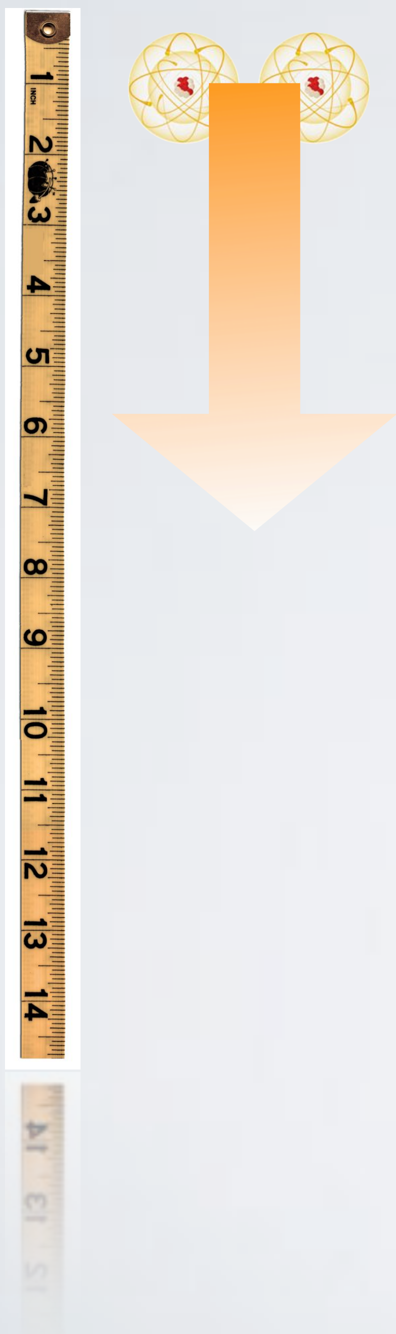

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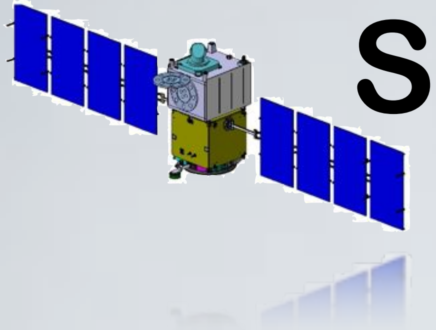

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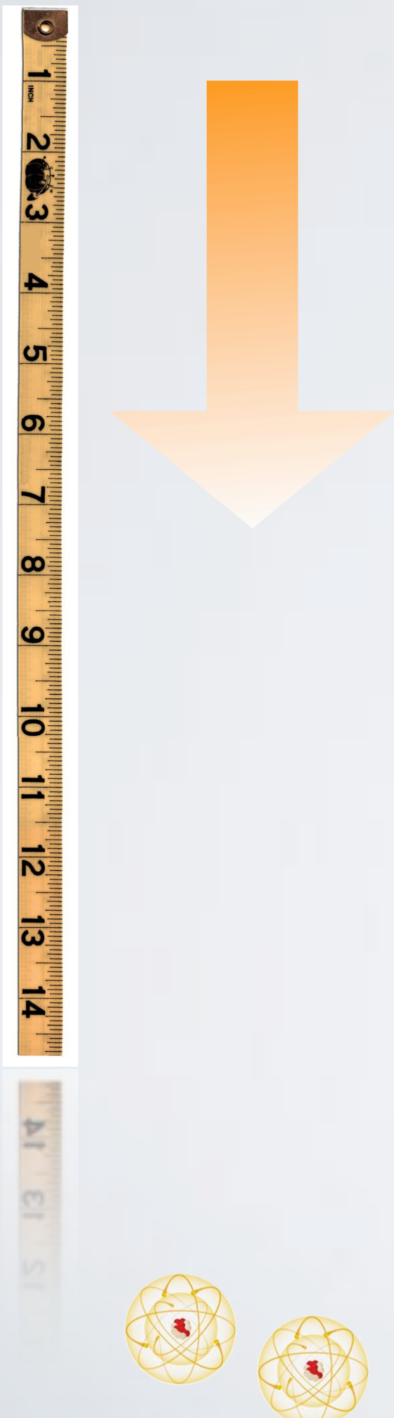
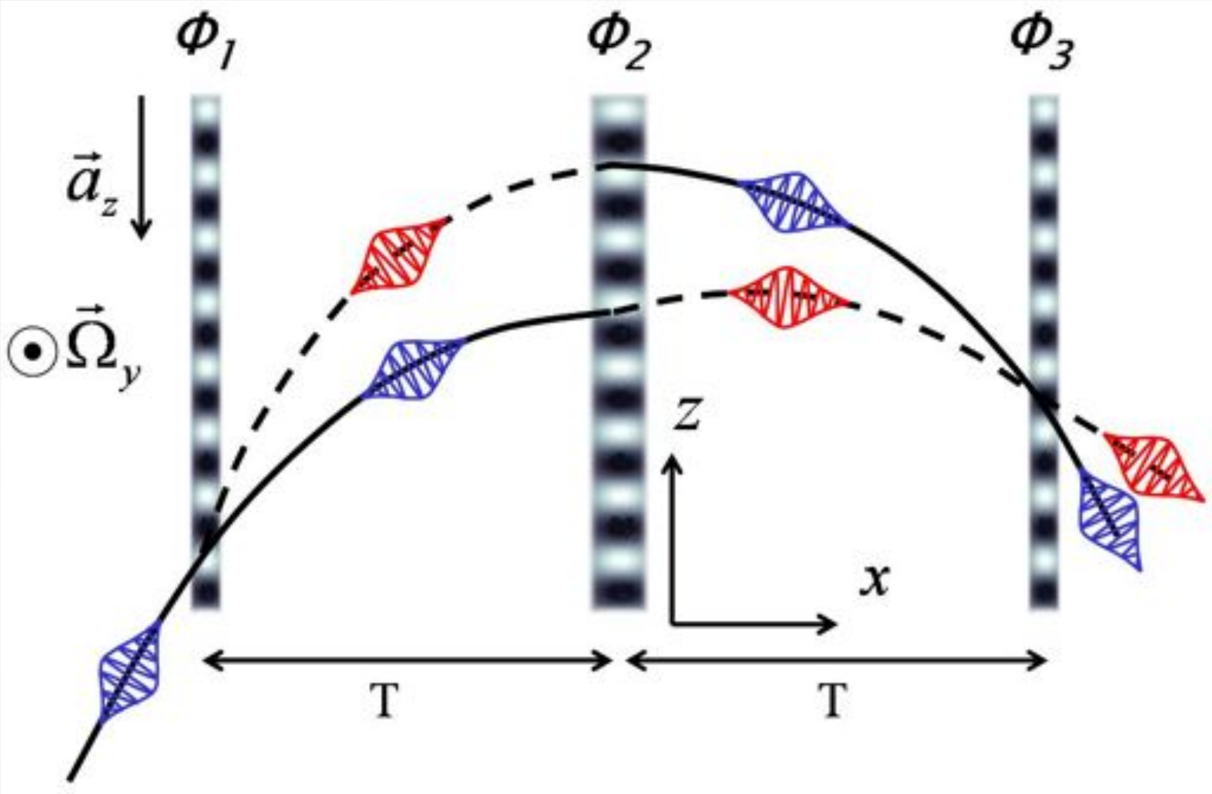


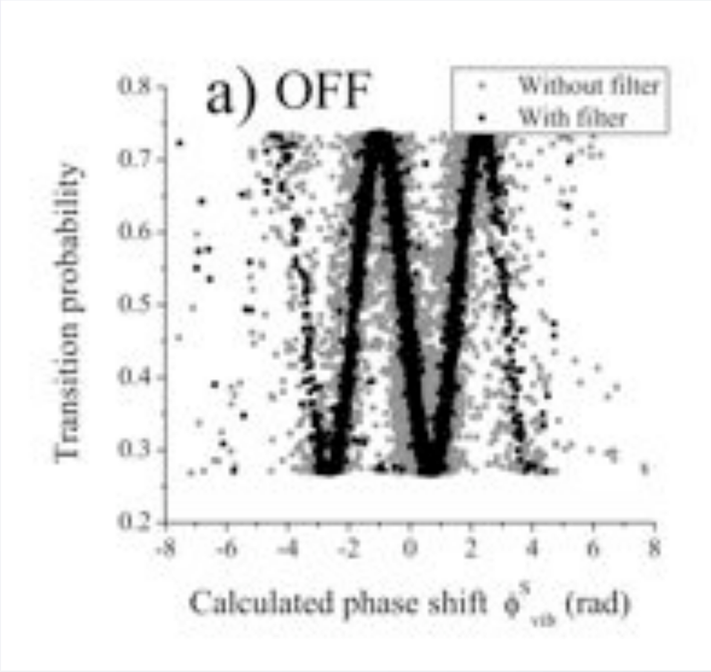
- Compare the free fall of **2 different atomic species**
- Atom interferometry : use a precise ruler to get the position in time

STE - QUEST

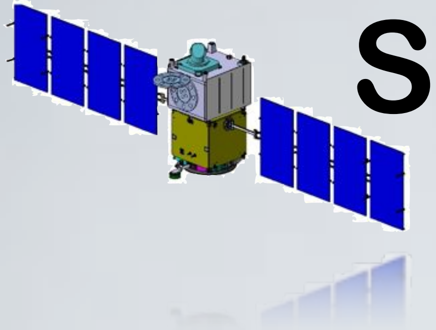
Atom Interferometer

- **Based on Raman pulses atom optics :** coherent manipulation of atomic wave packets with light
  - $\pi/2 - \pi - \pi/2$ (Kasevich & Chu 1991) : interferometer
  - $\pi/2$: creates a superposition of 2 different velocities : beam splitter
  - π : exchanges velocities : mirror





From S. Merlet, et al.
Metrologia 46 (2009), 87–94



STE - QUEST

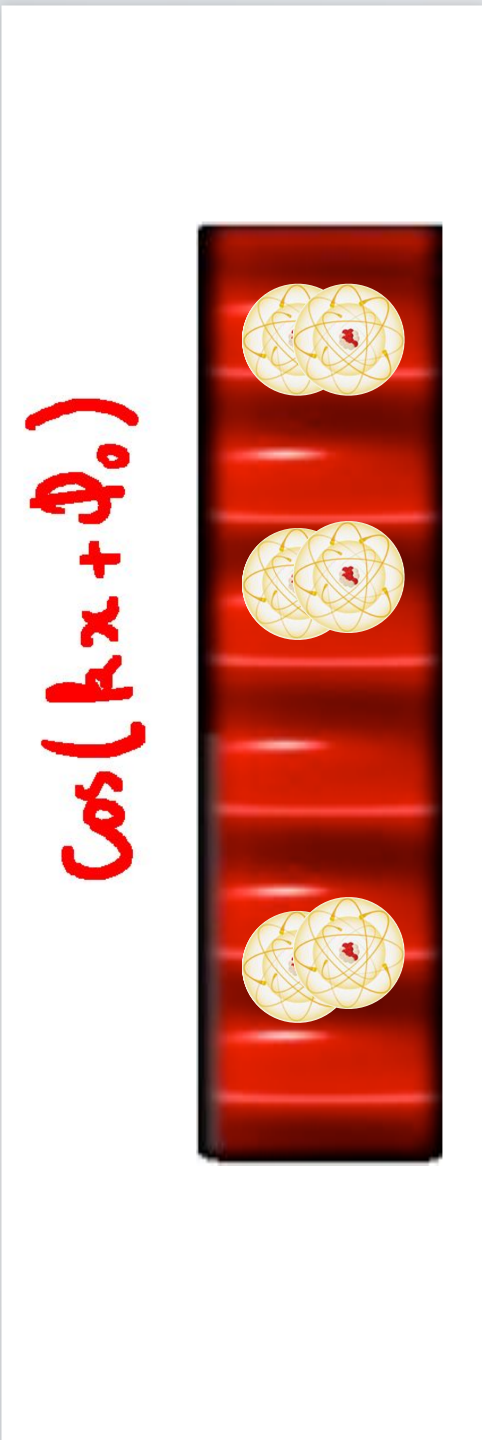
Atom Interferometer high accuracy and stability

- We use an (optical) ruler to precisely measure the modification of the (atomic) test mass position
- Atom sensor : Laser phase is read by atom interferometry.
- Relative displacement of the atomic inertial referential frame (at rest) compared to the referential frame of the payload (lasers)
- Sensitivity increasing as T^2: gain in micro-gravity (3 to 4 order of magnitude)

$$\Delta a_{min} = \frac{a|_{\Delta\phi_{acc}=1\,rad}}{\sqrt{N}} \equiv \frac{1}{k T^2 \sqrt{N}}$$

STE - QUEST

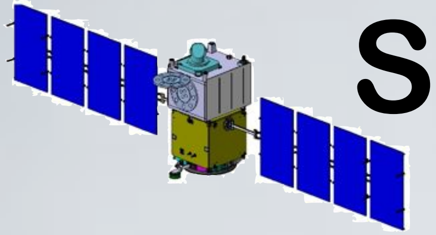
Test of the UFF



- Double species interferometer :
- Measure of the displacements of the compared to the same referential frame (payload)
- Differential atomic acceleration: independent of the carrier

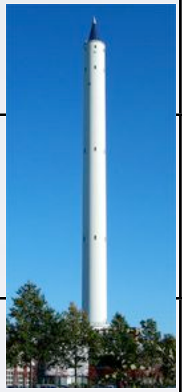
$$\Delta a_{min} = \frac{a|_{\Delta\phi_{acc}=1\,rad}}{\sqrt{N}} = \frac{1}{k T^2 \sqrt{N}}$$

Differential sensitivity: $5.4\ 10^{-12}\ m.s^{-2}/\sqrt{\tau}$



STE - QUEST

Platforms for experiments in extended free fall

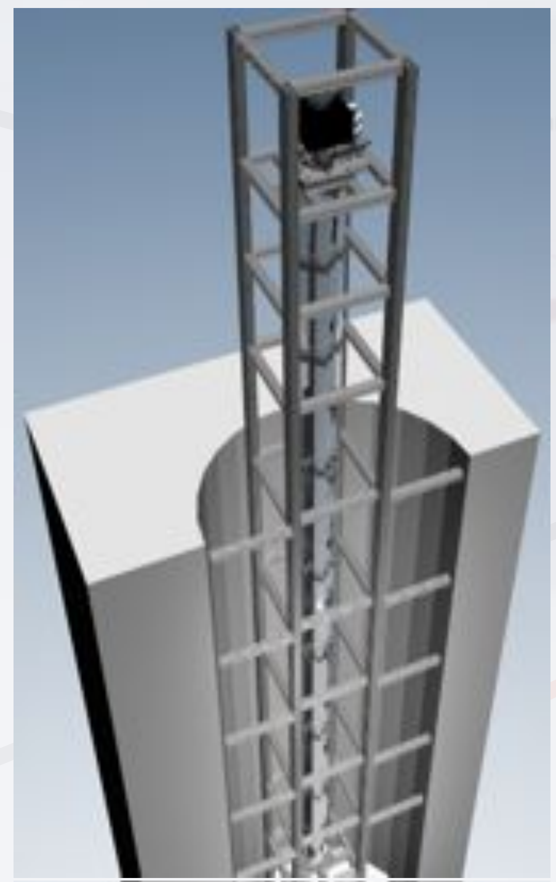
platform	µg-quality [g]	µg-duration
ground	10^{-6}	1 seconds
droptower 	10^{-6}	4.8 s, 9s with catapult
airplanes	10^{-2} 	20 seconds
ballistic rockets	 10^{-5}	up to 6 minutes
space carrier	10^{-6} 	3 days
ISS	 10^{-4}	days to years
satellite	10^{-7}	2-5 years

STE - QUEST

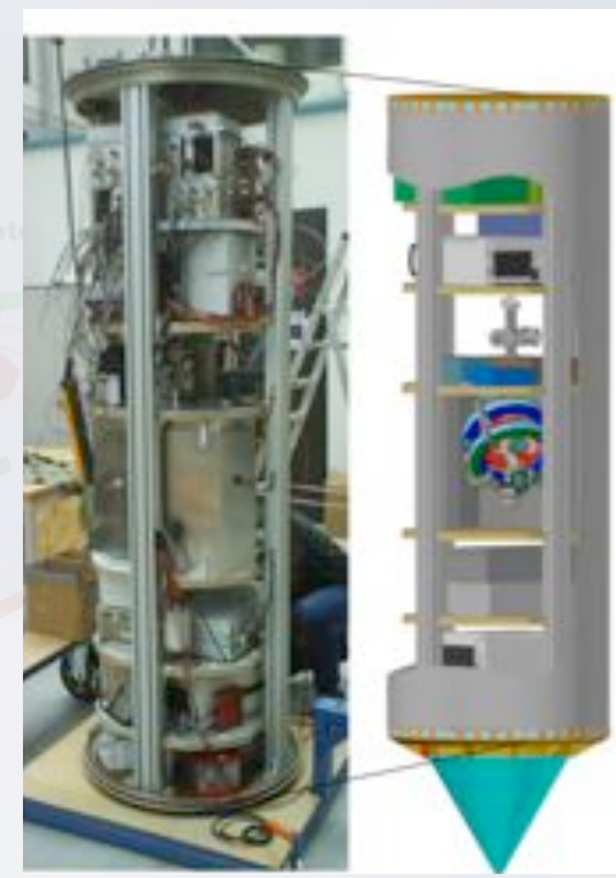
A class M mission to test gravitation with light and quantum particles

Atomic Interferometer basics

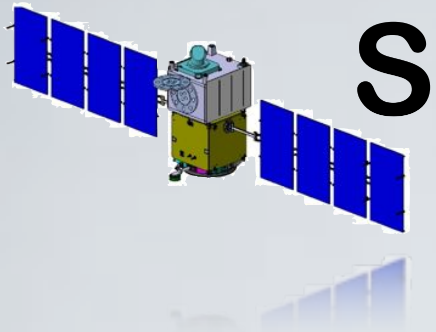
Ice experiment in 0-g plane



Ground 10 m experiment



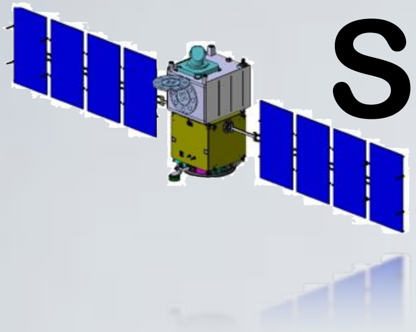
Quantus experiment in Bremen tower



STE - QUEST

Test of the UFF: orbit

- Choice of the orbit:
  - Inertial orbit (no spinning)
  - Low orbit to increase the signal: acceleration signal decrease as $1/r^2$
  - Reduction of the drag (acceleration noise): high enough orbit
  - Optimum orbit between 600 km and 3000 km
  - No drag-free system needed



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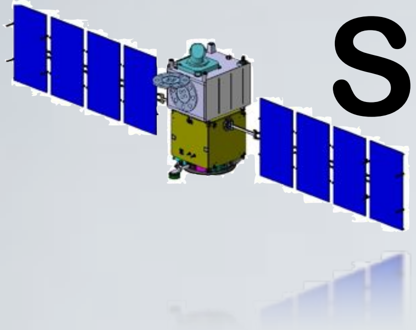

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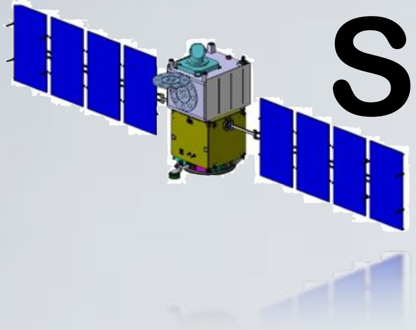

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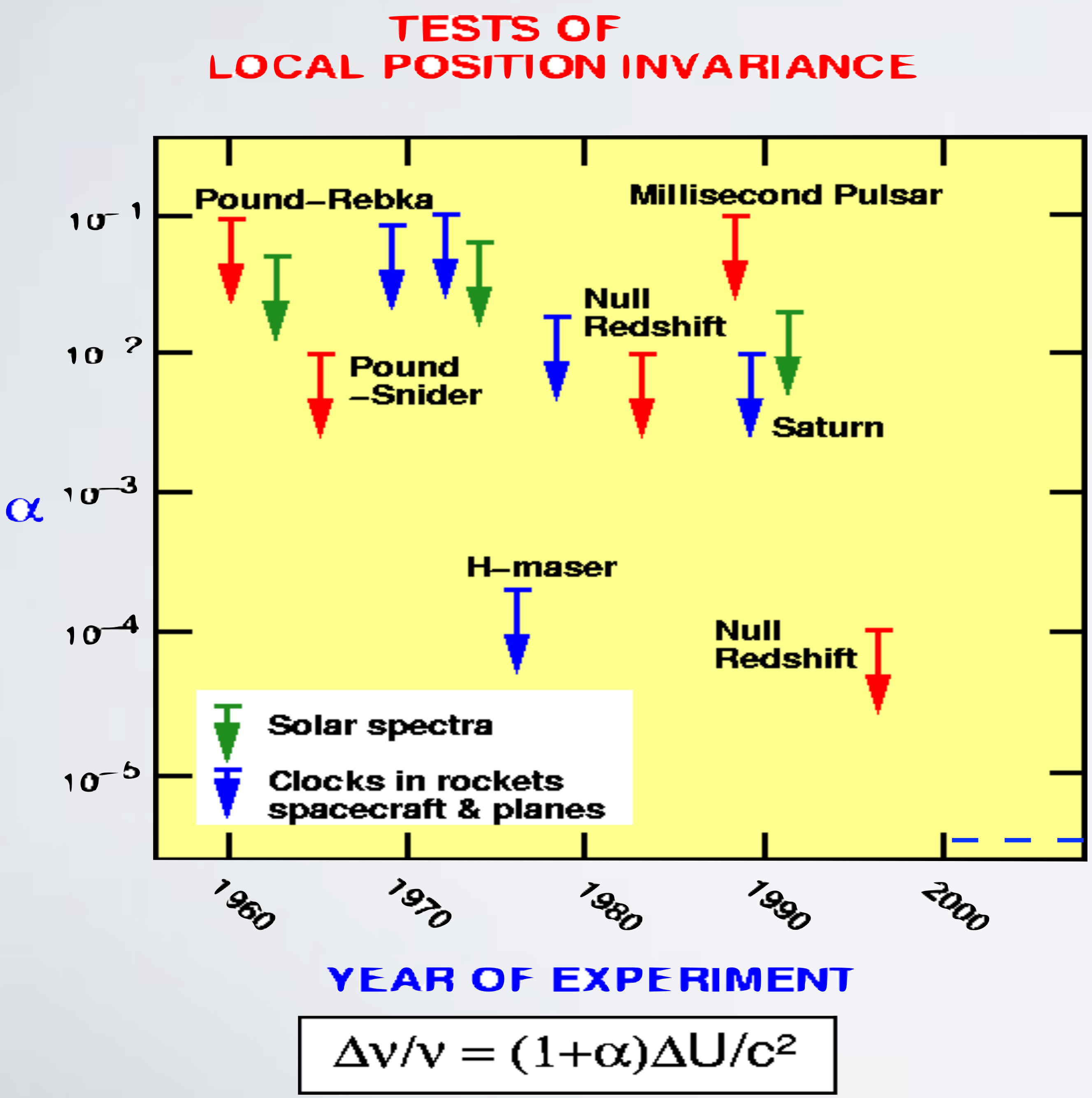
Local Position Invariance

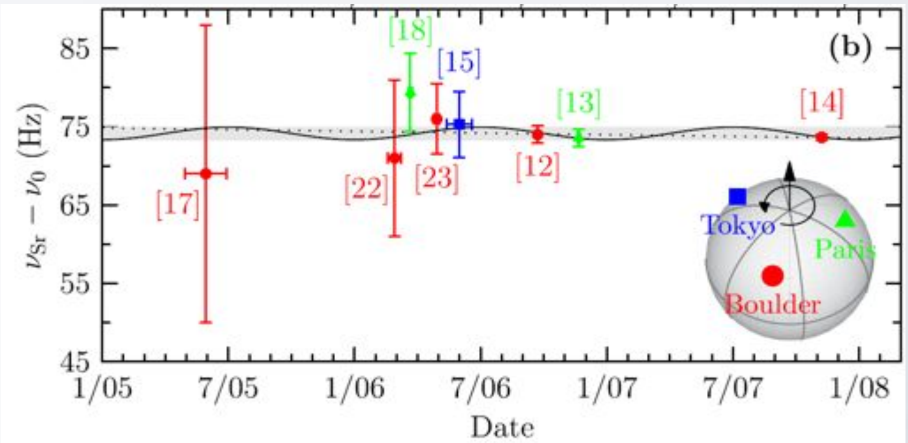


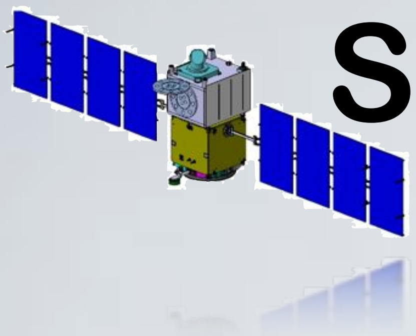
ACES

- Red shift test (GPA : 7×10^{-5})

$$\frac{\Delta\nu}{\nu} \stackrel{?}{=} \frac{\Delta U}{c^2}$$

- ACES: 2×10^{-6}
  - Null red shift test (Clock comparison)



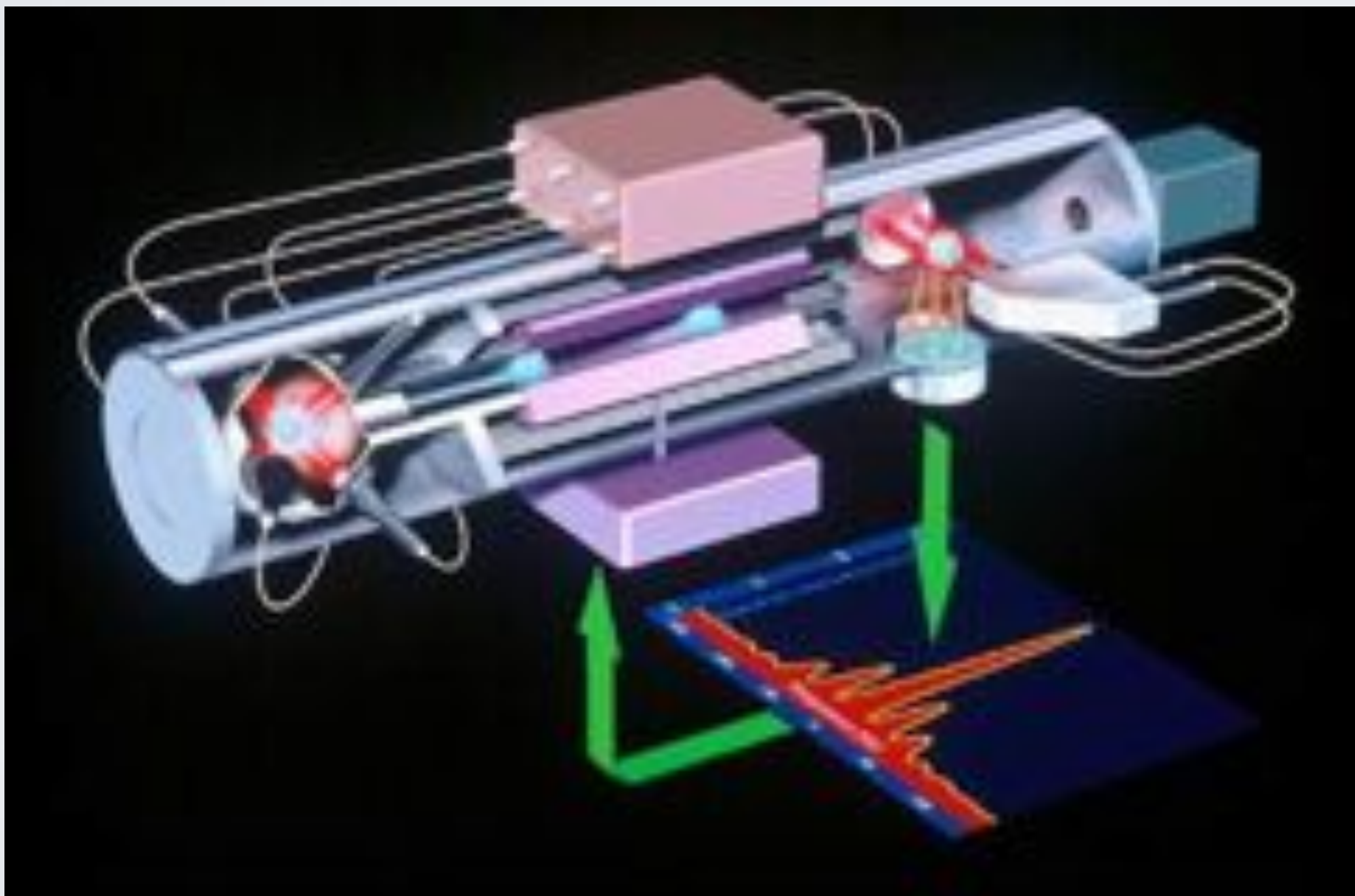


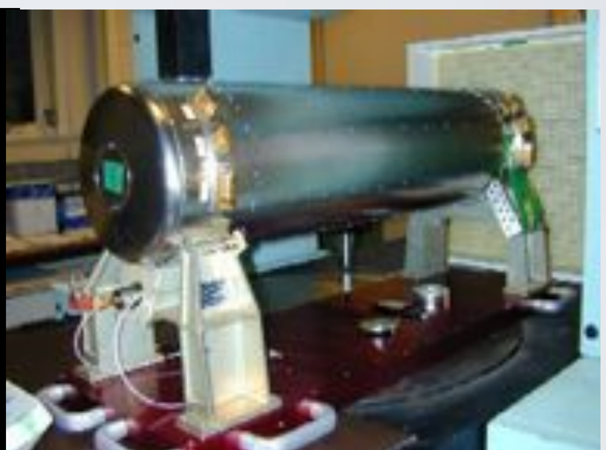
STE - QUEST

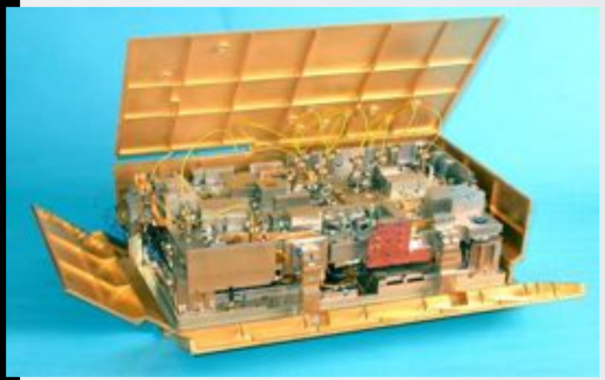
A class M mission to test gravitation with light and quantum particles

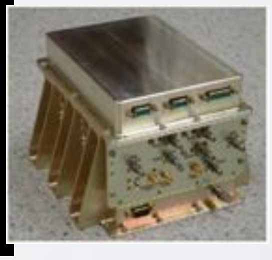
Atomic clocks basics with Rb atoms (gain of 3 to Cs)

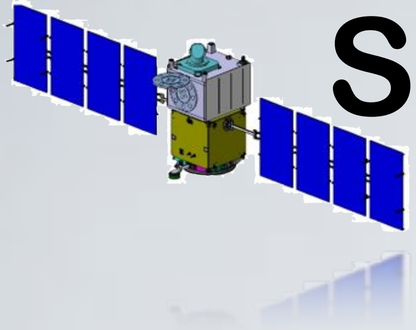
Pharao Cs clock (ACES mission)











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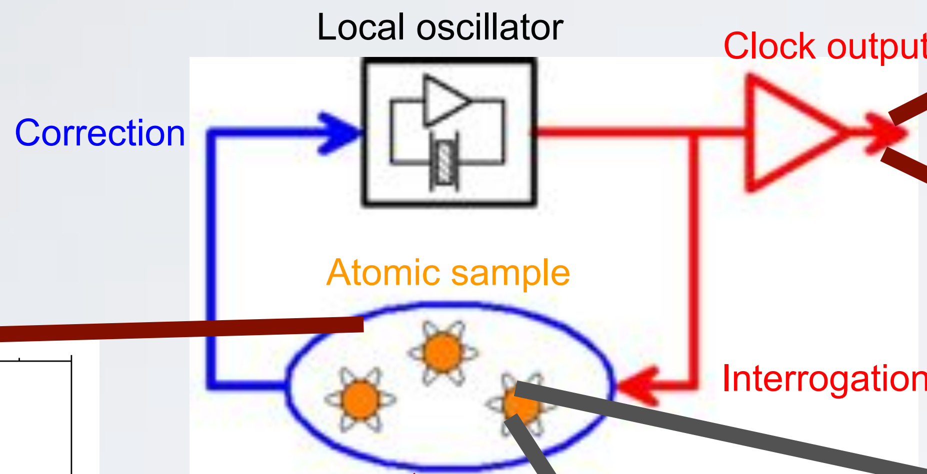
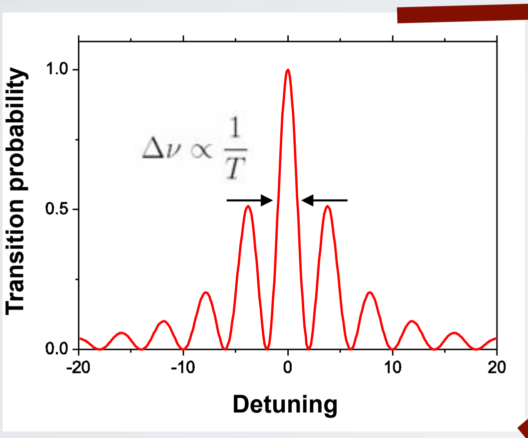
A class M mission to test gravitation with light and quantum particles

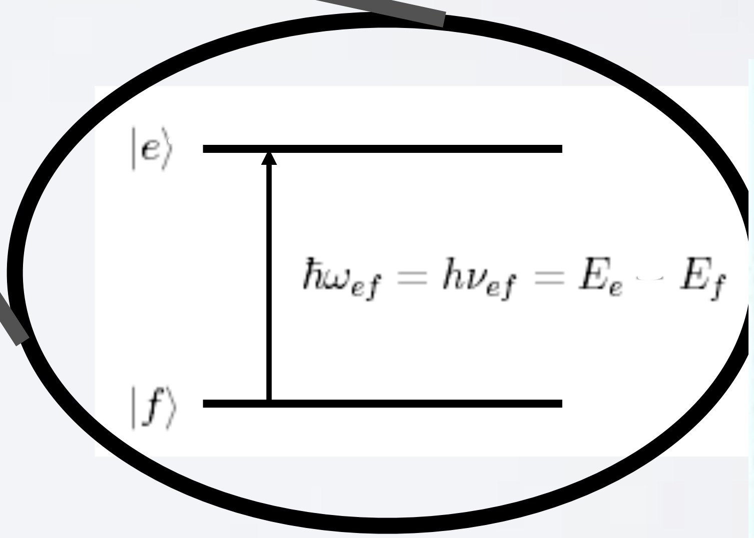
Atomic clocks basics

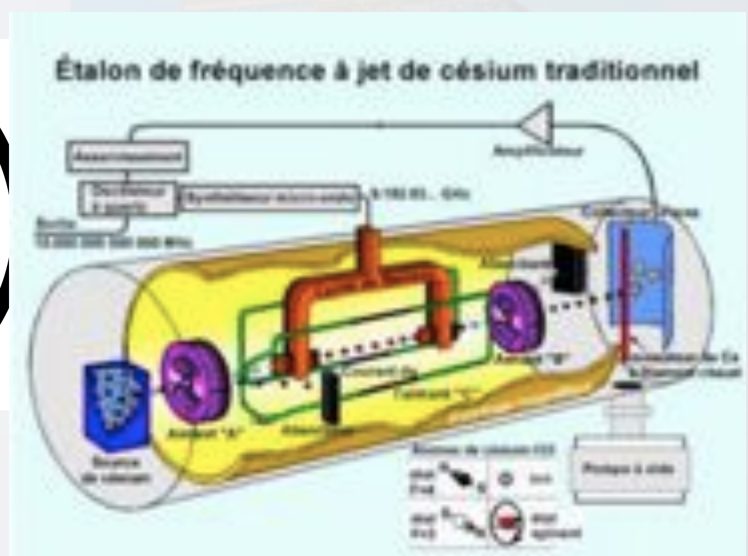


Ultra stable clock signal (10^{-16} accuracy and 3.10^{-17} stability)

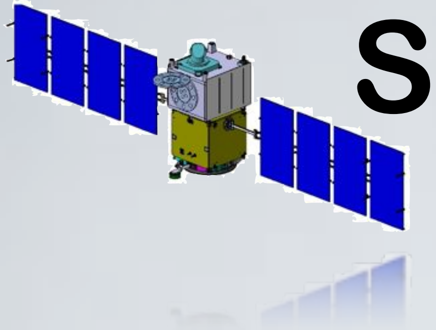


Precision increases with T





Precision spectroscopy of atomic transition

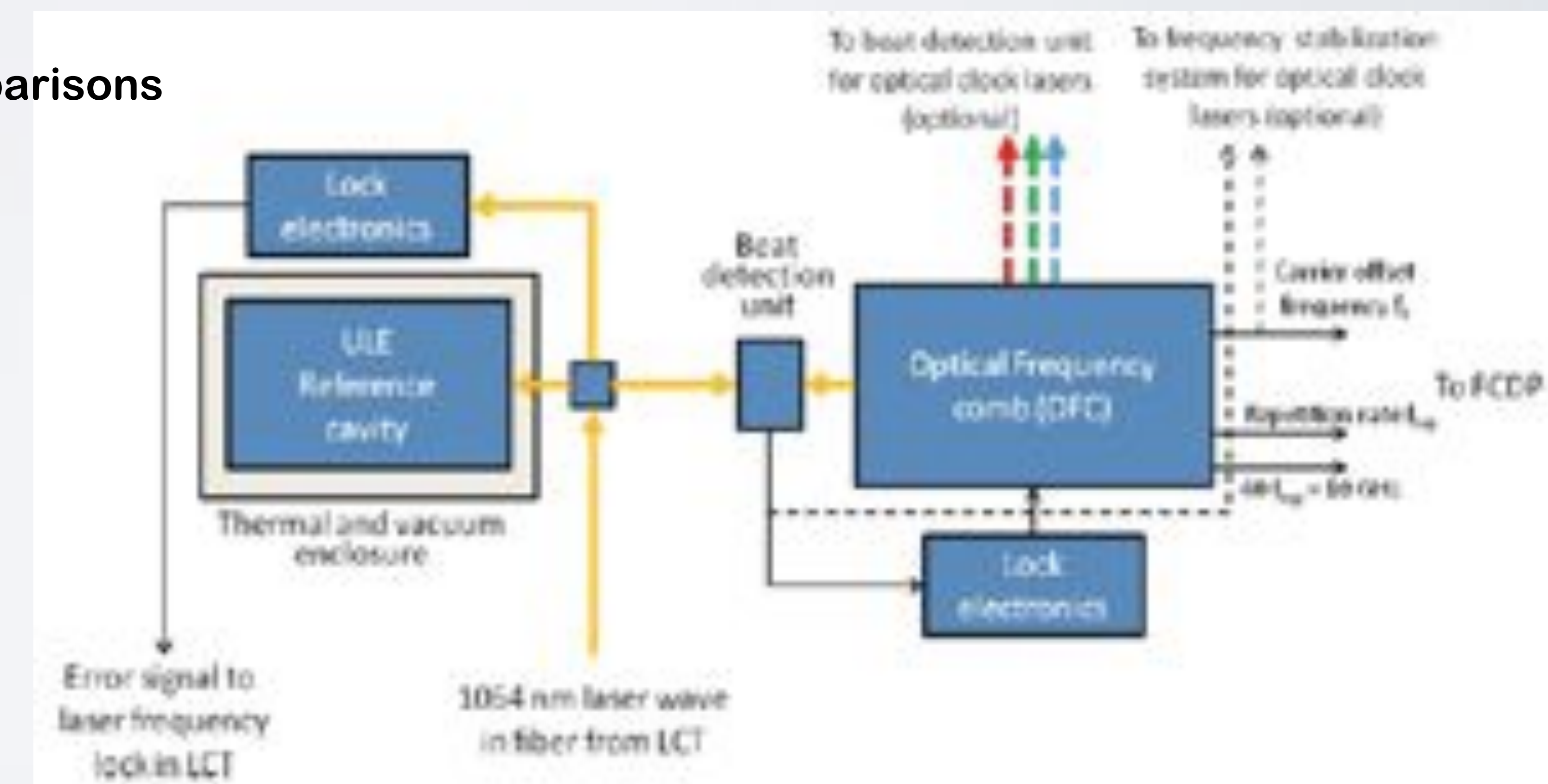


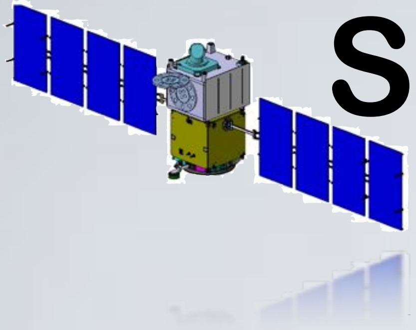
STE - QUEST

MOLO : local optic Oscillator/ micro-wave

- **Composition :**
  - Laser Nd:Yag with ultra-stable optical cavity
  - Frequency comb (OFC) : transfer the frequency stability from optical frequency domain to micro-wave domaine
  - Performances : $1x10^{-15}$ for 1 to 20 s

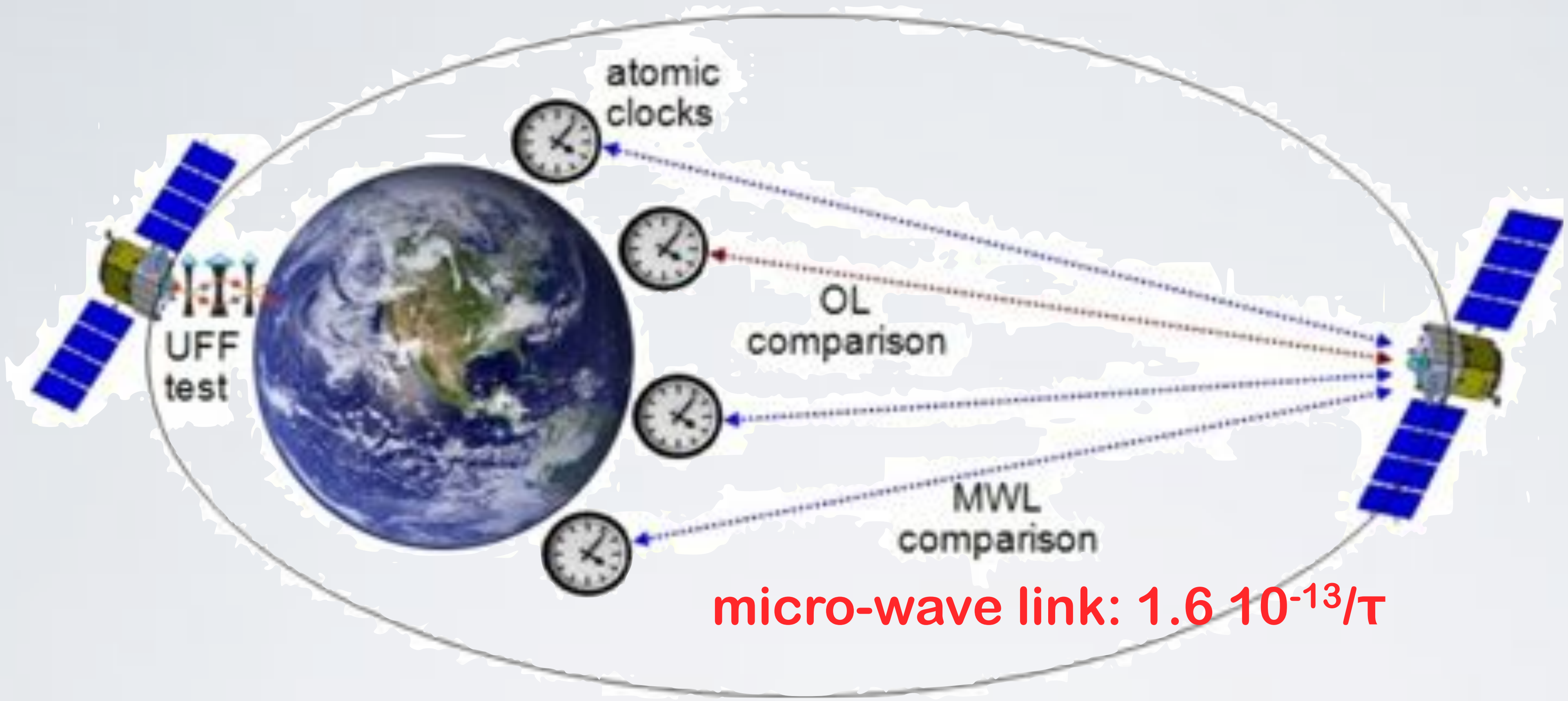
- **Use**
  - µwave : clock and interferometer
  - µwave : referencial frame for comparisons
  -





STE - QUEST

Test of the red shift: baseline configuration

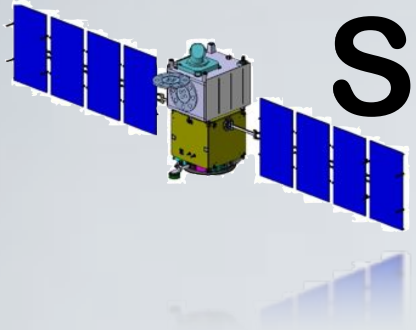


micro-wave link: $1.6\ 10^{-13}/\tau$

apogee 51 000 km

$\Delta U/c^2 \sim 6.2\text{x}10^{-10}$

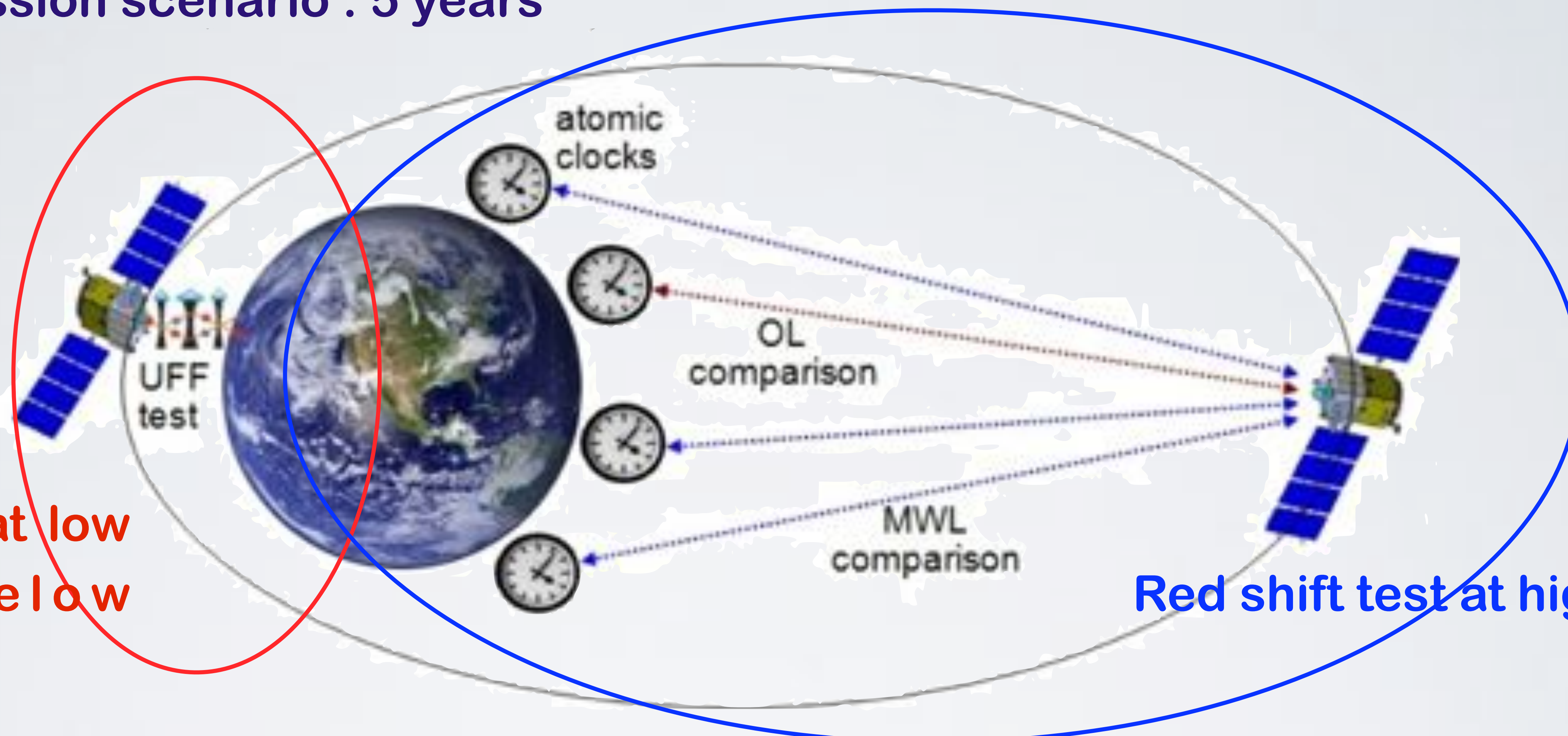
- Highly elliptic orbit: increase the red shift difference (1/r) and it's modulation
- microwave frequency transfer to ground
- Test of red shift by comparison between ground and space clock (test based on the accuracy $1\text{x}10^{-16}$): $1.6\ \text{x}10^{-7}$ (15 time better than ACES)
- Test based on the modulation during the orbit (test based on the stability $3\ \text{x}10^{-17}$) and averages over 1000 orbits: $2.7\ \text{x}10^{-7}$



STE - QUEST

A class M mission to test gravitation with light and quantum particles

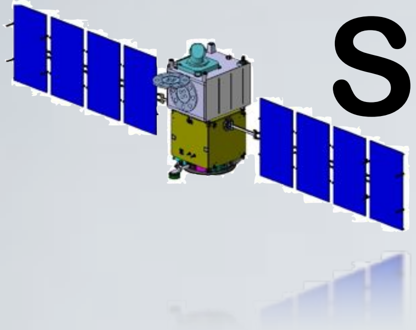
- Mission scenario : 5 years



- WEP test at low orbit (below 3000 km)

Red shift test at hight orbit

- Elliptic orbit 700-51 000 km
- Periodicity 16h
- Inclination
- Maximum eclipse 3h and 20 days/year



STE - QUEST

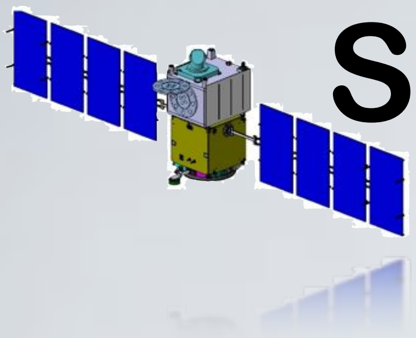
A class M mission to test gravitation with light and quantum particles

Fundamental Physics Science Objectives

- Universality of free fall (UFF, WEP) test using atom interferometry at 1×10^{-15}
- Test of Earth's gravitational redshift (ground to space clock comparison) at 1.6×10^{-7}
- Test of Sun's gravitational redshift at 6×10^{-7} (intercontinental ground-ground clock comparison at 10^{-18}).

Spin-off to other fields (outside fundamental physics)

- Comparison of distant terrestrial clocks at the level attained by the time of the mission (10^{-18} or better).
- Establishment of a new approach to the determination of the geopotential, with 1 cm equivalent height resolution.
- Demonstration of clock and link technology as well as high precision inertial sensors based on atom interferometers for future applications, e.g. in precision spacecraft navigation.
- Demonstration on high performance real-time range determination.
- Comparison of 3 different orbit determination systems: Laser-Ranging, µm-precision Microwave, Ranging, GPS-based orbit determination.



STE - QUEST

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