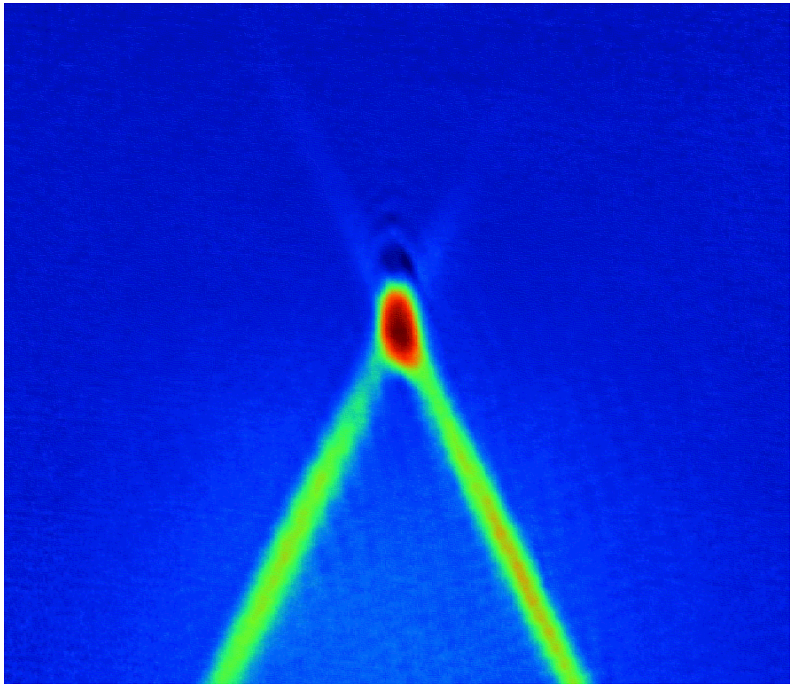
Atomic Quantum Sensors and Fundamental Tests



C. Salomon

Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris

ESA- ESTEC-FPRAT, January 21th, 2010

Fundamental Questions

1) **Missing mass in the Universe**

   Dark matter and dark energy represent 95% of the mass of the Universe but have unknown origin !

   New particles and/or change of the laws of gravity ?

2) **Atomic Sensors can tests fundamental laws with exquisite precision**

   Einstein's equivalence principle and Universality of Free Fall

   Tests of gravity in Earth orbit or at solar system scale

   Precision redshift measurement

   Variability of fundamental constants

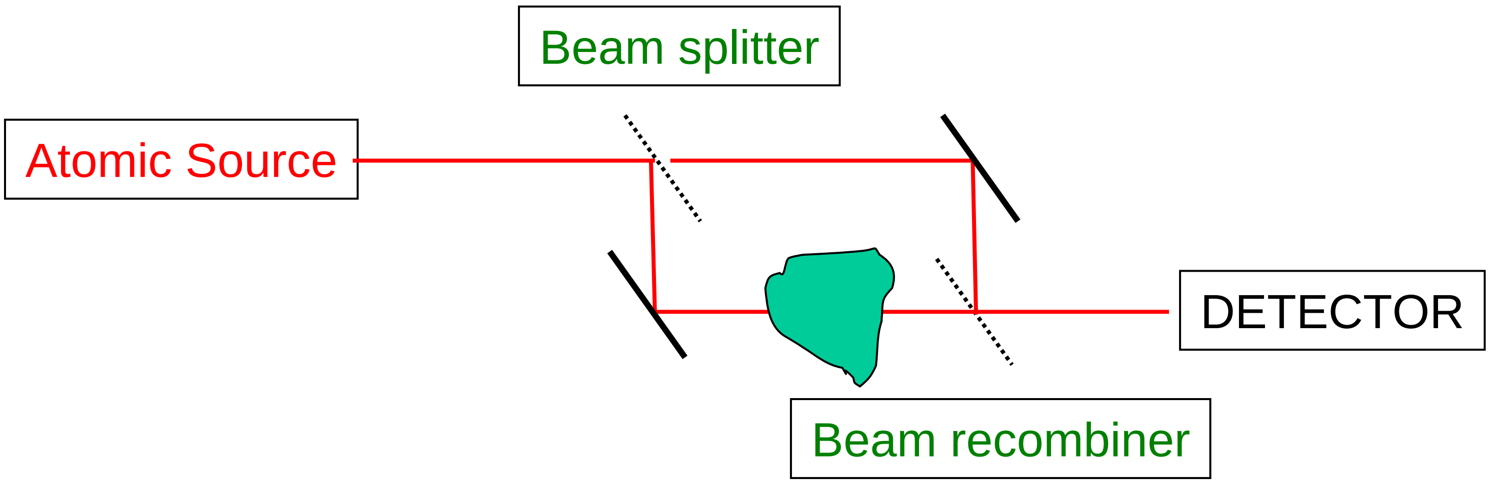
3) **Quantum sensors have societal applications**

   Accelerometry, Gravimetry, Navigation, GPS, GALILEO, Geodesy, Earth monitoring,…

Atom Interferometry

Matter wave interferometry: as old as Quantum Mechanics

Cold atoms: new opportunities with large De Broglie wavelength



Change of optical path-length… ⟶ Change of phase of interference pattern

Atom interferometry ⟶ Atomic source
Beam splitters
detectors

Atom interferometers and Clocks

Atoms have internal states

Two level atom: g, e

Laser resonant on g e transition

Neglect spontaneous emission

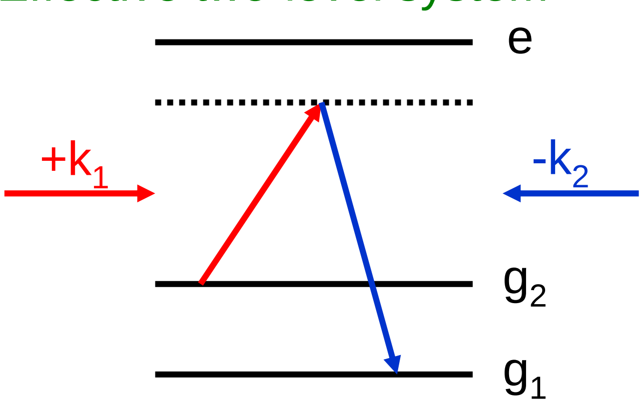
Use long lived upper states

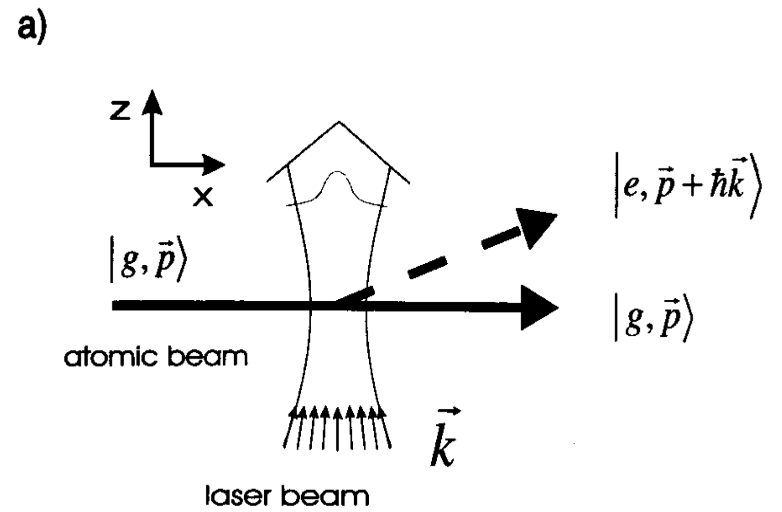
Mg, Ca, Sr, Yb, …

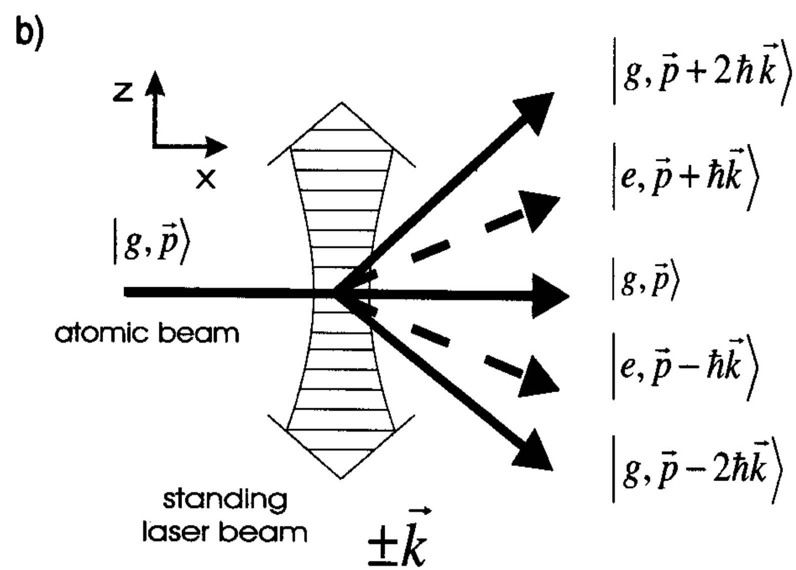
or

Raman Transition between hyperfine ground states in alkalis for instance

Effective two-level system

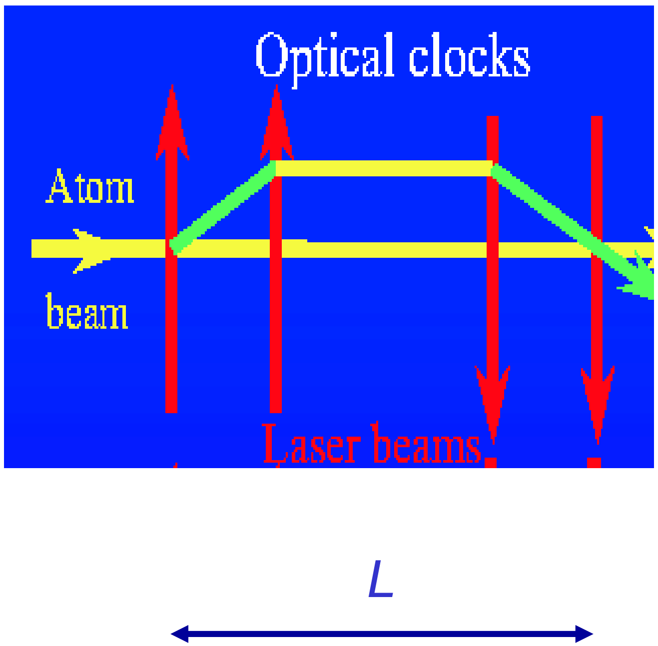






Matter-wave sensors and precision measurements

Clocks and Interferometers



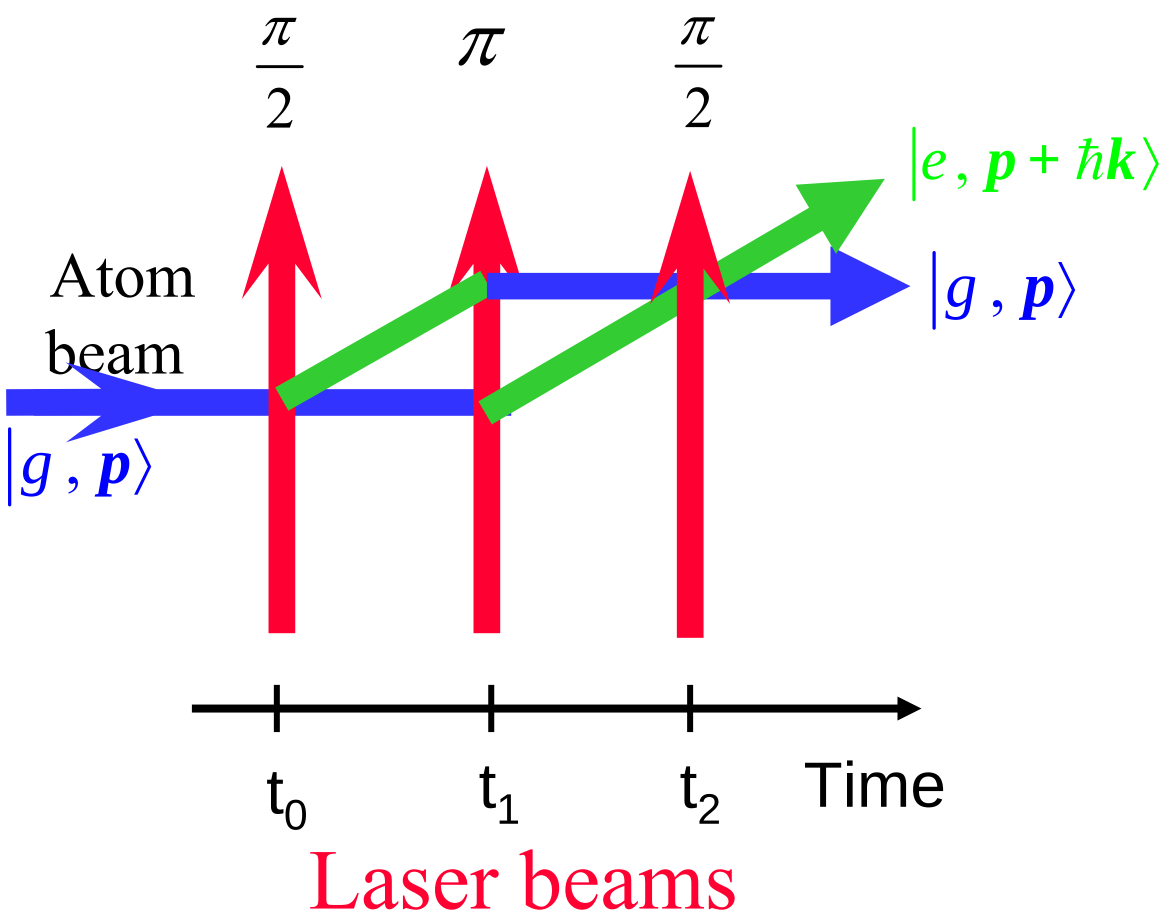
T : interaction time with ELM field
Slow atoms: *T* large; atomic fountain or microgravity
Trapped atoms: T large
Clocks: gain prop. To *T*

Inertial sensors:
Accelerometers: gain as T^2
Sagnac gyrometers : gain as *L T*

Current sensitivity:
Acceleration: $\delta g/g = 1.4\ 10^{-8}$ in 1s
Rotation: $\Omega = 6\ 10^{-10}$ rad s^{-1} in 1 s

Clocks:
Frequency stability: $\delta\nu/\nu = 2\ 10^{-15}$ in 1s
Accuracy: $= 8.6\ 10^{-18}$

Mach-Zehnder interferometer with light beams



$$\delta\phi = \phi_1(t_0) - 2\phi_2(t_1) + \phi_3(t_2)$$

Sensitive to rotation and accelerations: gyrometers and gravimeters

Cold atom gravimeter

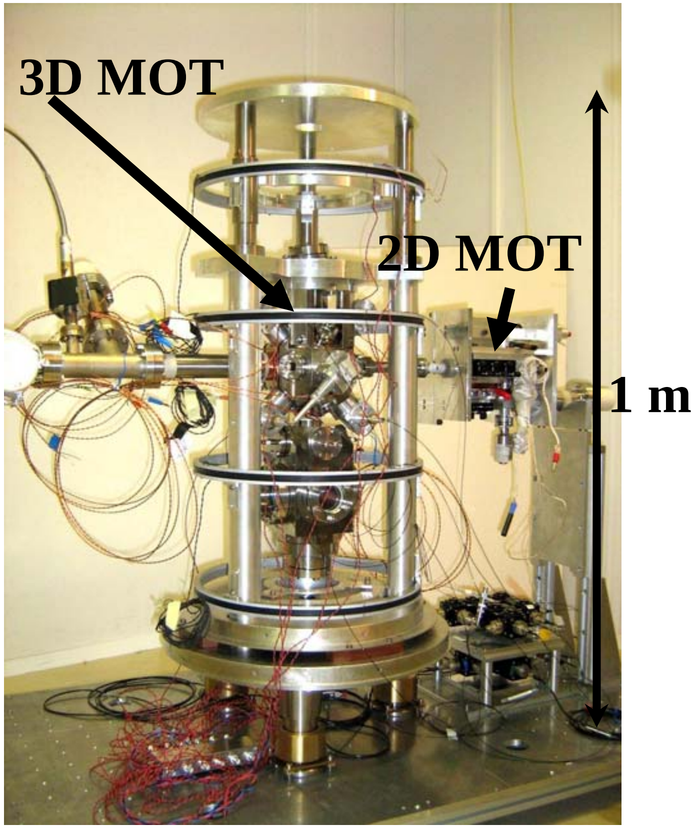
S. Chu
A. Peters et al.
Stanford

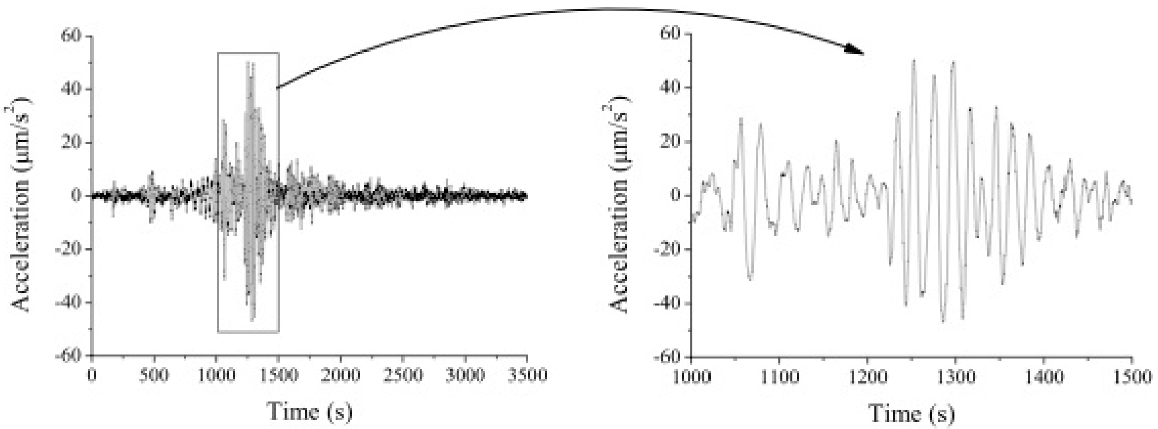
$$\delta\phi = -k_{eff}\,aT^2 = -k_{eff}\,gT^2 = -2k_L\,gT^2$$

Ground sensitivity: $\sigma_g \sim 10^{-7}$ m.s^{-2} at 1s
with interrogation time 100 ms
limited by vibrations

Extrapolation to space: $<10^{-10}$ m.s^{-2} at 1s
with interrogation time 2 s

With ultra-cold atoms: $\sim 10^{-11}$ m.s^{-2} at 1s
with interrogation time 10 s





Earthquake in China 2 Mars 20th 2008 (magnitude 7,7)

A. Landragin
F. Pereira
SYRTE

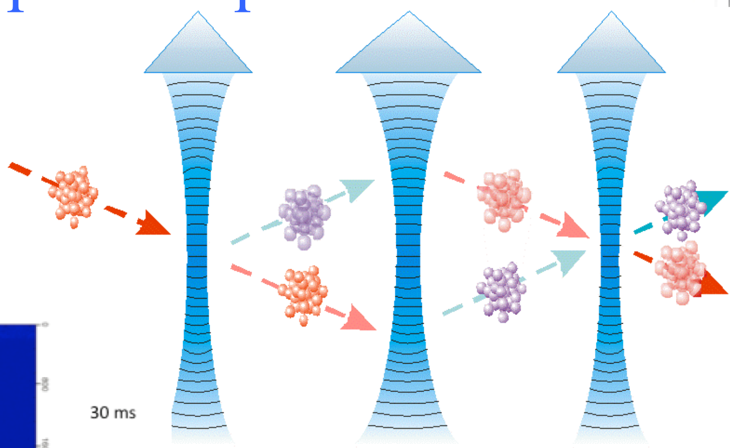
BEC in microgravity: QUANTUS

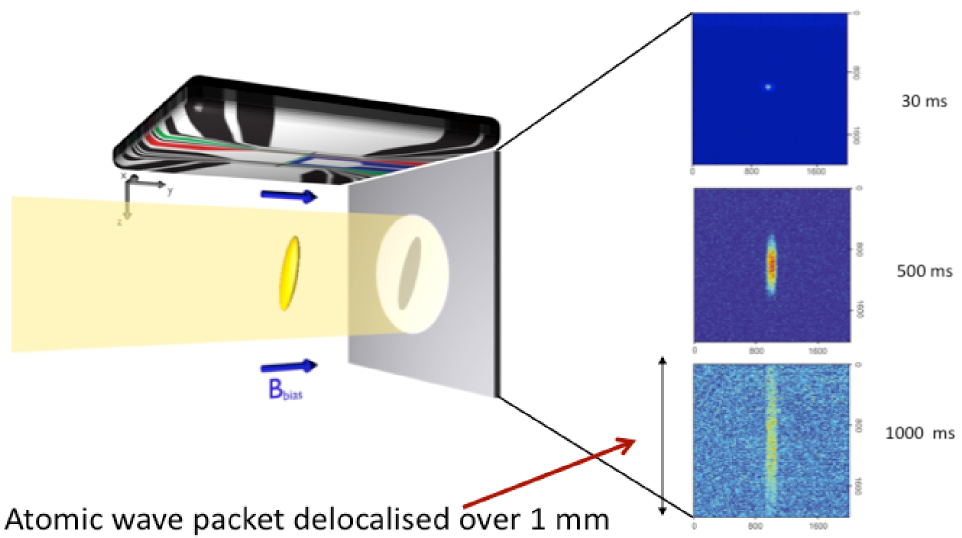
Coordinator E. Rasel

Exploring coherent matter waves at lowest energy scales, in particular for

... Precision inertial sensing

... Quantum test of the principle of equivalence beyond 1 part in 10^{15}





DLR

Achievements:

- > 170 drops
- Robust alignment
- 3 drops per day
- High complexity
- Study of Evolution & control of condensates

Goals:

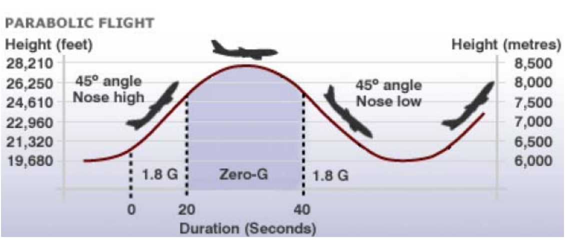
- Test of chip-based and all-optical atom lasers for precision inertial sensing
- Atom interferometry coherent matter waves
- Test of free fall of isotopes of potassium and rubidium

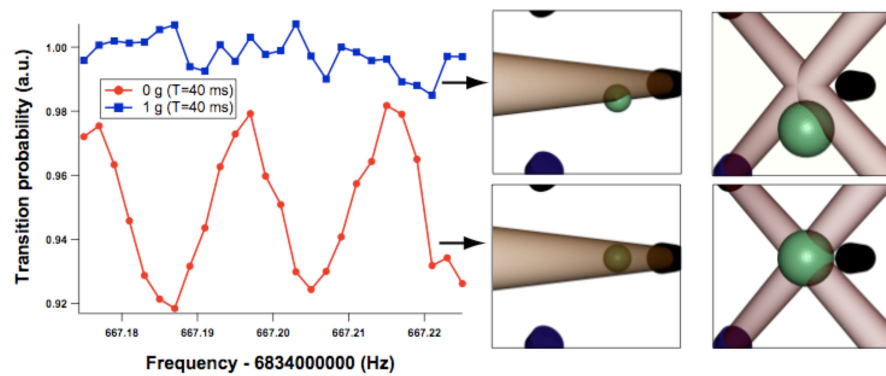
ICE: Atom accelerometer in microgravity

Coordinator P. Bouyer

- Operation of atom interferometer in the 0g airbus.

- Demonstration of atom accelerometer in weightlessness.
- Demonstrated background vibration suppression by correlation measurement of atom & classical accelerometer.

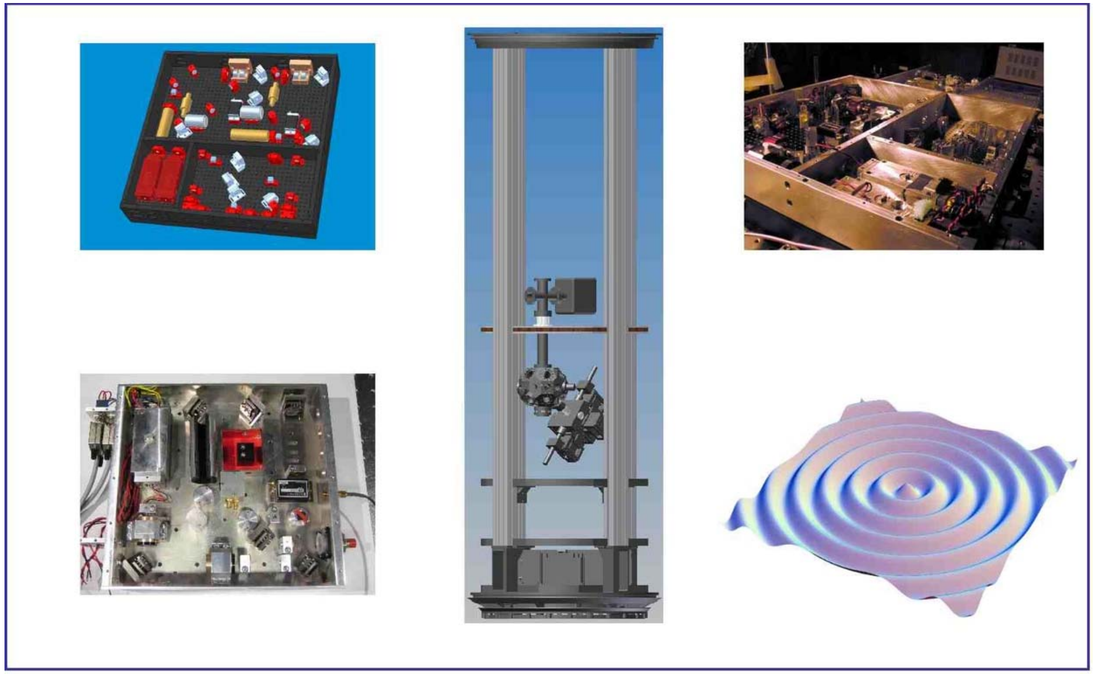




2 species atom interferometer : test of the equivalence principle @ 10^{-11} in the plane and 10^{-13} on ISS.

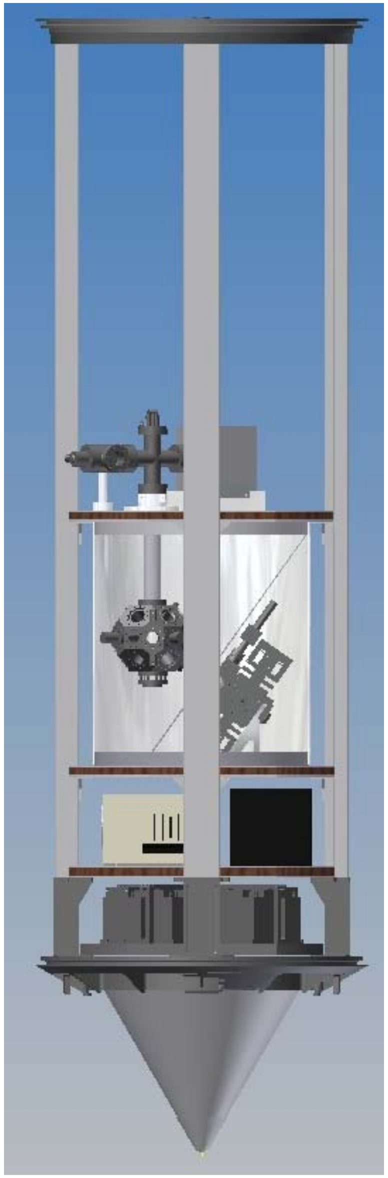
SAI - Space Atom Interferometer

Coordinator: Guglielmo M. Tino



SAI accelerometer

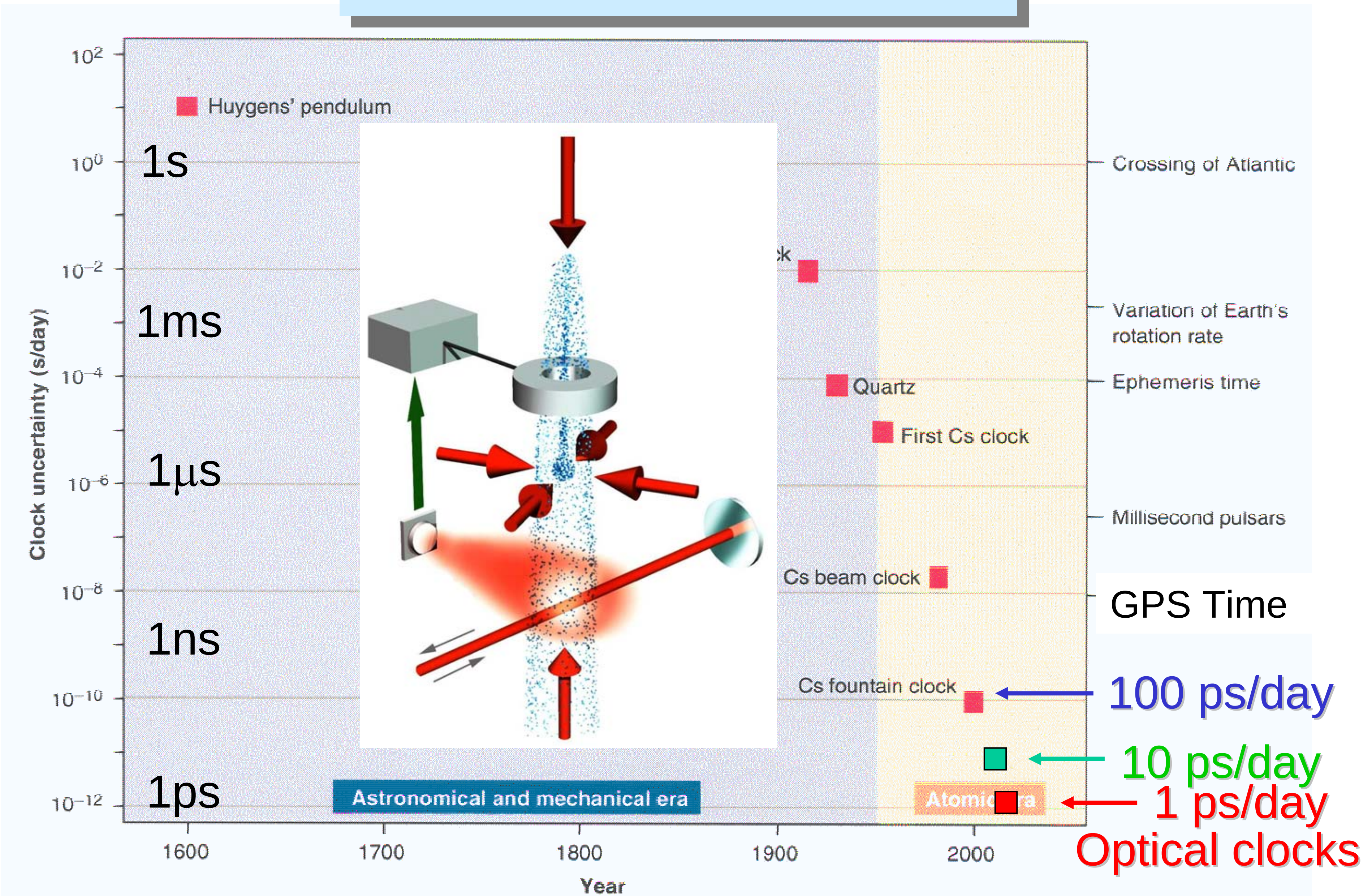
- Main goal: compactness/portability -> to fit into a drop-tower capsule
- Use same cell for trapping and detection (launch in 1-1-1 config.)
- HUB design for titanium vacuum cell
- Load 3D-MOT from 2D-MOT
- Magnetic shield on whole vacuum system
- Launch into a 20 cm tube
- Single axis Raman accelerometer
- sensitivity spec $3 \cdot 10^{-7}$ m/s^2 @ 1s



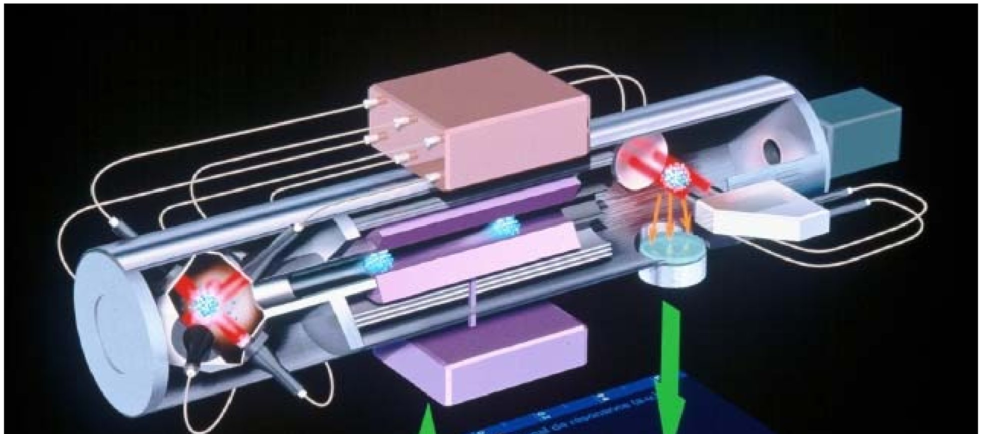
Quantum sensors (2)

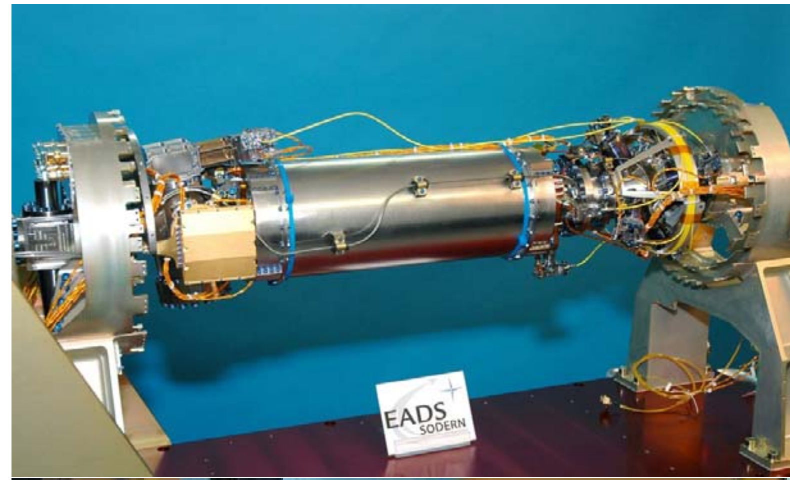
Cold Atom Clocks

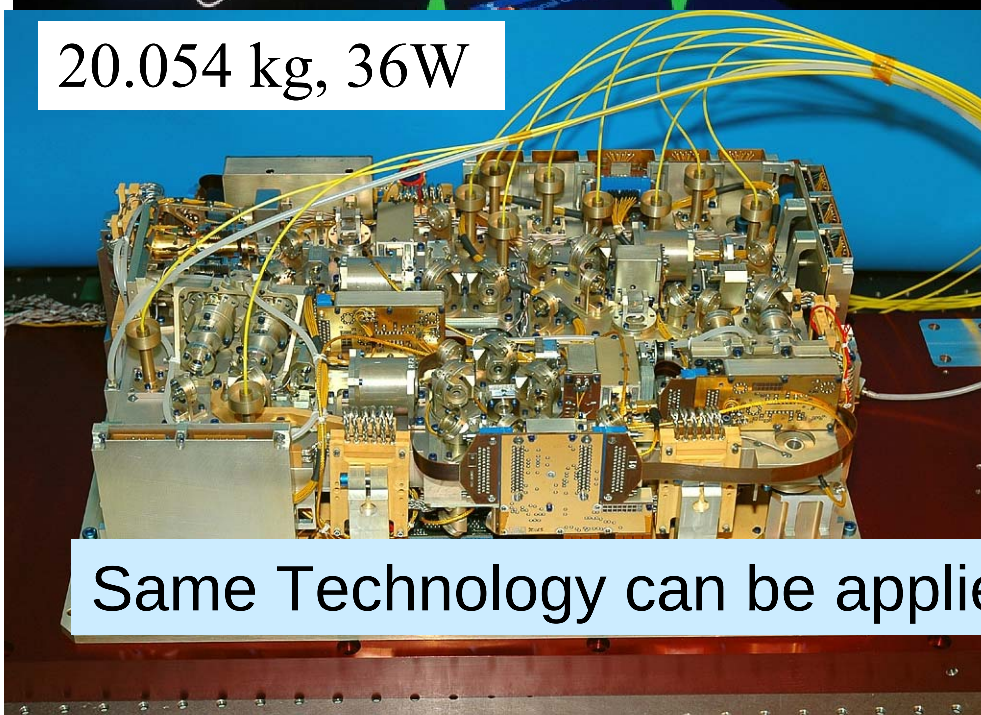
Precision of Time

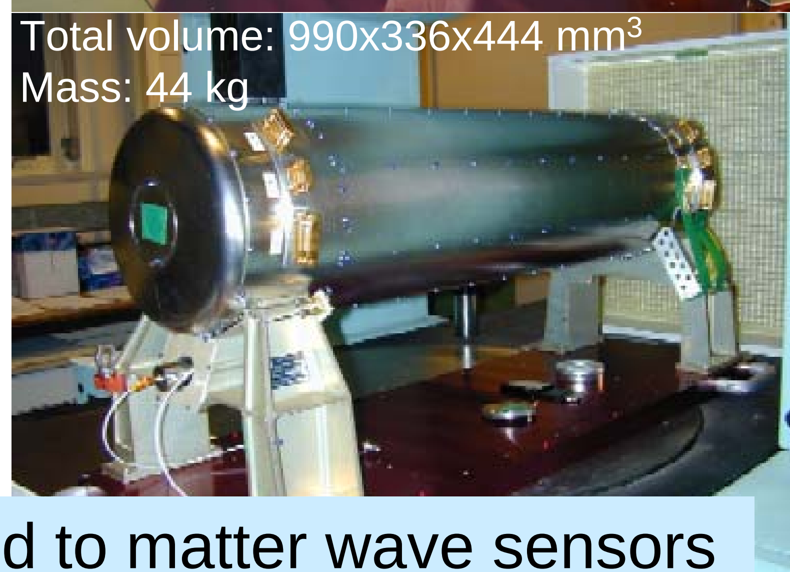


In Space: Cold Atom Clock in μ-gravity : PHARAO/ACES

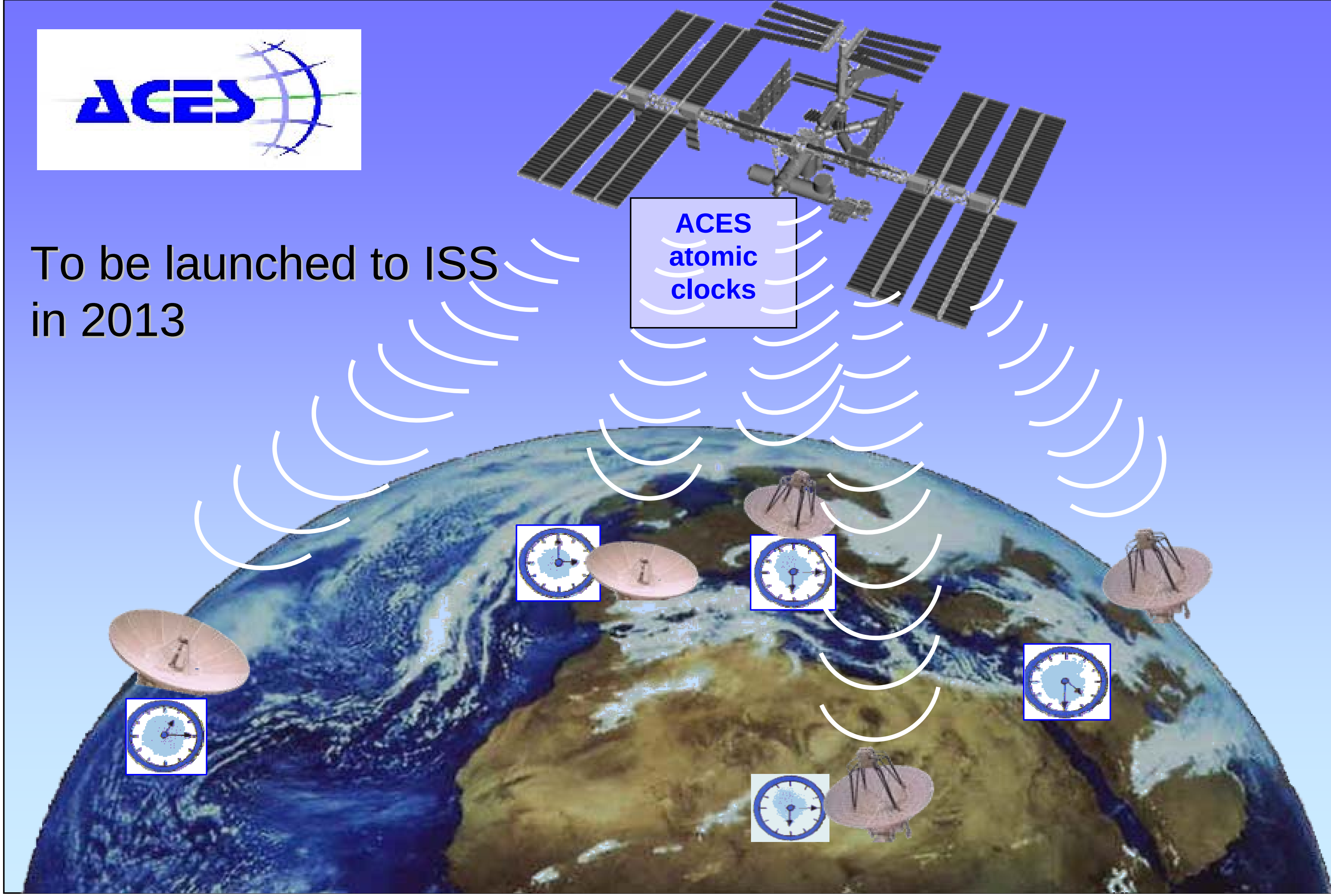








Same Technology can be applied to matter wave sensors



- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access

esa

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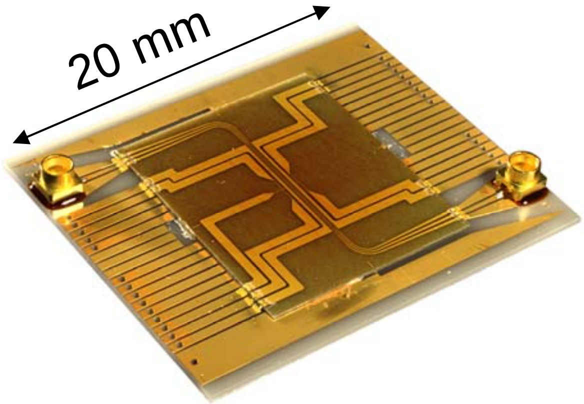
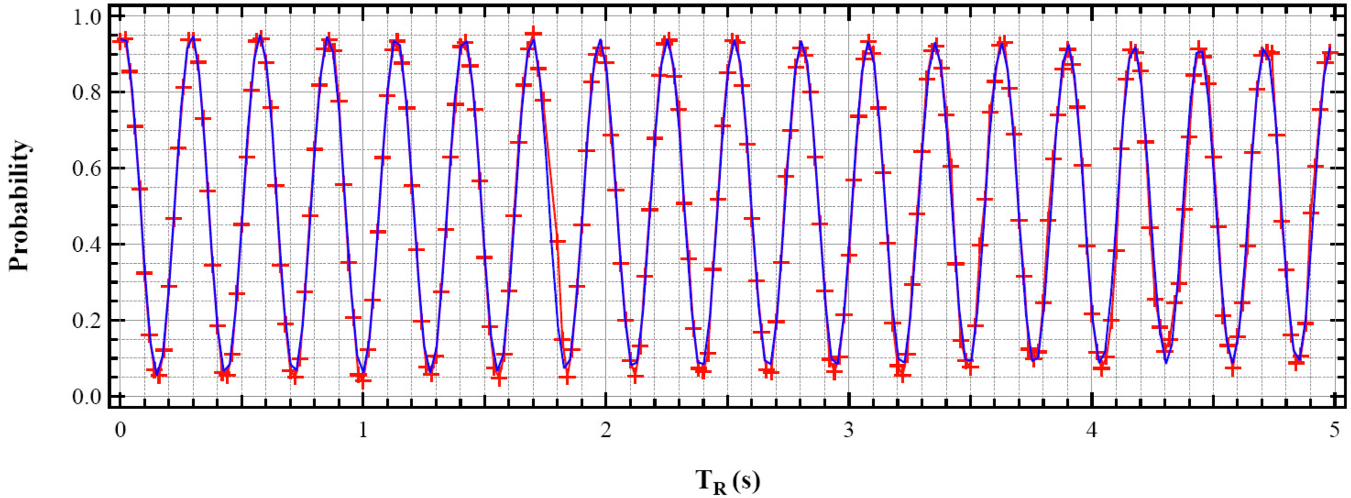
Trapped-atom clock on a chip



$F = 2, m_F = +1$
$F = 1, m_F = -1$ } experience same trapping potential (same magnetic moment)

$N \sim 3\ 10^4$ atoms
$T \sim 200$ nK
$d \sim 150\ \mu m$ atom-surface distance
result: $\tau \sim 17$ s coherence lifetime



P. Rosenbusch, J. Reichel, SYRTE-ENS, 2009

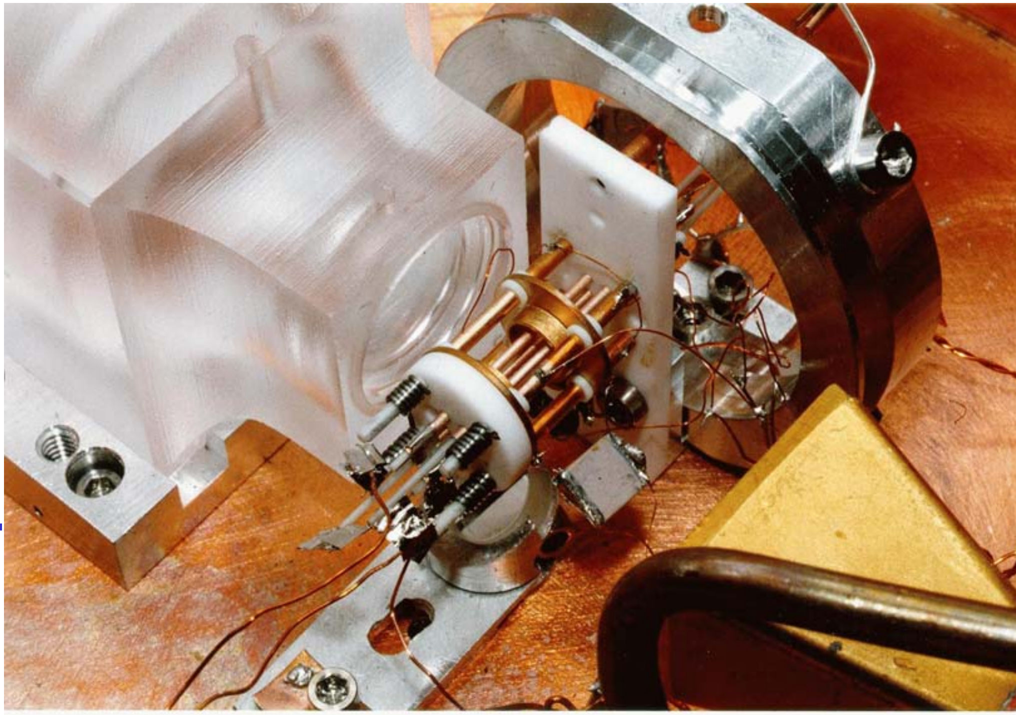
2 Families of Optical Clocks: Trapped Ions and Neutral Atoms

- Quality of the clock: $\nu/\Delta\nu \times S/N = 2\,\nu\,T \times S/N$
- Increase the frequency, increase T, increase S/N
- Trapped ions : T very long but only one (few) ion in the trap.
- Neutral atoms: T long and large numbers: improved stability

NIST : Rosenband et al.

- Al^+:optical transition
- Accuracy: 8.6 10^{-18}

A factor of 30 beyond the cesium accuracy !



- Neutrals: Ca, Sr, Yb, Mg, Hg,..
- Sr: 10^{-16} accuracy, Ye et al.
- TOKYO, JILA, SYRTE, PTB, FLORENCE,….

Space Optical Clocks (SOC:ELIPS-3)

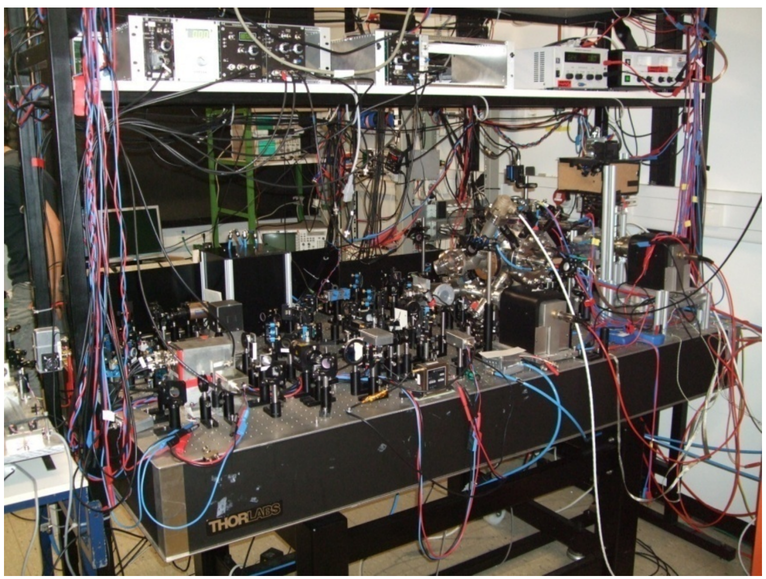
Coordinator S. Schiller, Duesseldorf

Goal: develop optical lattice clocks with inaccuracy at 10^{-17} level for space applications, in particular on ISS. Two approaches: Strontium and Ytterbium

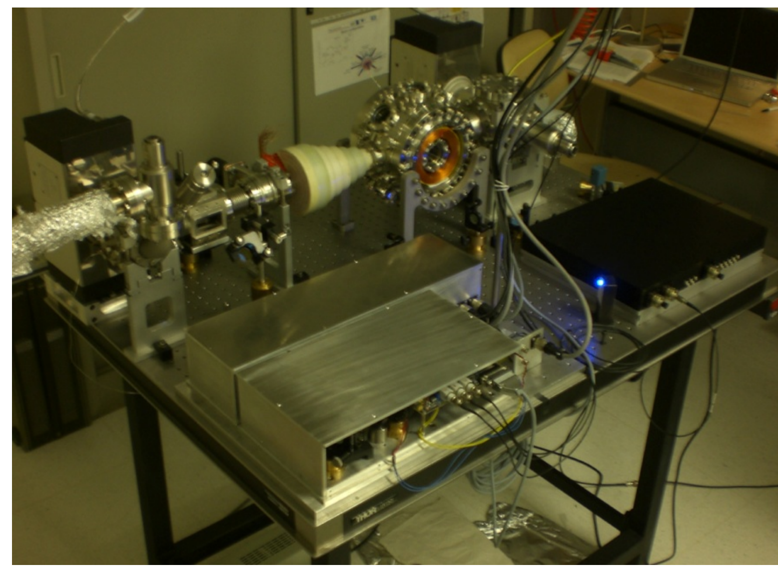
Pre-Phase A project (2007-10) : $1x10^{-16}$ on Sr clocks, development of compact subsyst.

Current status on stationary Sr clocks: Study of systematic effects at 10^{-16} level, Frequency instability $<1x10^{-15}$, transition linewidth 9 Hz, non-destructive detection

Transportable Yb clock system
all-diode laser based. Current status: routine operation of 2nd stage cooling, 2 Hz linewidth clock laser



Sr breadboard with modular subsystems and all-fiber light delivery. Current status: atomic beam production; transp. Sr clock laser with < 10 Hz linewidth

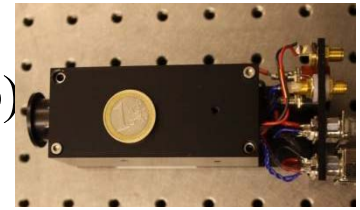


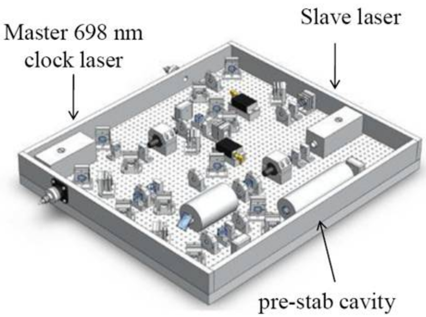
HEINRICH HEINE UNIVERSITÄT DÜSSELDORF · PTB · LENS · l'Observatoire de Paris · SYRTE · Systèmes de Référence Temps-Espace · cnrs · Ens

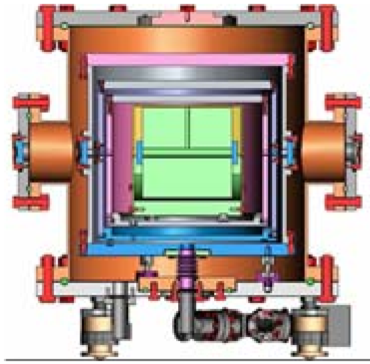
www.spaceopticalclocks.org

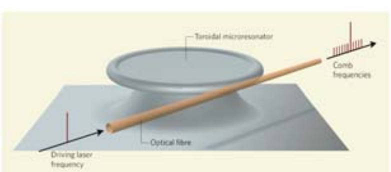
Space Optical Clocks (Phase 2, 2010-14)

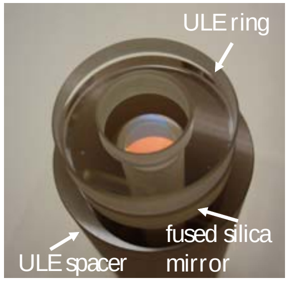
- **Goal:** Building on SOC-I results, develop transportable/breadboard lattice clocks with $5\text{x}10^{-17}$ inaccuracy, $< 1\text{x}10^{-15}/\tau^{1/2}$ instability (Sr, Yb)
- 2^{nd} generation breadboard Sr atomic and electrooptics system: < 170 kg, 1000 liter.
- Modular systems
- Develop reliable, compact and rugged lasers and subsystems
- Advanced atomic chambers, optimized w.r.t. size, black-body shift
- Transport and characterization of clocks at national metrology labs (PTB, INRIM)
- Laser diode reliability tests; compact frequency comb development
- 16 partners











Future Time Definition from Space

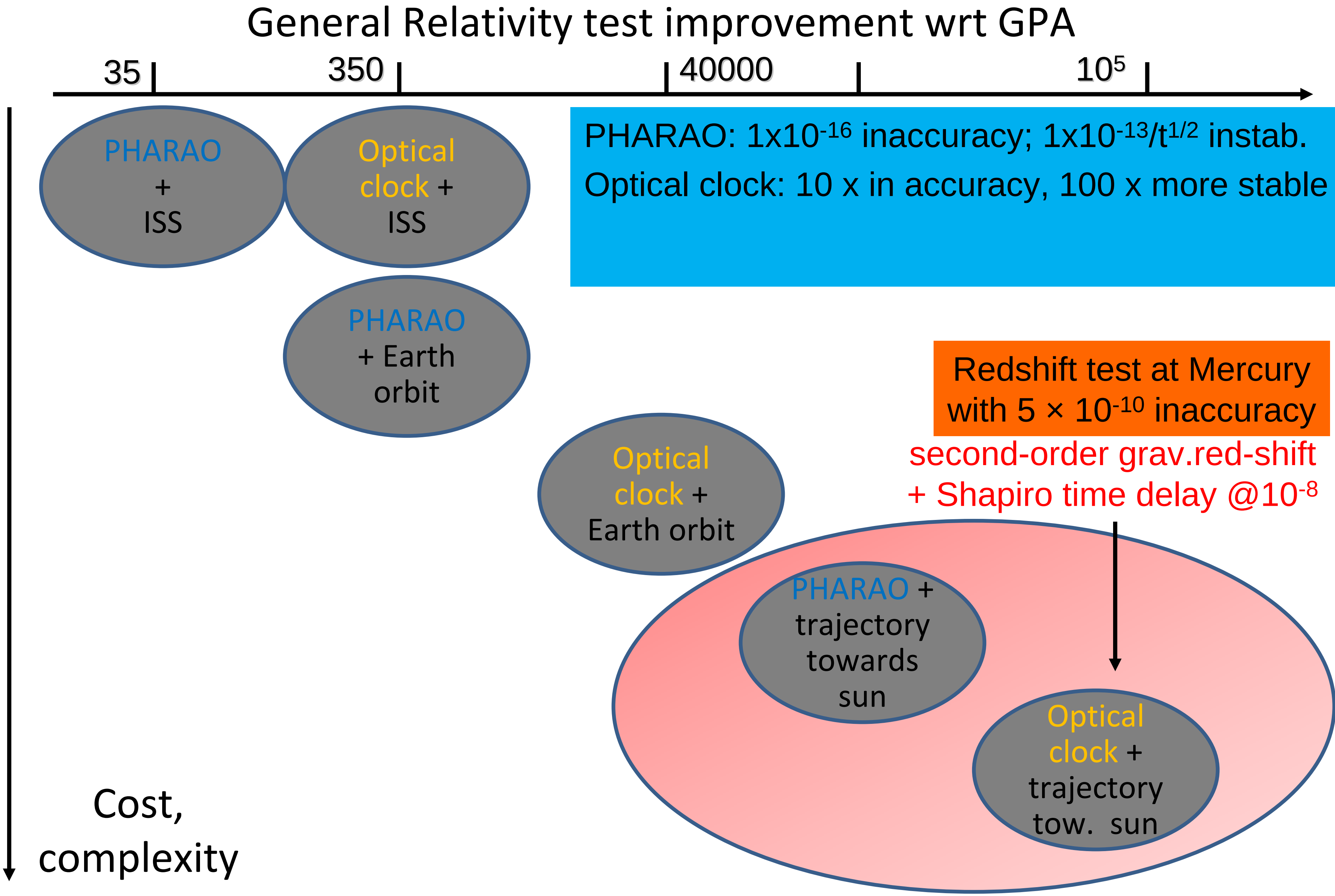
1) **The Earth gravitational potential fluctuations will limit the precision of time on the ground at 10^{-18}-10^{-19} (ie: cm to mm level)**

2) **The only Solution: set the reference clocks in space where potential fluctuations are vastly reduced**

3) **Improved Navigation, Earth Monitoring and Geodesy**

4) **Interesting for fundamental physics Tests**

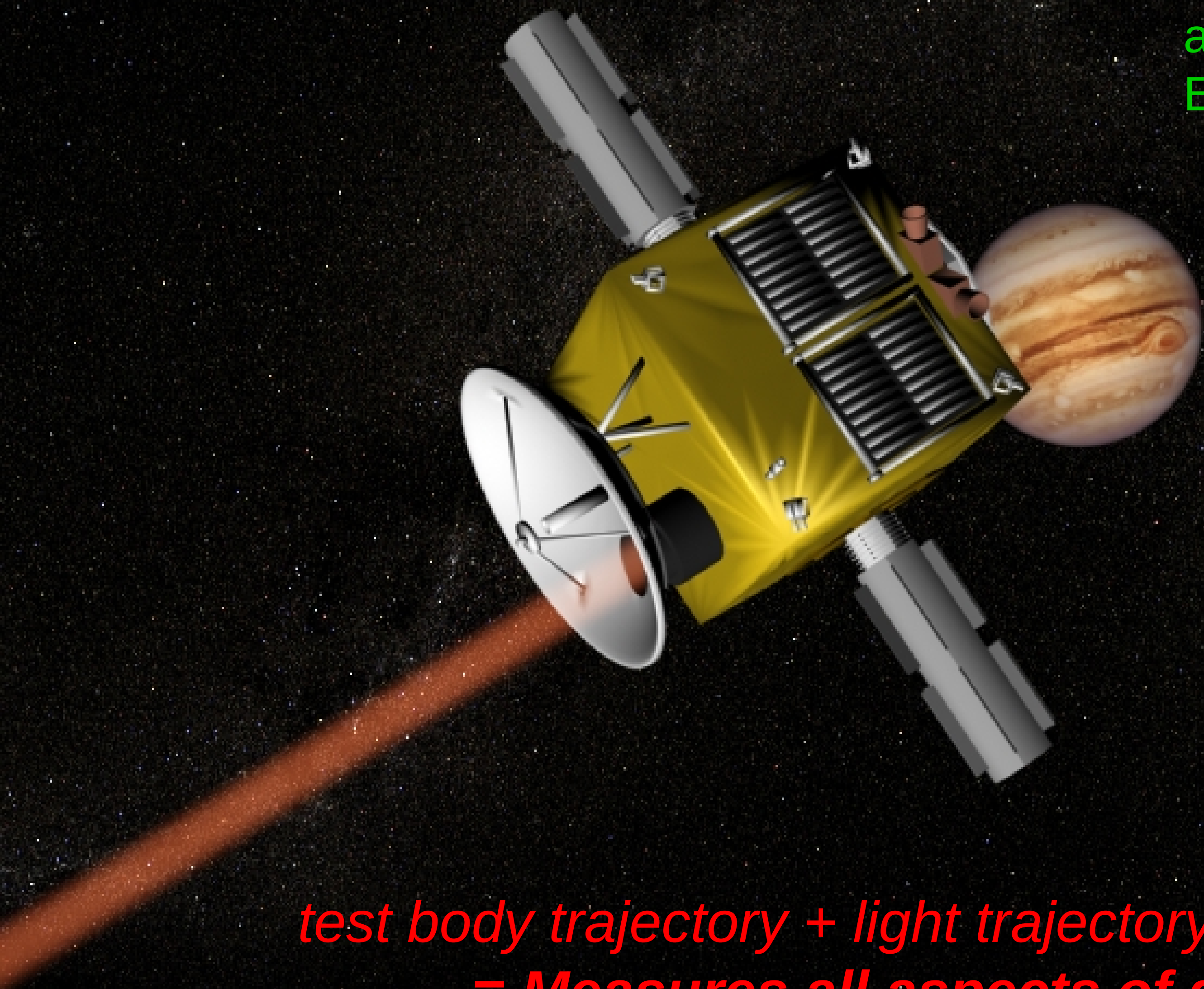
Mission opportunities with clocks



The SAGAS Project
test of gravity at solar system scale

arXiv: 0711.0304, (2008);
Exp. Astr. **23**, 651, (2009)

peter.wolf@obspm.fr



test body trajectory + light trajectory + proper time

= Measures all aspects of gravity !

Summary

Matter-wave interferometers and cold atom clocks have entered into high precision measurement phase

Technology has progressed fast with routinely working instruments
Fine structure constant @ 3 10^{-9}
Clocks reach stabilities and accuracies in the sub 10^{-17} range

Impressive efforts for miniaturization and reliability
Compact laser sources and atom chips
quantum gases sources: BEC in microgravity and atom lasers

Beyond ACES on the ISS (2013-2015)
Optical Clocks with 10^{-17} frequency stability in 2019 on the ISS or satellite
Test of Equivalence Principle in Space with quantum objects beyond 10^{-15}
Precise accelerometry demonstration

High precision clocks can bring tests of the laws of gravitation to a new level of precision

Coordinated action between ESA directorates is important !