Testing the equivalence principle with atom interferometry: the ICE experiment and the STE-QUEST mission

A. Landragin

l'Observatoire de Paris — SYRTE

Systèmes de Référence Temps-Espace

LNE — Le progrès, une passion à partager

CNRS — dépasser les frontières

UPMC PARIS UNIVERSITAS

IFRAF — Institut Francilien de Recherche sur les Atomes Froids

Outline

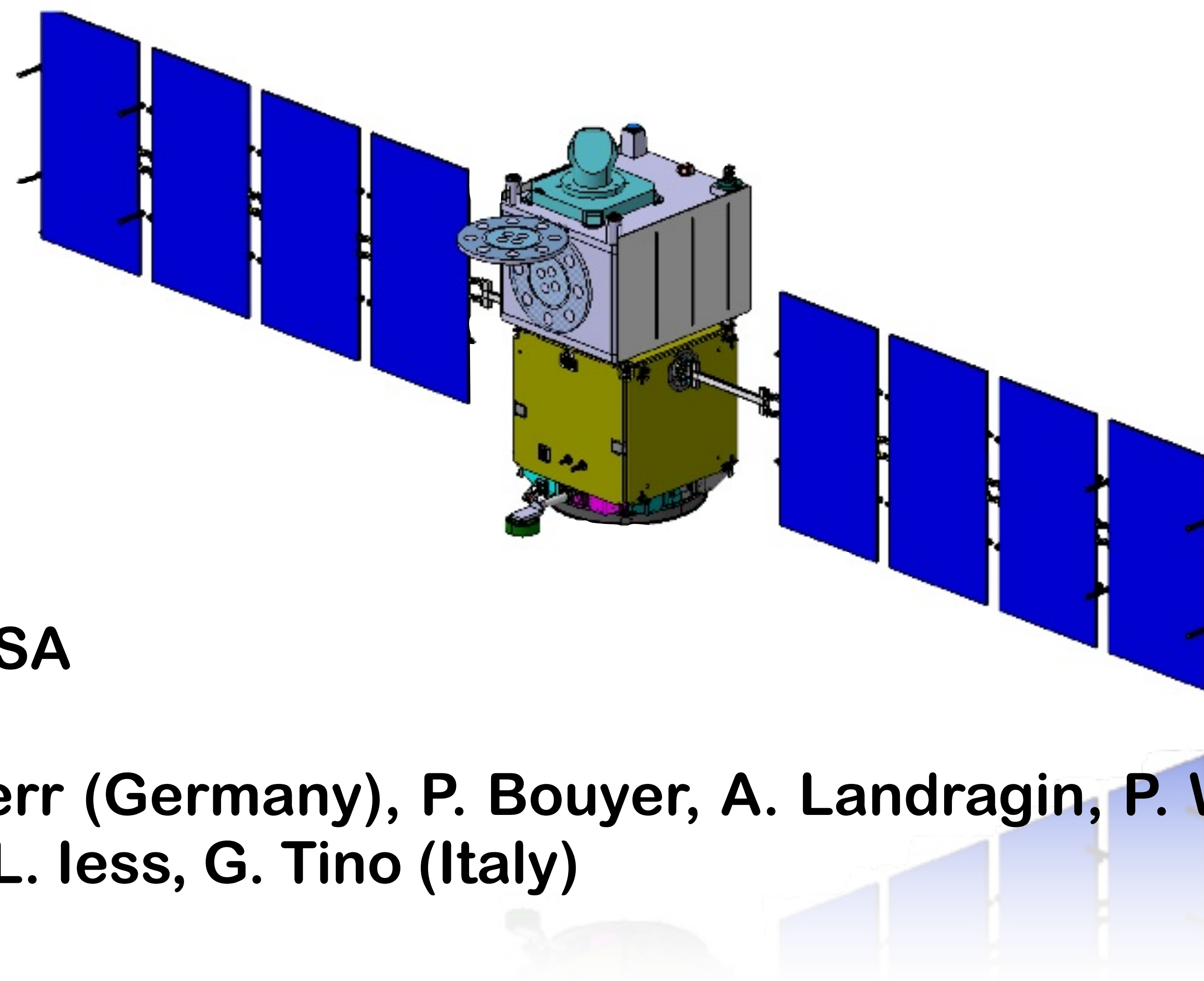
l'Observatoire de Paris | SYRTE
Systèmes de Référence Temps-Espace

1. STE-QUEST proposal
2. ICE : test of EP in 0-g
3. Conclusion

STE - QUEST

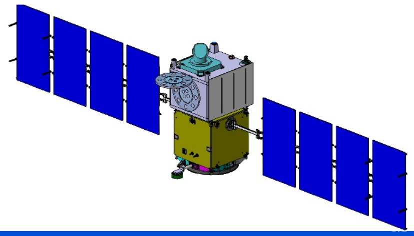
Space Time Explorer
&
Quantum Test of the Equivalence principle

A class M mission for cosmic vision 2020-2025



STE-Quest Science team ESA

E. Rasel, S. Shiller, U. Sterr (Germany), P. Bouyer, A. Landragin, P. Wolf (France), K. Bongs (UK), L. Iess, G. Tino (Italy)

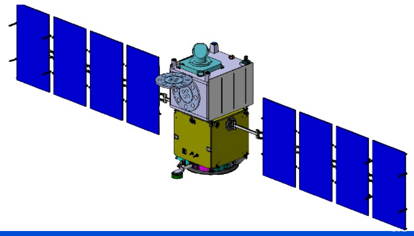


STE - QUEST

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

The Einstein equivalence principle (EEP) is the heart of gravitation theory. Test of two aspects :

- 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
    - Do 2 different clocks indicate the same time?
- Test bodies fall with the same acceleration independently of their internal structure or composition
  - Weak Equivalence Principle, or WEP
    - Do 2 different particles fall in the same way?



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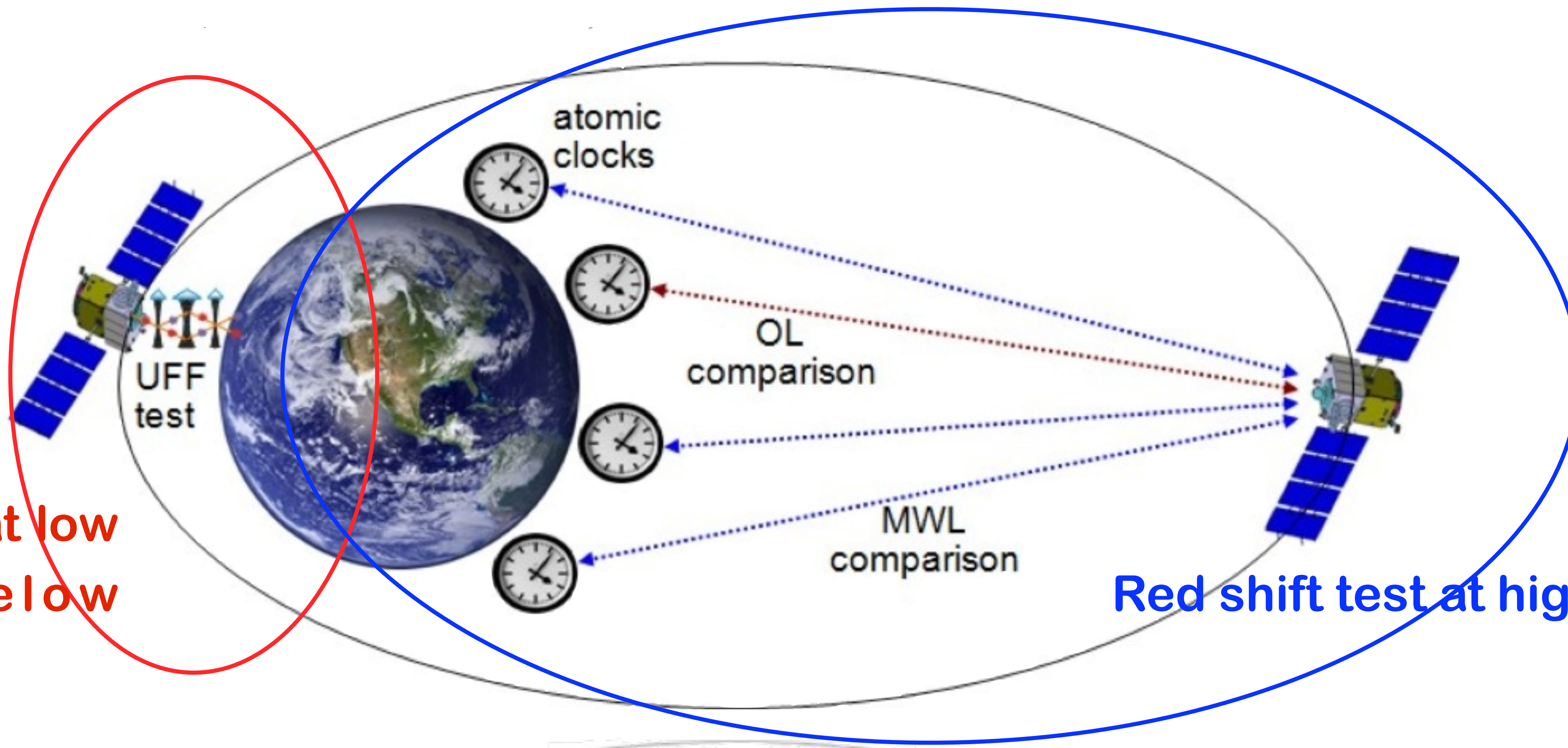
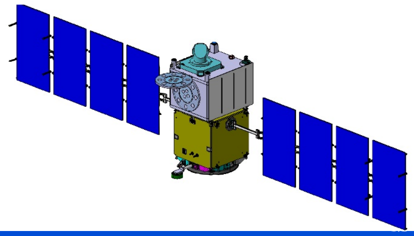
- Mission scenario : 5 years



- WEP test at low orbit (below 3000 km)

Red shift test at hight orbit

- Elliptic orbit 700-51 000 km
- Periodicity 16h
- Inclination ~70°
- Maximum eclipse 3h and 20 days/year



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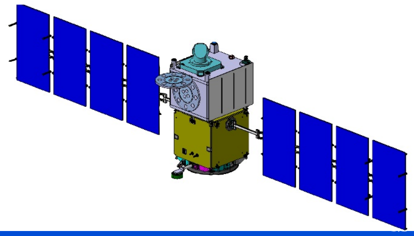
    - Do
- **The outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed**
  - **Local Position Invariance, or LPI**
    - **Test of the red shift**
- e outcome of any local non-gravitational experiment is independent of the velocity of the freely falling reference frame in which it is performed
  - Local Lorentz Invariance, or LLI



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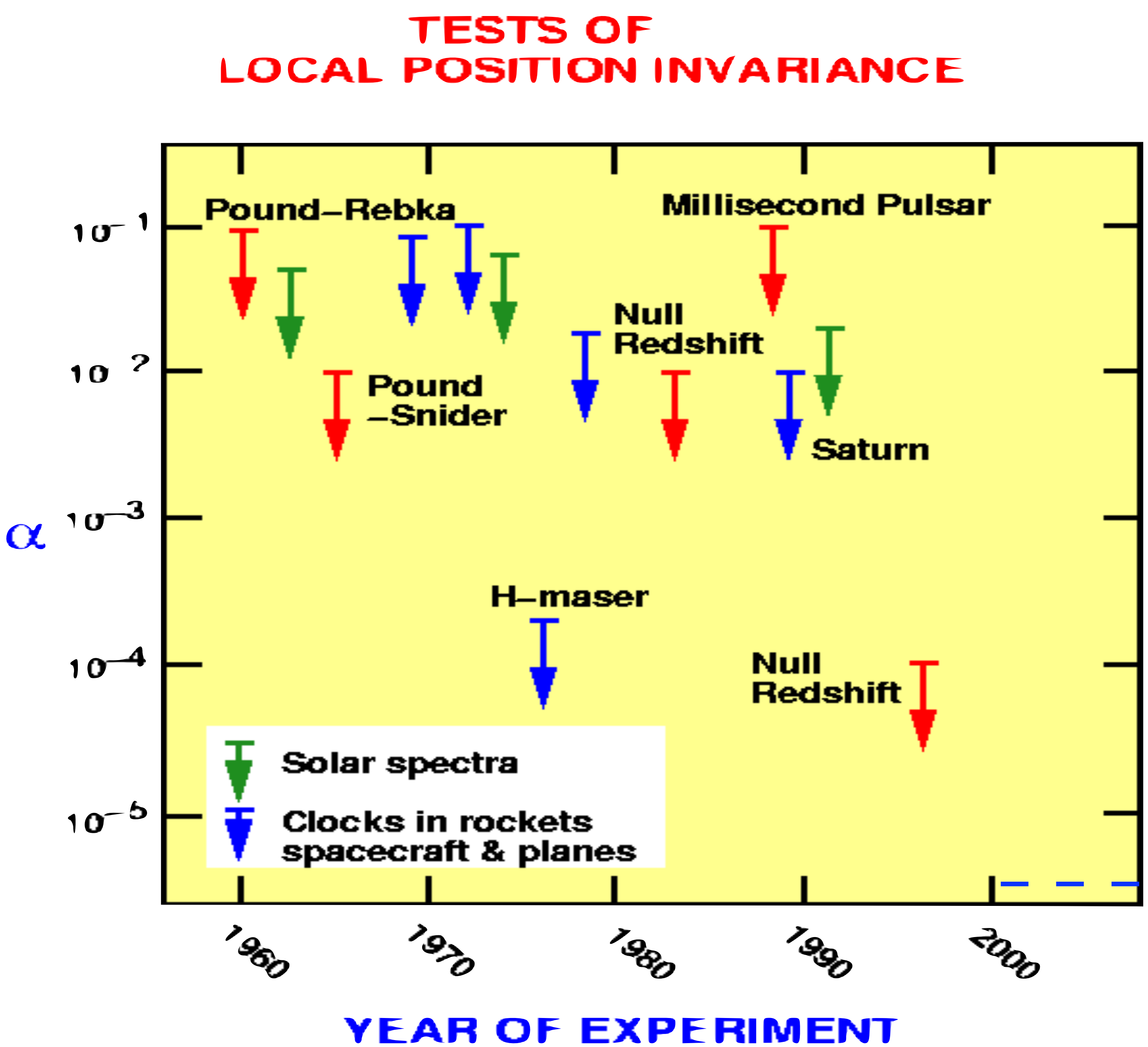
Local Position Invariance

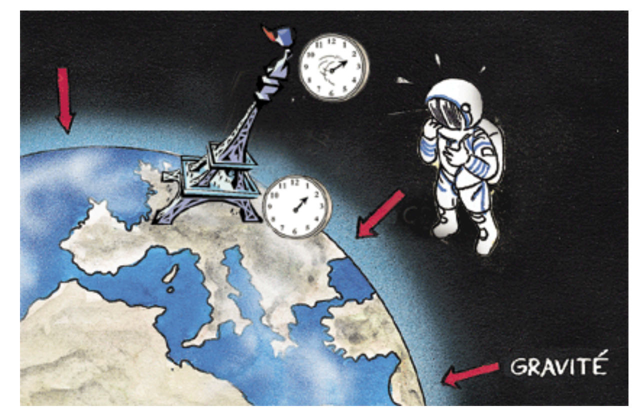


ACES

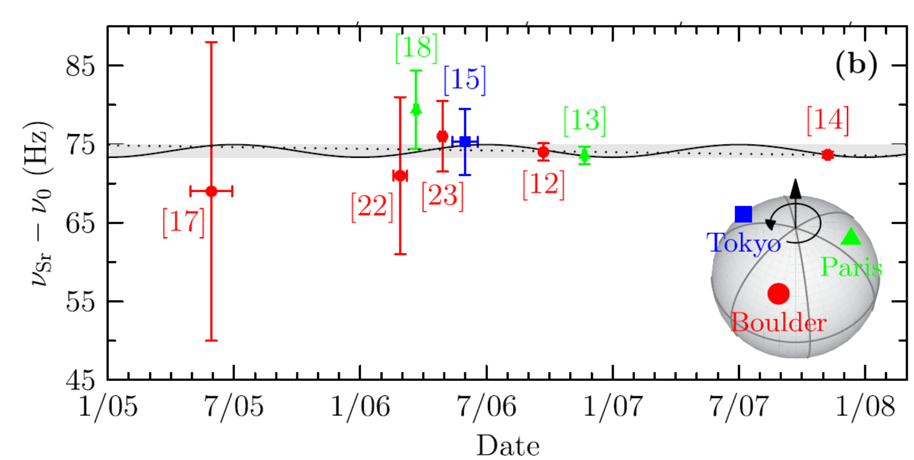
$$\Delta\nu/\nu = (1+\alpha)\Delta U/c^2$$

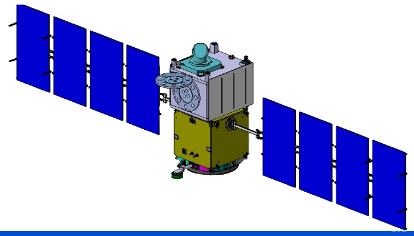
- Red shift test (GPA : 7×10^{-5})

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



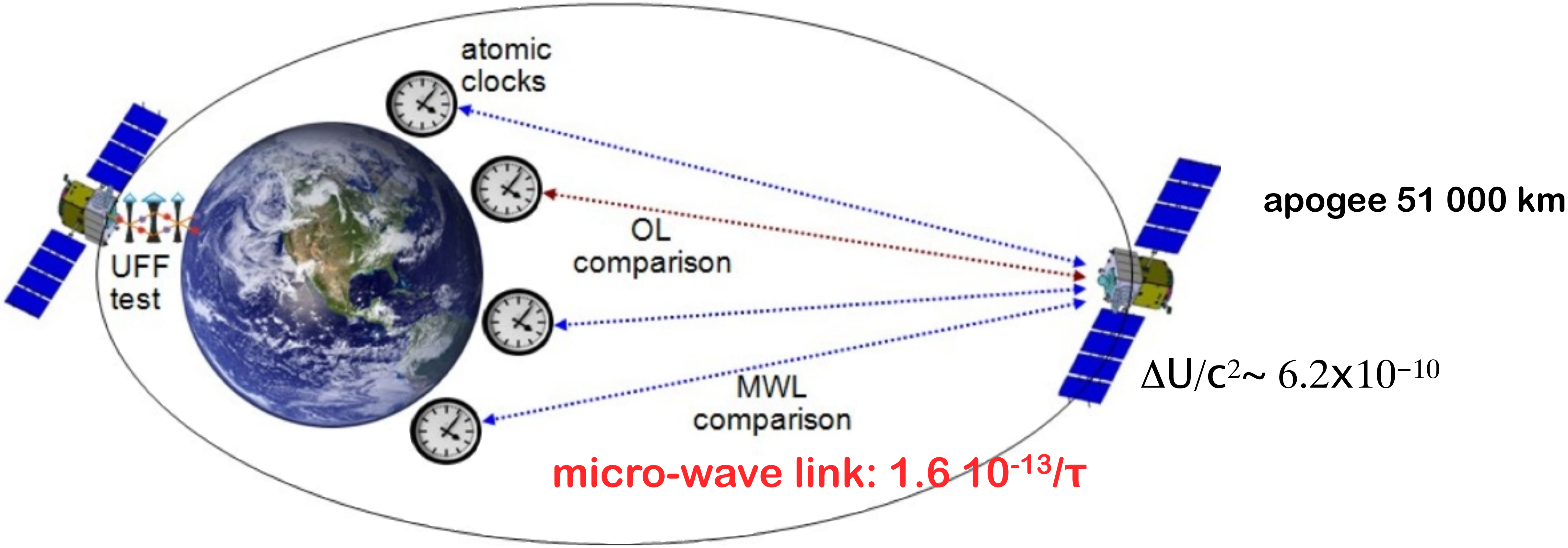
- ACES: 2×10^{-6}
- Null red shift test (Clock comparison)



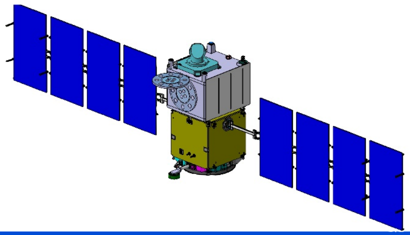


STE - QUEST

Test of the red shift: baseline configuration



- 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 $1\mathrm{x}10^{-16}$): $1.6\ \mathrm{x}10^{-7}$ (15 time better than ACES)
- Test based on the modulation during the orbit (test based on the stability $3\ \mathrm{x}10^{-17}$) and averages over 1000 orbits: $2.7\ \mathrm{x}10^{-7}$

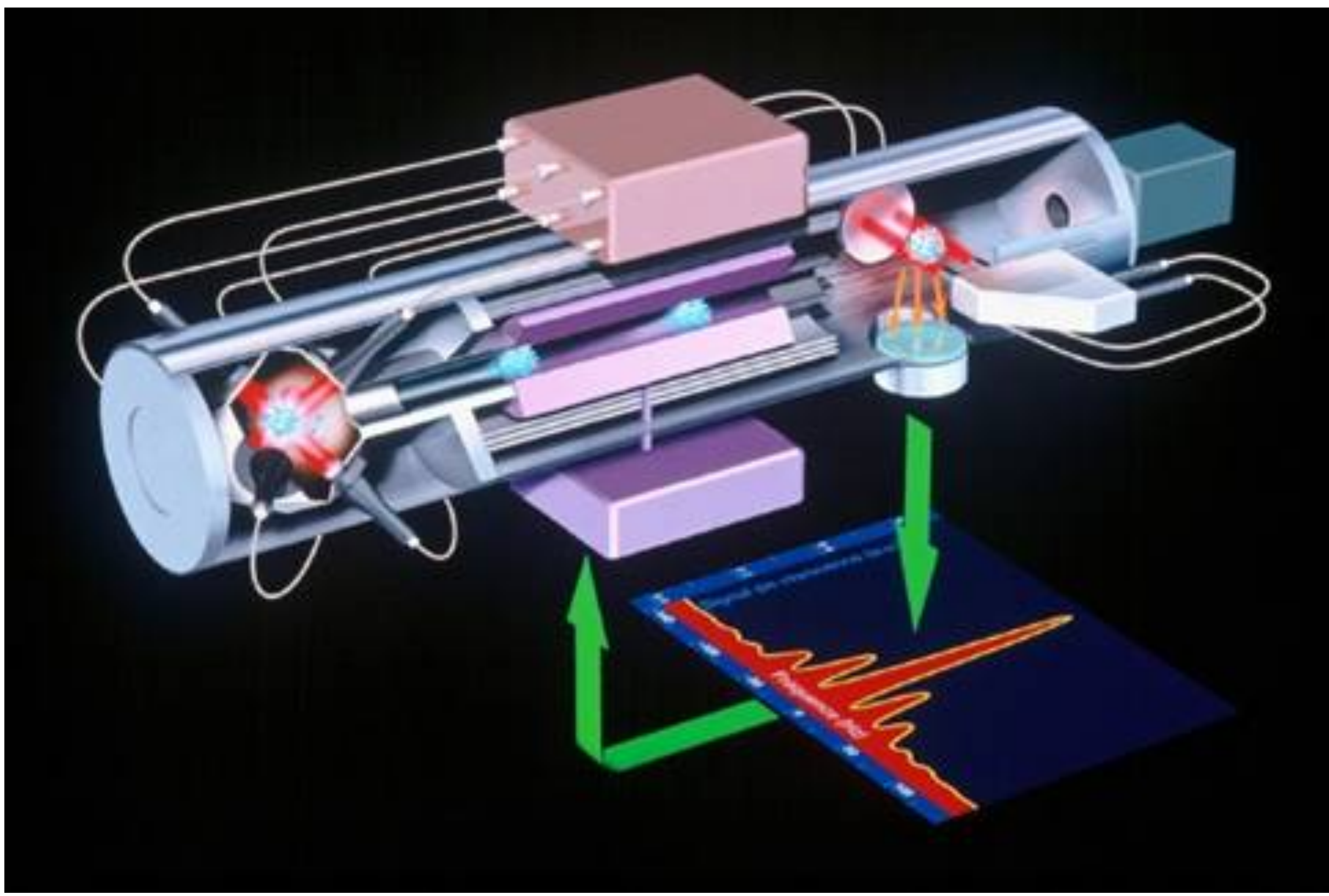


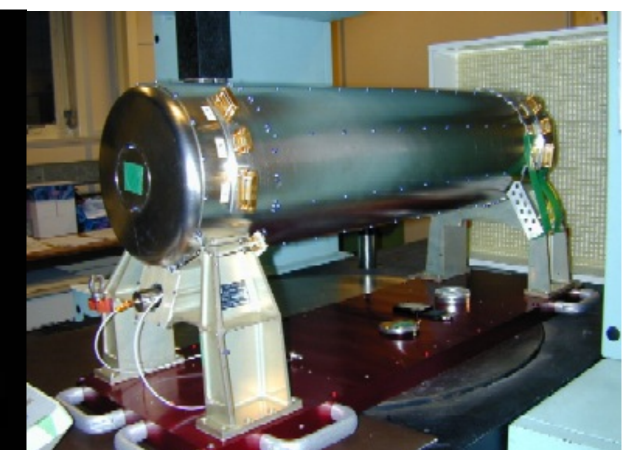
STE - QUEST

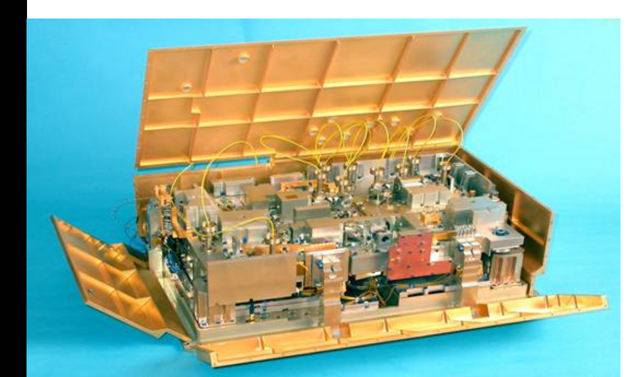
A class M mission to test gravitation with light and quantum particles

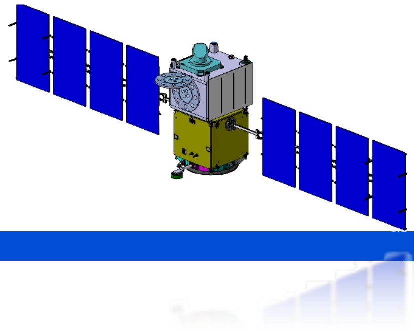
Atomic clocks with Rb atoms: low collisional shift (gain of 3 compare to Cs)

Pharao Cs clock (ACES mission)









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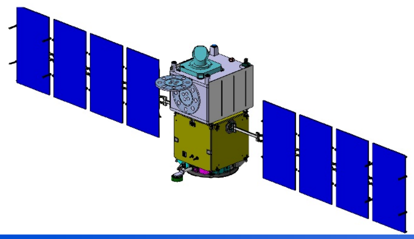

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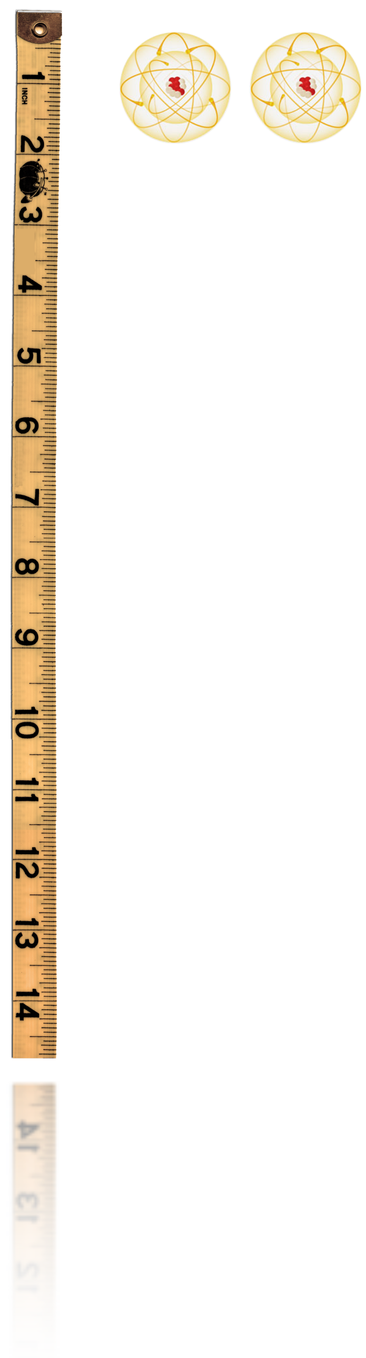
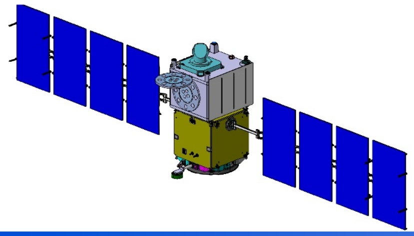


- Compare the free fall of 2 different atomic species: ^{85}RB and ^{87}RB

- Atom interferometry : use a precise ruler to get the position in time

- Measurement based on accuracy of the atomic sensors: no spinning of the satellite



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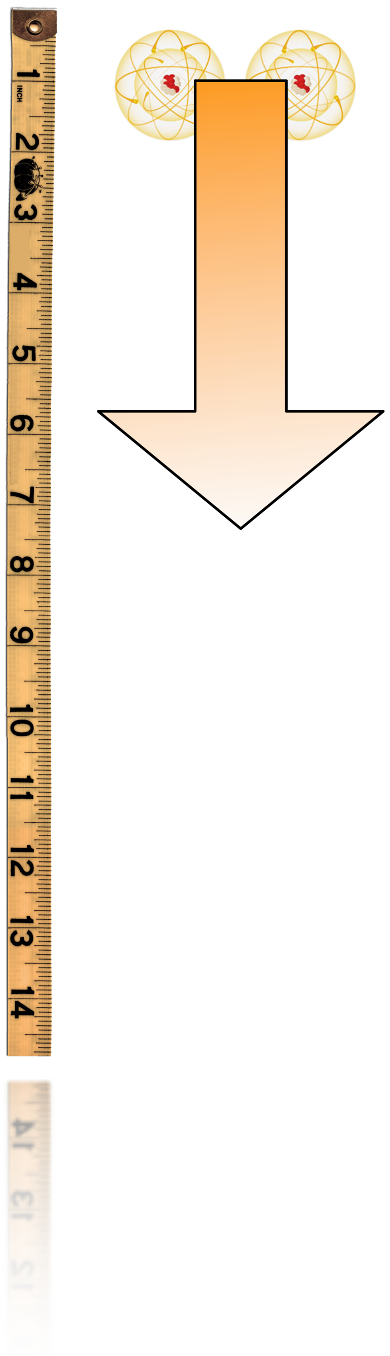

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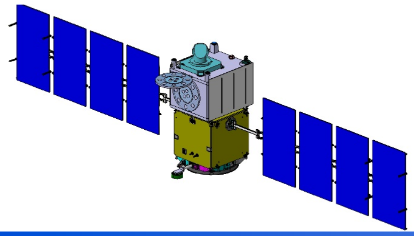

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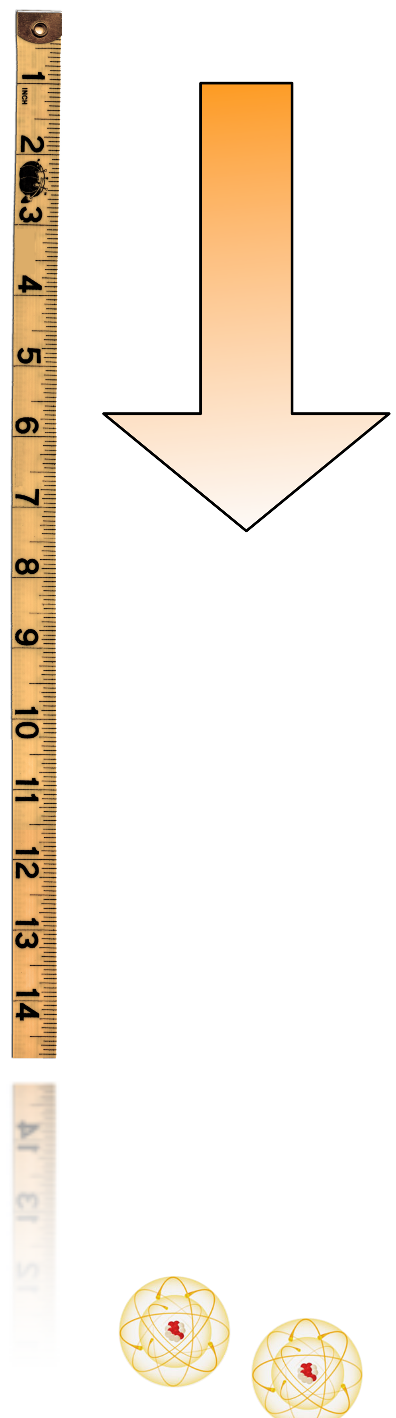

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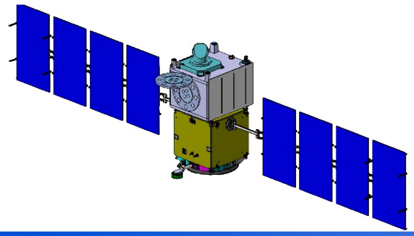
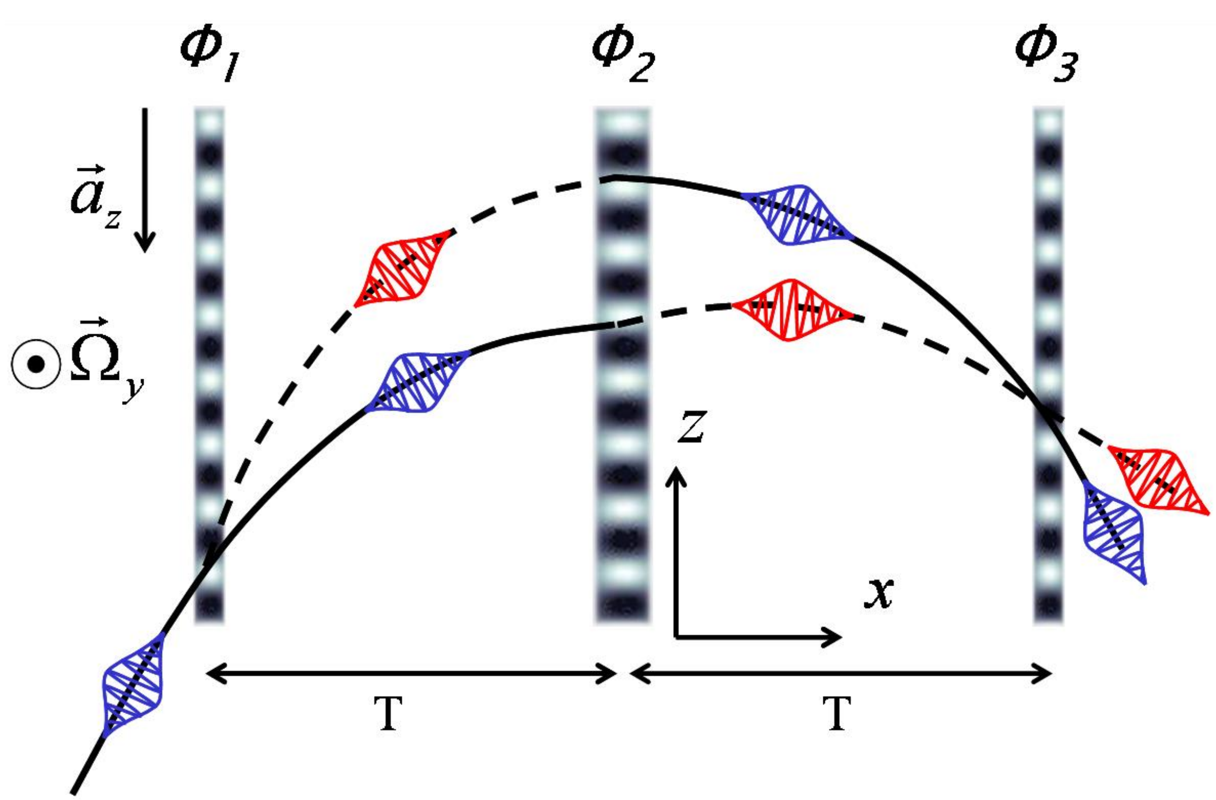
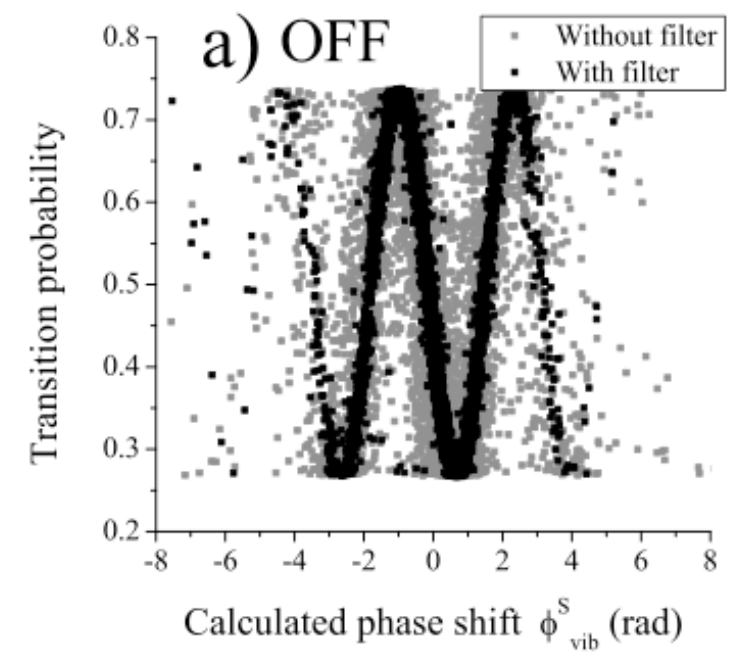


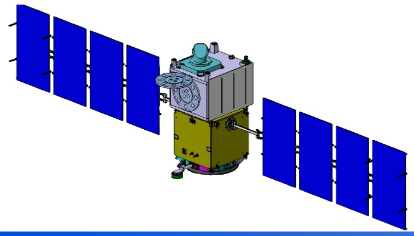
STE - QUEST

Atom Interferometer

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







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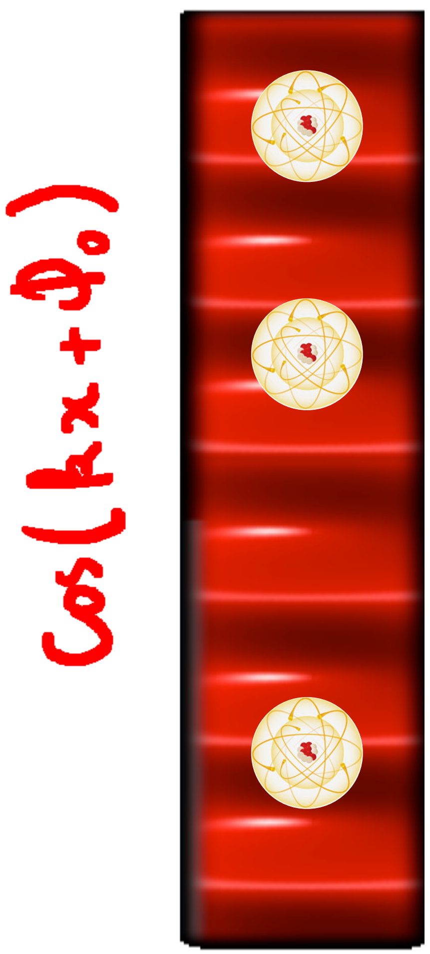
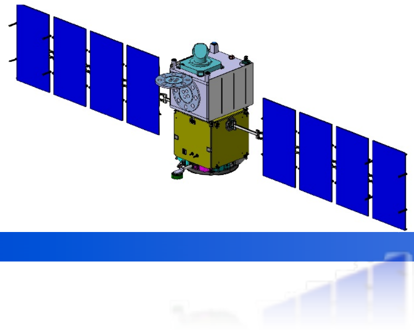
Atom Interferometer high accuracy and stability

- ✓ 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 with ultra-cold atoms)

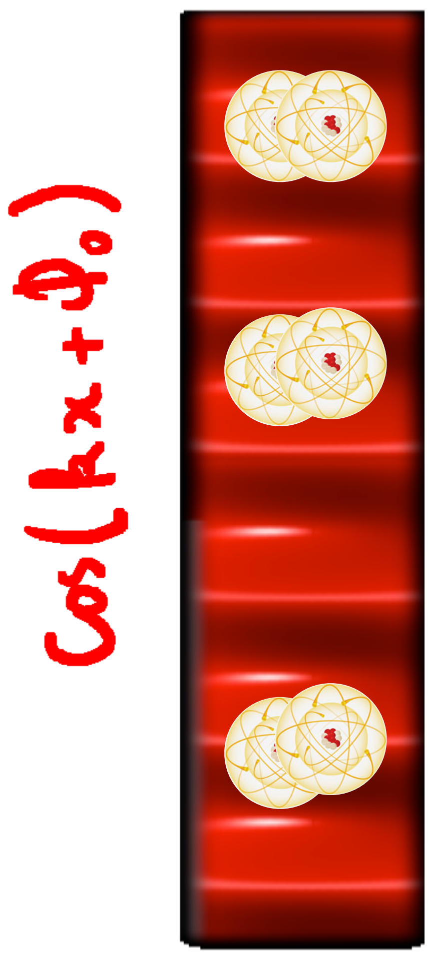
$$\Delta a_{min} = \frac{a|_{\Delta\phi_{acc}=1\,rad}}{\sqrt{N}} = \frac{1}{k T^2 \sqrt{N}}$$



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} $m.s^{-2}/\sqrt{\tau}$

Cycling time: 20 s

Sensitivity to Eötvös parameter: 2.3 10^{-14} per orbit

10^{-15} per year

The I.C.E. project: Towards a test of the Universality of Free Fall with atoms

R. Geiger, V. Ménoret, G. Stern, B. Battelier, P. Cheinet P. Bouyer
Laboratoire Charles Fabry de l'Institut d'Optique, Palaiseau
Laboratoire Photonique Numérique et Nanoscience, Bordeaux

N. Zahzam, Y. Bidel, A. Bresson
ONERA, Palaiseau

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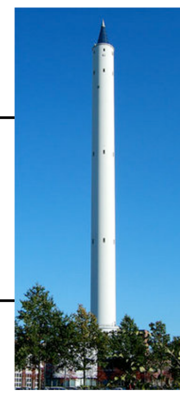
LNE-SYRTE, Observatoire de Paris

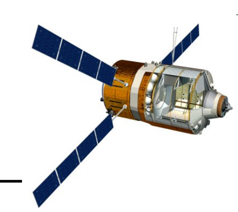
Systèmes de Référence Temps-Espace

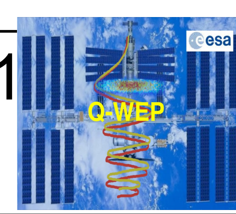
CENTRE NATIONAL D'ÉTUDES SPATIALES

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	up to 6 minutes
space carrier	10^{-6}	3 days
ISS	1	days to years
satellite	10^{-7}	2-5 years





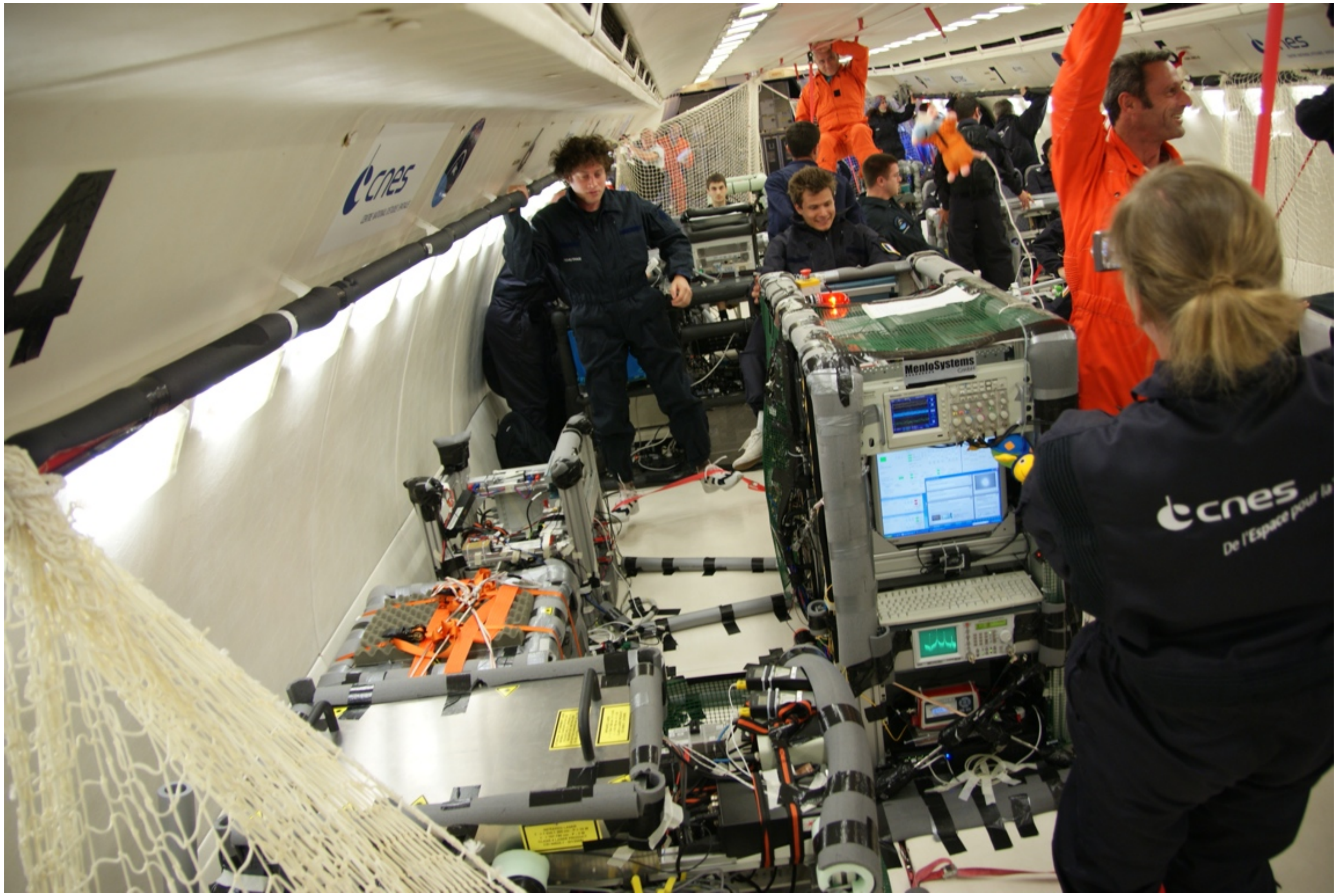


The I.C.E. setup in the flying lab

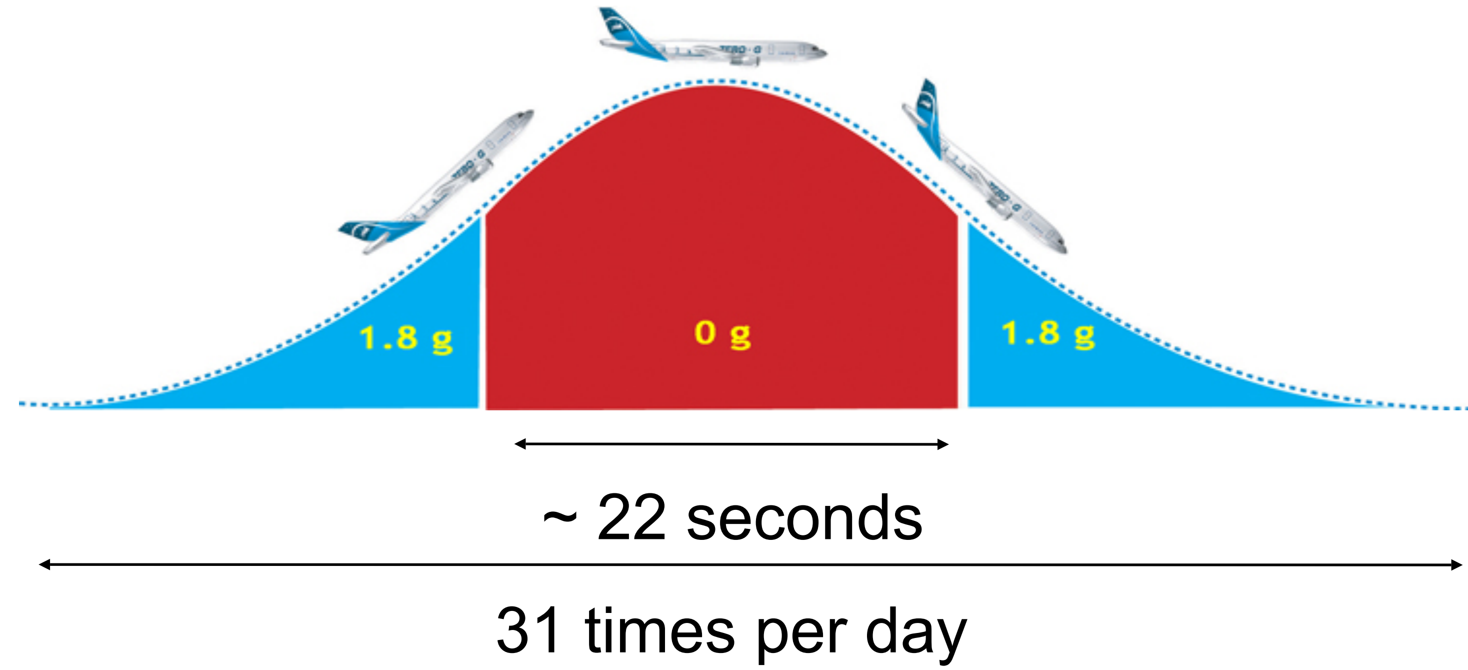
- Choice of the ^{87}Rb and ^{39}K atoms
- Fiber laser sources @ 1560 nm and 1534 nm, second harmonic generation → 780 and 767 nm for cooling and manipulating atoms

(Reliability of telecom lasers)

- 4 racks, 700 kg, 1000 W power consumption



An aircraft as experimental platform



Novespace A300-0g Airbus (Bordeaux, France)

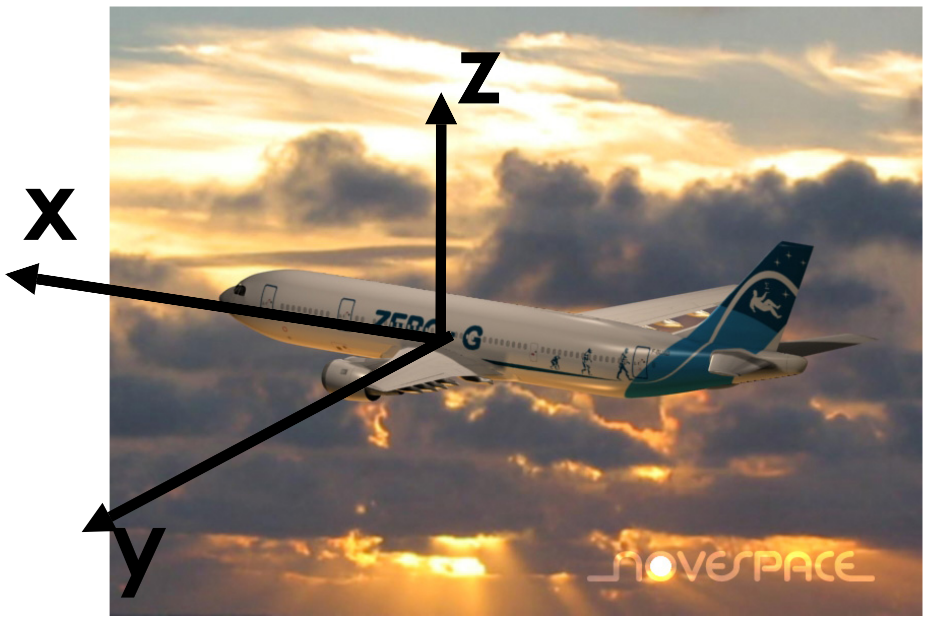
- 3 flight days in a campaign: microgravity total time ~ 30 minutes
- Measurement during 1-g and 0-g phases
- Vibrations, temperature fluctuations, experiment turned off at night

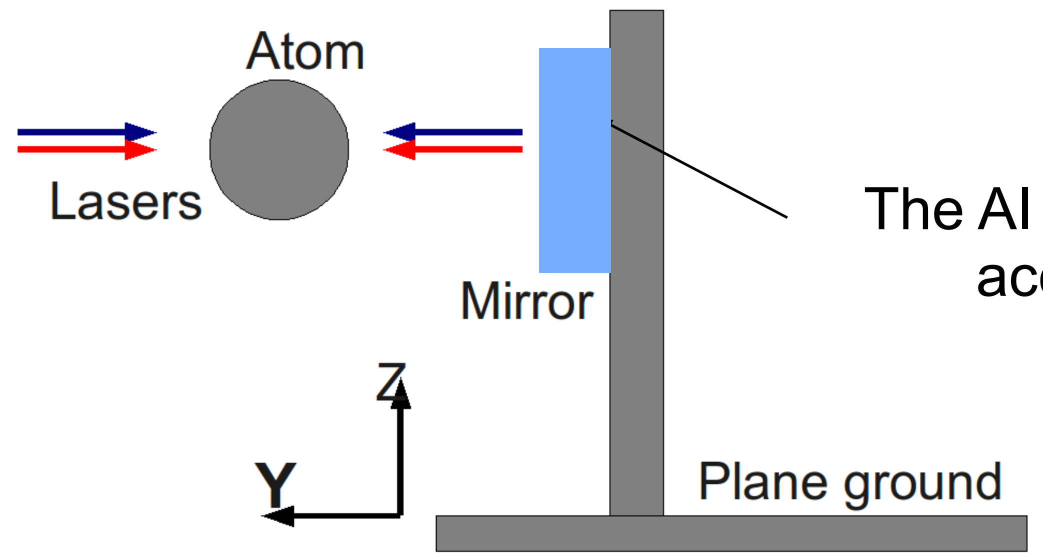
Ice: test in the 0-g plane

- Atomic sources: Rb and K together
  - laser sources : 780 and 767 nm
  - Vacuum system
  - Femto for frequency comparison
- Atom interferometer in the plane: Rb

R. Geiger at al., Nature Comm. 20th sept 2011

Precise acceleration measurements



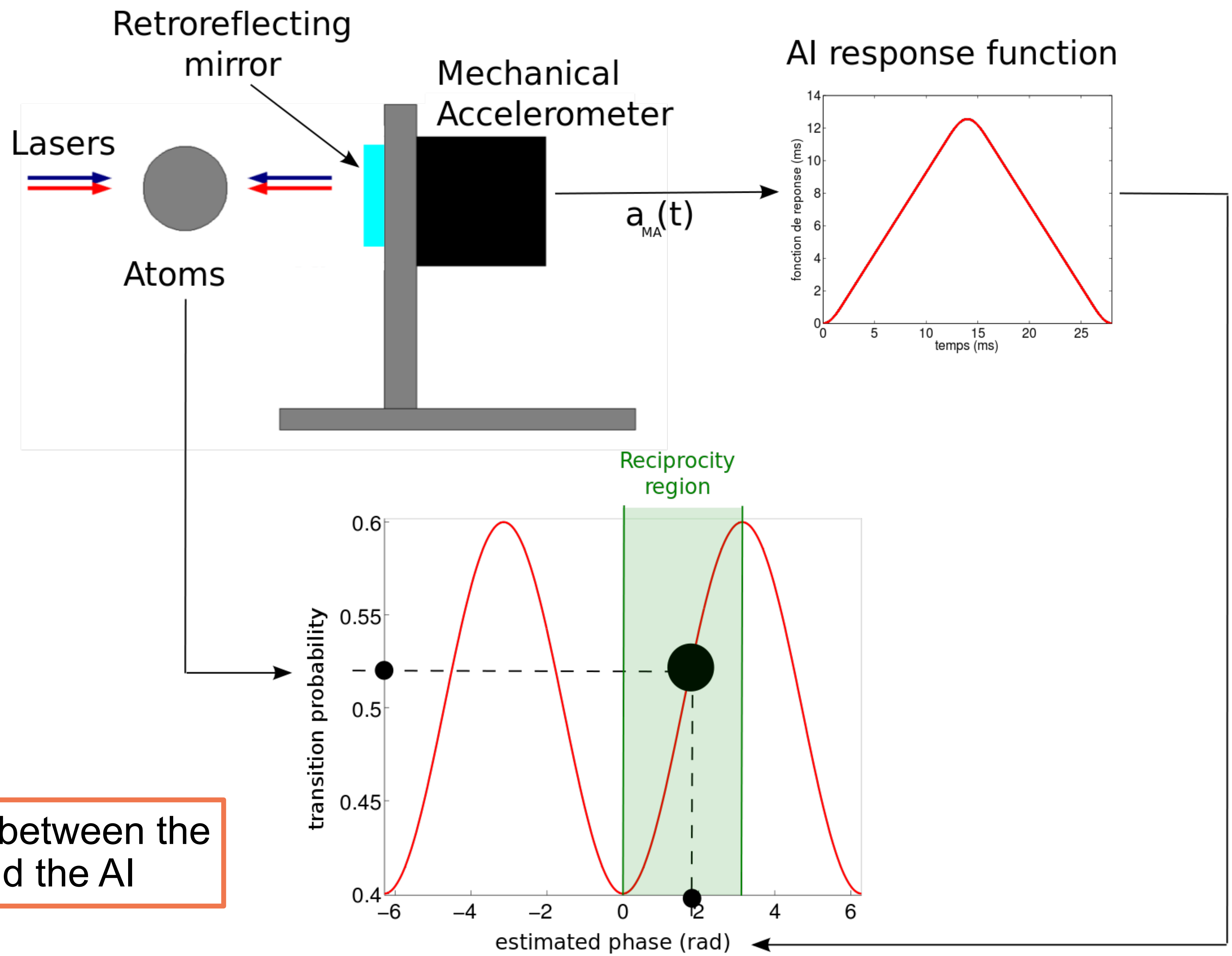


The AI senses the mirror acceleration, a_m

AI output signal: $$P = P_0 - A\cos\Phi$$

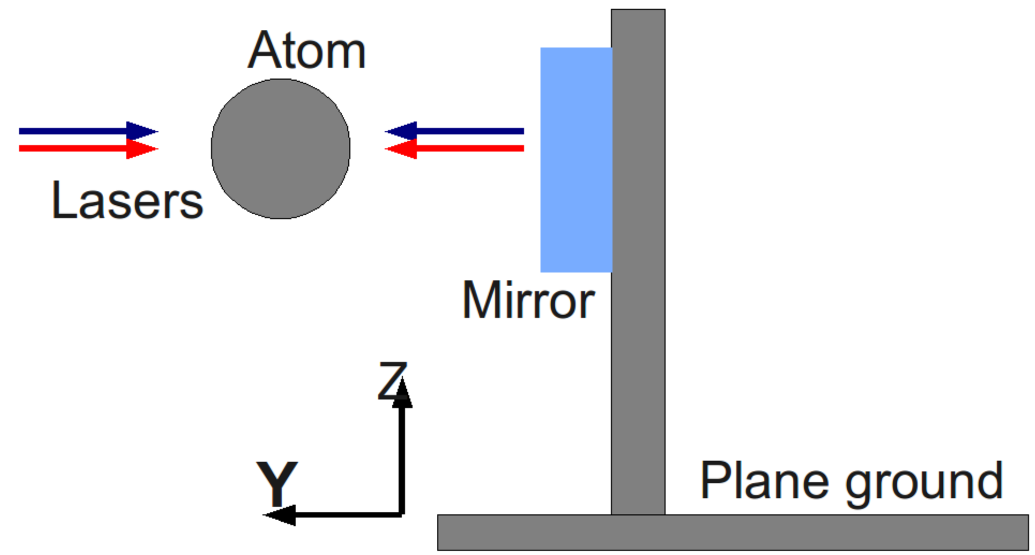
Link is lost if $\Phi > \pi$
(non-reciprocal response of the AI)

Correlation method



Correlation between the MAs and the AI

Precise acceleration measurements



$$P = P_0 - A \cos \Phi$$

out of the reciprocity region of the AI !

Acceleration fluctuations $\delta a_m \sim 0.5\ \mathrm{m.s^{-2}}$
→ phase fluctuations $\delta\Phi = \delta a_m \times k_{eff} T^2 \sim 8$ rad @ T=1 ms !

Solution to overcome the non-reciprocity problem:
1. Use an external device to measure the coarse accelerations
2. Use the AI for the high resolution measurement

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

Precise acceleration measurements

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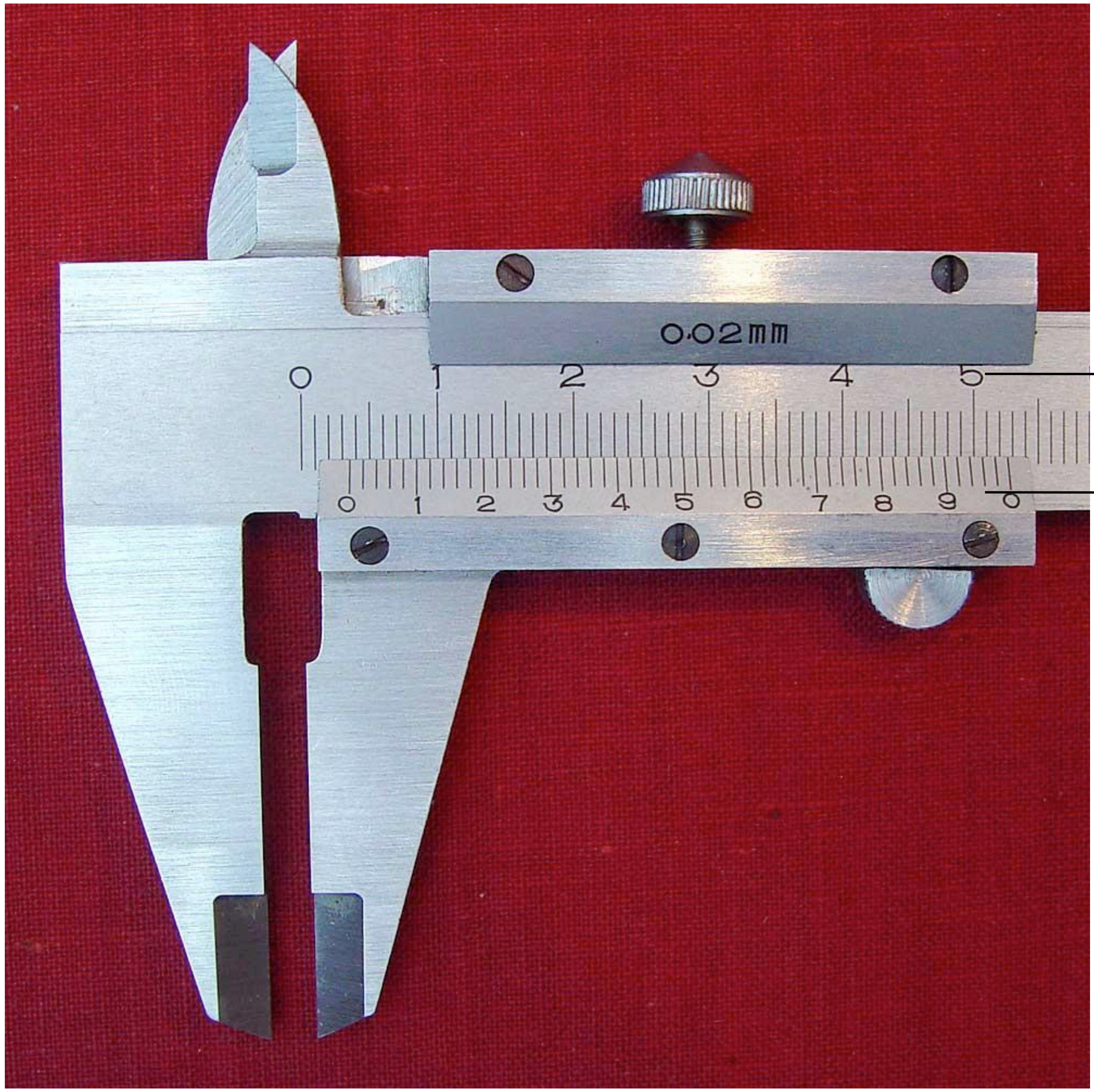
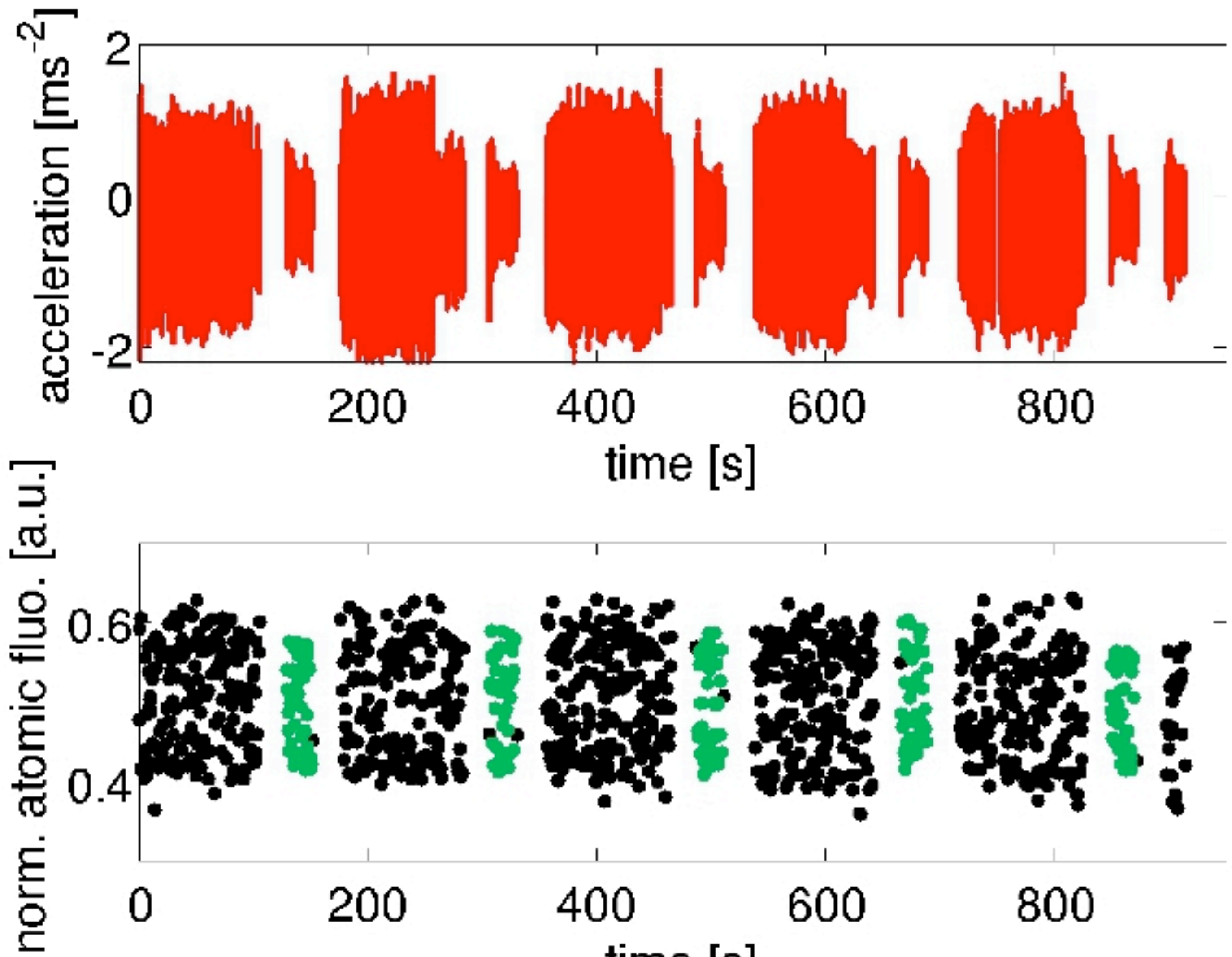


Similar to Vernier method

Mechanical accelerometer

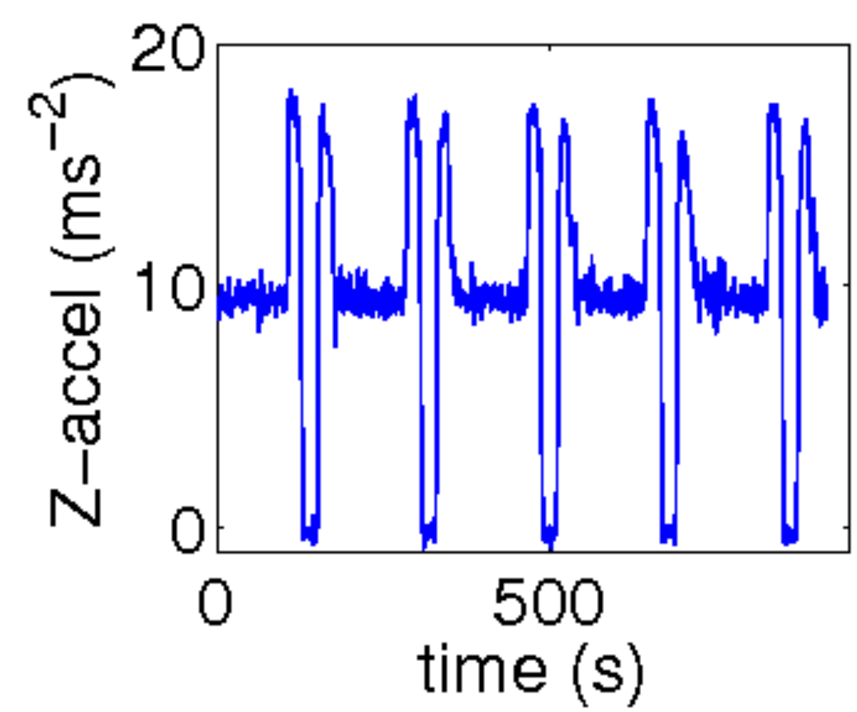
Atom interferometer

MAs-AI correlations

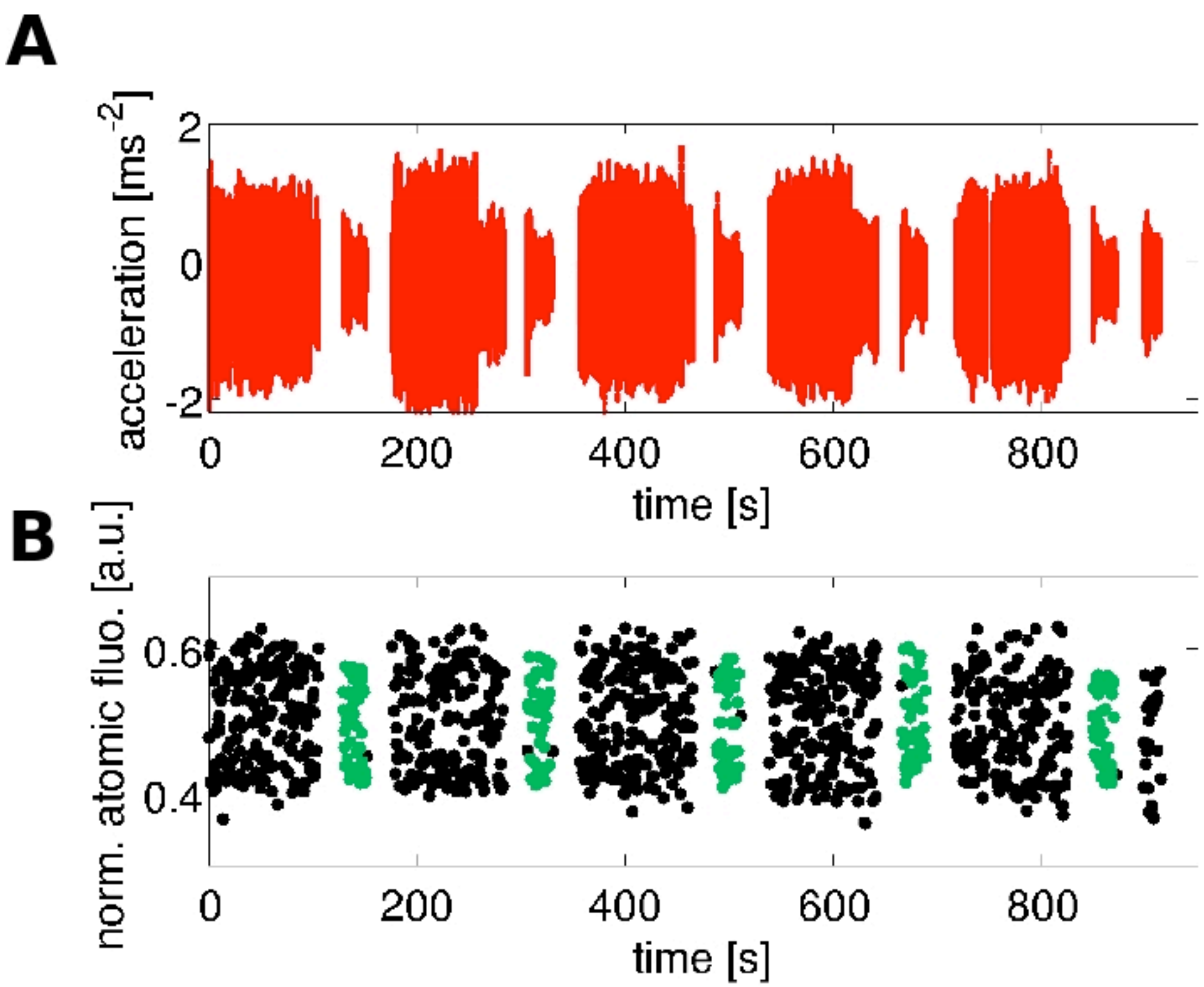


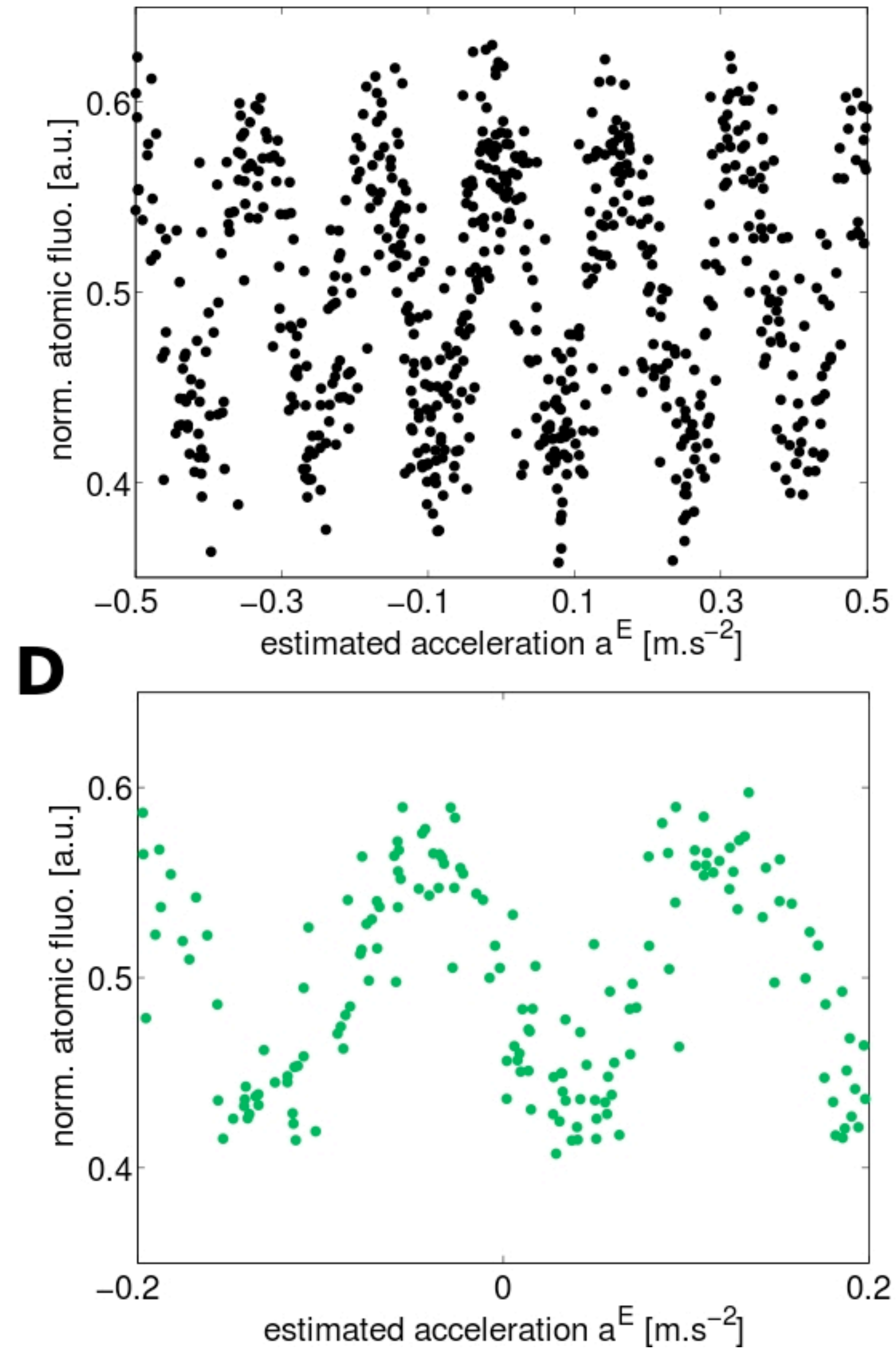
Mechanical accelerometers signal

Atom interferometer signal



MAs-AI correlations





1-g

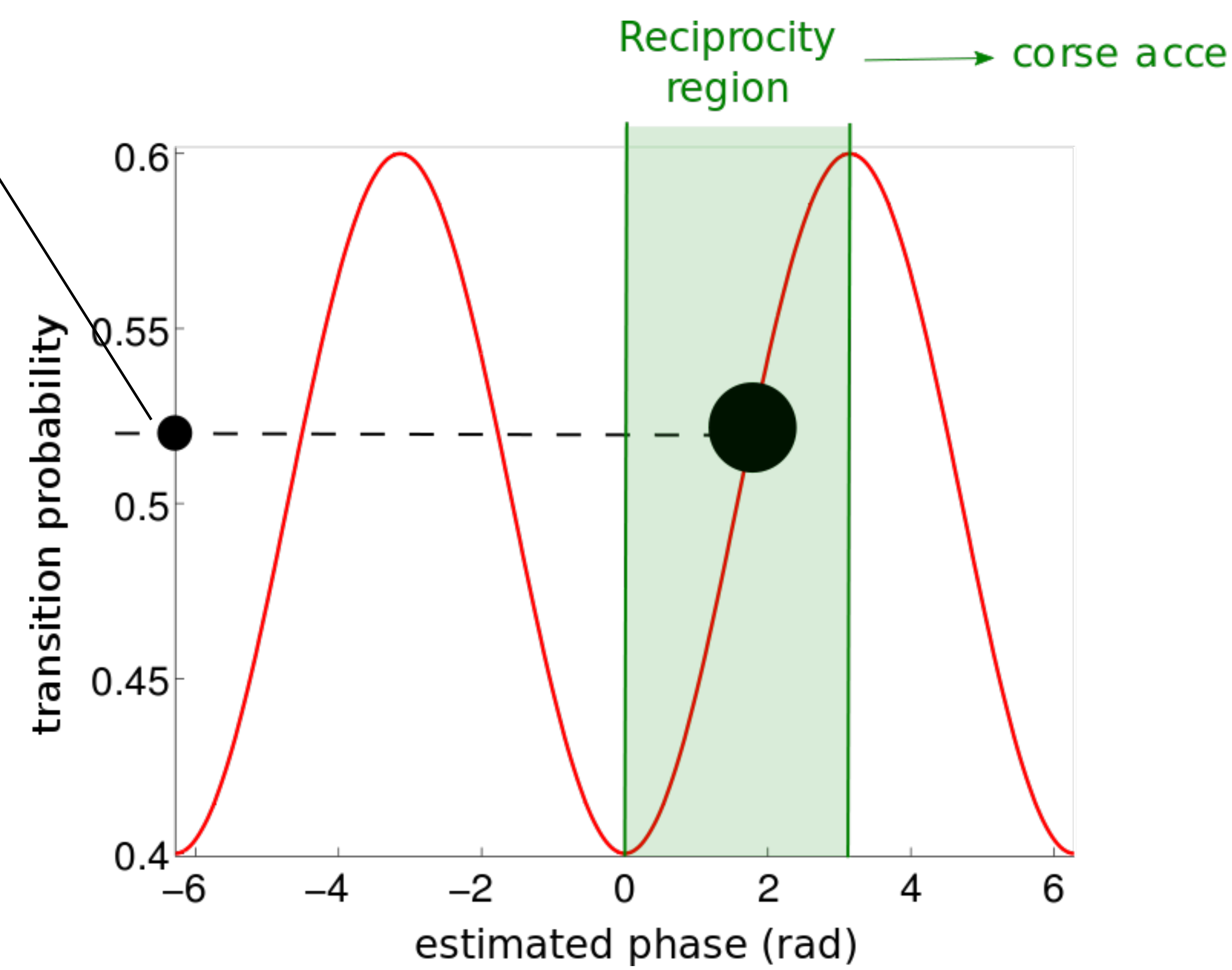
0-g

First matter wave inertial sensor in
an airplane and in microgravity!

Two-step acceleration measurement

- ✓ Coarse measurement with the MAs → fringe number where the AI operates every shot
- ✓ Fine measurement with the AI, within its reciprocity region

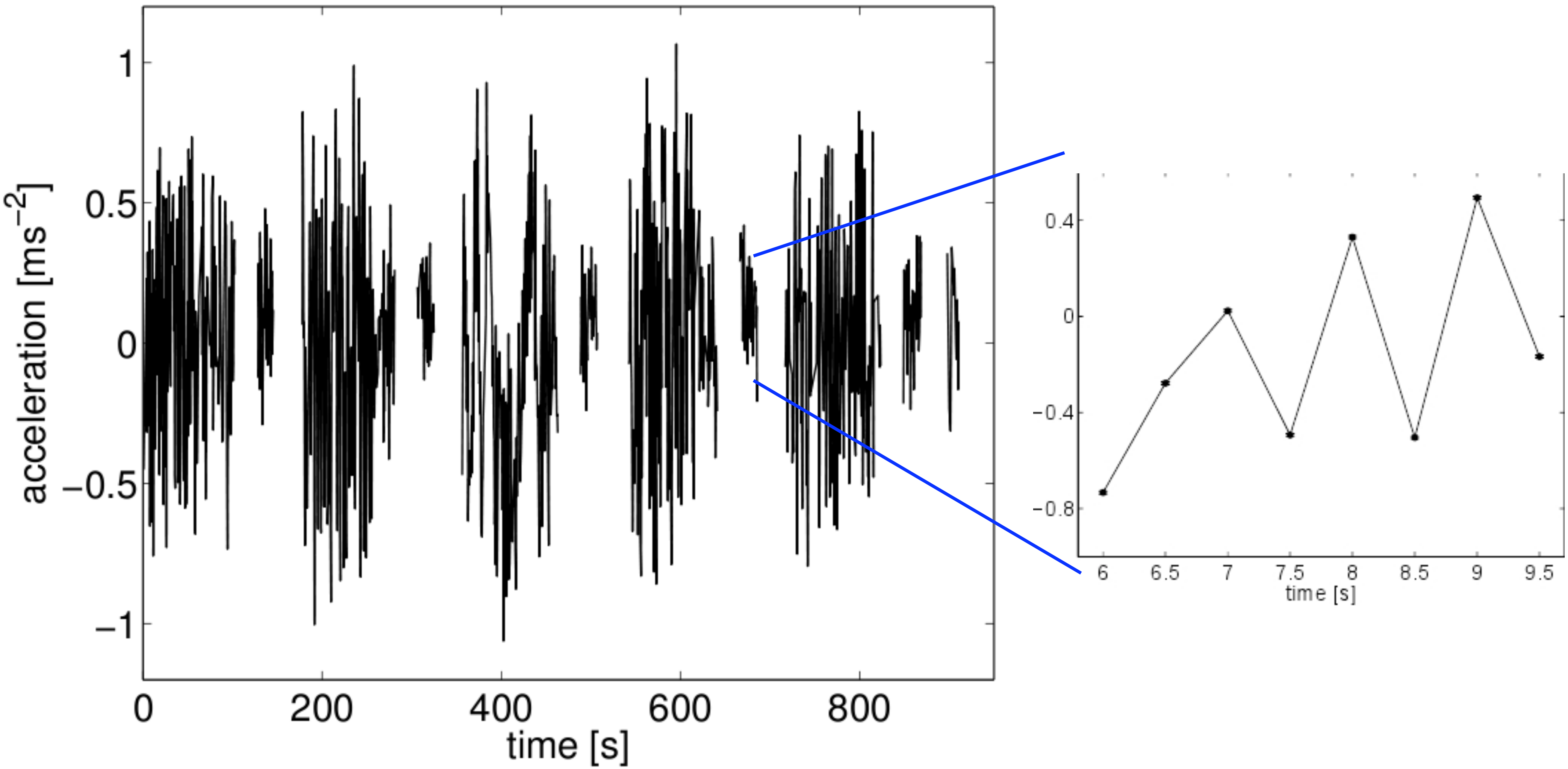
$$\tilde{a}(t_i) = \frac{1}{kT^2} \arccos\left(\frac{P_0 - P(t_i)}{A}\right)$$



Acceleration sensitivity determined by:

- Interrogation time (T)
- SNR of the interferometer

High resolution measurement



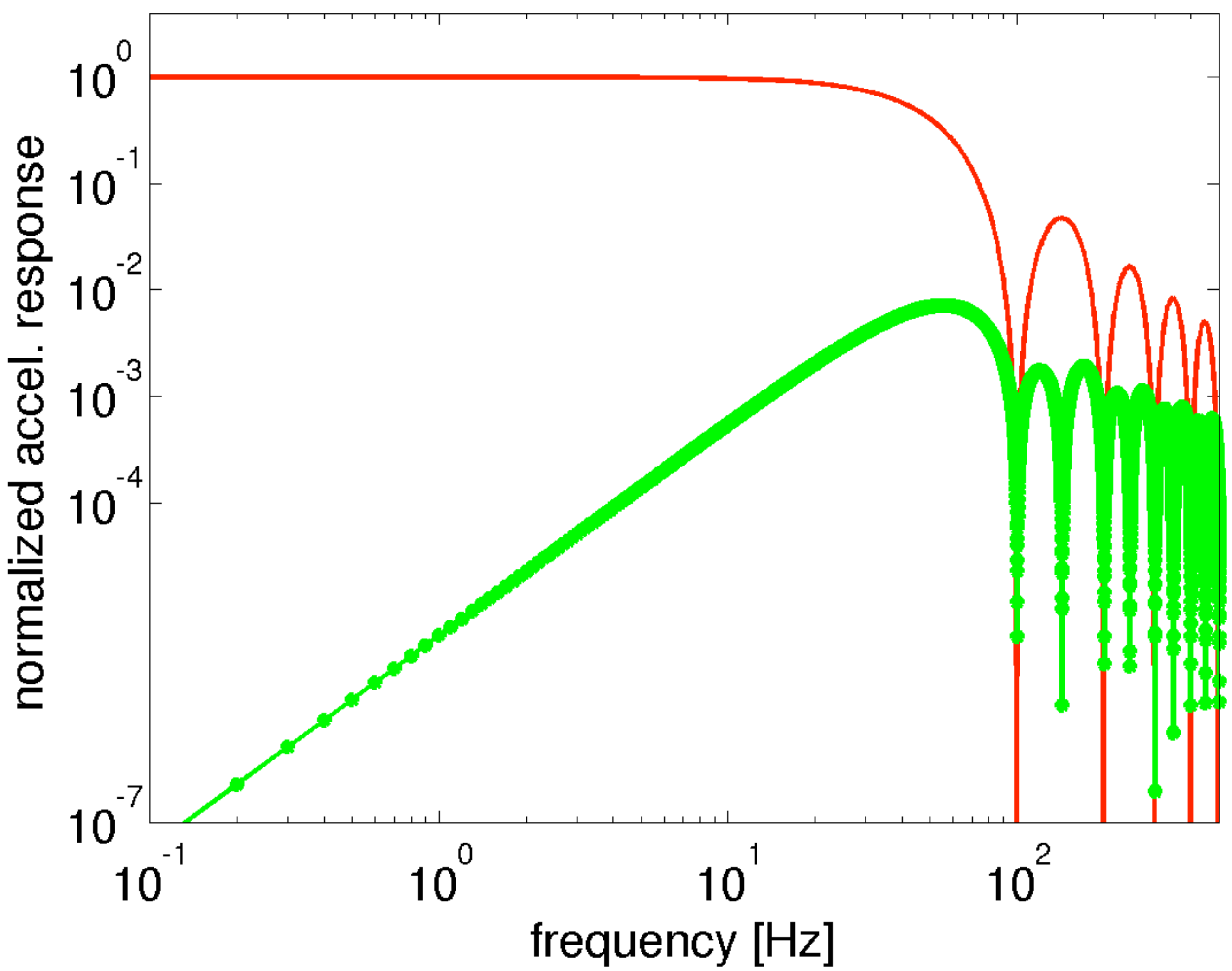
Resolution of the accelerometer: 300 times below the vibrations level in the plane!

Limited by performances of the MAs at low frequencies

Vibration rejection in a two-species AI

Close interrogation wavelengths:
λ_{Rb}= 780 nm / λ_K = 767 nm

Almost simultaneous operation
→ efficient vibration noise rejection



K- and Rb- interferometers with equal scale factor:

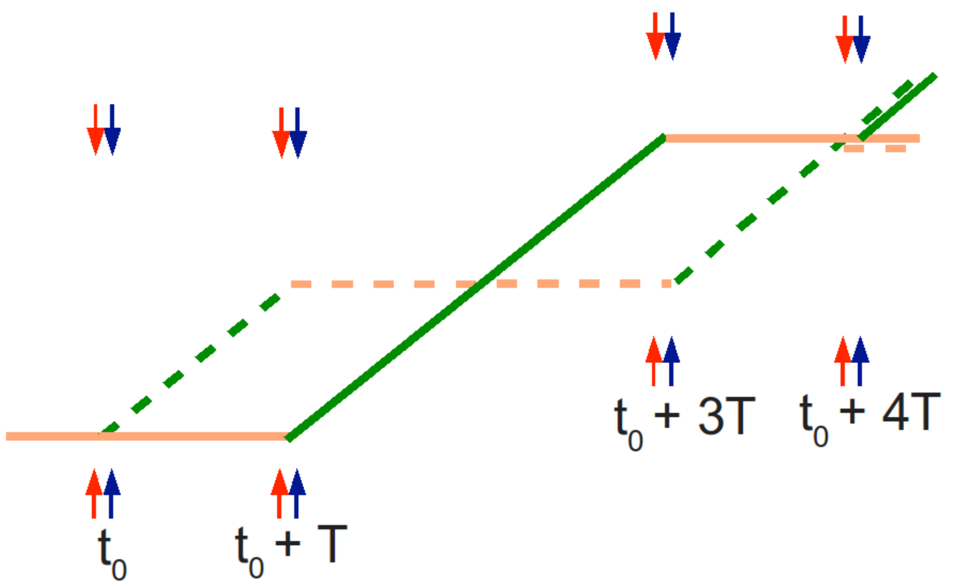
$$k_1 T_1^2 = k_2 T_2^2 = S$$

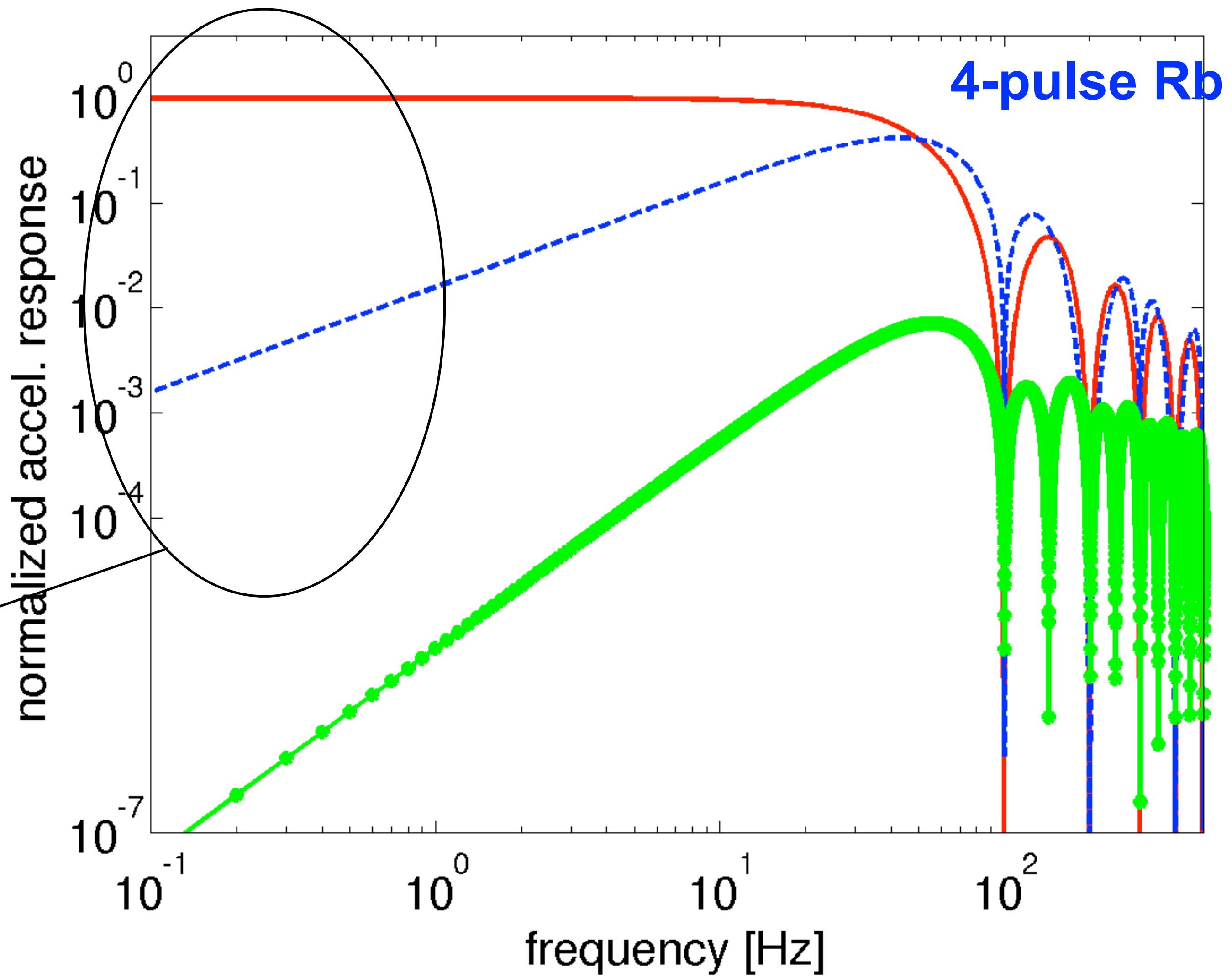
3-pulse Rb

3-pulse K/Rb

Investigation of vibration rejection in 0-g with a Rb 4-pulse interferometer

One-species 4-pulse interferometer:

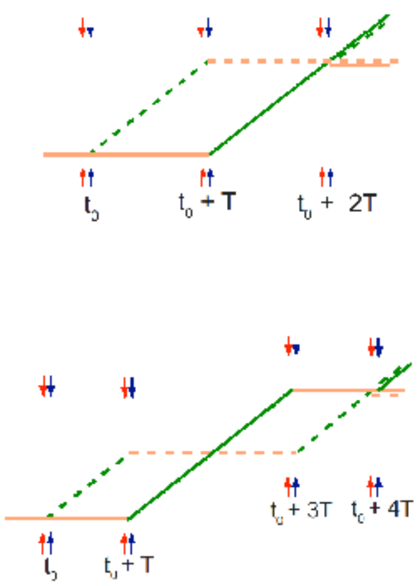




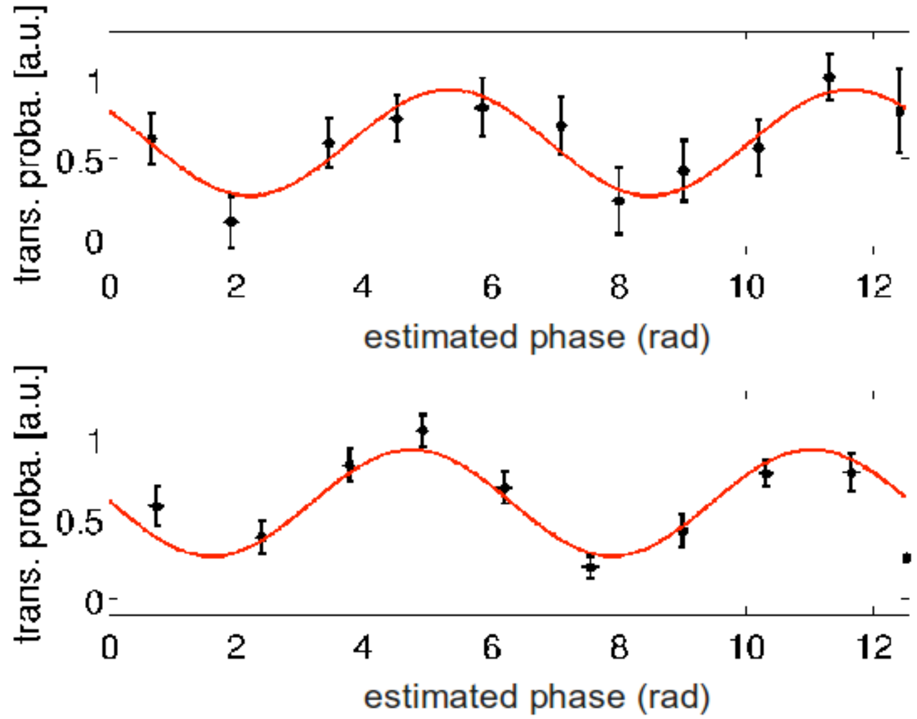
Successive operation of two A.I.

→ low frequency noise rejection

Comparison 3-pulse/4-pulse in 0-g



2T=20ms



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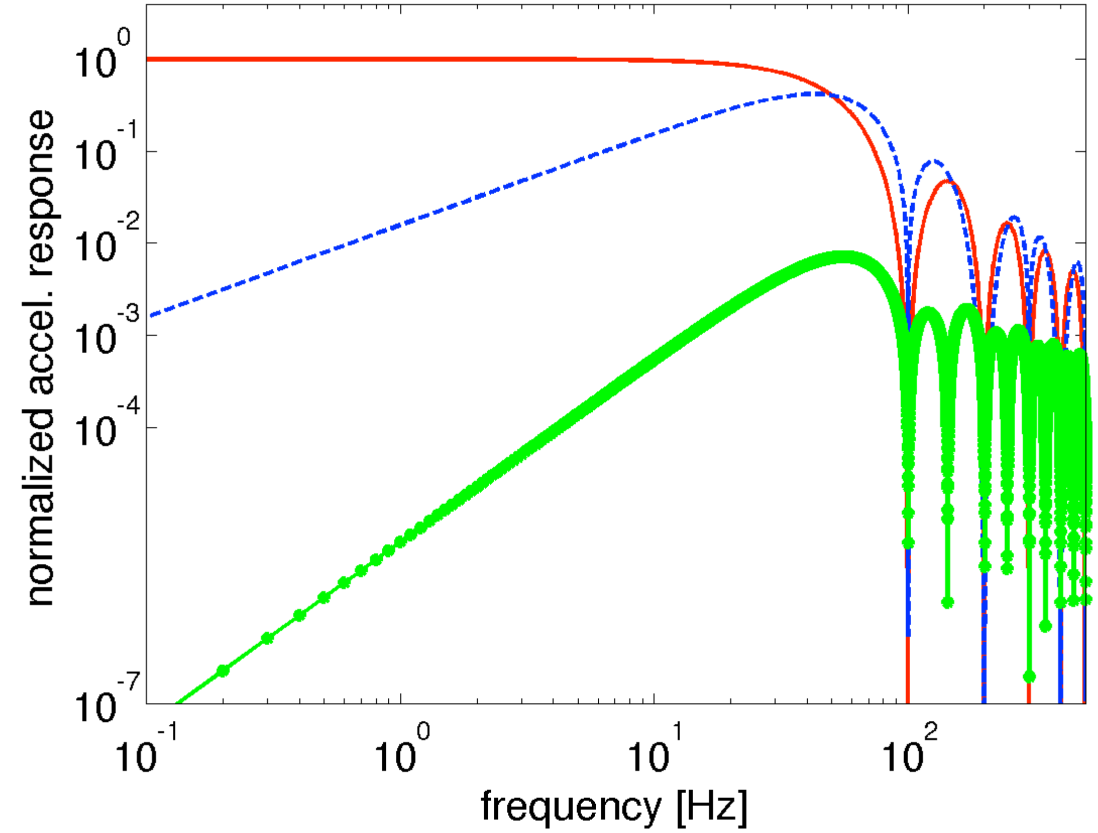

Expected rejection efficiency ~ 300 for the UFF test (in the plane)

G. Varoquaux *et al.*,
NJP **11**, 113010, 2009

Conclusion

l'Observatoire de Paris | SYRTE
Systèmes de Référence Temps-Espace

- ✓ Ice experiment has demonstrate atom interferometer in 0-g plane
  - ➡ technology demonstration for lasers (telecom techno)
    - cooling and interferometer
    - same laser telecom: dipole trap for BEC
  - ➡ principle demonstration for vibration rejection
    - no need for drag compensation
    - open other application fields as airborne gravi-gradiometry

- ✓ Important developments for STE-QUEST
  - ➡ ICE, Quantus
- ✓ Completed by measurements with Rb/K, and $^{85}Rb/^{87}Rb$