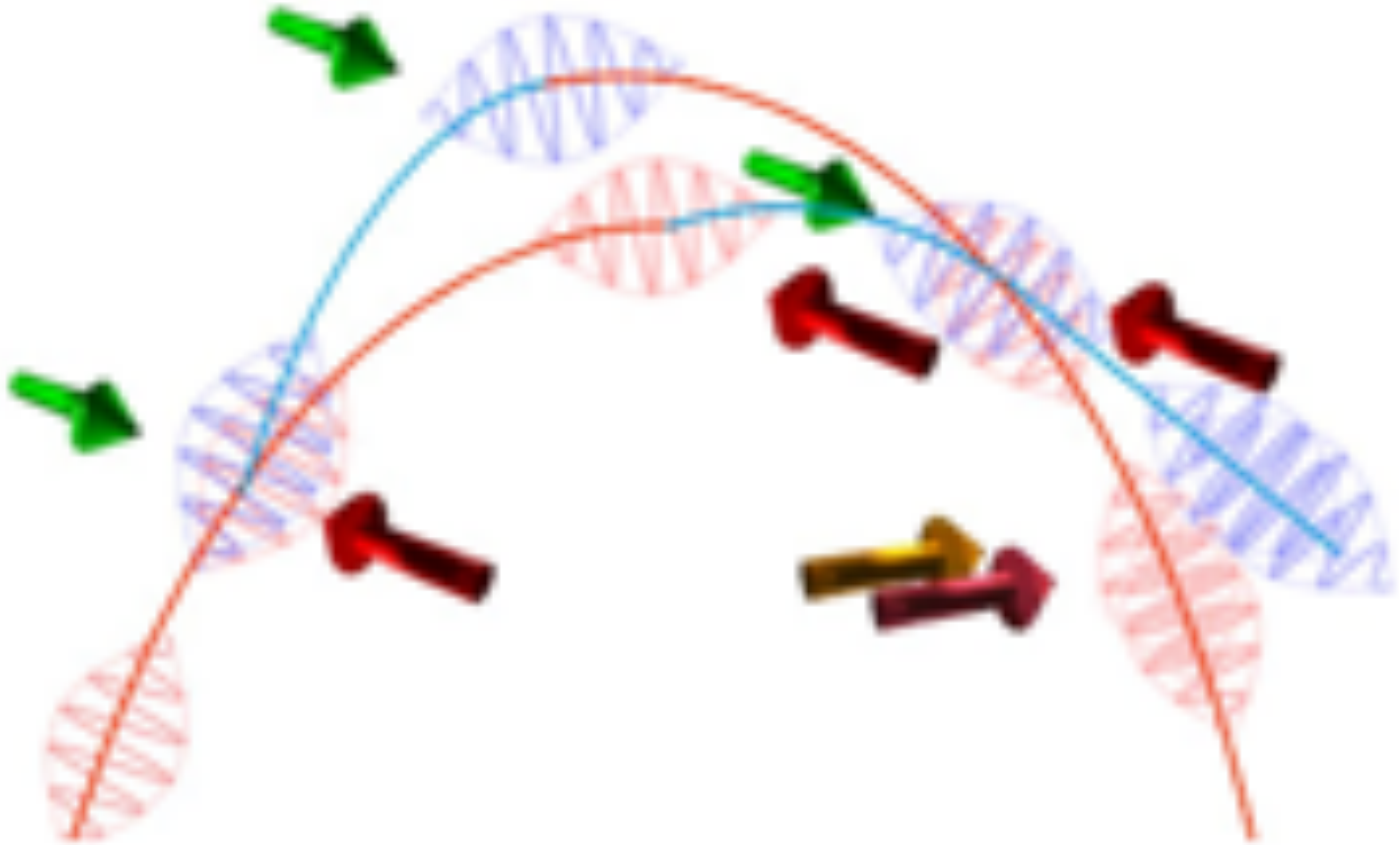
Nouveaux instruments en interférométrie atomique

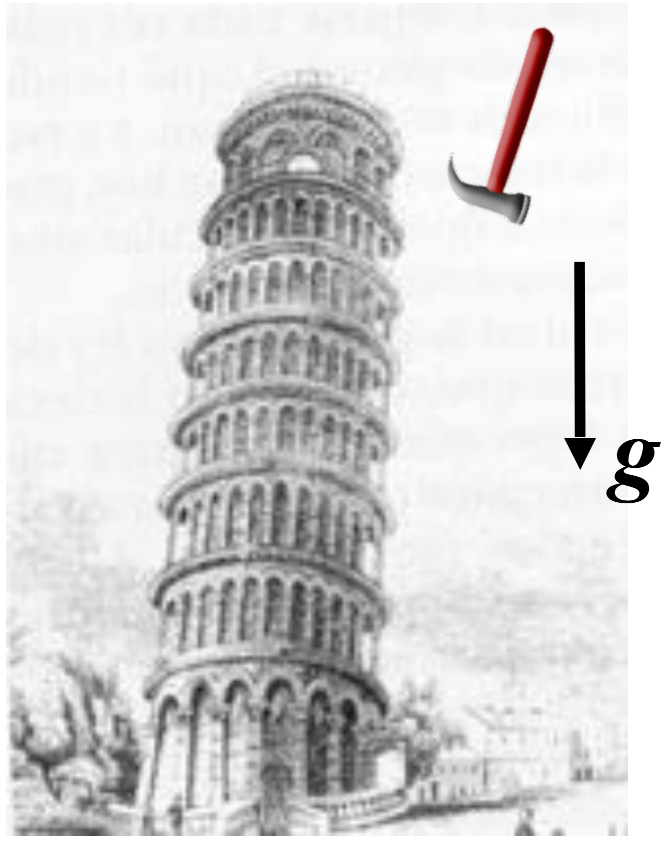


Arnaud Landragin

SYstèmes de Référence Temps-Espace

Atom interferometry as Inertial sensors

long term stability and accuracy

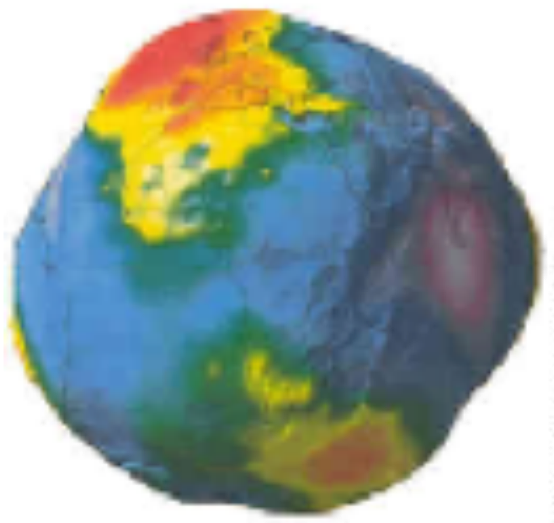


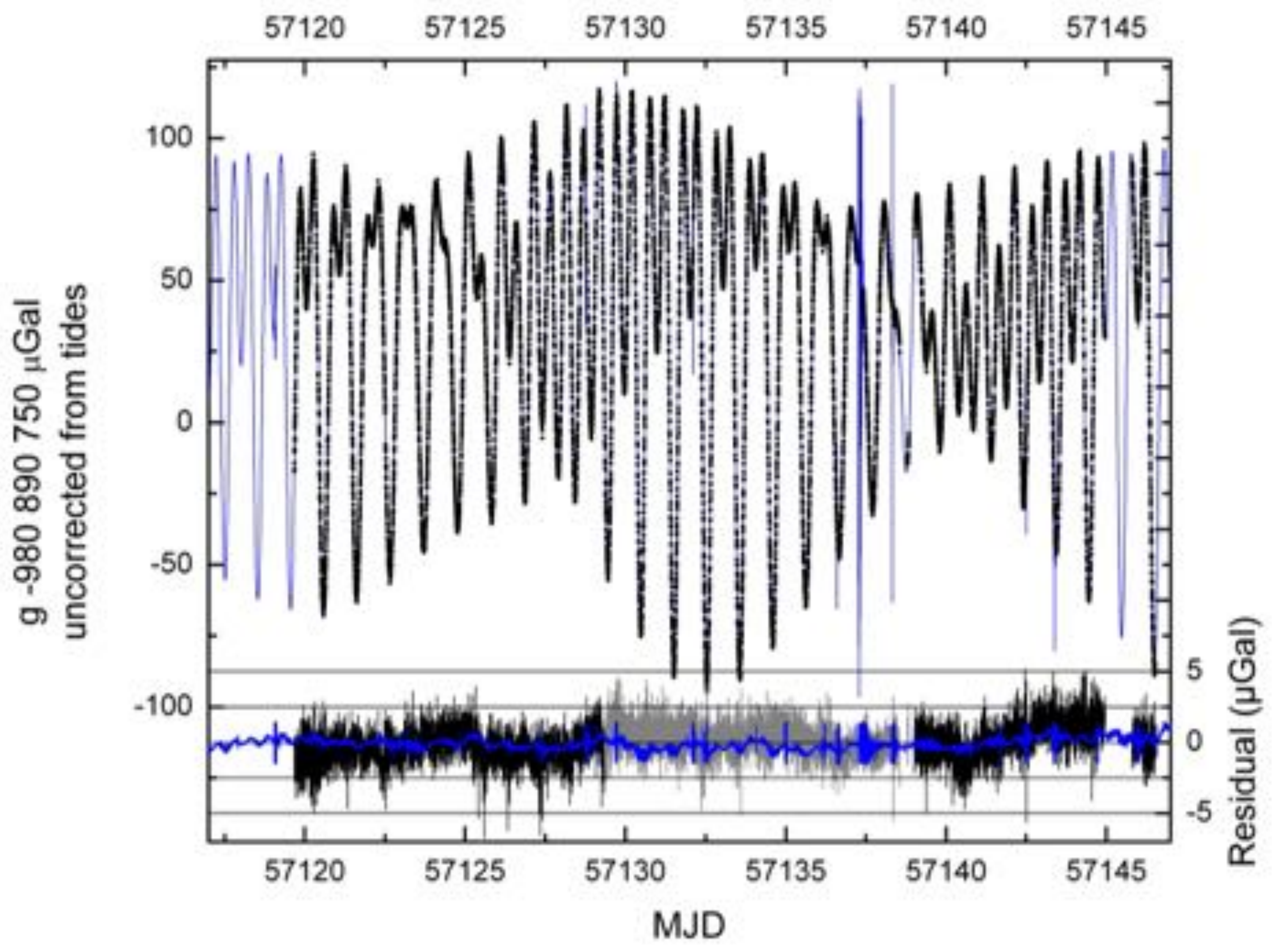
- Fundamental physics
  - ✓ measurement of α, G...
  - ✓ watt balance (gravimeter)
  - ✓ test of general relativity

    Einstein Equivalence Principle (STE-QUEST), anomalous gravity…(accelerometer)

    gravitational waves detection

- Inertial navigation plane, boat, submarine…





- Geophysics ground or space

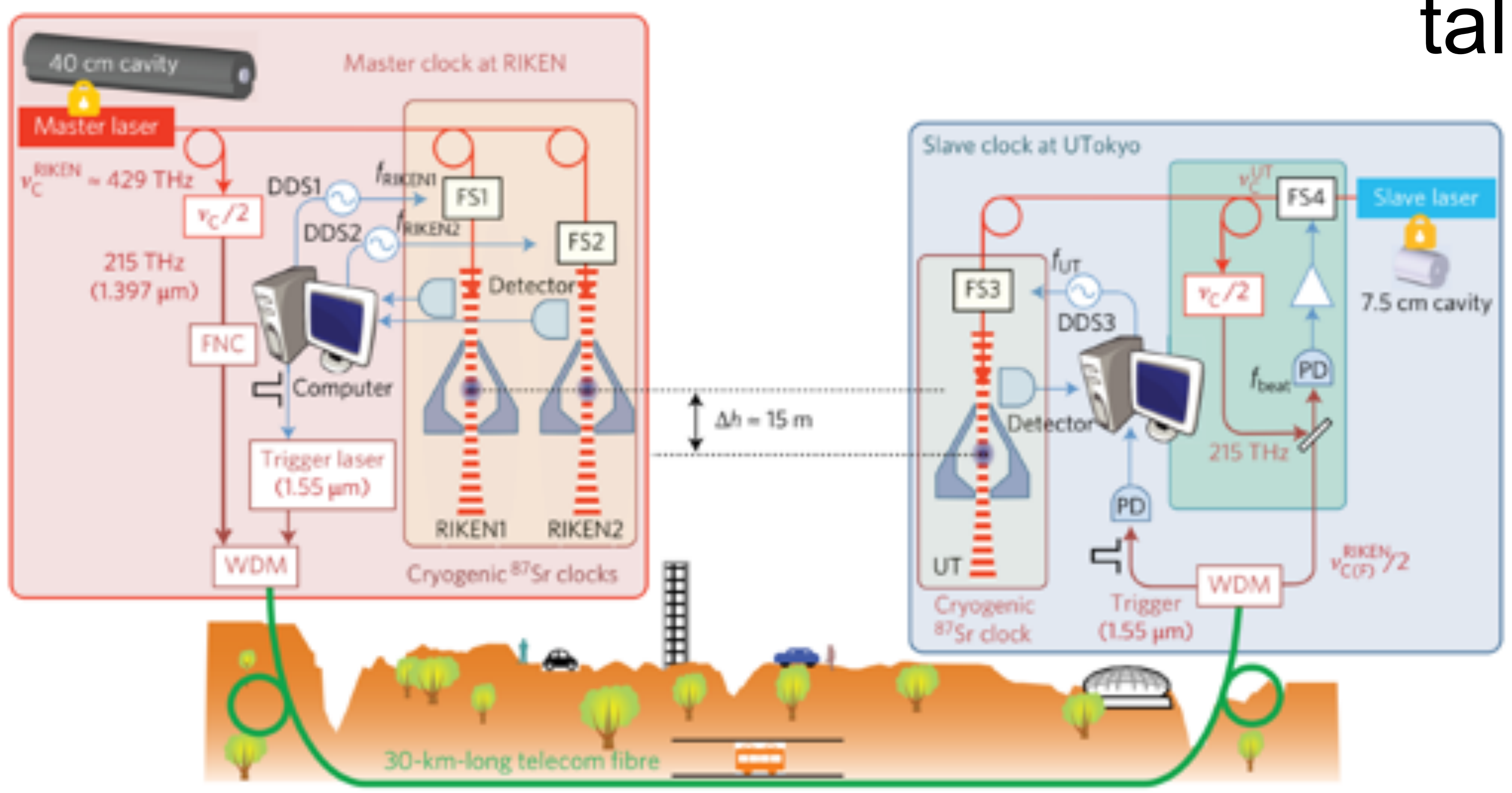
  Gravity field mapping, tidal effects, Earth's rotation rate,…

Chronometric geodesy: remote comparisons of optical clocks

talk of P. Delva

✓ Tokyo area

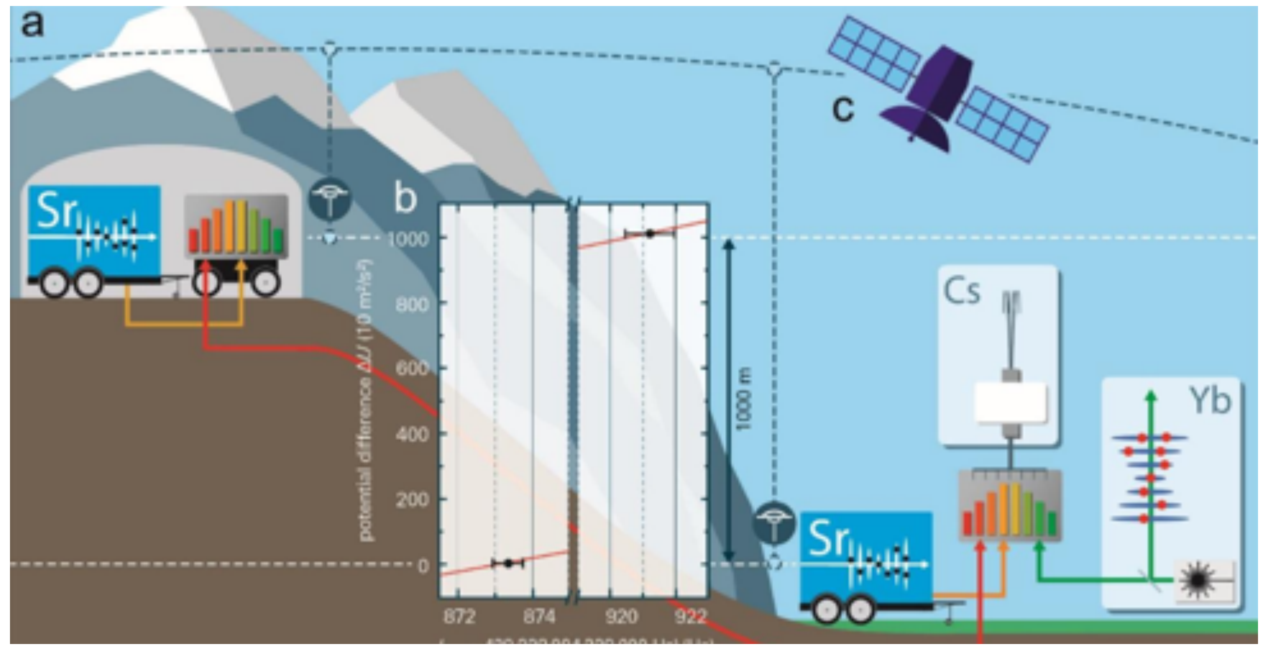
- RIKEN, UT
- Fiber: 30 km
- Spirit levelling, gravimetry: dh=5.9 mm
- u=5.9x10^{-18}



Nat. Photonics 10 (2016) 662–666

✓ Fréjus tunnel (LSM) – Torino

- PTB (Sr transp clk), INRIM, NPL
- Fiber: 150 km
- 1000 m height difference
- Underground, 1700 m rock coverage
- Geodesy + linkage: 1.8x10^{-17}
- u=1.9x10^{-15}



Nature Physics 14, 437–441 (2018)

✓ Paris - Braunschweig

- PTB transportable clock at SYRTE

Phys. Rev. Lett. (118) 221102 (2017)

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

Chronometric geodesy: remote comparisons of optical clocks

- ✓ **French fiber network:**
  - ➡ Refimeve+ (LPL, Renater, SYRTE…)
  - ➡ T-Refimeve
  - ➡ International connections
- ✓ **Ground - air- ground link**
  - ➡ Optical links (TOFU)
  - ➡ Collaboration (CNES/SYRTE/UWA)
- ✓ **Transportable clock**
  - ➡ Neutral Yb clock (SYRTE): ROYMAGE
  - ➡ 10^{-18} in relative accuracy (1 cm level)

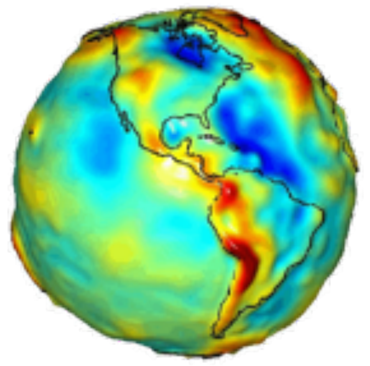
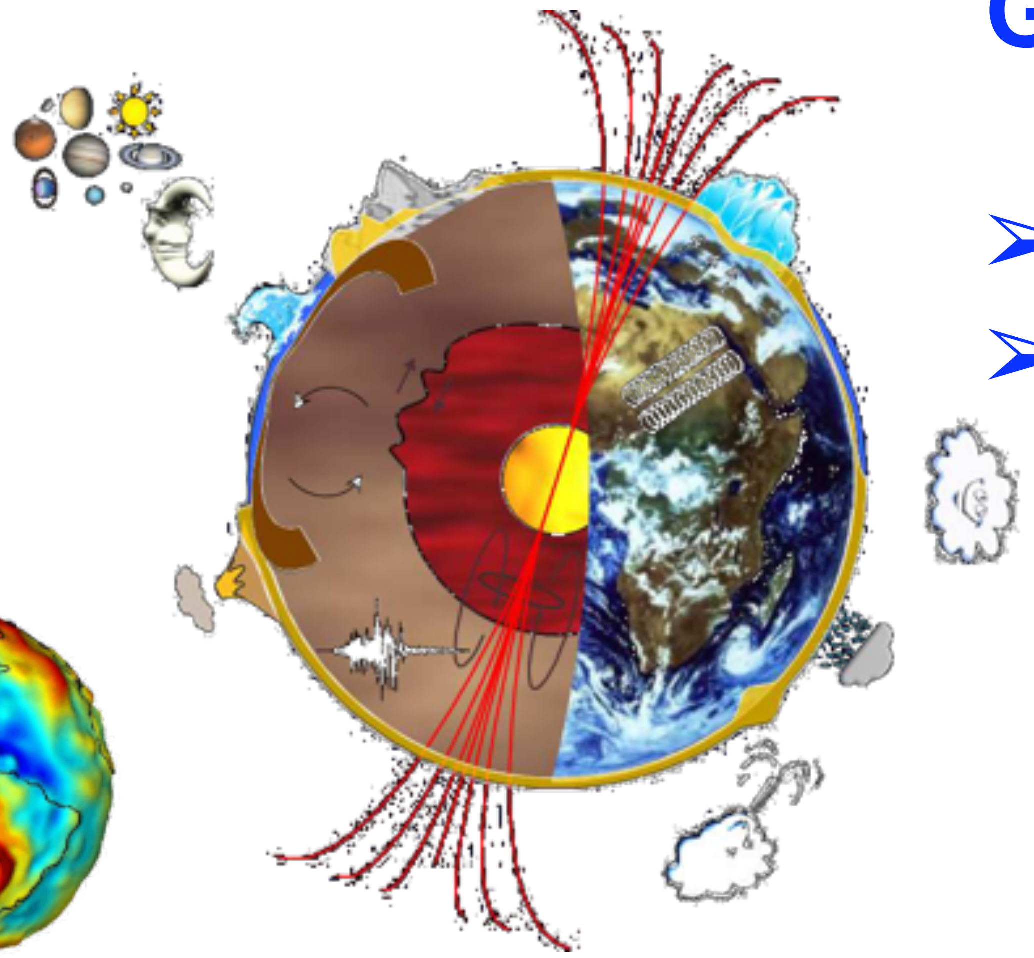
REFIMEVE+ network and international links to NMIs

Atom interferometry as Inertial sensors

Geophysics

Crustal deformations, mass changes, geoid, …



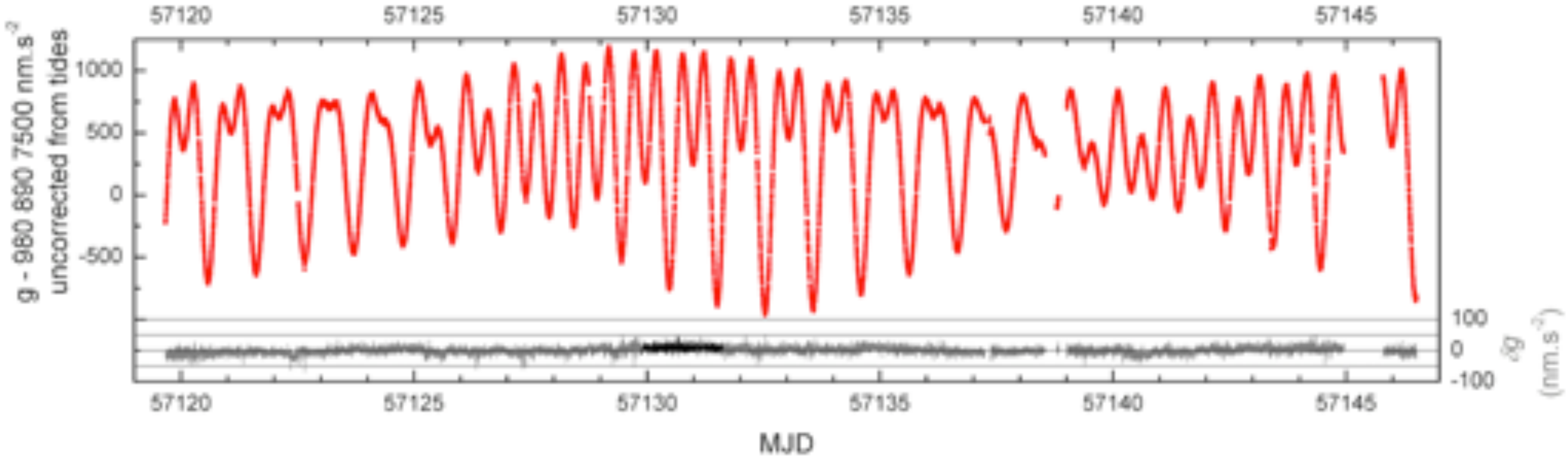



Gravimetry

- State of the art sensors competing with classical sensors
- Cold Atom Gravimeter has demonstrated :
  - Continuous long measurement
  - Accuracy: $< 2.10^{-8}$ m.s^{-2}

    R. Karcher, et al., New J. Phys. 20, 113041 (2018)
  - Better sensitivity : 5.7 10^{-8} m.s^{-2}.Hz$^{-1/2}$ to 6.10^{-10} m.s^{-2}

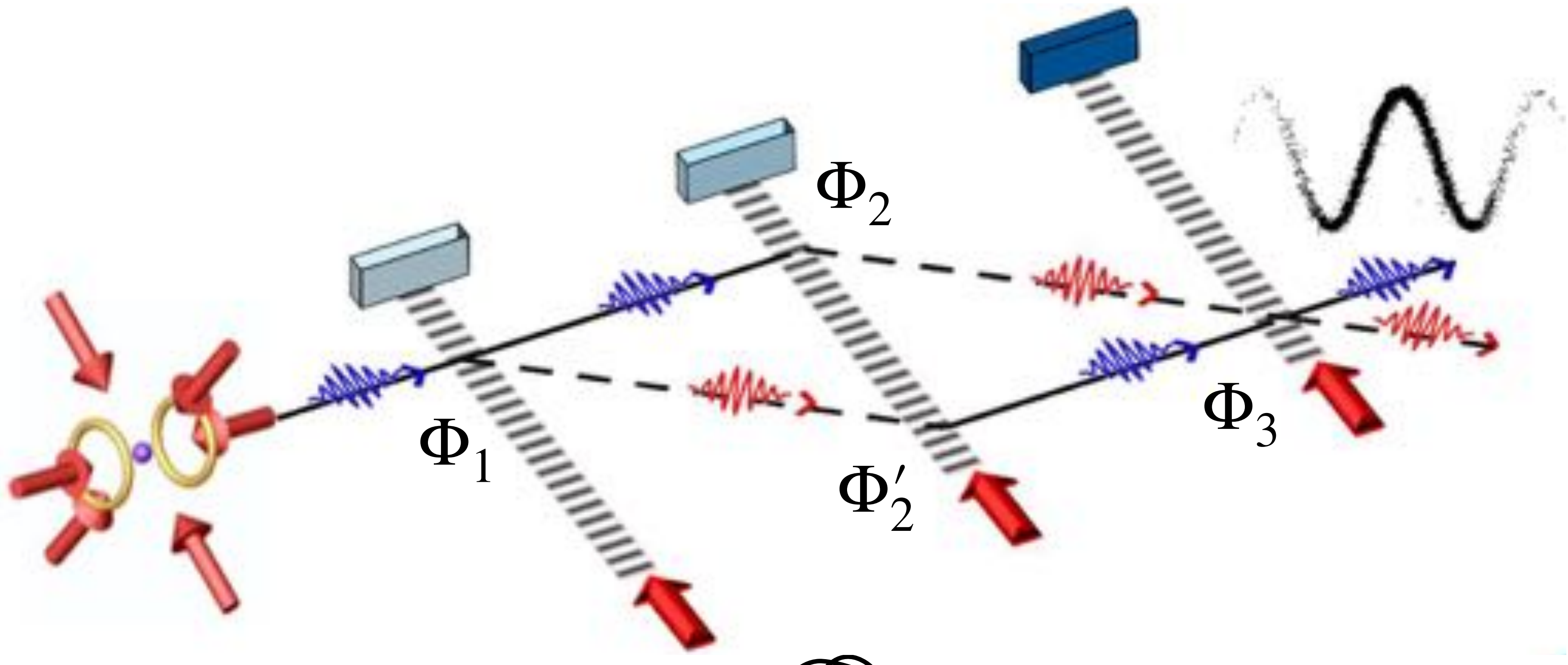
Correlation with classical sensor: *J. Le Gouët et al., Appl. Phys. B 92, 133–144, (2008)*
Stap-down configuration: *S. Merlet, et al., Metrologia 46, 87–94, (2009)*
Hybridization: *J. Lautier,et al. Appl. Phys. Lett. 105, 144102 (2014)*

Systèmes de Référence Temps-Espace

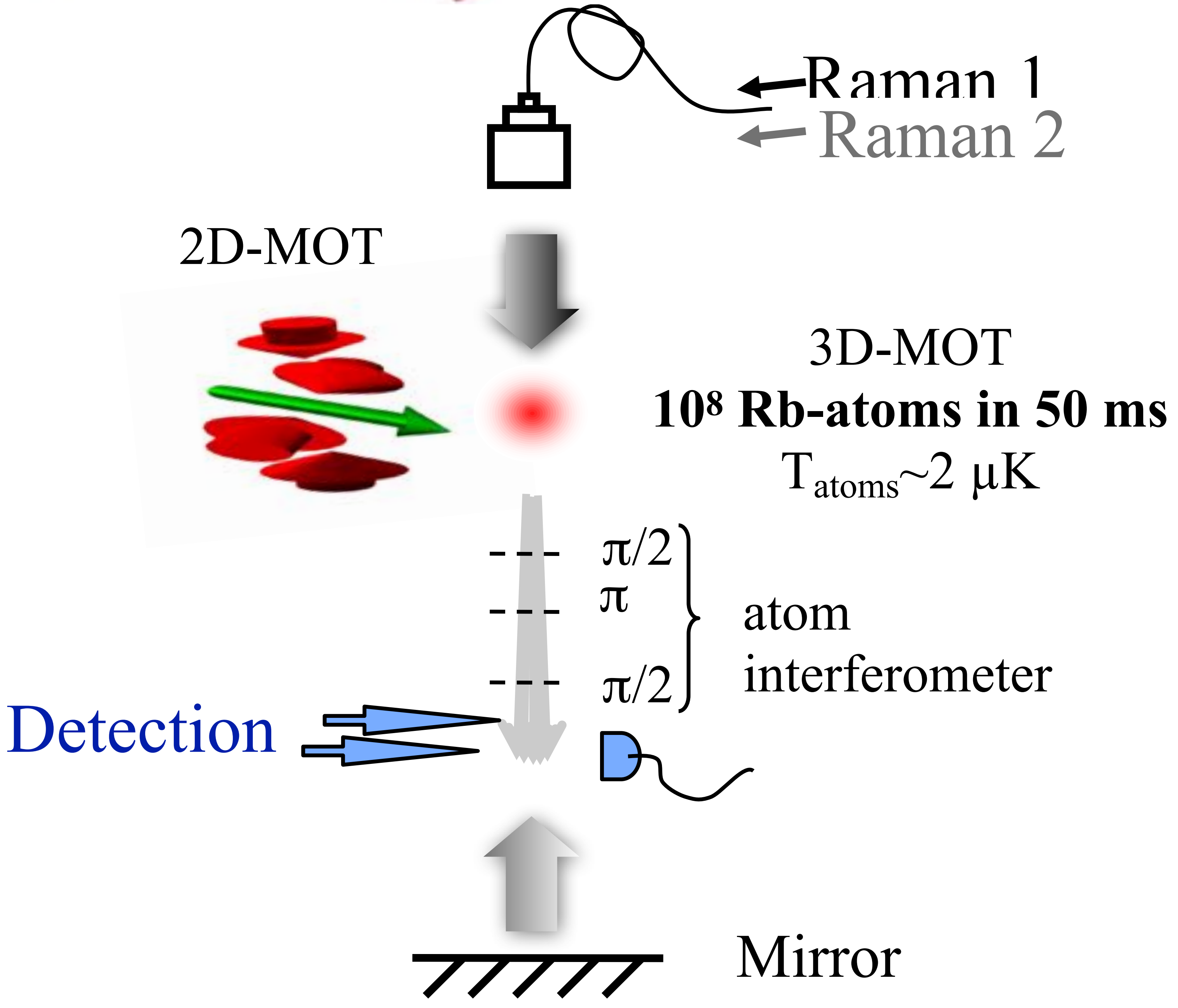
Gravimeter

Interrogation time: 160 ms
Cycling frequency: 3 Hz



Atom wave-packets diffracted by laser pulses

Most of the inertial sensors used two photon Raman transitions



First participations to BIPM international comparisons for gravimetry: 2009,11, 13…

Commercial instruments

✓ Compact gravimeter for in lab and on-field operation

Specifications & Characteristics

Sensitivity:	50 µGal/√Hz at a quiet place
Measurement frequency:	2 Hz
Long-term stability:	< 1 µGal
Accuracy:	under evaluation
Dimensions :	Sensor head: h = 70 cm / D = 38 cm
Laser & electronics:	100 x 50 x 70 cm³
Mass Sensor head:	25 kg, control unit : 75 kg
Power consumption:	250 W typical

µQUANS

Target field of applications: geosciences (geodesy, hydrology, vulcanology …)

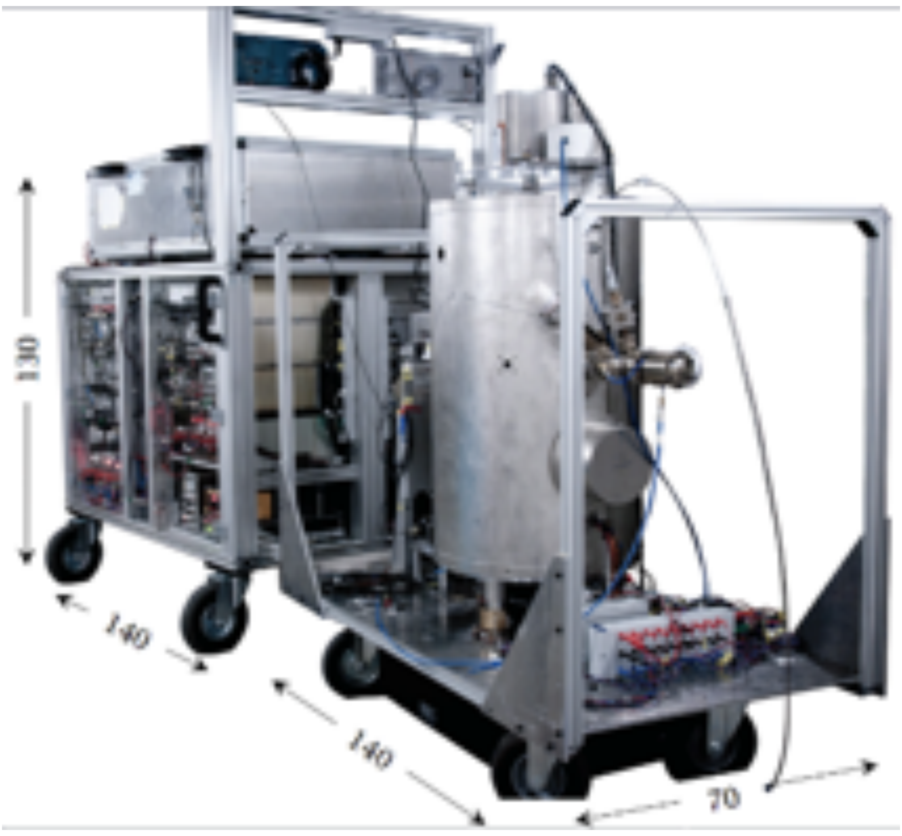
Atom gravimeter on the Mount Etna

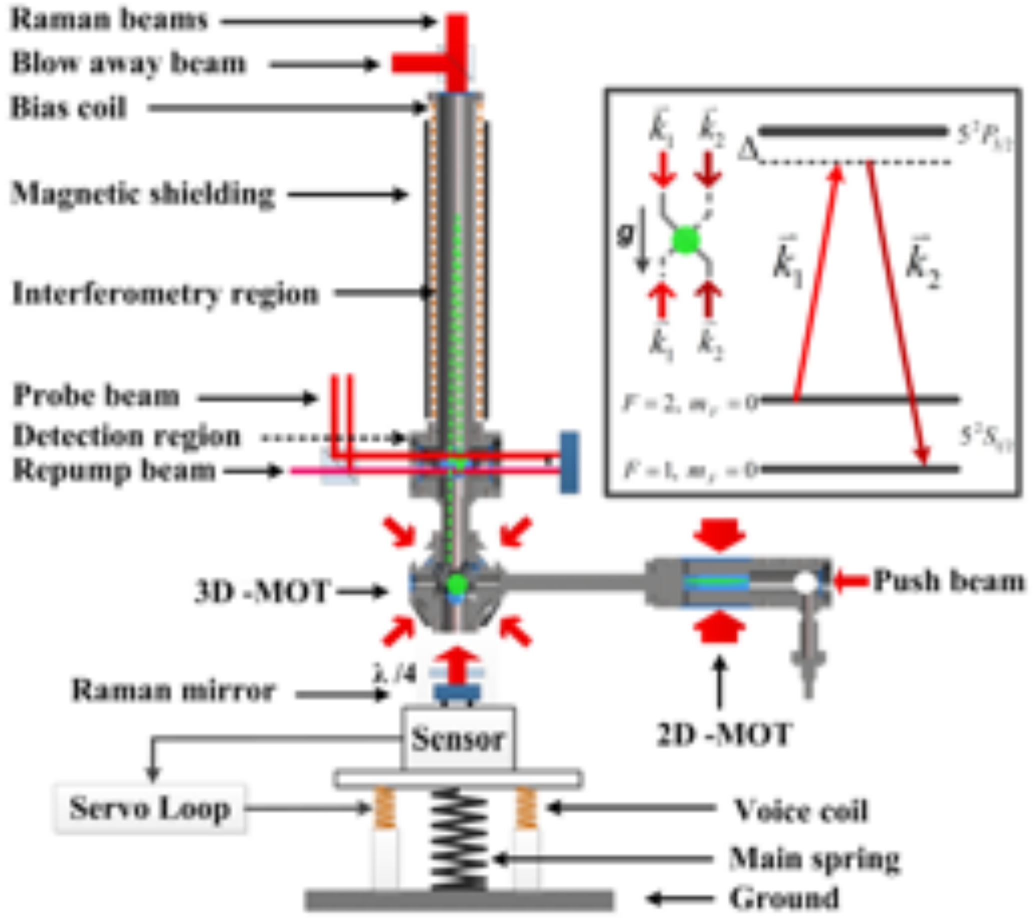
l'Observatoire de Paris | SYRTE

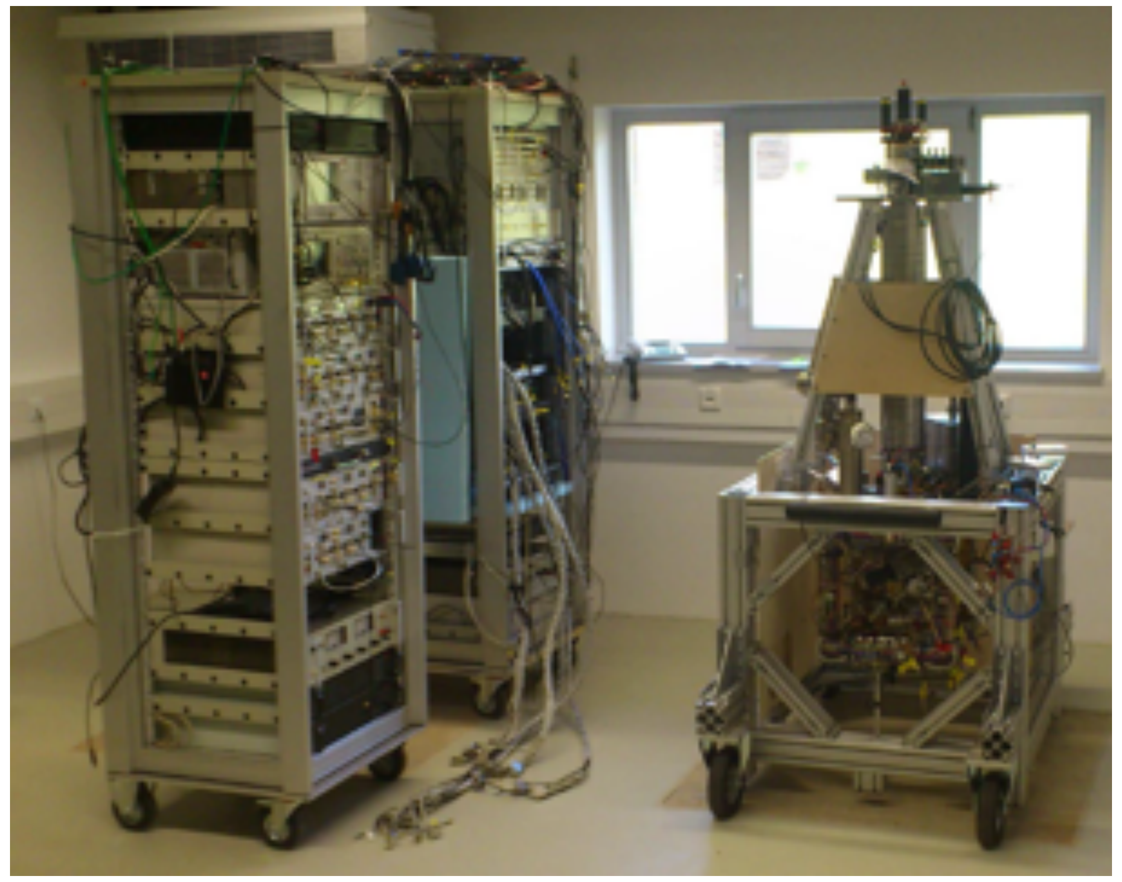
Systèmes de Référence Temps-Espace

State of the art instruments

- Many teams involved today in the development of atom gravimeters (at least 20)







	LNE SYRTE	WUHAN	HUB
2T (ms)	160	600	600
Sensitivity ($/\mathrm{Hz}^{1/2}$)	5.7 10^{-9}g	**4.2 10^{-9}g**	10 10^{-9}g
Long term stability	<10^{-10}g	5 10^{-10}g	**6 10^{-11}g**
Accuracy	**2 10^{-9}g**	TBD	3 10^{-9}g

Vibration noise is (always) the limit ⇒ Differences in 2T do not correlate with performances

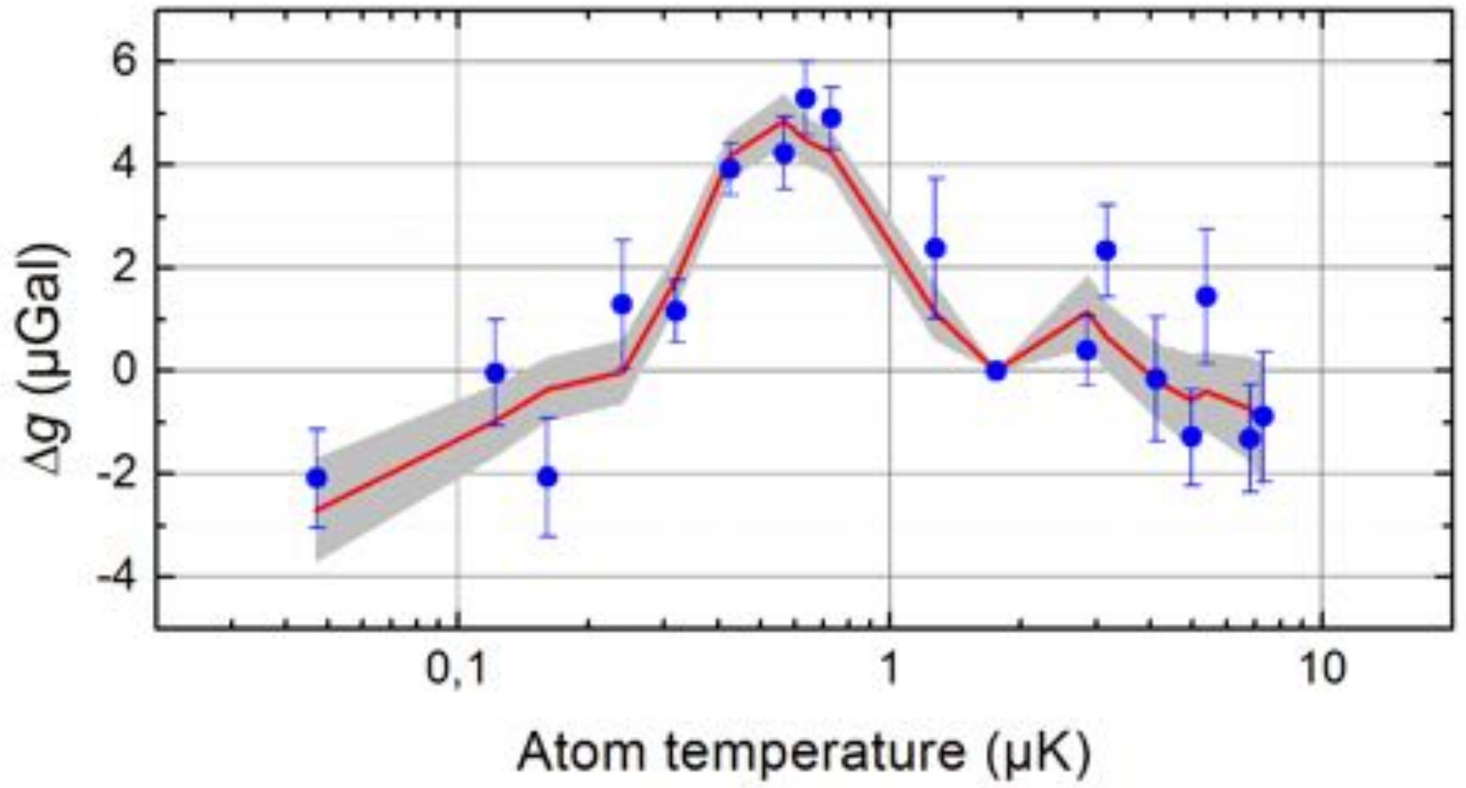
Motivation for the development of compact gravimeters (2T ≈ 100 ms, h ≈ 5 cm)

Accuracy

Effect	Bias μGal	u μGal
Alignments	0.3	0.5
Frequency reference	0.5	<0.1
RF phase shift	0.0	<0.1
vgg	-13.4	<0.1
Self gravity effect	-2.1	0.1
Coriolis	-5.3	0.8
Wavefront aberrations	-5.6	1.3
LS1	0.0	<0.1
Zeeman	0.0	<0.1
LS2	-3.6	0.8
Detection offset	0.0	0.5
Optical power	0.0	0.5
Cloud indice	0.4	<0.1
Cold collisions	<0.1	<0.1
CPT	0.0	<0.1
Raman α LS	0.3	<0.1
Finite Speed of Light	0.0	<0.1
TOTAL	**-28.5**	**2.0**

Evaporative cooling
in a dipole trap

Temperature range: [50 nK -7 µK]

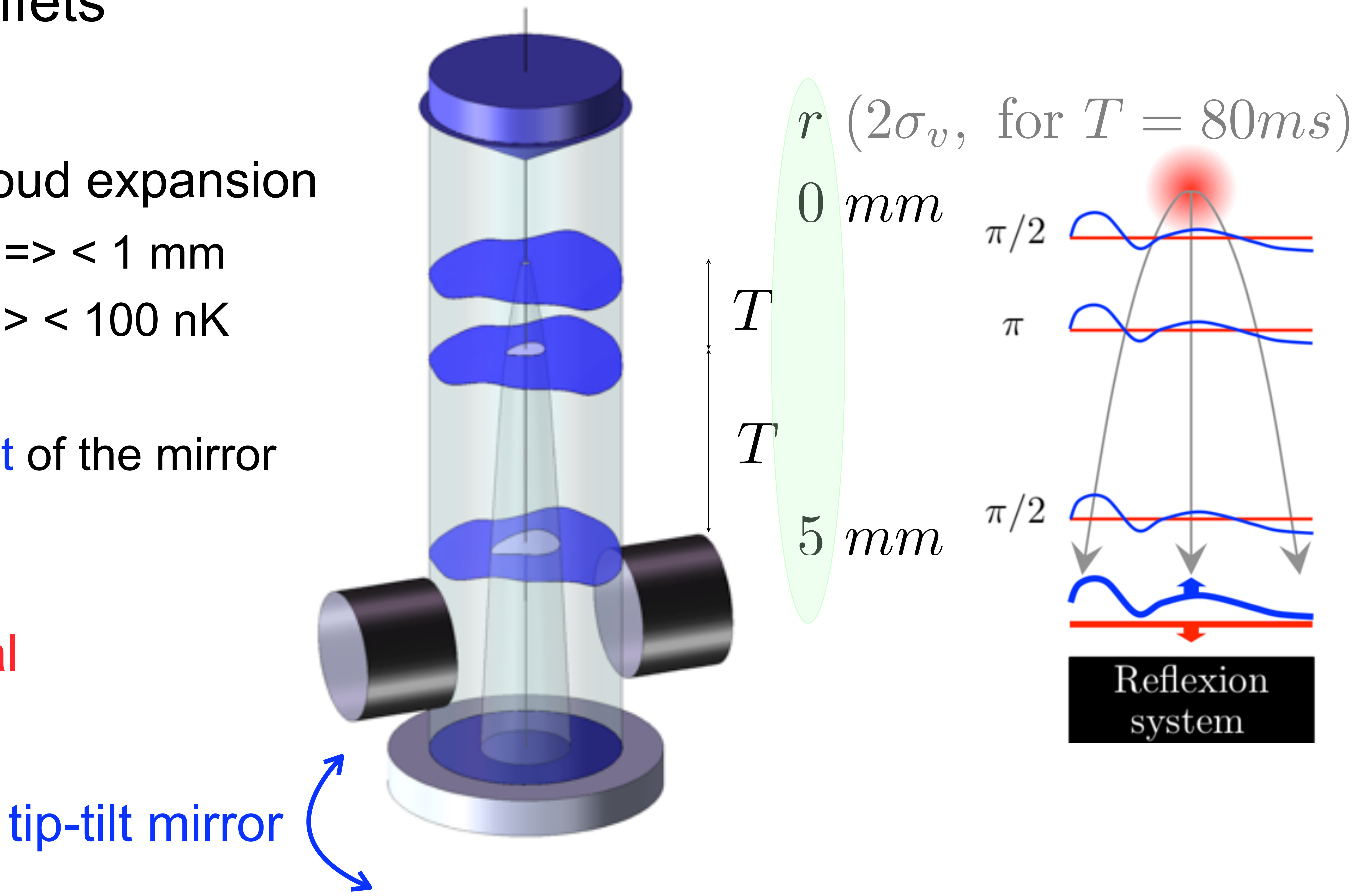


Improvement of the gravimeter

Reduction of systematic effets

- ✓ Coriolis : tip-tilt mirror
- ✓ Wavefront distortion and cloud expansion
  - ➡ Limit the expansion: 5 mm => < 1 mm
    Ultra-Cold Atoms: 2 µK => < 100 nK
  - ➡ Reduction of the wave front of the mirror

➡ Expected accuracy 0.5 µGal

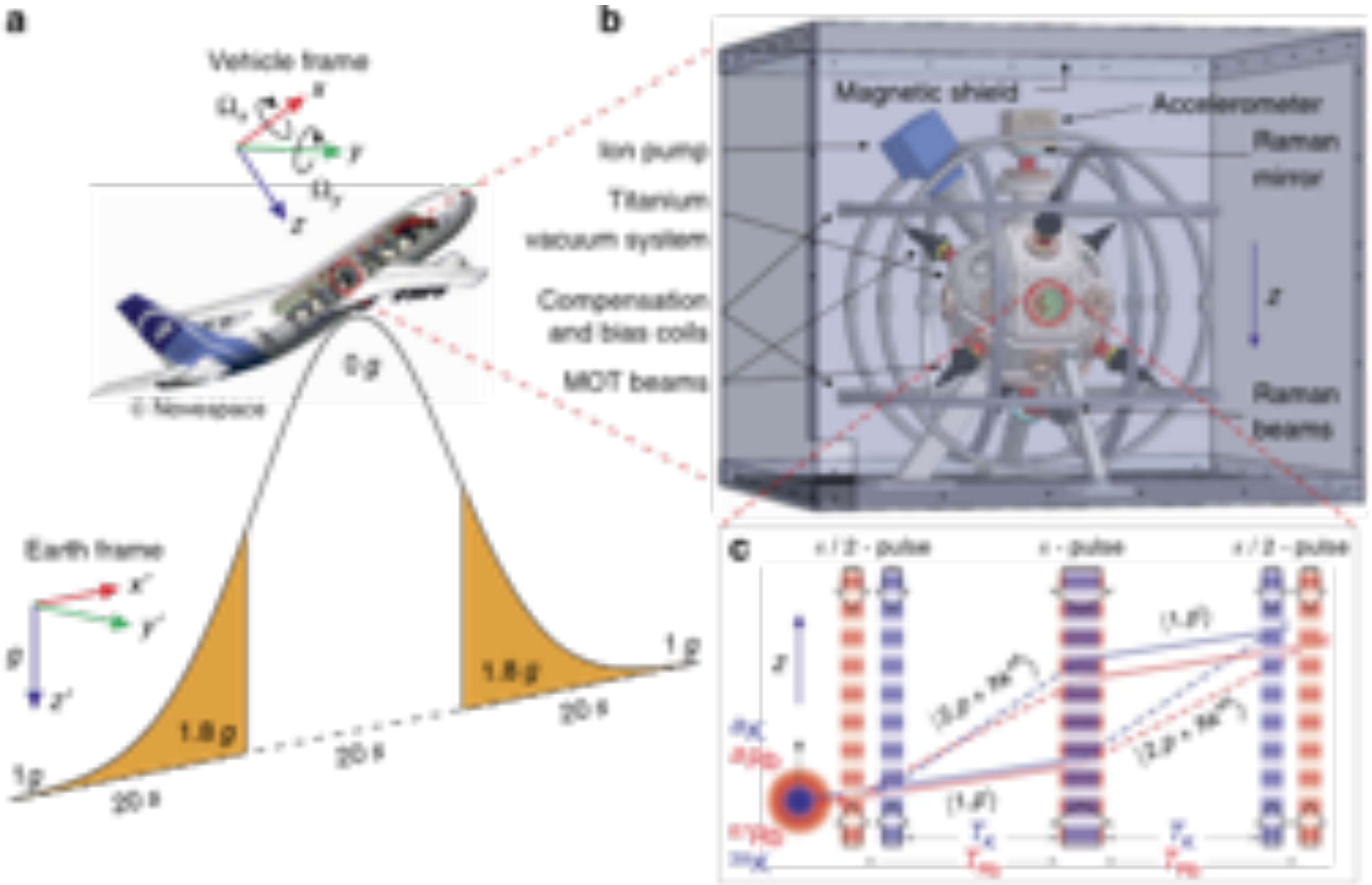


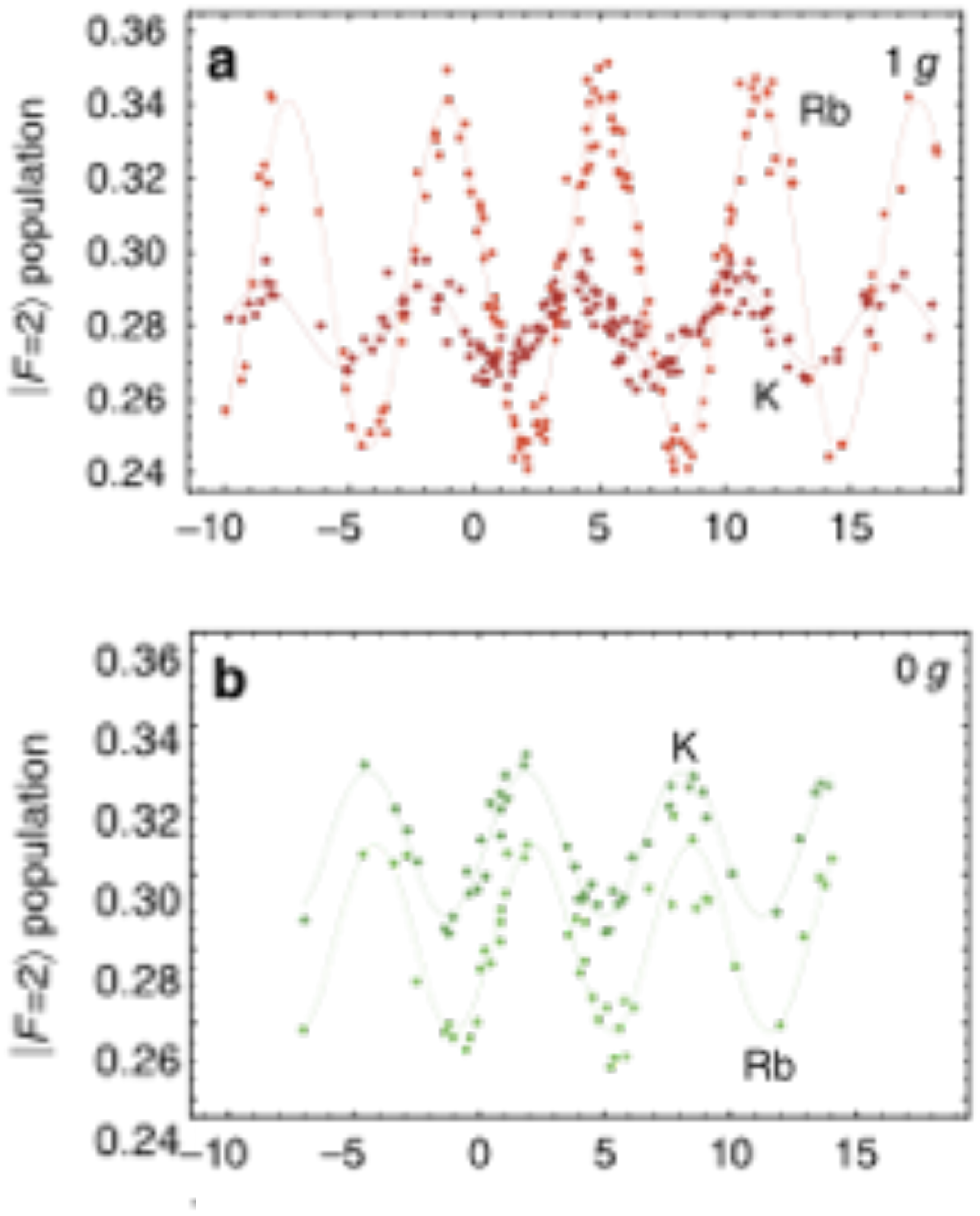
Onboard measurement in an airplane: test of the UFF in 0-g

ICE experiment (collaboration LP2N, SYRTE and CNES)

- Ice experiment in 0-g plane between $^{87}Rb/^{39}K$: uses of correlation with standard accelerometer ($\sigma_{vib} \simeq 0.05$ g rms)
- T limited by rotation induces lost of contrats (5°/s)

$$\eta_{0g} = (0.9 \pm 3.0) \times 10^{-4}$$





B. Barrett et al., Nature Communications 7, 13786 (2016)

On-board measurements

- ✓ Development of a compact **gravimeter for marine** gravimetry by ONERA

  Measurement campaigns on the Beautemps-Beaupré (French Navy)

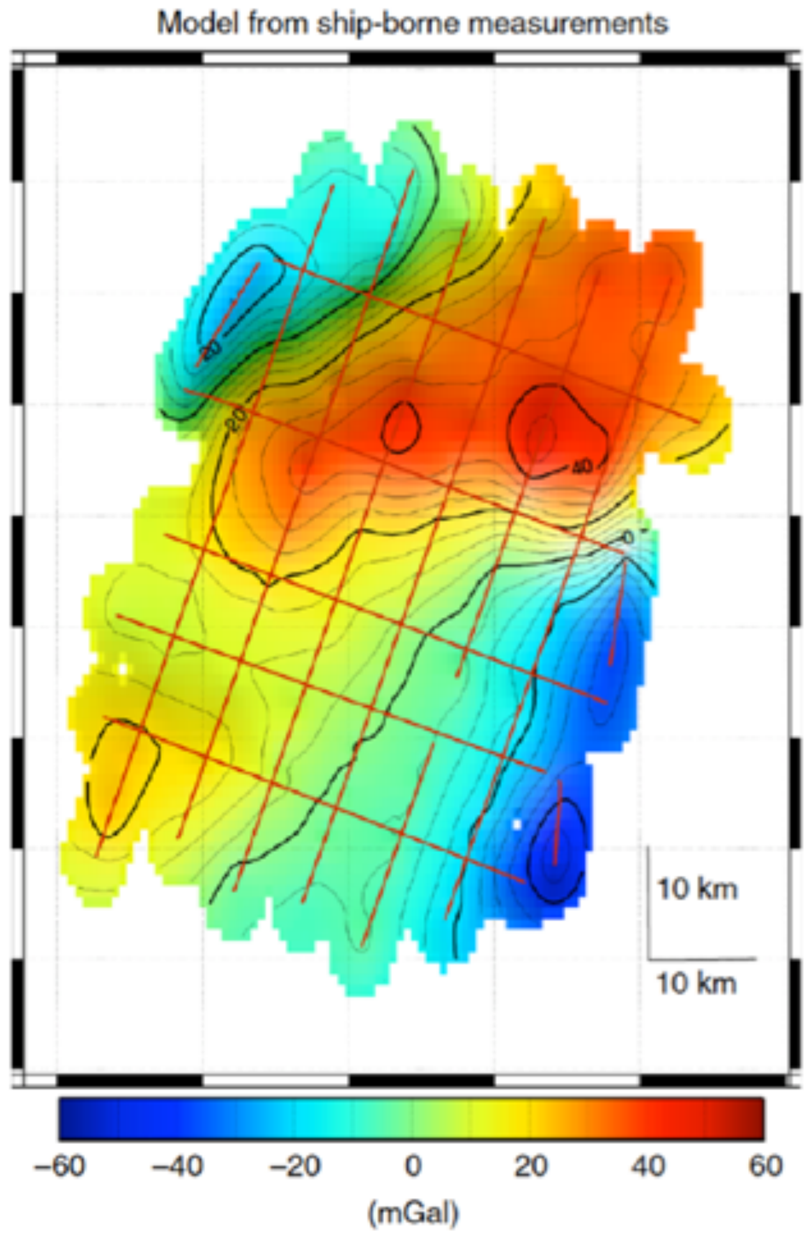
+ Campagne aéroportée *Y. Bidel et al J. Geod. 94, 20 (2020)*

KSS32 relative Marine Gravimeter (Bodenseewerk) — Cold Atom Gravimeter (Onera)

➡ Better performance for gravity mapping with the absolute atom gravimeter

➡ Suppression of calibration errors and drift corrections

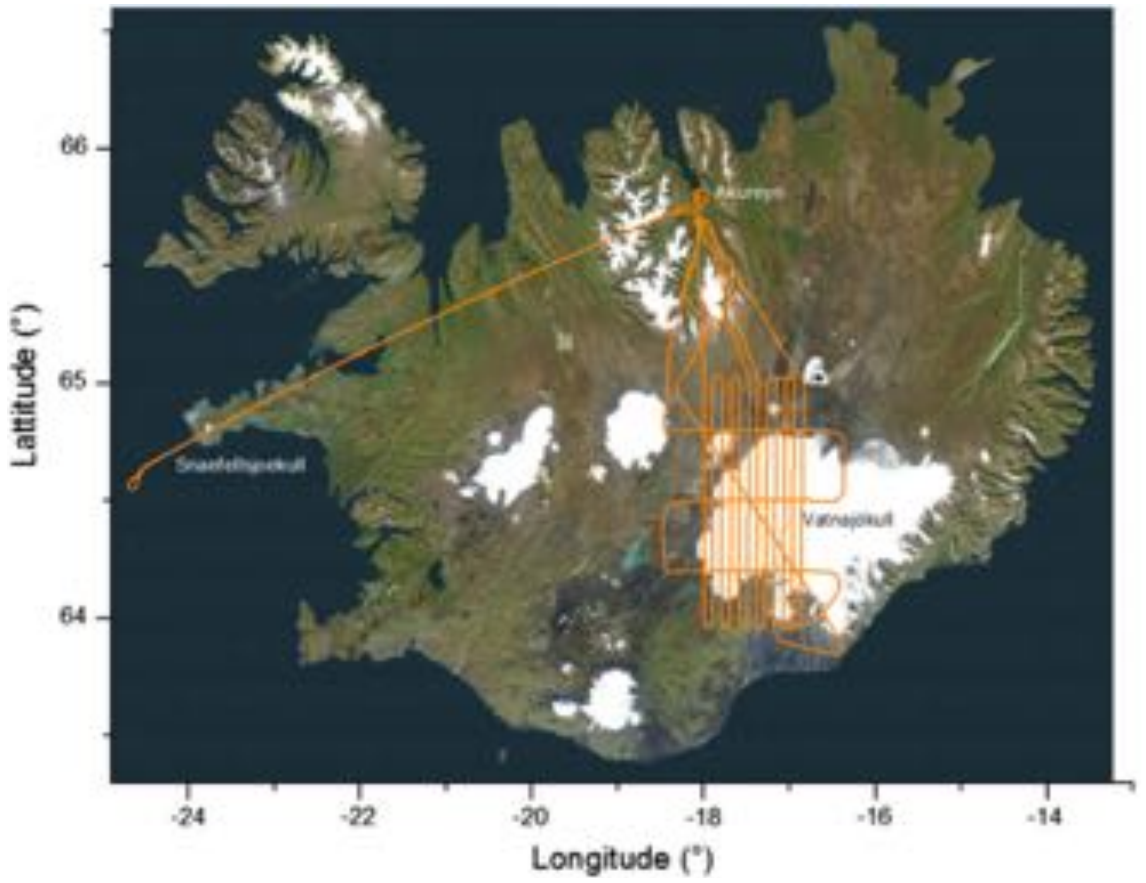
Y. Bidel et al Nat Commun. 9, 627 (2018)



→ Gain of a factor 2-3 on the uncertainty (mGal level)

+ **Plane campaign**: 1.7 to 3.9 mGal error

Y. Bidel et al J. Geod. 94, 20 (2020)



- ✓ **On-board strap-down atomic gravimeter**:

  ➡ Development of 3 axes accelerometer by iXatom (Labcom LP2N Bordeaux)

  ➡ No specific need of orientation (no gyro-stabilised platform)

  ➡ Expand the range of mobile carriers and applications

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

Increase the interaction time

Increasing T => increases
- the intrinsic sensitivity (the scale factor as T^2)

but also
- the size of the experiment

Need for Improved vibration isolation systems and/or perform differential measurements

Drop Vs Lauch (« fountain »)

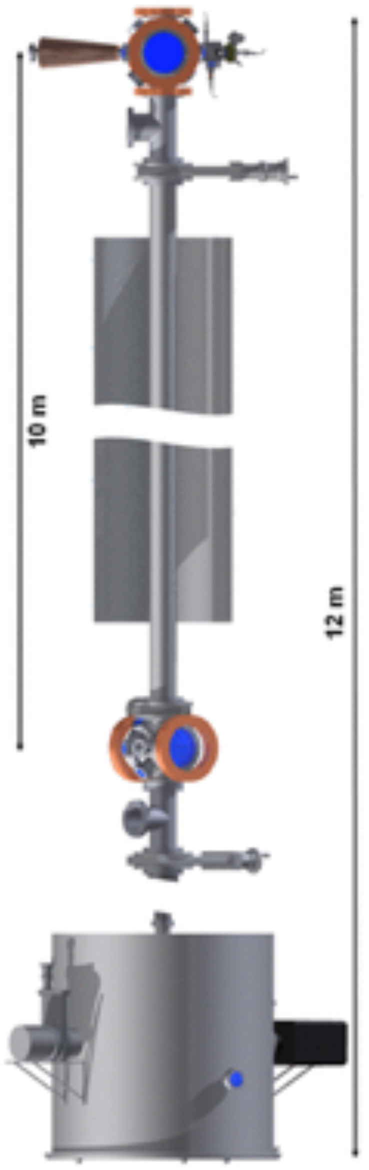
2T	H, release	H, fountain
20 ms	0.5 cm	0.1 cm
160 ms	**12.5 cm**	3 cm
600 ms	1.8 m	**45 cm**
2 s	20 m	5 m
2.8 s	40 m	**10 m**

Several projects of 10 m tall fountains

Stanford

Wuhan

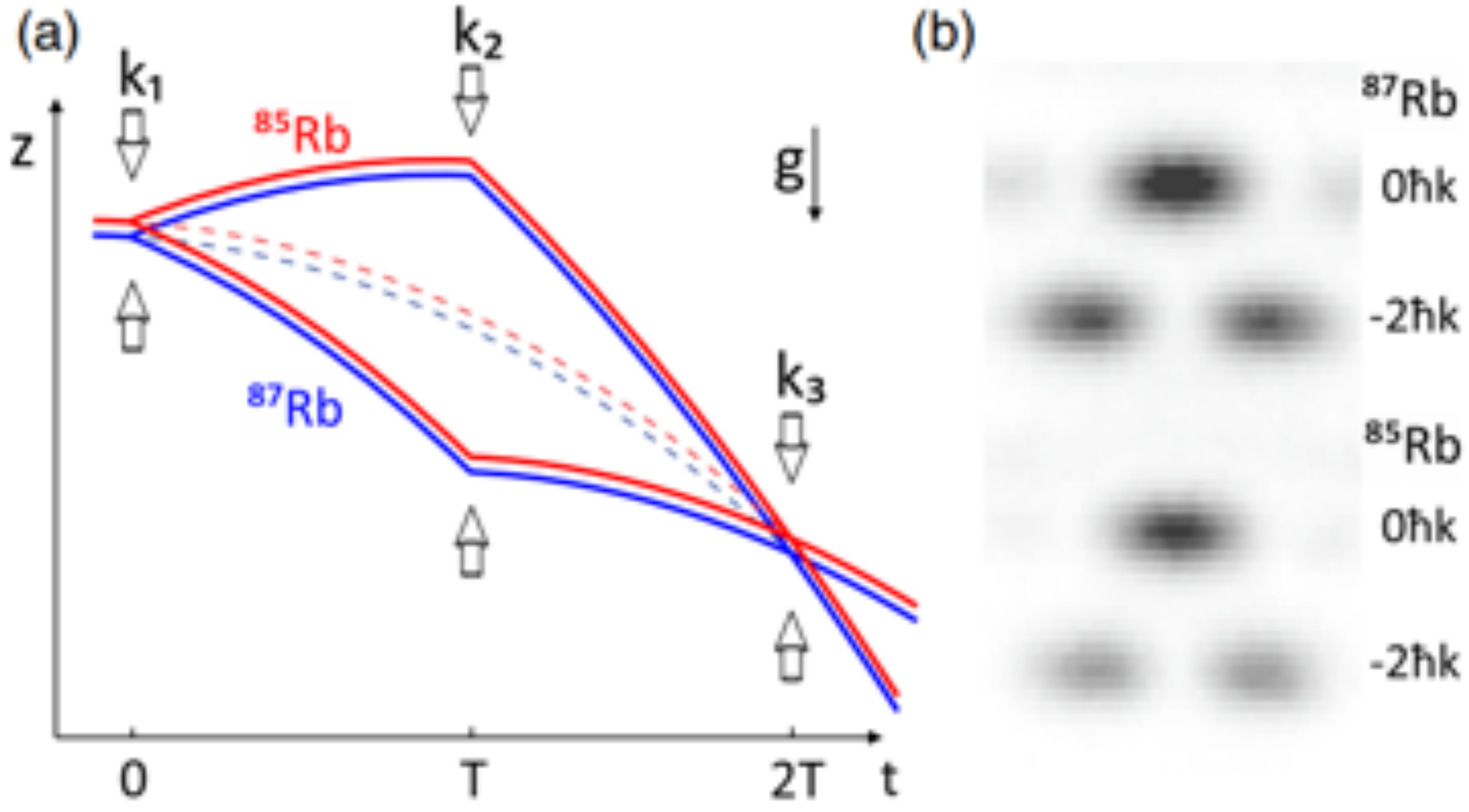
Hannover



Test of the WEP

Comparing gravity acceleration experienced by 85Rb and 87Rb

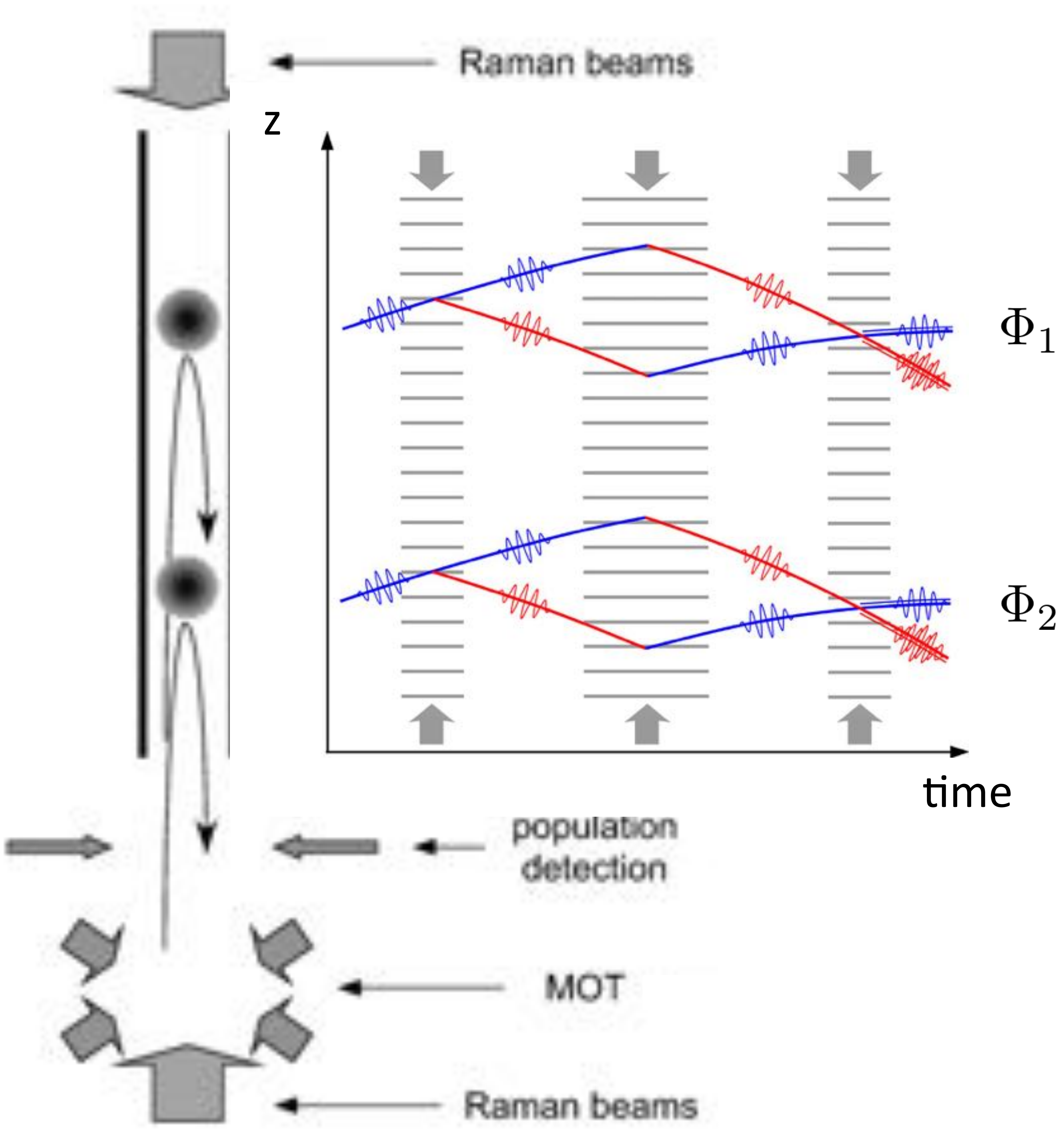
Asenbaum et al, PL 125, 191101 (2020)



Total interferometer duration 2T = 1910 ms => large differential sensitivity

Eotvos parameter $\eta = \dfrac{\Delta a}{g} = \left(1.6 \pm 1.8(\text{stat}) \pm 3.4(\text{syst})\right) \times 10^{-12}$

Gravity gradiometers

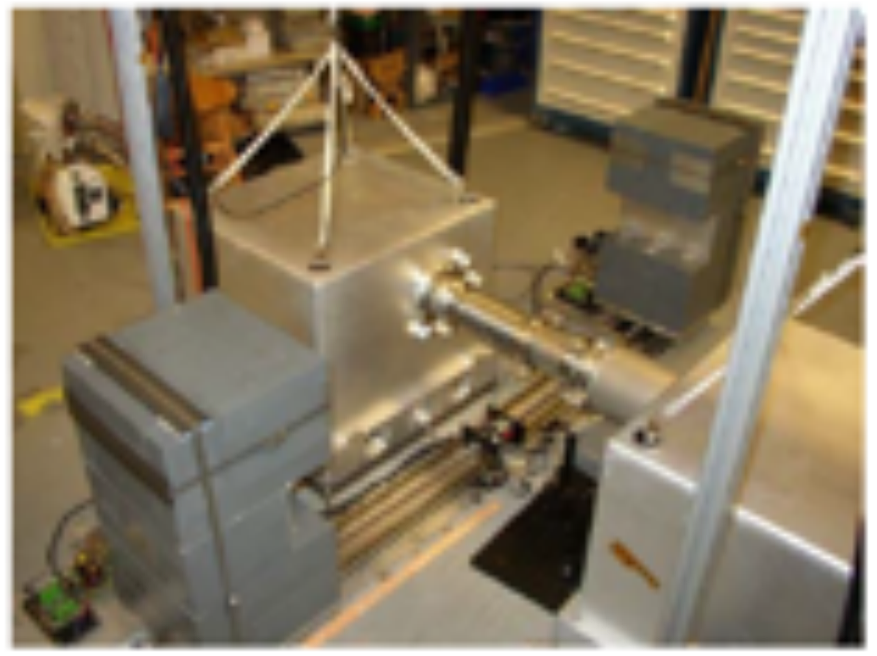


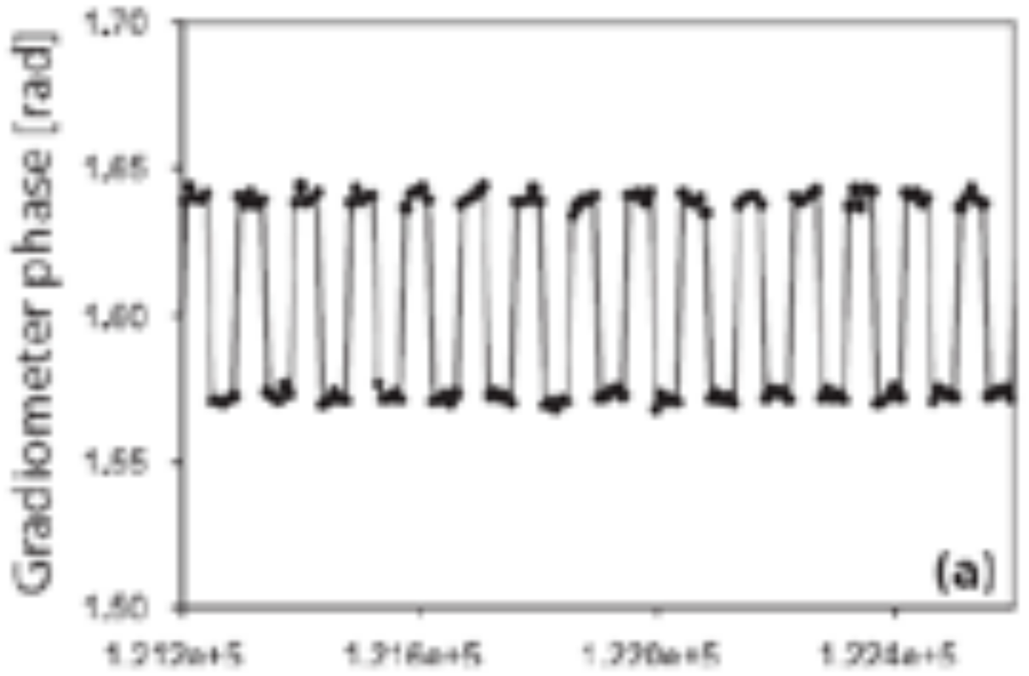
- Two simultaneous interferometers driven by the same lasers
- Differential measurement allows to derive the gravity gradient (3 10^{-7}g/m)
- Suppression of common mode noise, and in particular of vibrations
- Allows to reach the QSL and to benefit from the increase in the interferometer duration
- Suitable for on-board measurements

Gravity gradiometers:

Experiment in standard room with alcalin atoms

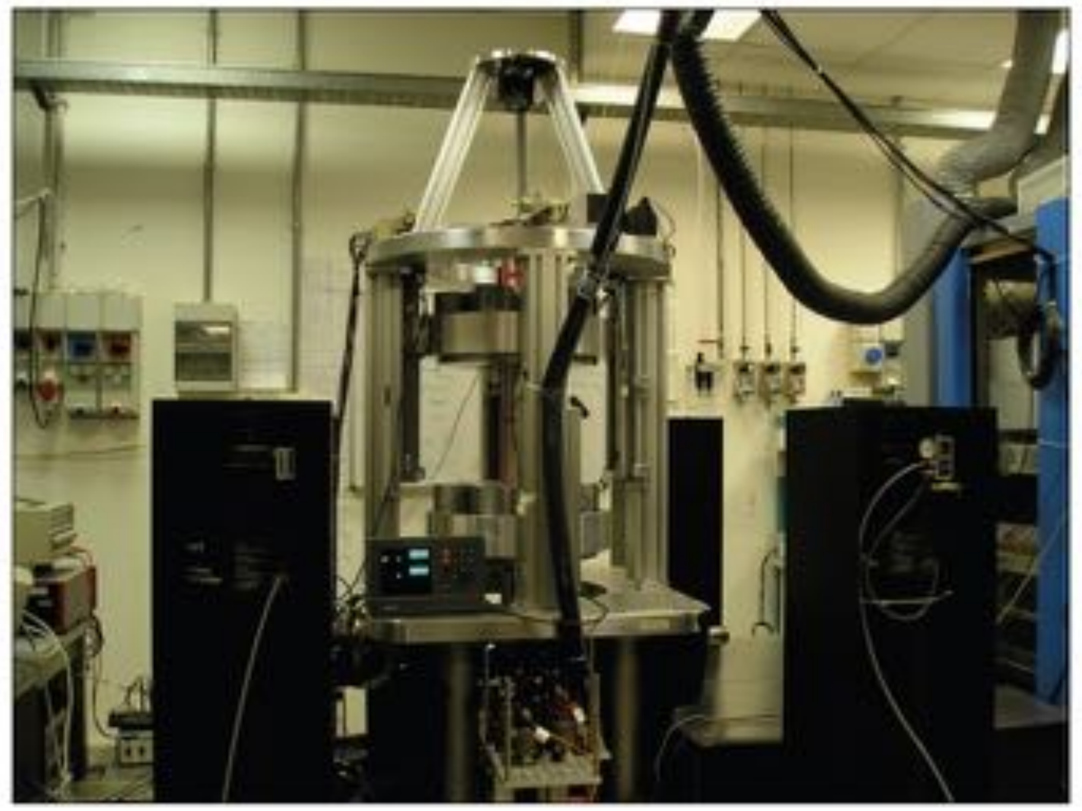
Stanford (M. Kasevich)

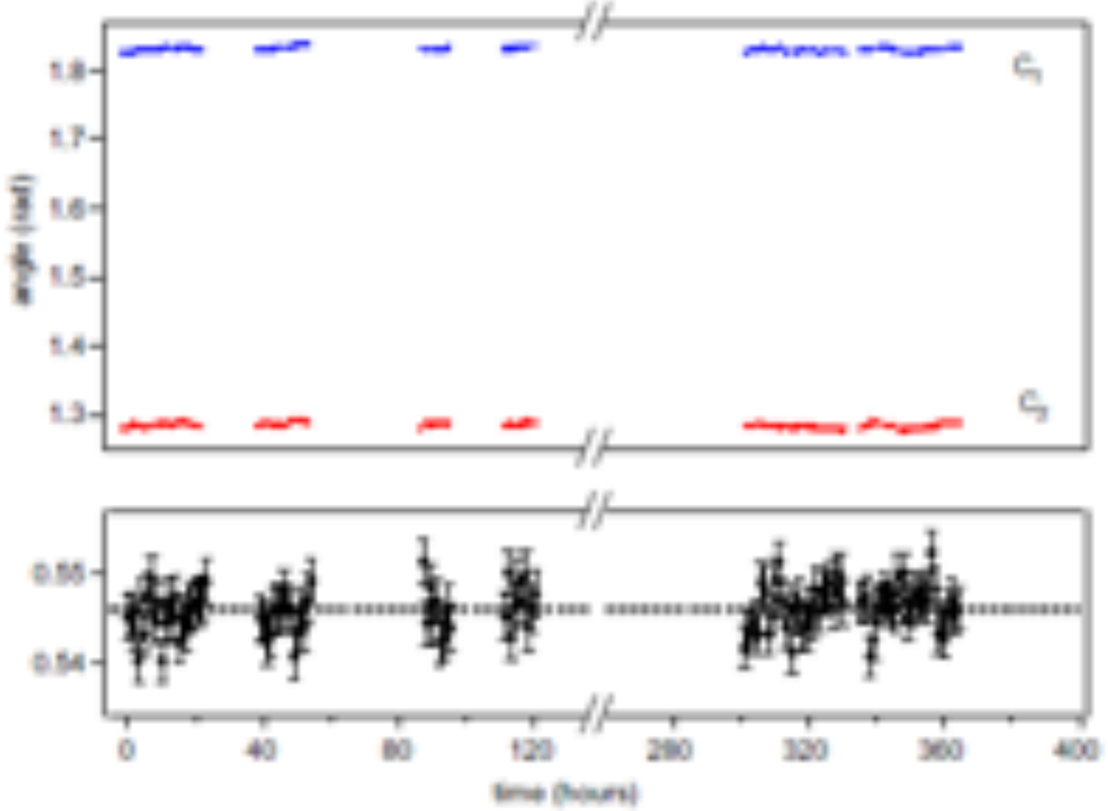




Phys. Rev. A 91, 033629 (2015)

Florence (G. Tino)





Nat. 510, 518 (2014)

G measurements

Differential acceleration stability: 10^{-11} g

Statistical uncertainty: 2 10^{-4} on G

Best sensitivity: 60 -100 E/√Hz

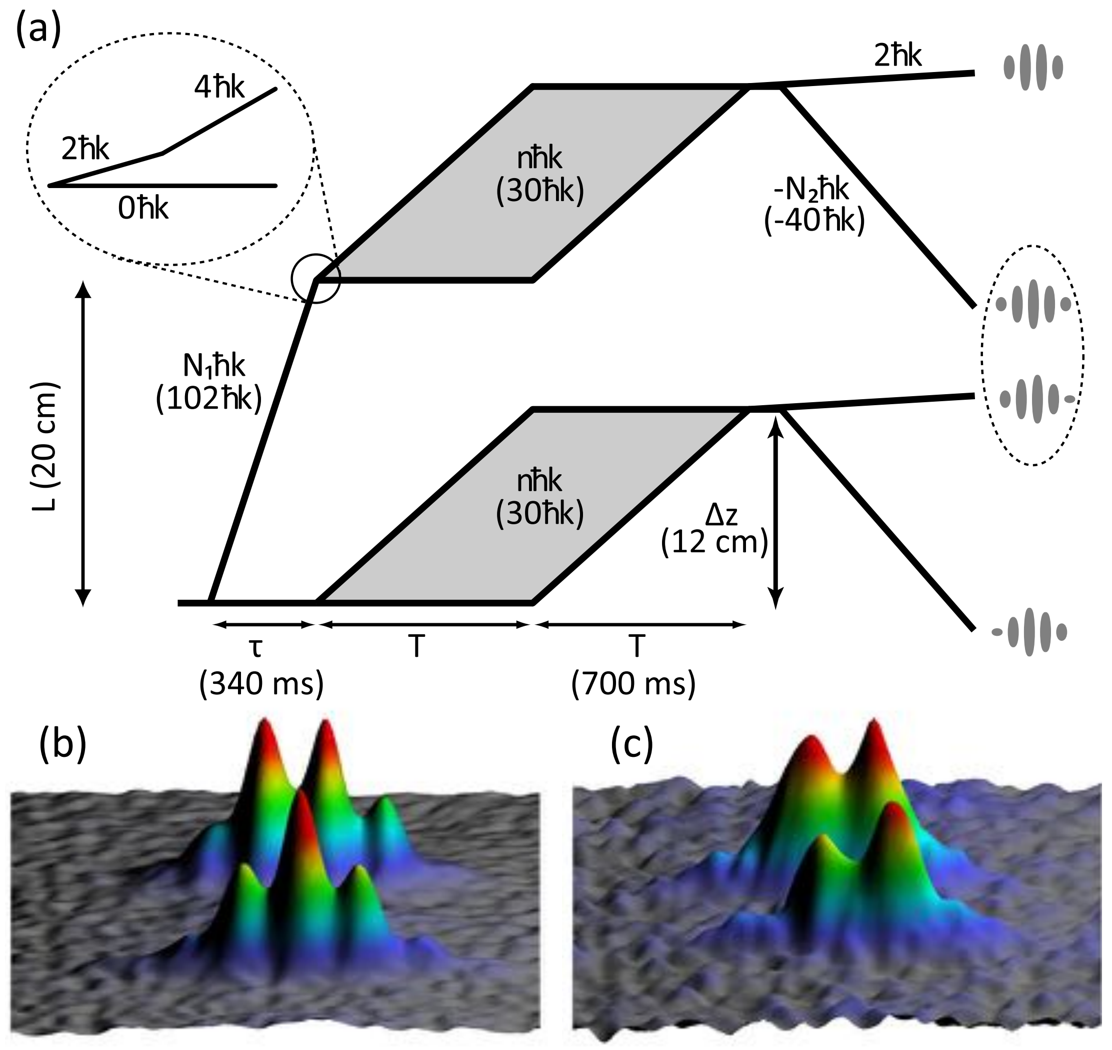
Stability down to 0.4 E

(1 E = 10^{-9} s^{-2})

Experiment in tower

Stanford (M. Kasevich)

10 m tower and multi-$\hbar$k

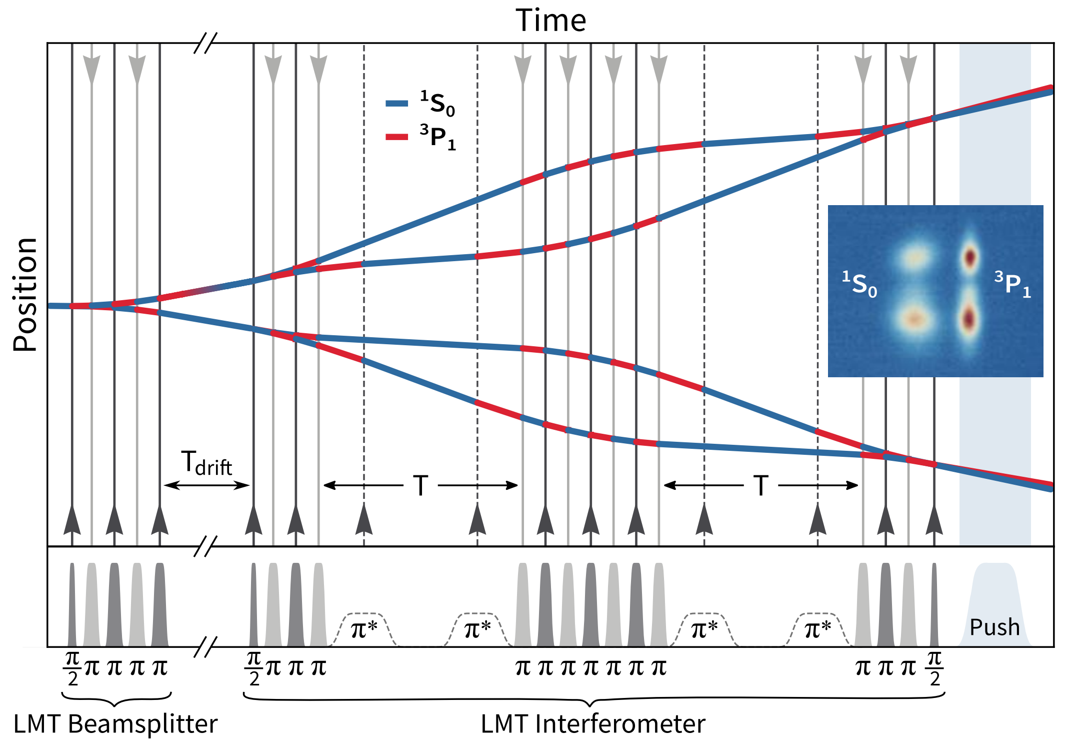


Phys. Rev. Lett. 118, 183602 (2017)

Sensitivity: 13 E/√Hz

With alcalin-like atoms

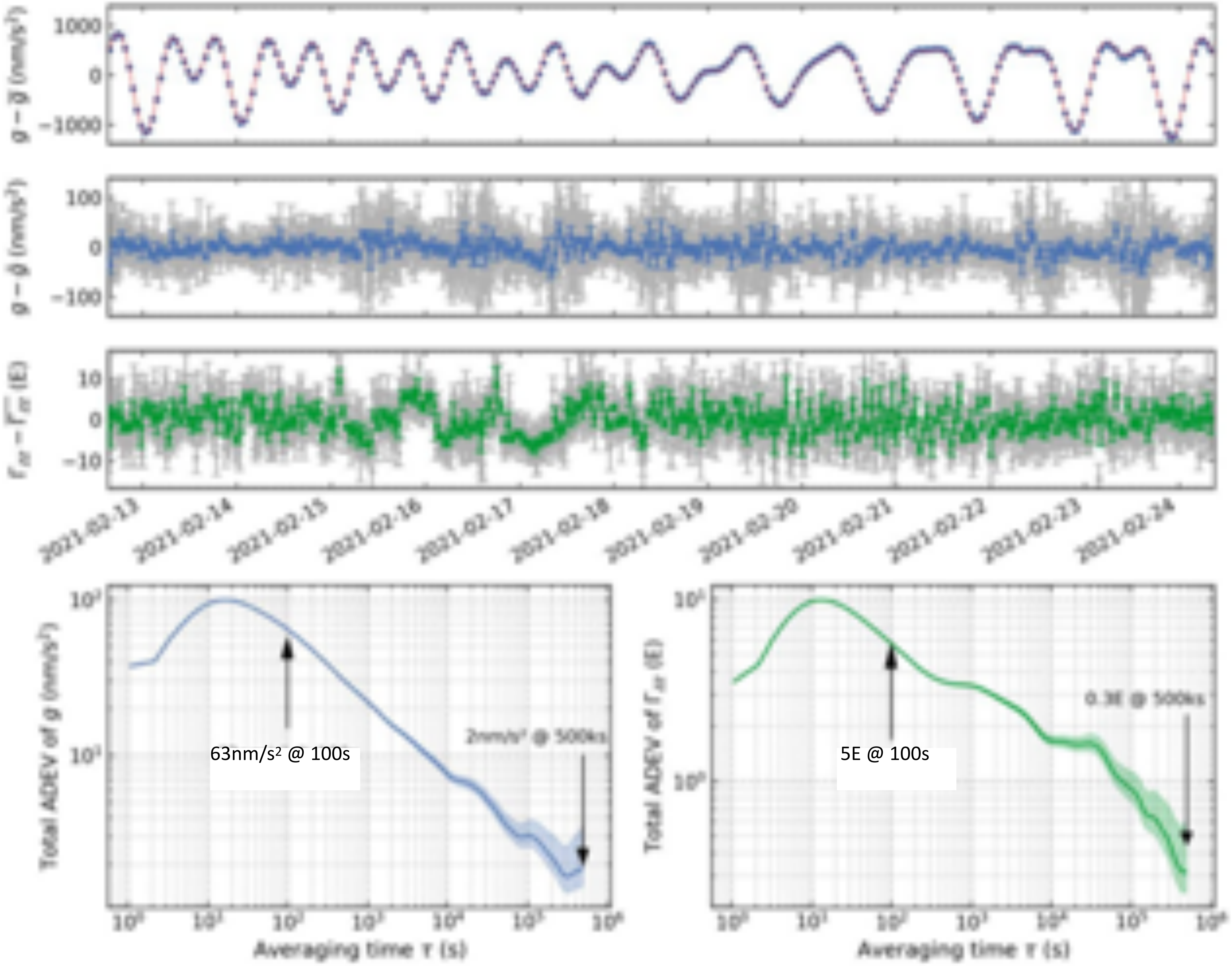
- Possibility of many $\hbar$k
- Suitable for very long distance



Phys. Rev. Lett. 124, 083604 (2020)

The DQG: Differential Quantum Gravimeter

- ✓ Simultaneous measurement of g and δg/δz: development of a compact commercial gravi-gradiometer



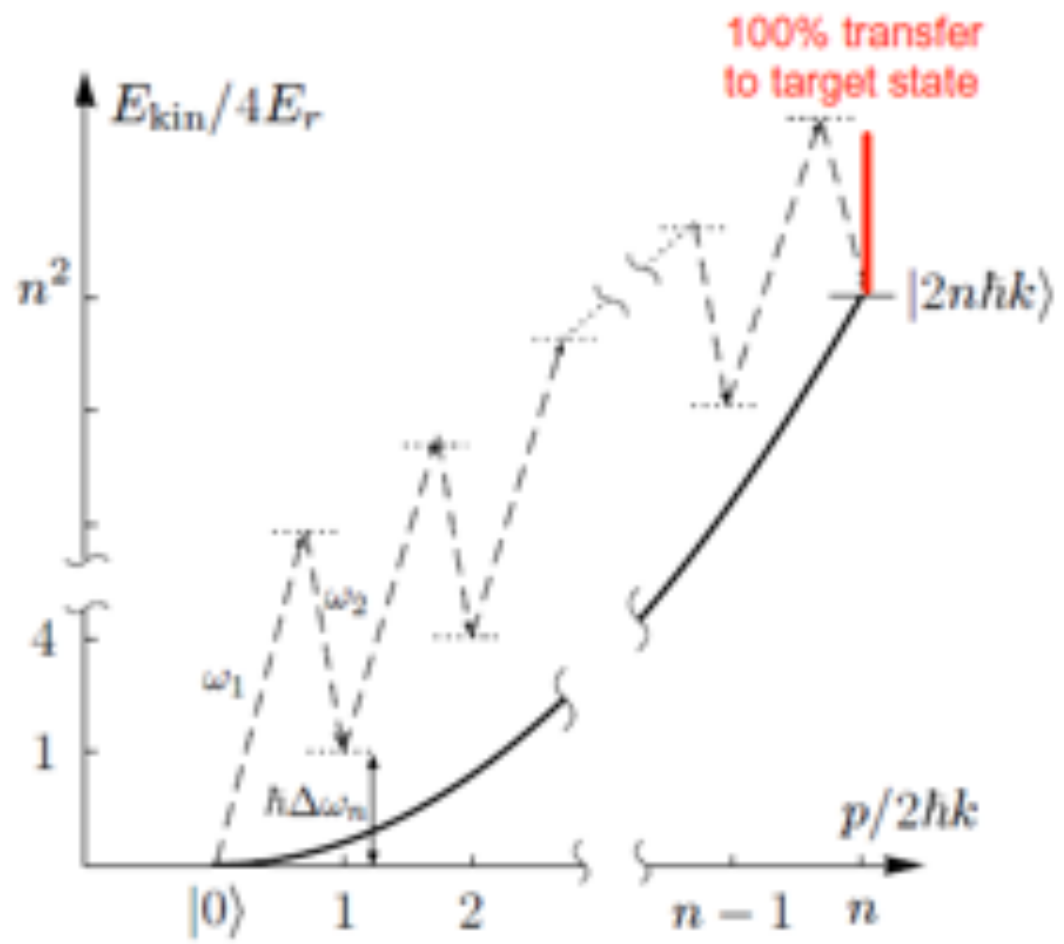
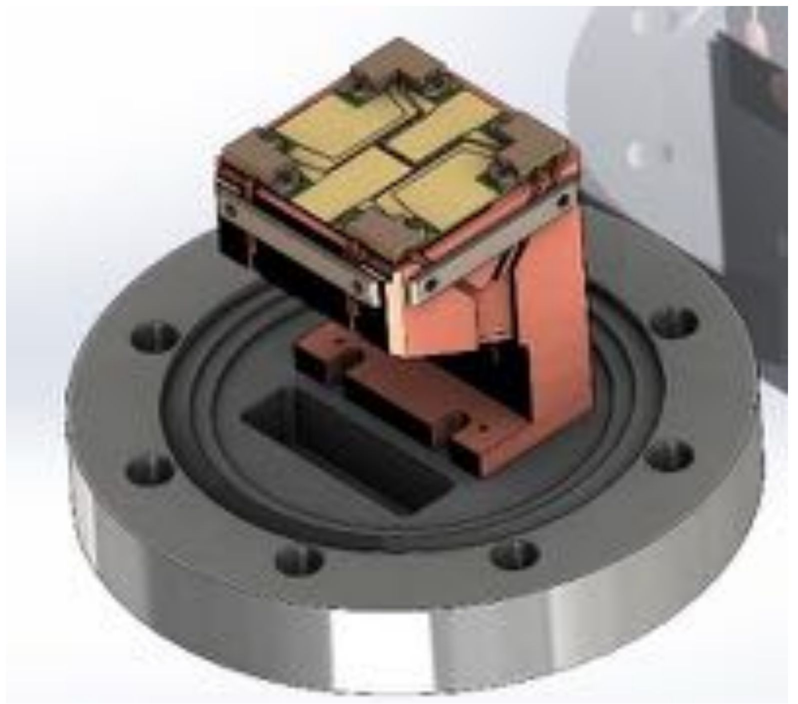
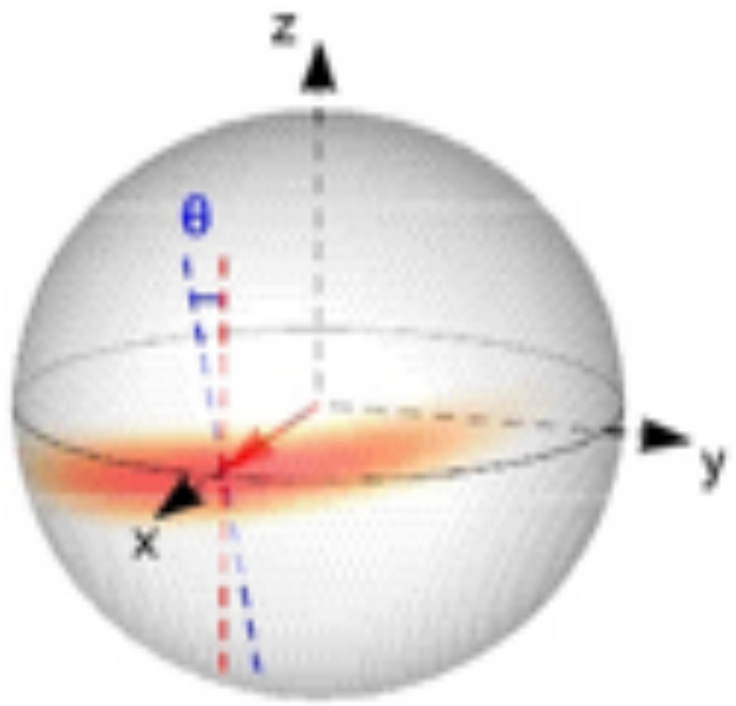
Submitted for publications: see talk of V. Menoret

μQUANS

l'Observatoire de Paris | SYRTE

Gravity - gradiometer at SYRTE

✓ Ideal test bed for the development of new methods

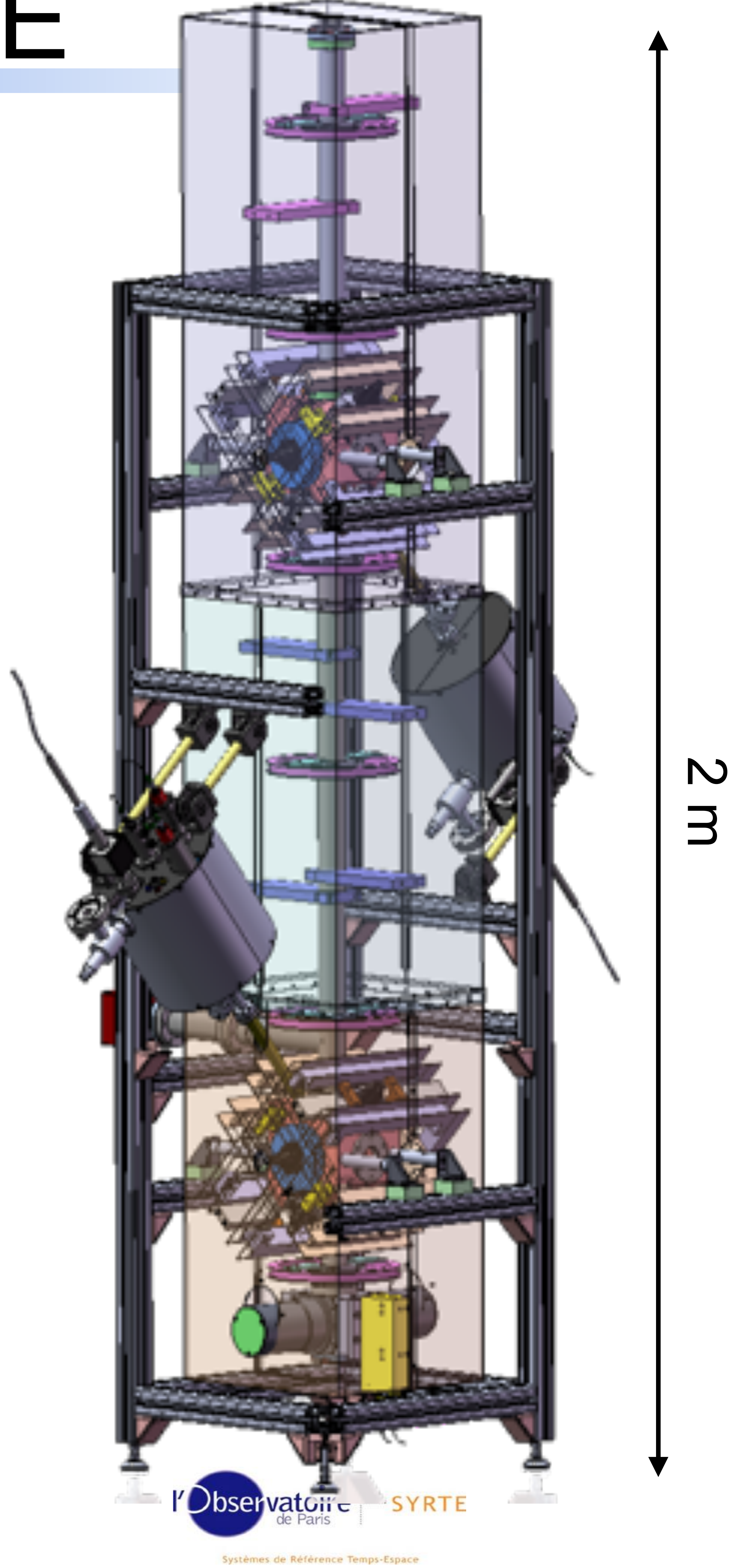
High order Bragg diffraction Gain x 100 separation	Ultracold atoms (atom chips)	Spin squeezing
		

➡ **Expected sensitivity: 10^{-10} s^{-2} = 0.1 E at 1s**

More than one order of magnitude better than state of the art sensors based on differential accelerometry

➡ **Method to reduce the size at constant sensitivity**

➡ **Demonstration for space gradiometry**

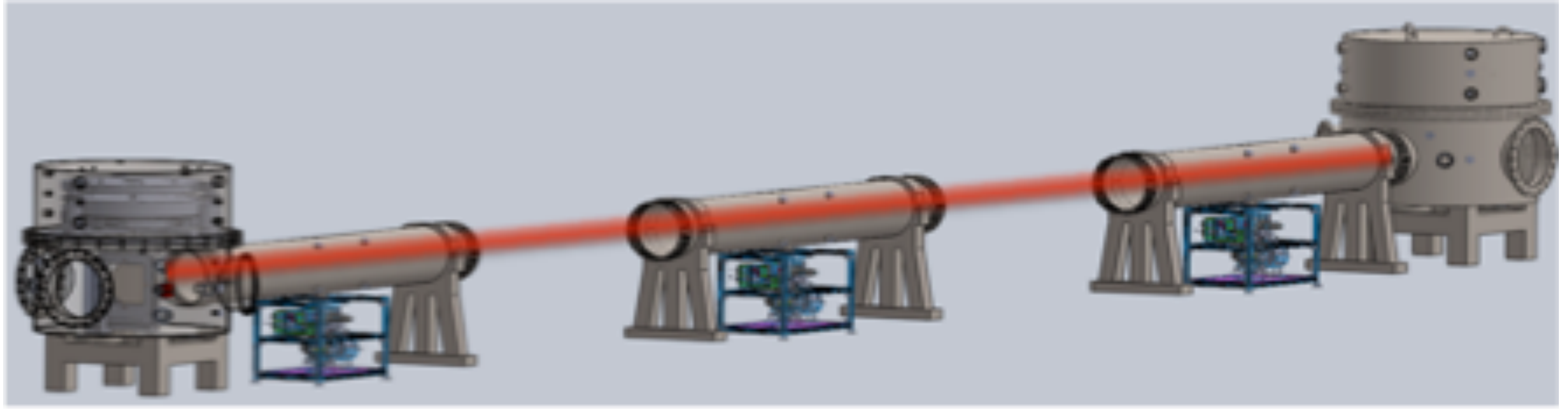


MIGA : Gravitation et Géophysique avec des capteurs atomiques

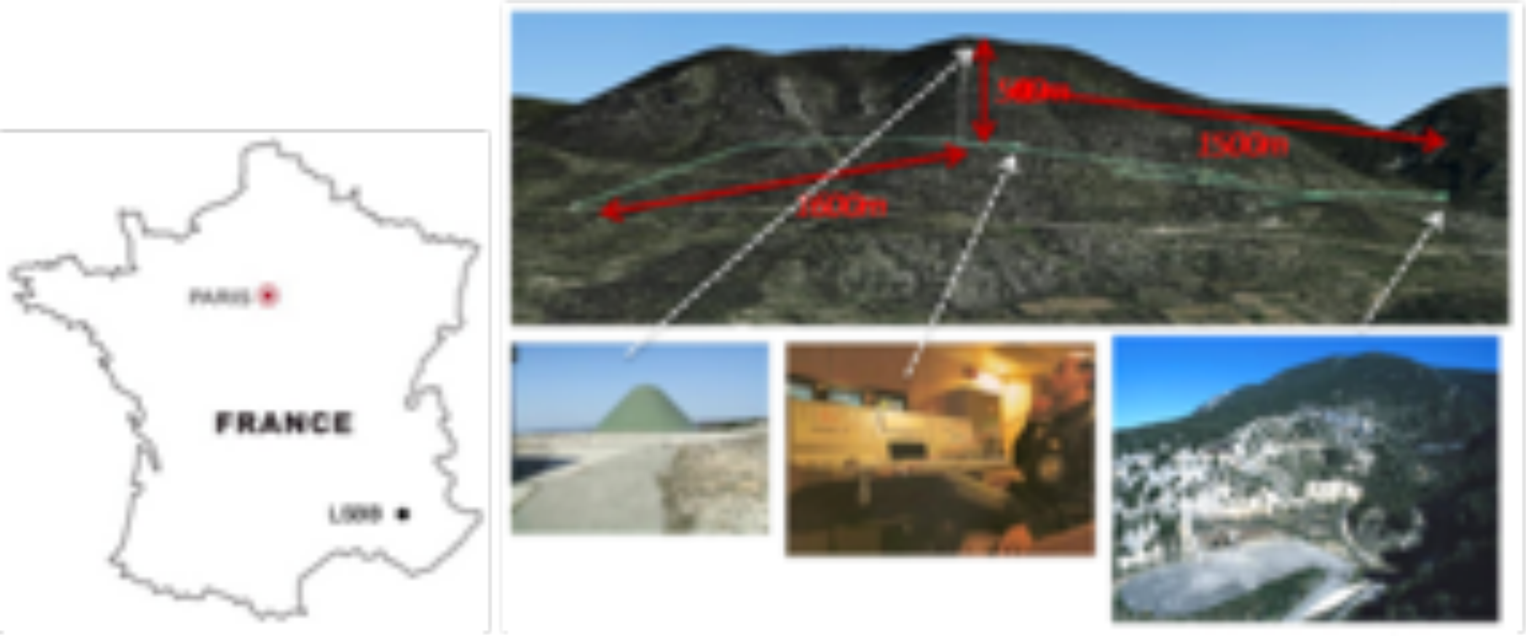
Equipex lead by LP2N, consortium of15 laboratories

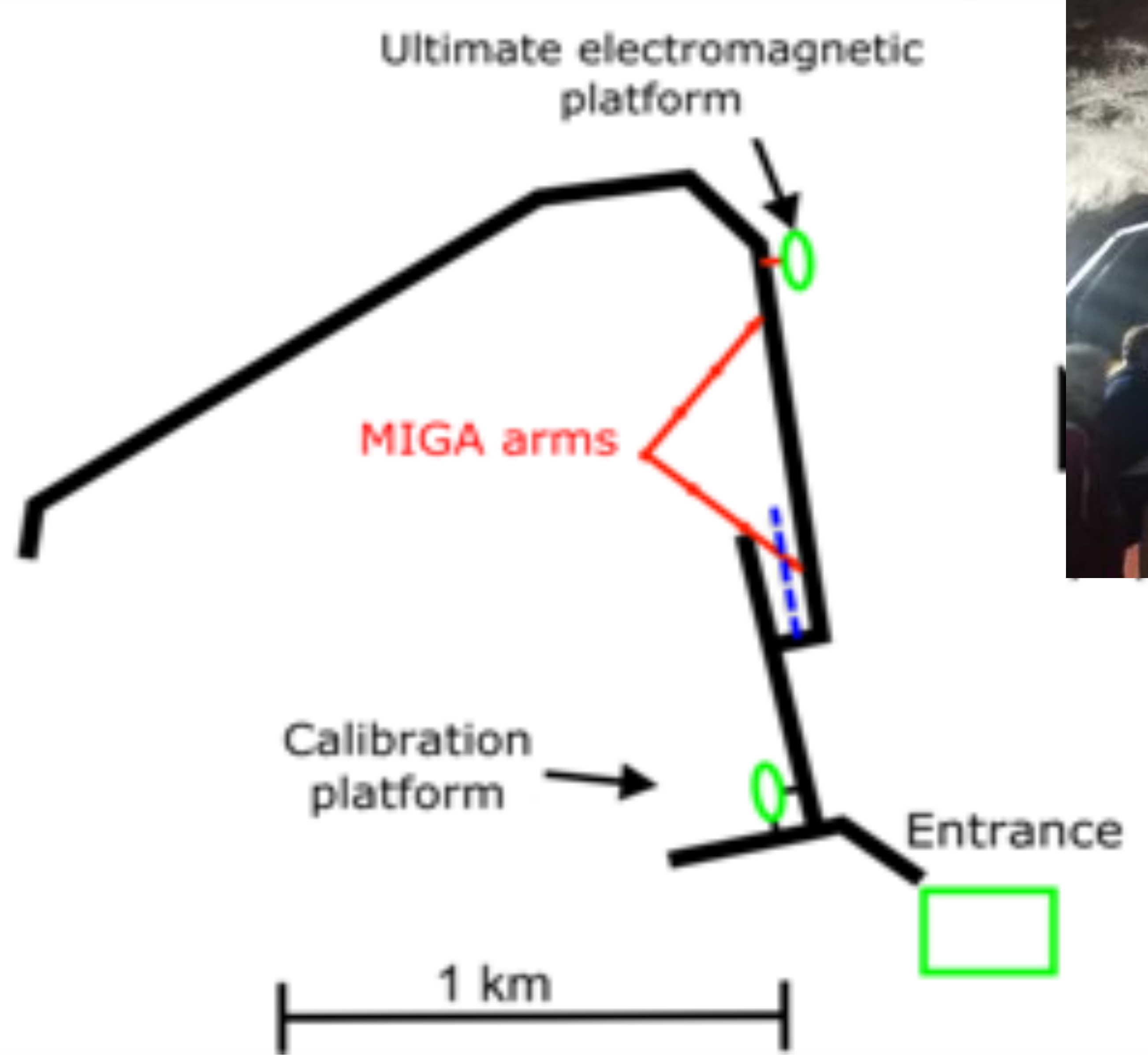
Very long baseline gradiometer with 3 interferometers 150 m appart

Scientific Reports 8, 14064 (2018).



- ✓ Underground mass distributions
  Hydrology, …
- ✓ Demonstrator for gravitational wave detection





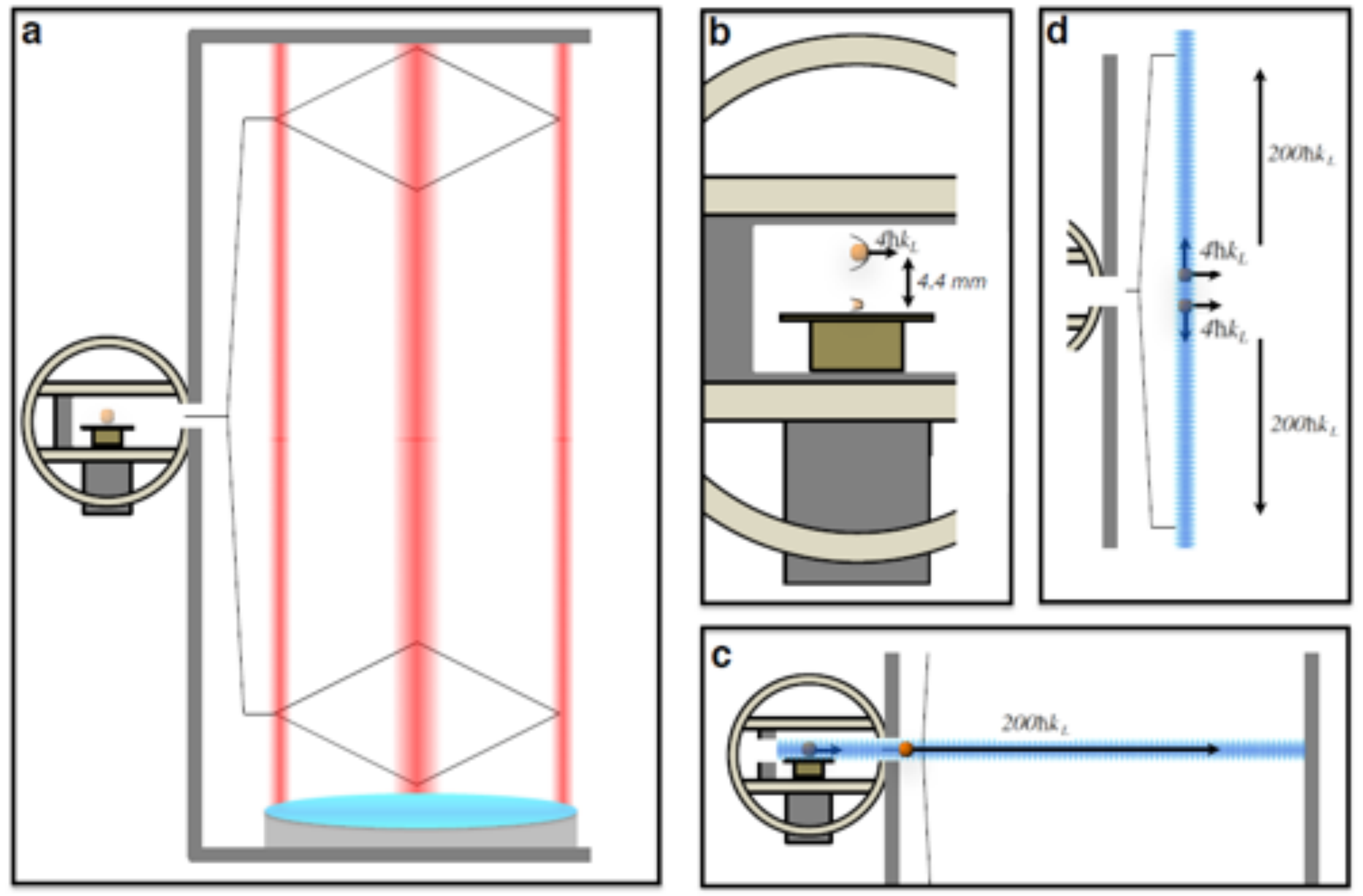
Inauguration projet LSBB 2020, 16/11/2021

LSBB Laboratoire Souterrain à Bas Bruit
Low Noise Inter Disciplinary Underground Science & Technology

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

Space gradiometry

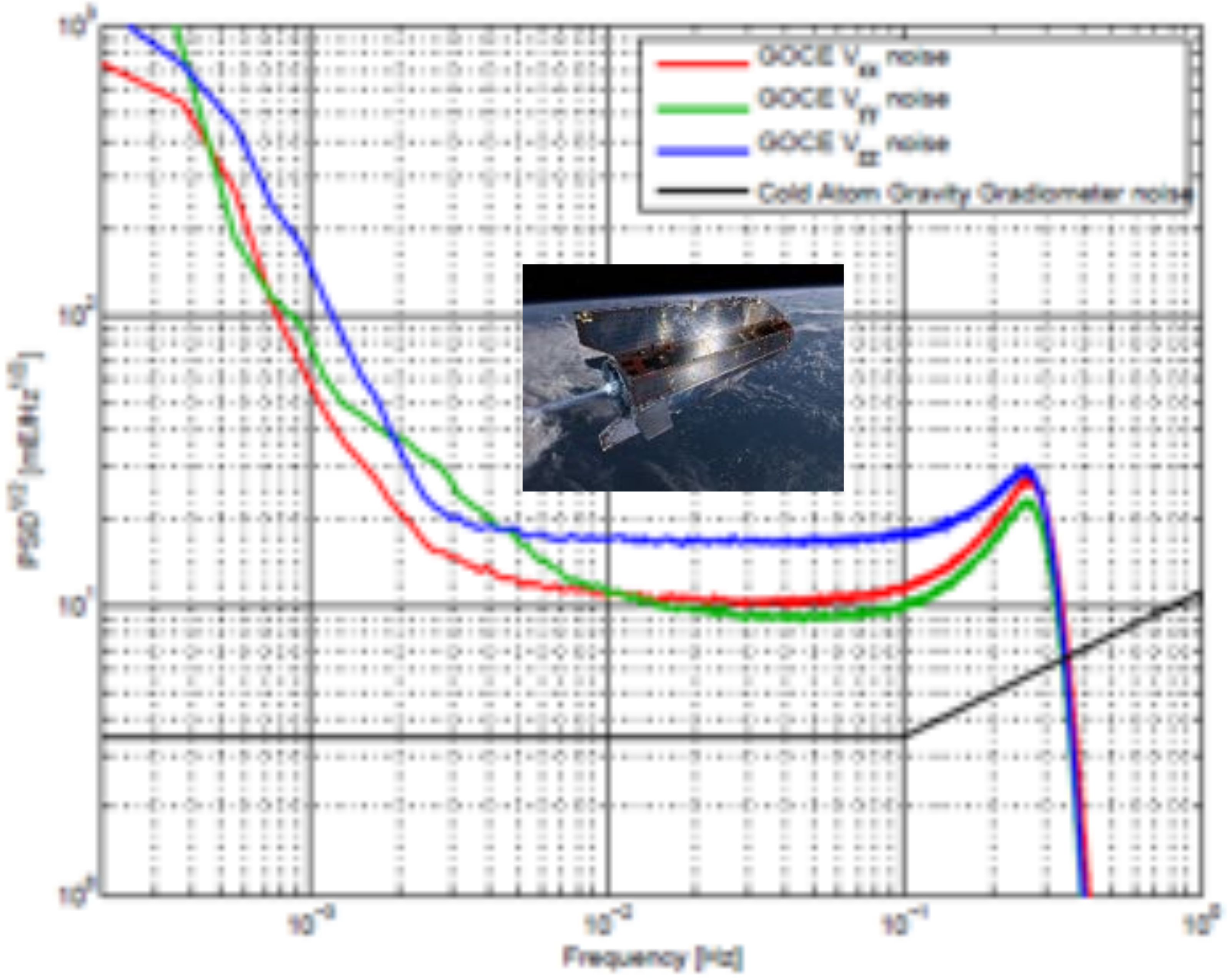
CNES phase 0 study GRICE
ESA CAI study (*A. Trimeche et al., "Concept study and preliminary design of a cold atom interferometer for space gravity gradiometry", Classical and Quantum Gravity 36, 215004 (2019)*)



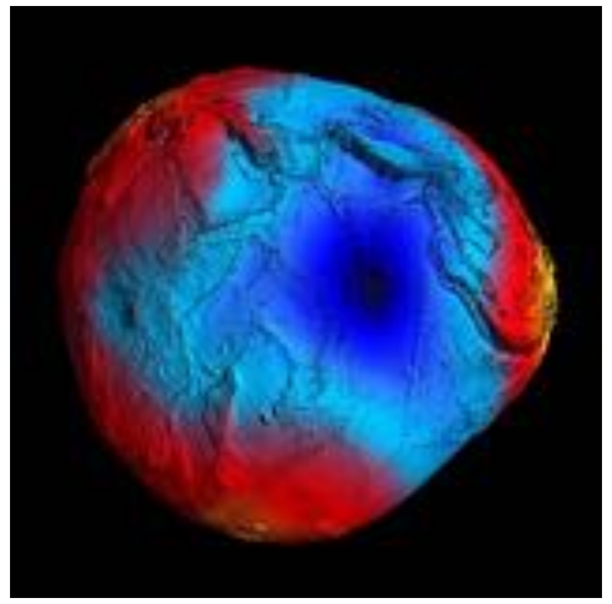
- Ultracold atoms on a chip at T_{at}=100 pK
- Transport and splitting
- Two interferometers separated by 50 cm
  Duration 2T = 10 s

Expected sensitivity : 3.5 mE/Hz$^{1/2}$

Comparison between electrostatic sensors (GOCE)/quantum sensors



Benefit from atomic sensors:
Stability of the scale factor +
Good control of systematics



⇒ Better long term stability
⇒ Better determination of the gravity field

EU call for a demonstrator (talk of Q. Beaufils)

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

Double axis cold atom gyroscope

- ✓ 4 pulse gyroscope

Sagnac Effect: Area x Particle Energy

$$\boxed{\Delta\Phi_{SAGNAC} = \frac{2E\vec{A}\cdot\vec{\Omega}}{\hbar c^2}}$$

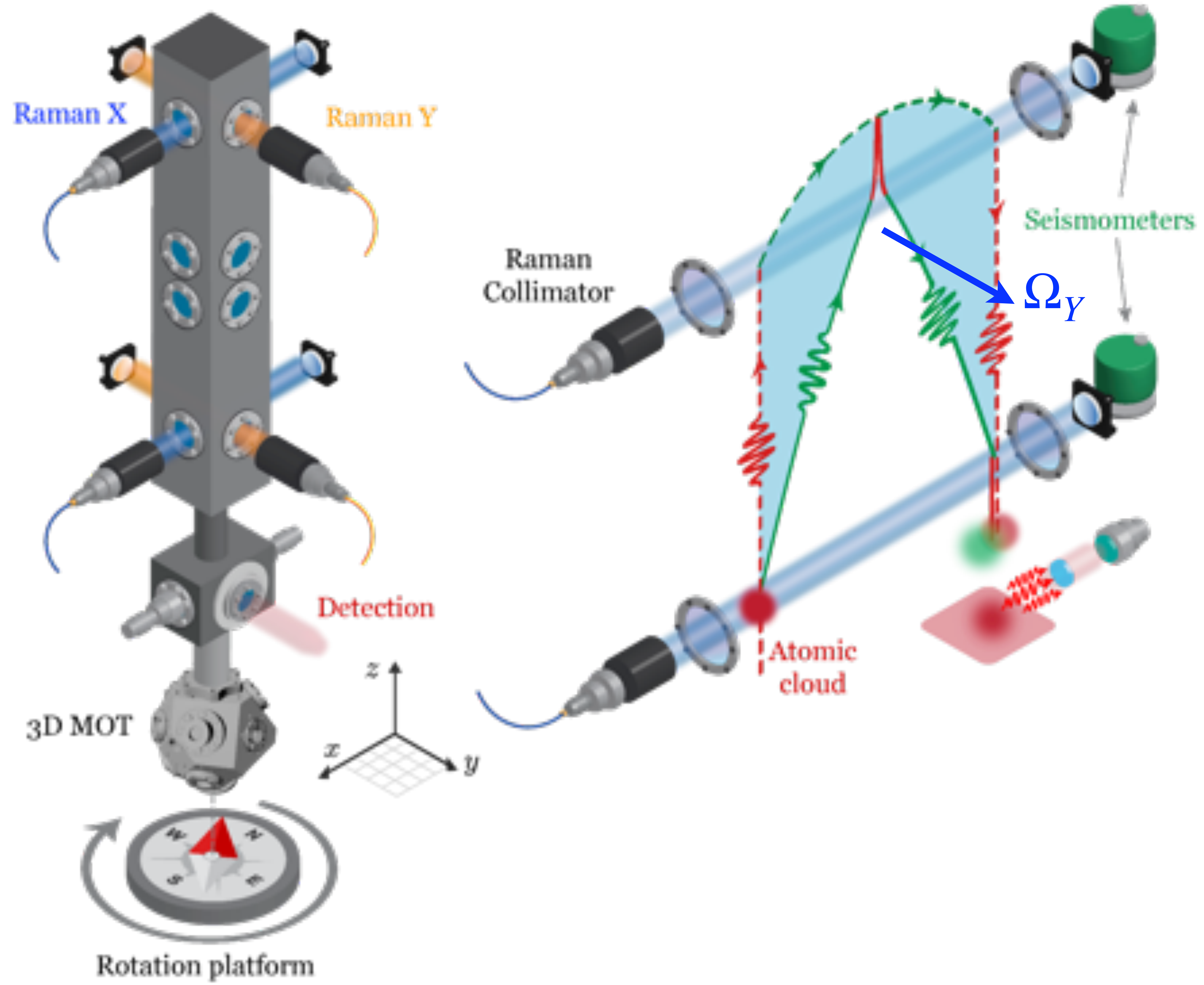
- ✓ « Pure Gyroscope »

=> not sensitive to DC acceleration

Extremely large area up to 11 cm^2 (interf. duration $2T = 800$ ms)

- ✓ Record sensitivity:
  - ➡ short term: 3.10^{-8} rad.$s^{-1}.\tau^{-1/2}$ (100 µ°.$hr^{-1/2}$)
  - ➡ long term < 3.10^{-10} rad.s^{-1} (60 µ°/h)

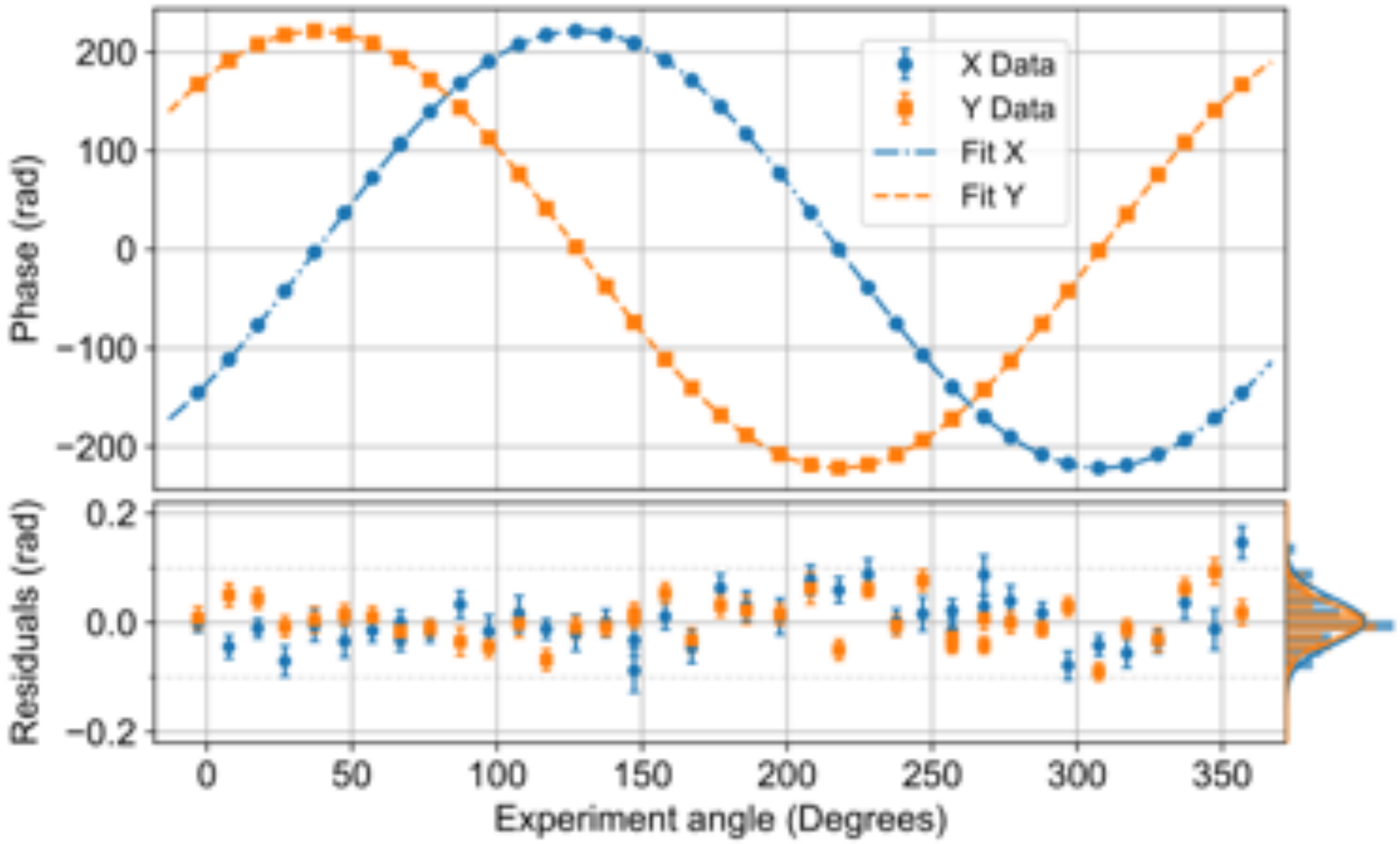
X and Y axis Raman lasers X axes Raman lasers => Ω_Y



I. Dutta, et al., Phys. Rev. Lett. ***116****, 183003 (2016)*
D. SAVOIE et al., Science Advances 2018; 4:eaau7948

l'Observatoire de Paris | SYRTE

Test of the Sagnac effect



$$\Phi_\Omega = \frac{T^3}{2}(\overrightarrow{k_{eff}} \times \vec{g}) \, . \, \overrightarrow{\Omega_E}$$

$$= \boxed{\frac{T^3}{2}(k_{eff} \; g \; \cos(\alpha_h))} \; \boxed{\Omega_E \cos(\theta_{Lat} + \xi)} \; \cos(\theta_N)$$

Sagnac scaling factor
∝ physical area

Local horizontal components of Ω_E:
latitude (geoid)+
S-N deviation

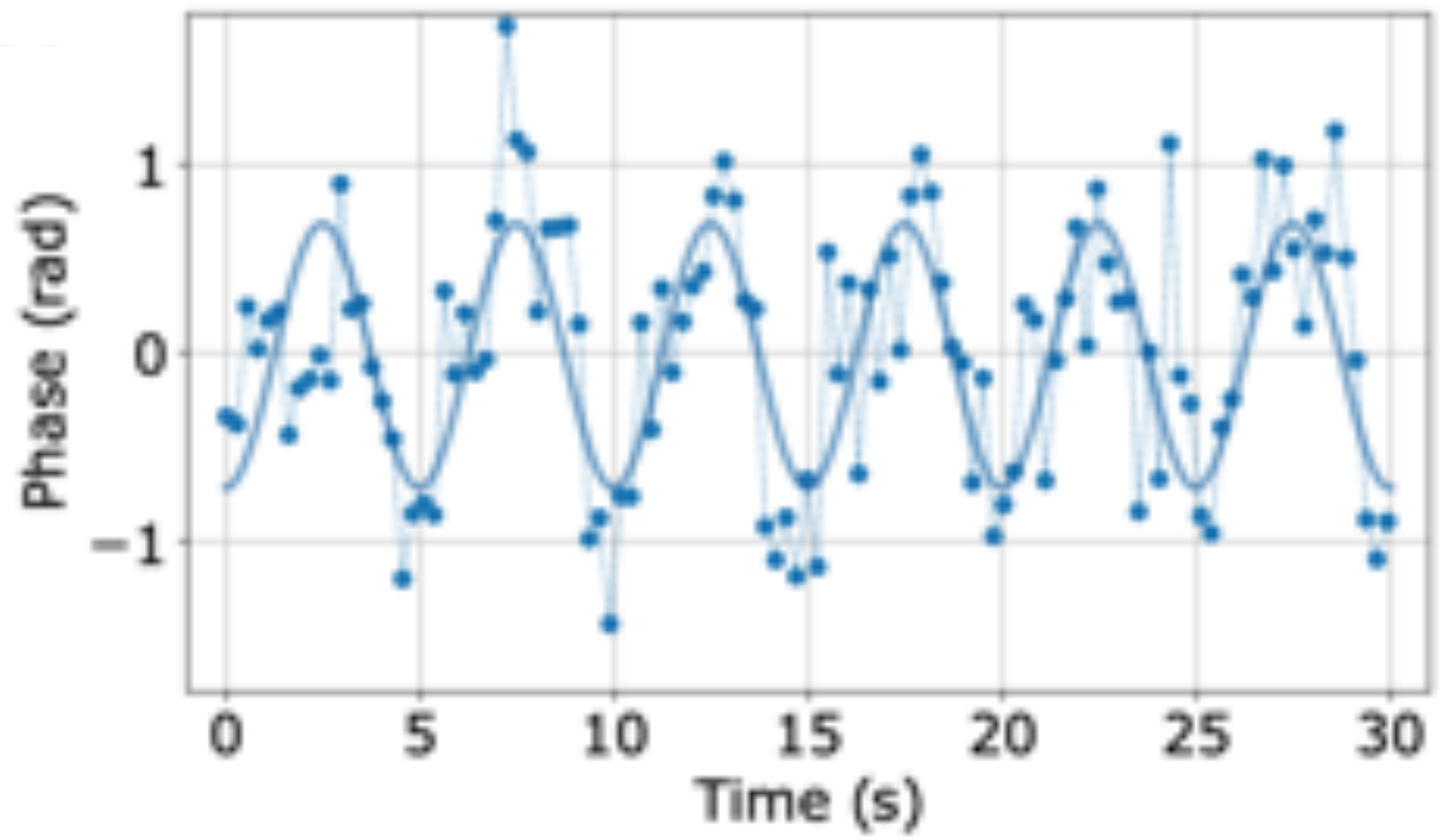
Platform orientation

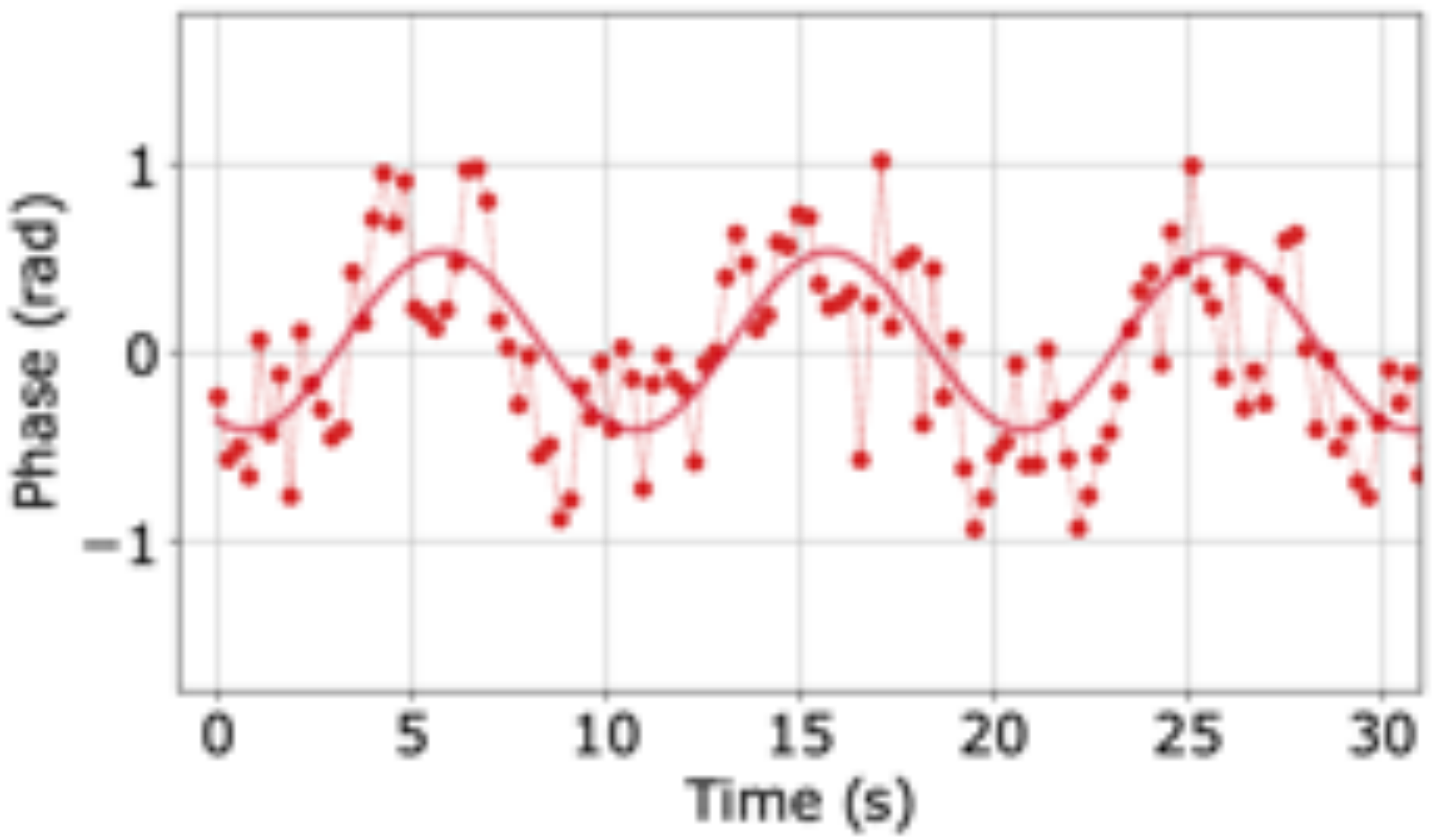
- ✓ Test of the **Sagnac effect** with matter-waves (submitted for publication):
  - ➡ No deviation to the expected values (< 1. 10^{-5}) **in agreement to ± 2.5 10^{-5}** in relative value
  - ➡ 20 times higher accuracy than previous experiments

Dynamical measurements of rotation rate

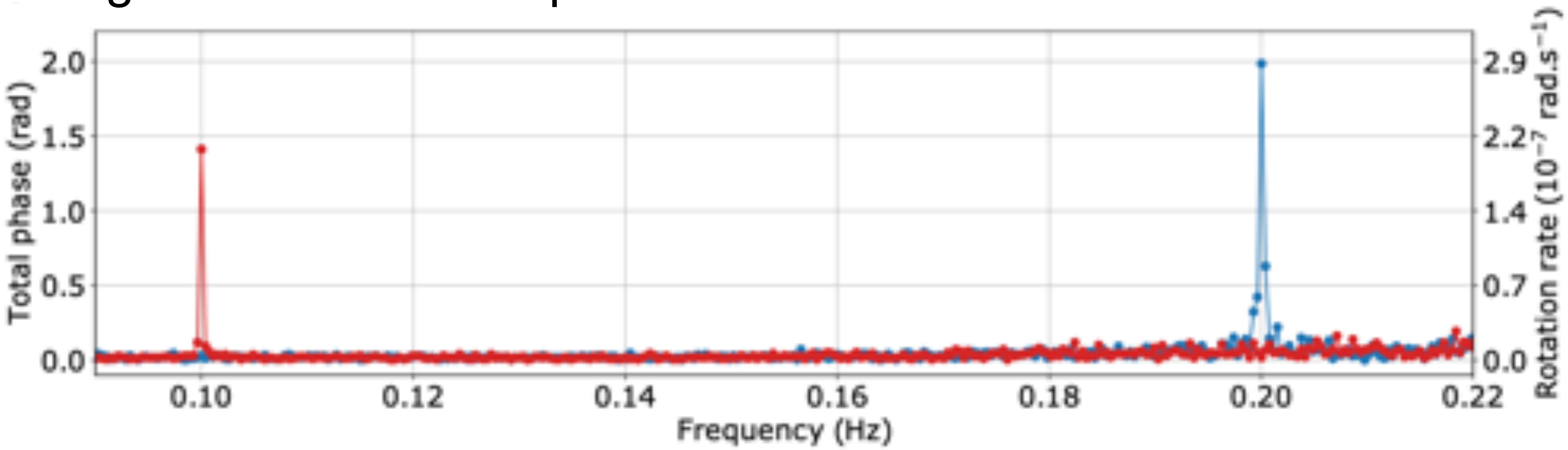
Test with sinusoidal modulation at 5 and 10 s of the rotation rate.

Continuous measurements (no dead time): repetition rate > 3 Hz





Agreement in the amplitude to better than 5 %

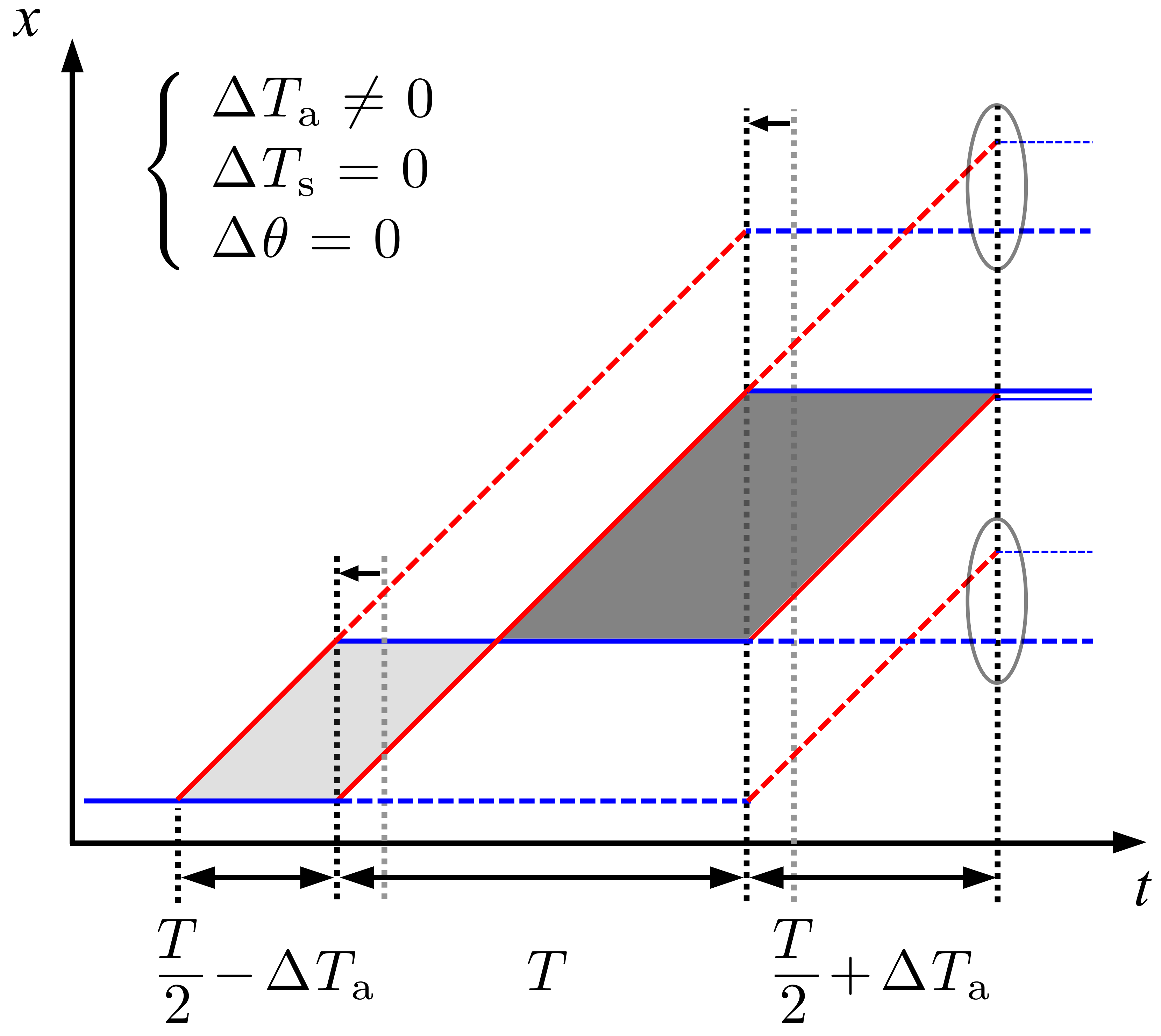


D. SAVOIE et al., Science Advances, Vol. 4, no. 12, eaau7948 (2018)

Tailoring Multiloop Atom Interferometers

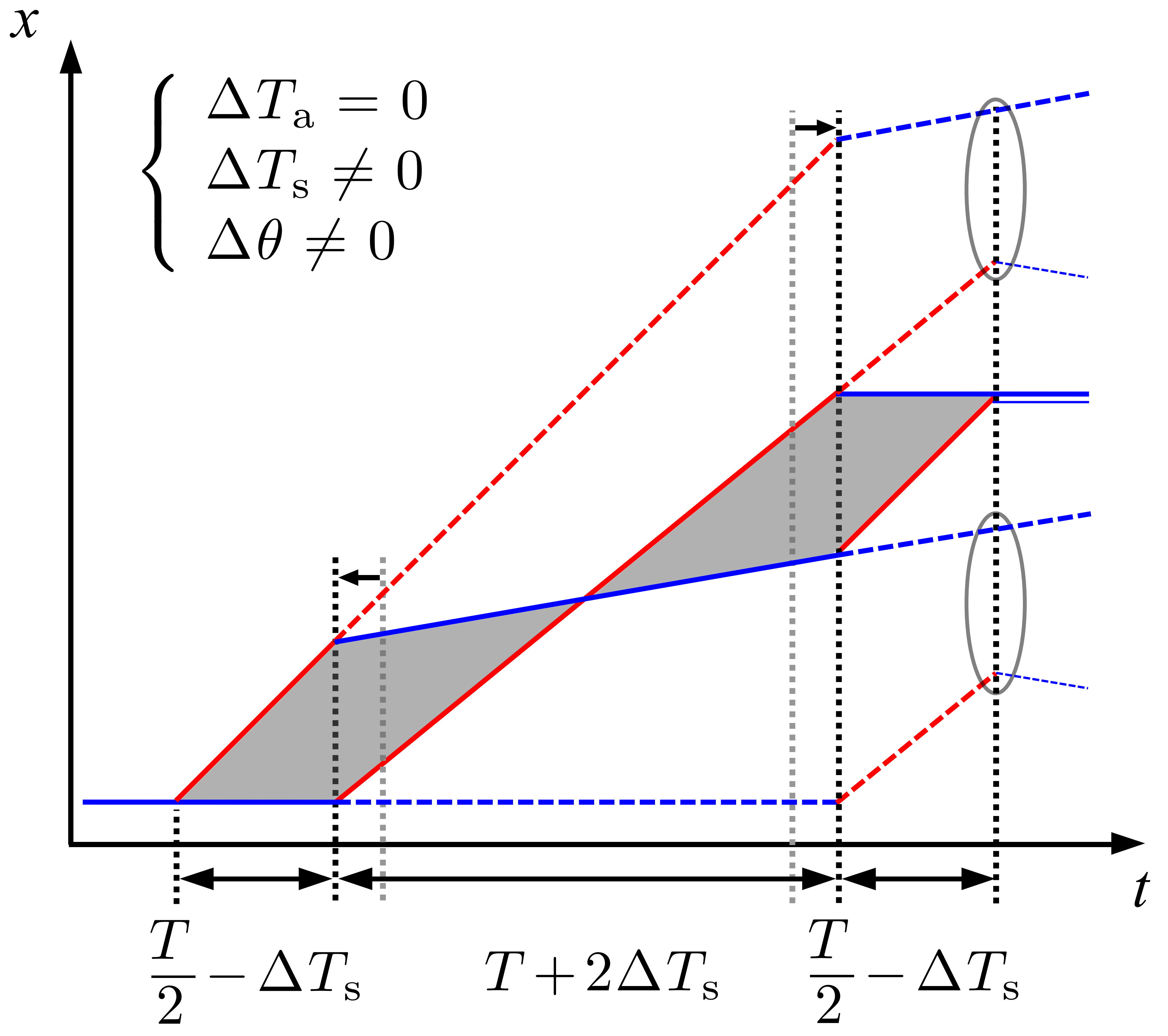
Variable momentum transfert and symmetric timing change: Tailoring of the sensitivity

With DC acceleration

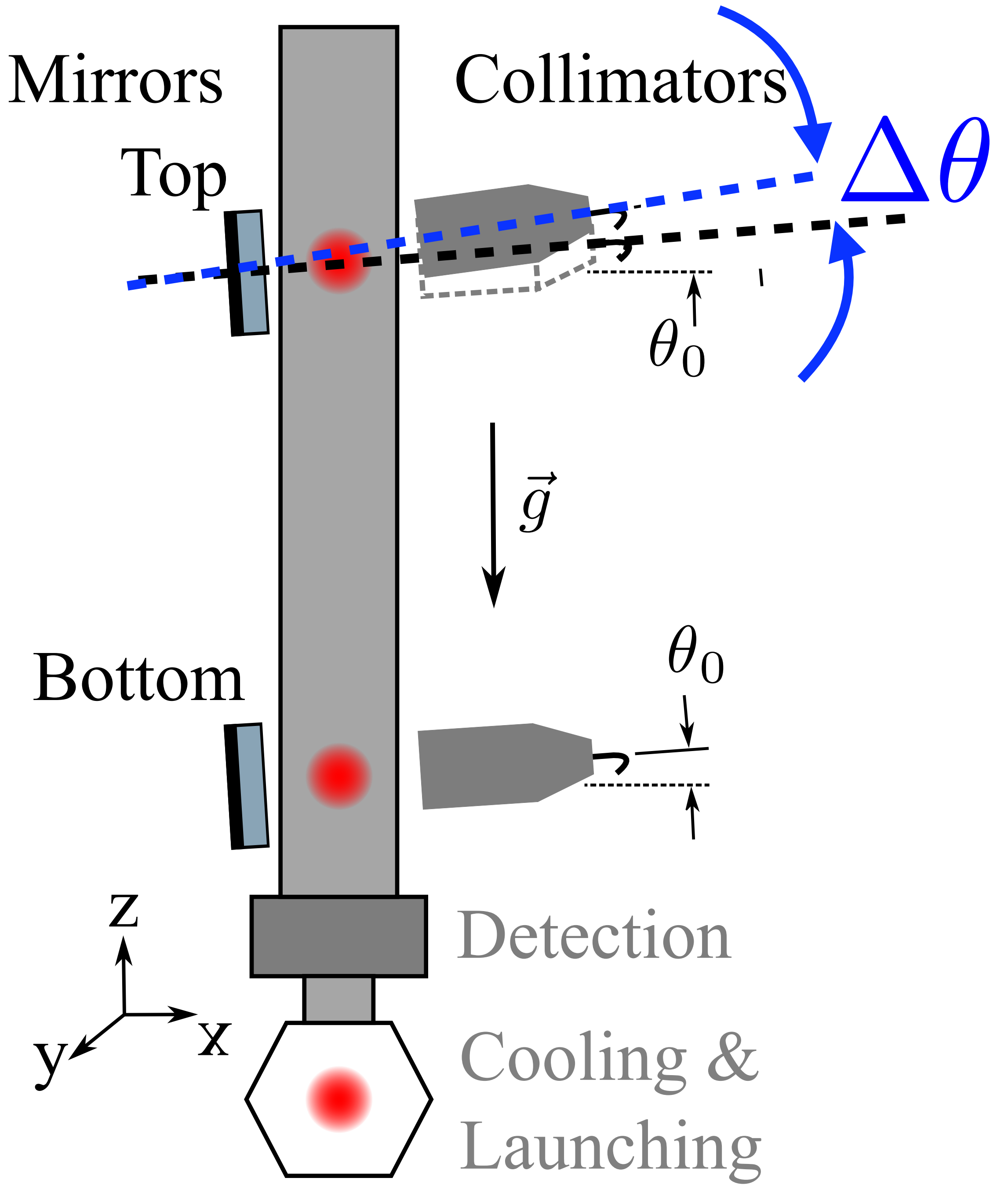


$$\Delta\phi_{acc} = 2a.k_{eff}T.\Delta T_a$$

No sensitivity to DC acceleration



*L. A. Sidorenkov, et al., PRL **125**, 213201 (2020)*

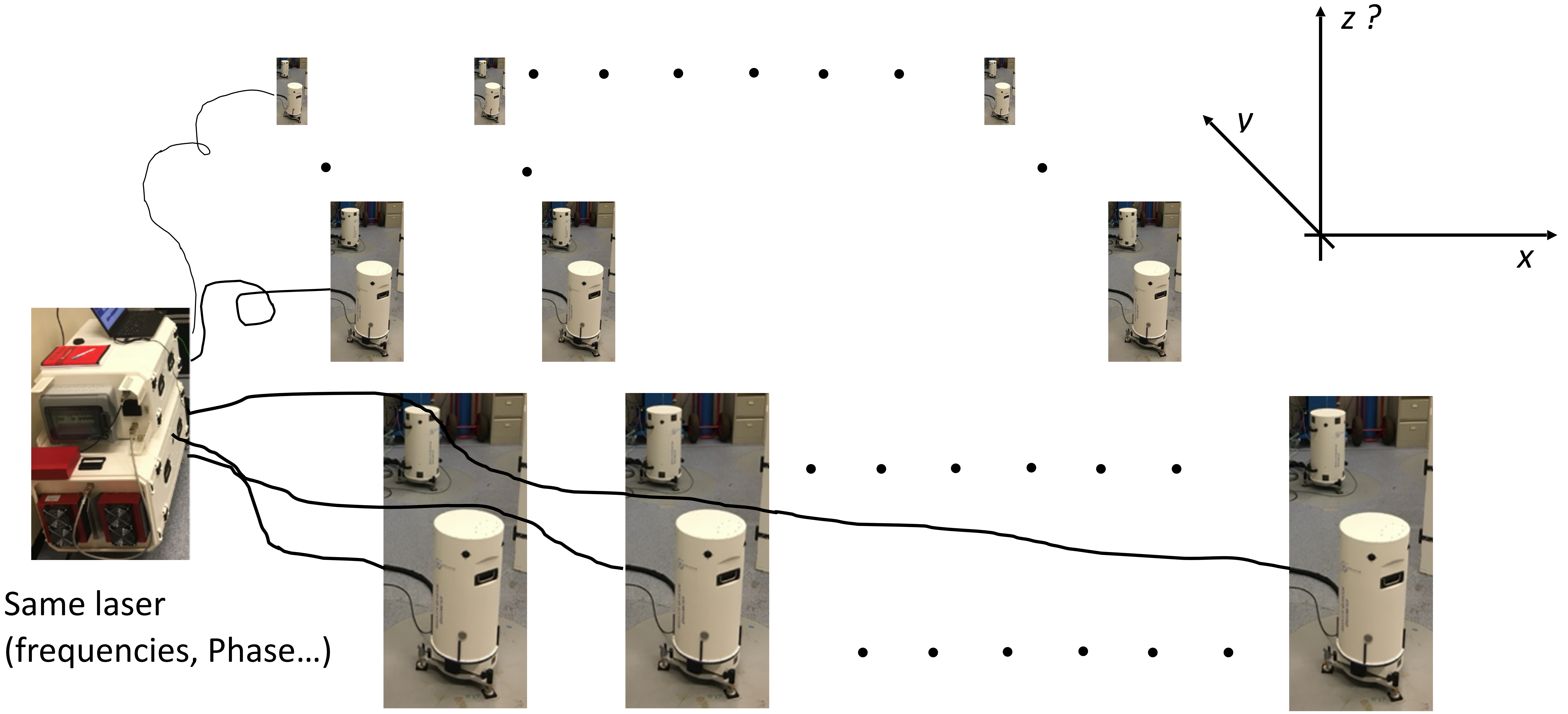


Successive measurements in $+/-\Delta T_a$

➡ séparation between Horizontal rotation from acceleration

Networks

- ✓ Networks of clocks, gravimeters and/or gradiometer, gyroscopes:
  - ➡ at short distance (noise reduction between)
  - ➡ at long distance: interest of fiber networks?, entanglement measurements

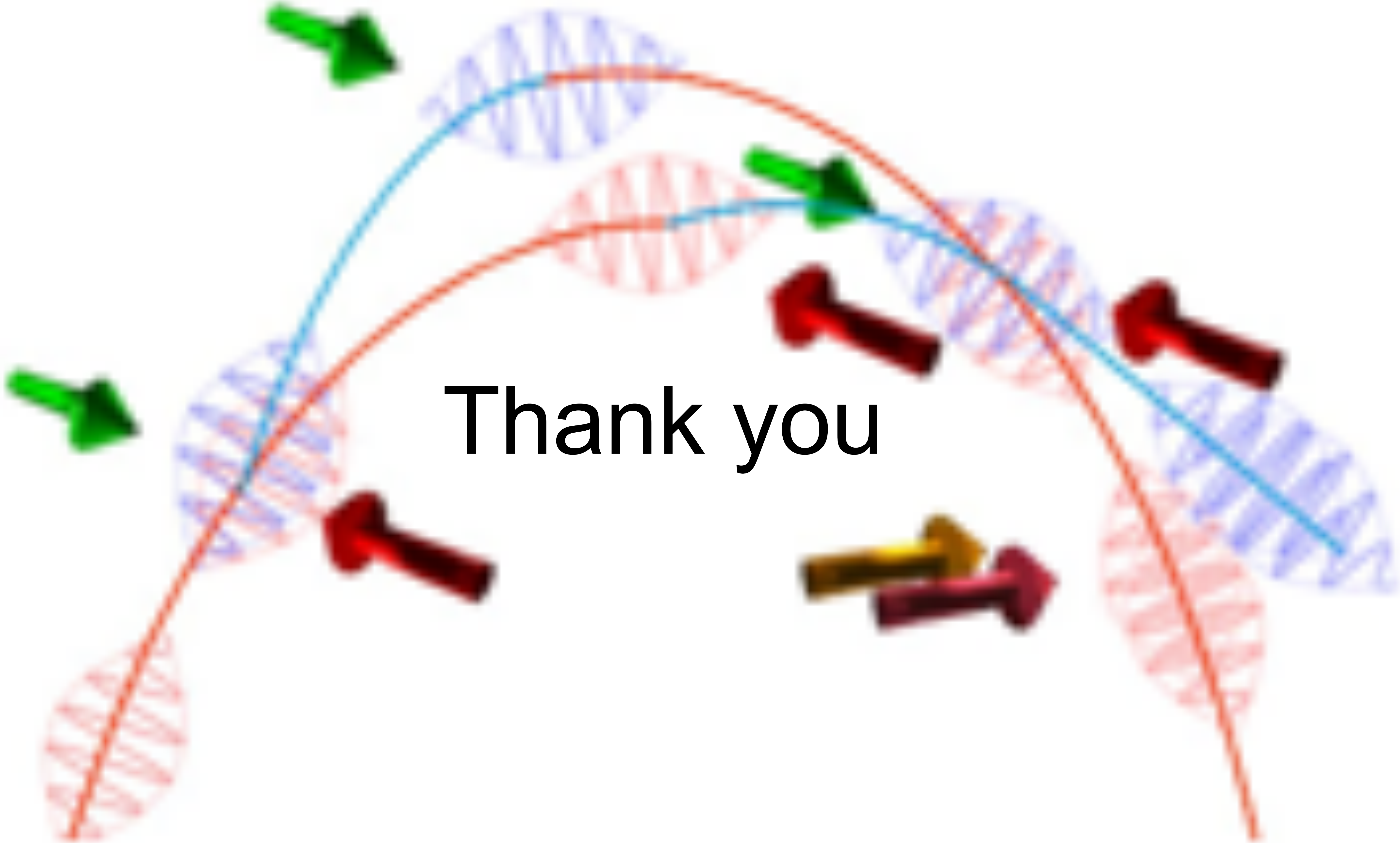


Summary

- ✓ Chronometric geodesy
  - ➡ Technologic developments…
- ✓ Gravimetry
  - ➡ State of the art: sensitivity and accuracy, but room for improvement
  - ➡ Mobile gravimetry
- ✓ Gradiometry
  - ➡ In progress (atomic physic studies)
  - ➡ Space application (EU call for a demonstrator)
  - ➡ MIGA
- ✓ Quantum sensors offer many possibilities and configurations
  - ➡ Gyroscope
  - ➡ Multi-axes: 3D, rotation + acceleration
  - ➡ Development of quantum technologies (multi-$\hbar$k, entanglement…)
- ✓ Need for scientific case in g2
  - ➡ Gradio on ground (slow movement)
  - ➡ Interest of horizontal gradient? ($\delta a_x/\delta z$, $\delta a_z/\delta x$, ou $\delta a x_z/\delta x$ …)
  - ➡ Networks
  - ➡ Combinaison of sensors and deployments

PEPR Quantique: « Capteurs **Q**uantiques à **A**tomes **F**roids : mesure du **C**hamp de pesanteur **A** toutes les échelles » (SYRTE/LP2N/LKB/LCAR début en 2022)

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



Thank you