Towards a two-axis cold-atom gyroscope for rotational seismology

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SYRTE Laboratory, Paris Observatory and Sorbonne University

EGU - sharing geoscience online – May 6th, 2020

Context

- Cold-atom interferometry: 1991
- 2020: more than 45 research groups (academic) and 7 companies
- **Main idea:** use well-controlled atoms and light-matter interaction to measure **accurately** inertial signals → same spirit as for atomic clocks
- Target applications:

Tests of fundamental physics

(quantum mechanics, relativity)

Metrology (kg, G, α)

Geosciences

Inertial navigation?

Gravitational wave detection?

Review: https://arxiv.org/abs/2003.12516

Outline

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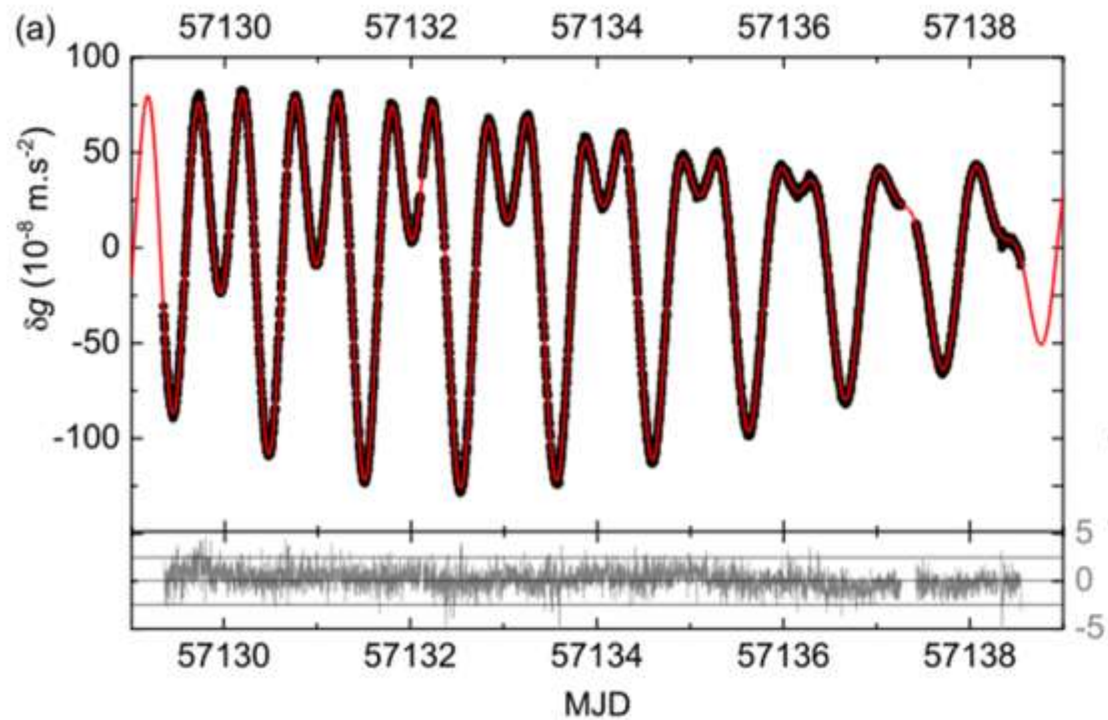
- Few examples of important achievements
- Principle of light-pulse atom interferometry
- High-stability cold-atom rate gyroscope

Famous example: the gravimeter

- First participation to international comparaisons of absolute gravimeters (2009)
- State-of-the art accuracy: $1.2 \times 10^{-9}\, g$ (stability $< 10^{-10} g$)
- Used in the French Kibble Balance for the realization of the kg



SYRTE ultracold-atom gravimeter : R. Karcher et al, NJP 20, 113041 (2018)

Onboard atom interferometers

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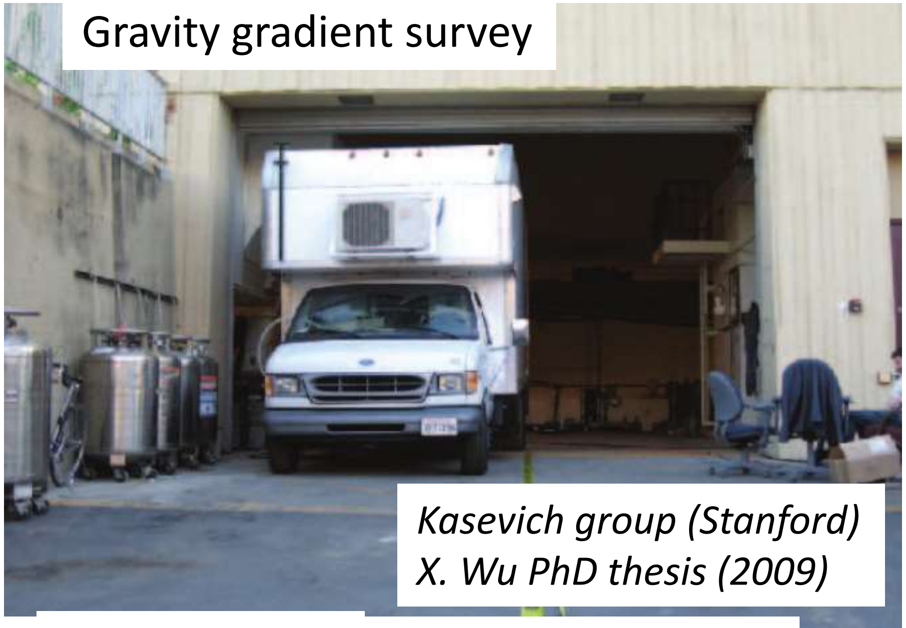
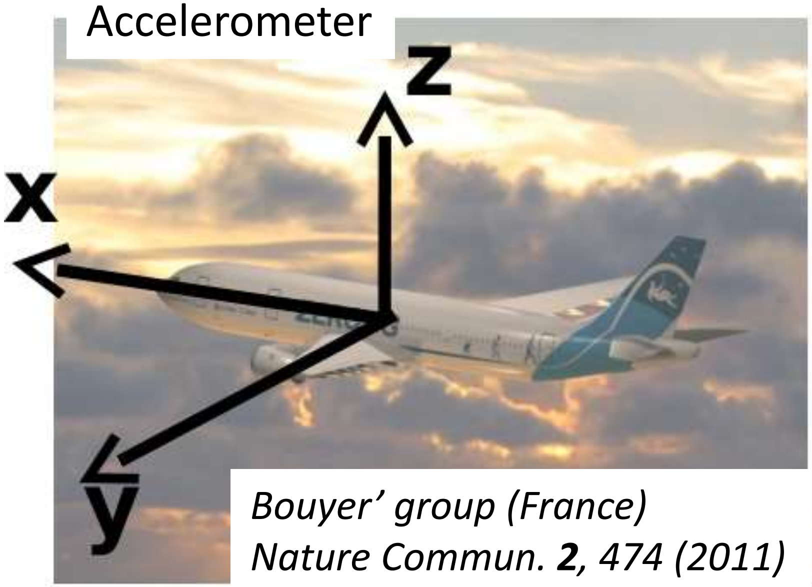
Gravity gradient survey



Kasevich group (Stanford)
X. Wu PhD thesis (2009)

Accelerometer



Bouyer' group (France)
Nature Commun. ***2****, 474 (2011)*

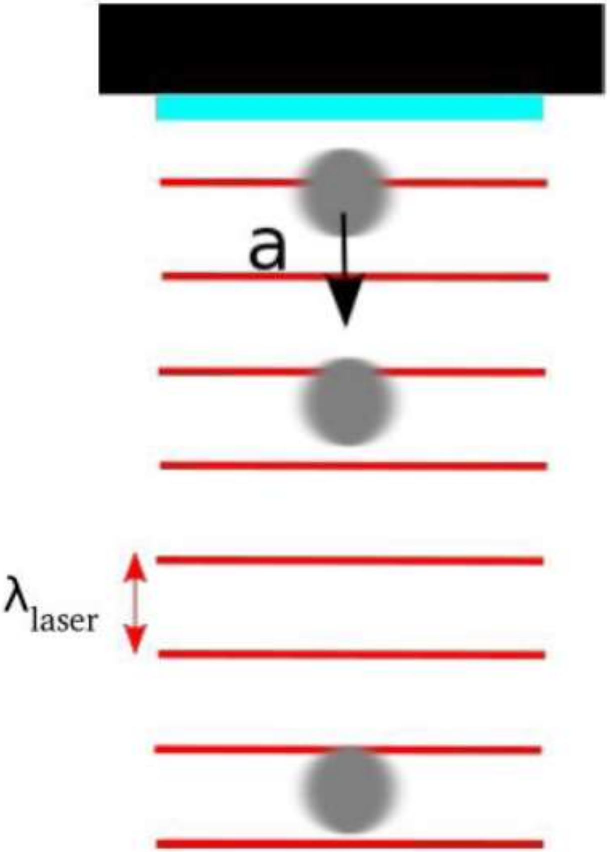
Absolute marine gravimetry

ONERA team (France)
Nature Commun. ***9****, 627 (2018)*

Simplified principle

Use free falling atoms to read the phase of a laser linked to an accelerated frame

→ Measurement of distances in units of laser wavelength



Number of graduations $\sim \dfrac{aT^2}{\lambda_{laser}}$

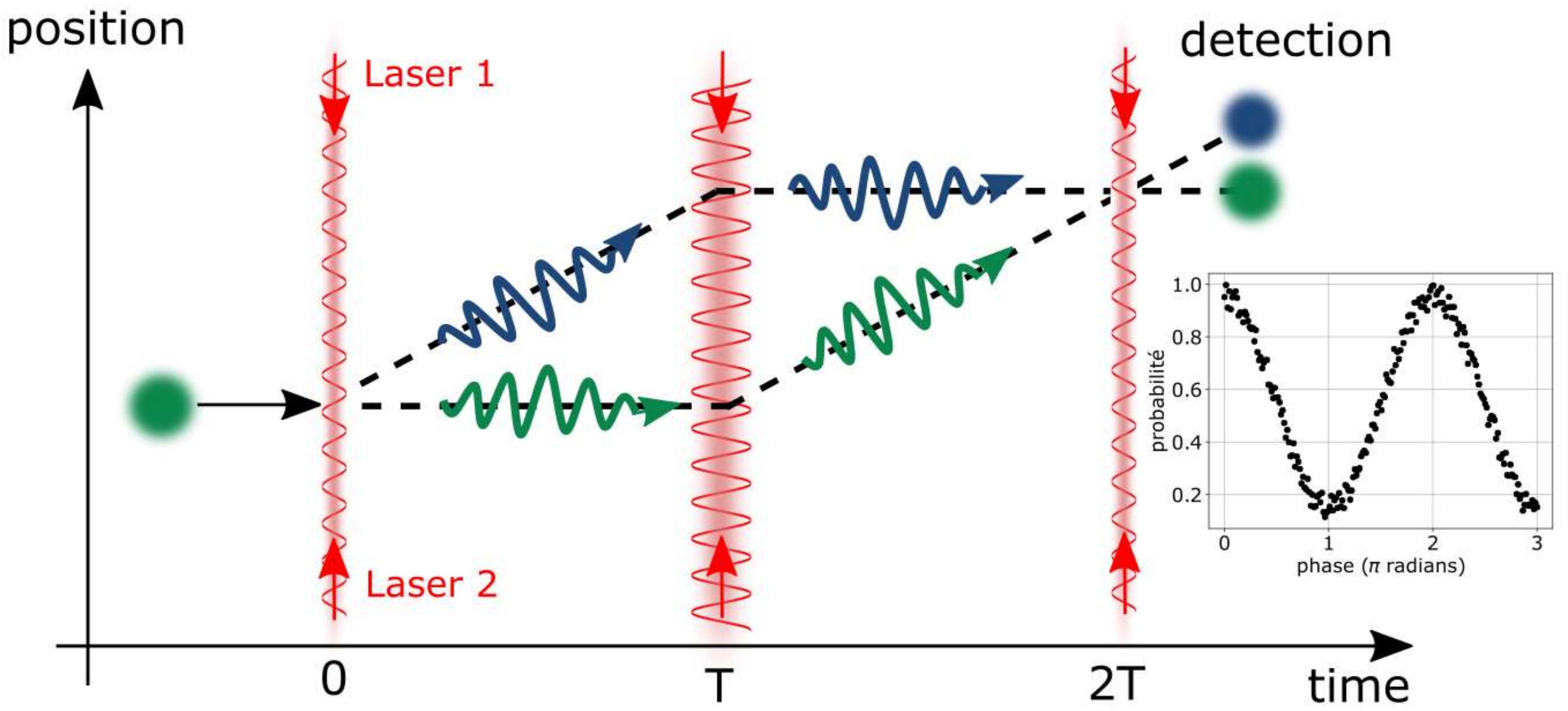
Orders of magnitude :

- $T = 100\ ms$; $\lambda = 0.5\ \mu m$;
- Resolution $\sim \lambda/100$ (SNR = 100)
- 1 measurement per second

→ Acceleration sensitivity $\sim 10^{-7}\ m.s^{-2}/\sqrt{Hz}$

Principle of Atom Interferometry

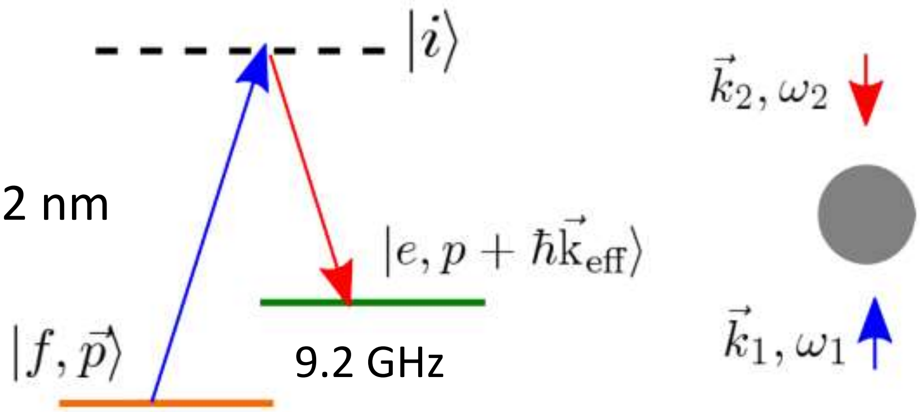
- Analogy with a Mach-Zehnder optical interferometer
- Use laser pulses to coherently split and recombine an atomic wave



Two-wave interference signal : $P = P_0 + A\cos(\Delta\Phi)$

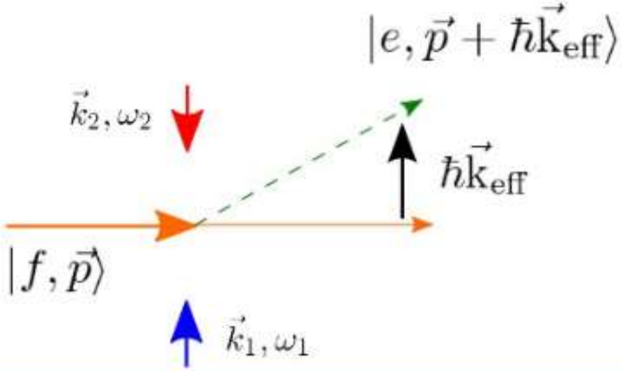
Stimulated Raman transitions

Cesium atom, D_2 line @ 852 nm



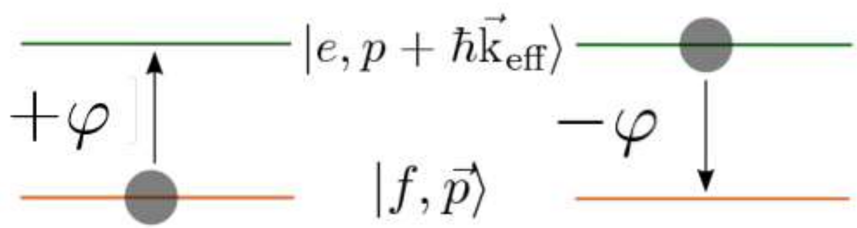
Momentum transfer

$$k_{eff} = k_1 + k_2 \sim 0.7\ cm/s$$

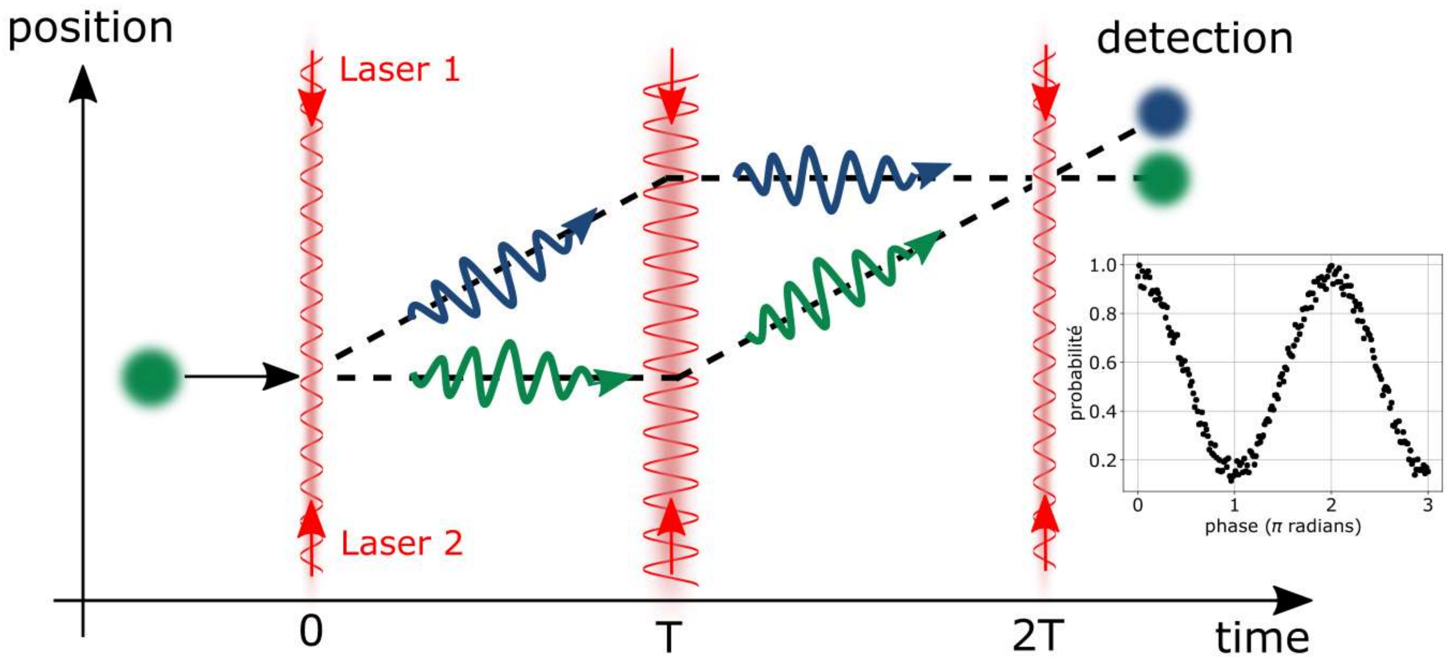


Laser phase difference imprinted on the atoms

$$\varphi = \phi_1 - \phi_2 = \vec{k}_{\text{eff}} \cdot \vec{r}(t)$$



Interferometer phase



Top path : $\varphi(0) - \varphi(T)$

Bottom path : $\varphi(T) - \varphi(2T)$

$$\longrightarrow \quad \Delta\Phi = \varphi(0) - 2\varphi(T) + \varphi(2T) = \frac{4\pi g T^2}{\lambda}$$

Sampling of the atomic trajectory with a laser ruler at 3 different times.

Absolute inertial sensor

Sensor output signal : $\Delta\Phi = \frac{4\pi T^2}{\lambda} \times g$

→ the scale factor can be known with high accuracy ($< 10^{-9}$)

Inertial sensitivity scales with T^2

→ want long T (few 100 ms typically)

→ need atoms with rms velocities $\sim cm/s$ → μK temperatures

Orders of magnitude :

- $T = 100\ ms$; $\lambda = 0.5\ \mu m$; SNR = 100
- 1 measurement per second

→ Acceleration sensitivity $\sim 10^{-7}\ m.s^{-2}/\sqrt{Hz}$

Cold-atom gyroscope

Photons versus atoms

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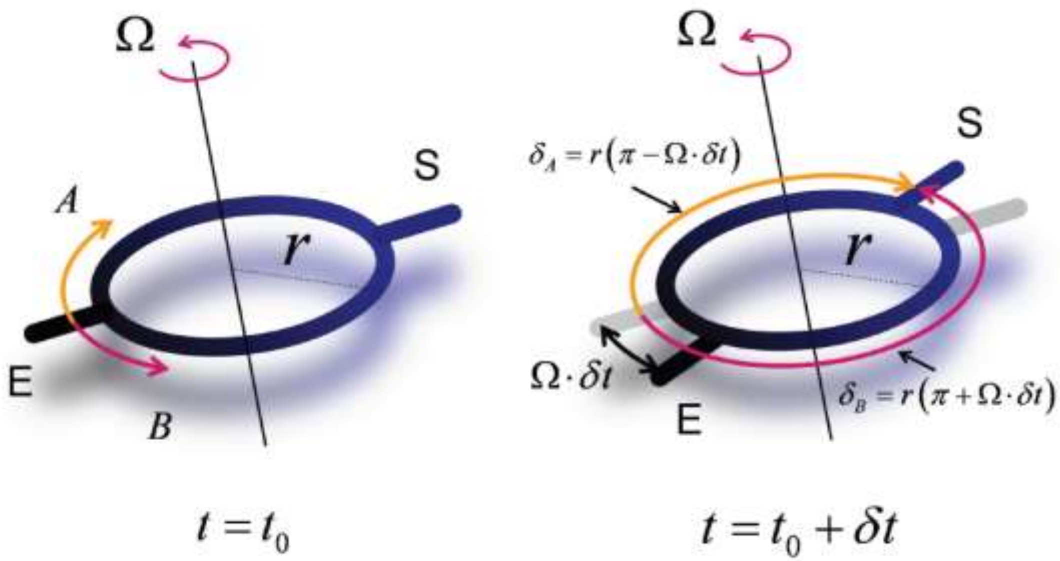
Sagnac effect



total energy

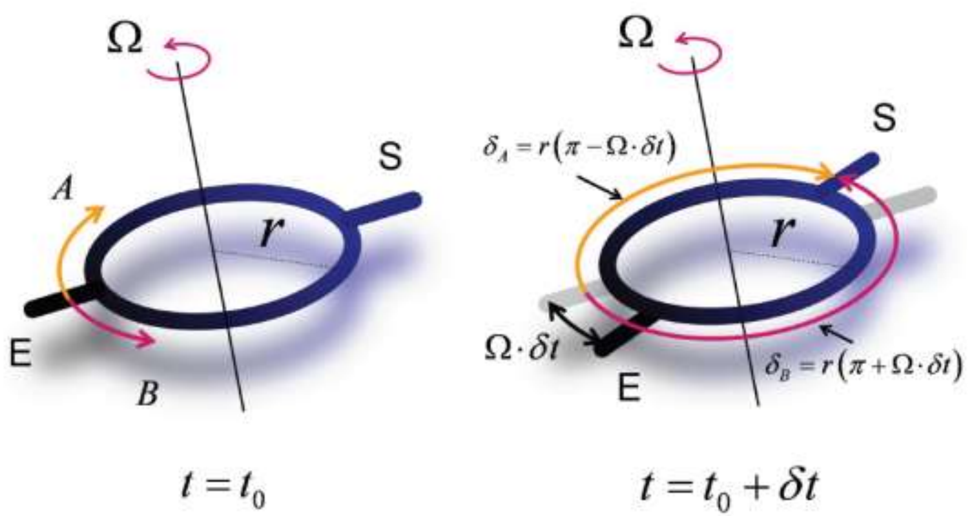
$$\Delta\Phi_{\Omega} = \frac{4\pi E}{hc^2}\vec{A}\cdot\vec{\Omega}$$

Physical area of the interferometer

C.R. Physique 15, 875-883 (2014)
arxiv:1412.0711

Photons versus atoms

Sagnac effect



Photons :

- A : cm² to m²
- $E \sim 1$eV

Atoms :

- A : mm² to cm²
- $E \sim 10^{11}$eV

+11 - 2 = 9 orders of magnitude

Shot noise ($\sigma_\phi \simeq 1/\sqrt{n}$):

- $10^{-9}\ rad/\sqrt{Hz}$ for photons
- $10^{-3}\ rad/\sqrt{Hz}$ for atoms

-6 orders of magnitude

C.R. Physique 15, 875-883 (2014) , arxiv:1412.0711

Gyroscope-accelerometer

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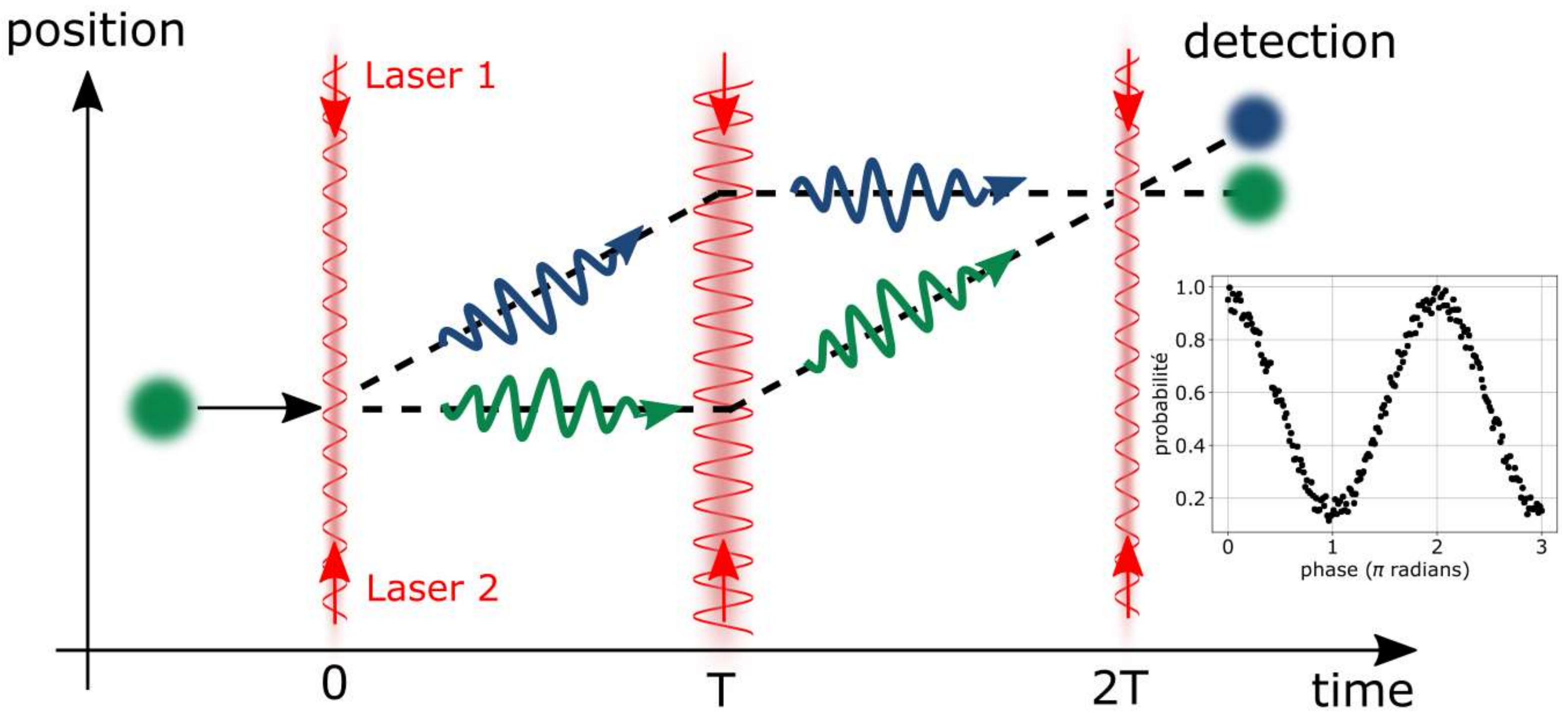

$$\Phi = \phi(0) - 2\phi(T) + \phi(2T) = \vec{k}_{eff}\vec{a}T^2 + 2\vec{k}_{eff}(\vec{v} \times \vec{\Omega})T^2$$

acceleration | rotation

4-light pulse atom interferometer

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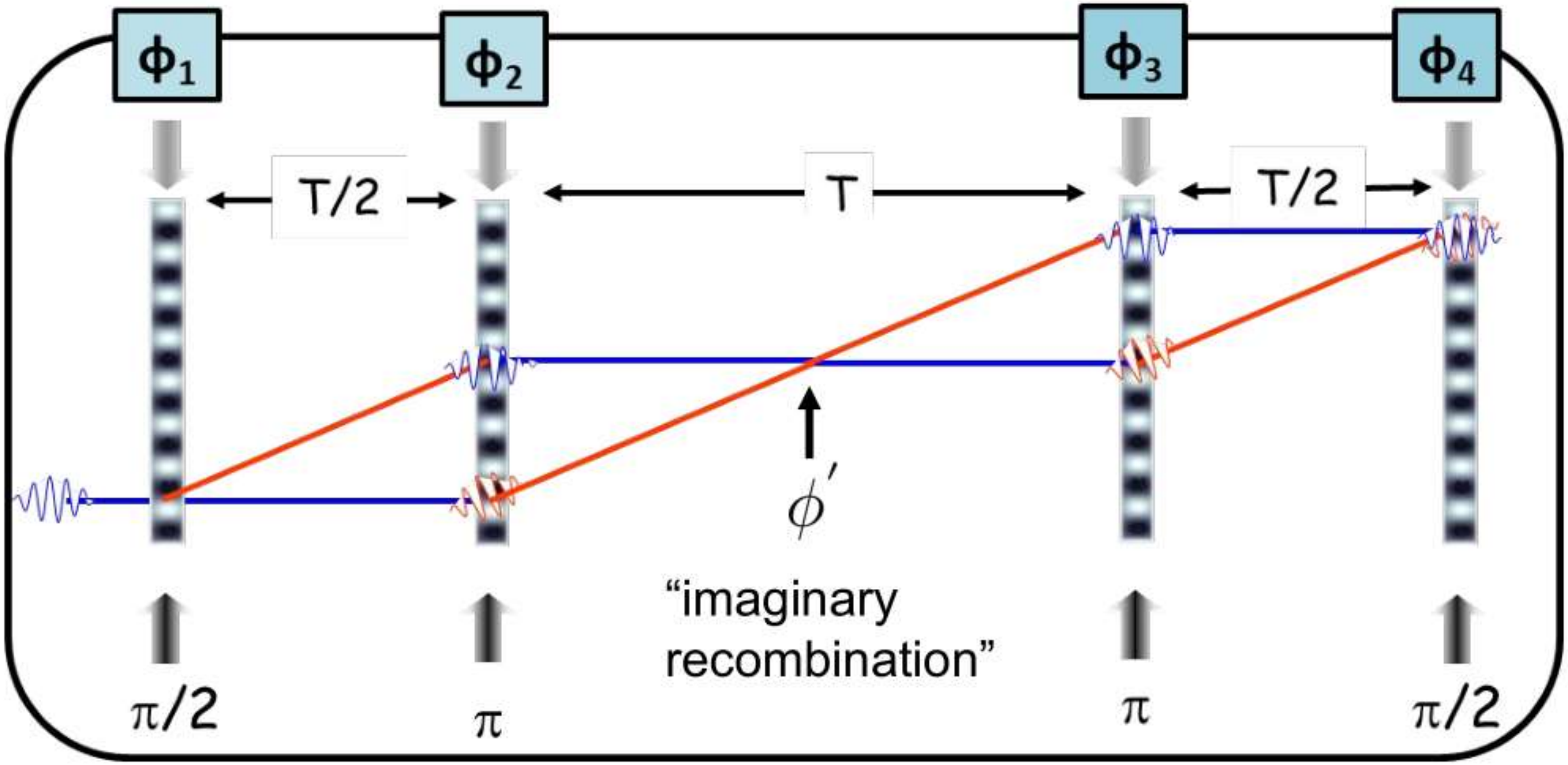


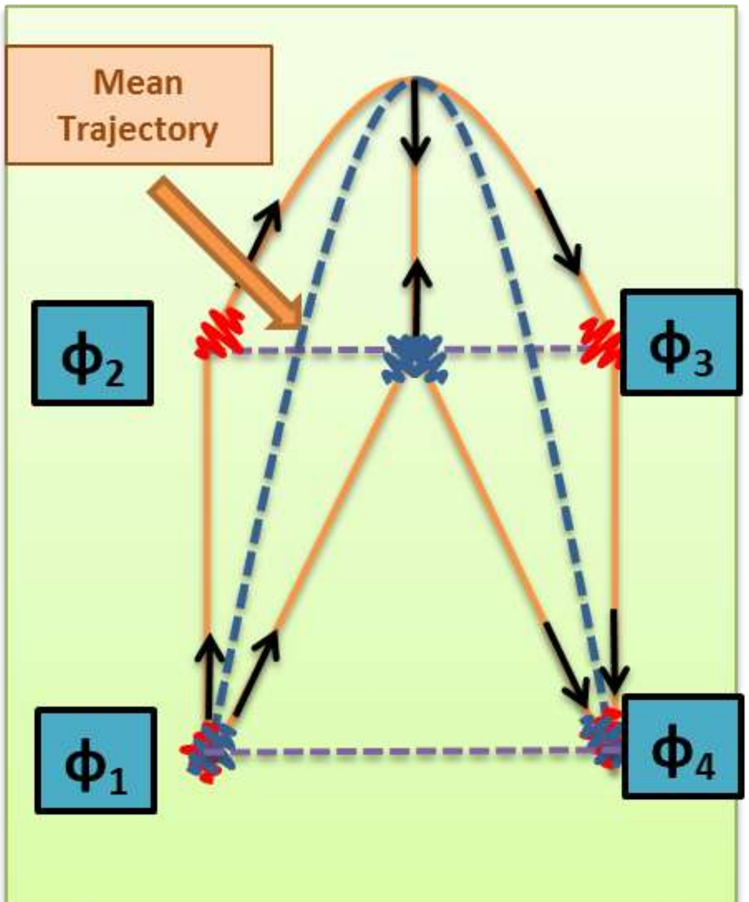
$$\Phi = \phi_1 - 2\phi_2 + \phi' - (\phi' - 2\phi_3 + \phi_4)$$

→ Zero sensitivity to DC acceleration (still sensitive to AC accelerations)

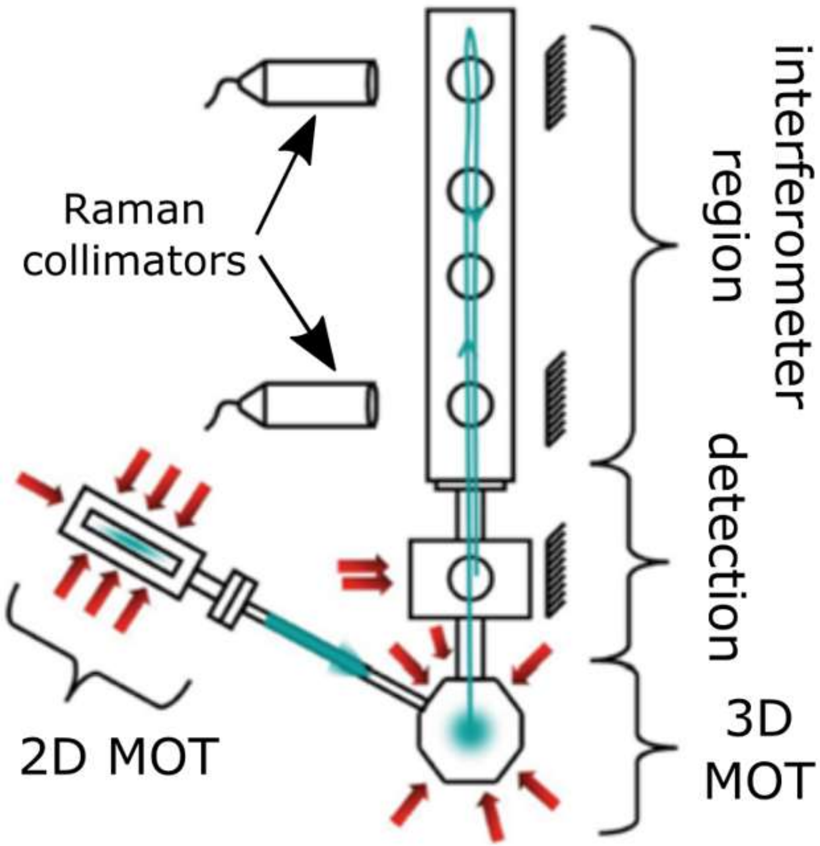
→ Pure rate gyroscope.

B. Canuel et al., PRL 97, 010402 (2006

4-light pulse gyroscope



« Butterfly » configuration



Scale factor of the gyroscope

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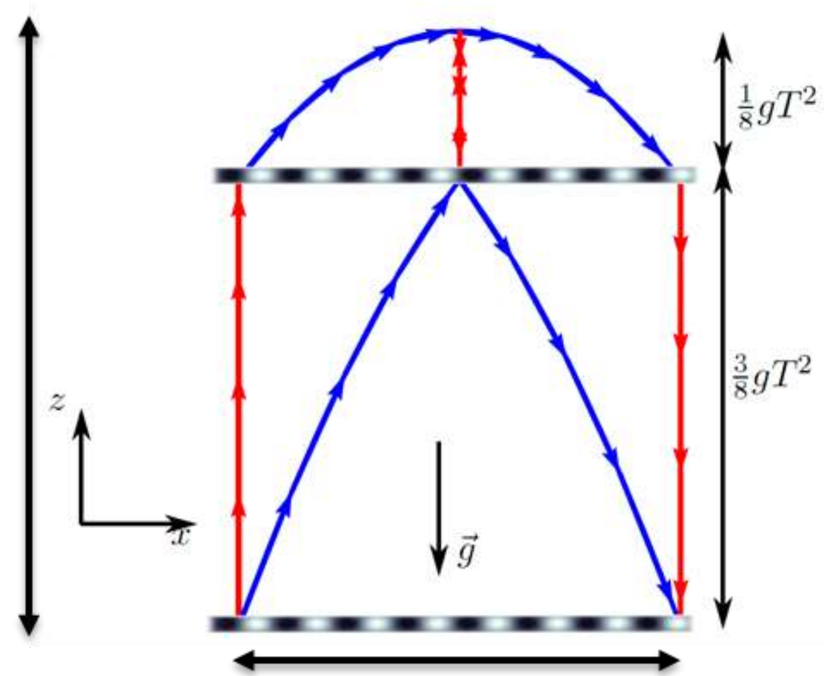
$$\Phi_\Omega = \frac{1}{2}\vec{k}_{\text{eff}} \cdot \left(\vec{g} \times \vec{\Omega}\right) T^3$$

Area : $A = \frac{1}{4}\frac{\hbar k_{eff} T^3 g}{M}$

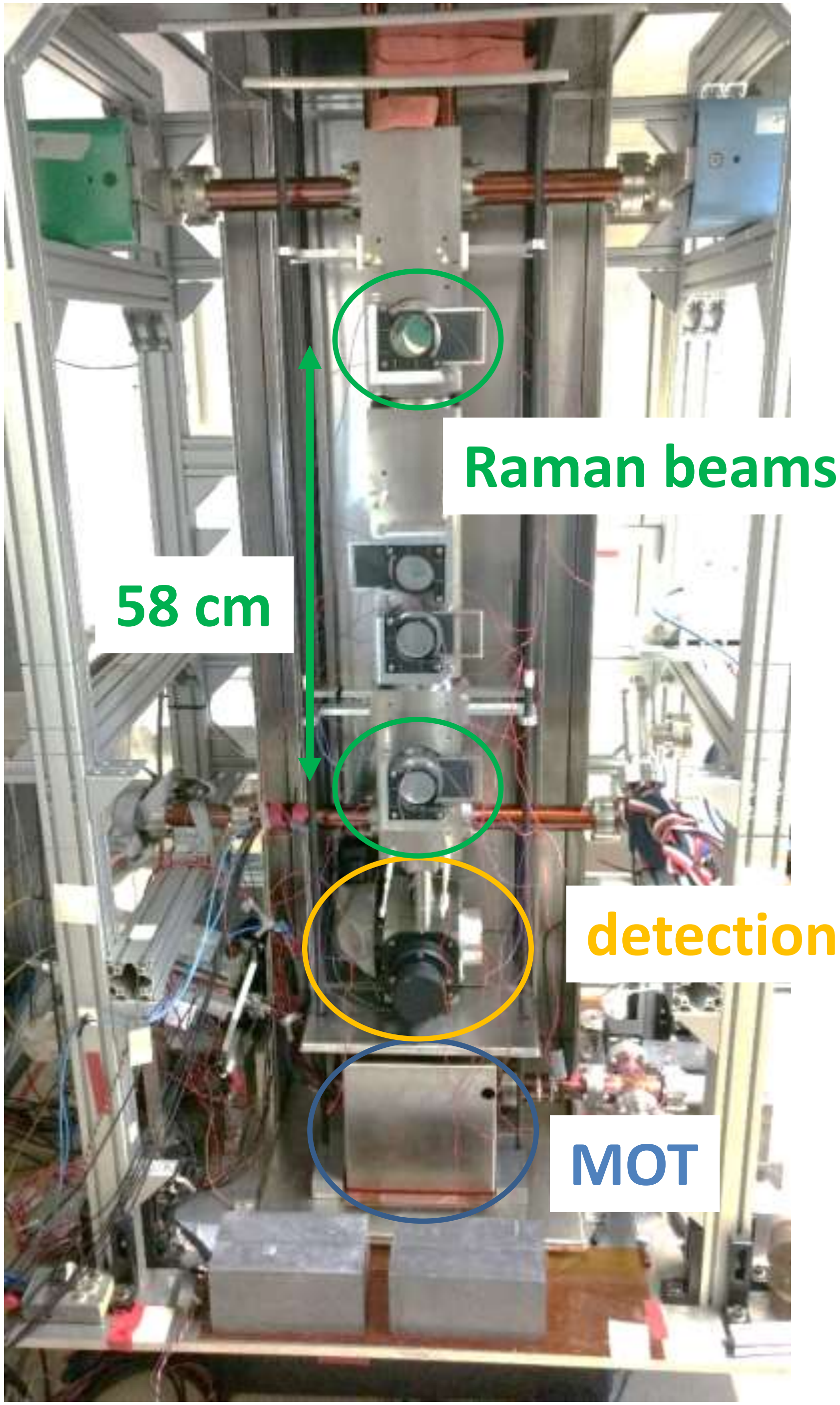
78 cm



2.8 mm

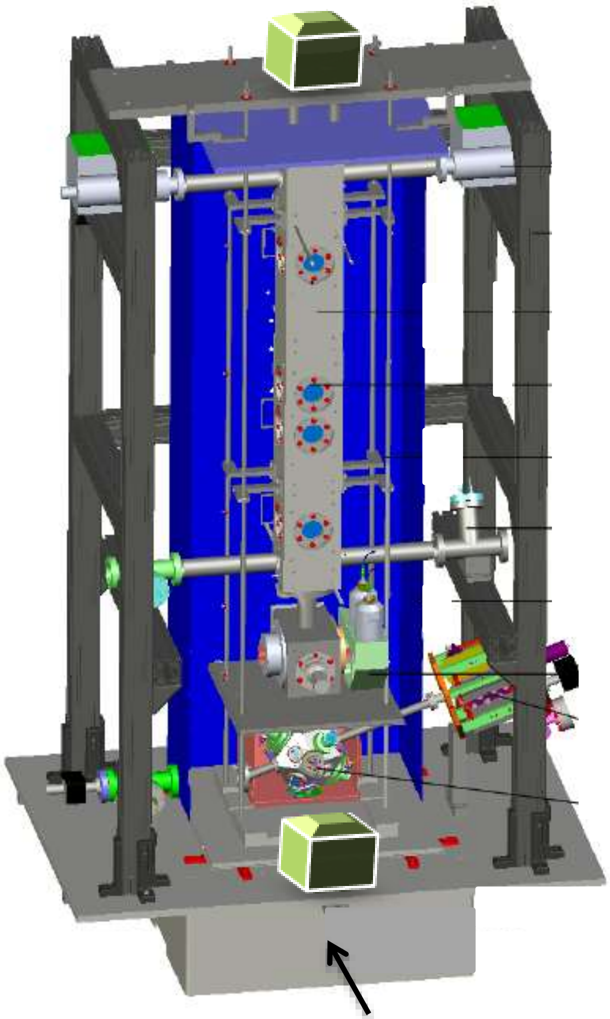
800 ms interrogation time → **11 cm^2 area**

Earth rotation rate (52 $\mu rad.s^{-1}$) → 220 rad phase shift

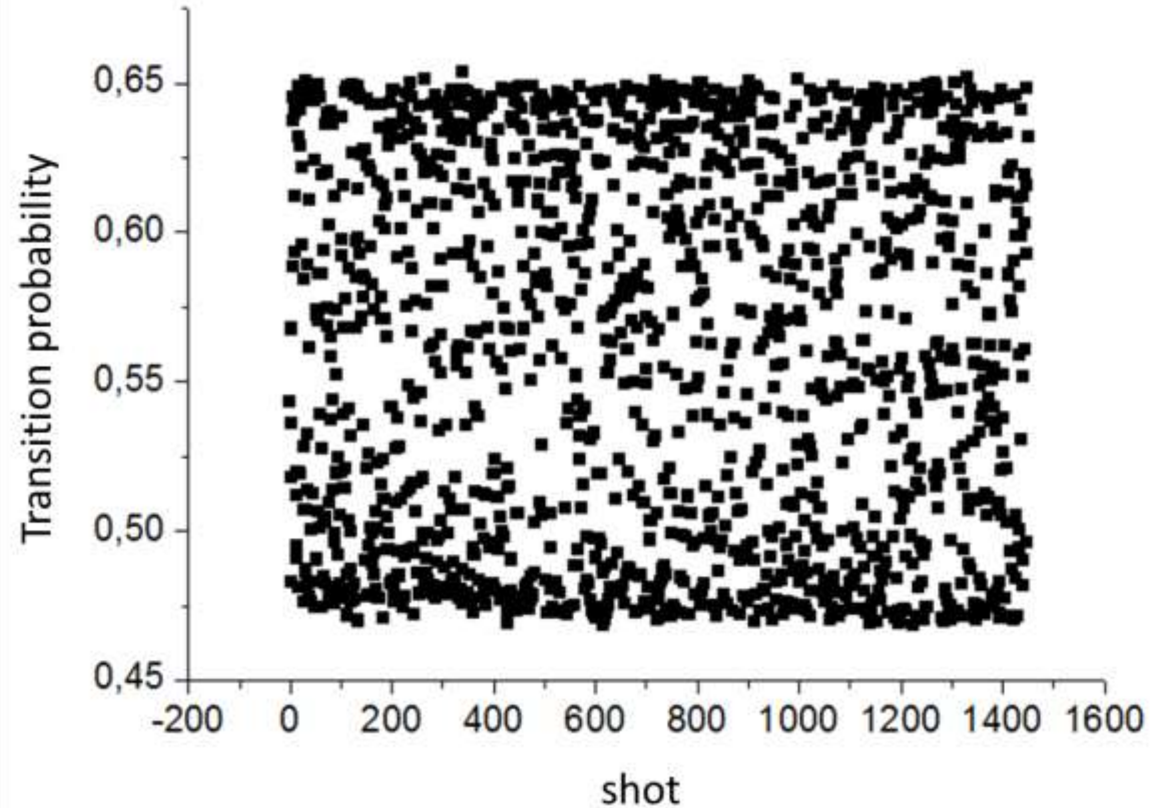


- Size: 1.5 m x 0.7 m x 0.7 m
- 10^7 Cesium atoms at 1.2 µK
- launched vertically at $5\ m.s^{-1}$
- passive isolation platform (> 0.4 Hz)
- 2 Magnetic shields
- …

Vibration noise rejection

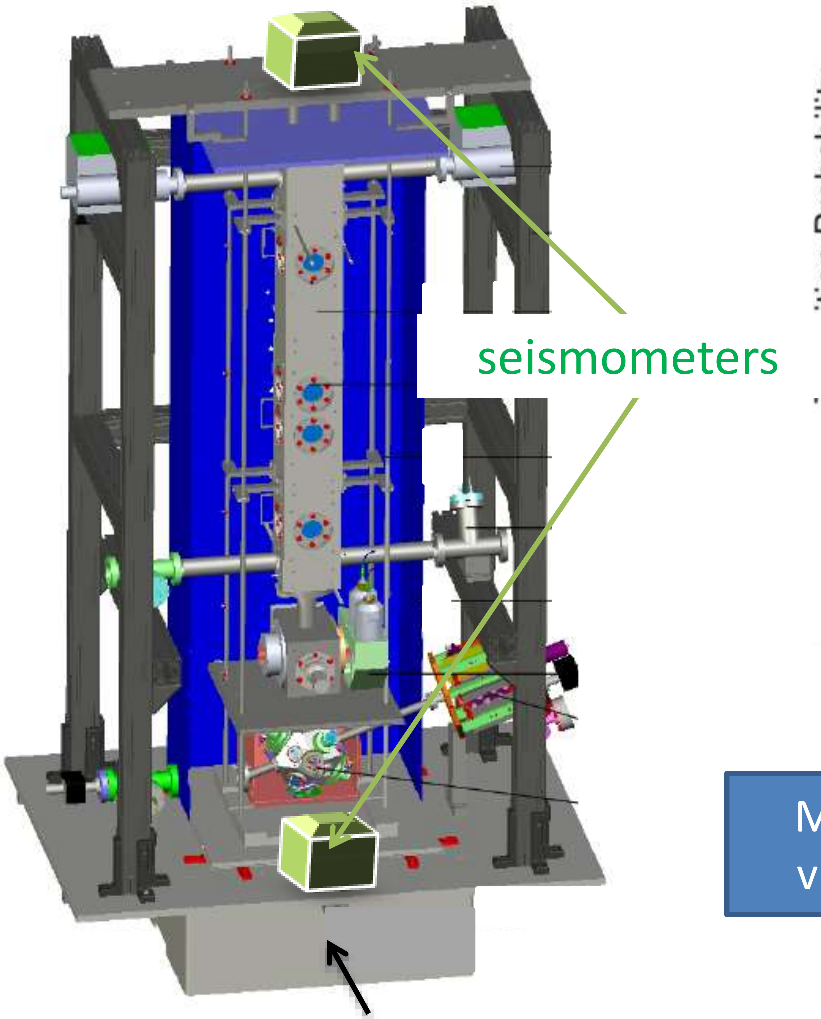


Vibration isolation platform

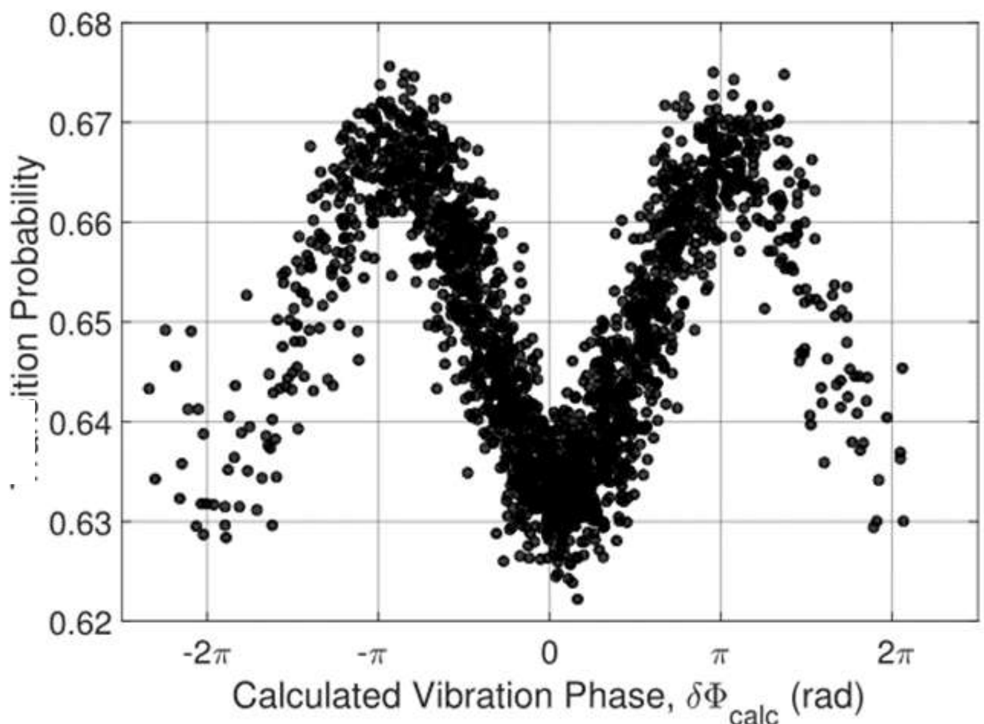


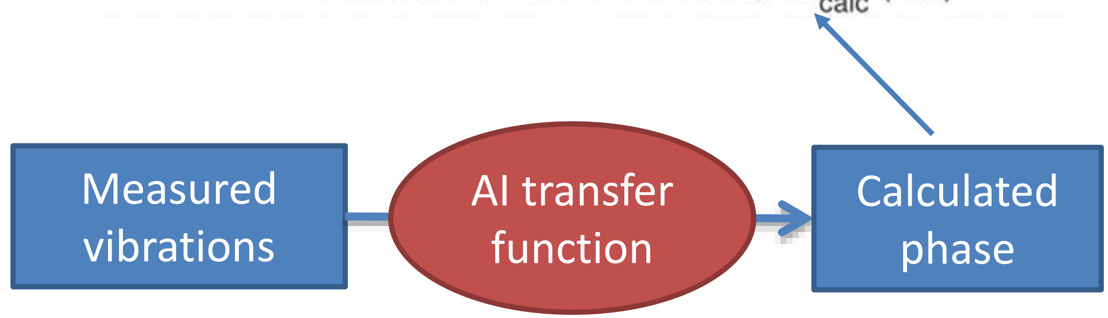
Vibration noise covers several rad rms

Vibration noise rejection



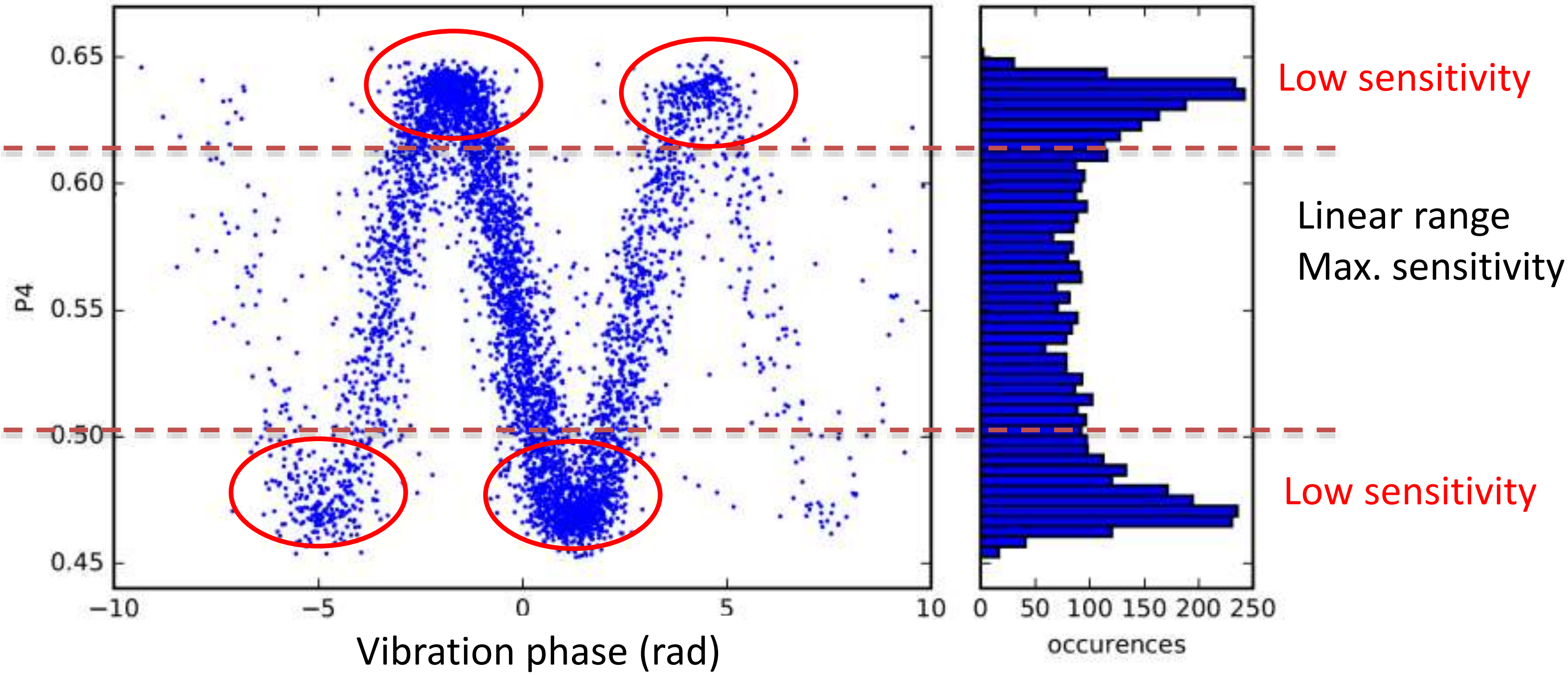
Vibration isolation platform





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

Operation in the linear regime



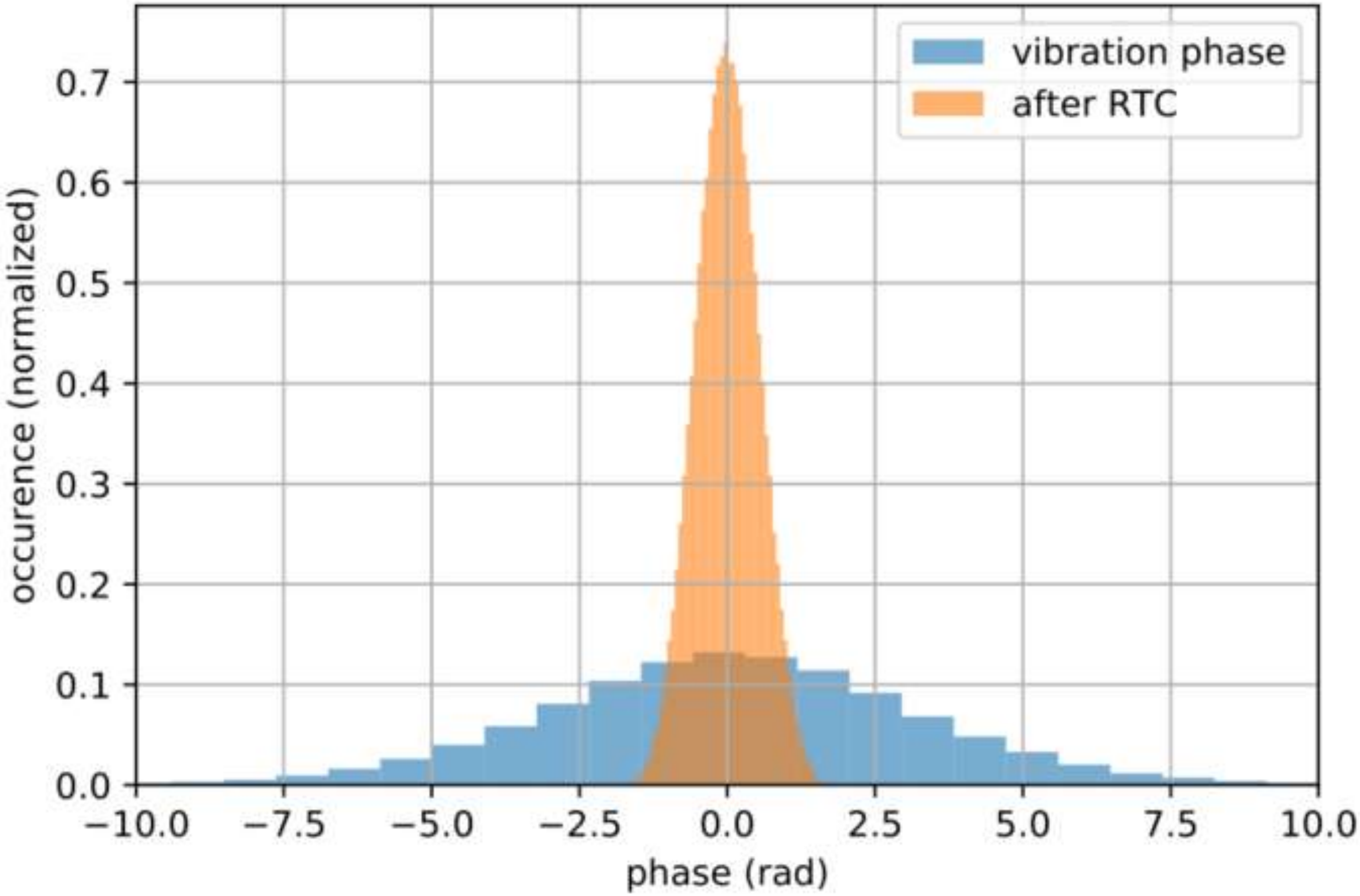
Real-time calculation of the vibration-induced phase (at each shot)

+ feedback to the Raman laser relative phase

+ lock at mid-fringe → **operation in the linear regime.**

J. Lautier et al, Appl. Phys. Lett. 105, 144102 (2014

Operation in the linear regime



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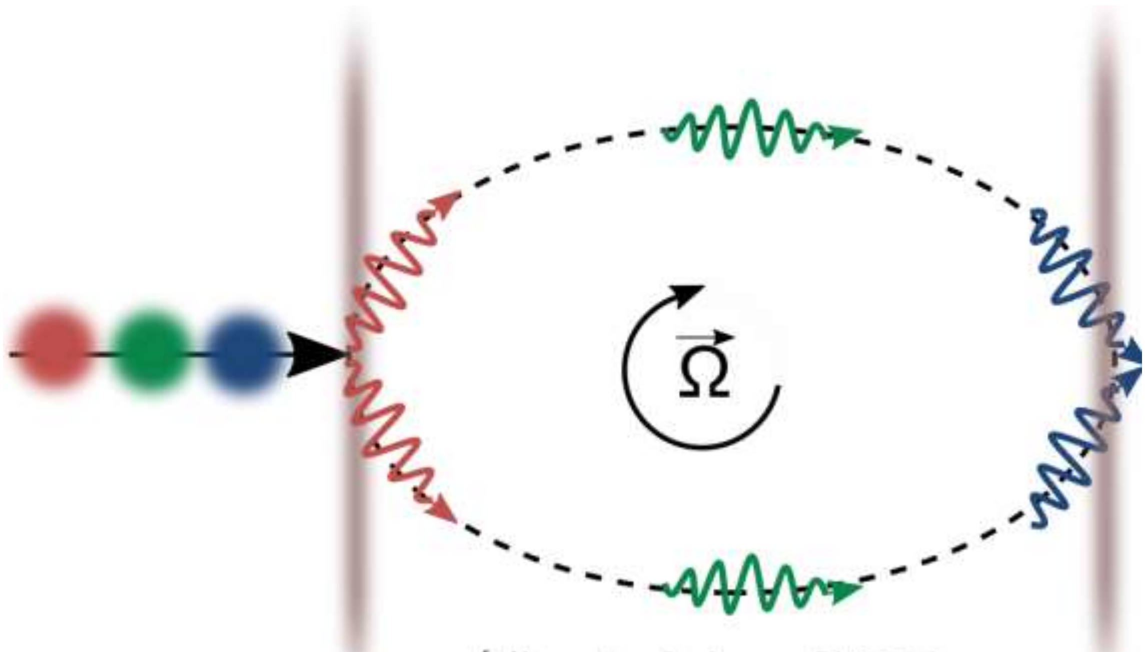
Removing dead times and increasing the sampling rates



I. Dutta et al., PRL **116**, 183003 (2016)

D. Savoie, M. Altorio et al, Science Advances, **eaau7948** (2018)

Dead times in quantum sensors

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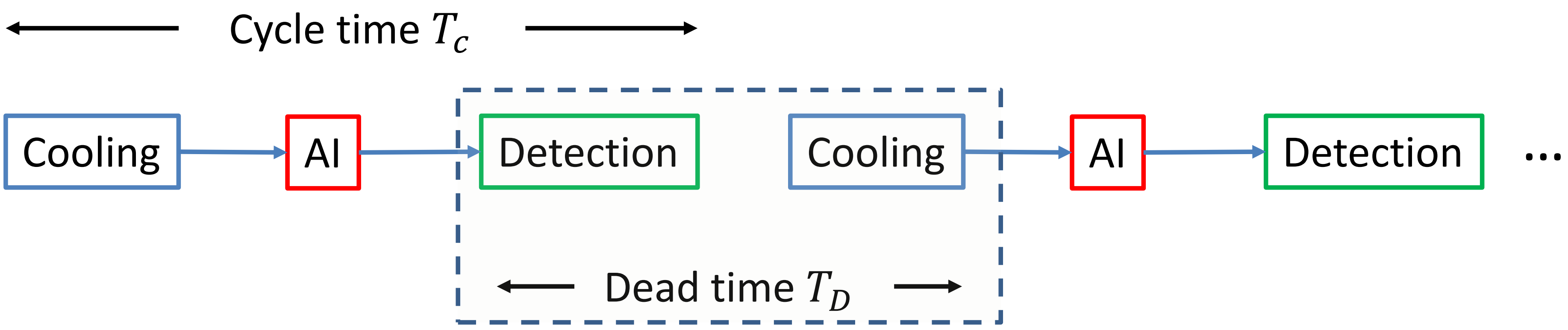
Sequential operation of cold atom interferometers:

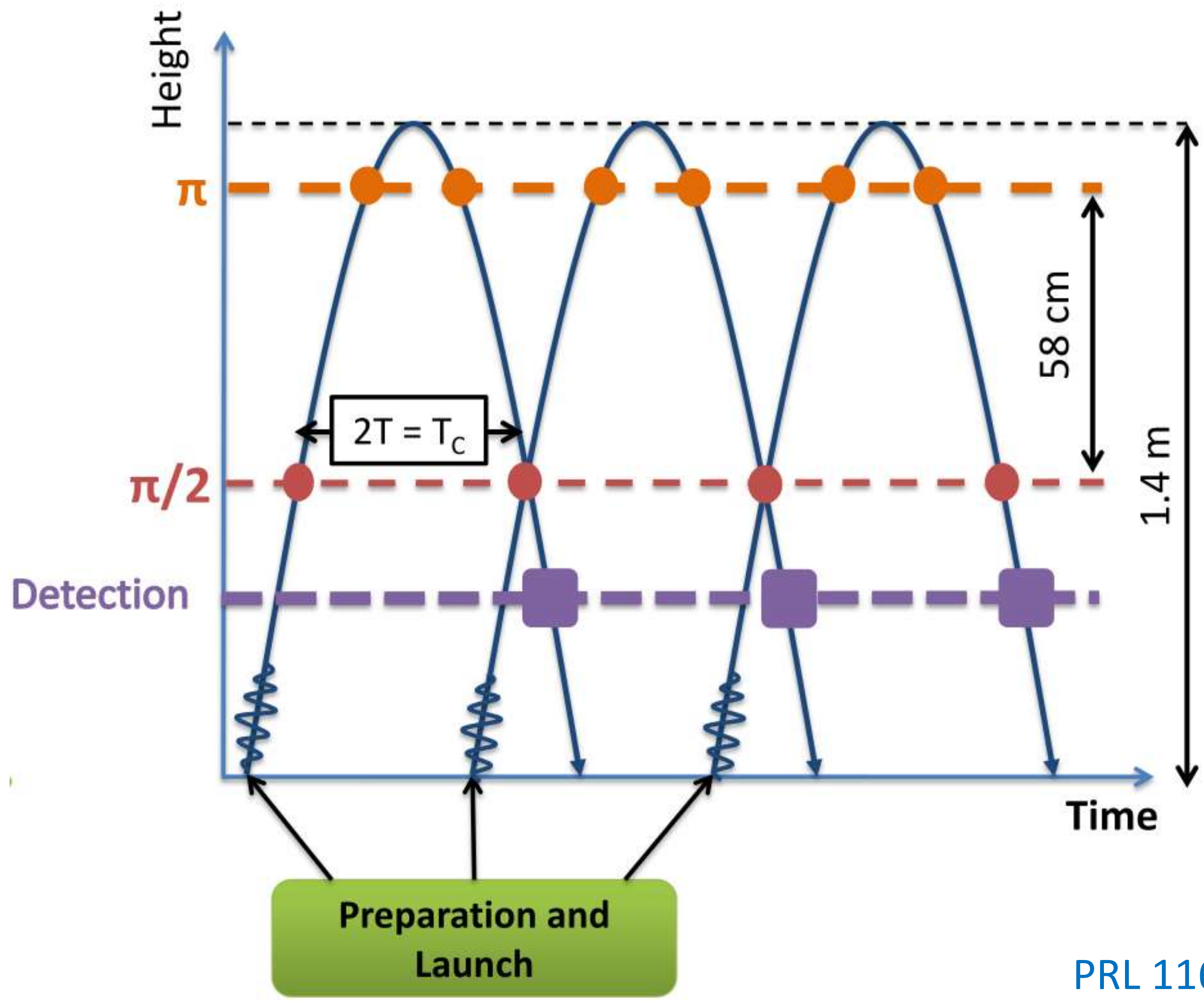


Dead times → (inertial) noise aliasing + loss of information

→ prevents from reaching the quantum noise limit.

Ingredient # 1: Continuous sensor

Joint interrogation: prepare the cold atoms and operate the interferometer in parallel

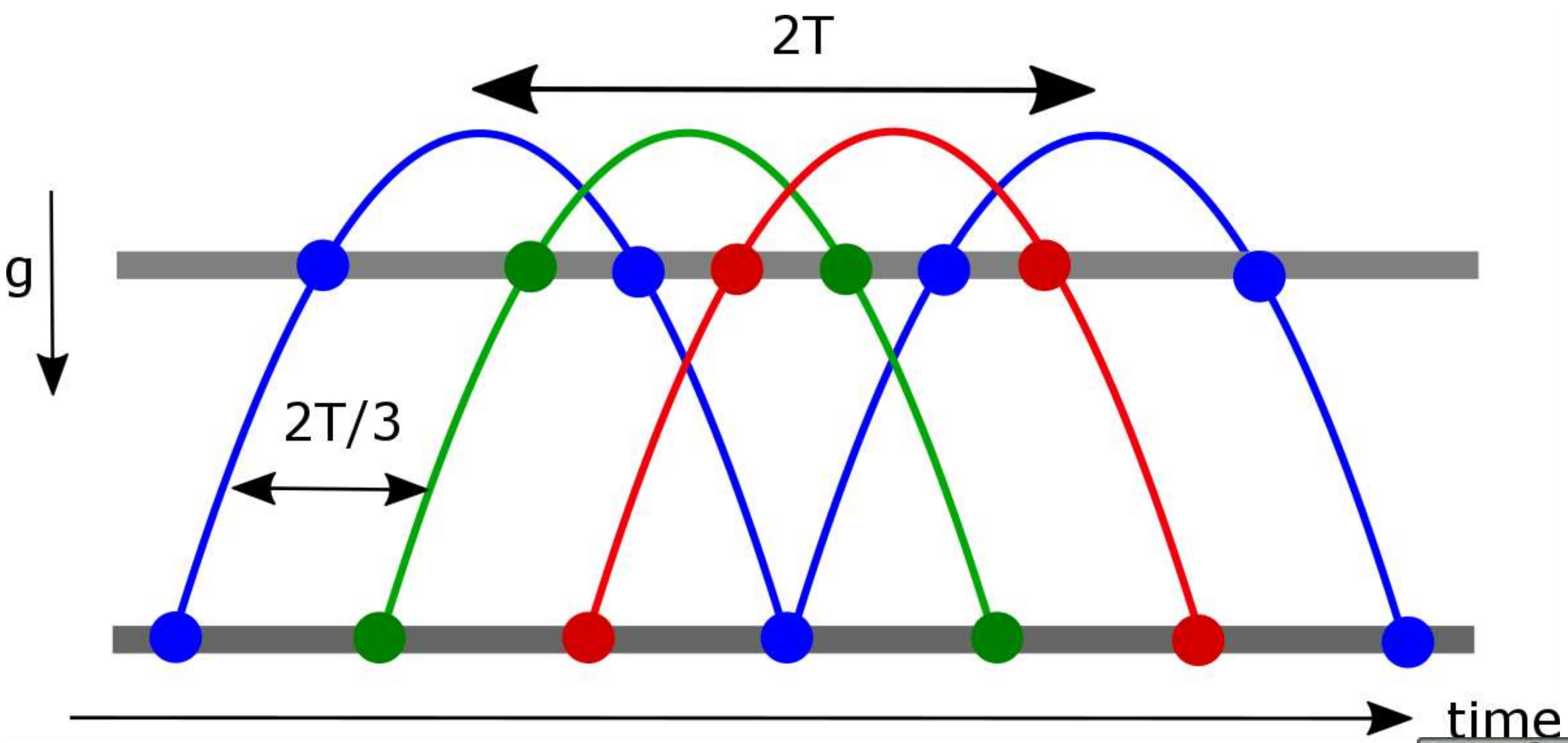


PRL 116, 183003 (2016)

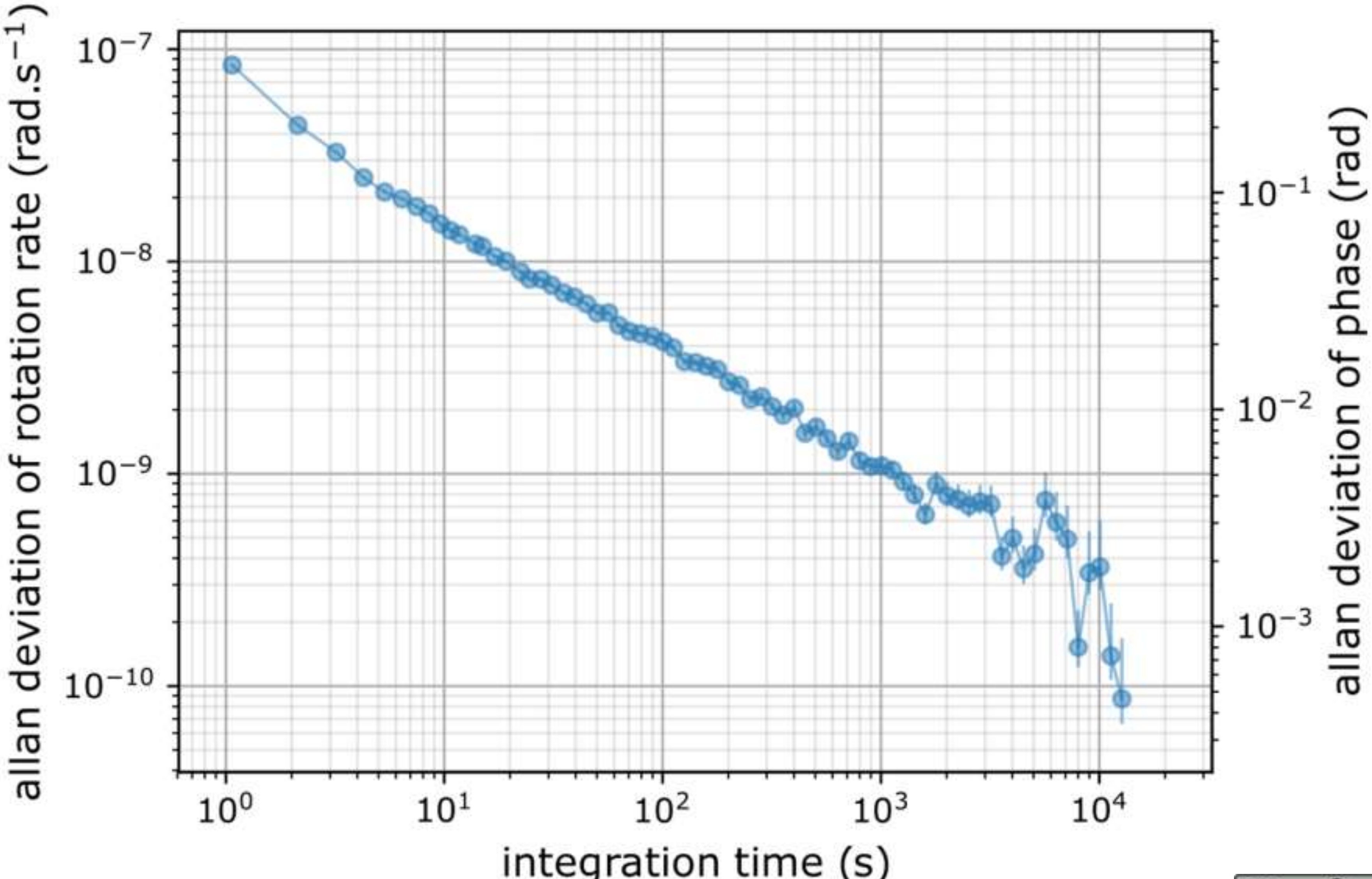
Ingredient #2: interleaving

We interleave several sequences of long-T interferometers

→ $T_c = 2T/3 = 267\ ms$ ($3.75\ Hz$ cycling frequency)

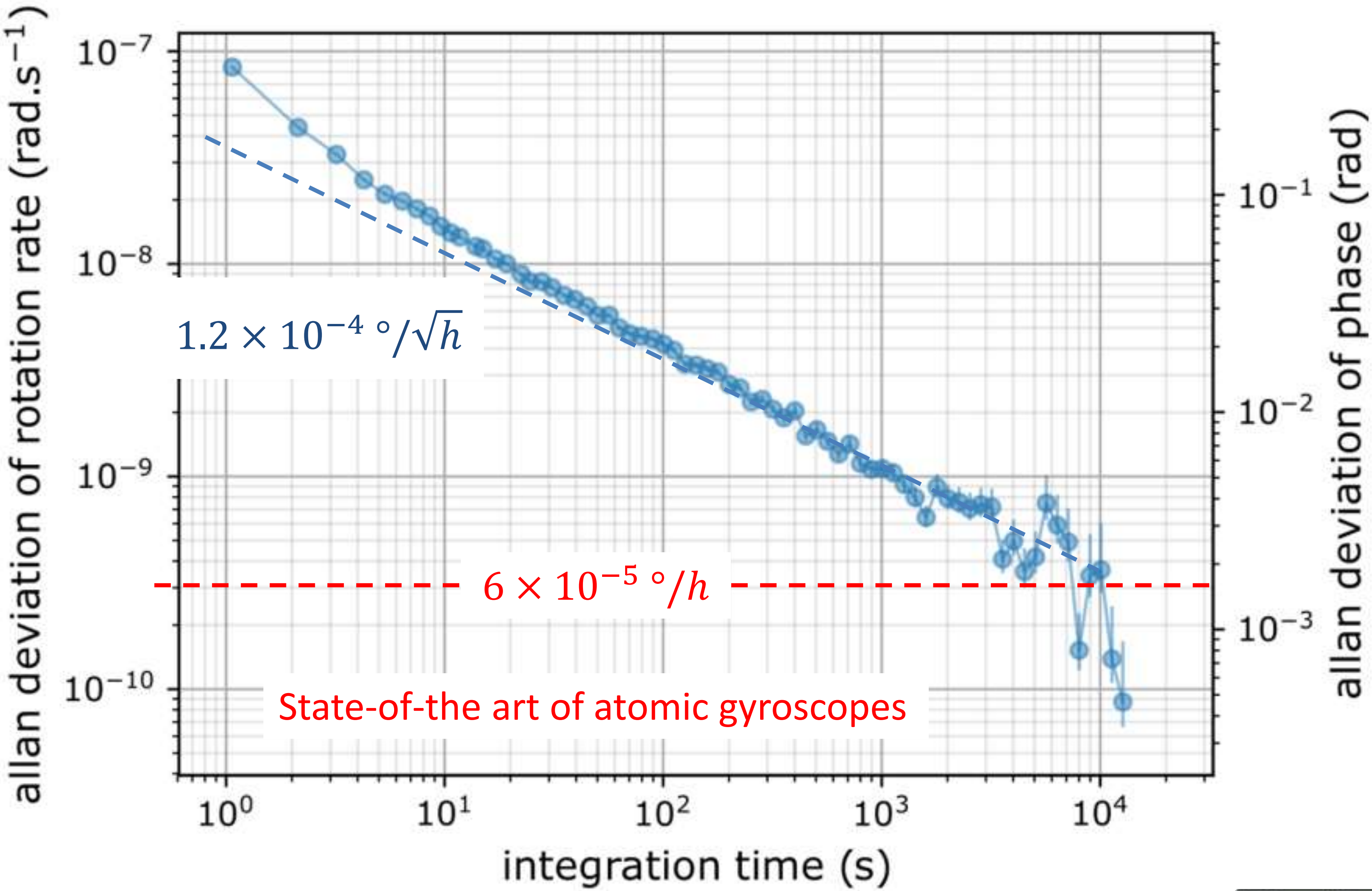


Gyroscope stability



Savoie et al, Science Advances (2018)

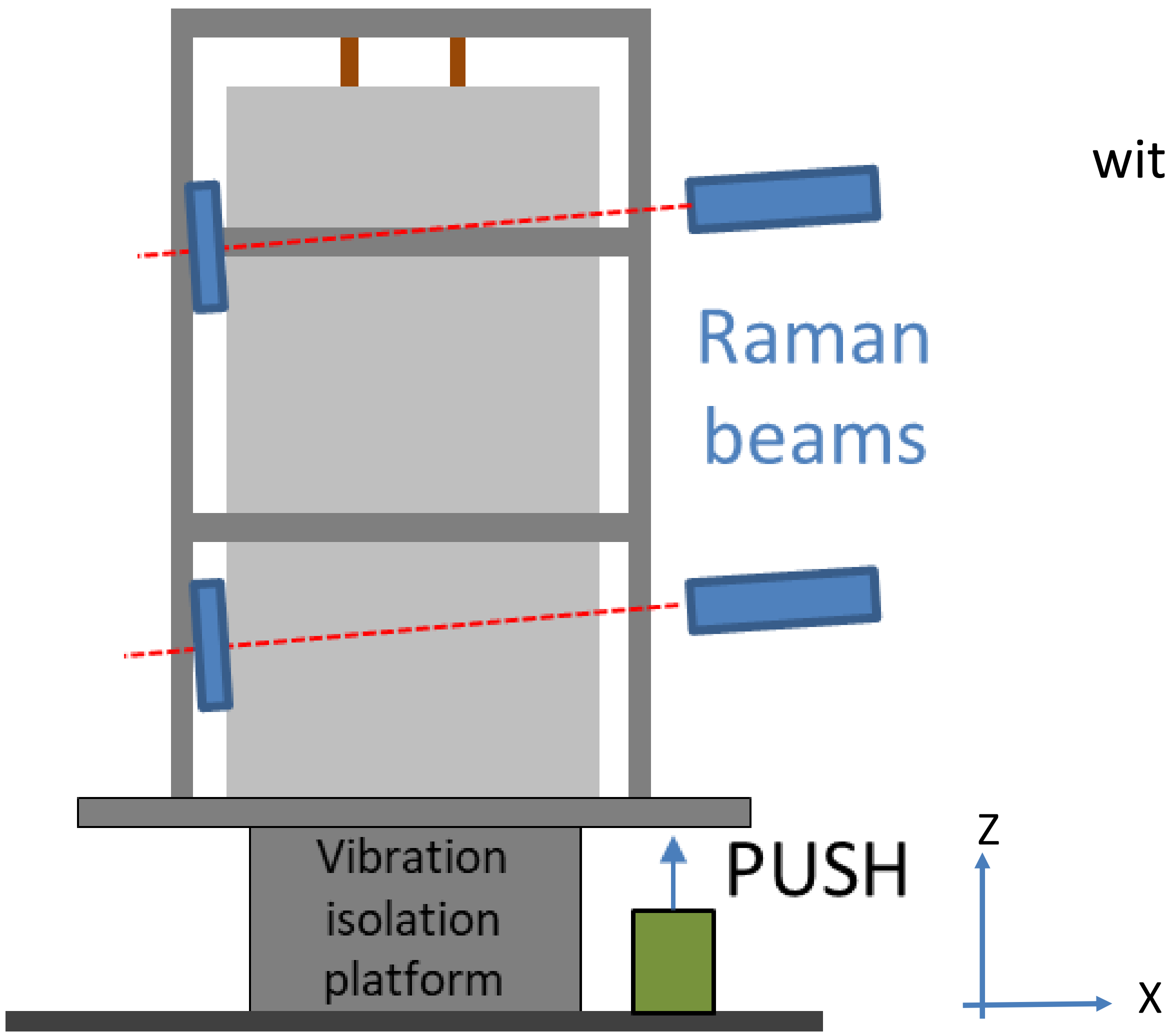
Gyroscope stability



Savoie et al, Science Advances (2018) *M. Altorio et al, arxiv: 1912.04793*

Dynamic rotation rates

Apply sinusoïdal modulations of the rotation rate

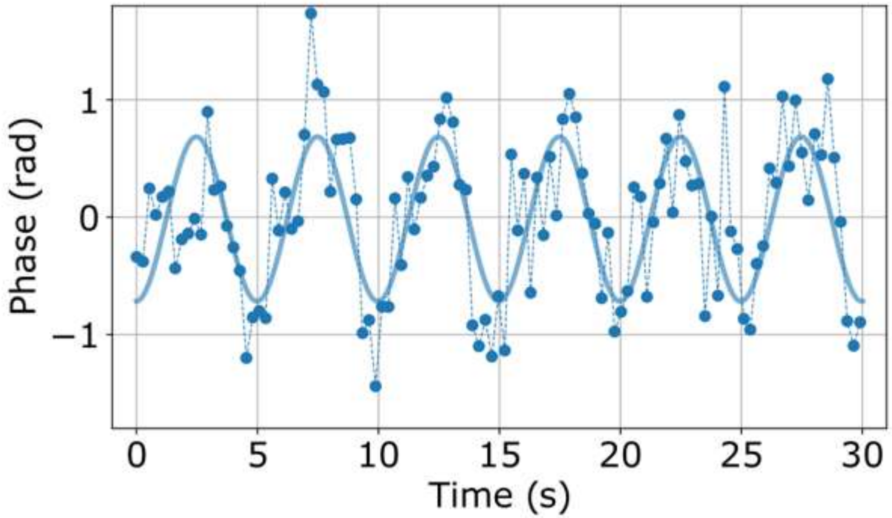


$$\vec{\Omega} = \Omega_0 \cos(\omega t)\vec{u_y}$$

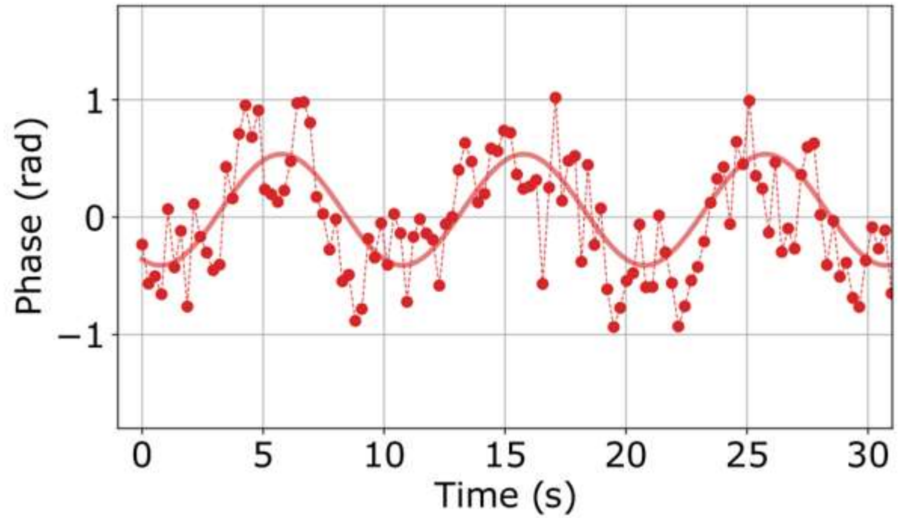
with $\Omega_0 \sim$ few $10^{-7}\, rad.s^{-1}$

Dynamic rotation rates

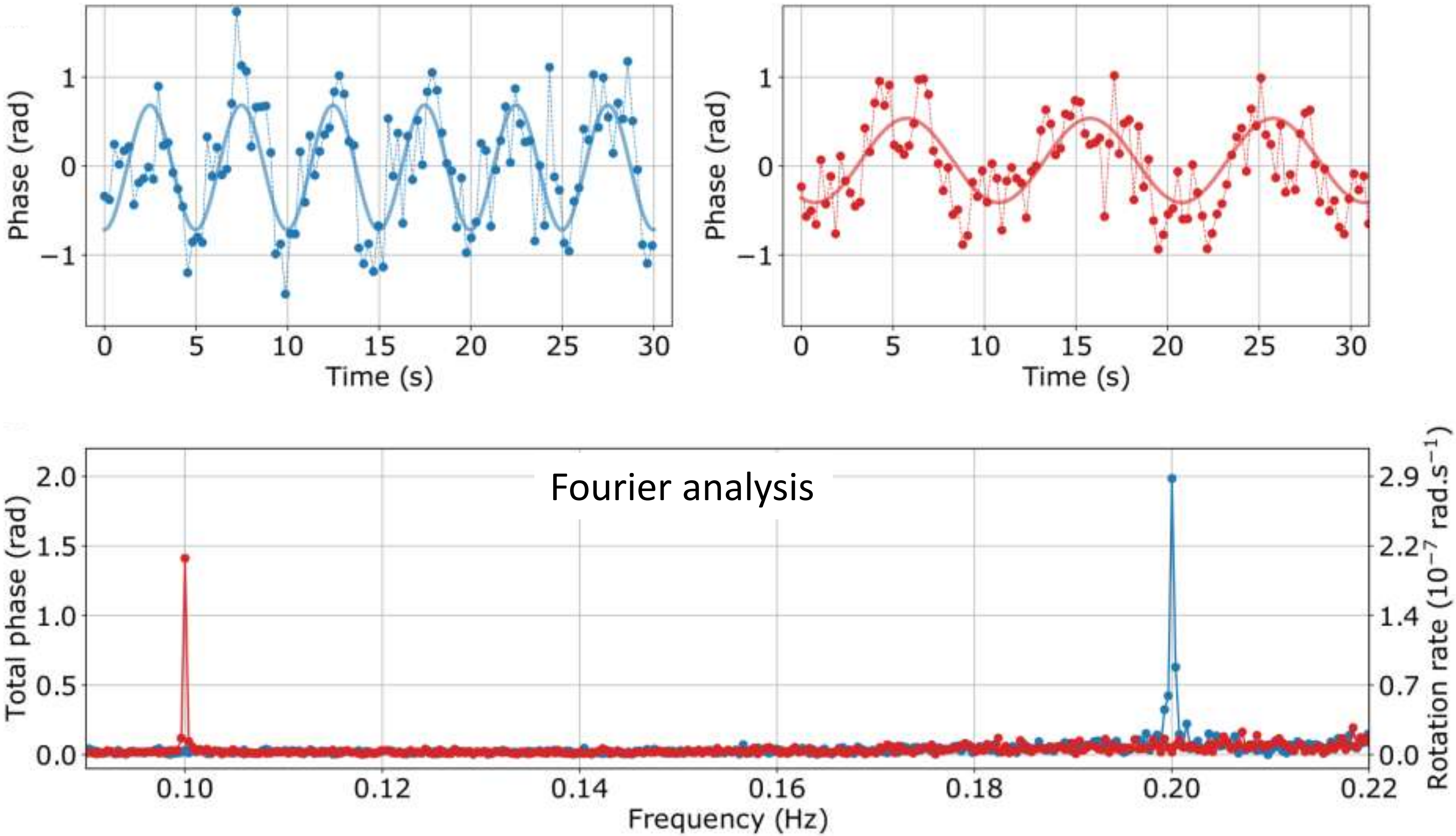
Modulation with 5 s period



Modulation with 10 s period



Dynamic rotation rates



Our measurements match with the expectation within 5% accuracy

Next generation of gyroscope

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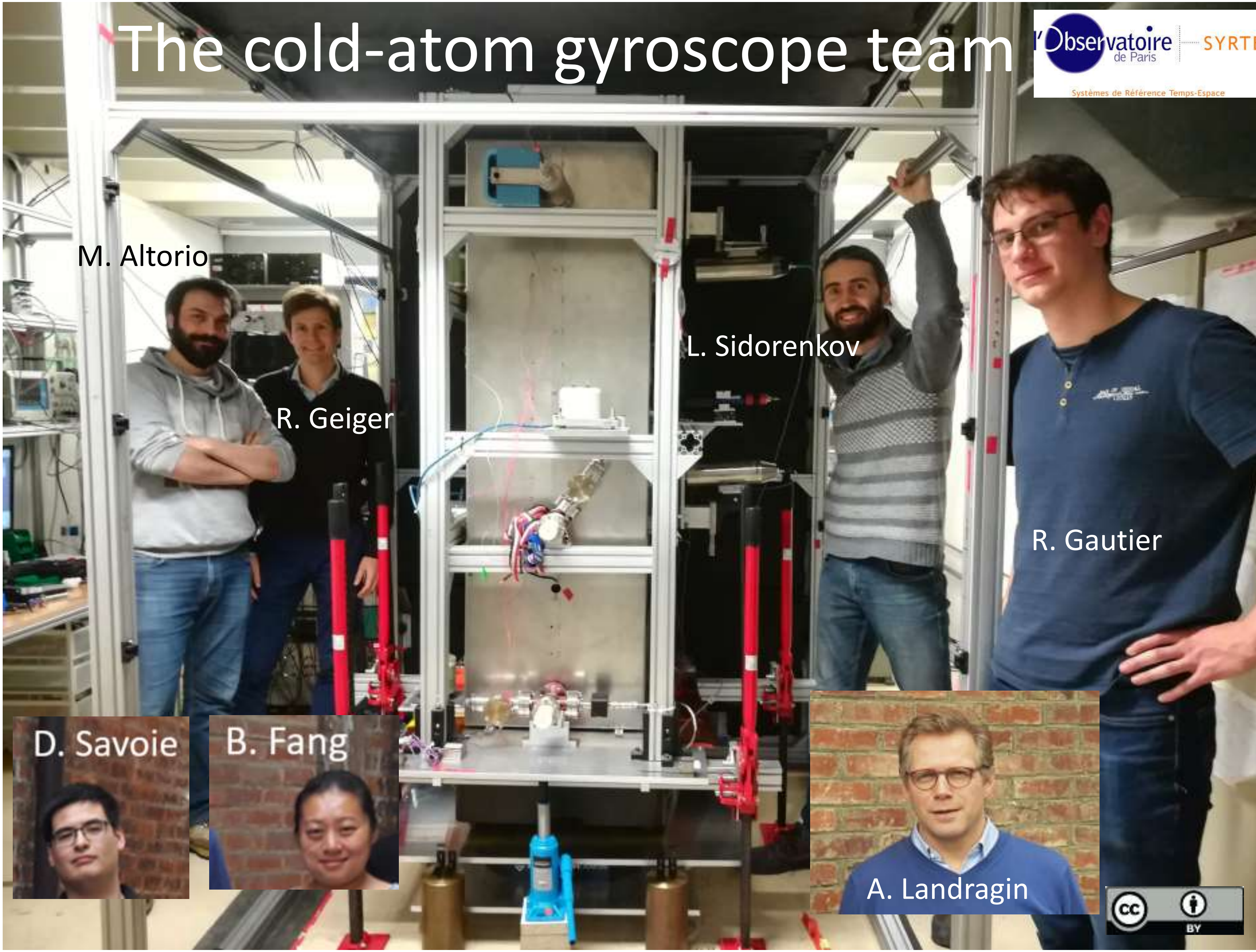
- Current sensitivity to ground rotations (detection noise limit): $5\ nrad.s^{-1}/\sqrt{Hz}$
- Maximum sampling rate: 4 Hz
- One axis gyro (horizontal)

Design of a new setup

- Two axes (horizontal)
- Improved detection noise floor: $0.1\ nrad.s^{-1}/\sqrt{Hz}$
- Sampling rate of 10 Hz
- Improved stability: operation during several days


The cold-atom gyroscope team
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M. Altorio
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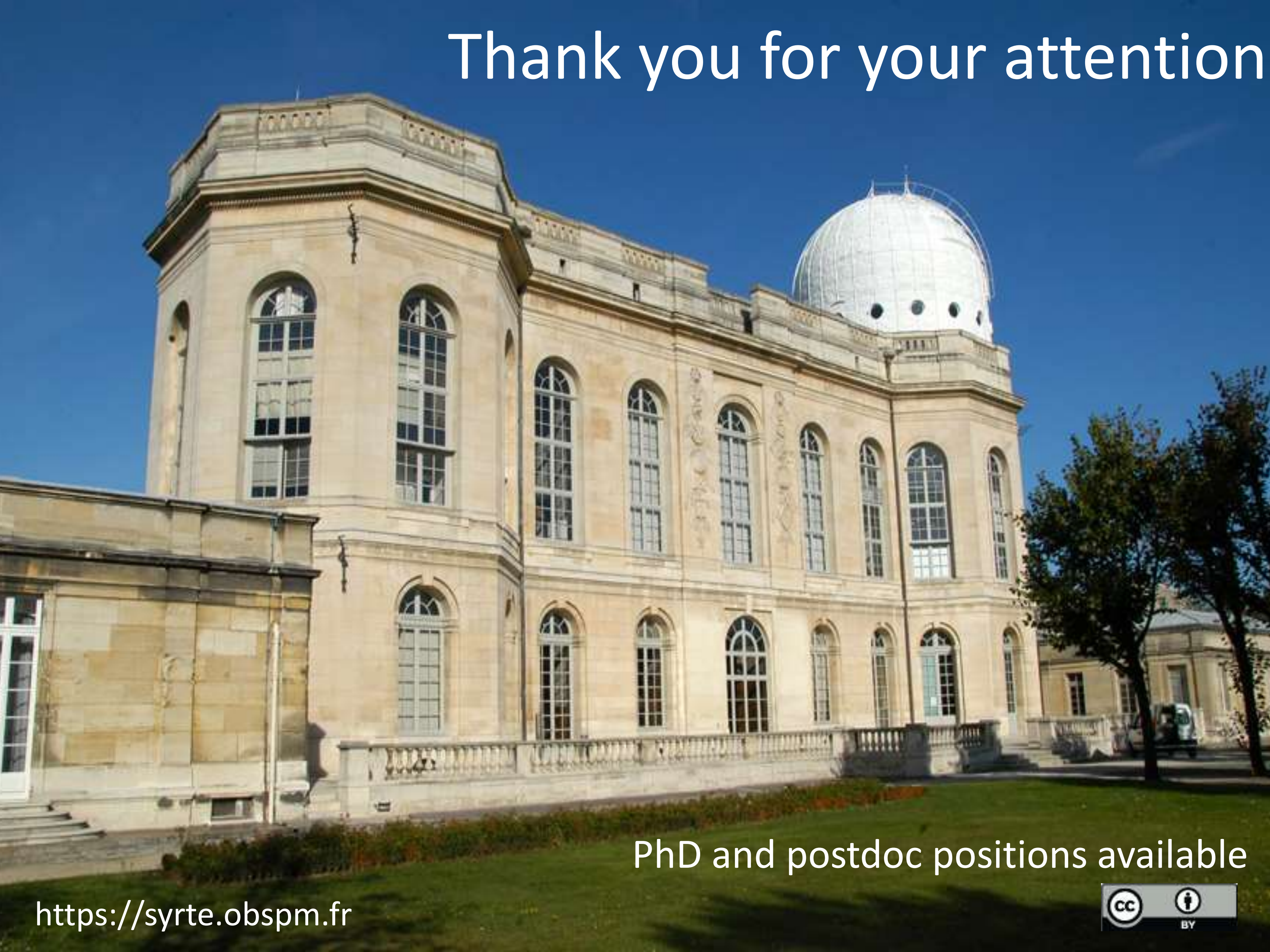
R. Gautier
D. Savoie
B. Fang
A. Landragin

Thank you for your attention



PhD and postdoc positions available

https://syrte.obspm.fr

Dynamic rotation rates

$$\Phi = \frac{1}{2}\vec{k}_{\mathrm{eff}} \cdot (\vec{\Omega}_E \times \vec{g})T^3$$ (usual term)

$$+ \frac{3}{4}\vec{k}_{\mathrm{eff}} \cdot (\vec{\Omega}_F \times \vec{g} + \xcancel{\vec{\Omega}_E \times \vec{a}} + \xcancel{\vec{\Omega}_F \times \vec{a}})T^3$$ (modulation term)

$$\boxed{\Phi_{\mathrm{dyn}}(t) \simeq \frac{3}{4}\vec{k}_{\mathrm{eff}} \cdot (\vec{\Omega}_F(t) \times \vec{g})T^3}$$