Interleaved Matter-wave Gyroscope with $2 \times 10^{-10}\ rad.s^{-1}$ Stability

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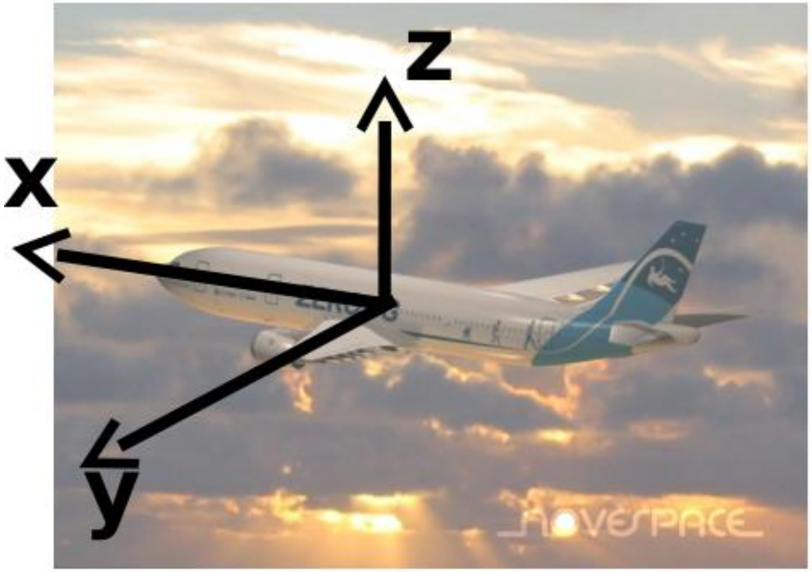
Outline

- Applications of cold-atom inertial sensors
- The SYRTE cold-atom gyroscope
- Interleaved operation without dead times
- Gyroscope sensitivity and stability

Applications of cold-atom inertial sensors

- **Navigation** :

→ onboard accelerometers, gyroscopes, gravimeters, gradiometers



Six-axis inertial sensor

Canuel et al, PRL 97, 010402 (2006)

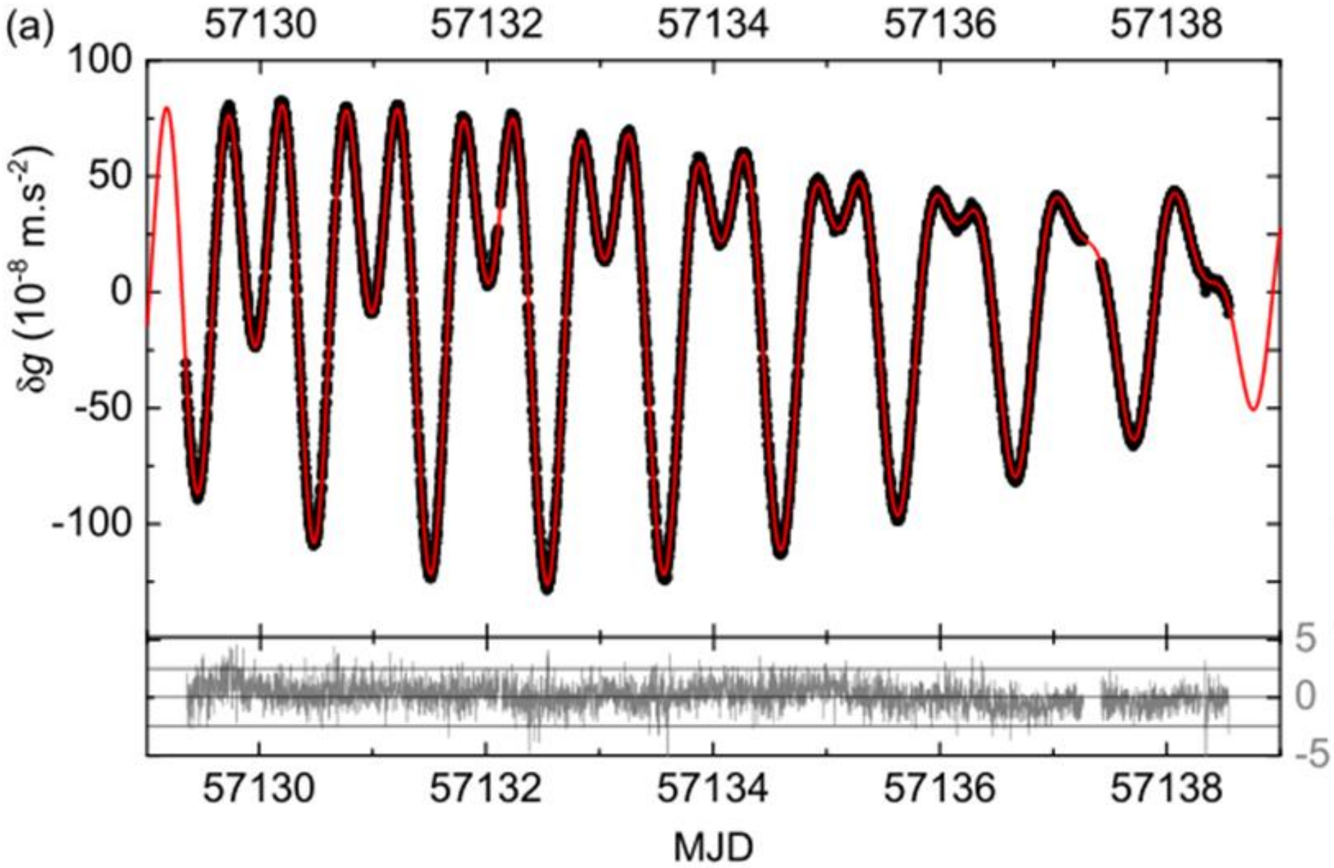
Navigation with a cold-atom gravimeter:

Bidel et al, Nature Communications 9, 627 (2018)

The duration of navigation is given by the **stability** of the sensor.

Applications of cold atom inertial sensors

- **Geosciences**: monitoring global phenomena (e.g. $\vec{\Omega}_{Earth}(t), \vec{g}(t)$)



Absolute gravimetry

Fang et al,

arXiv:1601.06082

(SYRTE, Paris)

Freier et al,

arXiv:1512.05660

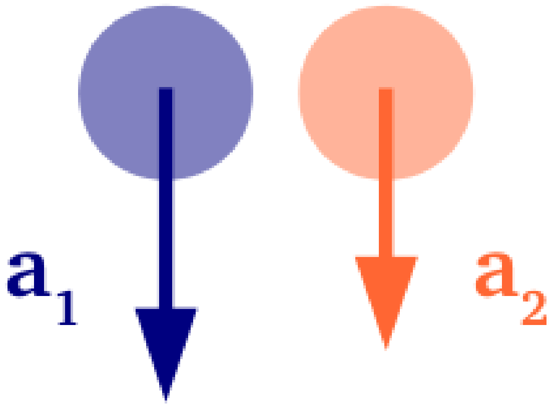
(HU Berlin)

Best atomic gravimeters: stability $< 10^{-10}\ g$ and accuracy of $\sim 3 \times 10^{-9}\ g$

Applications of cold atom inertial sensors

- **Fundamental physics**

Universality of Free Fall



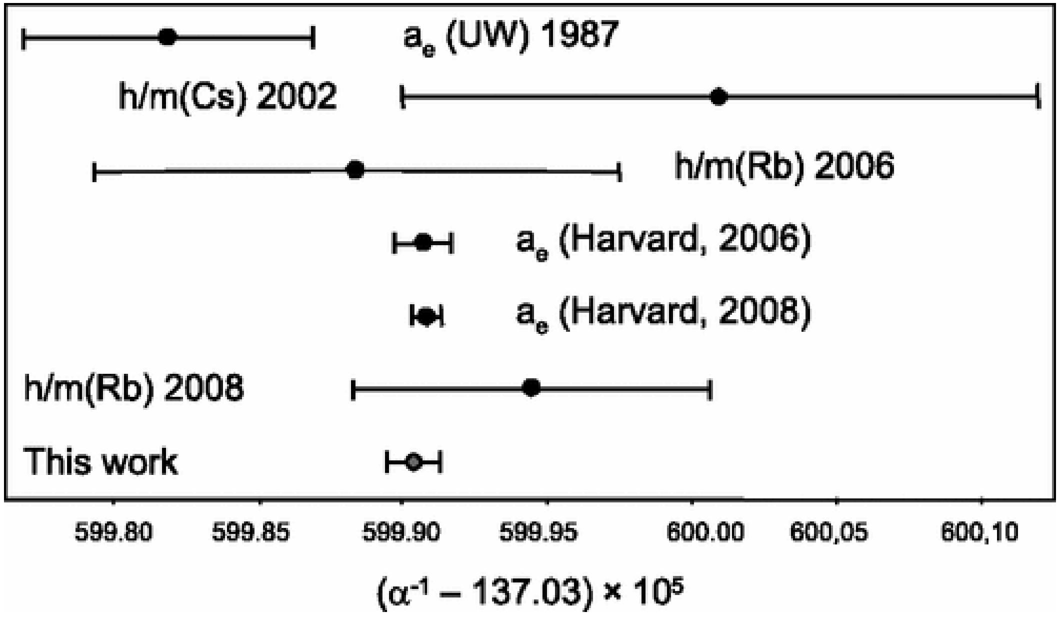
Zhou et al, PRL (2015)

Aguilera et al, CQG (2014)

Rosi et al, Nature Commun. (2017)

Accuracy $\sim$ few 10^{-9} on $\delta a/a$

Test of QED (measurement of recoil velocity)



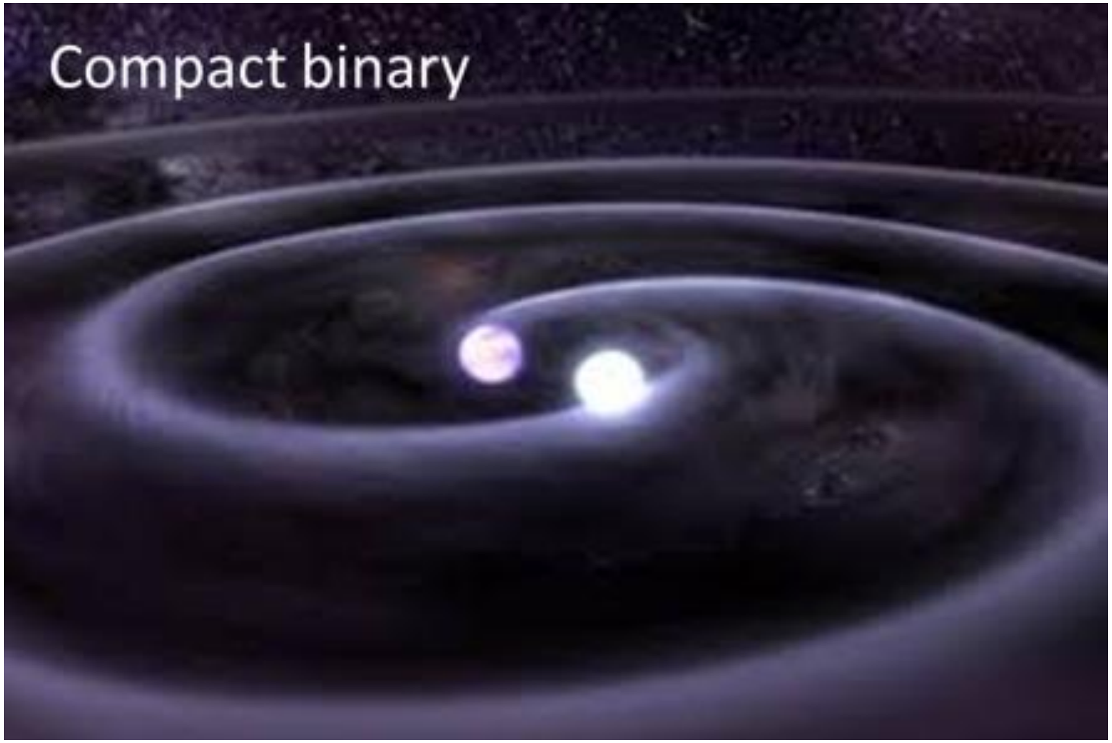
Bouchendira et al, PRL (2011)

6×10^{-10} relative accuracy on α

Applications of cold atom inertial sensors

- **Gravitational wave astronomy ($\sim 0.1 - 10$ Hz band)**

→ Use free falling atoms instead of suspended mirrors to detect changes in laser phase

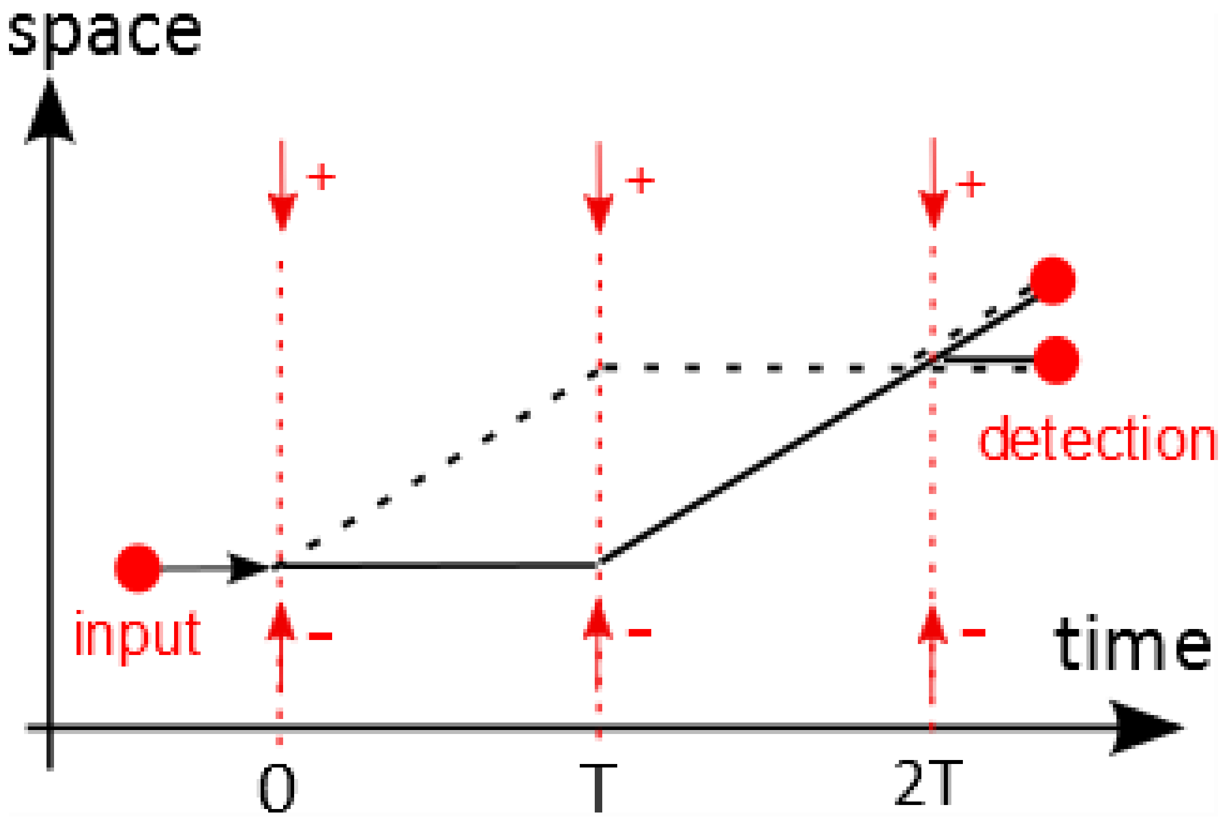


Hogan et al, PRA (2016)

Chaibi et al, 2016 PRD (2016)

Principle of Atom Interferometry

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

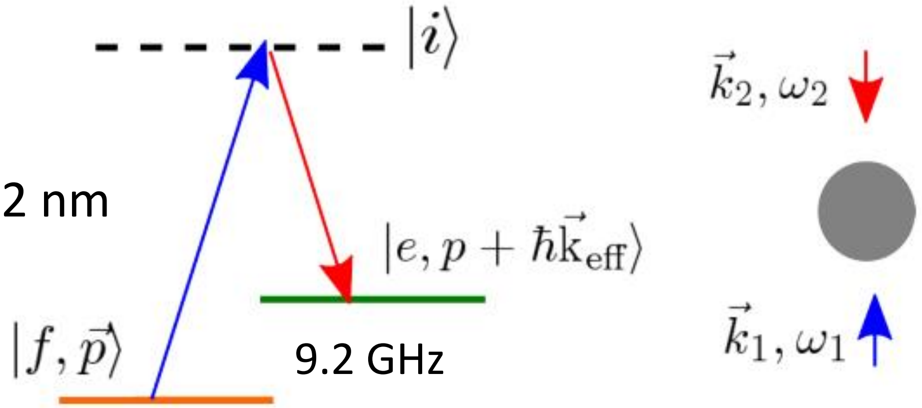


Two-wave interference :

$$P = P_0 + A\cos(\Delta\Phi)$$

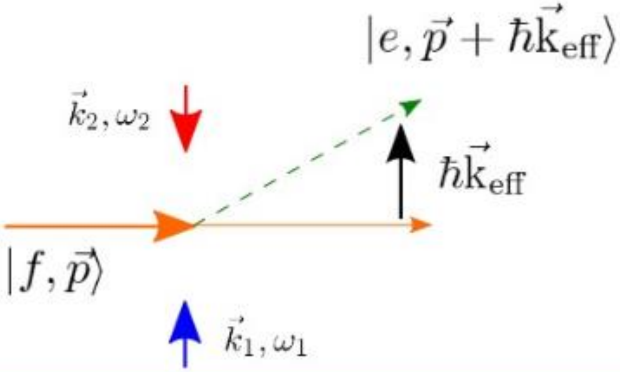
Stimulated Raman transitions

Cesium atom, D_2 line @ 852 nm



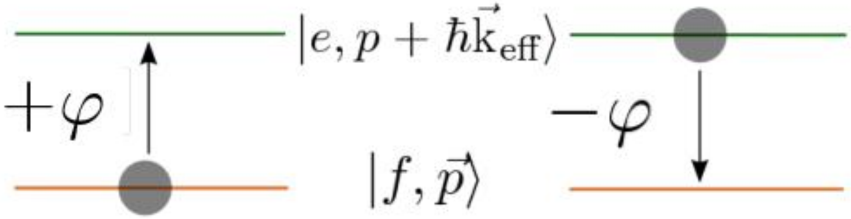
Momentum transfer

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

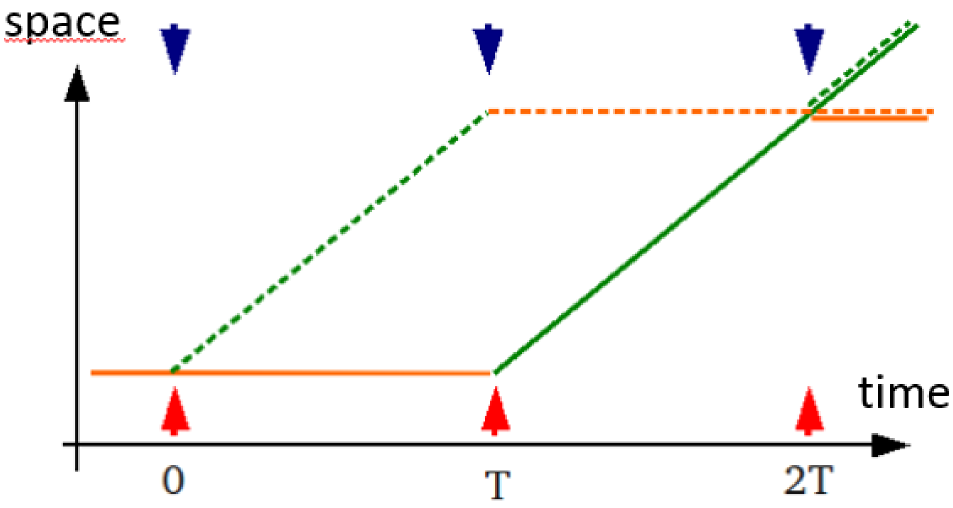


Laser phase difference imprinted on the atoms

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



Interferometer phase



UP $\varphi(0) - \varphi(T) + \varphi(2T)$

DOWN $0 + \varphi(T) + 0$

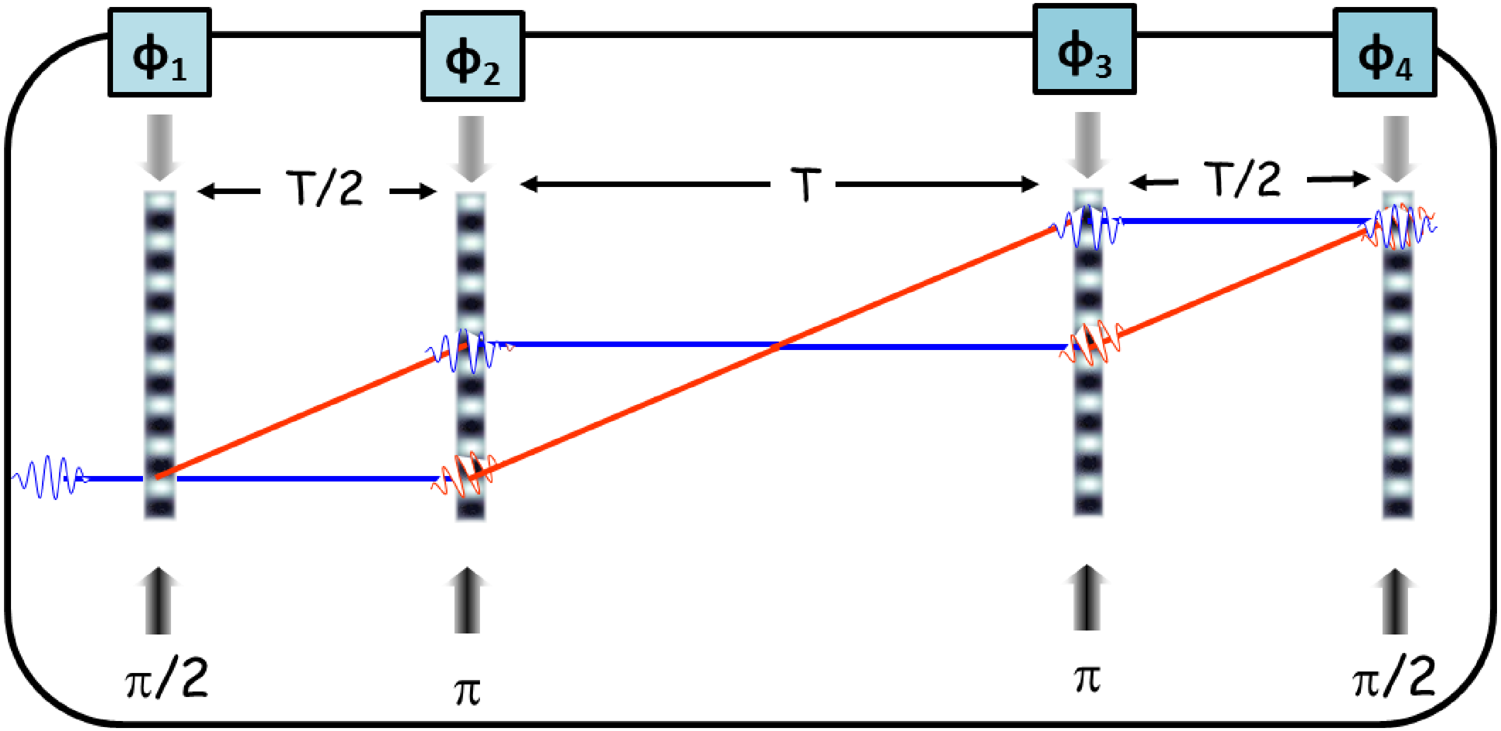
$$\longrightarrow \quad \Delta\Phi = \vec{\mathrm{k}}_{\mathrm{eff}} \cdot \vec{a} T^2$$

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

The SYRTE cold-atom gyroscope

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

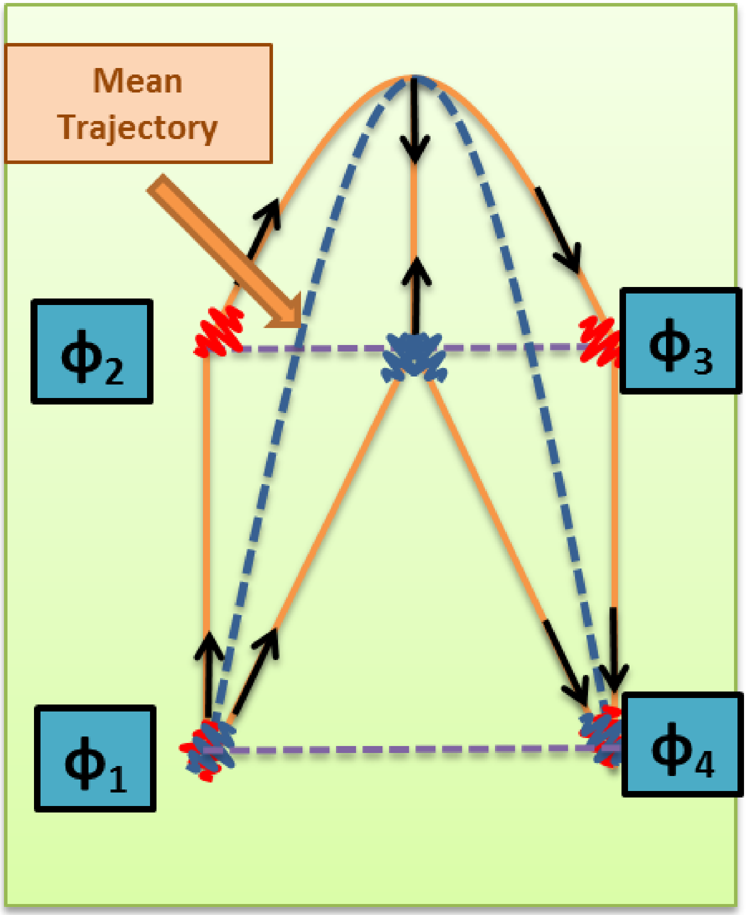
4-light pulse atom interferometer



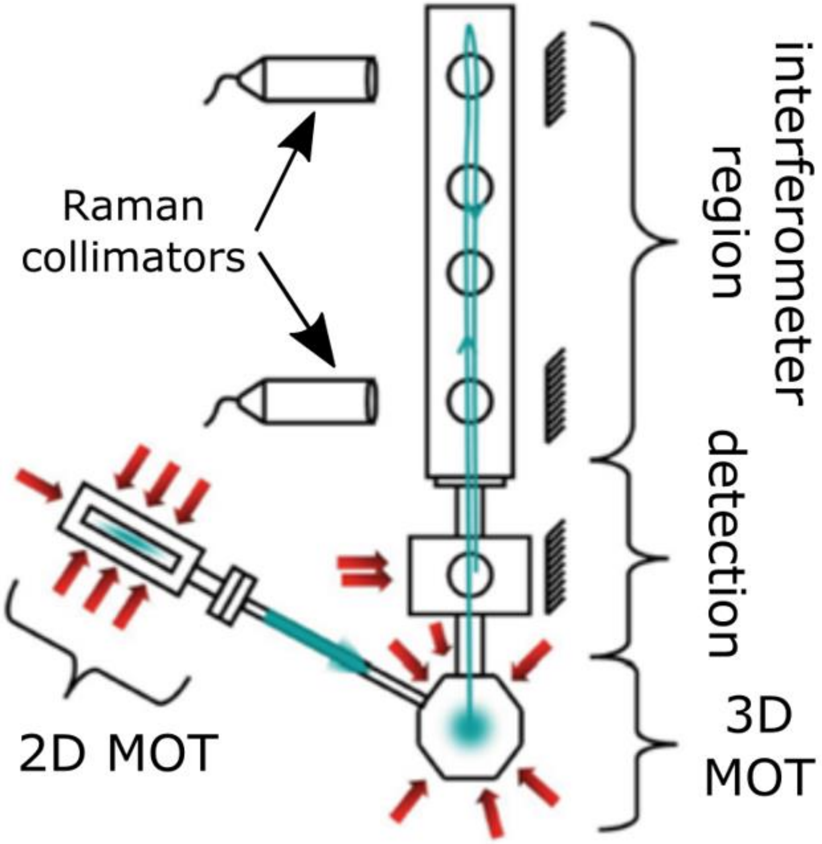
$$\boxed{\Delta\phi = \phi_1 - 2\phi_2 + 2\phi_3 - \phi_4}$$

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

4-light pulse gyroscope



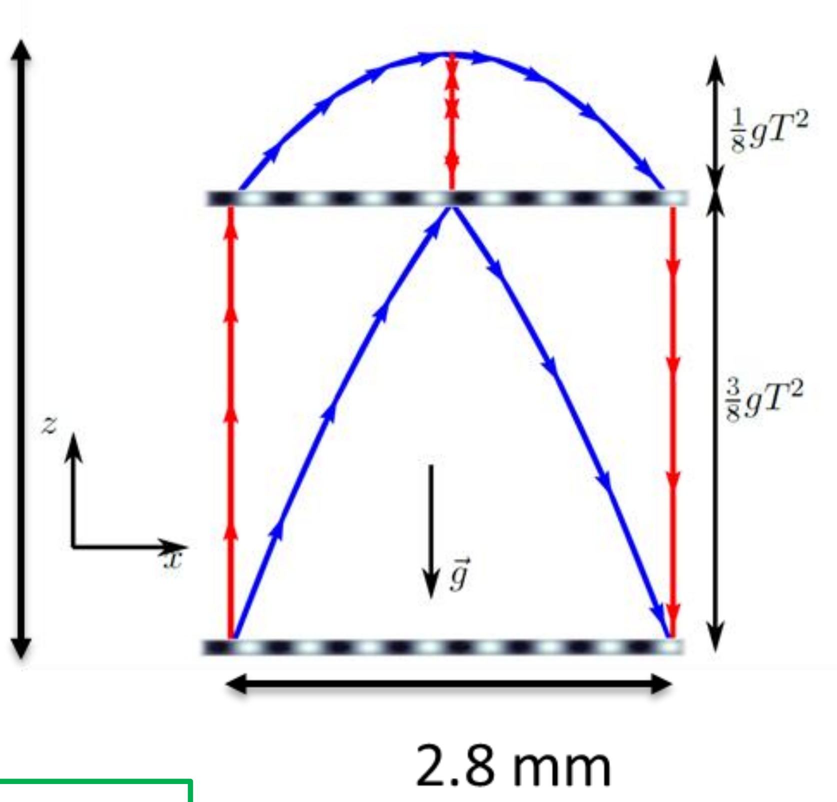
« Butterfly » configuration



Scale factor of the gyroscope

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

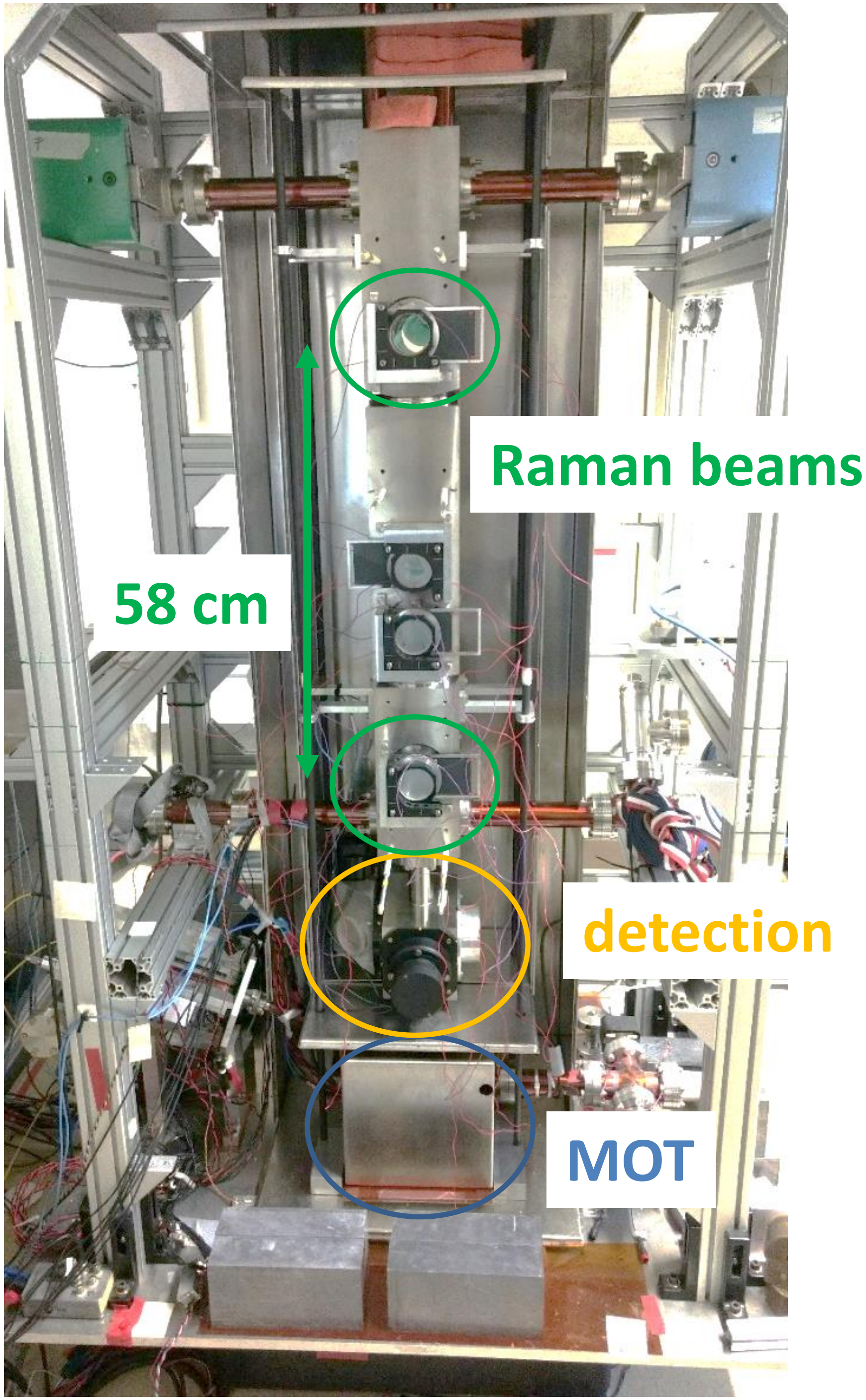
Sagnac area : $A = \frac{1}{4}\frac{\hbar k_{eff}T^3 g}{M}$



800 ms interrogation time → **$11\ cm^2$ Sagnac area**

$1\ rad.s^{-1}$ rotation signal → $5\times10^6\ rad$ phase shift

(Earth rotation rate → 200 rad phase shift)

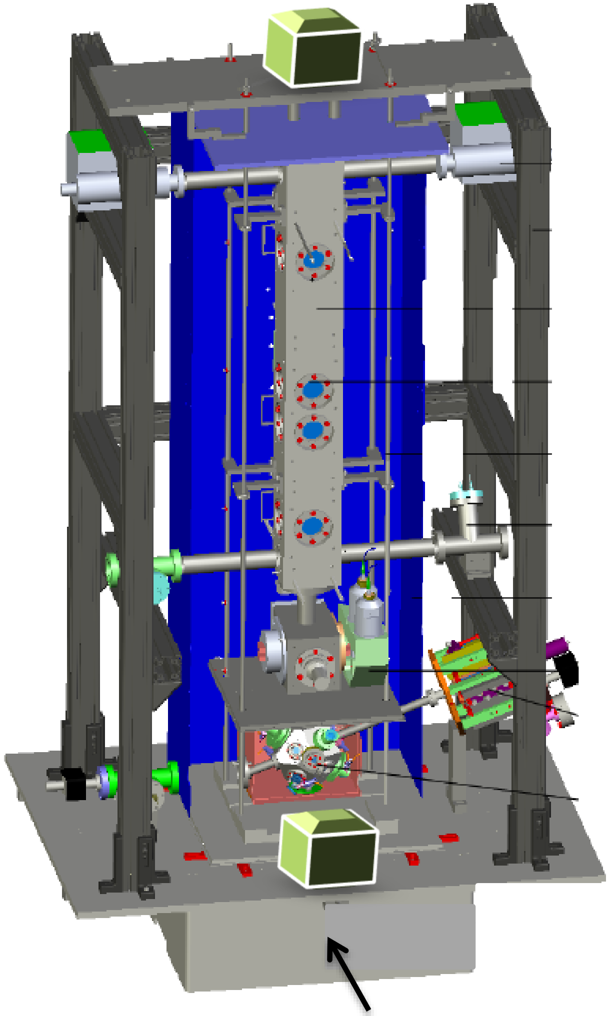


- 4×10^7 Cesium atoms @ 1.2 µK

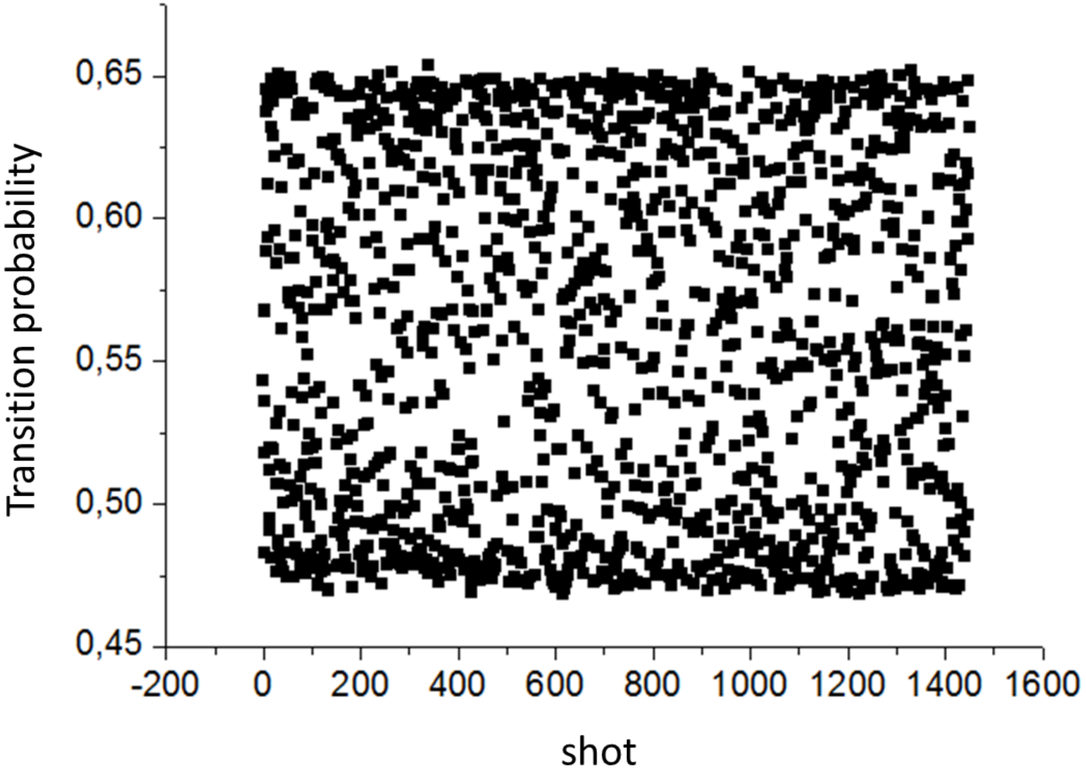
  launched vertically at $5\ m.s^{-1}$
- Relative alignement of the beams

  < 2 µrad
- passive isolation platform (>0.4 Hz)

Vibration noise rejection

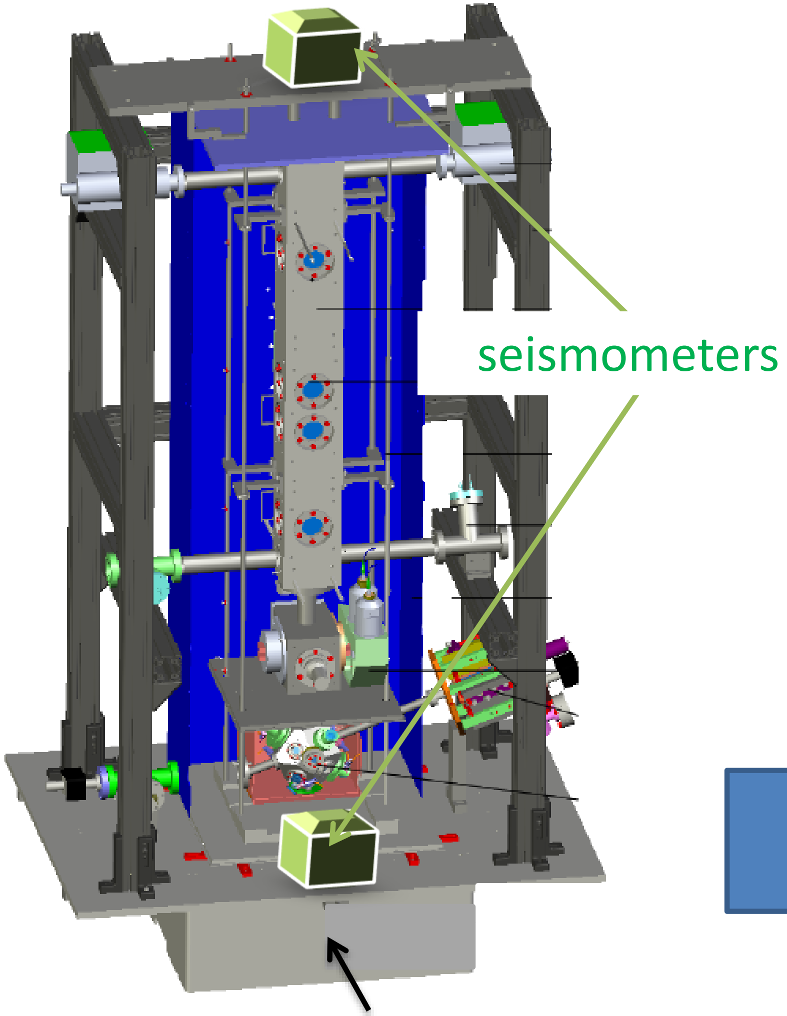


Vibration isolation platform

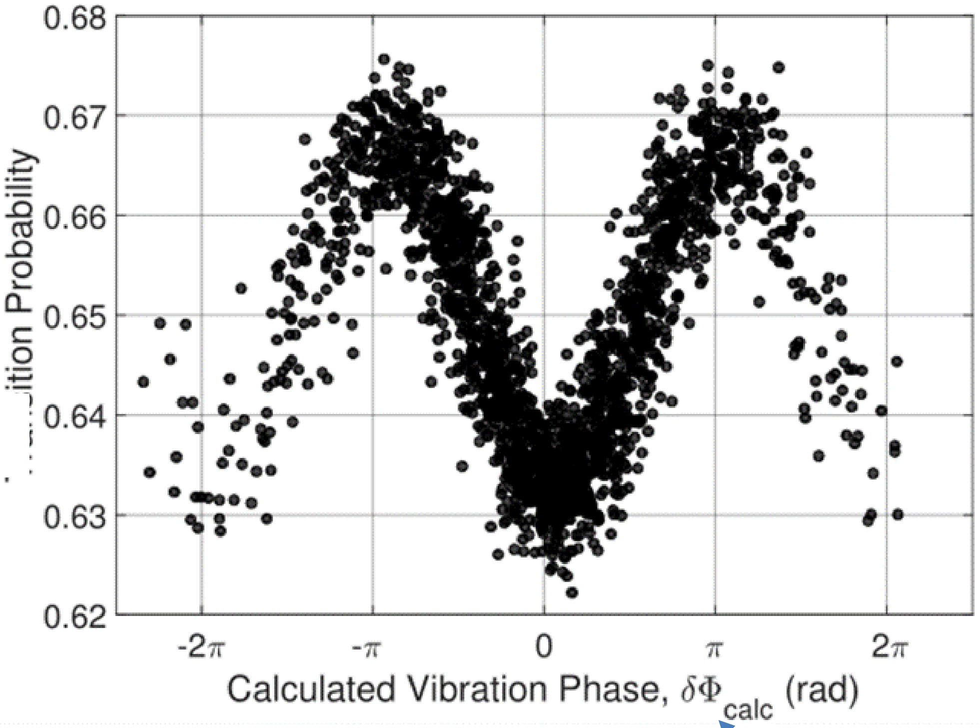


Vibration noise ~ several rad rms

Vibration noise rejection



Vibration isolation platform



Measured vibrations → AI transfer function → Calculated phase

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

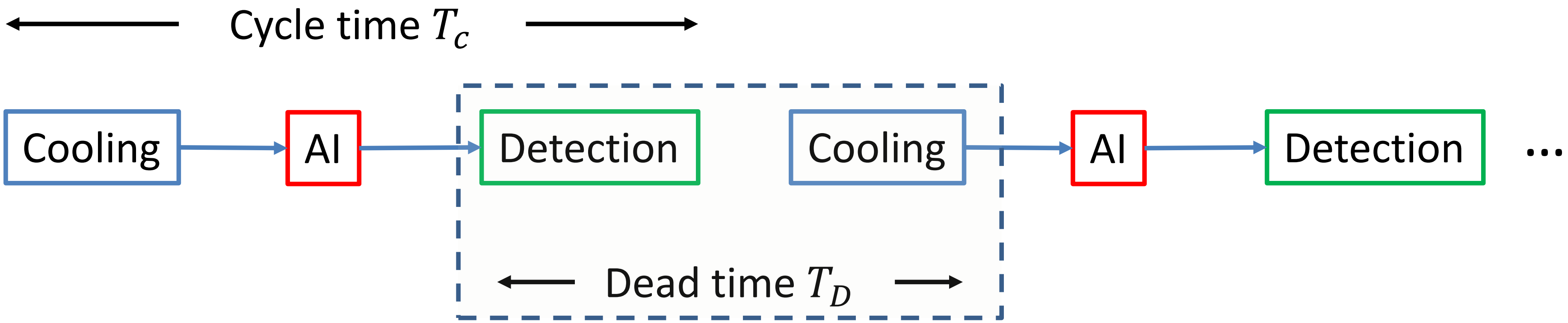
High sampling rate gyroscope without dead-times

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

D. Savoie, M. Altorio et al, *in preparation*

Dead times in quantum sensors

- Sequential operation of cold atom interferometers

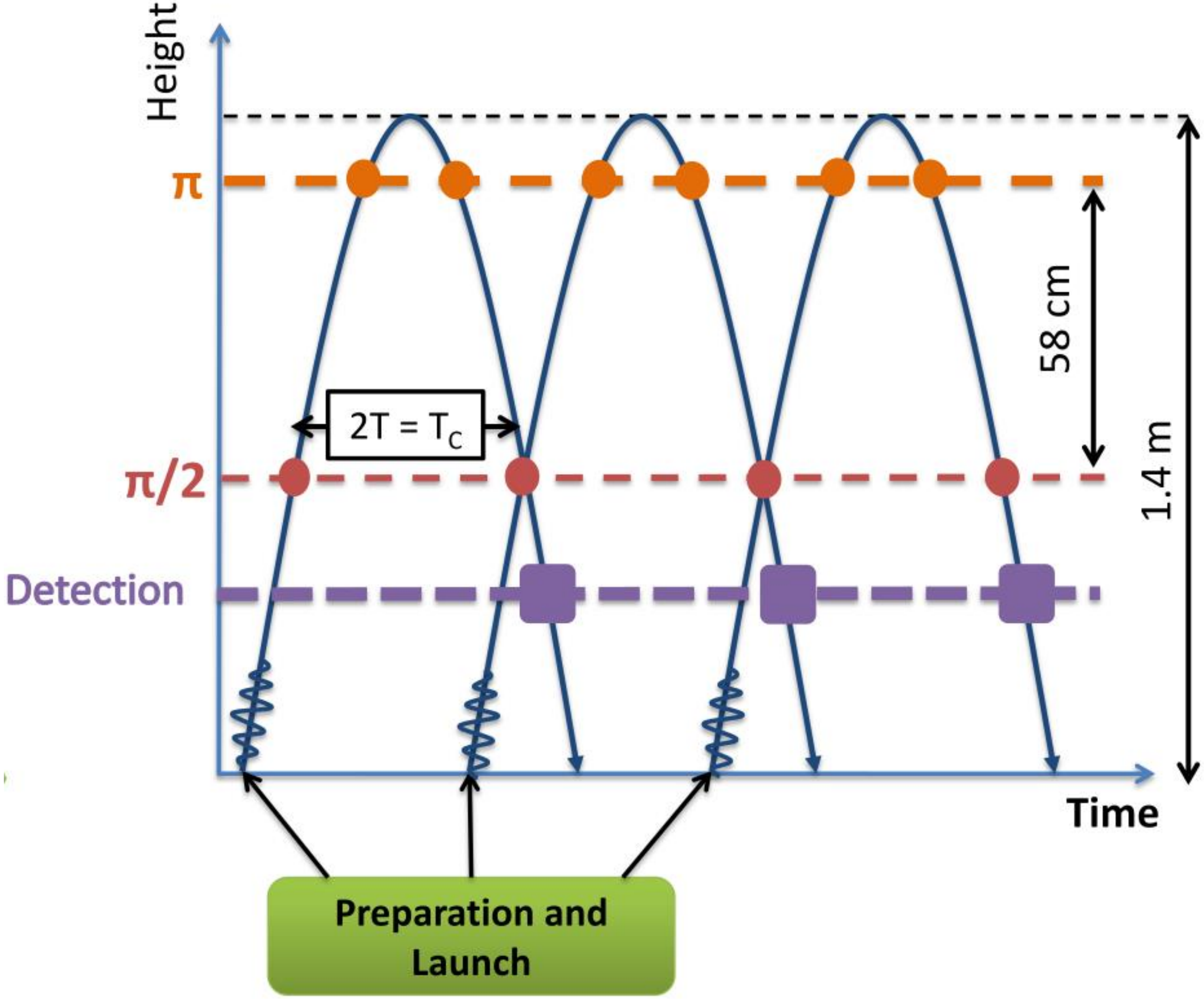


Dead times → (inertial) noise aliasing (Dick effect) + loss of information

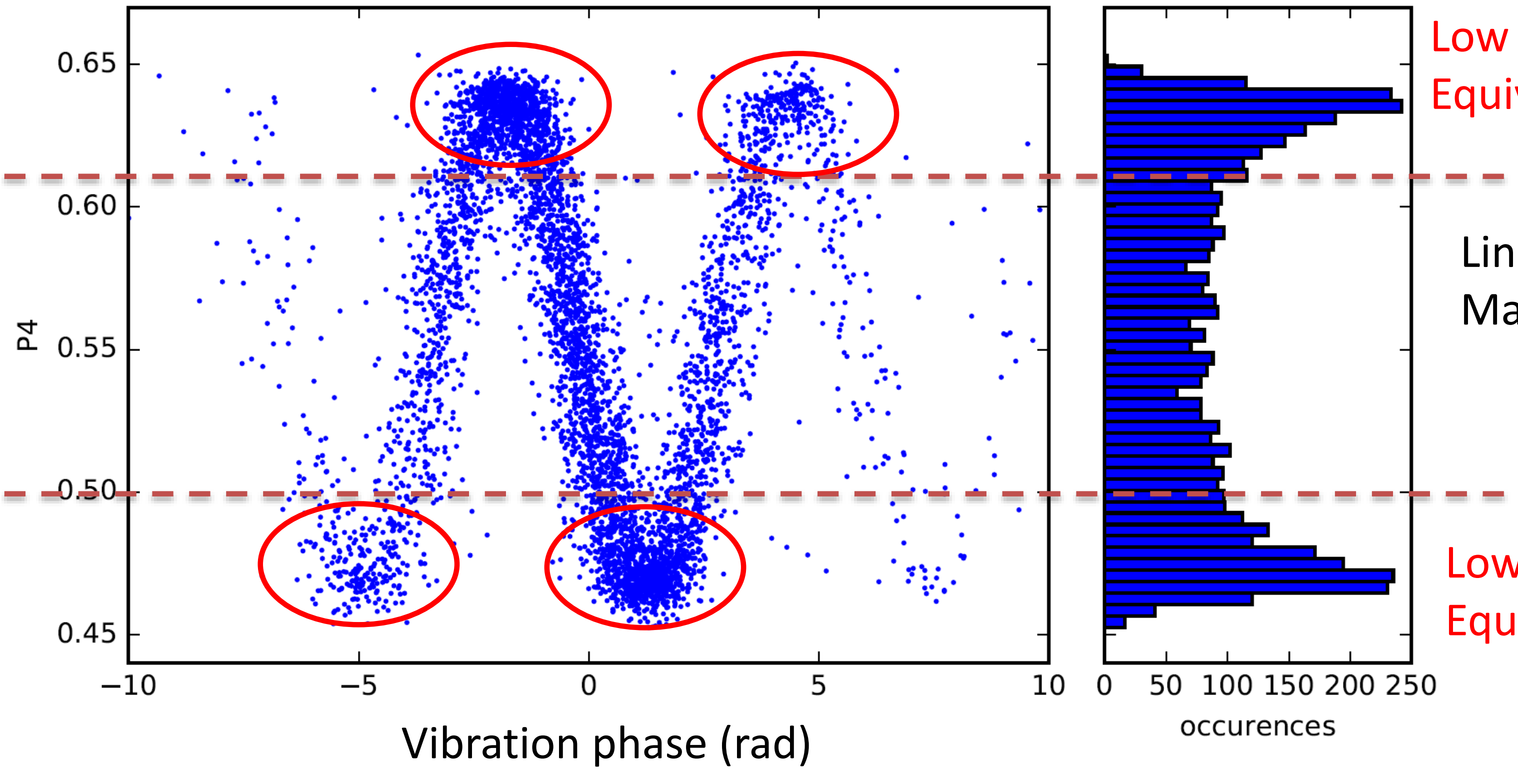
→ prevents from reaching the full potential of atom interferometers.

Continuous (zero dead time) sensor

Joint interrogation scheme: prepare the cold atoms and operate the AI in parallel



Operation in the linear regime

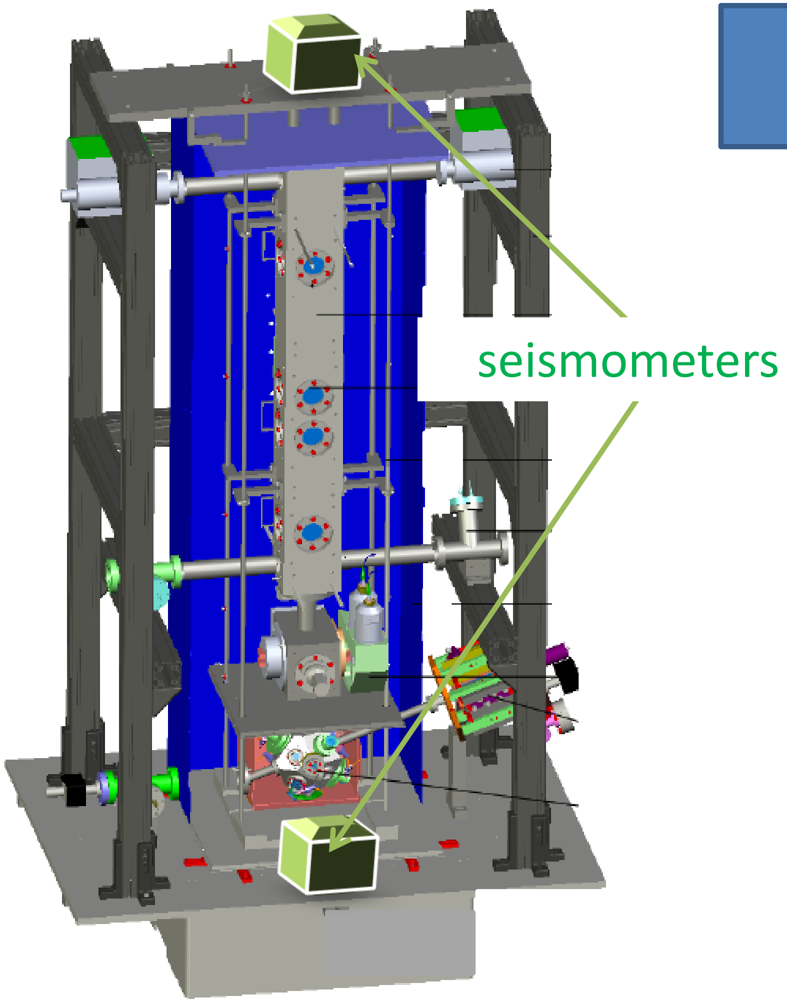


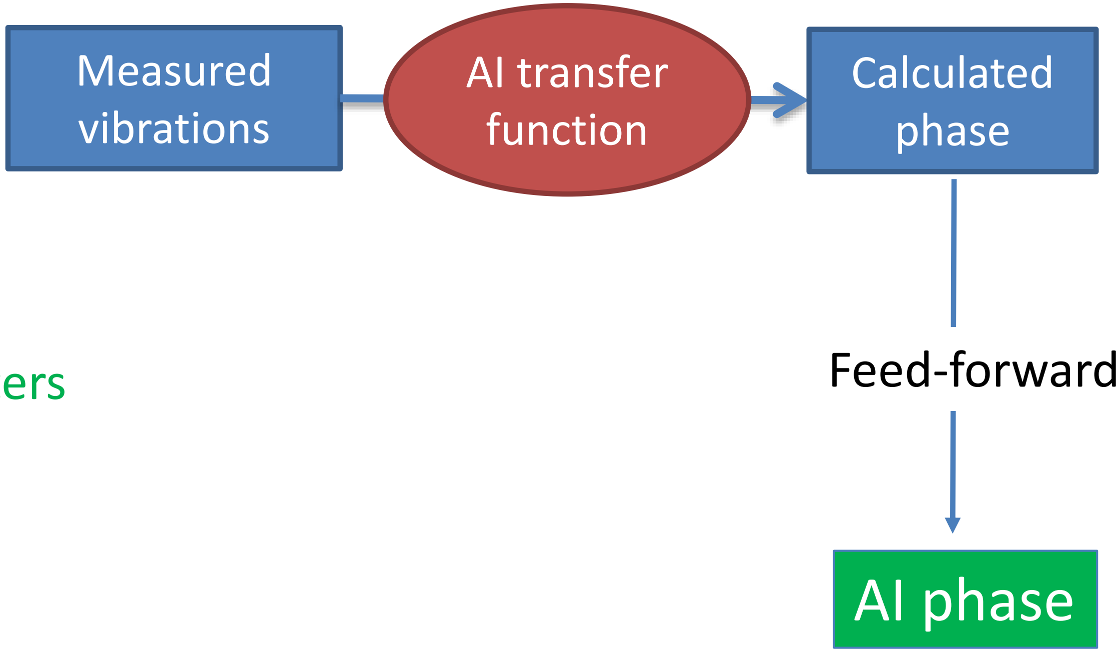
Low sensitivity
Equivalent dead time

Linear range
Max. sensitivity

Low sensitivity
Equivalent dead time

Vibration noise rejection




Measured vibrations

AI transfer function

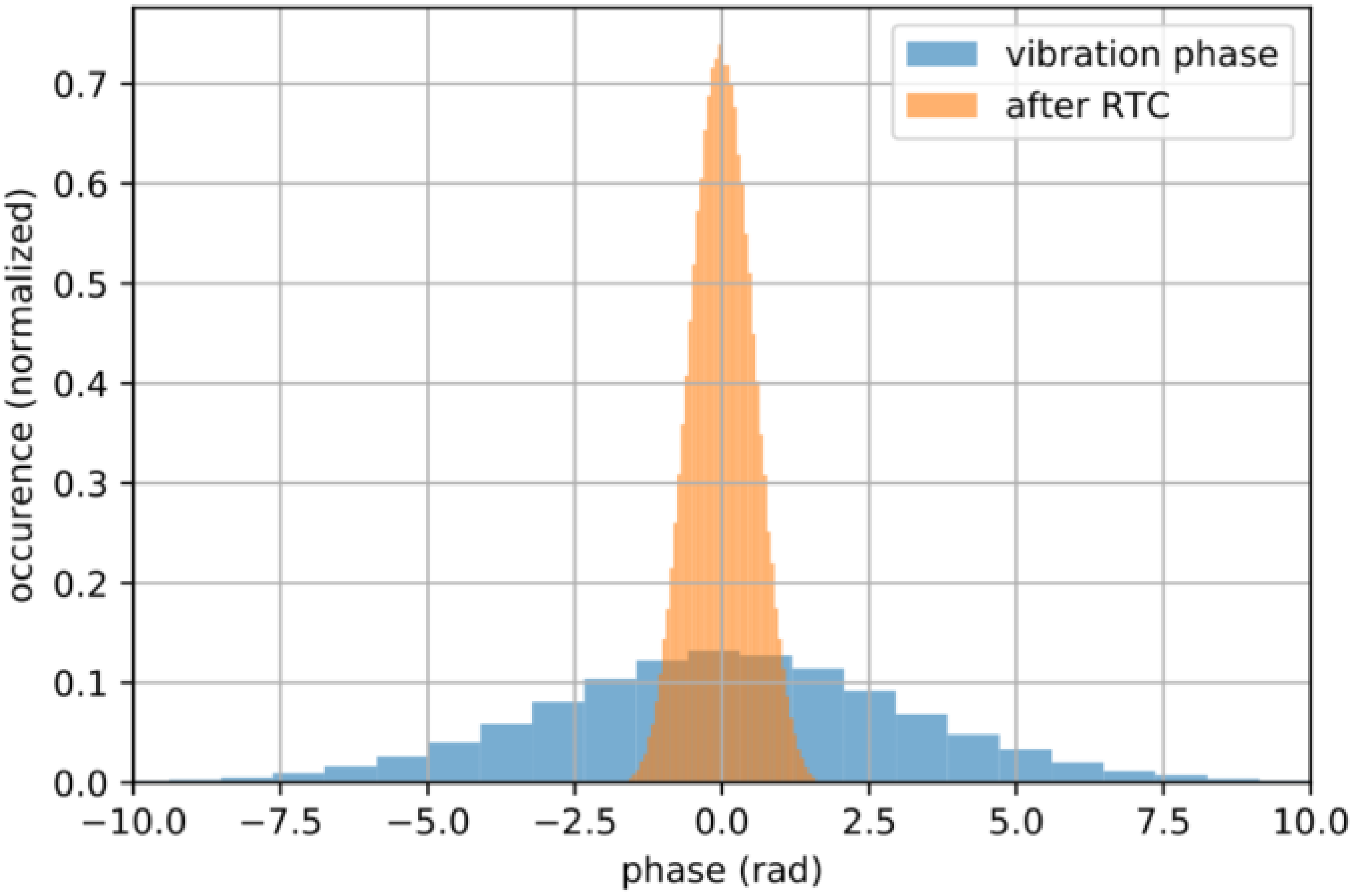
Calculated phase

Feed-forward

AI phase

J. Lautier et al, App. Phys. Letters **105** 144102 (2014)

Operation in the linear regime



Joint mode + linear range → sensor effectively operating without dead times.

Higher bandwidth, high sensitivity

In previous works, the bandwidth was increased by reducing the interrogation time

→ Important drop of sensitivity as $\Phi \propto T^2$

Rakholia et al, Phys. Rev. Applied 2, 054012 (2014)

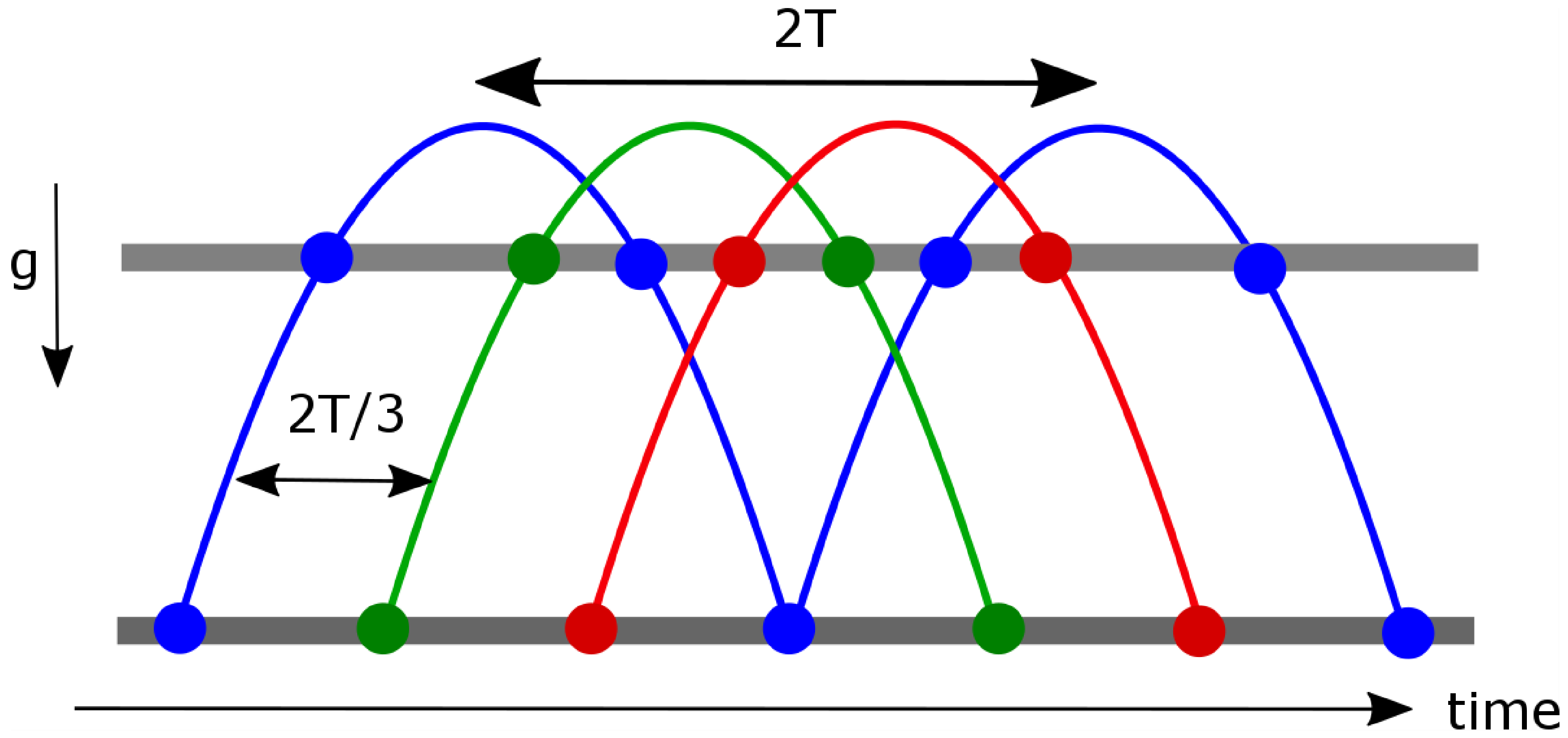
Higher bandwidth, high sensitivity

In previous works, the bandwidth was increased by reducing the interrogation time

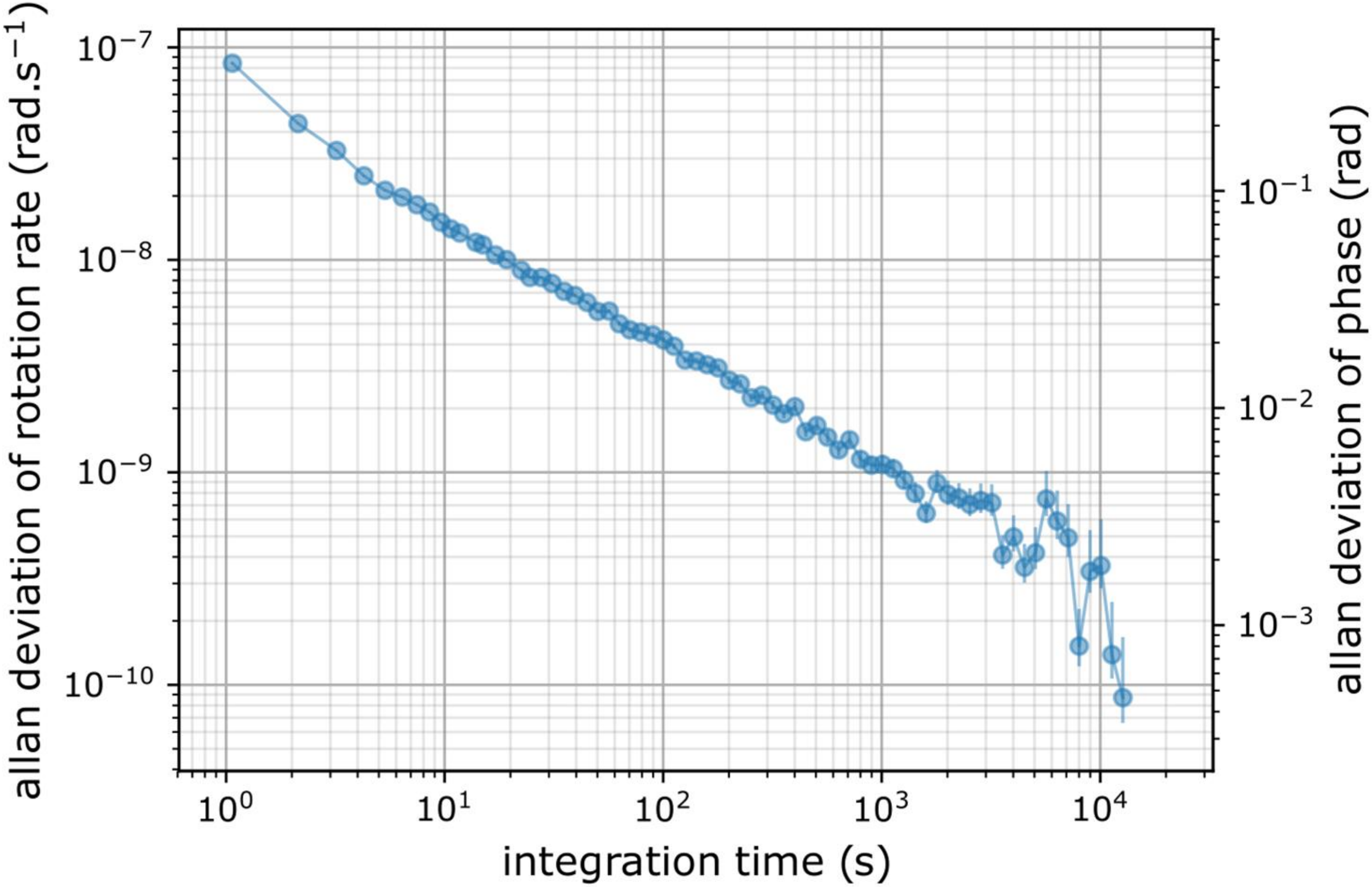
→ Important drop of sensitivity as $\Phi \propto T^2$

We instead interleave several sequences of long-T interferometers

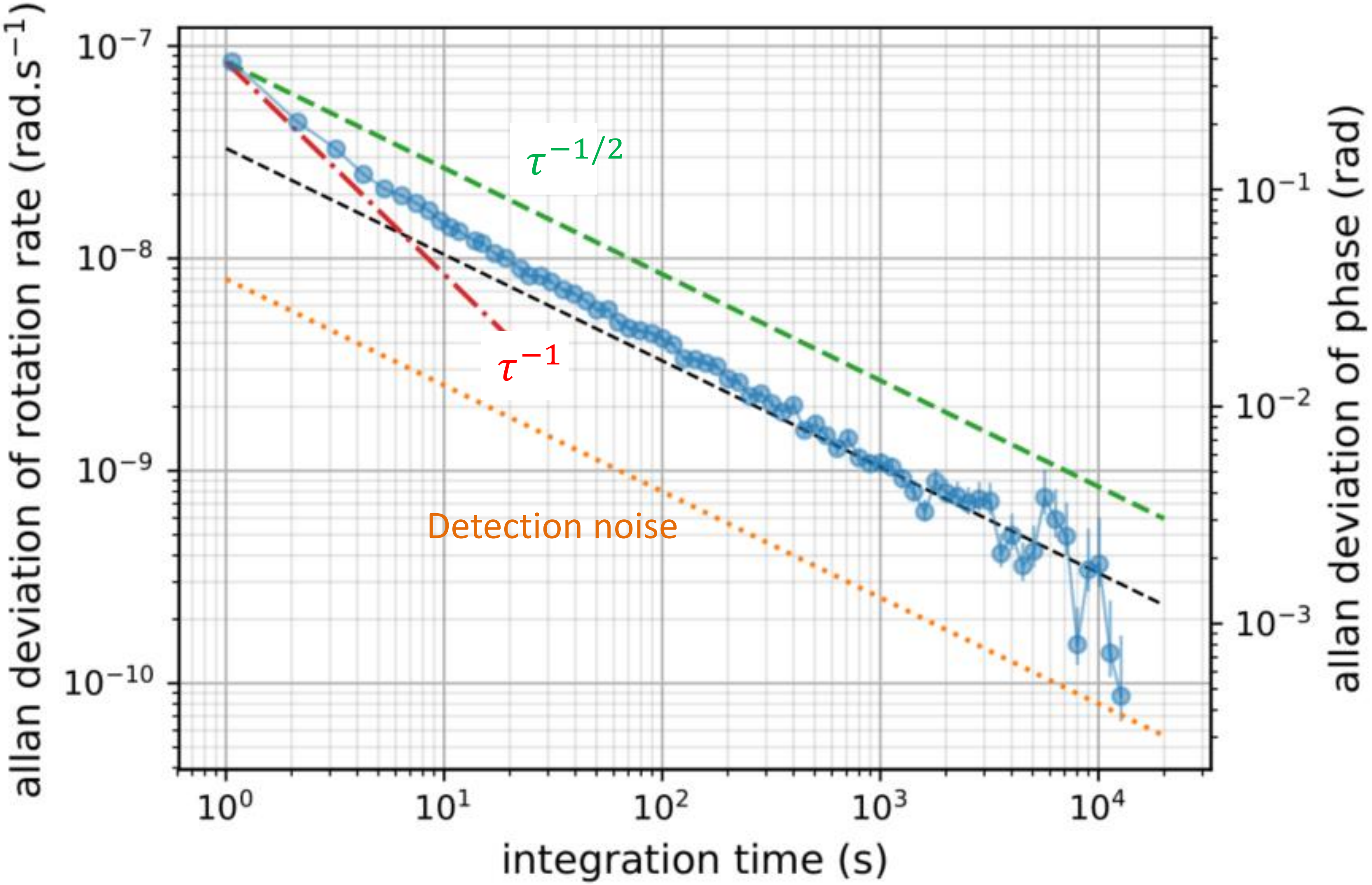
→ $T_c = 2T/3 = 267\ ms$ ($\simeq 4\ Hz$ cycling frequency)



Gyroscope stability

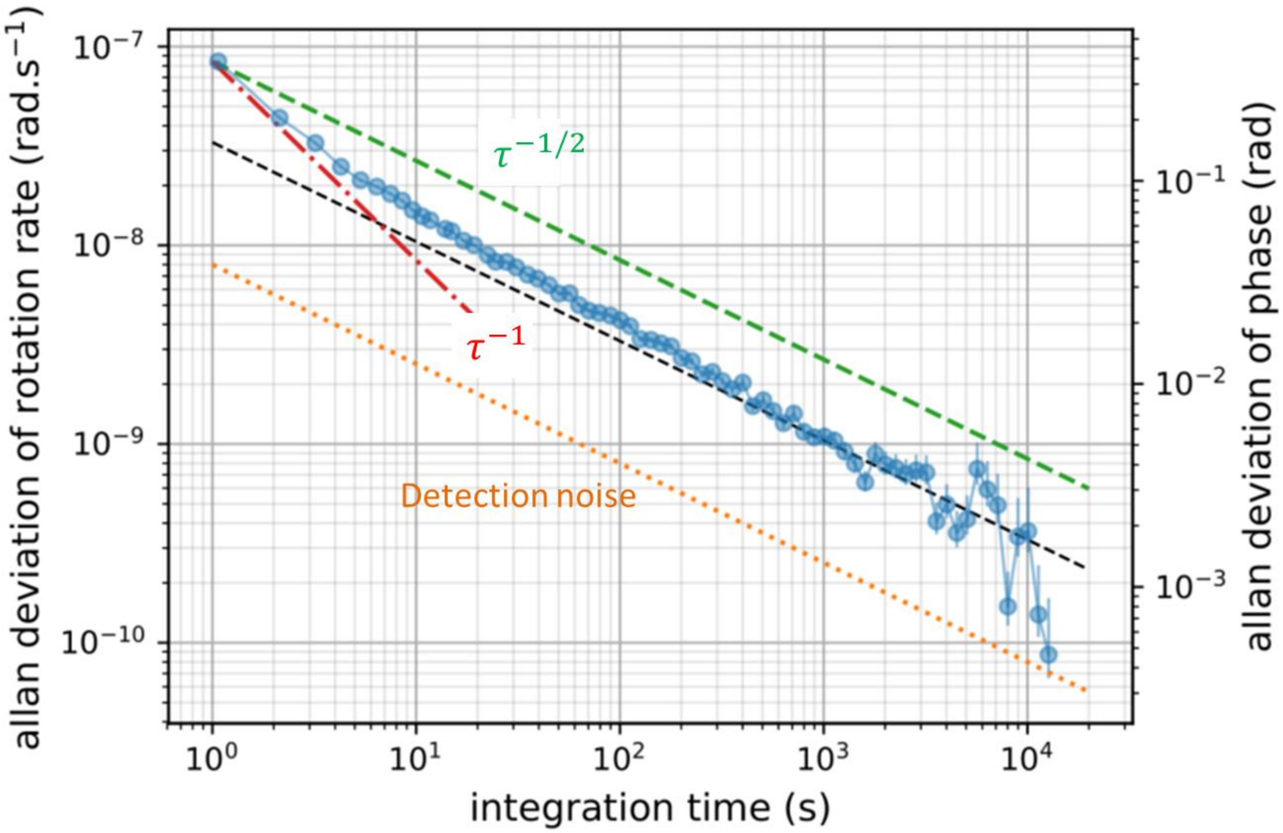


Gyroscope stability



Record short term sensitivity : $3 \times 10^{-8}\ rad.s^{-1}.Hz^{-1/2}$

Gyroscope stability



Efficient averaging of vibration noise due to fast sampling

Record short term sensitivity : $3 \times 10^{-8}\ rad.s^{-1}.Hz^{-1/2}$

Long-term stability and accuracy

- Record **long term stability** : $2 \times 10^{-10}\ rad.s^{-1}$ after $\sim 3 \times 10^{4}\ s$ of integration time (main limitation: imperfect atom' trajectory)

→ **For the first time, a cold-atom gyroscope competes with state-of-the-art laser gyroscopes in terms of sensitivity and stability.**

- Ongoing evaluation of the gyroscope **accuracy** for the measurement of the Earth rotation rate at Paris Observatory

→ Current limitation : 1° uncertainty in the pointing of geographic North

→ Experiment on a turntable.

→ Goal: measurement with $1 \times 10^{-9}\ rad.s^{-1}$ accuracy.

Conclusions

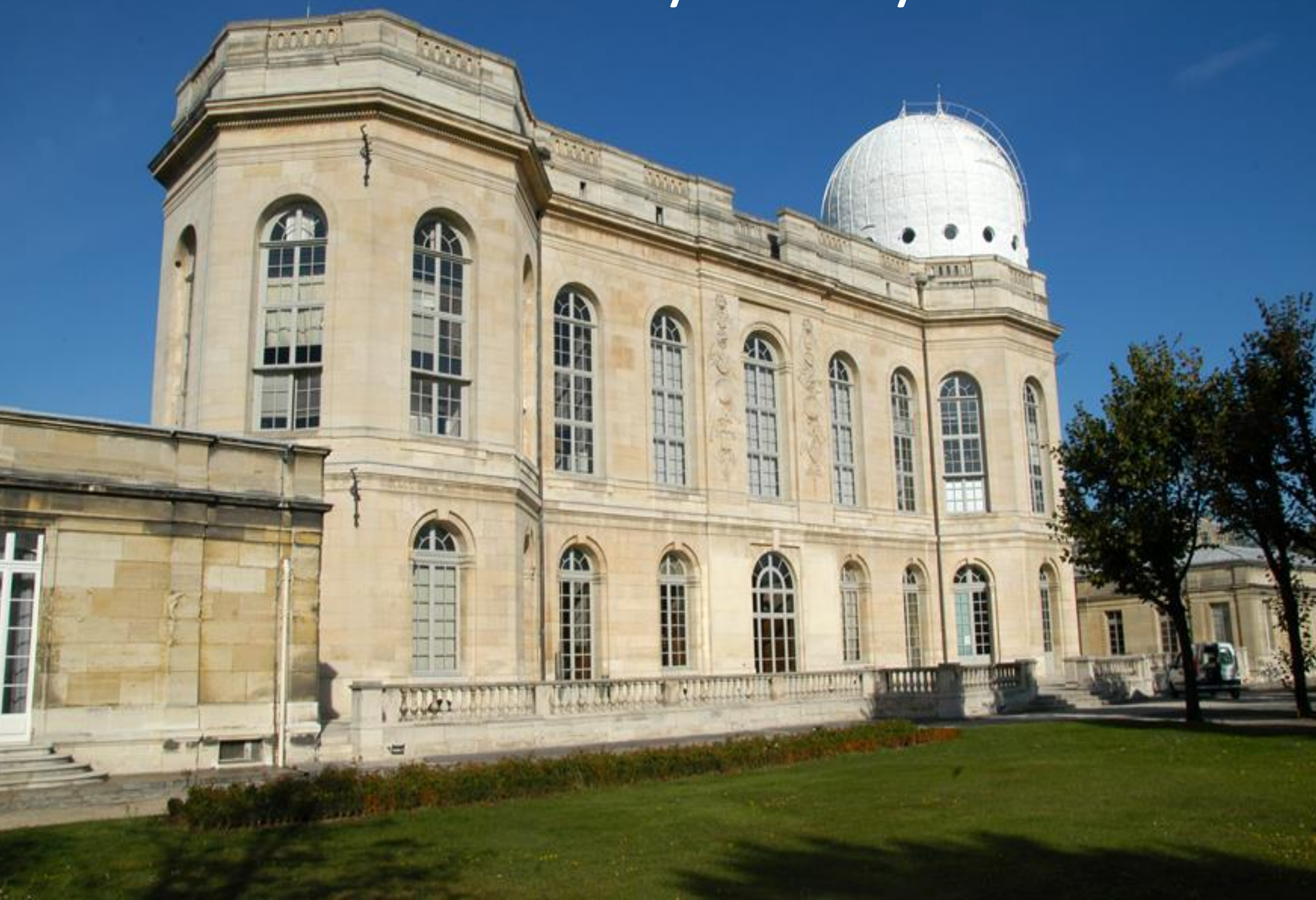
- Several applications of cold atom inertial sensors, when accuracy and/or long-term stability are required
- Dead times and low sampling frequencies strongly limit the potential impact in field applications or for monitoring AC (~ few Hz) signals
- We demonstrated a zero dead-time gyroscope with 4 Hz sampling frequency
- State of the art sensitivity |stability: $3 \times 10^{-8}\ rad.s^{-1}.Hz^{-1/2}$ | $2 \times 10^{-10}\ rad.s^{-1}$

→ Competes with the best fiber-optic gyroscopes

- Interleaving : generic technique for other sensors (gravimeter, gradiometer).

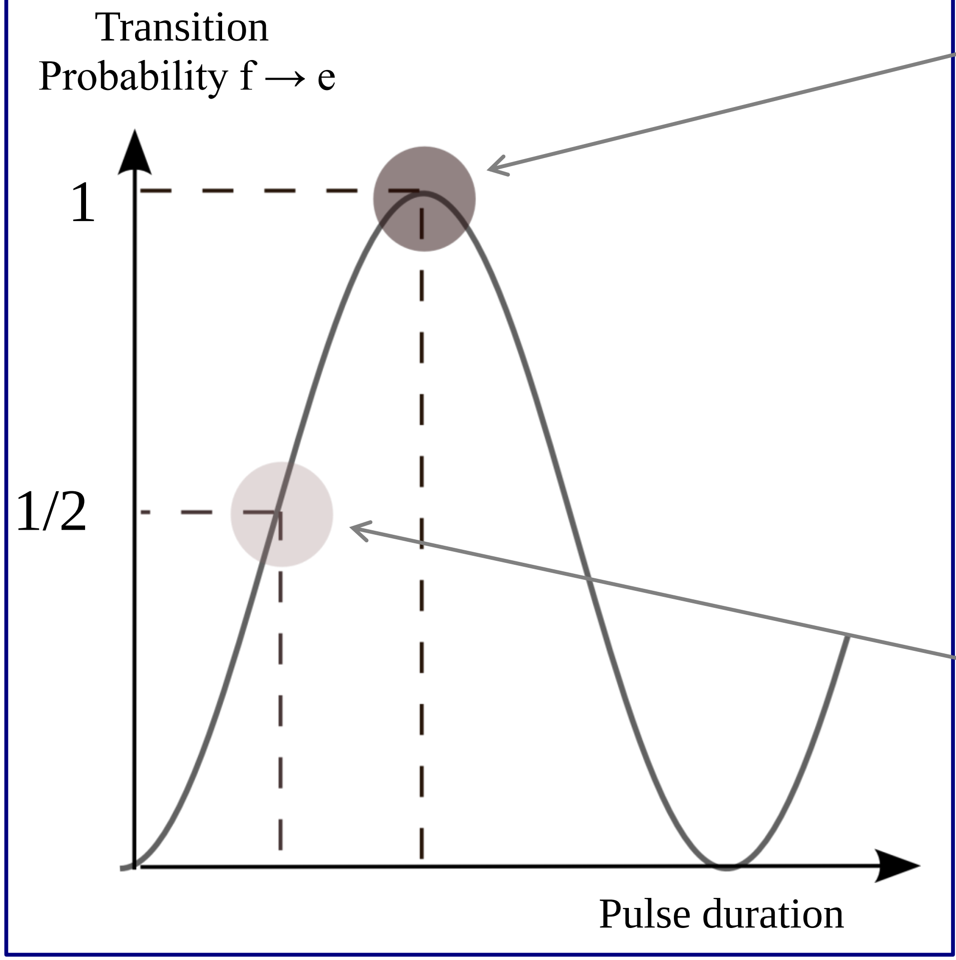
The gyroscope team

Thank you for your attention

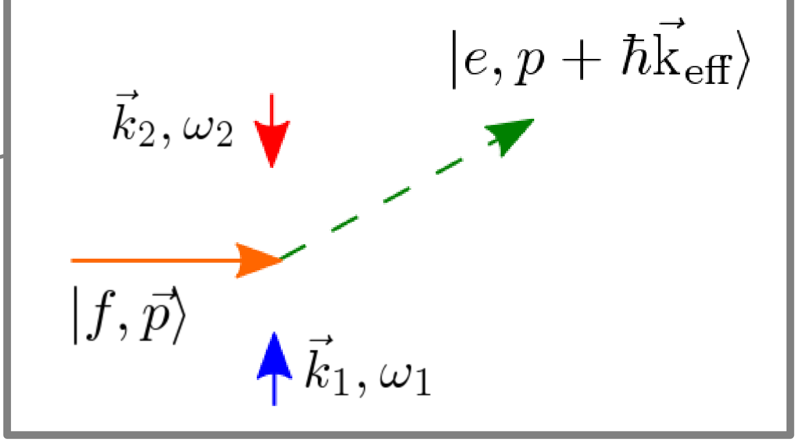


Interferometer building blocks

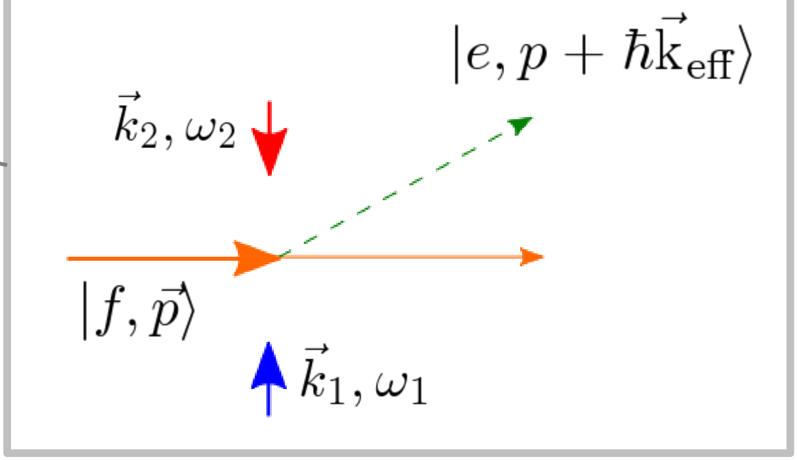
Rabi oscillation between
|f> and |e>



"π" pulse = mirror

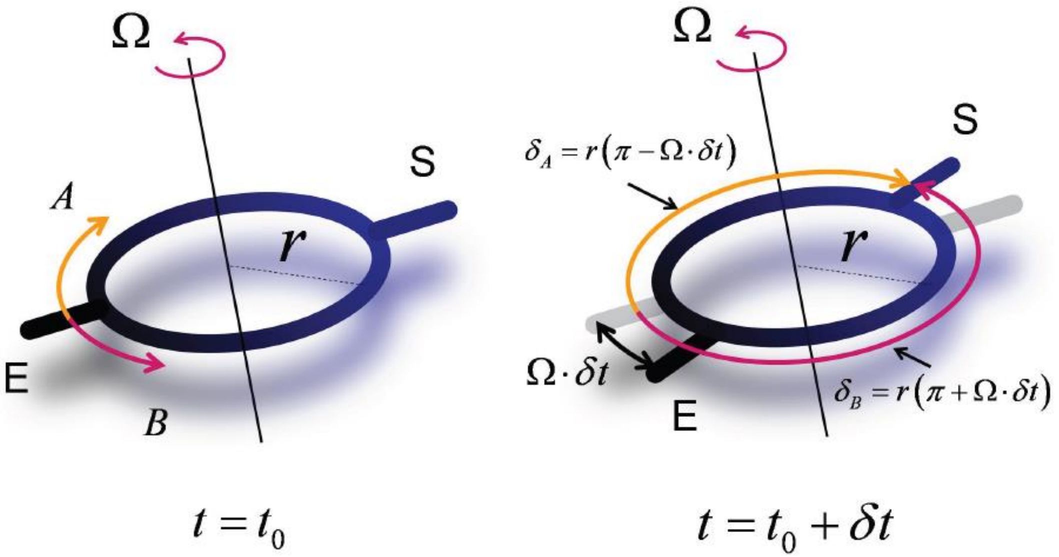


"π/2" pulse = beam splitter



Photons versus atoms

Sagnac effect



total energy

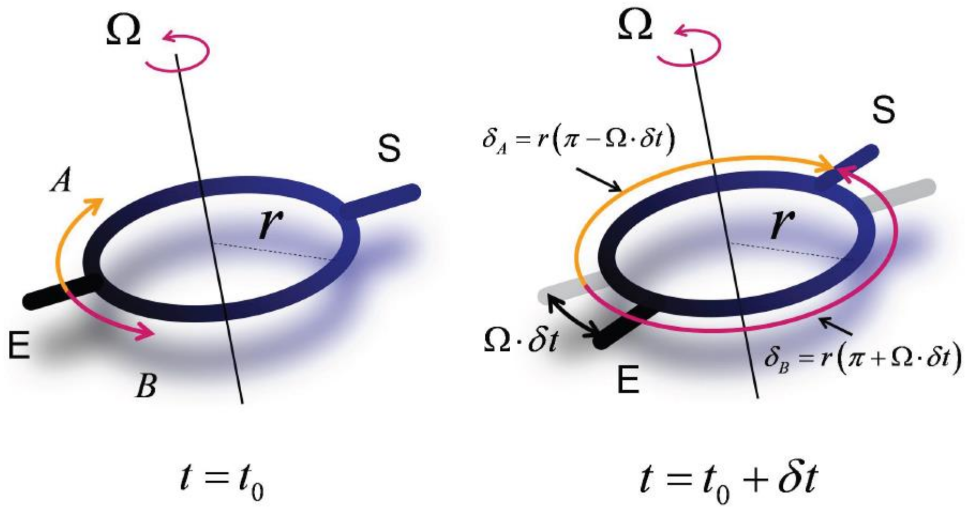
$$\Delta\Phi_{\Omega} = \frac{4\pi E}{hc^2} \vec{A} \cdot \vec{\Omega}$$

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
- $E \sim 1\text{eV}$

Atoms :

- A : mm² to cm²
- $E \sim 10^{11}\text{eV}$

+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

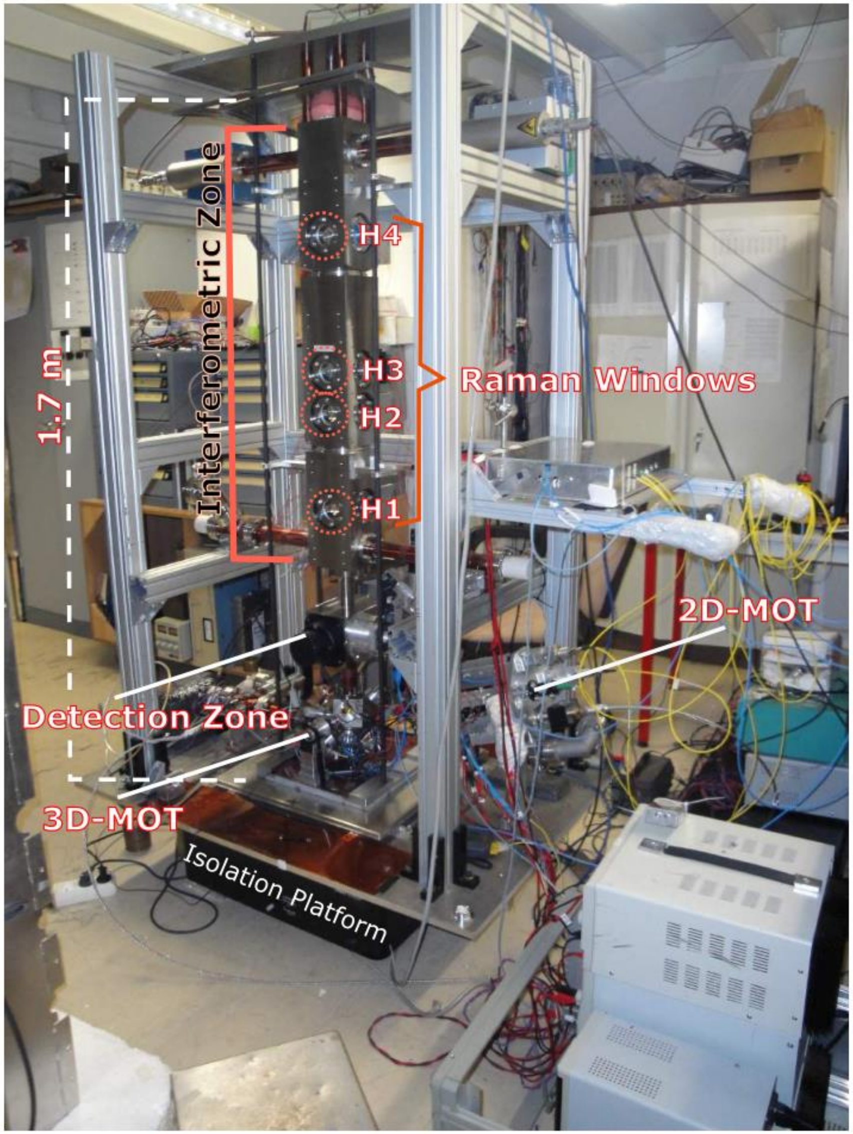
Shot noise ($\sigma_\phi \simeq 1/\sqrt{n}$):

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

-6 orders of magnitude

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

Experimental setup

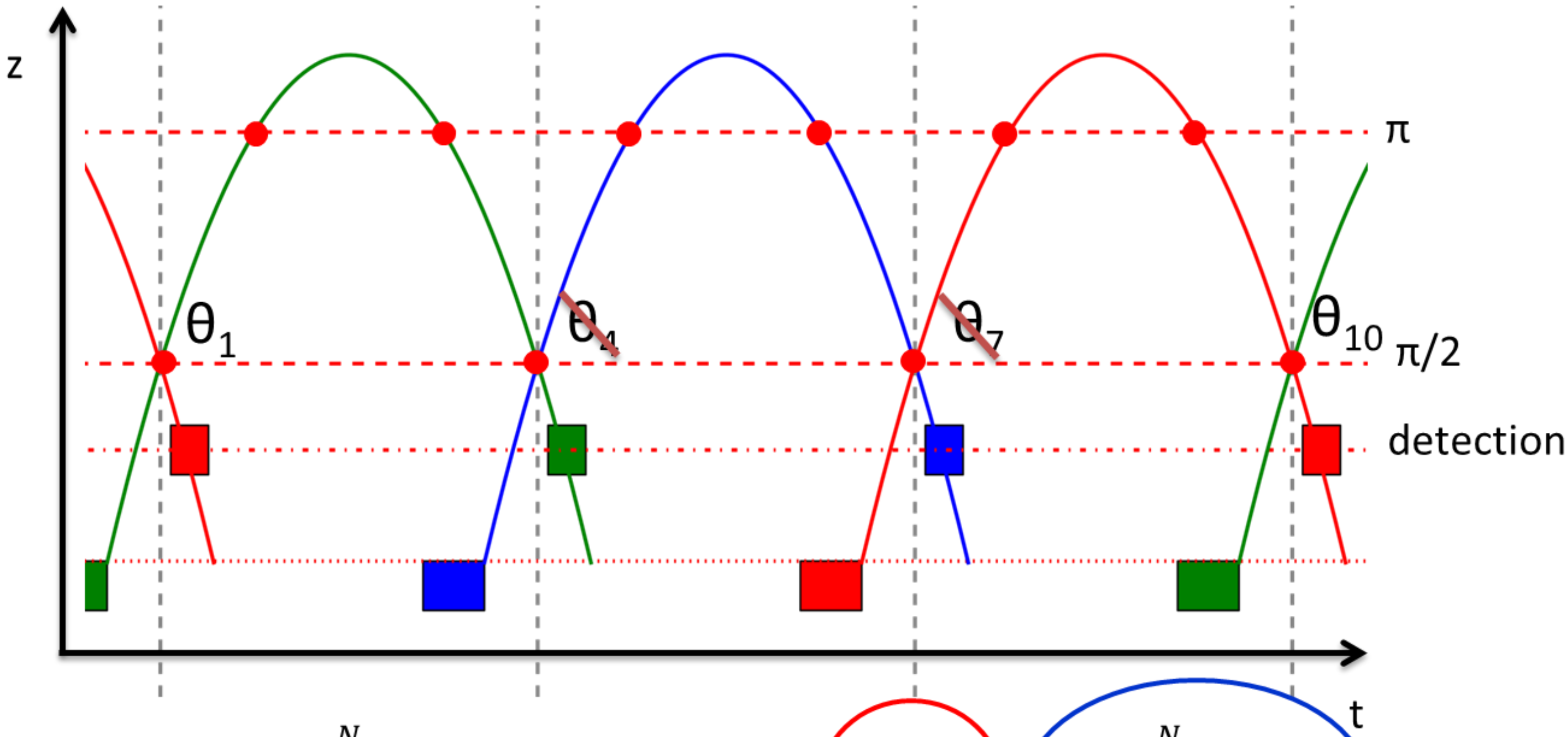


- 4×10^7 Cesium atoms @ 1.2 µK launched vertically at $5\ m.s^{-1}$
- Relative alignement of the beams < 2 µrad
- Mitigation of vibration noise

→passive isolation platform (>0.4 Hz)

Efficient averaging of vibration noise

1. Rotation noise is canceled from shot to shot by the joint measurements



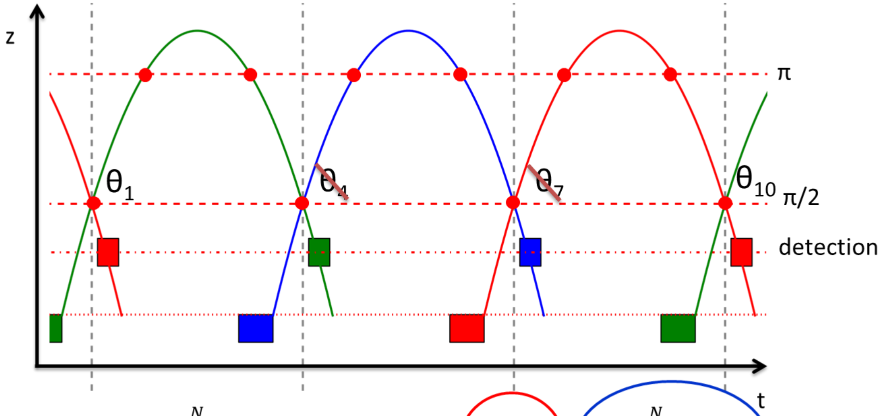
$$\Omega = \frac{1}{2NT}\sum_{i=1}^{N}\left(\boxed{\theta_{3i+3}-\theta_{3i}} + \boxed{\delta\theta_i^{NC}}\right) = \boxed{\frac{\theta_{3N}-\theta_1}{2NT}} + \boxed{\frac{1}{2NT}\sum_{i=1}^{N}\delta\theta_i^{NC}}$$

➔ Integration as $\frac{1}{N}$

➔ Integration as $\frac{1}{\sqrt{N}}$

Efficient averaging of vibration noise

1. Rotation noise is canceled from shot to shot by the joint measurements



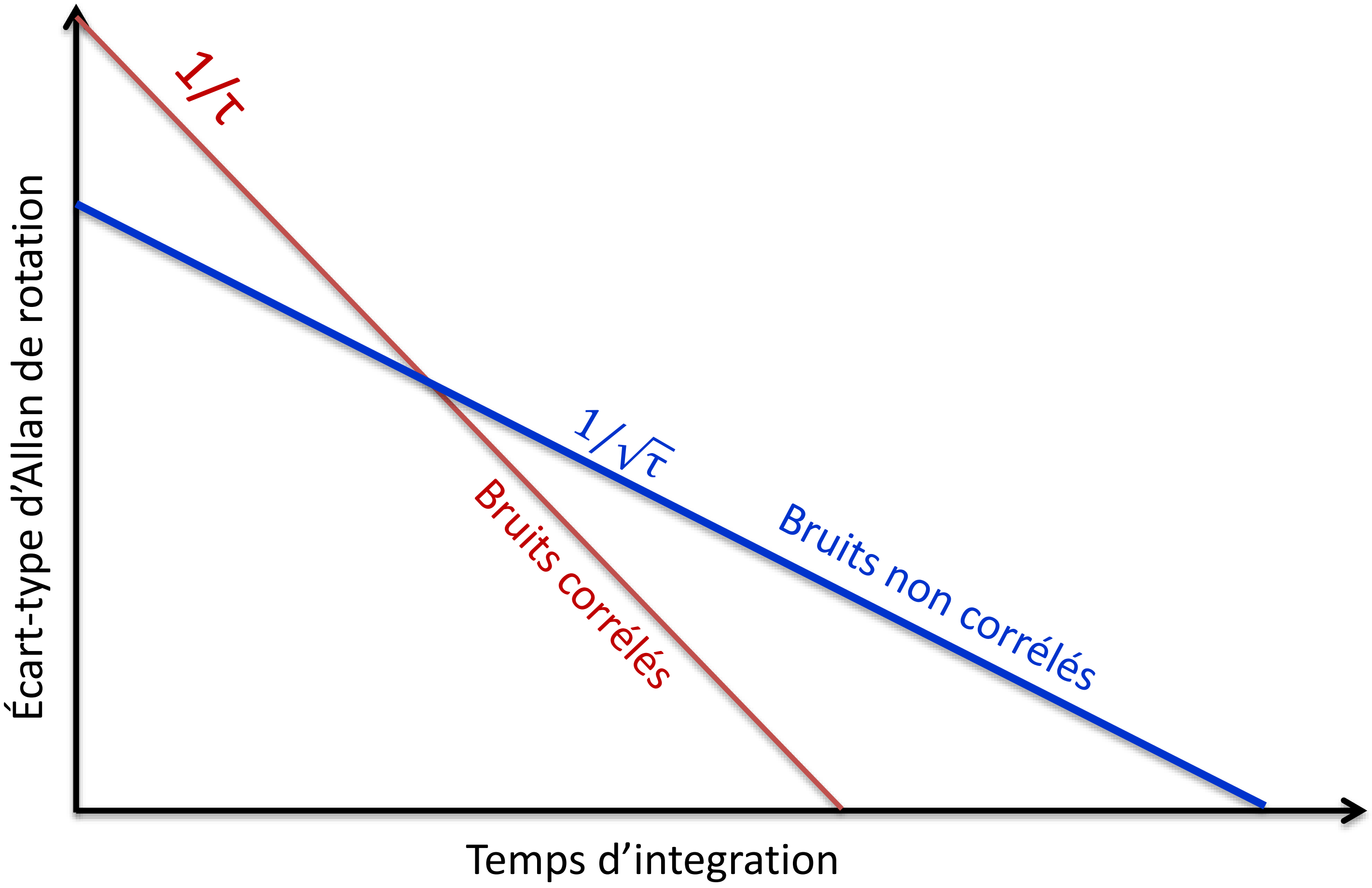
$$\Omega = \frac{1}{2NT}\sum_{i=1}^{N}\left(\boxed{\theta_{3i+3}-\theta_{3i}}+\boxed{\delta\theta_i^{NC}}\right) = \frac{\theta_{3N}-\theta_1}{2NT} + \frac{1}{2NT}\sum_{i=1}^{N}\delta\theta_i^{NC}$$

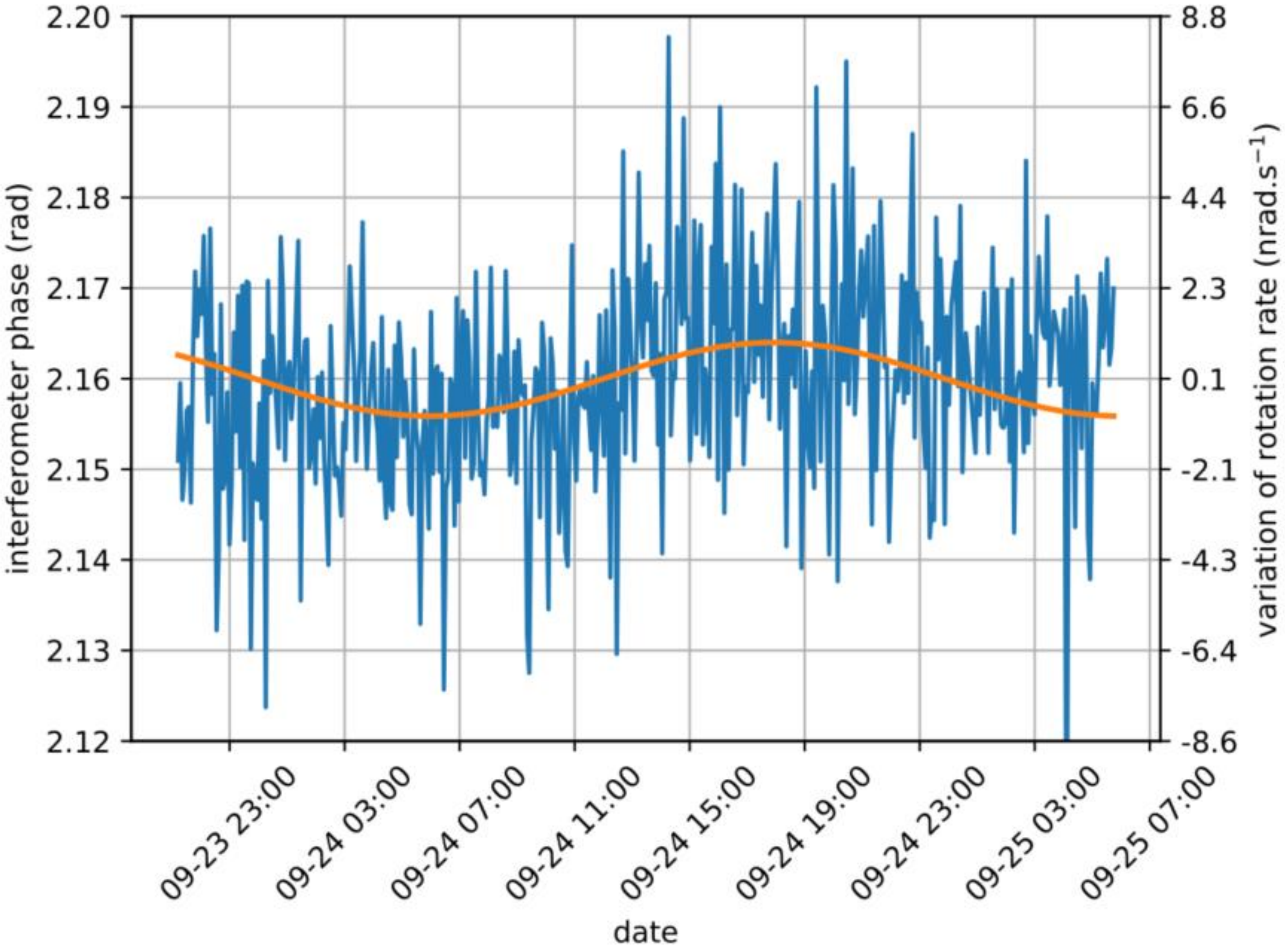
→ Integration as $\frac{1}{N}$

→ Integration as $\frac{1}{\sqrt{N}}$

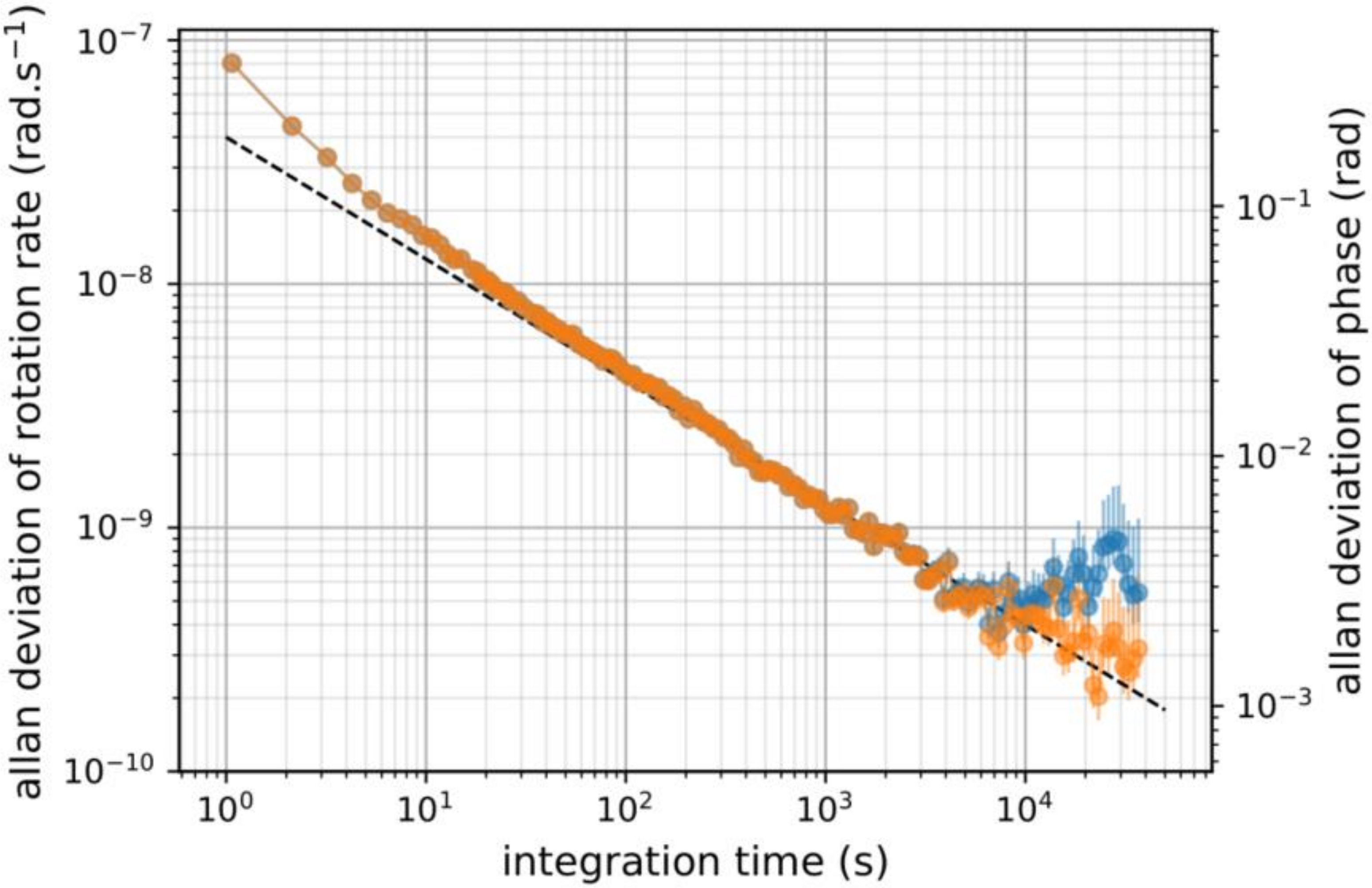
2. Acceleration noise at frequencies $< \frac{1}{T_c} \simeq 4\ Hz$ is correlated from shot to shot

→Interleaving allows to reduce the effect of vibration noise, which is the most important noise contribution in cold-atom inertial sensors.

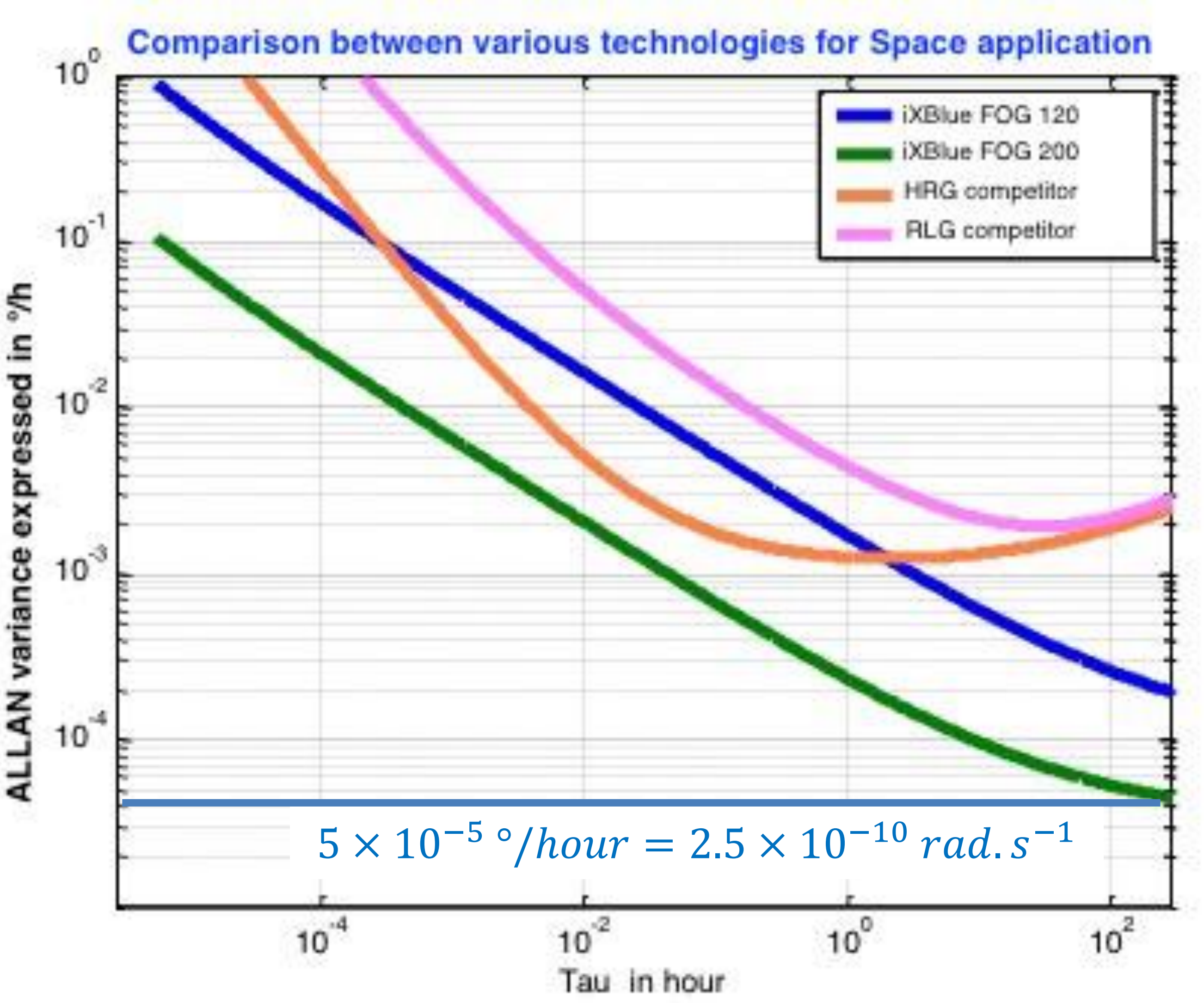

$1/\tau$
$1/\sqrt{\tau}$
Bruits corrélés
Bruits non corrélés
Écart-type d'Allan de rotation
Temps d'integration


2.20
2.19
2.18
2.17
2.16
2.15
2.14
2.13
2.12
interferometer phase (rad)
8.8
6.6
4.4
2.3
0.1
-2.1
-4.3
-6.4
-8.6
variation of rotation rate (nrad.s^{-1})
09-23 23:00
09-24 03:00
09-24 07:00
09-24 11:00
09-24 15:00
09-24 19:00
09-24 23:00
09-25 03:00
09-25 07:00
date

Long-term stability and accuracy

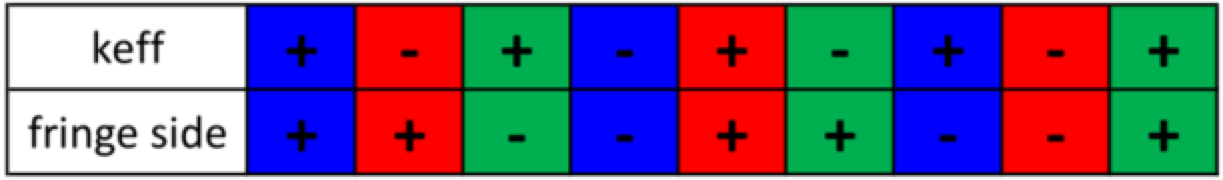


iXblue ultimate-performance Fiber-Optic Gyroscope (FOG)

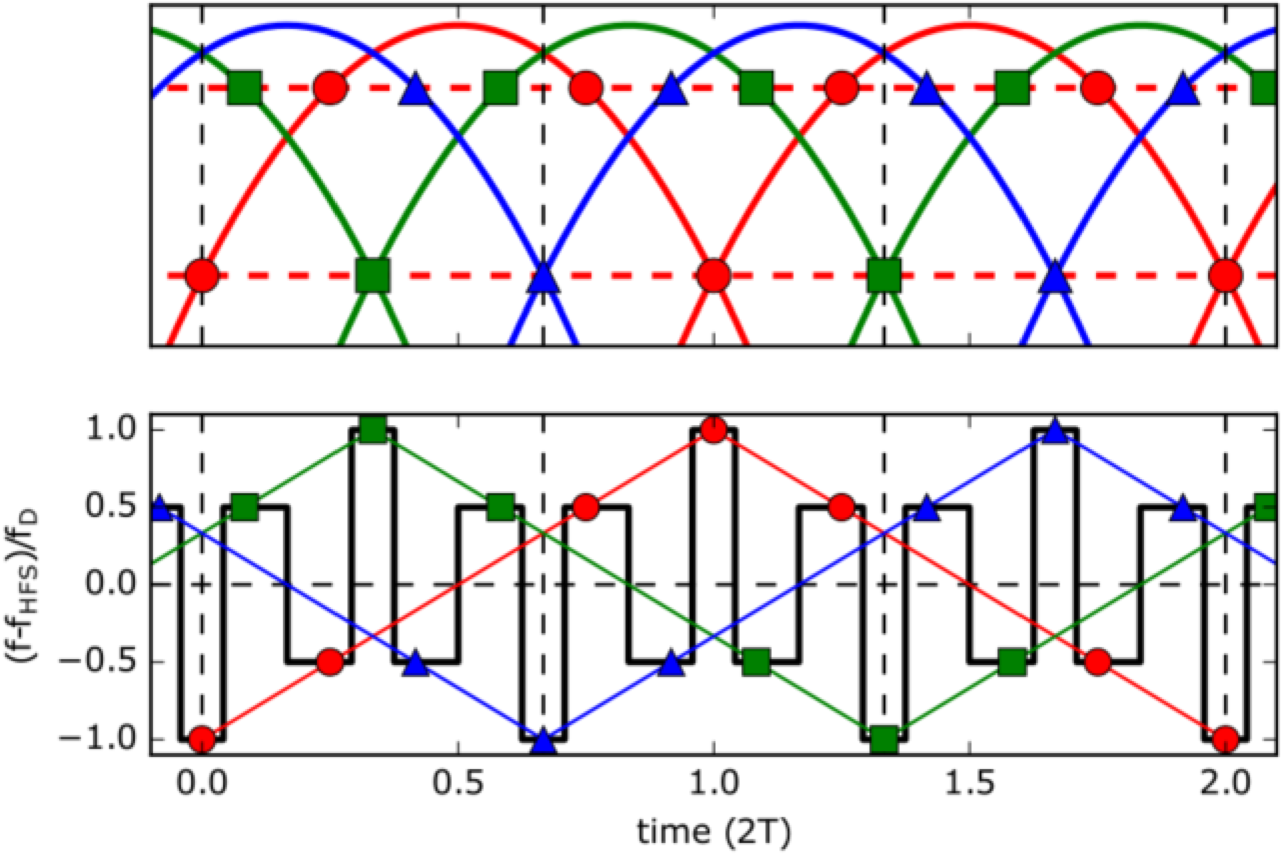


$$5 \times 10^{-5}\ °/hour = 2.5 \times 10^{-10}\ rad.s^{-1}$$

Details of the sequence

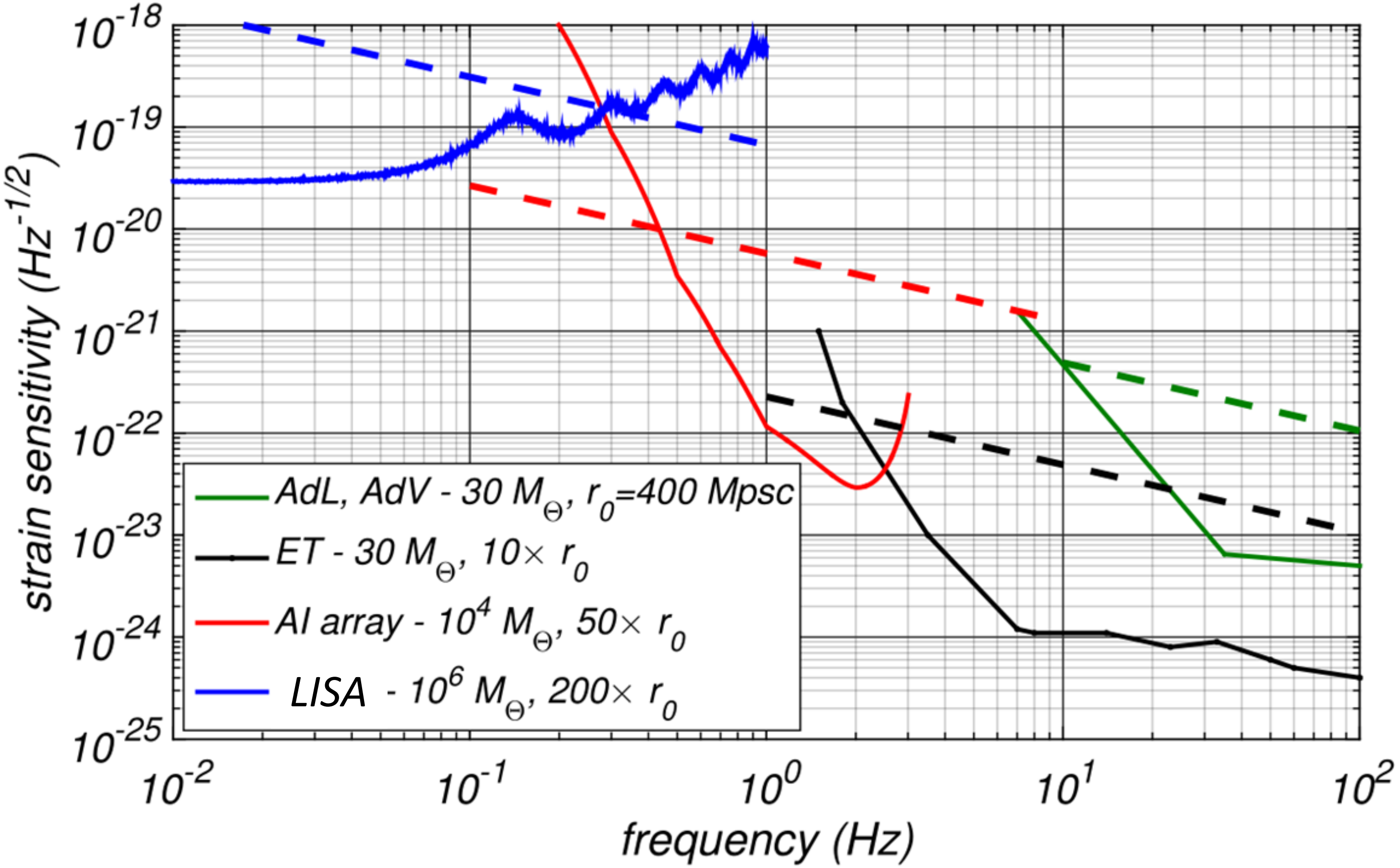


keff	+	-	+	-	+	-	+	-	+
fringe side	+	+	-	-	+	+	-	-	+



Perspectives

- Gravitational wave detection (MIGA project, France)



RG,
[arxiv: 1611.09911](https://arxiv.org/abs/1611.09911)

Perspectives

- Gravitational wave detection (MIGA project, France)

$$\left(S_h(\omega)\right)^{1/2} = \left(\frac{2\eta}{\dot{N}_{at}}\right)^{1/2} \frac{1}{4Lnk\sin^2(\omega T/2)}.$$

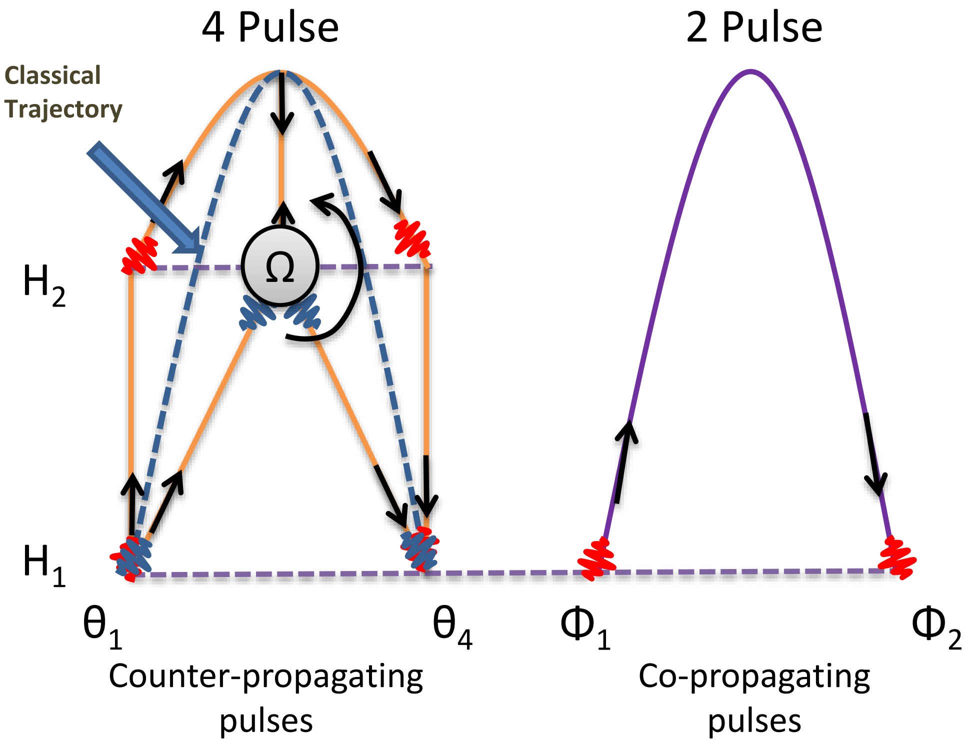
- 10^{12} atoms per second, 20 dB squeezing
- $n = 1000$ momentum transfers of $\hbar k$
- $\sim 1\, nK$ temperature

→ $10^{-20}\ /\sqrt{Hz}$ strain noise

→Huge challenge for cold atom physics !

Efficient noise averaging

Proof of principle with a 2-light pulse interferometer



Gryoscope

$$\Omega = \frac{\theta_4 - \theta_1}{2T}$$

Fountain Clock

$$f = \frac{\Phi_2 - \Phi_1}{2\pi T}$$

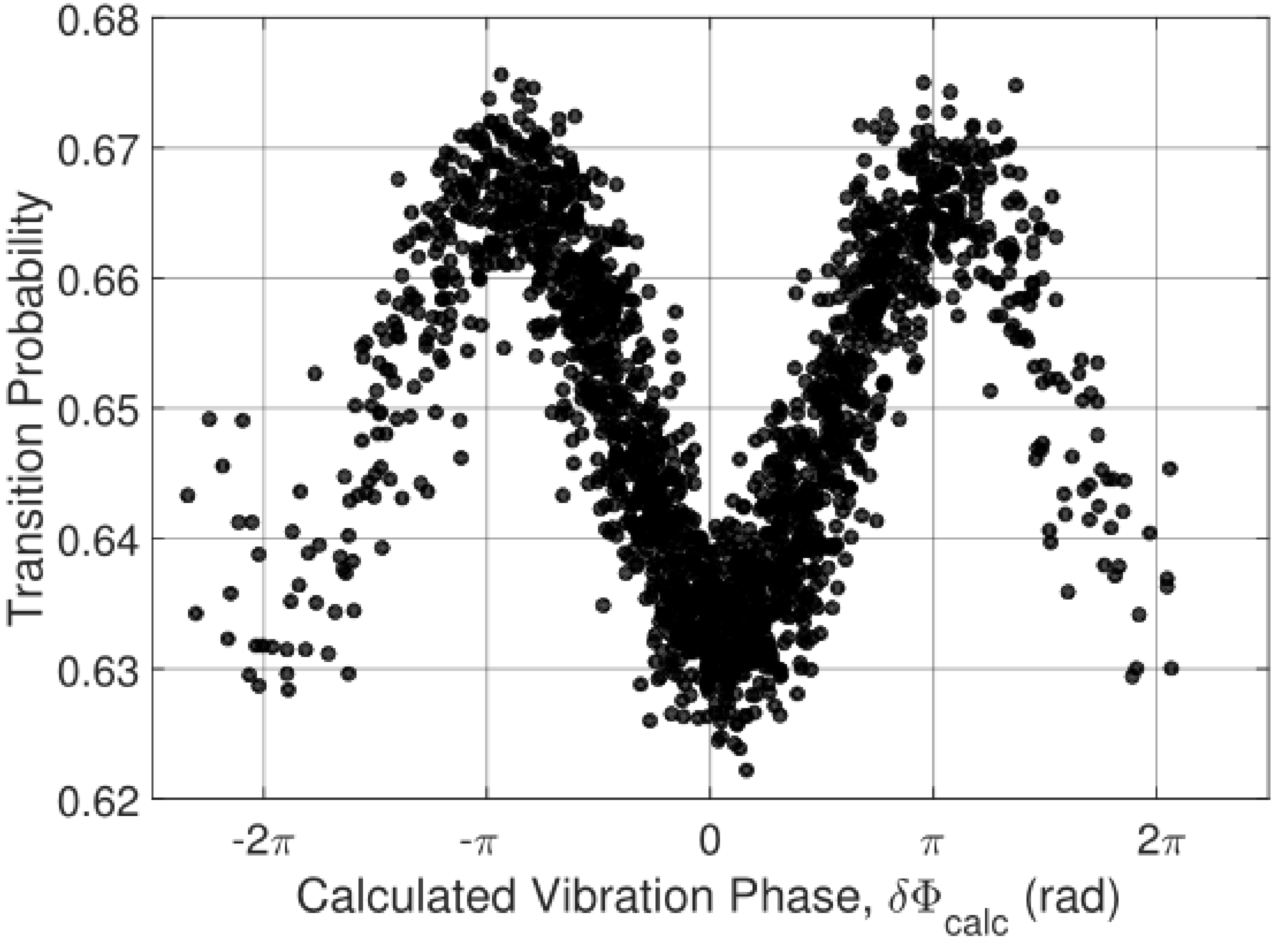
Inertial Noise in Gyro

=

Local Oscillator Noise in Clock

Rejection of vibration noise

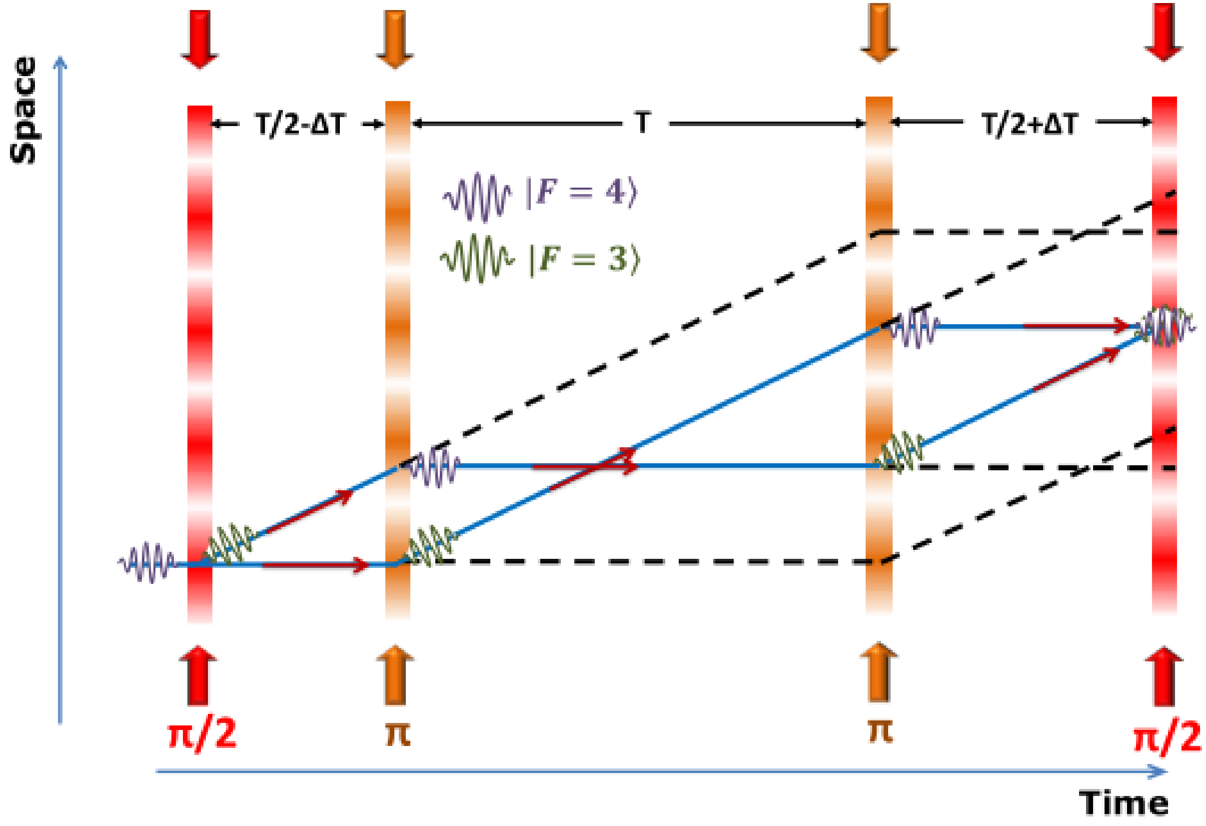
Correlation of the AI with the mechanical accelerometers:



SNR limited by detection noise

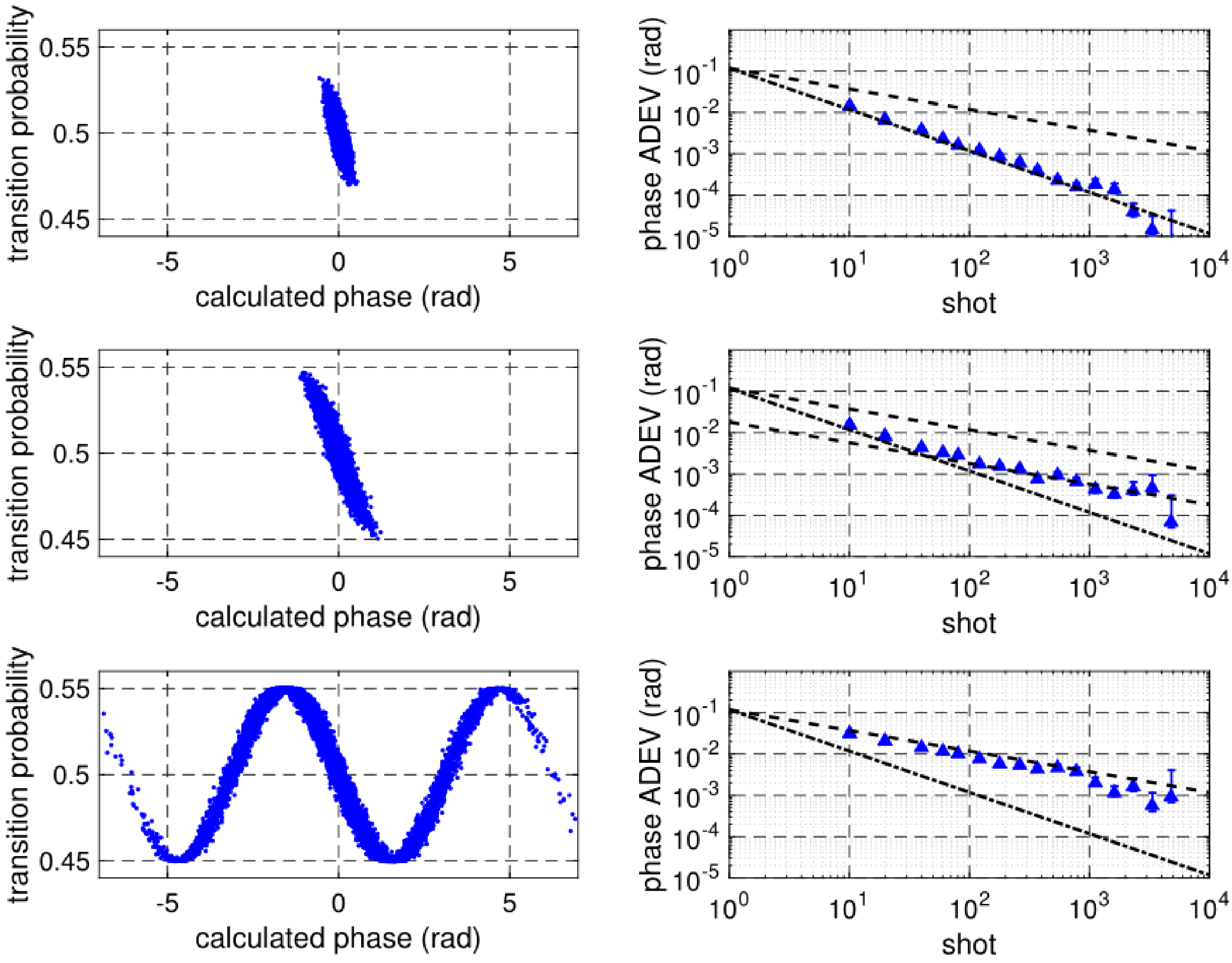
Parasitic interferometers

Introduce an assymetry to avoid recombination of parasitic interferometers



Stockton et al, PRL 107, 133001 (2011)

Limitation to $1/\tau$ due to the AI non-linearity

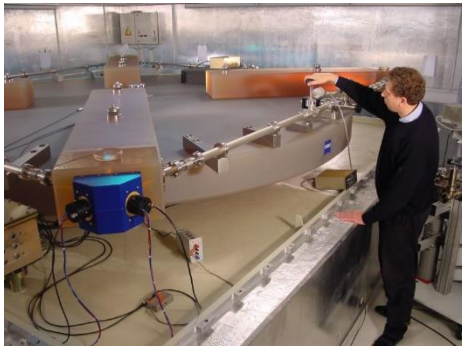


State of the art of gyro technologies

Fiber optics gyro

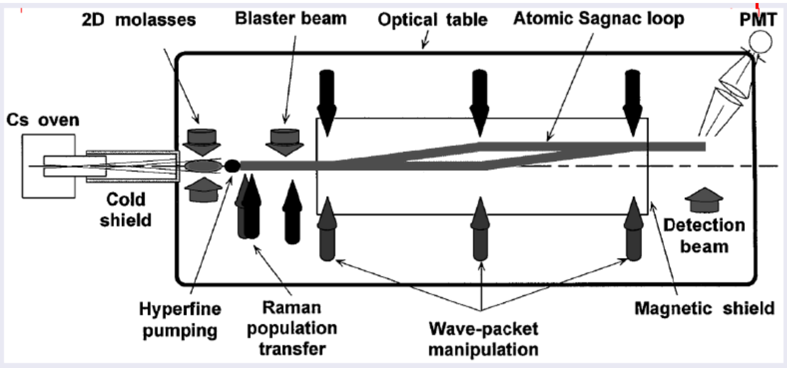
iXBlue FOG 200, navigation
Short term : 6x10^{-8} rad.s^{-1}.Hz$^{-1/2}$
Long term : 2x10^{-10} rad.s^{-1} in 8 days

Gyrolaser



G-Ring 16 m², geoscience
Short term : 3x10^{-11} rad.s^{-1}.Hz$^{-1/2}$
Long term : 6x10^{-13} rad.s^{-1} en 2 h

Atomic beam gyro



Stanford, [Durfee 2006]
Long terme : 5x10^{-10} rad.s^{-1} in 2000s

Cold-atom gyroscope

Gyro I SYRTE : 1x10^{-8} rad.s^{-1} à 2000 s

SYRTE large area gyroscope
Short term : 3x10^{-8} rad.s^{-1}.Hz$^{-1/2}$
Long term : 2x10^{-10} rad.s^{-1} in 8 h