Atom-interferometric gravito-inertial sensors:

Ongoing and future projects

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SYRTE laboratory, Paris Observatory

Workshop on future instruments for gravity-based earthquake early warning

APC, Paris, 10th January 2017

Outline

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- Principle of a cold atom inertial sensor (reminder)

→ Interferometer transfer function

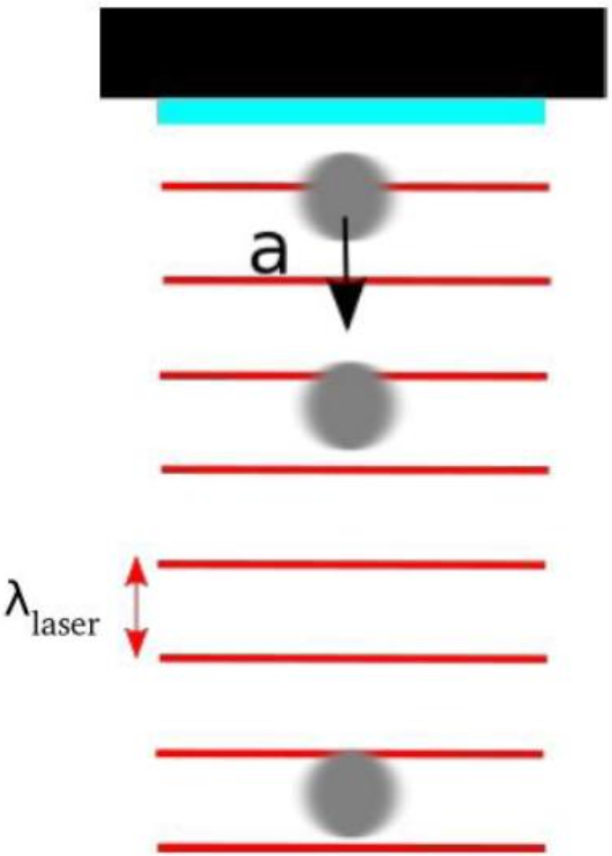
→ Sensitivity curve

- Some ongoing and future projects in France
  - Gravimeter and gradiometer at SYRTE
  - MIGA (large scale gradiometer)

Simplified principle of a cold atom sensor

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

→ Measurement of distance in units of laser wavelength



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

Orders of magnitude :

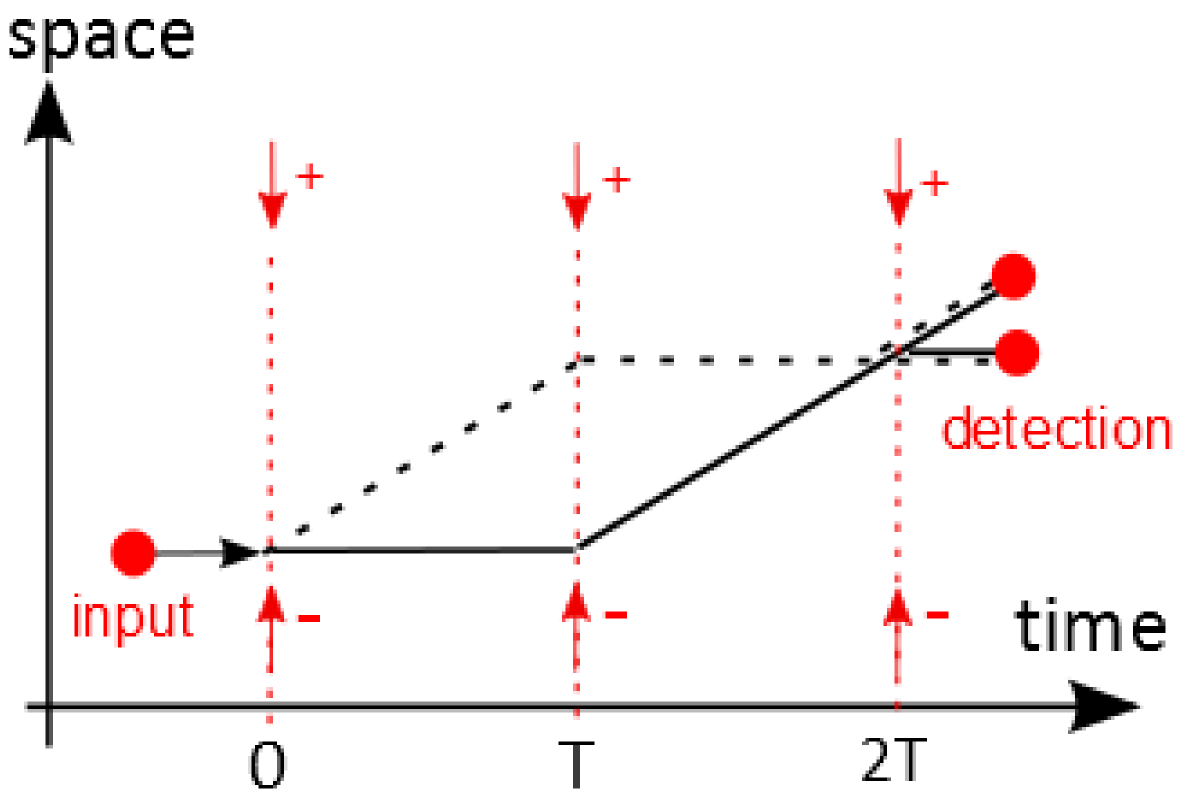
- $T \sim 100\ ms$; $\lambda \sim 0.5\ \mu m$;
- Resolution on the distance $\sim \lambda/100$ (SNR = 100)

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

Concept similar to a free-falling corner cube gravimeter

Principle of Atom Interferometry

- Analogy with a Mach-Zehnder optical interferometer
- Use laser pulses to coherently manipulate a matter-wave



Two photon transitions

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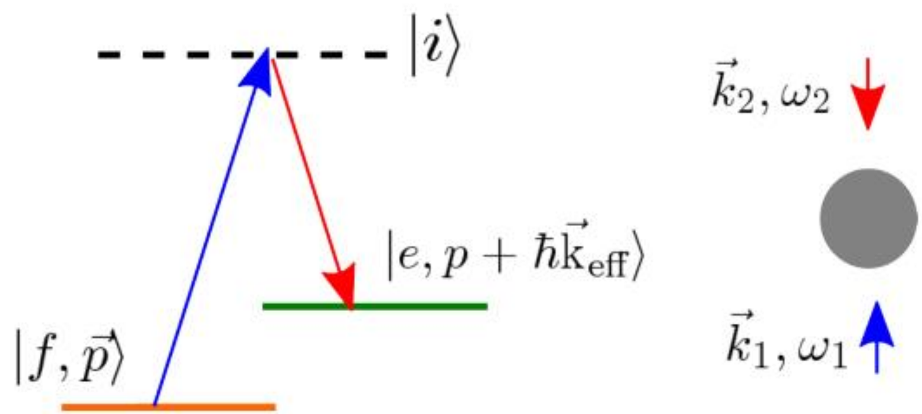
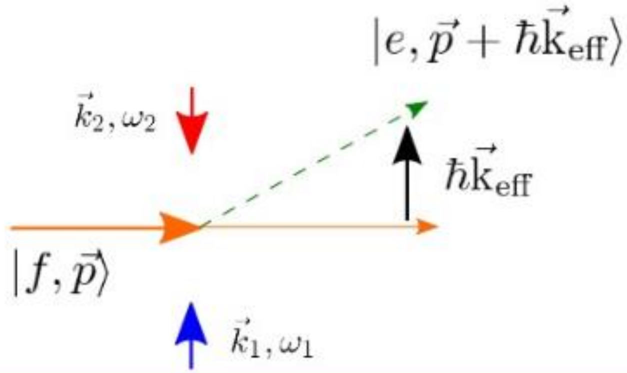
Example : with stimulated Raman transition



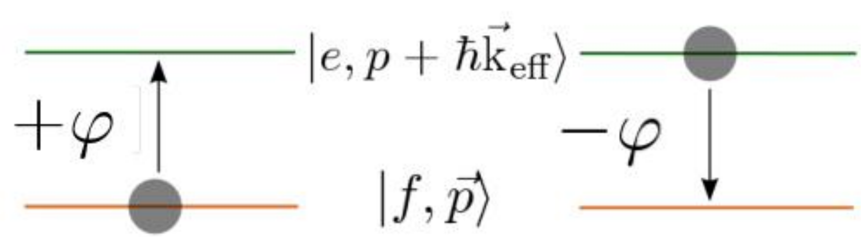
Momentum transfer

$k_{eff} = k_1 + k_2 \sim 1\ cm/s$



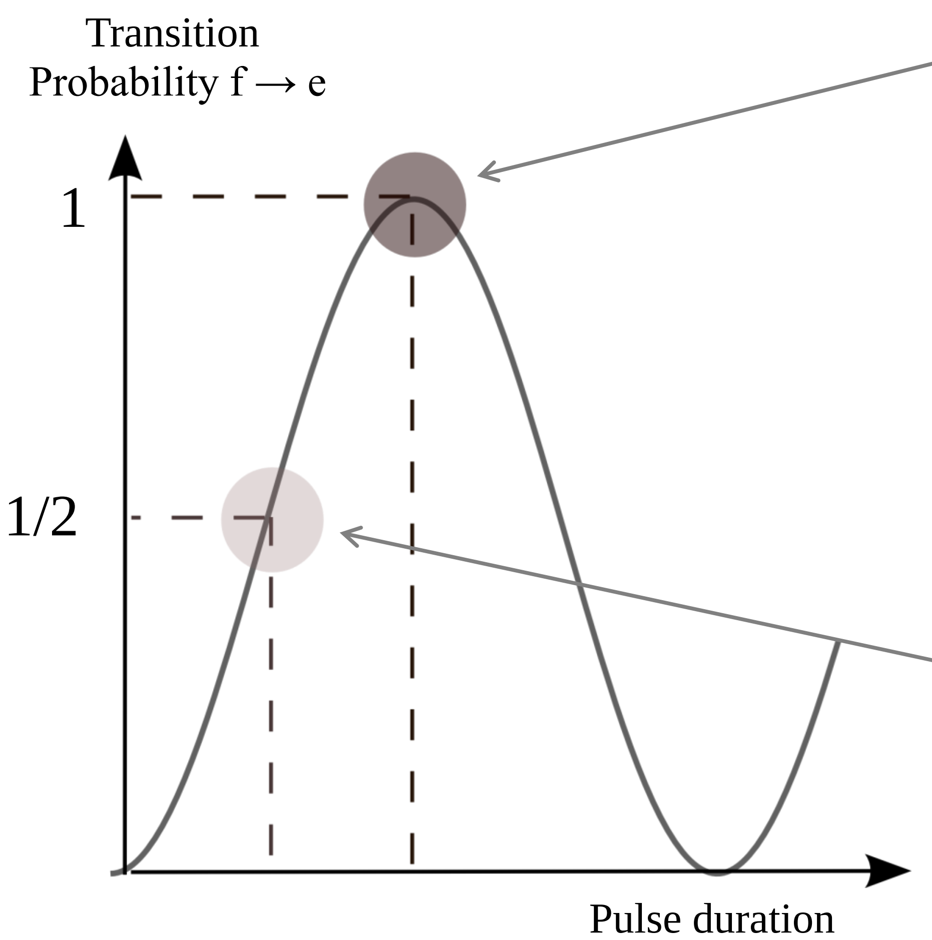
Laser phase difference imprinted on the atoms

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

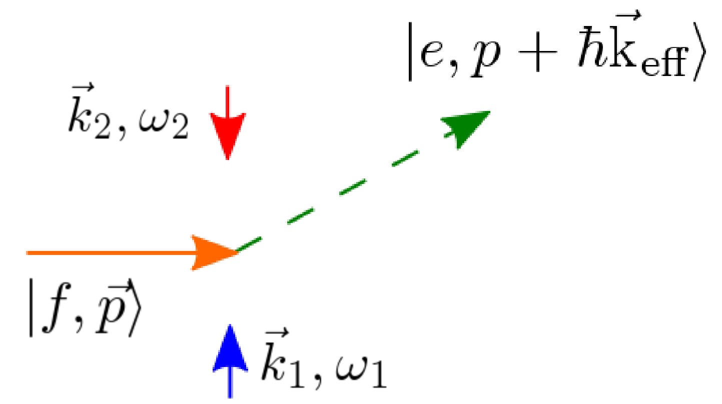


Interferometer building blocks

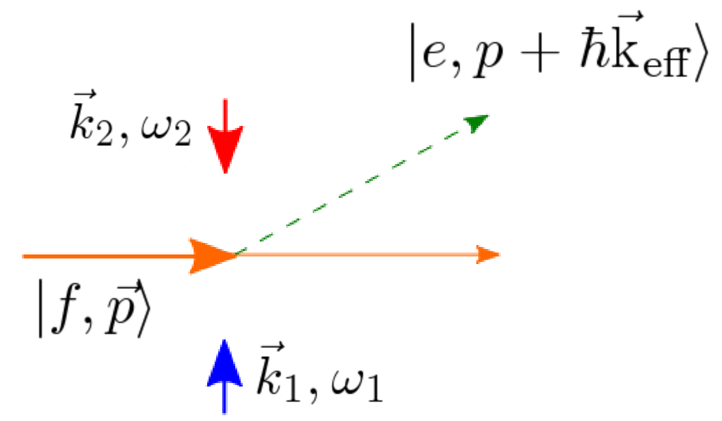
Rabi oscillation between
|f> and |e>



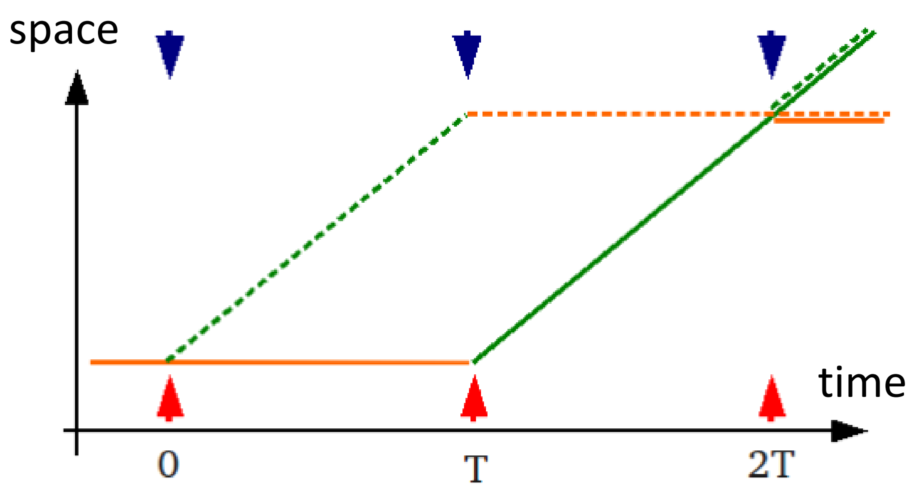
"π" pulse = mirror



"π/2" pulse = beam splitter



Interferometer phase



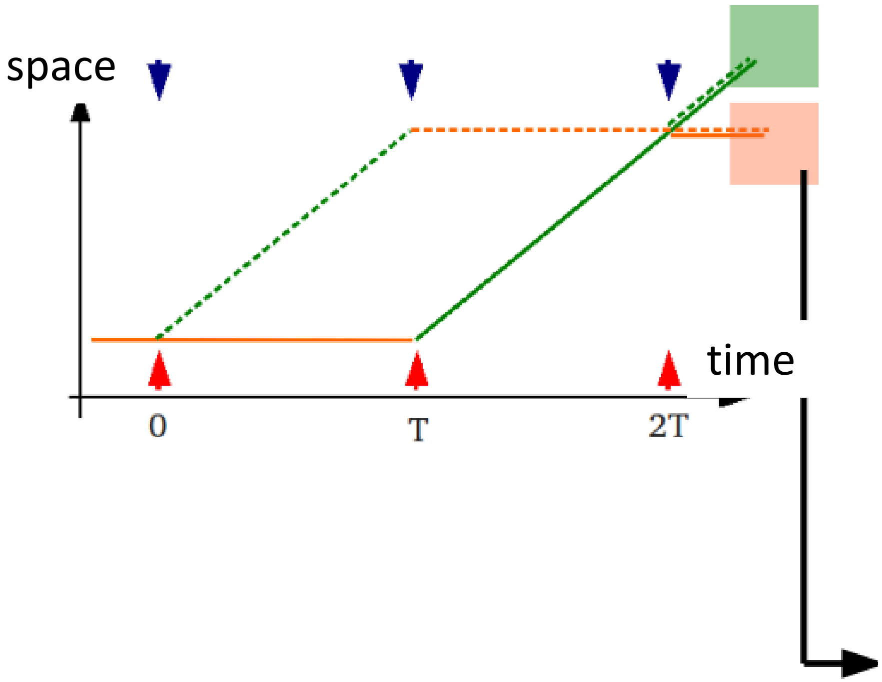
UP $\varphi(0) - \varphi(T) + \varphi(2T)$

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

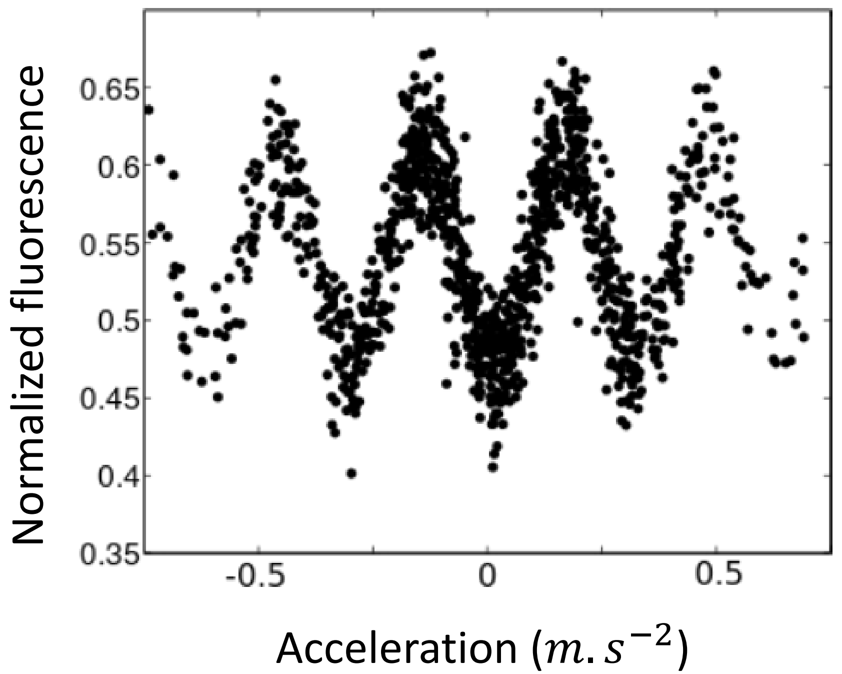
$$\Delta\Phi = \vec{k}_{\rm eff} \cdot \vec{a}T^2$$

Simple picture of the AI : sampling of the atomic trajectory by the lasers at 3 different times.

Measurement of the phase difference



Normalized detection of the atomic populations



Typical values :

- 2T = 200 ms, 10^6 atoms @ 1 µK
- Lasers of ~ 100 mW power, 1 cm beam radius, phase locked < mrad level
- Cycling frequency ~ 1 Hz.

Sensitivity function (transfer function)

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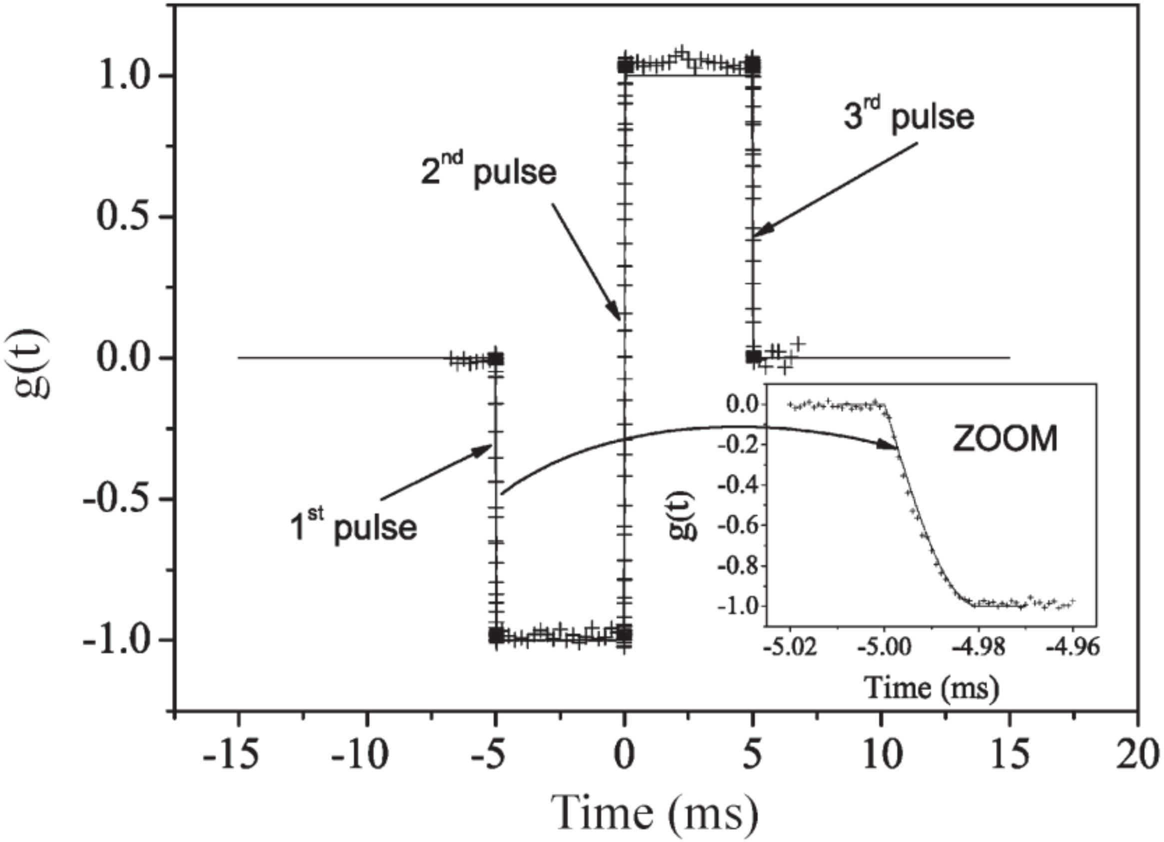
- Response of the atom interferometer to an instantaneous change of (laser) phase

$$g_s(t) = \lim_{\delta\phi \to 0} \frac{\delta\Phi(\delta\phi, t)}{\delta\phi}$$

$$\delta\Phi = \varphi_1 - 2\varphi_2 + \varphi_3$$



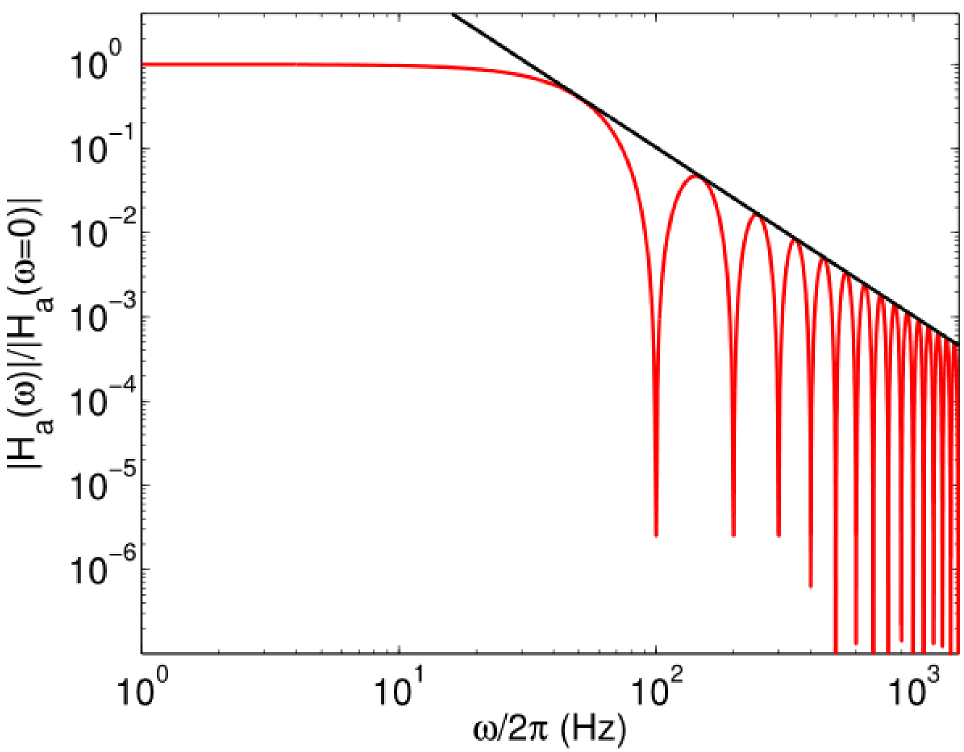
Cheinet et al, IEEE 57, 1141 (2008)

Sensitivity function (transfer function)

Phase sensitivity function in Fourier space: $H(\omega) = 4\sin^2(\frac{\omega T}{2})$

Acceleration transfer function :

$\varphi(t) = k_{eff}\, x(t) \rightarrow \ddot{\varphi}(t) = k_{eff}\, a(t) \rightarrow H_a(\omega) = \frac{k_{eff}}{\omega^2} H(\omega) = k_{eff} T^2 sinc^2(\frac{\omega T}{2})$

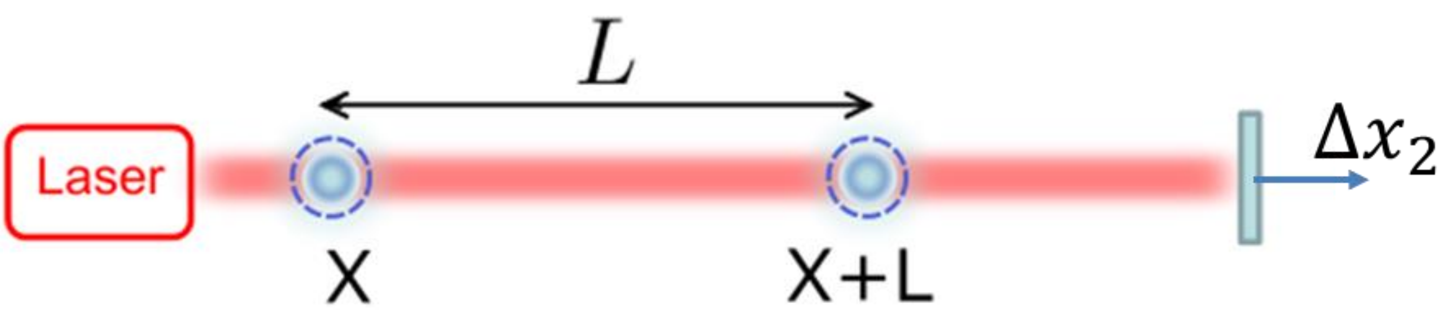


Second order low pass filter,

cutoff frequency = 1/(2T)

AI gradiometer

- Measurement of the differential phase between 2 physically separated AIs
- Gradiometer signal = $\phi(X) - \phi(X+L)$ = $k_{eff}T^2(a(X) - a(X+L))$



- Position noise of the retro-reflecting mirror is common → rejection of Δx_2.

Shot noise limit for a gradiometer

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Shot noise limited phase sensitivity for each interferometer: $$S_\phi(\omega) = \frac{\eta}{\dot{N}_{at}} \left(\frac{\mathrm{rad}^2}{\mathrm{Hz}}\right)$$

$\dot{N}_{at}$ =Cold atom flux

η = squeezing parameter ($\eta < 1$ for sub shot noise detection)

Gravity gradient sensitivity :
(in s^{-4}/Hz)

$$S_\Gamma(\omega) = \frac{2\eta/\dot{N}_{at}}{\left(nLk_{eff}T^2 sinc^2(\omega T/2)\right)^2}$$

n = number of two photon transitions

L = baseline (distance bewteen the two atom clouds)

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  - **Gravimeter and gradiometer at SYRTE**
  - MIGA (large scale gradiometer)

Cold-atom gravimeter (2003 →)

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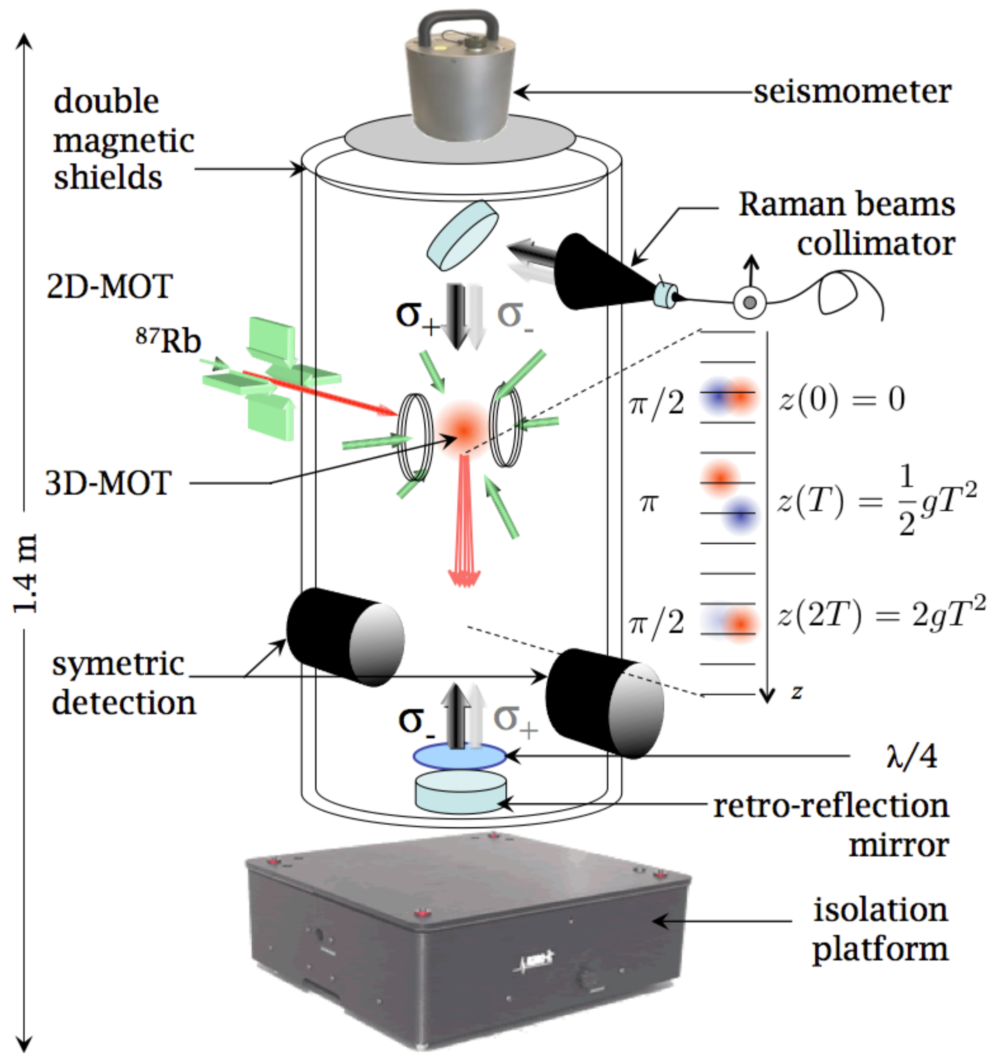

Cold-atom gravimeter (2003 →)

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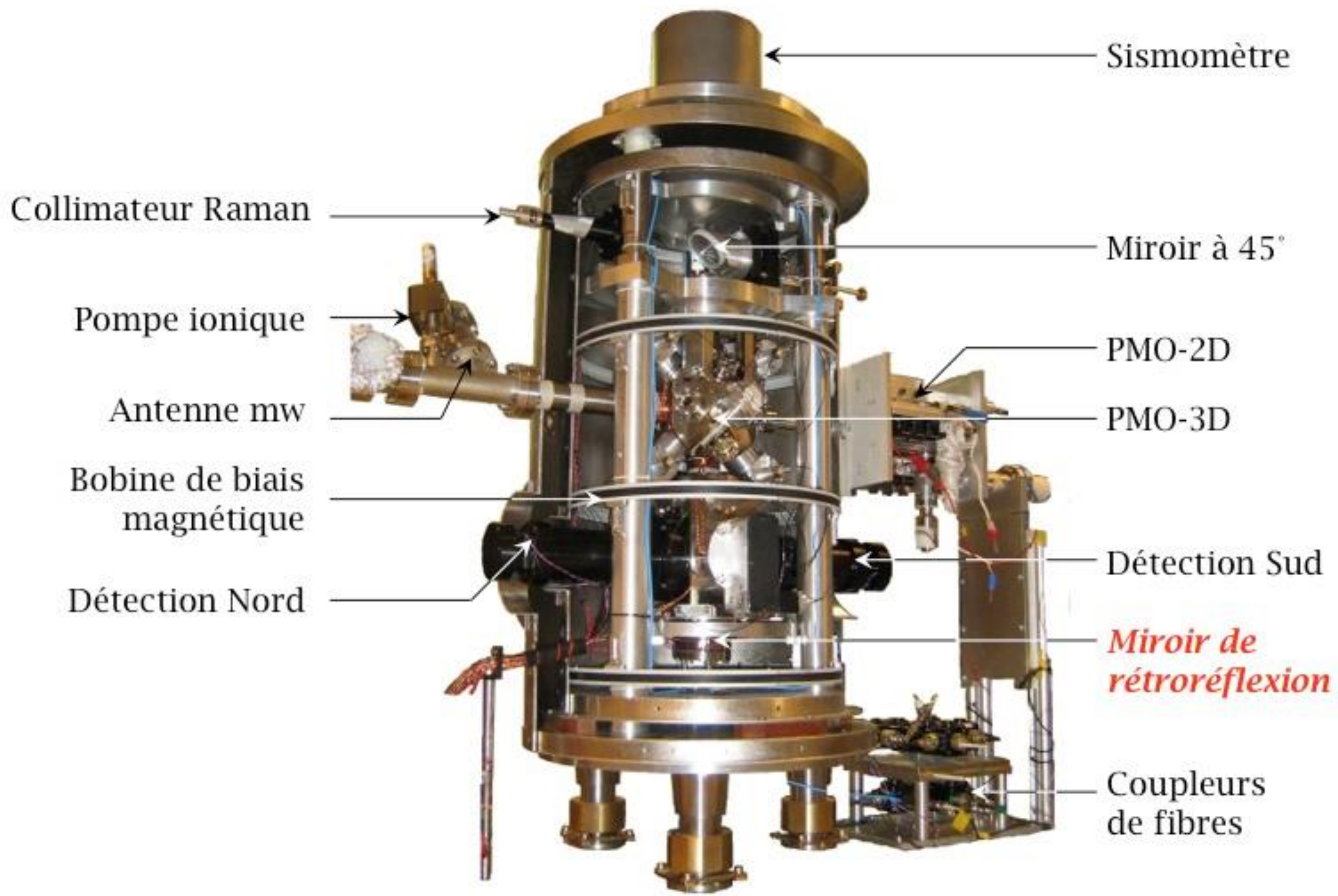
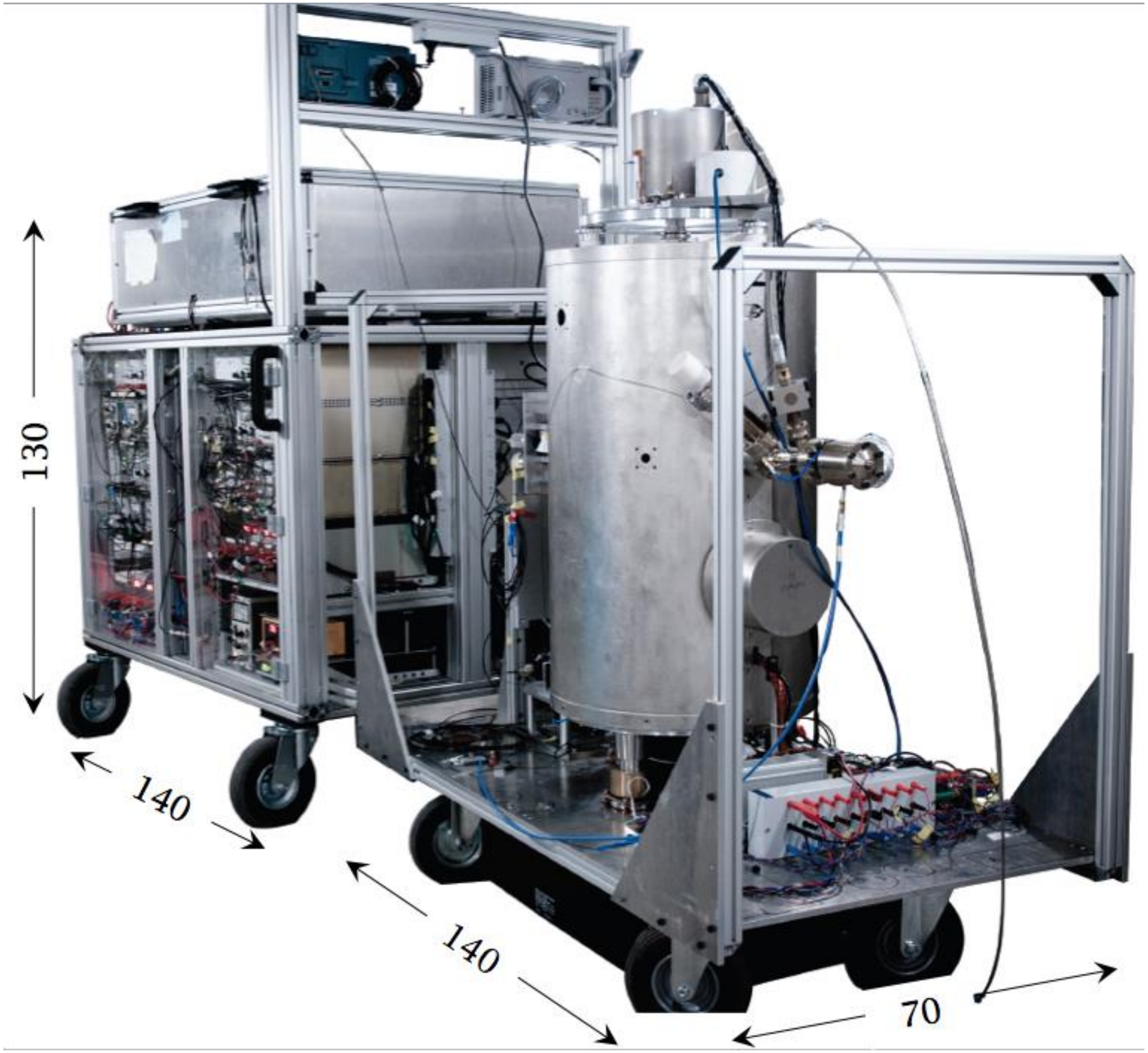


Transportable gravimeter



Sensitivity, accuracy

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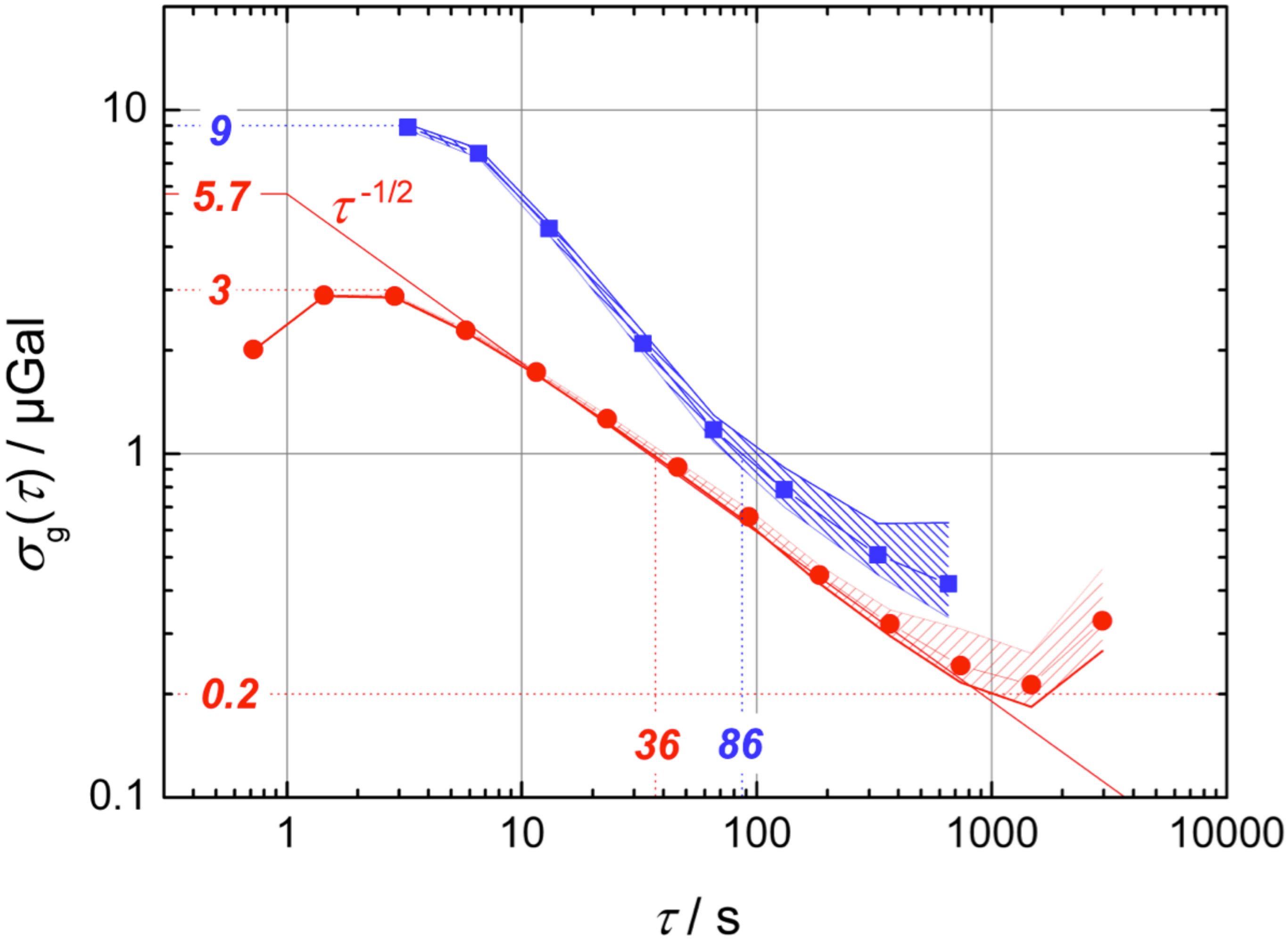

P. Gillot et al, Metrologia 51, L15-L17 (2014)

Sensitivity, accuracy

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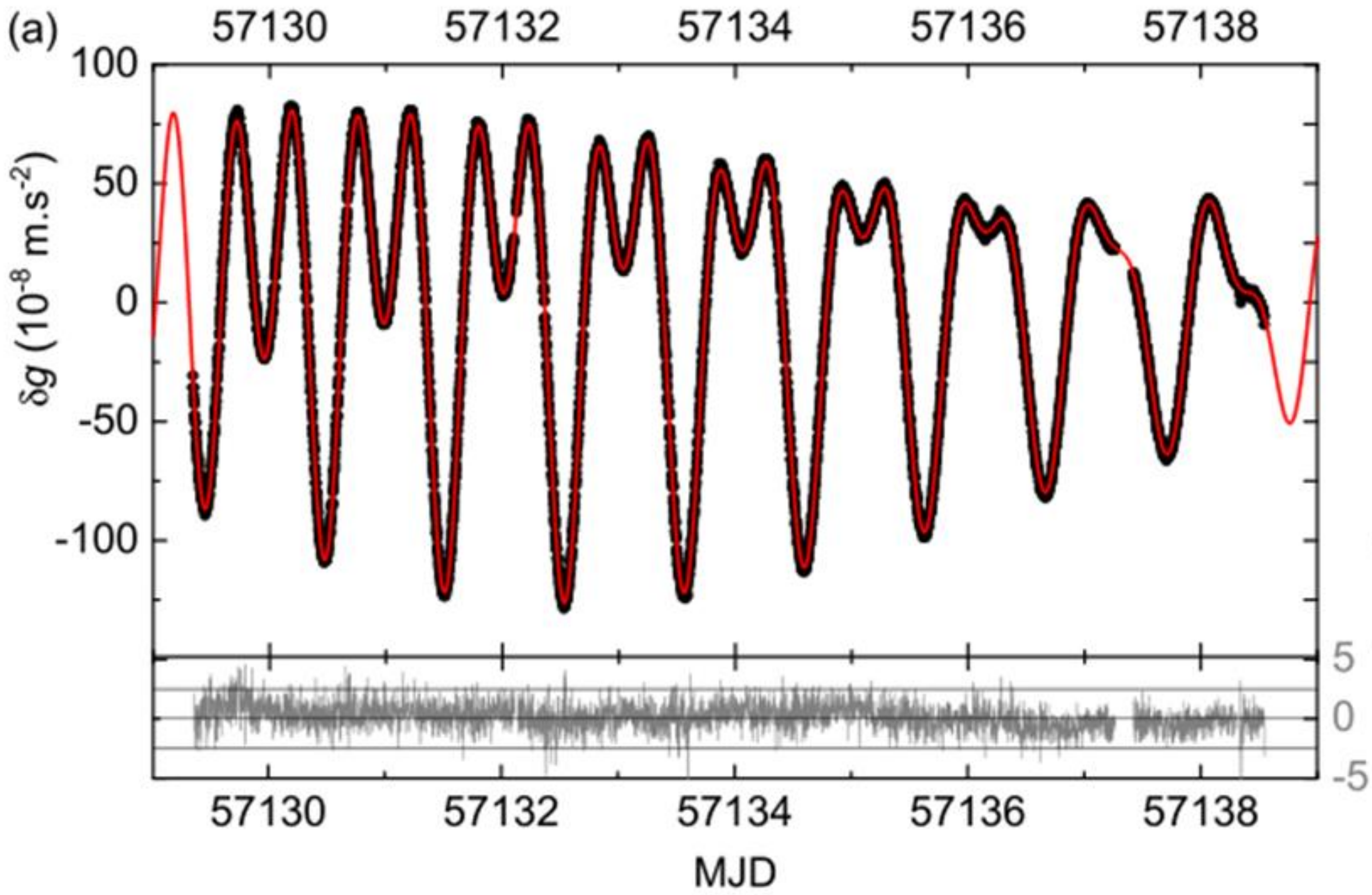
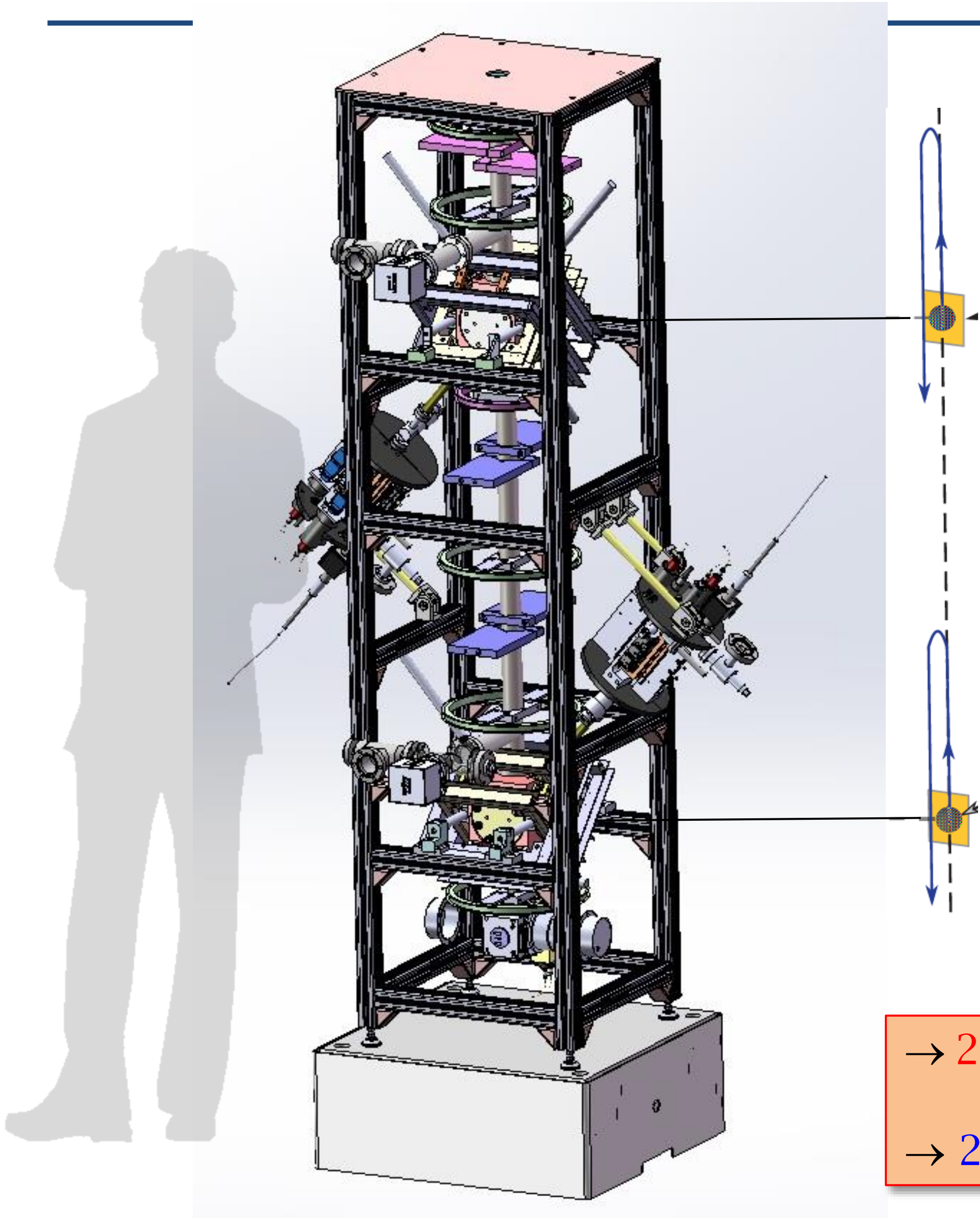


Accuracy : $4\ \mu Gal$ (Louchet-Chauvet et al, NJP 13, 065025 (2011))

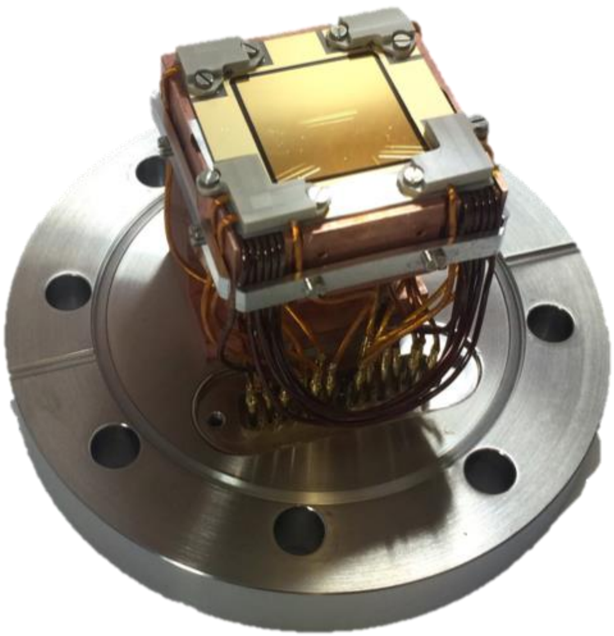
SYRTE atomic gradiometer (2016→)

Langlois et al, Phys. Rev. A 96, 053624 (2017)

AtoM Interferometry dual Gravi-GradiOmeter: AMIGGO



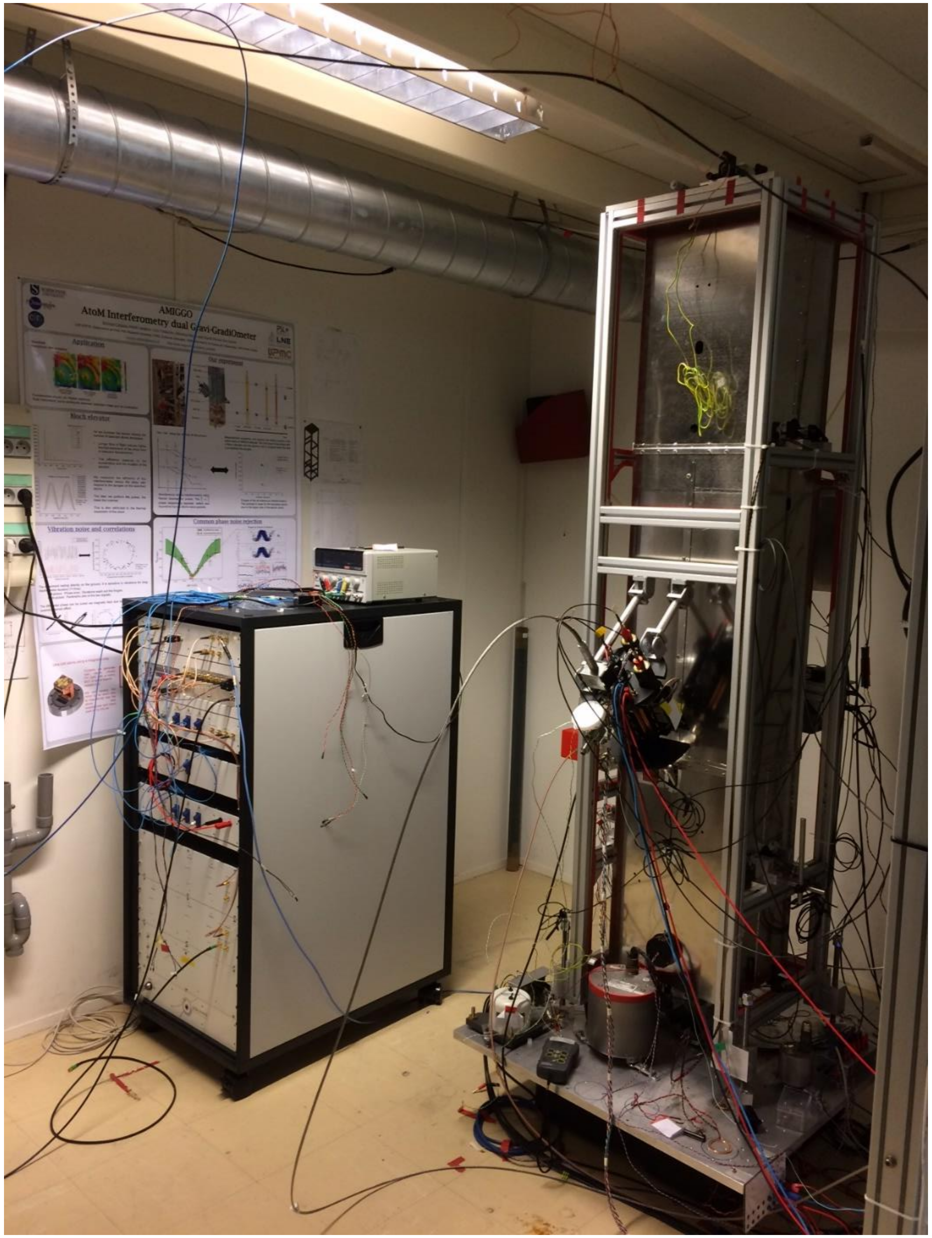
Ultracold atoms
Fast generation on atom chips



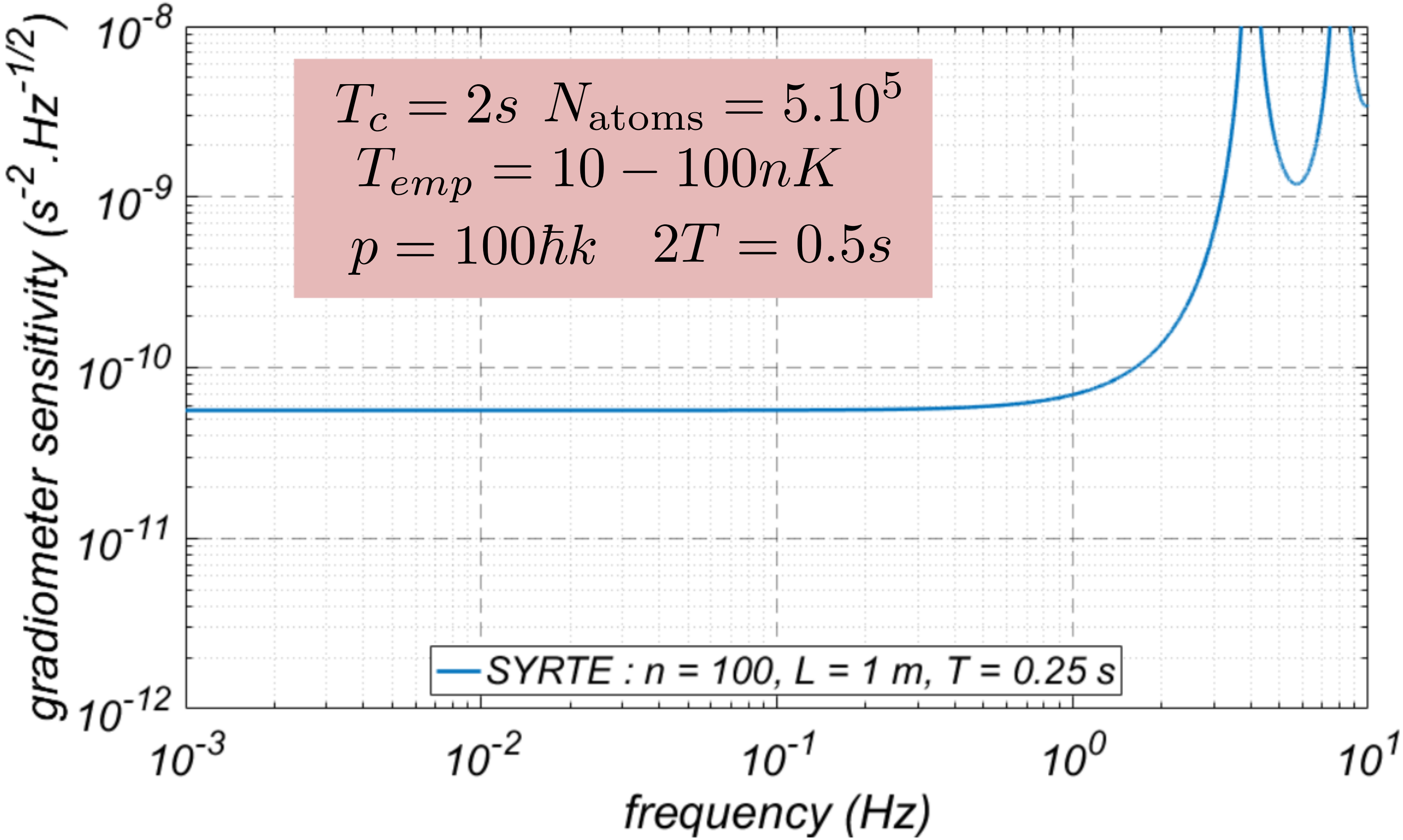
→ 2 ultracold Rb clouds obtained on 2 chips

→ 2 clouds launched with elevator

AtoM Interferometry dual Gravi-GradiOmeter: AMIGGO



SYRTE gradiometer target sensitivity



The MIGA project :

Matter wave laser Interferometric Gravitation Antenna

References

- *R. Geiger et al, arXiv:1505.07137 (2015)*
- *B. Canuel et al, Proceedings SPIE,* arXiv:1604.02072 (2016)

The MIGA project

- 10 years (2013 – 2023), 9 M€, 13 research institutes, 2 companies
- **Goal : precision gravity measurements with Atom Interferometry (AI)**
- Design and realization of an instrument for 2 applications:

1. *Monitoring of underground mass distributions*

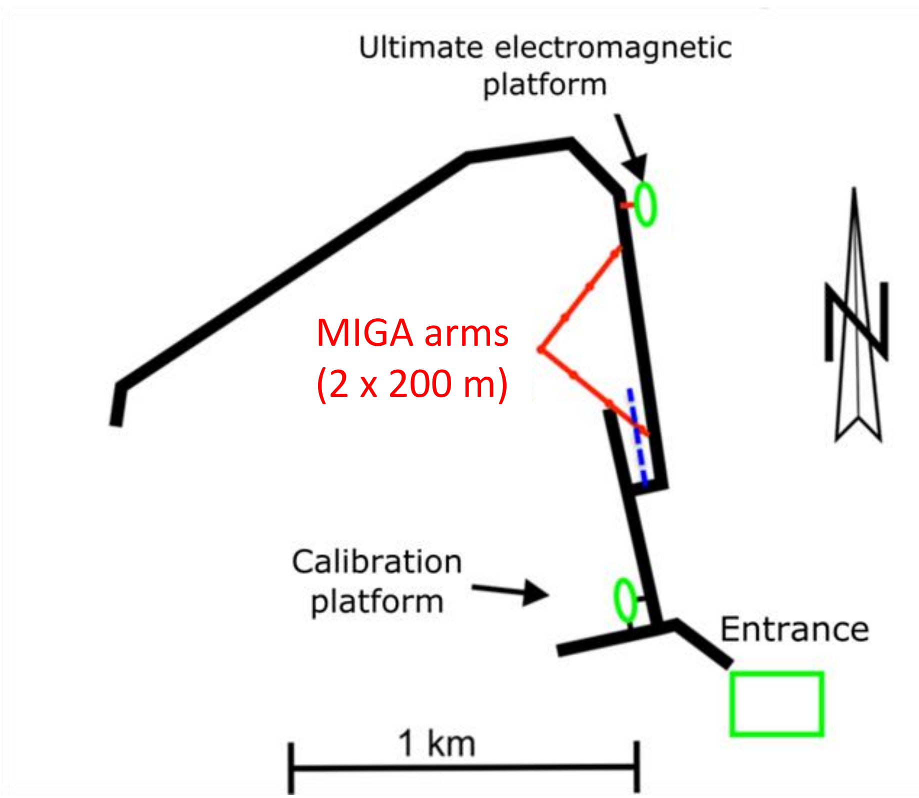
   → Applications: geophysics, hydrology

2. *Test setup for applications of AI to gravitational wave (GW) detection*

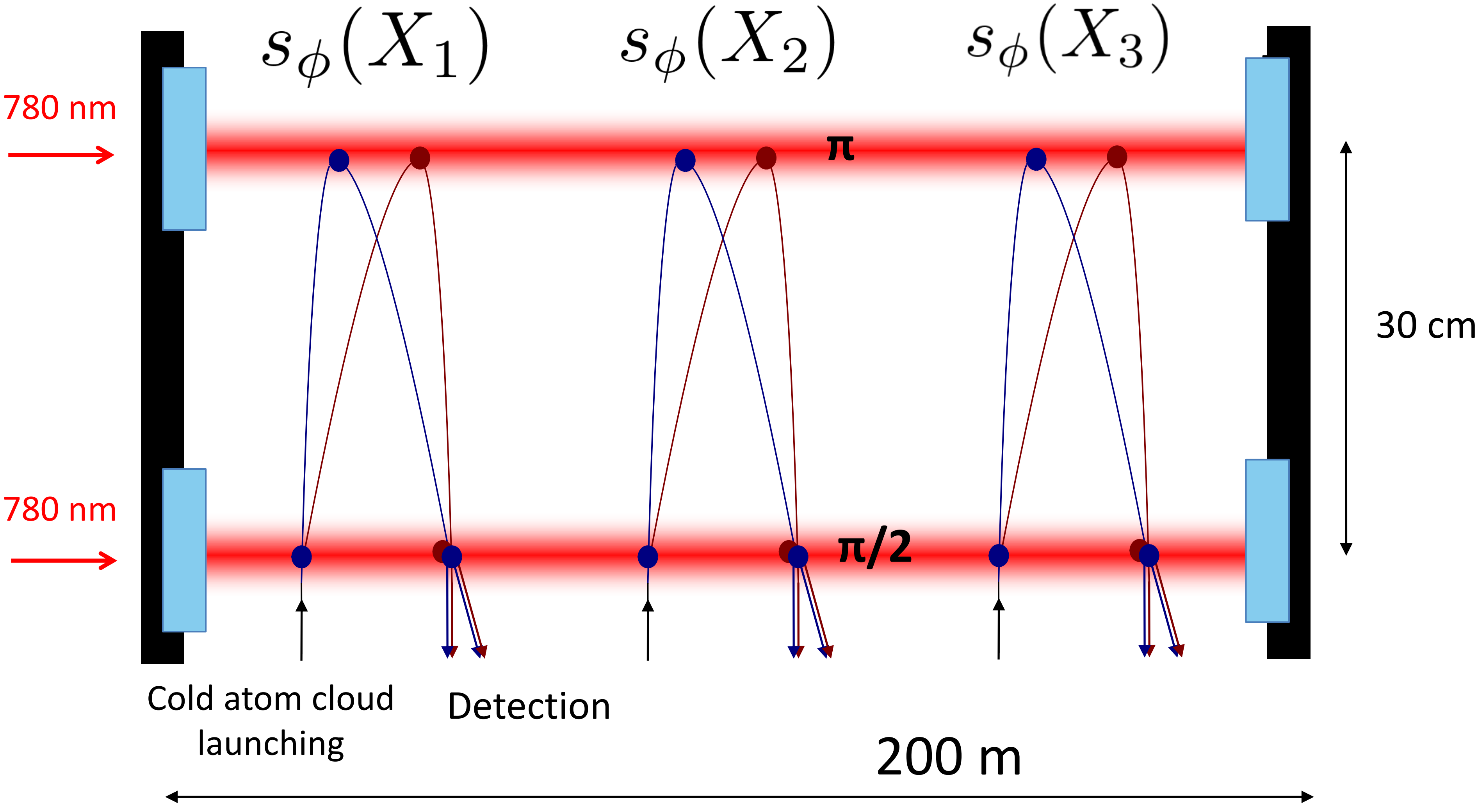
Overview of the MIGA project

Implementation site

- Low noise underground laboratory
- Site of (hydro)-geological interest



MIGA geometry

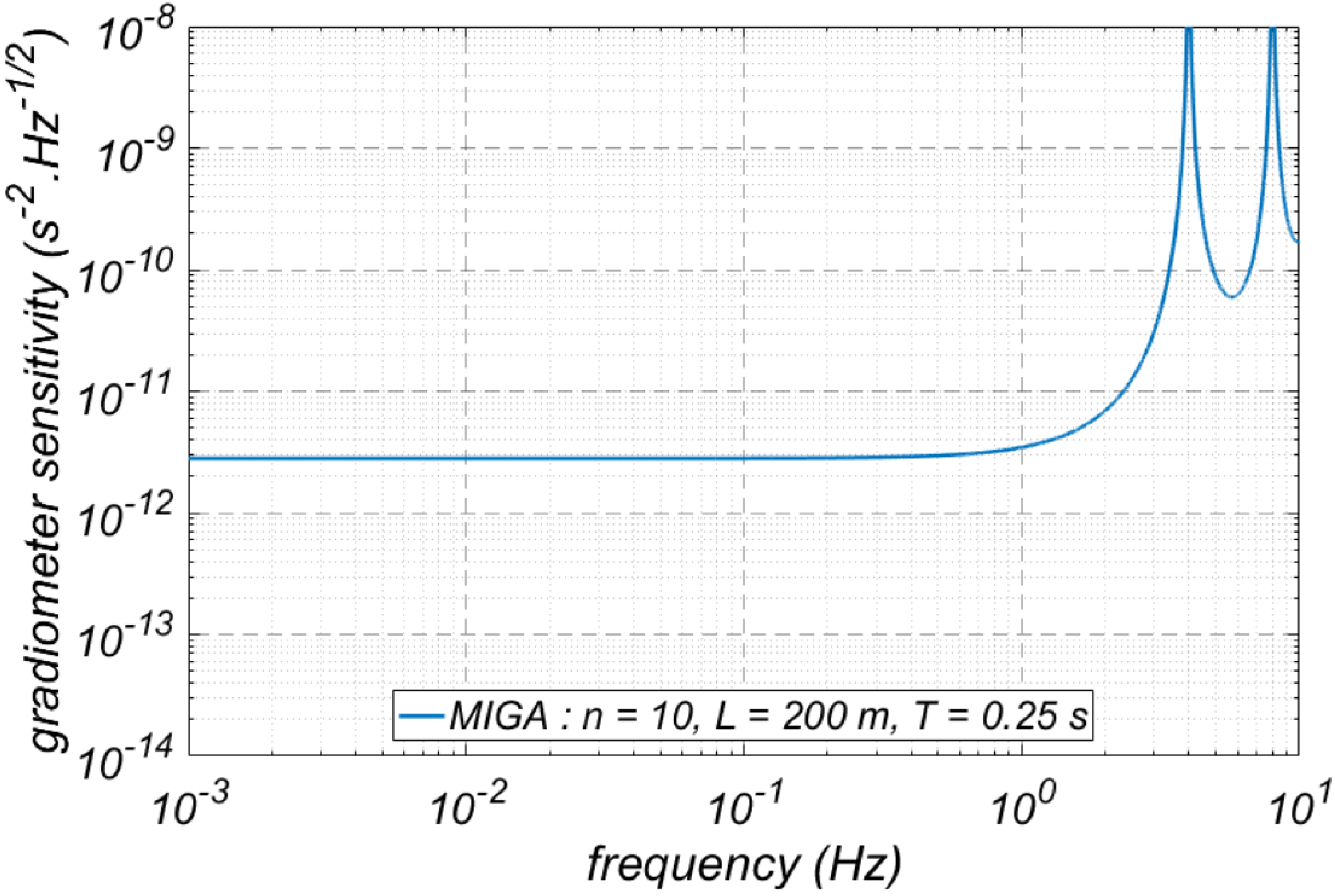


MIGA main subsytems

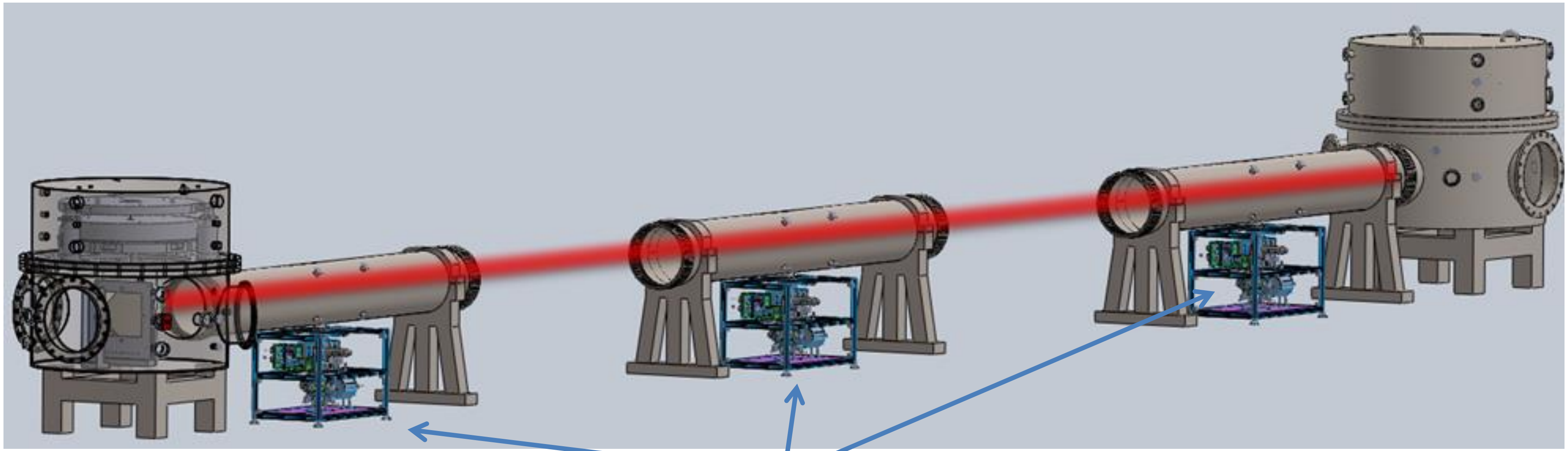
- LP2N (Talence, PI): vacuum systems, coordination of the project
- SYRTE (Paris) : cold atom source and detection system, AI expertise
- ARTEMIS (Nice): cavity mirror suspensions, GW detection expertise
- µQuans (Talence): laser systems
- LSBB (Rustrel): tunnels & site management, geophysics expertise

MIGA installation at LSBB : mid 2018

MIGA target sensitivity

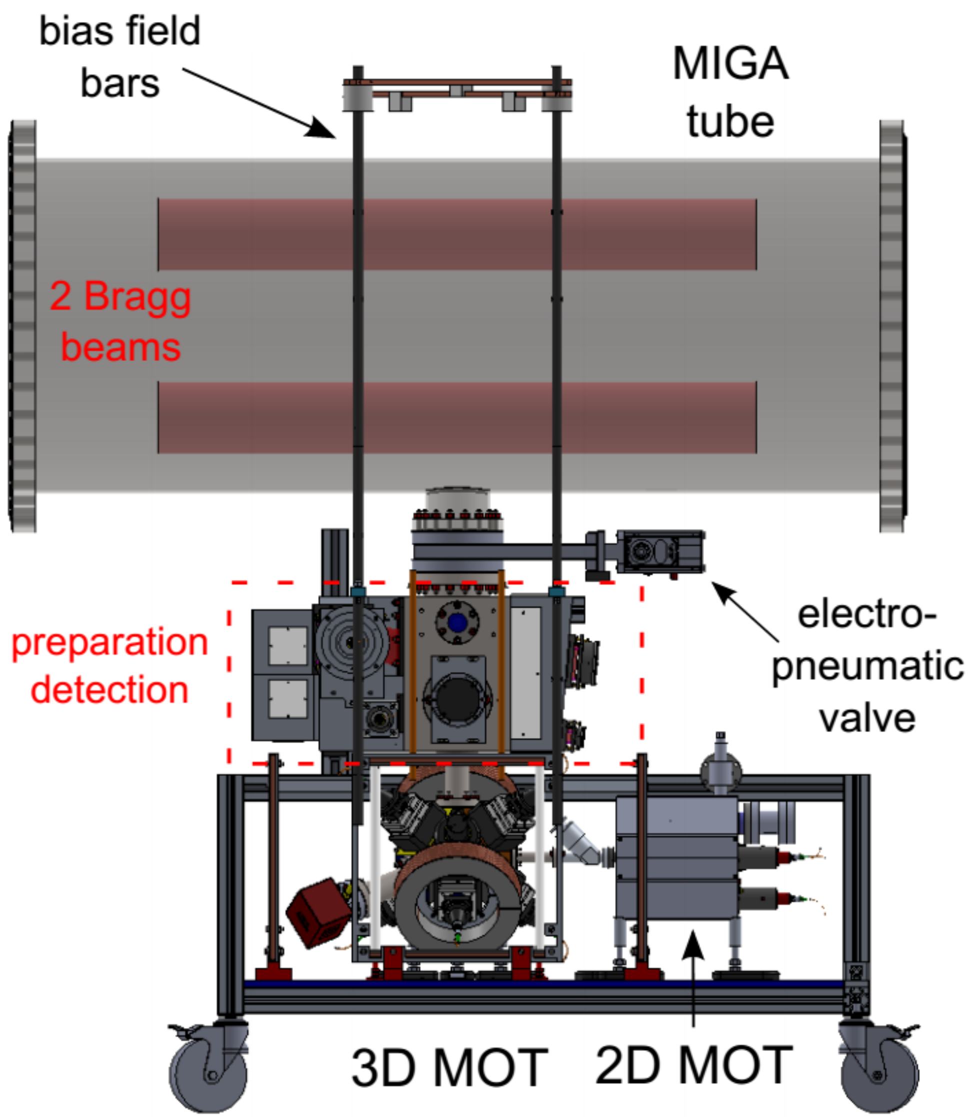


MIGA vacuum system (L2PN)



AI sensors

Cold atom source (SYRTE)



10^8 atoms at 2 μK

launched at 4 m/s

MIGA : status and perspectives

- First cold atom source delivered by SYRTE to LP2N (June 2015)
- Beginning of the digging of the MIGA galleries at LSBB (Spring 2018)
- MIGA installation at LSBB in 2020
- MIGA commissioning and data runs: 2021-2023
- Plans for a design study of a larger infrastructure at European scale (ELGAR).

Conclusion

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- Technology developped for more than 15 years at SYRTE
- Metrological expertise, industrial transfer (µQuans company)
- Large-scale French ongoing project: MIGA (PI: LP2N laboratory)

Requirements for an early-warning Earthquake system ?

- Gravimeter: need to resolve < 1 nm/s^2 in 100-300 s

→ seems difficult currently with an atomic gravimeter (vibration limit)

- Gradiometer: specifications are within reach, but needs technology development
- Other experiments of potential interest: gyroscope-accelerometer ?

→ Combine two-axis acceleration and rotation data: interesting ?

Thank you for your attention

Extra slides

Perspectives

- Industrial transfer (e.g. muquans in France; AO Sense in California)

- Long term stability : $4 \times 10^{-10}\ g$; accuracy: few $10^{-9}\ g$; market : geophysicits
- 15 years of academic research + 5 years of development

4-light pulse gyroscope

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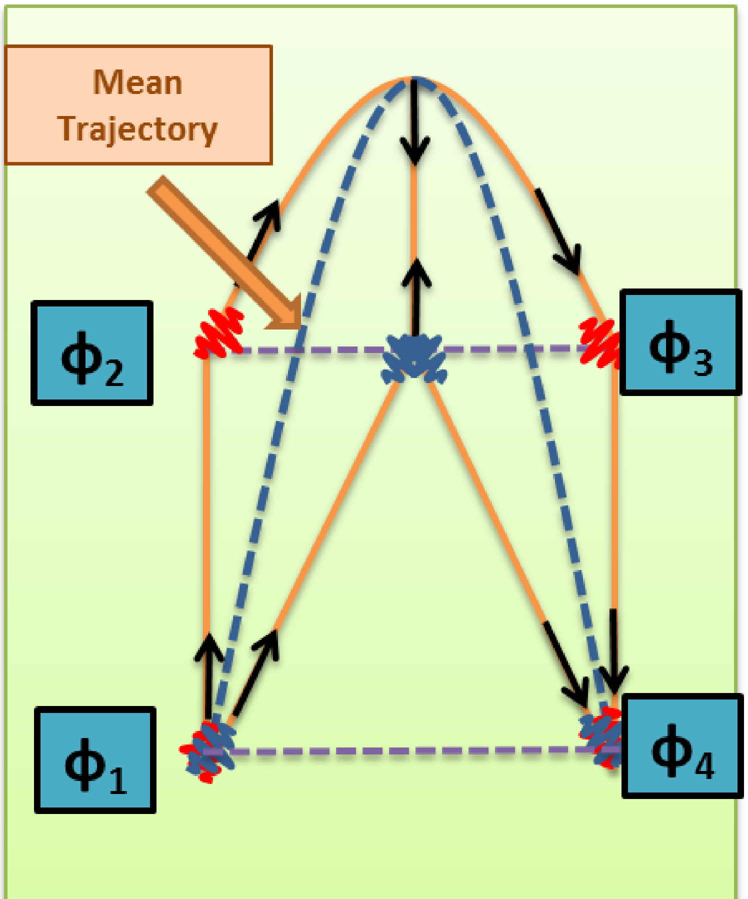
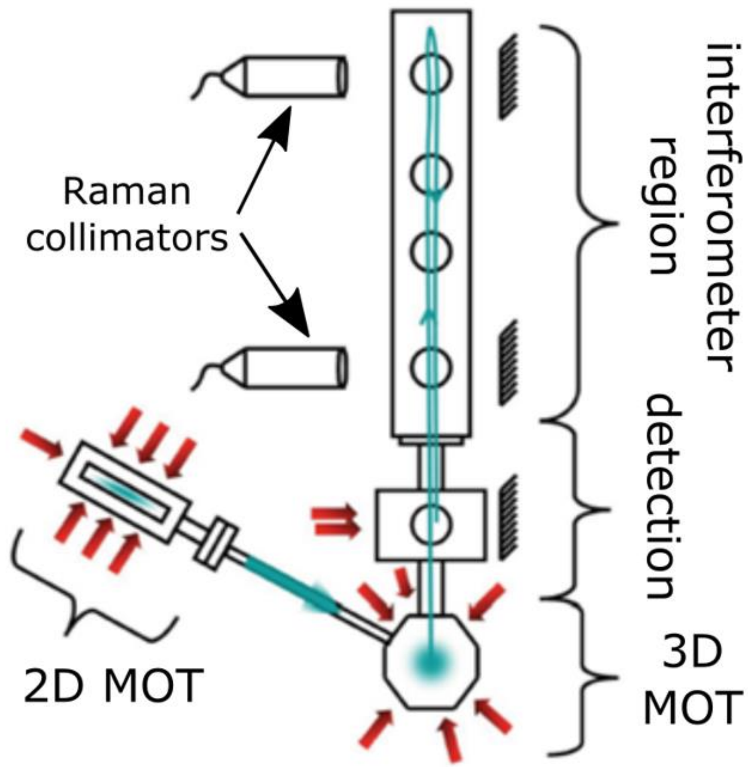


« Butterfly » configuration



Scale factor of the gyroscope

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

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

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

$1\ rad.s^{-1}$ rotation signal → $5 \times 10^6\ rad$ phase shift

Experimental setup

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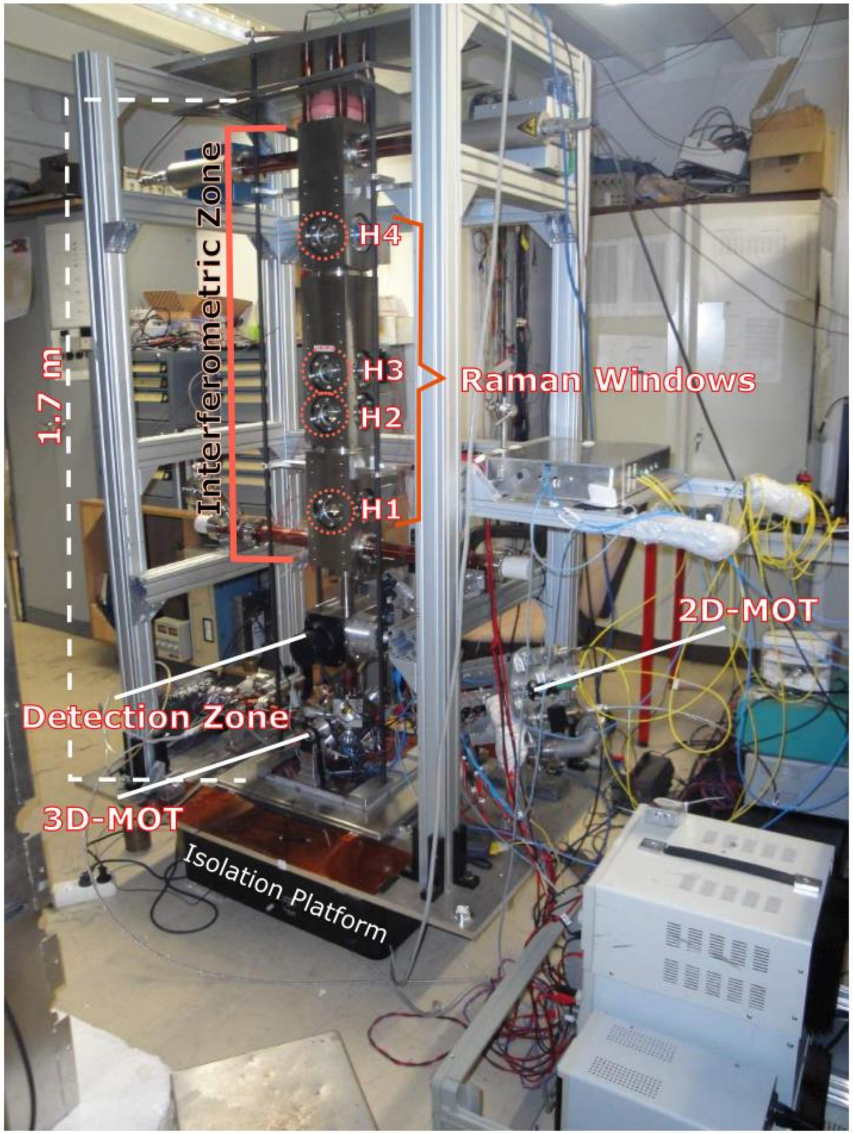

I. Dutta, PhD Thesis

- 4×10^7 Cesium atoms @ 1.2 µK launched vertically at $5\ m.s^{-1}$
- Relative alignement of the beams < 3 µrad
- Mitigation of vibration noise

→passive isolation platform (>0.4 Hz)

→ noise rejection with classical sensors

Rejection of vibration noise

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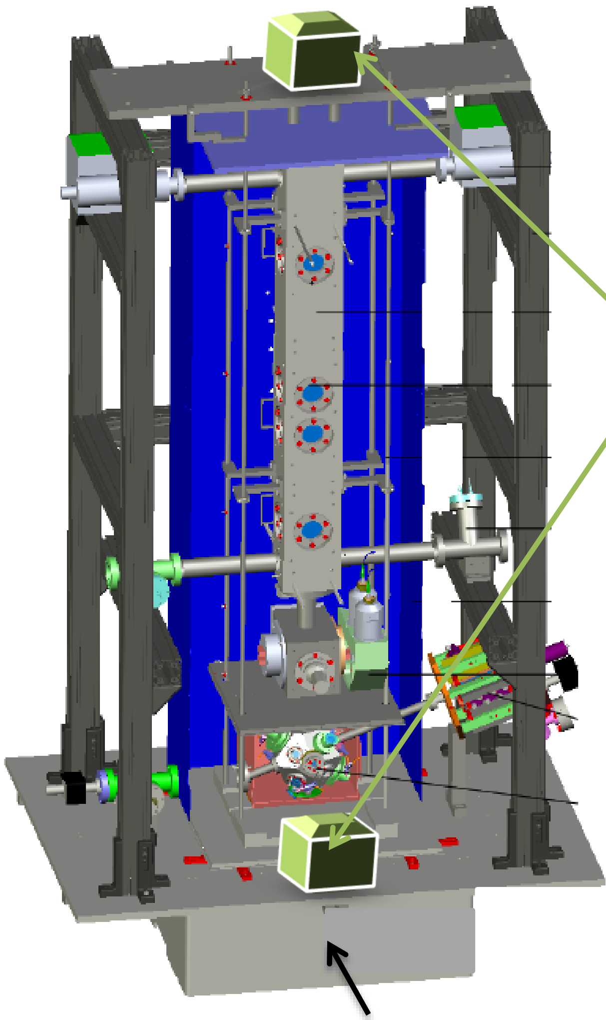

Vibration isolation platform

Measured vibrations → AI transfer function → Calculated phase

feedback

AI

seismometers

→rejection efficiency ≈ 20

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

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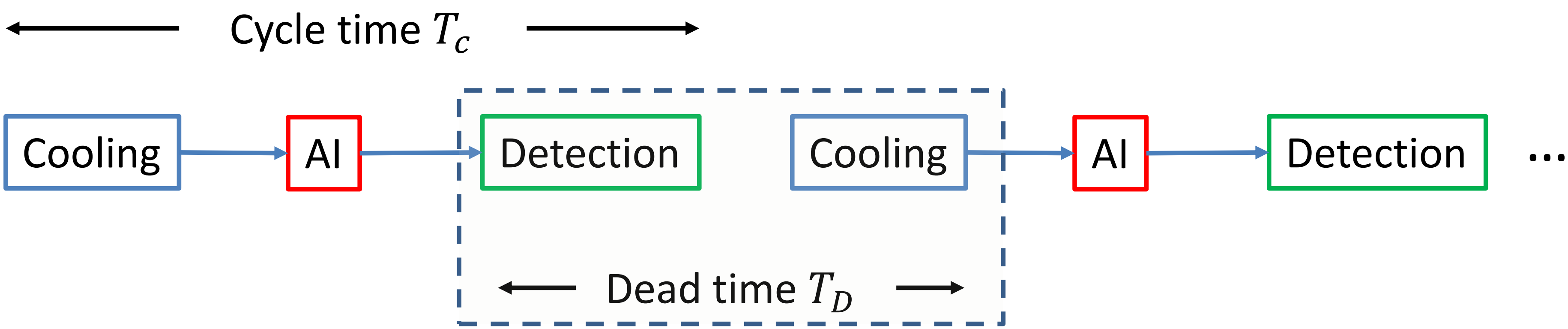
Demonstration of a cold atom sensor without dead times

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

Dead times in quantum sensors

- Sequential operation of cold atom interferometers

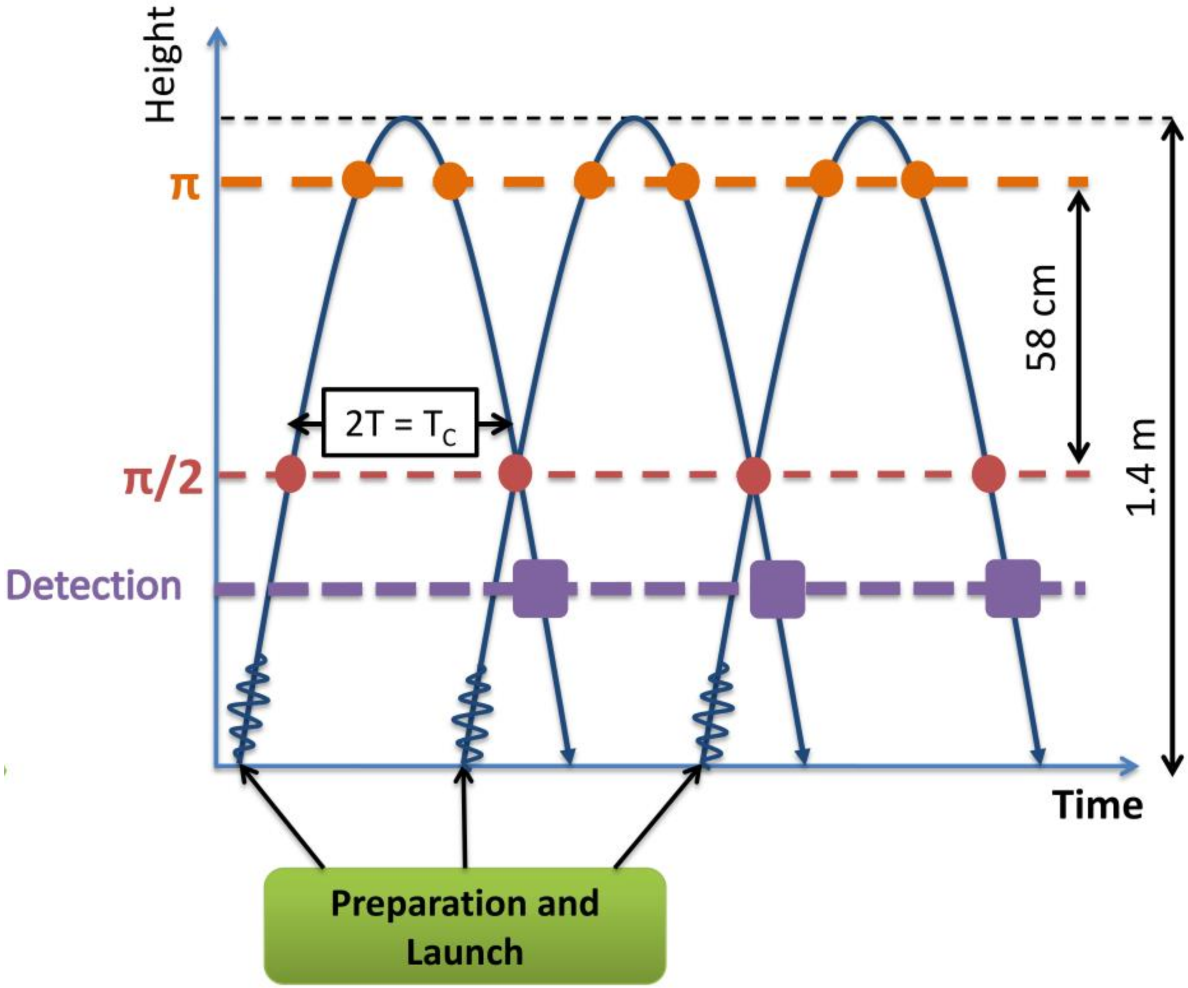


Dead times → (inertial) noise aliasing (Dick effect) + loss of information

→ prevent from reaching the full potential of atom interferometers

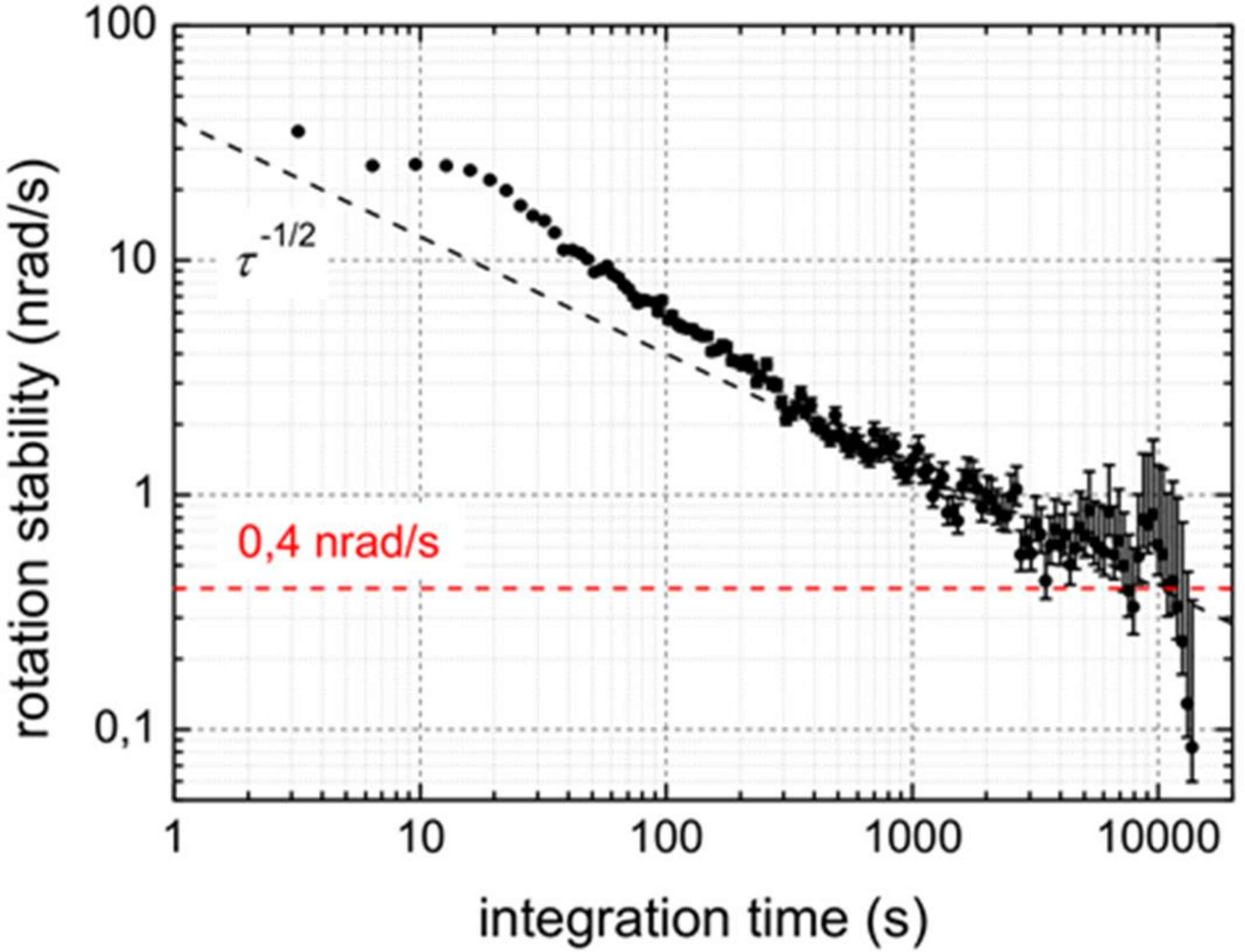
Continuous (zero dead time) sensor

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



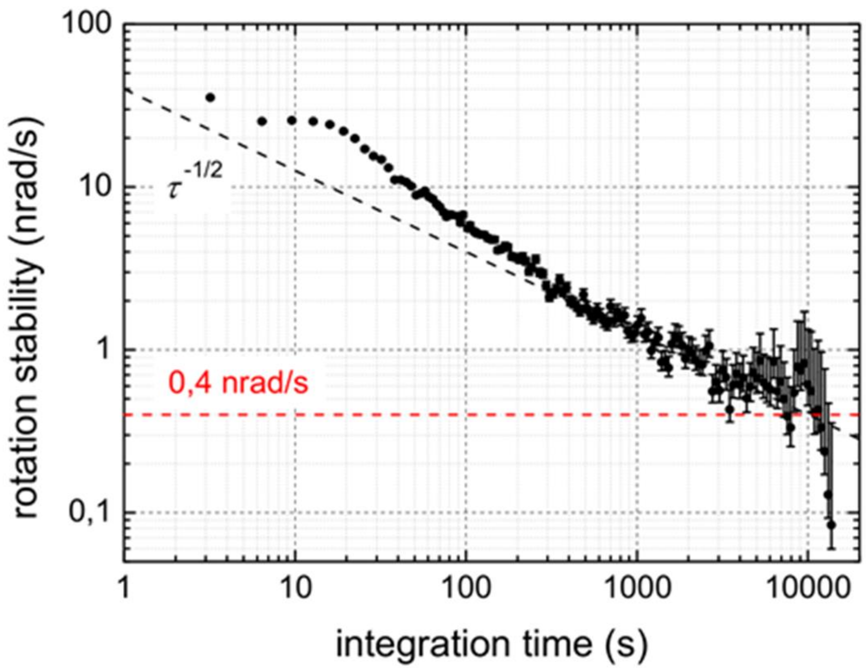
Dutta et al.,
PRL 116, 183003
(2016)

Gyroscope stability



State of the art of atomic gyroscopes

Gyroscope stability



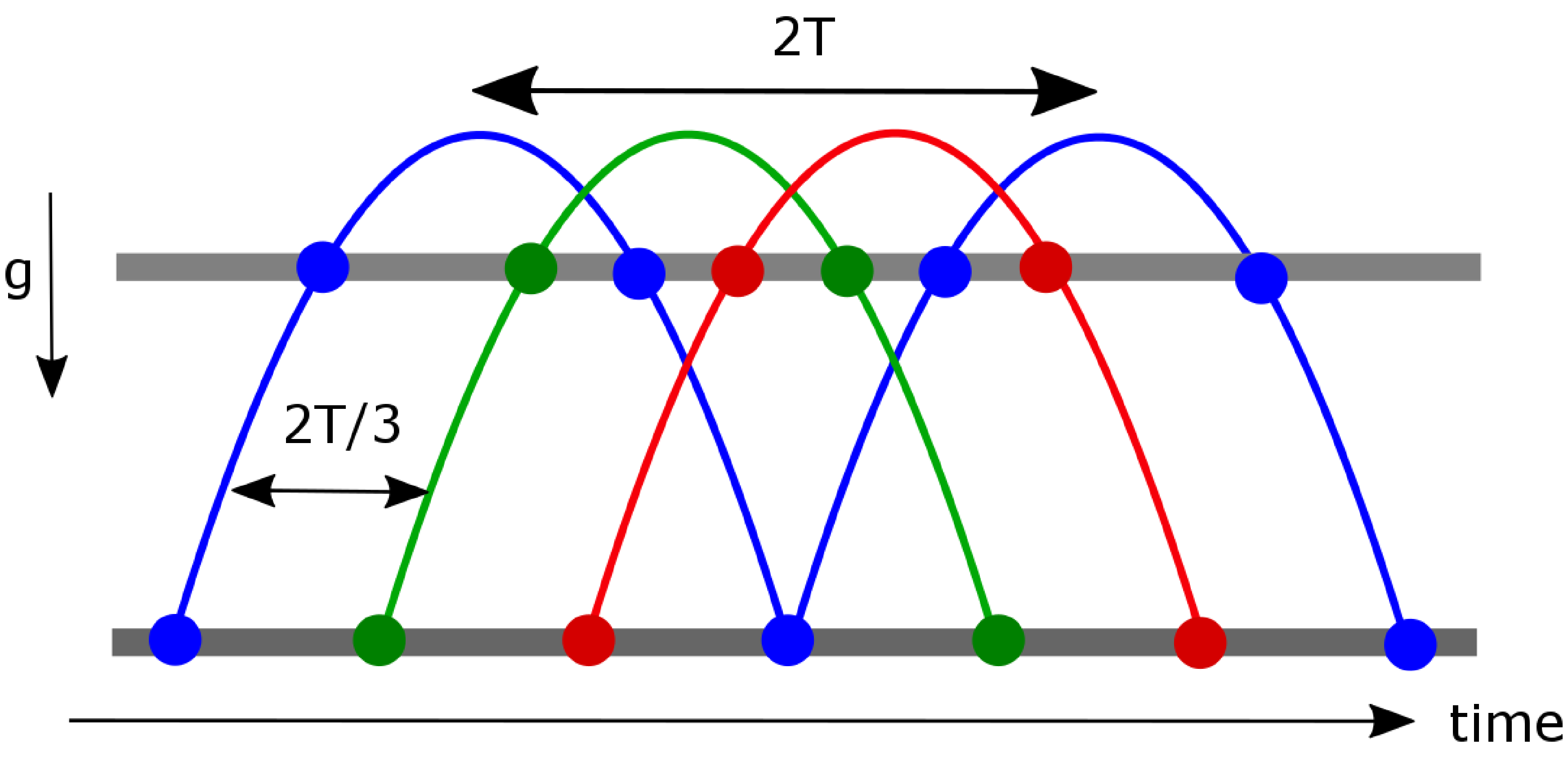
State of the art of atomic gyroscopes

Short term stability still limited by residual vibration noise

	$nrad.s^{-1}.Hz^{-1/2}$
Current short term	40
Measured detection noise contribution	8
Quantum projection noise (10% contrast)	2.5
Measured laser noise contribution	4

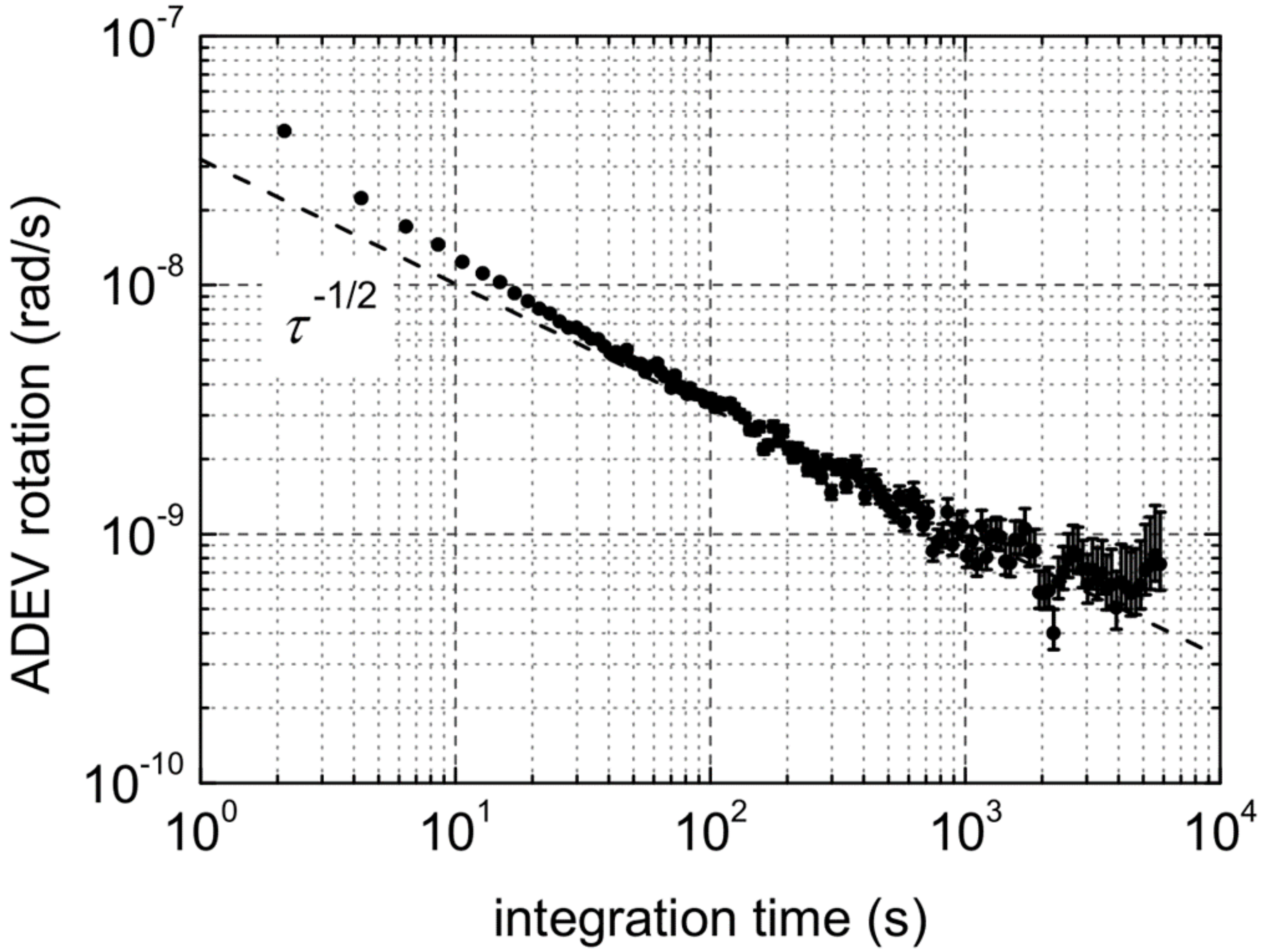
Higher bandwith sensor

Interleave 3 joint interrogation schemes → $T_c = 2T/3 = 266$ ms (~4 Hz cycling frequency)

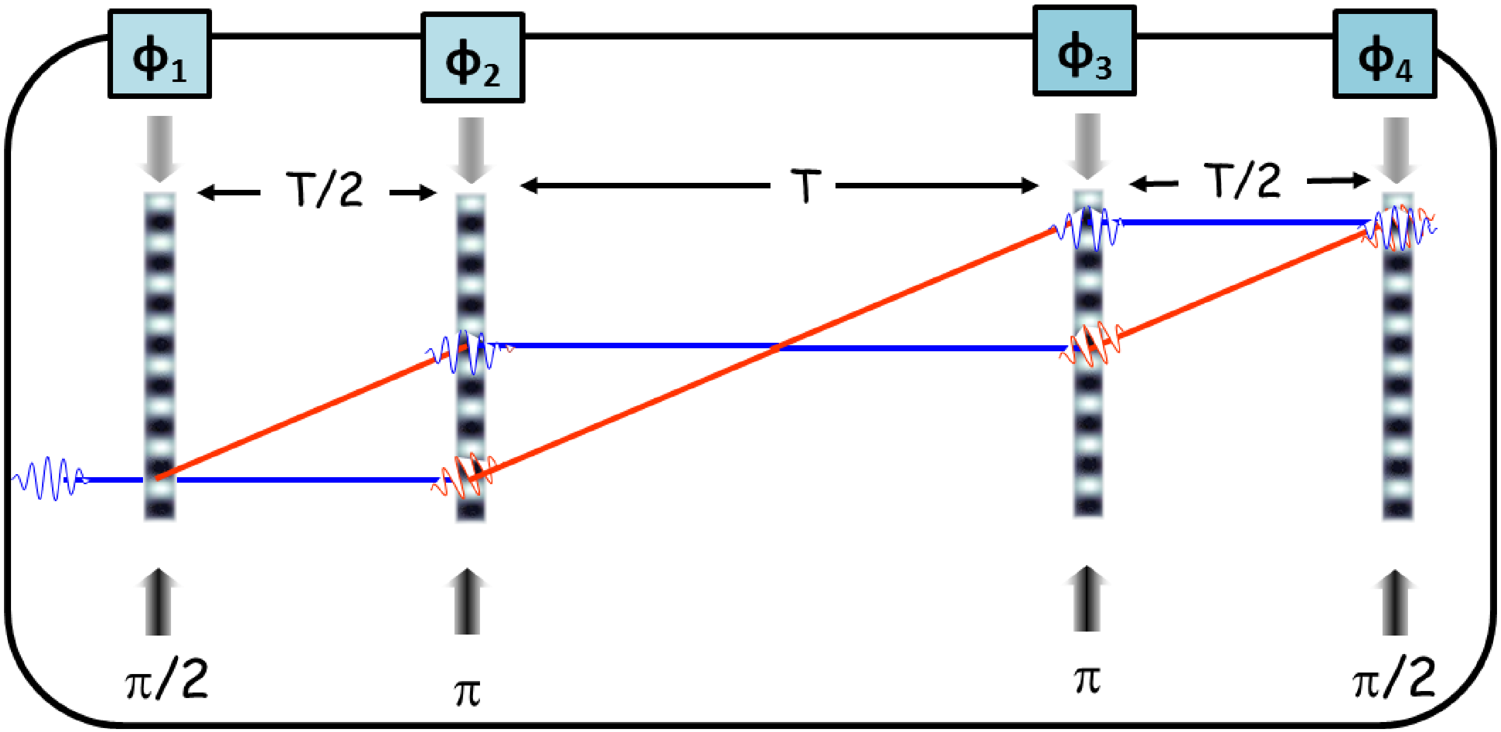


Higher bandwith sensor

Improved short term stability : 30 $nrad.s^{-1}.Hz^{-1/2}$



4-light pulse atom interferometer



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

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

Title

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