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DEVELOPMENT AND OPERATIONAL UTILISATION OF QUANTUM GRAVITY SENSORS

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Exploring the Dark Side of the Universe 2024
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Gravity measurement with cold atoms

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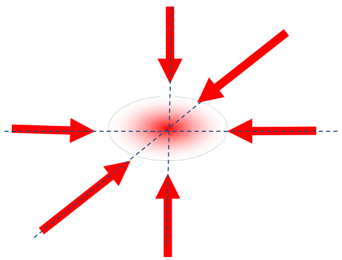
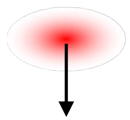
Operating principle : ballistic free fall measurement

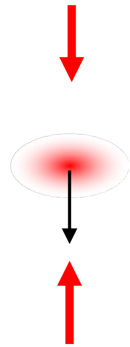
Preparation of the atom cloud



Free fall

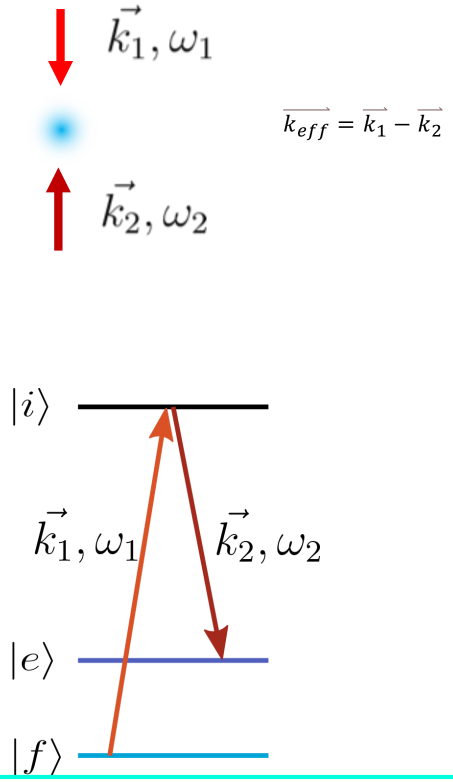


Interrogation of the atom cloud



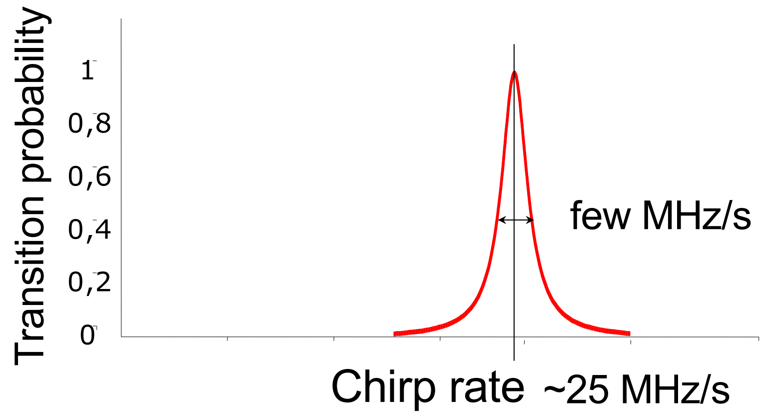
Stimulated Raman transition

2-photon transition with counterpropagating lasers



Doppler effect during the free fall $\Delta f = \dfrac{k_{eff}\,gt}{2\pi}$

=> need to chirp the laser frequencies



=> Low resolution g measurement

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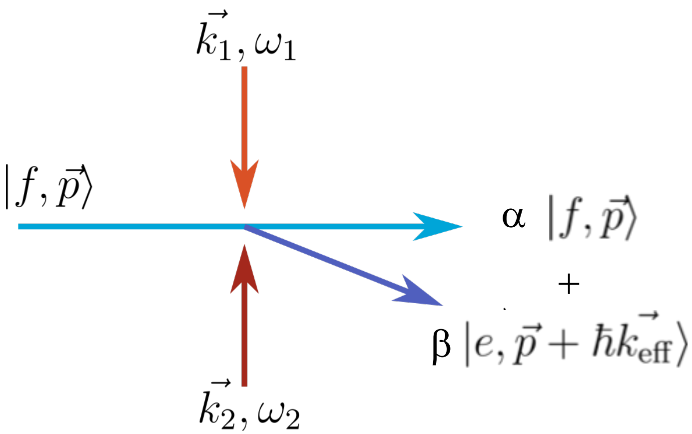
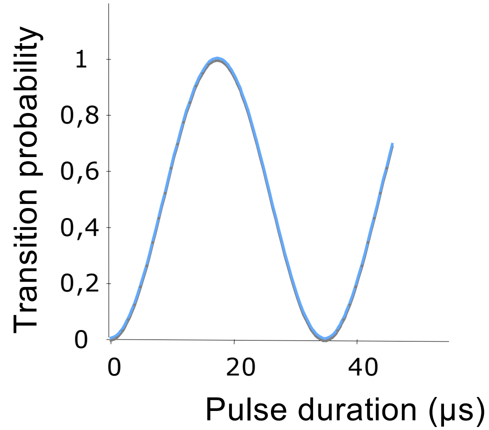
Stimulated Raman transition (2)

Simultaneous modification of internal and momentum states of the atom



Rabi oscillation between ground and excited state

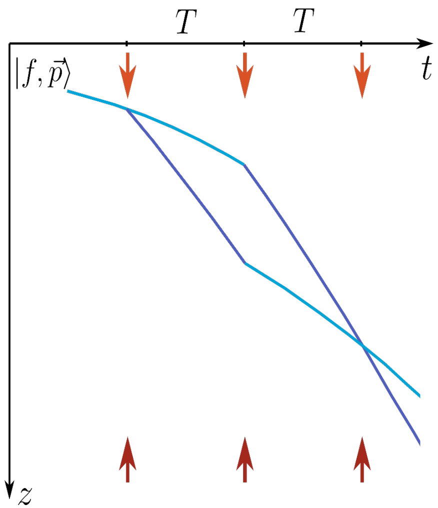


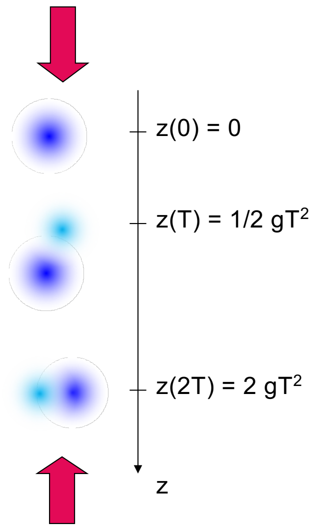
π/2 pulse : atomic wave splitter

π pulse : atomic mirror

Matter wave interferometry

- **Atomic Mach-Zehnder interferometer with stimulated Raman transitions**





Atomic phase shift results from the laser phase difference during the 3 pulses

$$\Delta\varphi = k_{\text{eff}} g T^2$$

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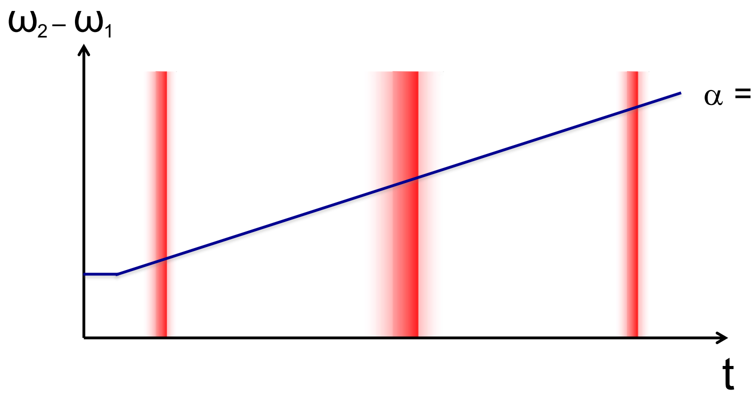
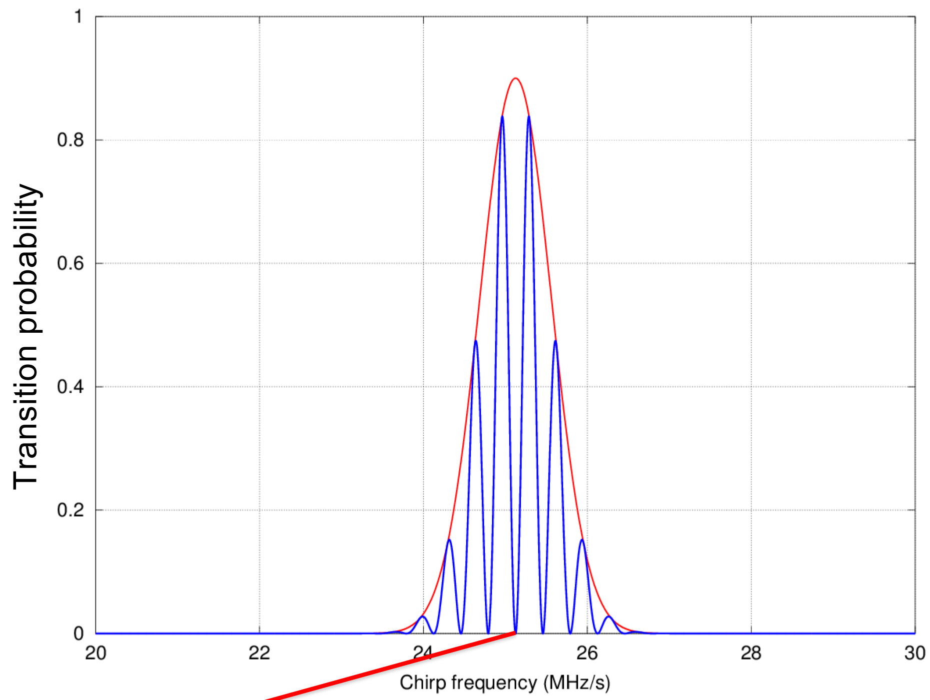
Matter wave interferometry : practical implementation





$$\boldsymbol{g} = \frac{\alpha_0}{k_{eff}}$$

High resolution g measurement

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From the lab to the real world

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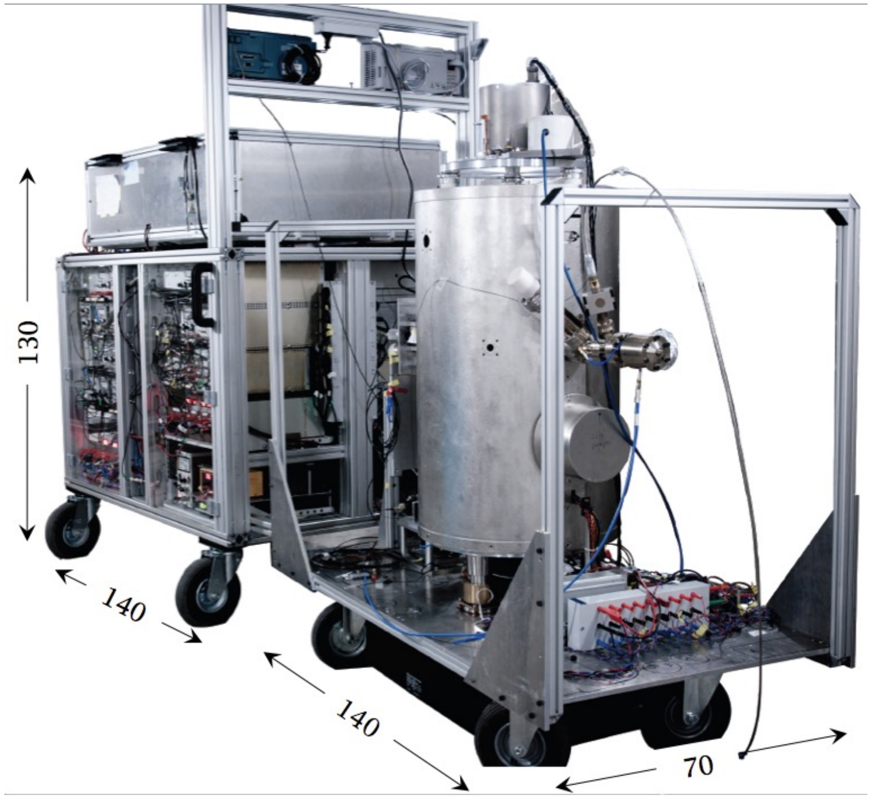
Scientific background

- **First theoretical proposition : Bordé (1989)**
- **First demonstration : M. Kasevich and S. Chu (1991)**
- **First convincing comparisons with classical gravimeters : S.Merlet and F. Pereira (2009)**



Bordé, Physics Letters, A140, 10-12 (1989)
Kasevich and Chu, PRL 67, 2 (1991)
Z Jiang et al 2012 Metrologia 49 666

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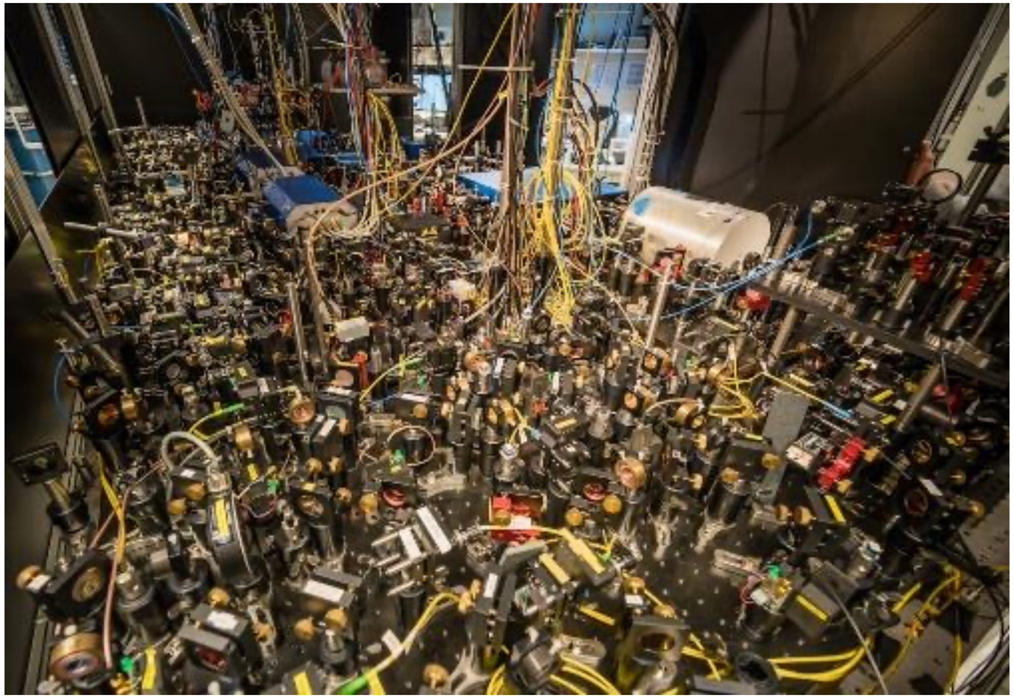
A huge technological challenge

- Intelligent laser system:
  - -Several wavelengths
  - -Accurate optical frequency
  - -Spectral agility
  - -Complex sequence
- Ultra high vacuum environment, non magnetic
- Low noise electronics
- Complex software : real time, large data volume

- Outdoor operation
- Transportability
- Reliability
- Cost effectiveness…..
- Compatible with industrialization



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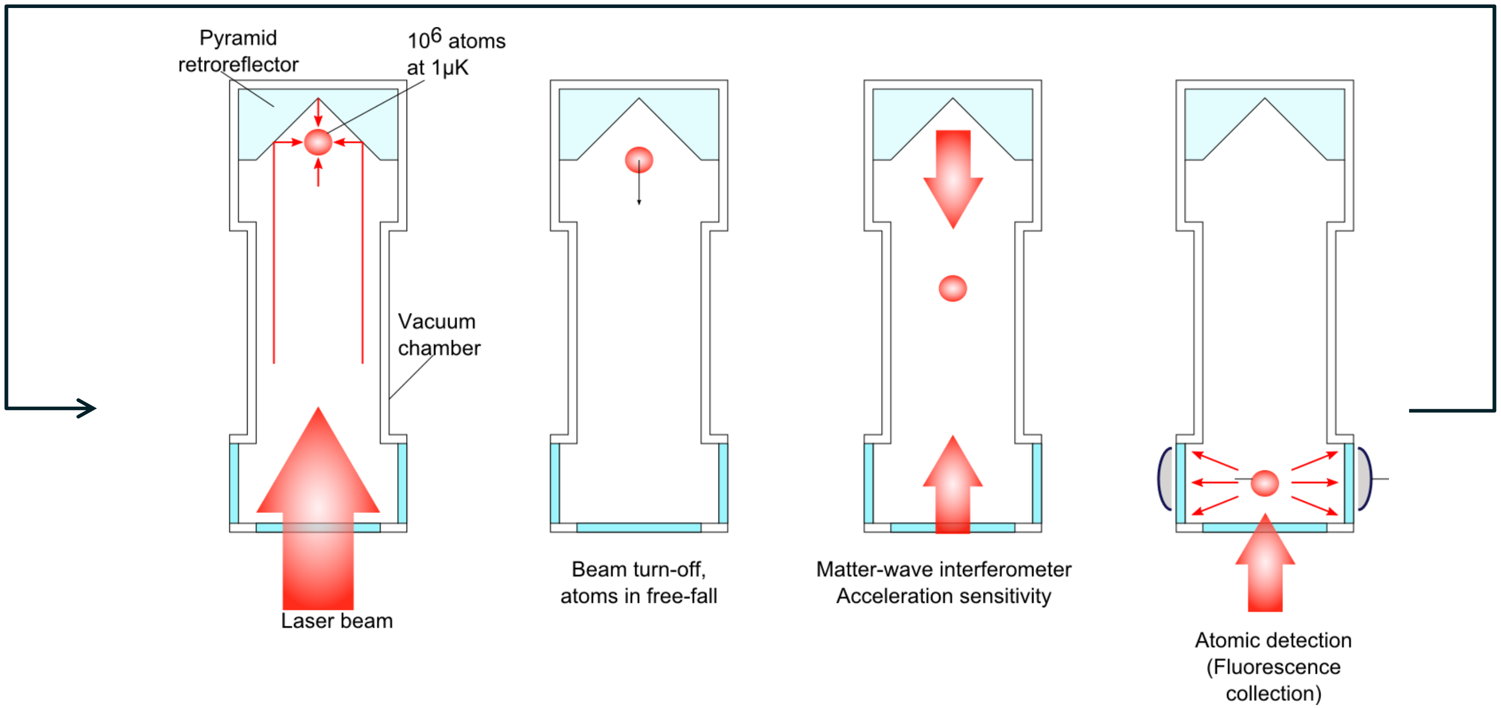
Our key innovation : the pyramidal reflector

2008, CNRS patent, Arnaud Landragin and Philippe Bouyer :

Cold atom interferometry sensor



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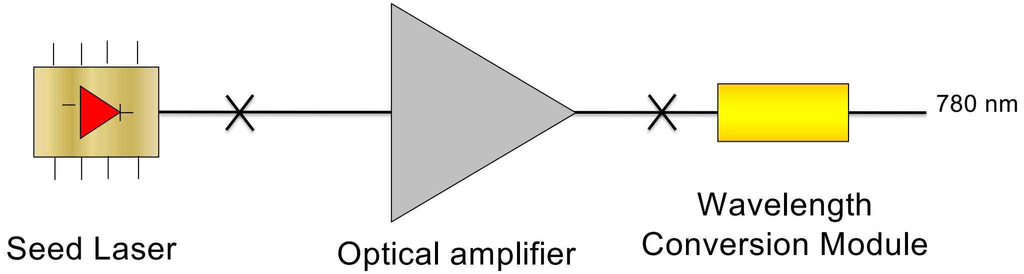
Disruptive laser technologies

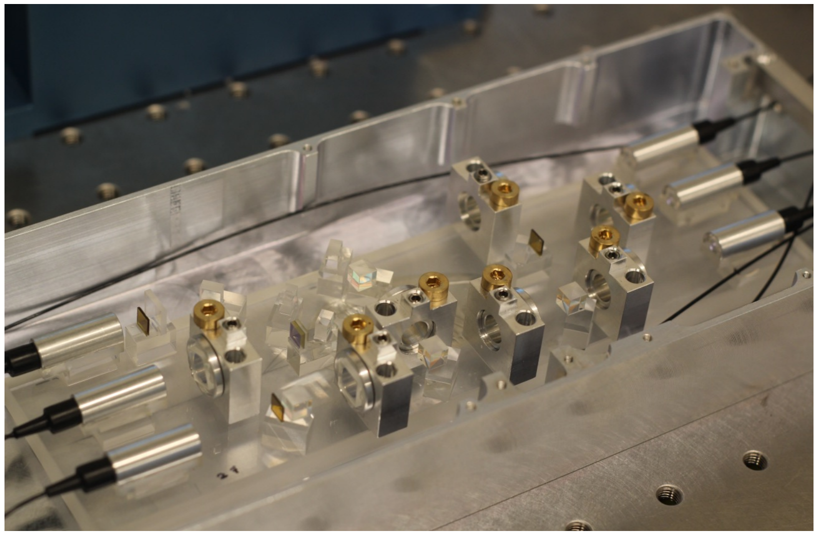
- Generation of 780 nm with frequency doubling of 1560 nm



=> Access to telecom components :

- Extreme optical performances
- completely fibered technology => no optical alignment
- Robustness (Telcordia qualified)
- Reliability

- Micro optical benches:
  - Fibered inputs & outputs
  - Telcordia qualified
  - Wide range of optical functionalities

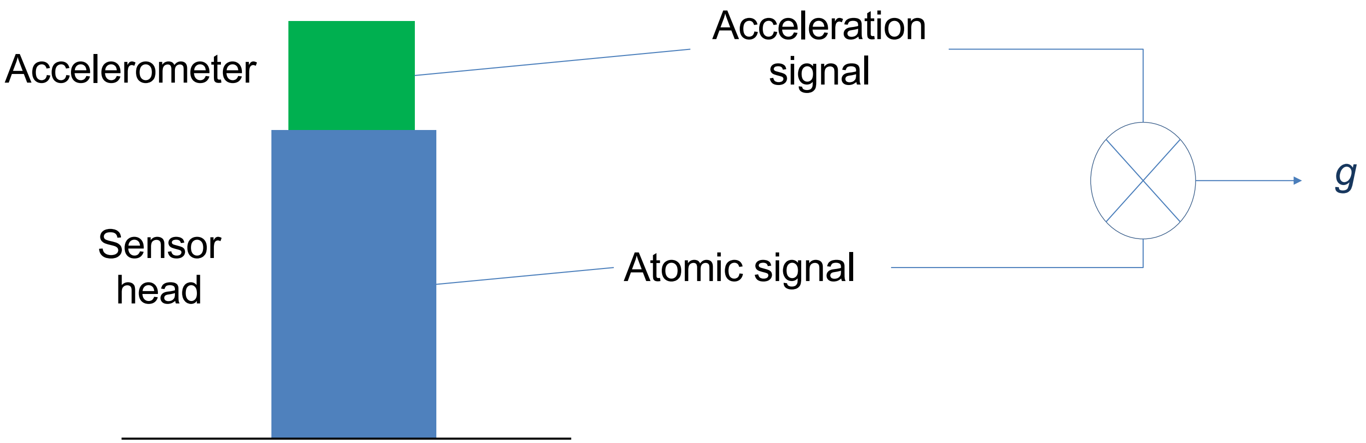


Compensation of ground vibrations

- The gravimeter measures the relative acceleration between the free-falling atoms and the sensor head:

$$a_{measured} = g + \text{vibration noise}$$

- Vibration rejection : correlation with a high performance accelerometer



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Field Absolute Quantum Gravimeter

Fully integrated

- Home-made electronics, software, vacuum…
- Integrated supervision and monitoring
- Robust and compact design

High performance

- Continuous absolute gravity measurements over months
- Resolution 1 µGal = 10 nm.s^{-2} (~10^{-9}g)

User friendly

- Easy to install and operate
- Intuitive software
- Remote operation

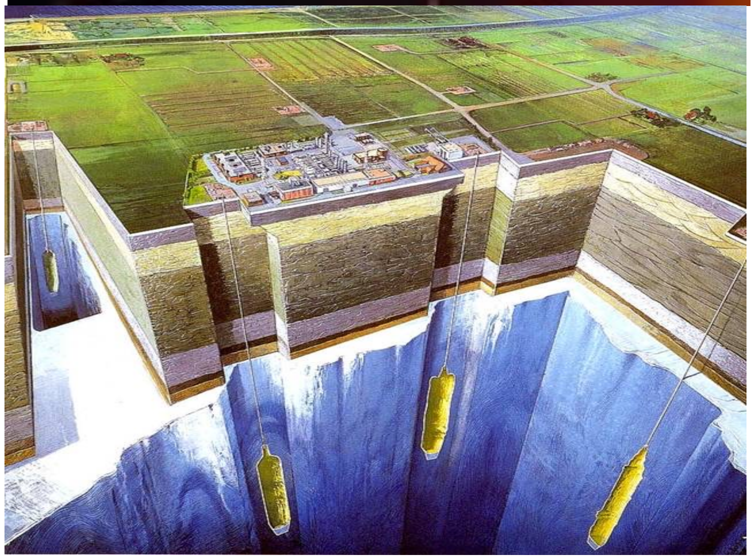
Applications of quantum gravimeters

Markets and applications

Monitoring of the Earth:
- Volcanology
- Seismology

Sustainable management of underground resources :
- Geothermics & Hydrology
- Oil & gas
- Mining industry

Subsurface imaging :
- Civil Engineering
- Void, tunnel and cavity detection



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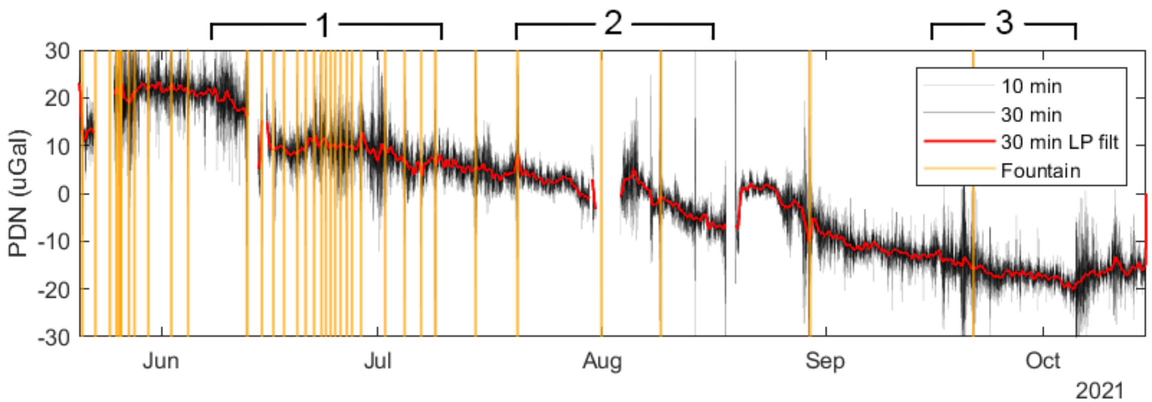
Volcano monitoring: the NEWTON-g project

L. Antoni-Micoller et al., Geophys. Res. Lett., vol 49, issue 13 (2022)
Carbone, D.,et al, Gas buffering of magma chamber contraction during persistent explosive activity at Mt. Etna volcano, Commun Earth Environ 4, 471 (2023).

AQG installed on Mt Etna in July 2020

- 2800 m elevation
- 2.7 km from summit craters



Hard conditions

- Volcanic tremor / eruptions => seismic noise
- Temperature changes
- Corrosive and dusty atmosphere
- Difficult access (impossible in winter)
- Unstable off-grid power supply

Onboard quantum gravimeter

Quantum gravimeters :

- long-term surveys
- no need for calibration on ground
- High resolution

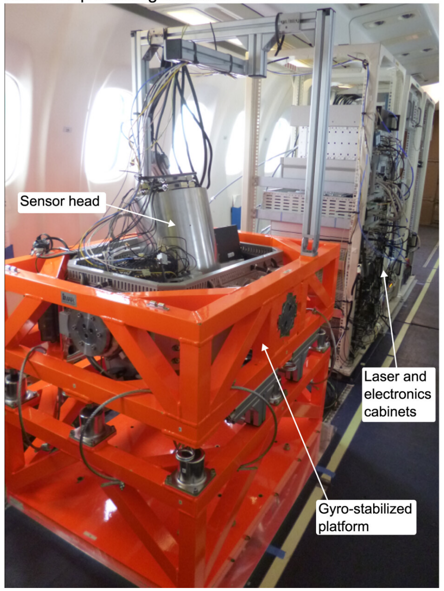
Pioneering results by ONERA in France

- Seaborne and airborne demonstrations

In-house development under way

- High performance quantum gravimeter
- Compatible with DriX Ocean USV
- Long-term autonomous gravity mapping

GIRAFE quantum gravimeter



Bidel et al., Nat. Commun 9, 627 (2018)
Bidel et al., JGR Solid Earth 128, e2022JB025921 (2022)

Towards a Quantum Inertial Measurement Unit

- **Classical sensors**
  - High dynamic range, linear
  - Continous, high frequency
  - Bias + drifts

- **Quantum sensors**
  - Accurate, low bias
  - High sensitivity
  - Low dynamic range (non linear)
  - Dead times

- **We need to handle**
  - Rotations and accelerations
  - Random orientations
  - Multiple axes
  - Data fusion (hybridizing classical and quantum sensors)

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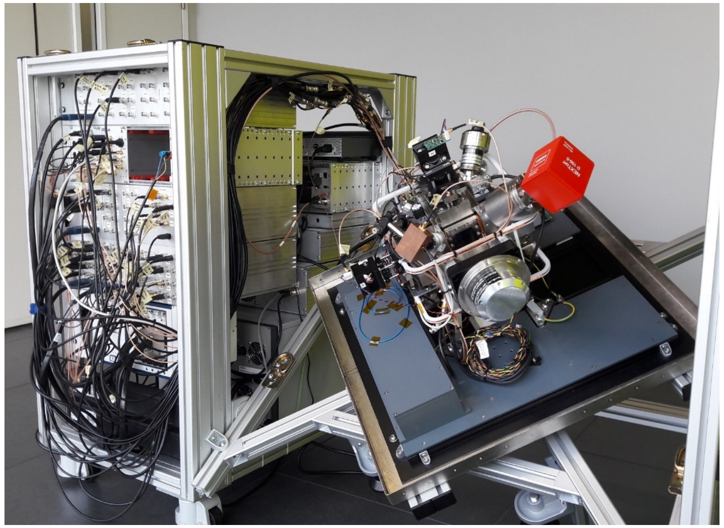
LP2N Laboratoire Photonique Numérique & Nanosciences

IXATOM
Quantum technologies for high end Inertial Sensors



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université de BORDEAUX

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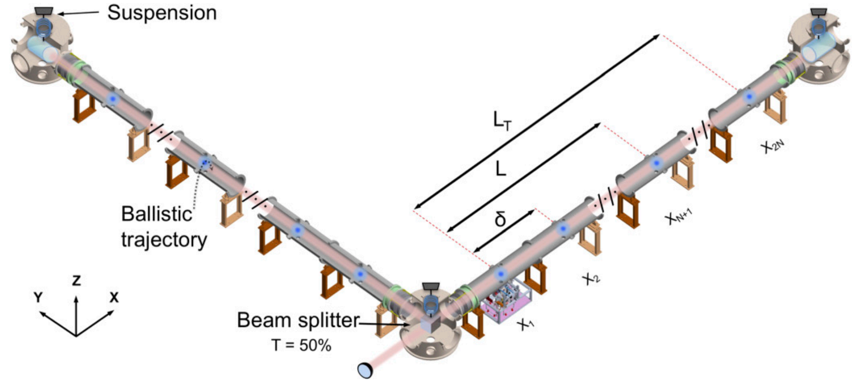
Large scale Matter wave interferometers (ELGAR, European Laboratory for Gravitation and Atom-interferometric Research)

- Motivation : measure Gravitational Waves in the infrasound band (0.1–10 Hz)

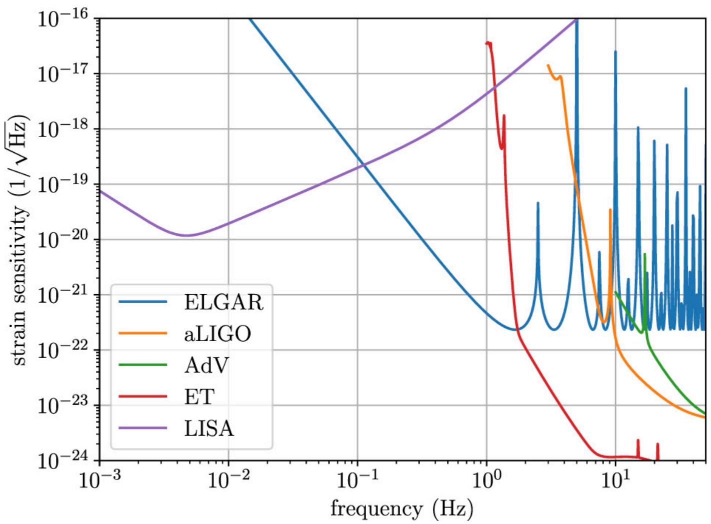


- 2D array of quantum gravity gradiometers :
  - 32 km arm length
  - 80 sensors along each arm

- Targeted performances :

Strain sensitivity of 3.3 × 10^{-22} $Hz^{-1/2}$ at the peak

Frequency of 1.7 Hz limited by atom shot noise



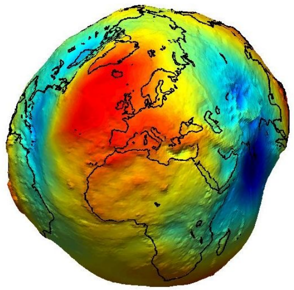
Space quantum sensors

Environmental and climatic stakes

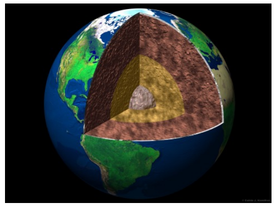

Glaciology


Hydrology

Geodesy




Oceanography


Internal Geophysics

- **Natural resources management**
- **Natural disasters forecast**
- **Monitor and understand global warming**

CARIOQA (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry)

- Mission: demonstrate the operation of a Quantum Accelerometer **on a satellite.**
- **Scientific data feedback:** performance validation and Thermosphere modelling.

Conclusion

- **Quantum gravity sensors commercially available**
  - Several key advantages with respect to other techniques.
  - Strong technical expertise to build reliable and high performance instruments, suited for use on the field.
- **Intense R&D activity for preparation of next generation instruments**
  - Differential quantum gravimeter.
  - Onboard gravimeter.
  - Space quantum accelerometer.
- **High maturity technology available for other applications of quantum technologies**