MIGA : a test bench for gravitational wave observation with cold atom interferometers

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For the MIGA collaboration

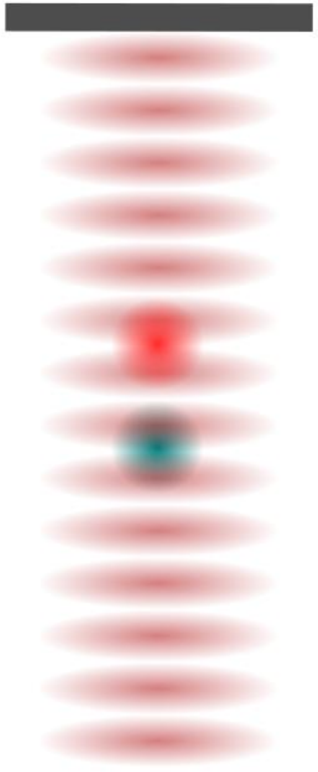
Introduction – cold atom interferometers

Inertial sensing technologies based on atom interferometry : 30 years of development.

Applications :

- Gravimetry/Gradiometry
- Intertial sensing and navigation
- Fundamental physics

State of the art : measure of **g** on Earth with a few $\mathbf{10^{-8} m/s^2}$ **uncertainty**.

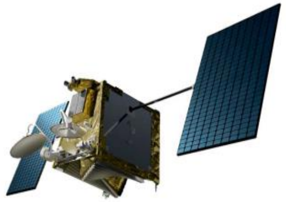


Overview of the current landscape

MuQuans/Xblue

Commercial applications

Lab experiments



Space projects (CAL, CARIOQA)

Large infrastructures (MIGA)

Tests of fundamental physics (STE-QUEST)

Spatial geodesy

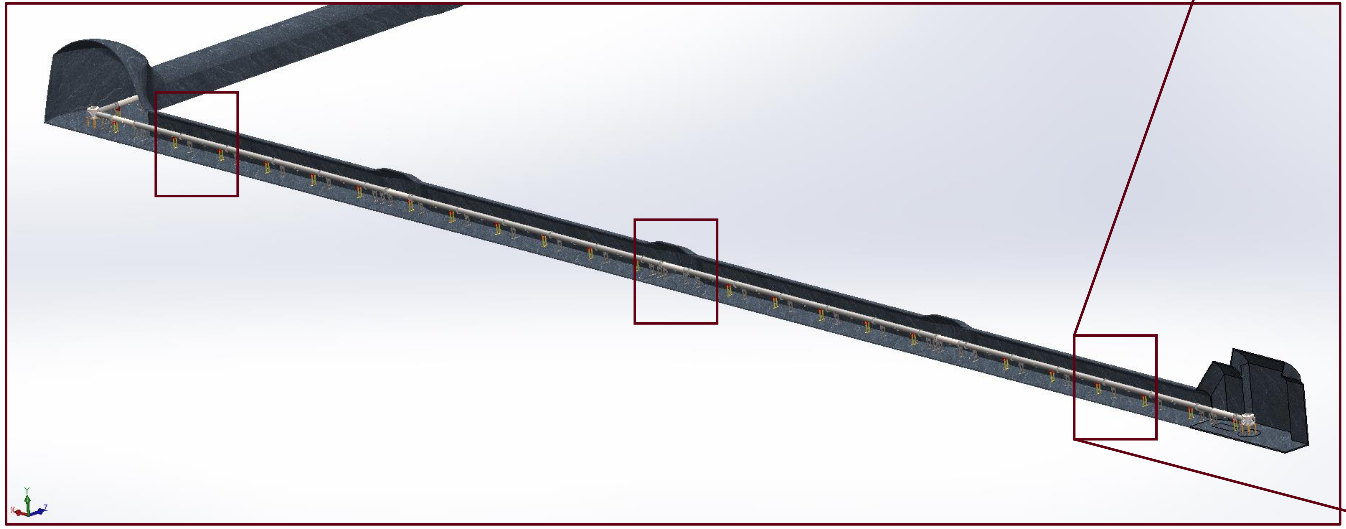
GW observation (ZAIGA, ELGAR)

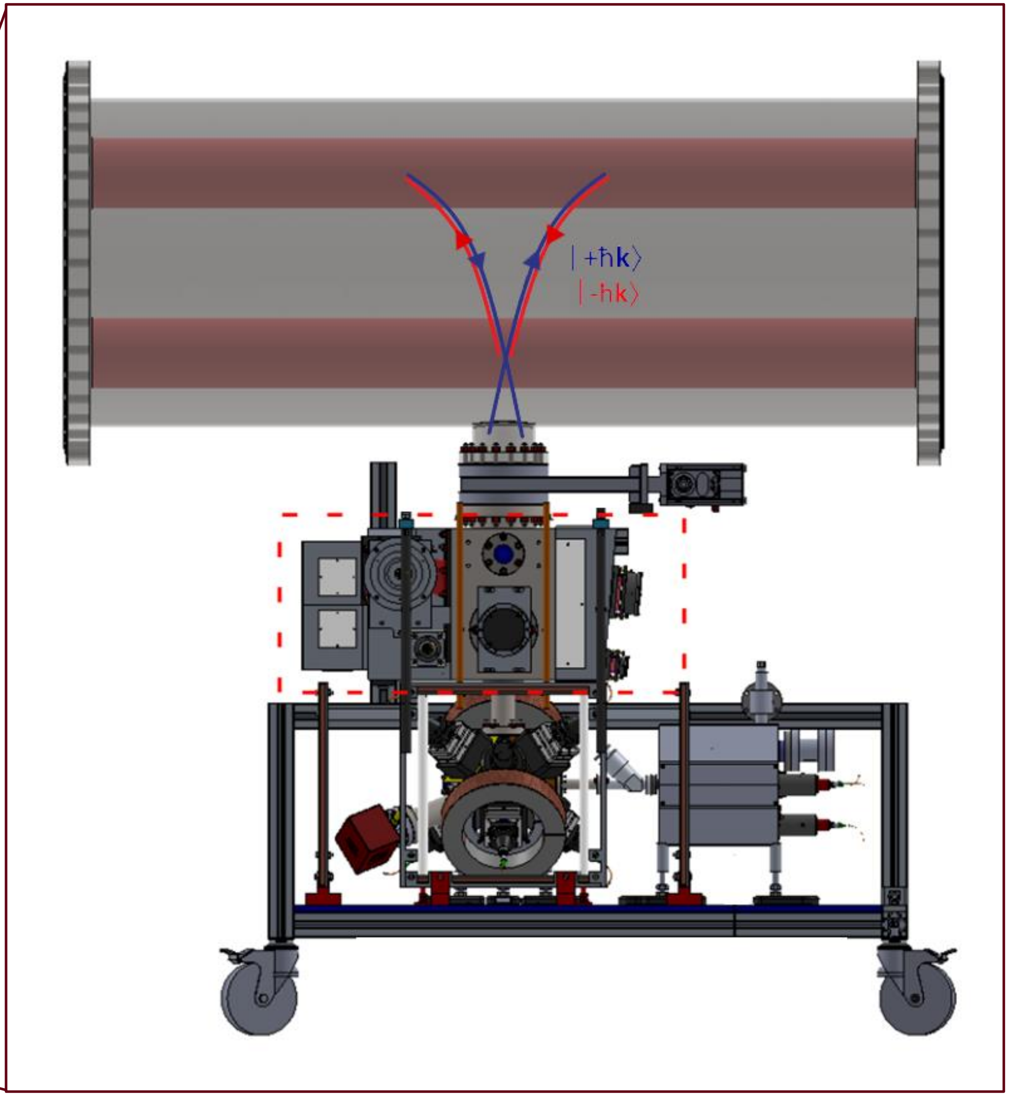
Tests of fundamental physics

Geosciences (Geodynamics, Hydrogeology)

The MIGA Project

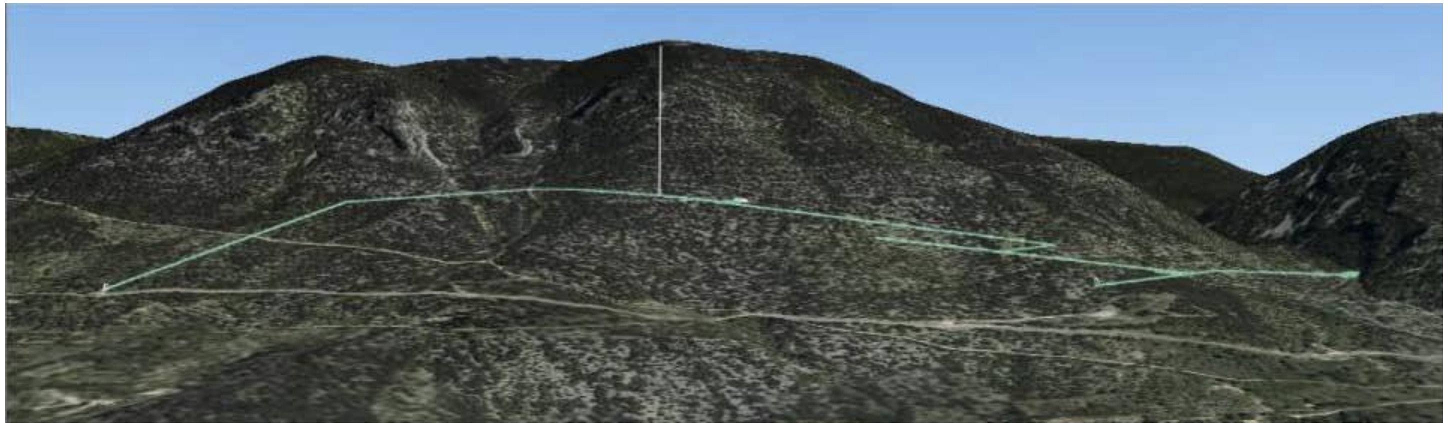
- Long baseline (150m) cold atom gradiometer.
- 3 atom interferometers on the same pair of lasers.
- Underground facility at LSBB: ideal environment.
- Gravity gradient sensitivity of $10^{-13}s^{-2}/\sqrt{Hz}$@ 2Hz





Implementation at LSBB

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

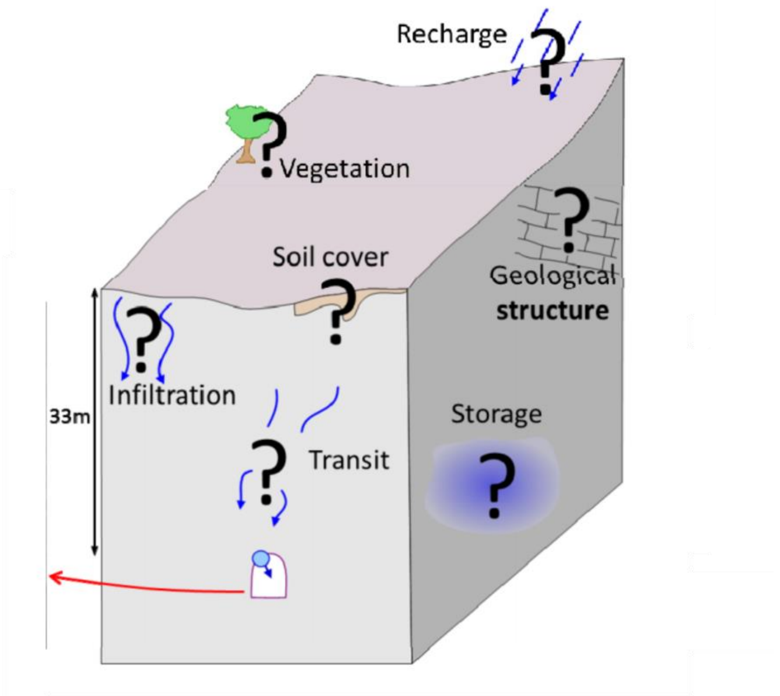


Partners :

French “Equipement d’Excellence” Initiative
17 partners

Applications

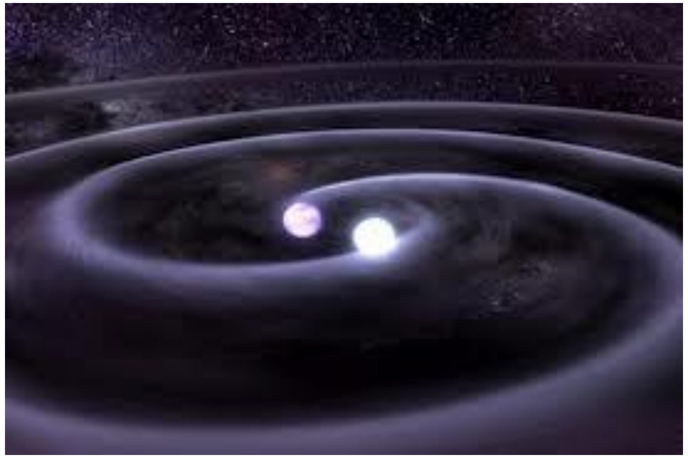
- **Karstic aquifers: complex multi-scale hydrodynamics**



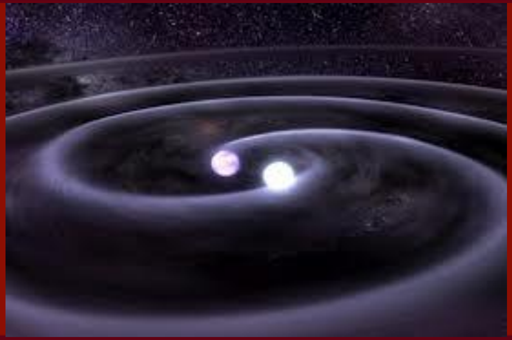
Courtesy: C. Danquigny, Univ. Avignon

Non-invasive measurements to construct and constrain hydrodynamics numerical models.

- **Demonstrator for gravitational wave observation**



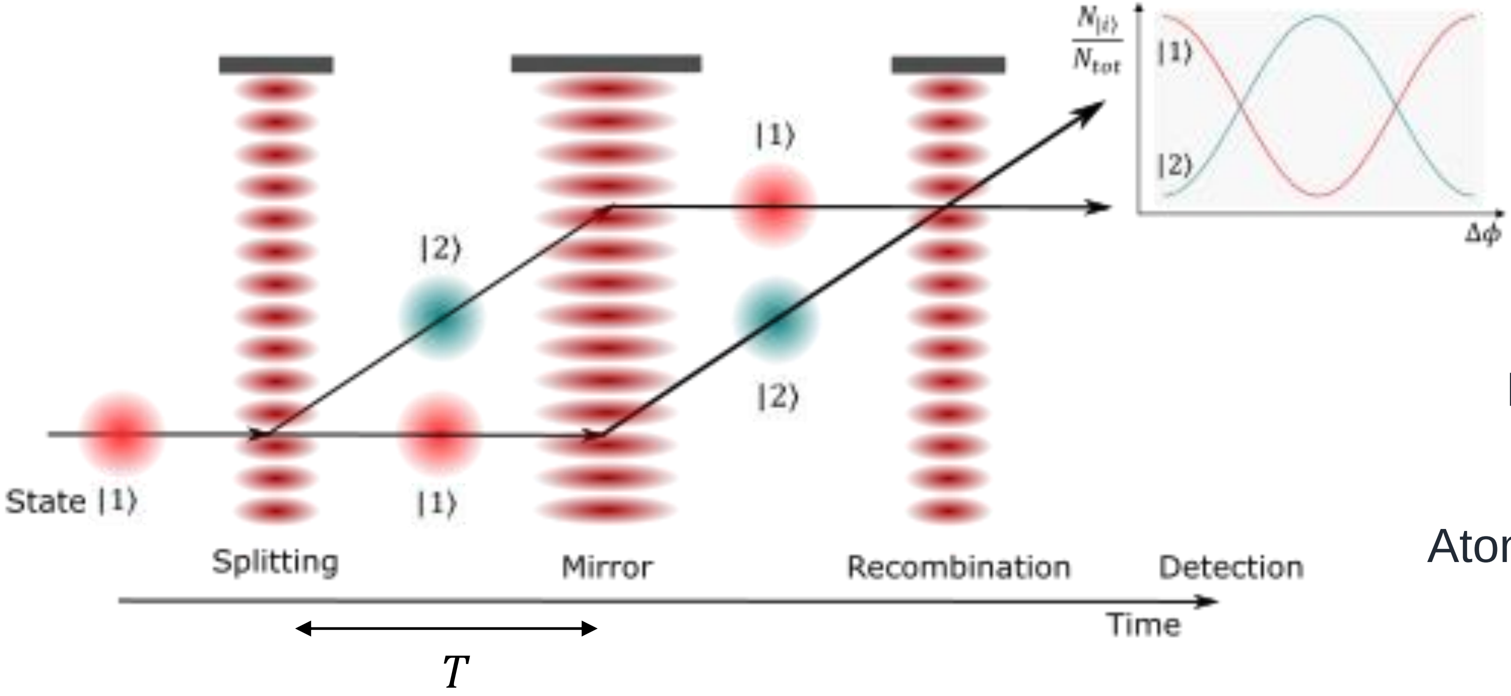
Performances study and proof of concept for future large infrastructures.



Sensitivity to gravitational waves

Principle of an atom interferometer (AI)

MIGA
MATTER WAVE LASER - BASED INTERFEROMETER



$$\Delta\Phi = \varphi(0) - 2\varphi(T) + \varphi(2T)$$

Acceleration

Phase

$$\Delta\Phi \propto k_{eff} a T^2$$

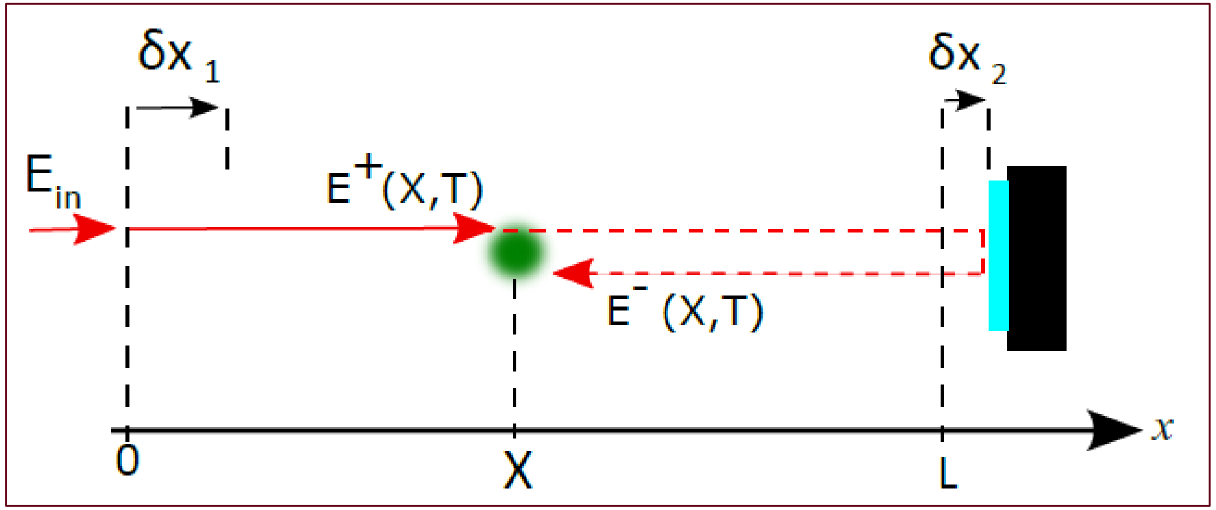
Atomic momentum

Interrogation time

$$\sigma_\Phi \propto \frac{1}{\sqrt{N}}$$

Atom number

Effect of a GW on the interferometer



The AI records the relative phase between the 2 counter-propagating lasers:

$$\phi(t) = \varphi^{+}(t) - \varphi^{-}(t)$$

The GW affects this relative phase (it changes the ‘light travel time’ t_r) :

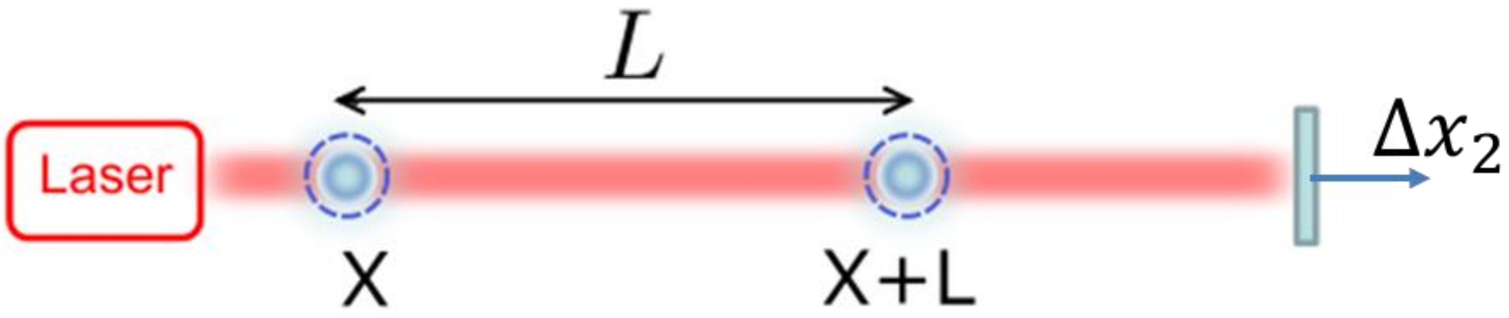
$$\varphi^{-}(t) = \varphi^{+}(t - t_r) \rightarrow \phi(t) = \frac{d\varphi}{dt}(t) \times t_r \quad \text{with} \quad t_r = \frac{2(L-X)}{c} \times \frac{h(t)}{2}$$

$$\phi(t) = \frac{4\pi\nu_0(L-X)}{c} \times \frac{h(t)}{2}$$

$$\Delta\Phi = \varphi(0) - 2\varphi(T) + \varphi(2T) \sim kh(L-X)\sin^2\frac{\omega T}{2}$$

Case of a differential gradiometer

- Measurement of the differential phase between 2 physically separated AIs
- Gradiometer signal = $\phi(X) - \phi(X+L)$



- Position noise of the retro-reflecting mirror is common

→ rejection of Δx_2.

$$\psi(X,t) = 2nk\left[\frac{L\ddot{h}(t)}{2} + a_x\left(X+L,t\right) - a_x\left(X,t\right)\right] \otimes s_\alpha(t)$$

GW signal

Gravity gradient

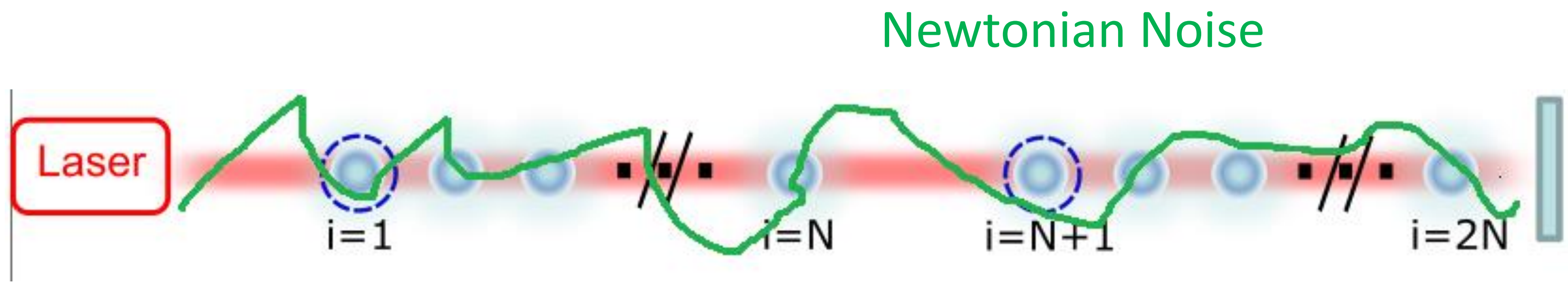
AI sensitivity function

Newtonian noise

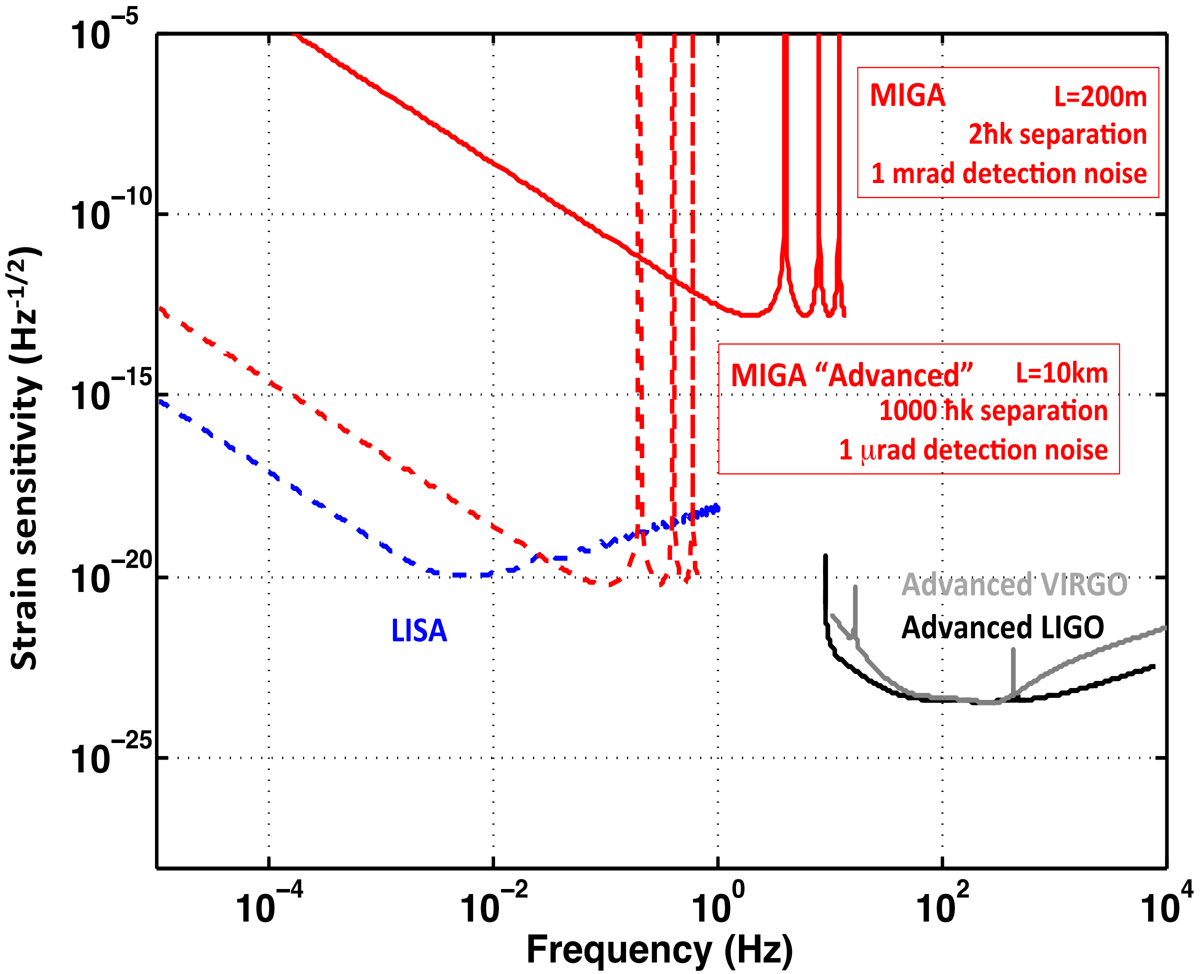
General idea : repeat the gradiometer experiment to average the Newtonian Noise (NN).

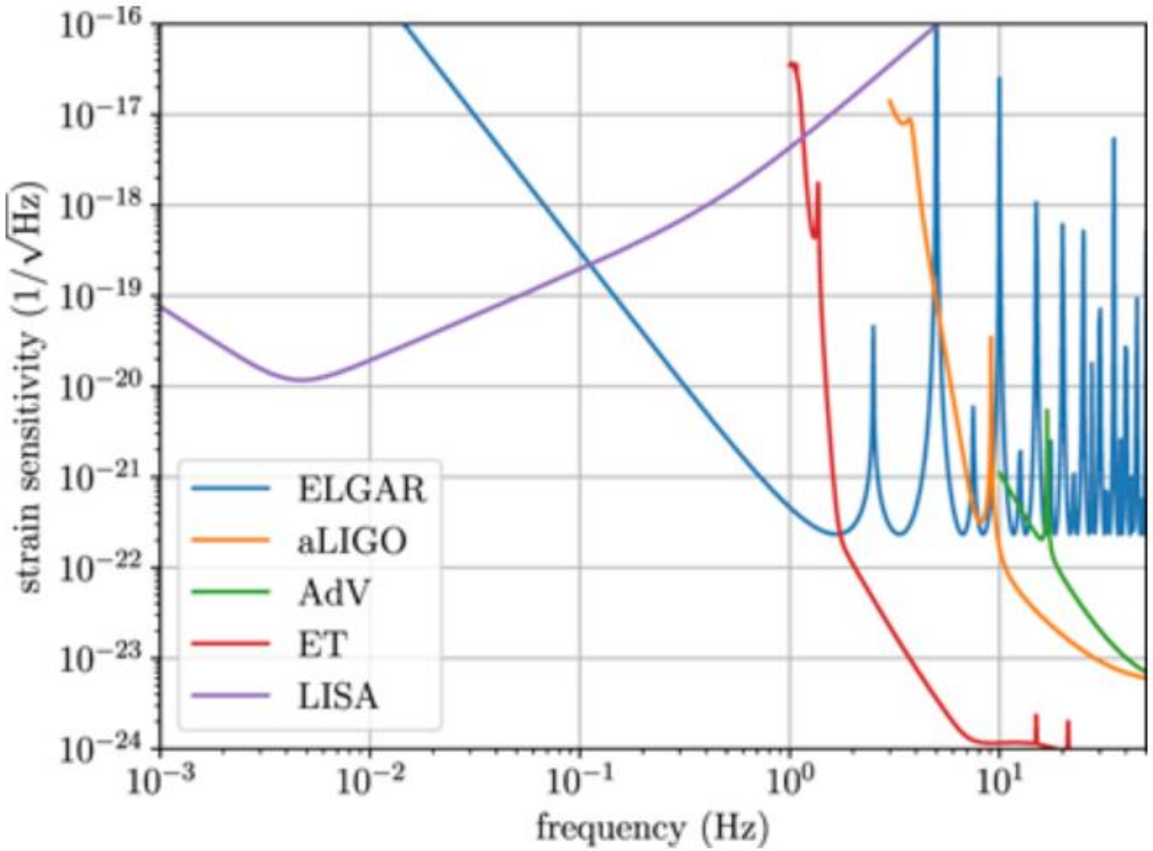
NN characteristic length (few km at most) << GW wavelength

→ average the NN to zero.



Strain sensitivity

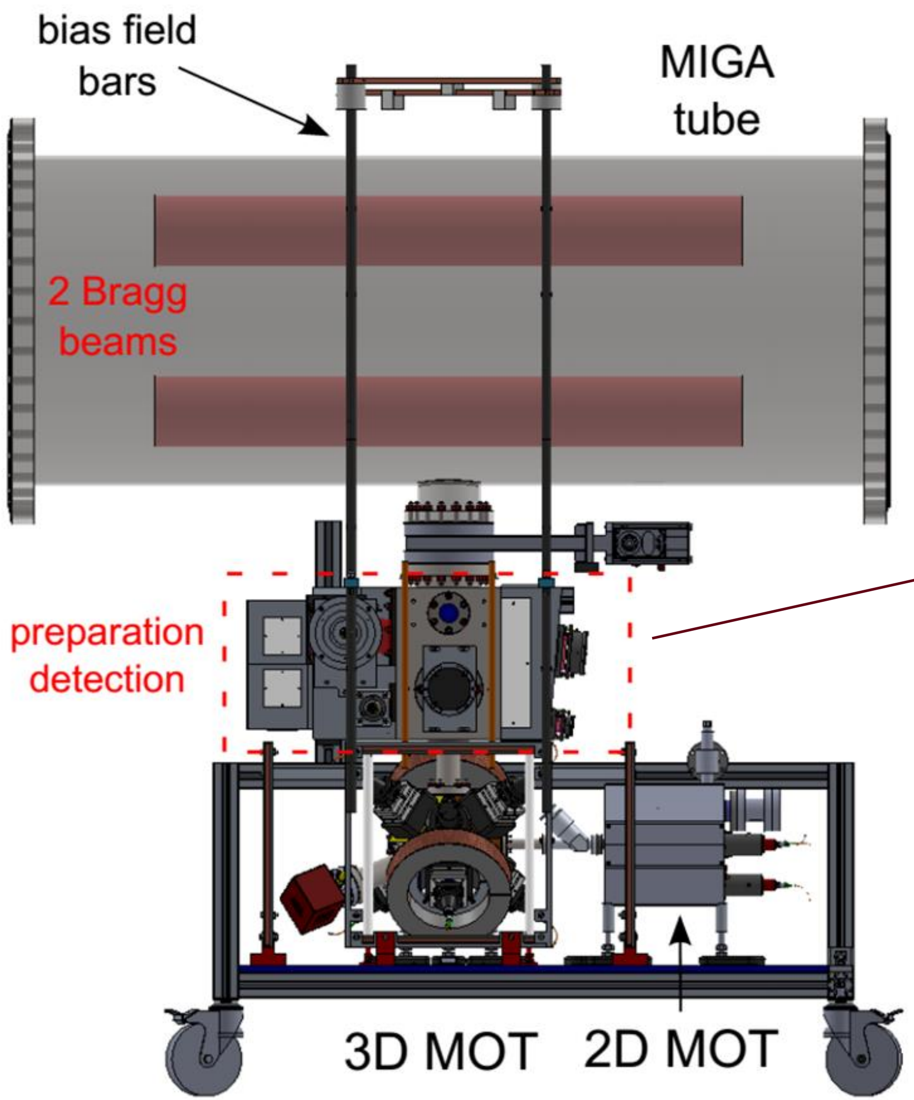


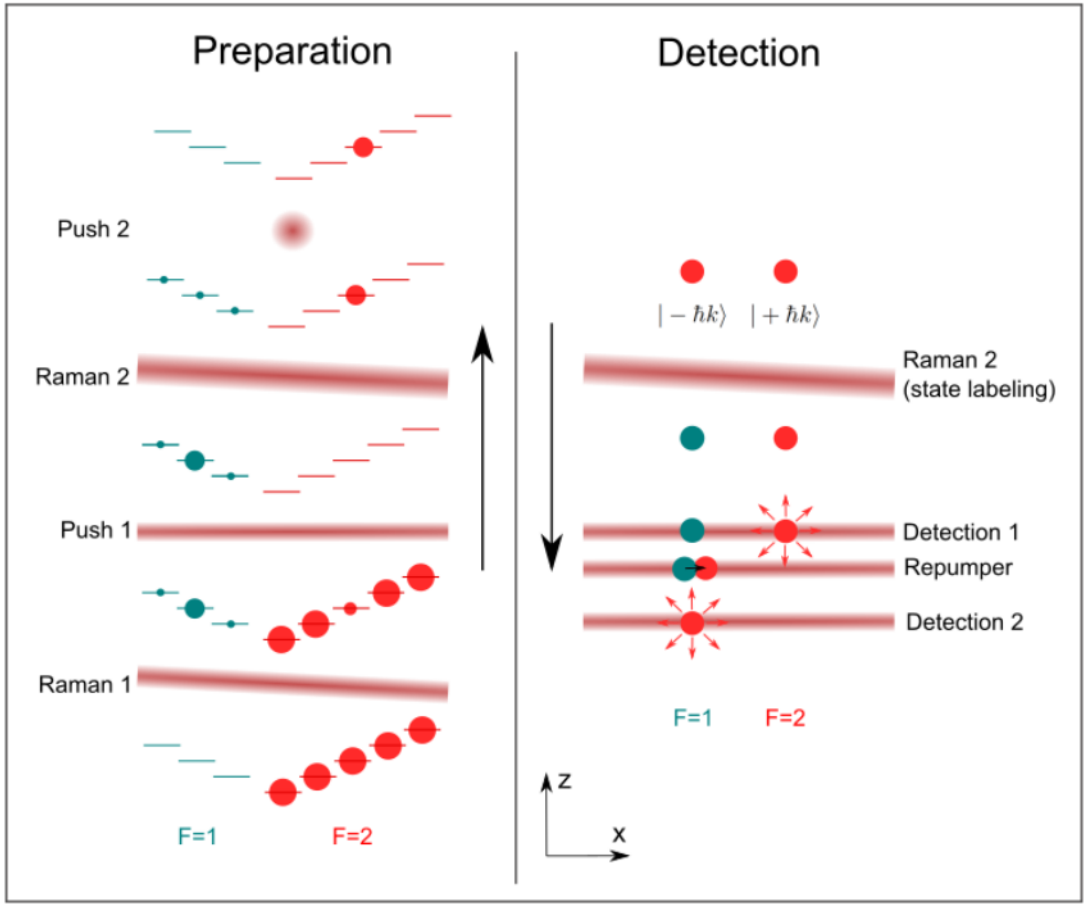


ELGAR project (B. Canuel *et al* 2020 *Class. Quantum Grav.* **37** 225017)

Status of the project

The atom heads





SYRTE l'Observatoire de Paris | PSL
SYstèmes de Référence Temps-Espace

Raman velocity selection and detection

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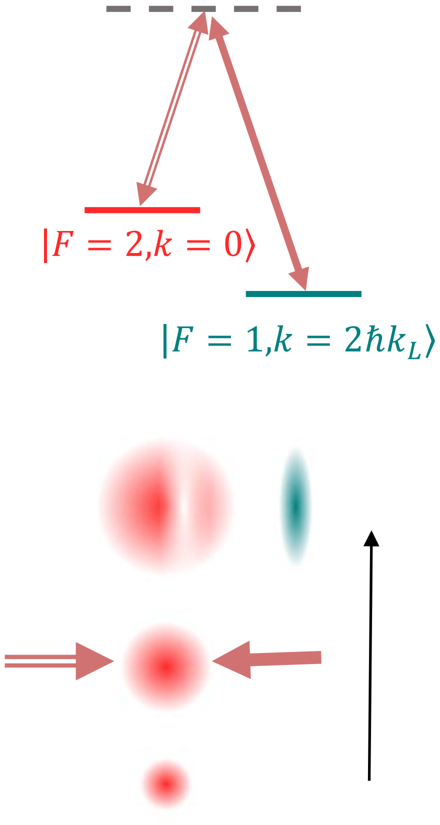
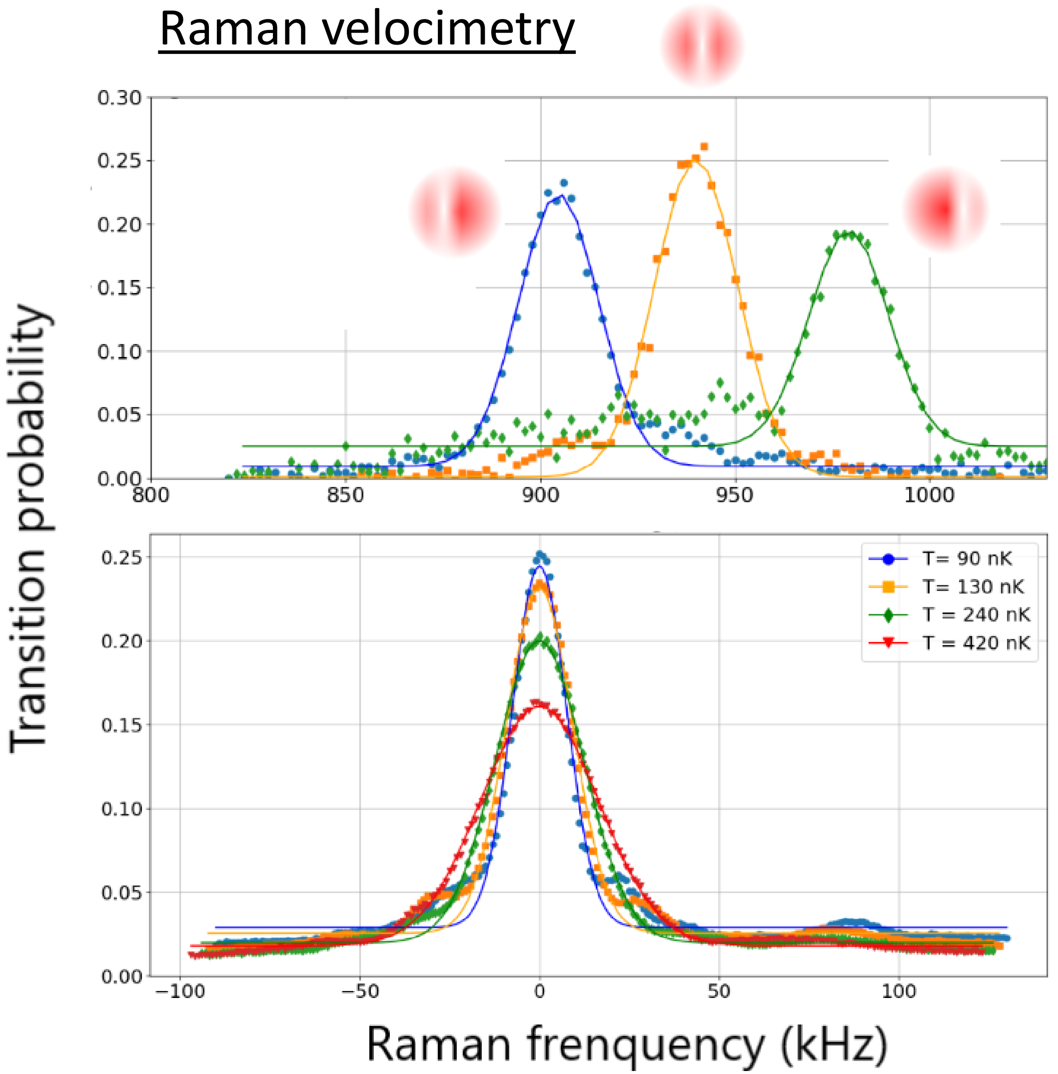
MATTER WAVE LASER - BASED INTERFEROMETER



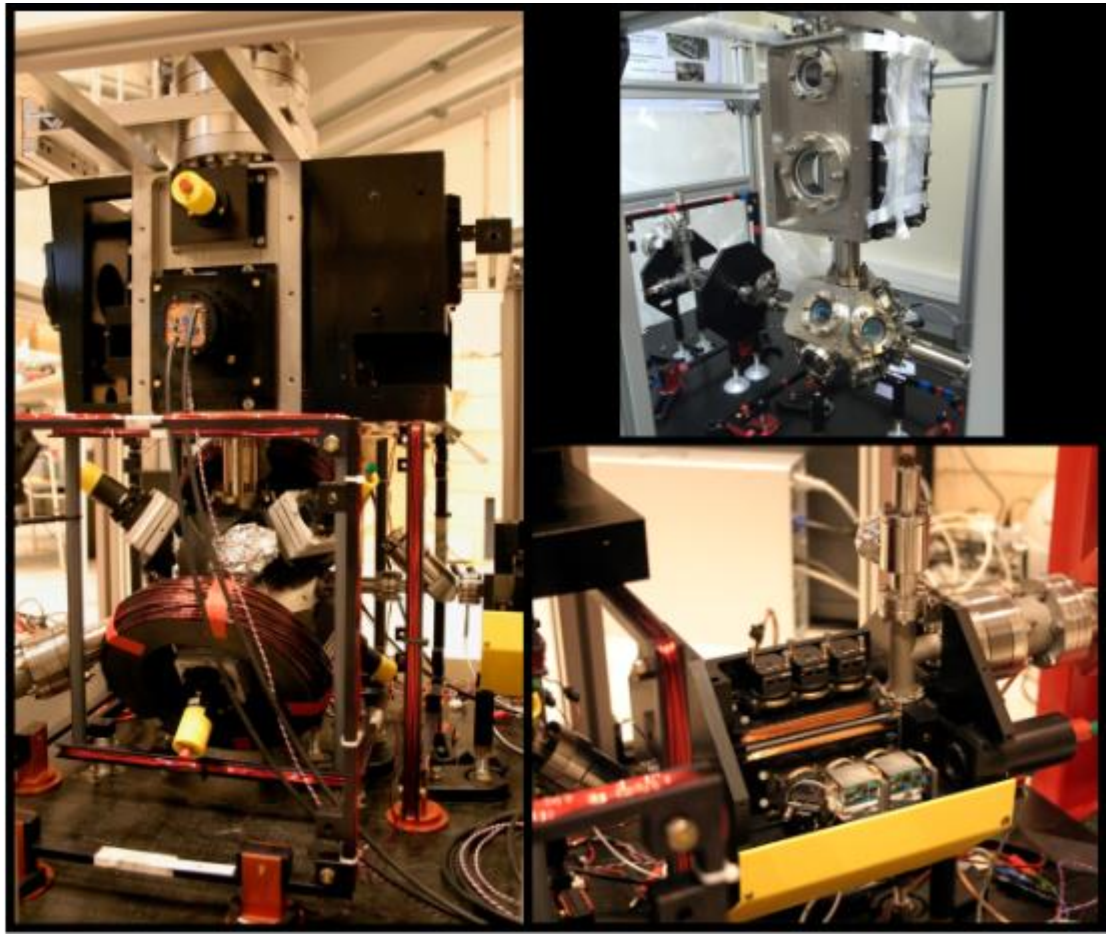
2 photon coherent
Raman transitions

<u>Raman velocimetry</u>



<u>Q. Beaufils et al. arXiv 2209.10234</u>

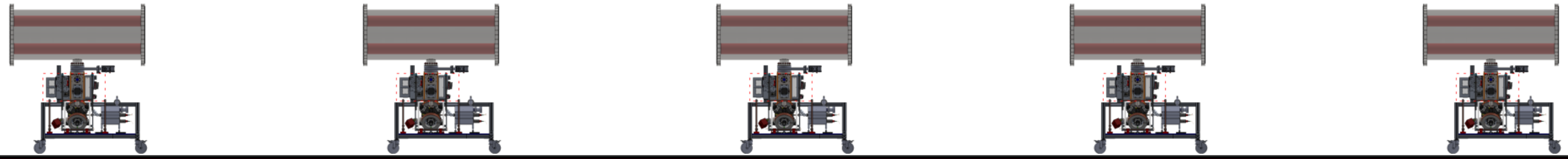
The atom heads



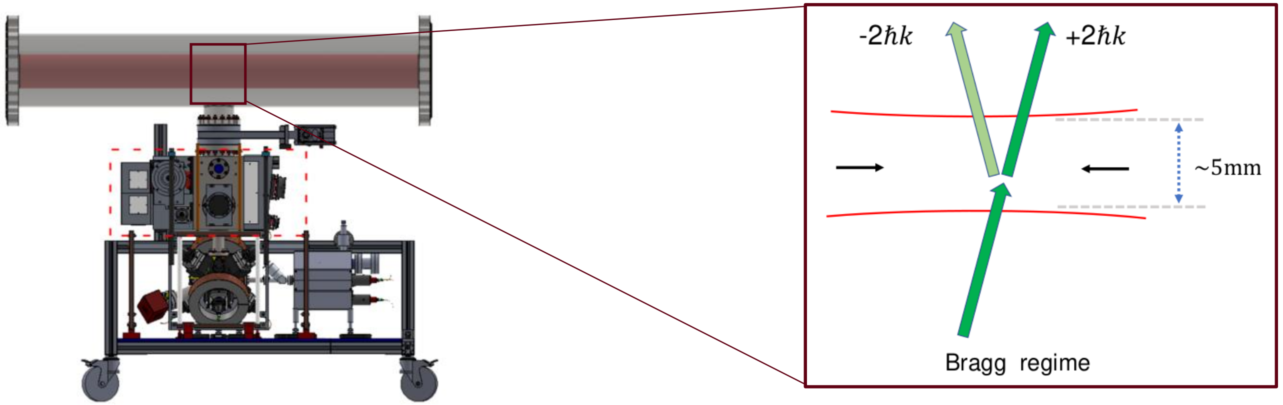
5 atom heads were produced at SYRTE

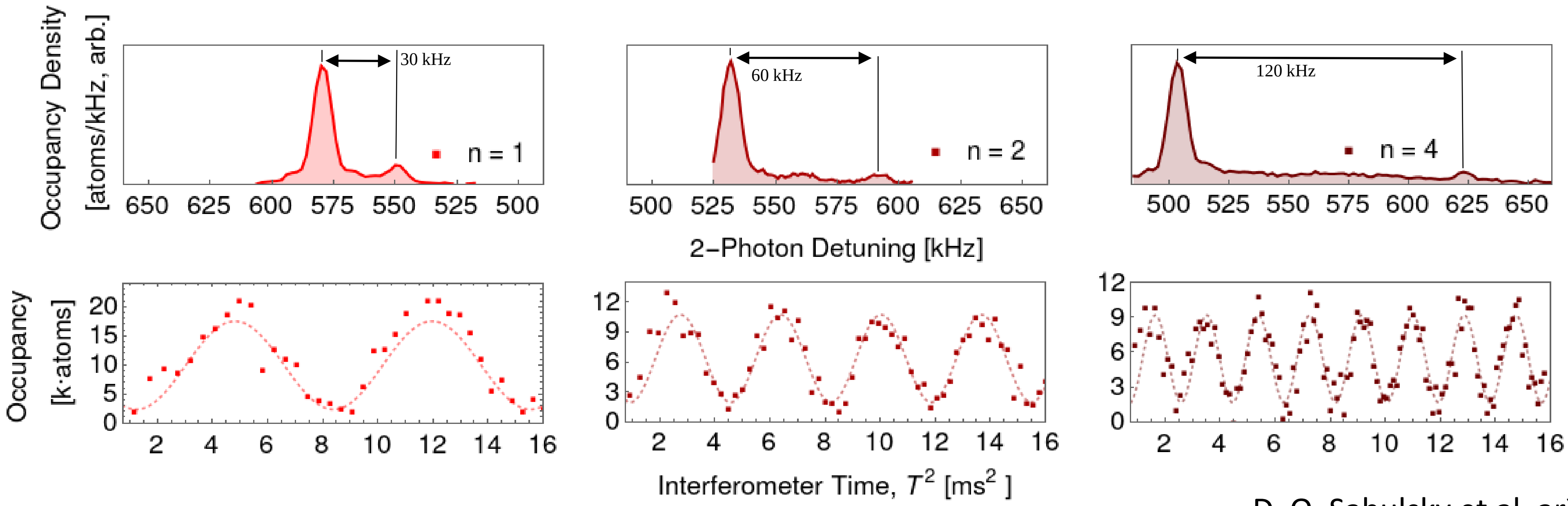
10^7 atoms/s flux in the right state for interferometry.

Effective temperature down to 50 nK (in one direction)



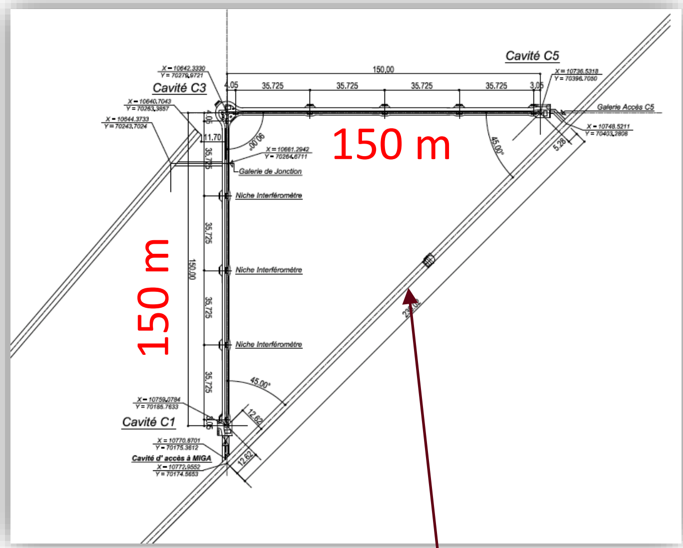
Intracavity interferometry in Bordeaux

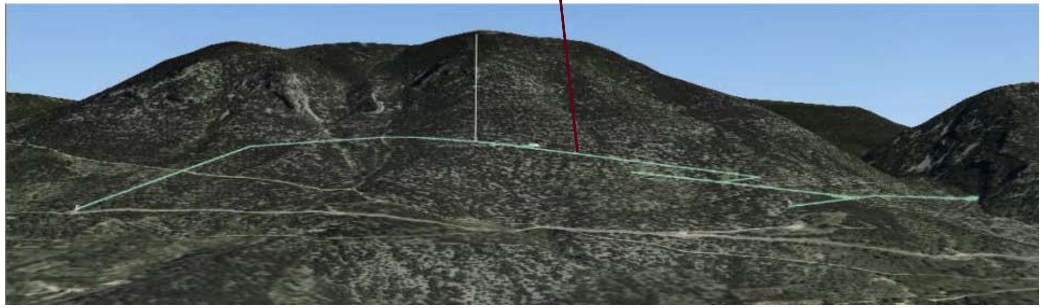


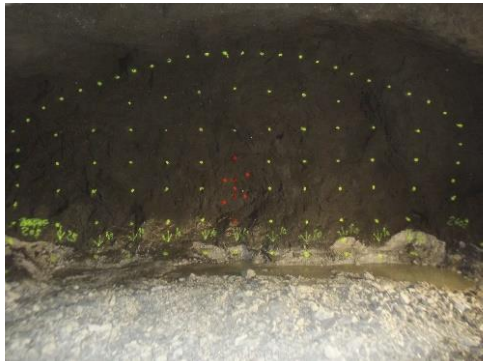


D. O. Sabulsky et al. arXiv: 2201.11693

Installation in LSBB







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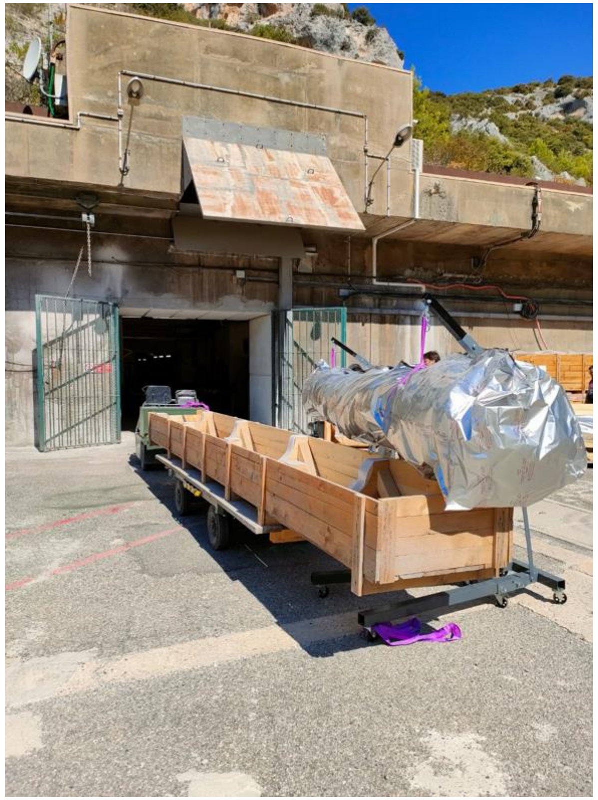

25 tubes to transport, connect and bake for high vacuum

Conclusion

MIGA
MATTER WAVE LASER - BASED INTERFEROMETER

- **GW detection with AI**: use free falling atoms instead of suspended mirrors
- → potential gain at low frequency (< 10 Hz)
- Possibility to reduce the effect of **Newtonian Noise on ground**

- Many **challenges** in cold atom physics to reach $\sim 10^{-20}/\sqrt{Hz}$ around 1 Hz
- → AI could nicely **complement (or combine with)** optical interferometry
- **MIGA** : proof of concept + applications in geosciences.

- Ongoing effort for a design study at the European level (ELGAR project).