MIGA and atom gradiometry noise analysis

B. Canuel, LP2N,IOGS/CNRS/Univ. Bordeaux

For the MIGA consortium

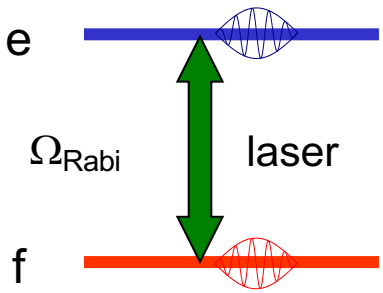
Outline

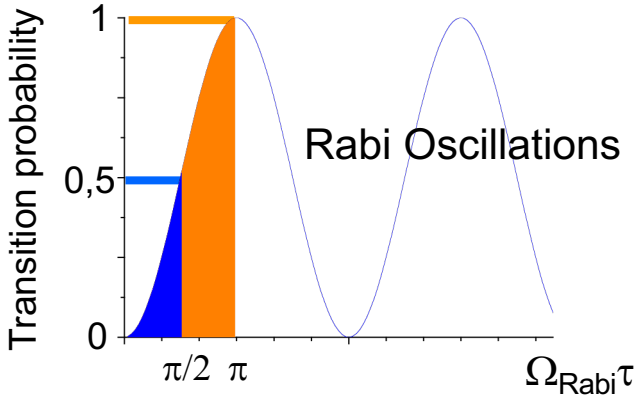
- Atom interferometry and gradiometric configuration.
- Recent advances of MIGA at LSBB
- First results of the MIGA gradiometer at LP2N and noise analysis

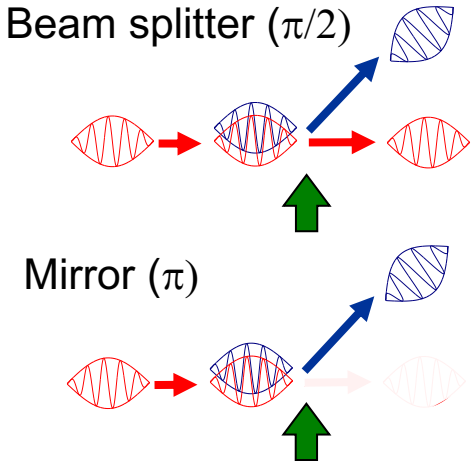
Atom interferometry

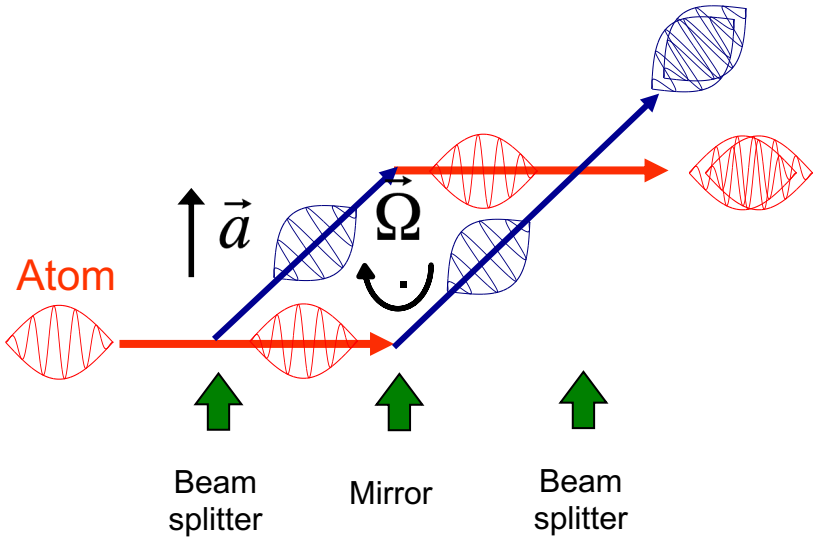
Atom interferometry

- Exploit wave nature of matter
- Particularly sensitive to inertial effects : acceleration, rotations, gravity, gravity gradient and curvature









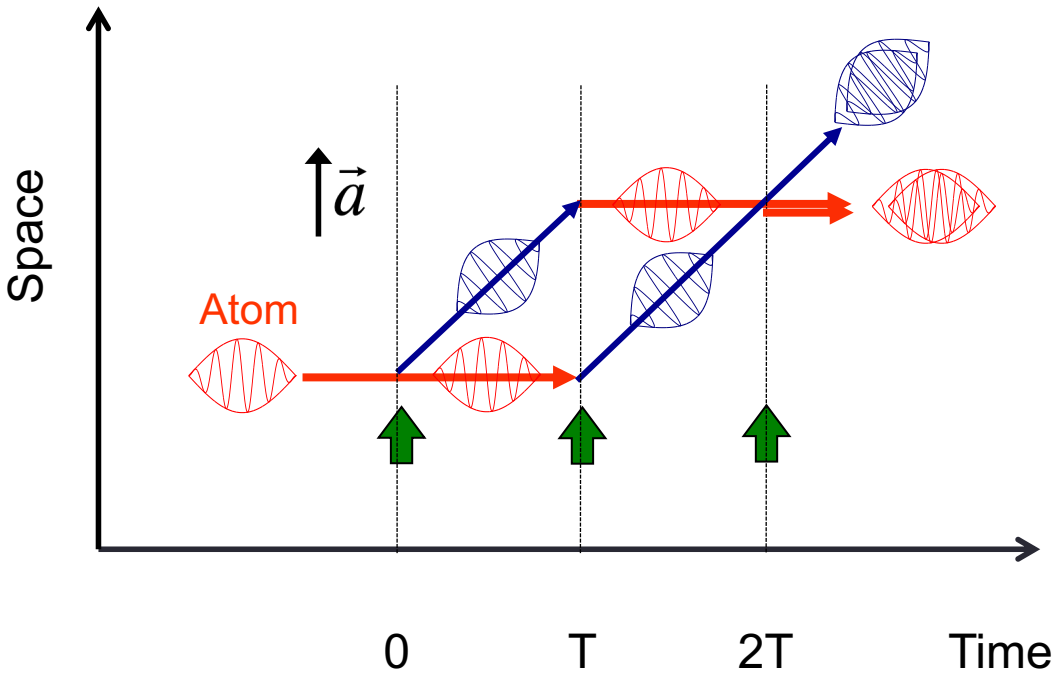
$$P = \frac{1}{2}(1 + \cos\Delta\Phi_{AT})$$

$$\downarrow$$

$$\propto \varphi_l$$

Measures the evolution of the MW with respect to laser field

Sensitivity of a detection noise limited Atom Interferometer



$$P = \frac{1}{2}(1 + \cos\Delta\Phi_{AT})$$

Measurement process:
Use fluorescence detection to measure the transition probabilty.

$$|\Psi\rangle = a_f|f\rangle + a_e|e\rangle \qquad |a_e|^2 = P \qquad |a_f|^2 = 1 - P$$

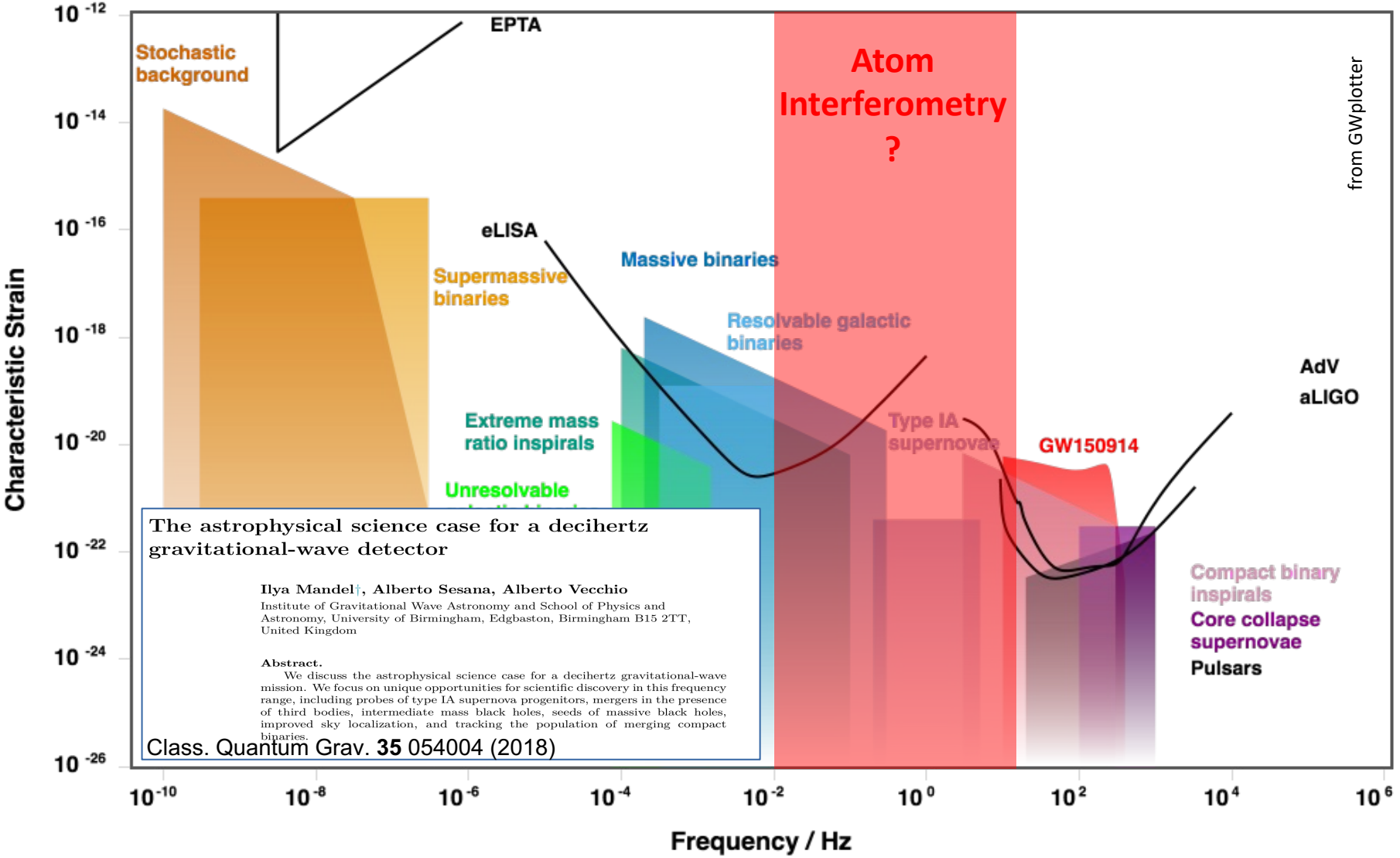
Each atom projected on one of the two states

Poissonian statistics ⟶ Noise prop $\boxed{1/\sqrt{N_{at}}}$

$N_{at} = 10^6$ ⟶ $\delta(\Delta\Phi_{AT}) = 1$ mrad

Sensitivity to acceleration $\Delta\Phi_{AT} = k_{eff} a T^2$ 2T=1 s, λ=780 nm $\delta a_{min} \approx 10^{-10}$ **m.s^{-2}**

Low frequency GW detectors

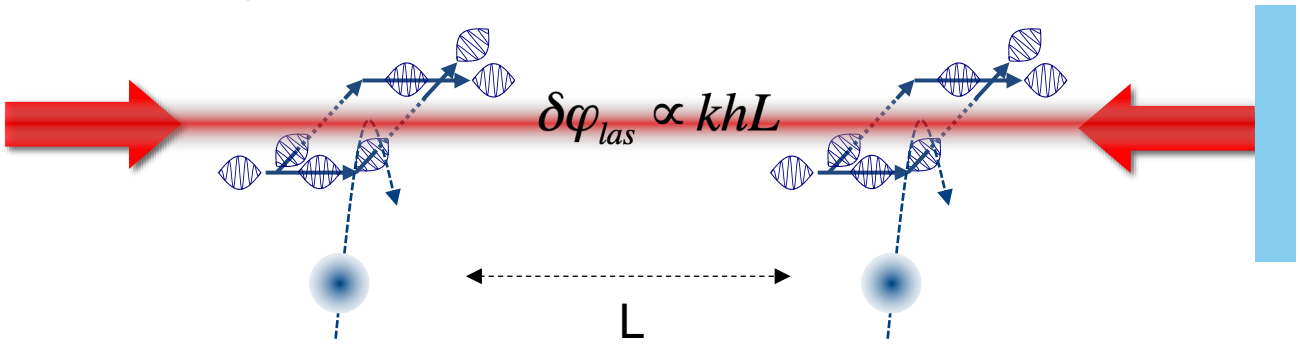


A. Sesana, “Prospects for Multiband Gravitational-Wave Astronomy after GW150914”, Phys. Rev. Lett. 116, 231102 (2016)

J. Harms, B. Slagmolen, R. Adhikari, M. Miller, M. Evans, Y. Chen, H. Muller, and M. Ando, “Low-frequency terrestrial gravitational-wave detectors,” Phys. Rev. D, 88 (2013)

Cold atoms for GW detection ?

Let's use free falling atoms as "test masses" instead of mirrors

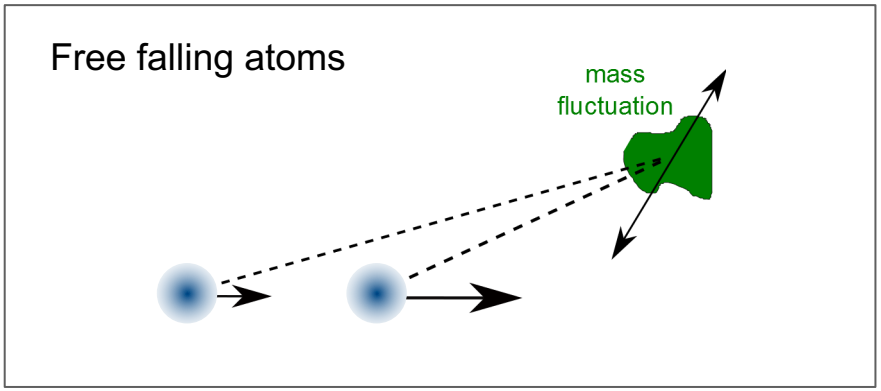


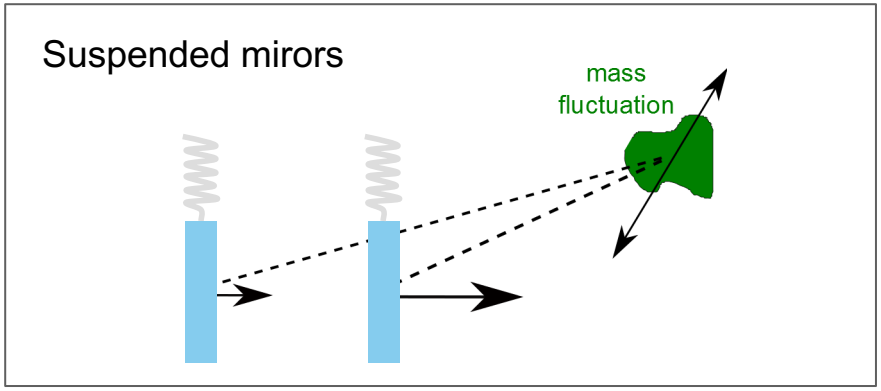
PHYSICAL REVIEW D **78,** 122002 (2008)

Atomic gravitational wave interferometric sensor

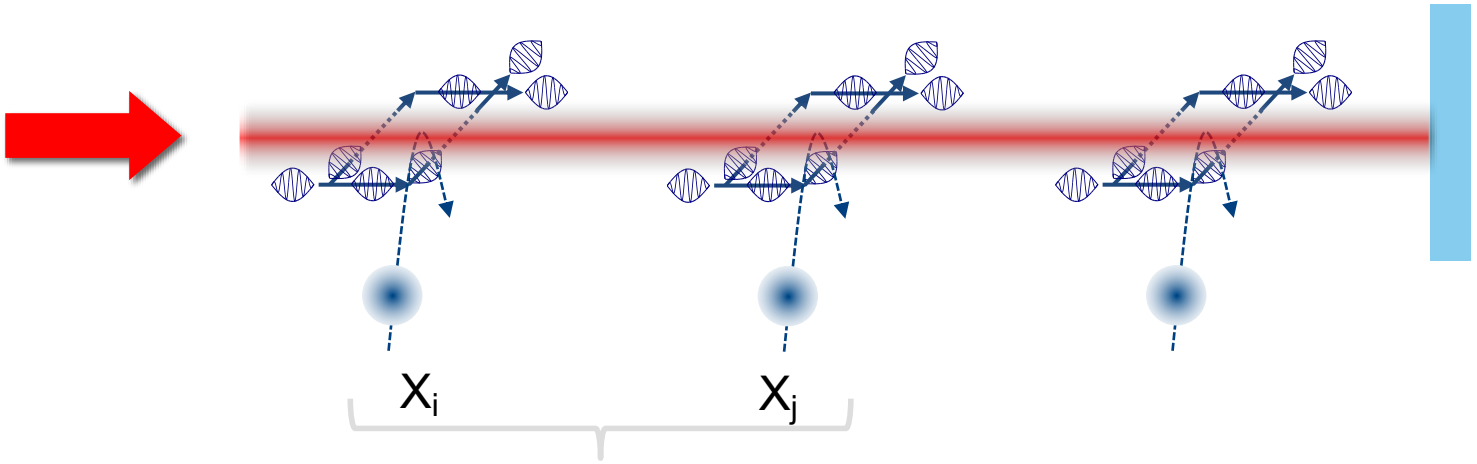
Savas Dimopoulos,[1,*] Peter W. Graham,[2,†] Jason M. Hogan,[1,‡] Mark A. Kasevich,[1,§] and Surjeet Rajendran[1,2,‖]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*SLAC, Stanford University, Menlo Park, California 94025, USA*
(Received 28 August 2008; published 19 December 2008)

Strong rejection to seismic noise.
Sensitivity to Gravity Gradient Noise is the same !





Use network of AI



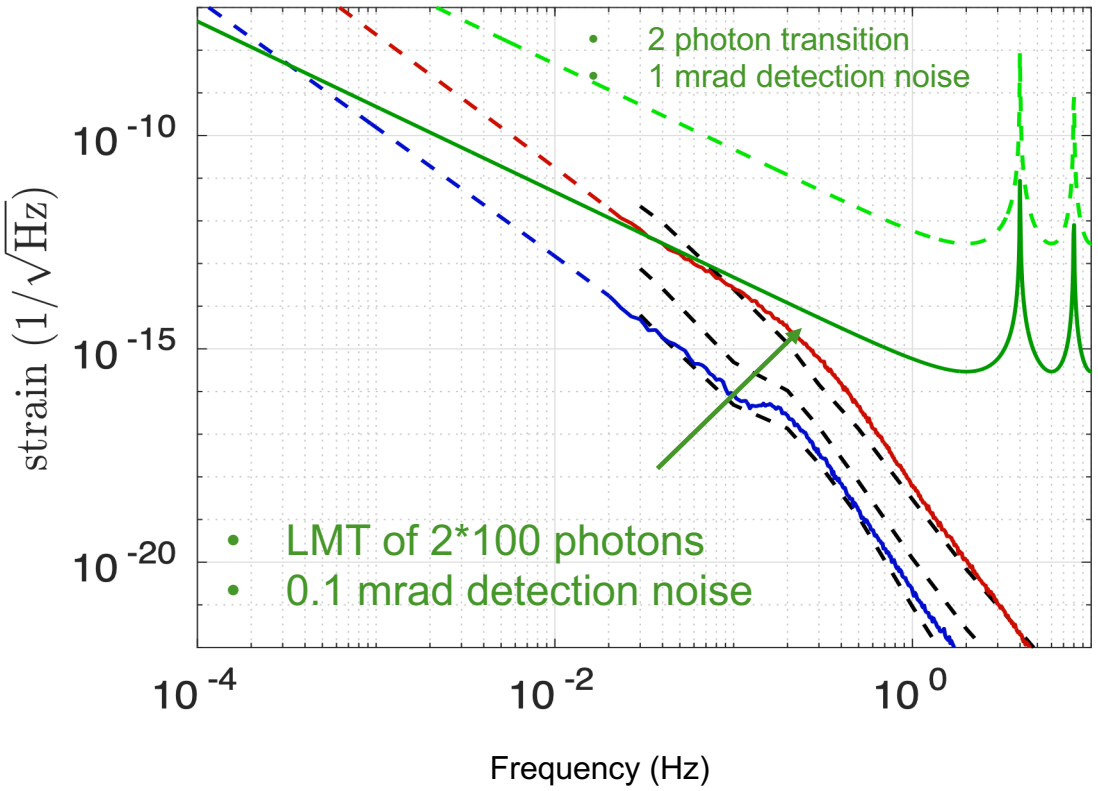
$\Delta\phi_{at}^{i}-\Delta\phi_{at}^{j}$

- GW $\propto kh(X_i - X_j)$
- Gravity Gradient $\propto 2kT^2\left[a(X_i) - a(X_j)\right]$

Discrimination between GW effects and gravity gradients using the spatial resolution of the antenna

- Low frequency (10^{-2}-10 Hz) GW detection limited by detection noise

MIGA projected sensitivity



- Initial strain sensitivity 2.10^{-13} at 2 Hz.
- Study advanced measurement strategies & atom manipulation techniques

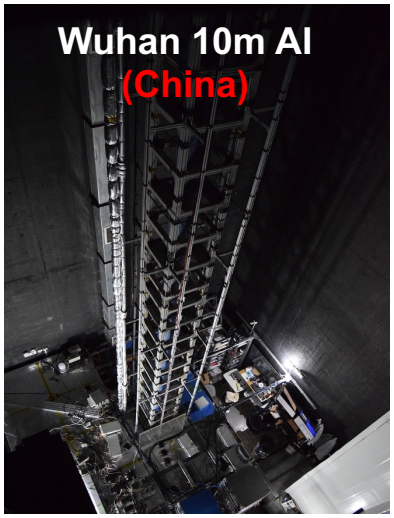
  Challenge for atom optics
  - « LMT » techniques
  - High atom flux
  - Squeezing techniques
- Fill the sensitivity gap for GW detection
- Advanced studies of GGN

Further applications:

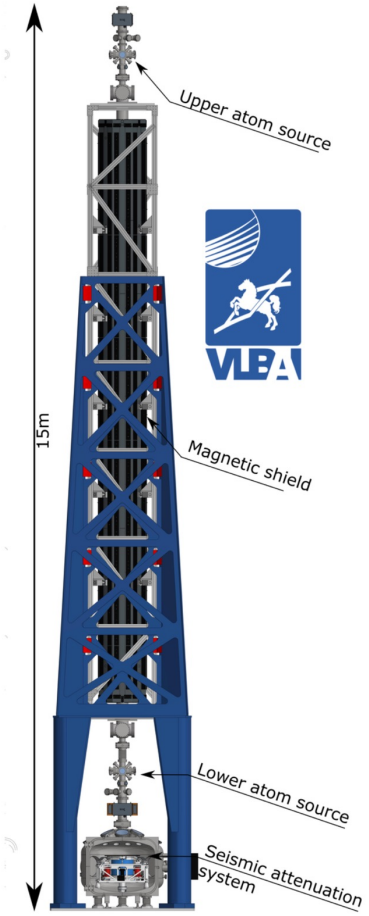
- Dark matter searches
- Tests of general relativity (EP, Lens-Thirring...)
- Study of geophysical processes at global or local scale.
- New class of advanced quantum sensors (rotation, acceleration..)

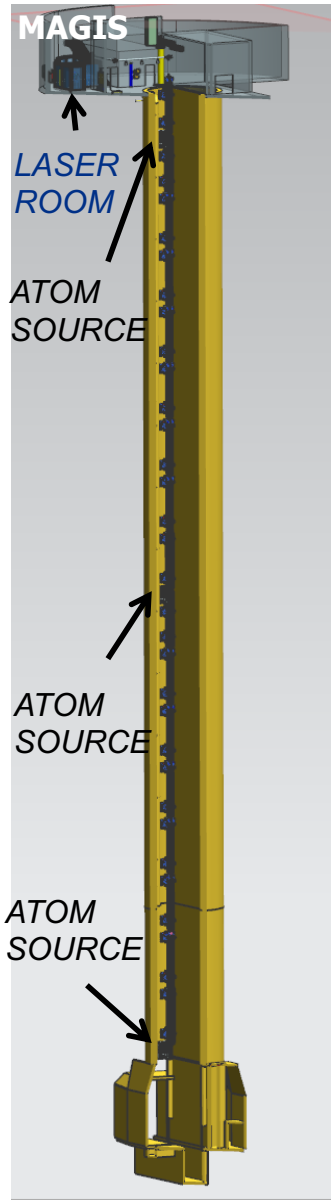
International context



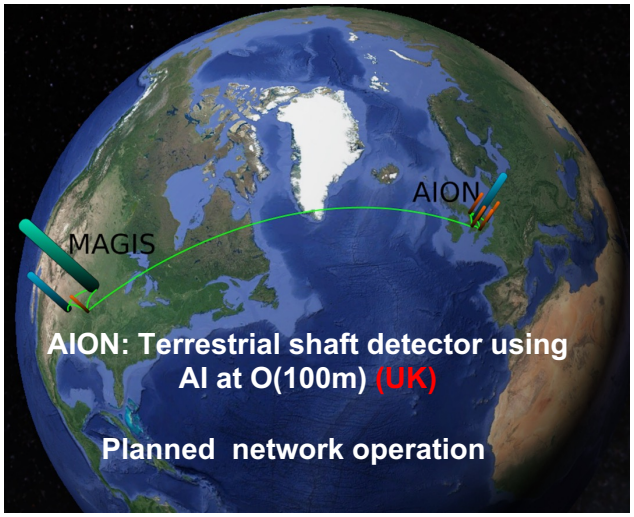


VLBAI: Terrestrial tower using atom interferometer O(10m) (Germany)

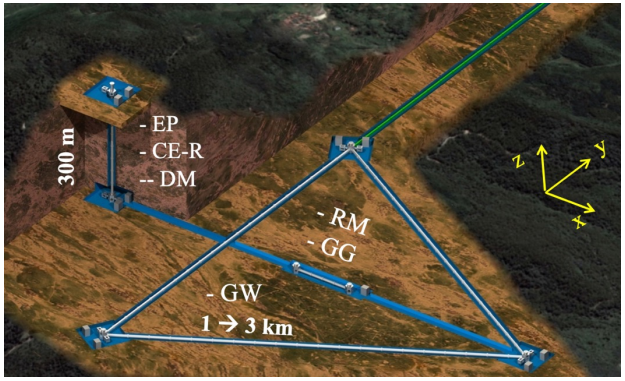




MAGIS: Terrestrial shaft detector using atom interferometer at O(100m) Fermilab (US)



ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m) (China)

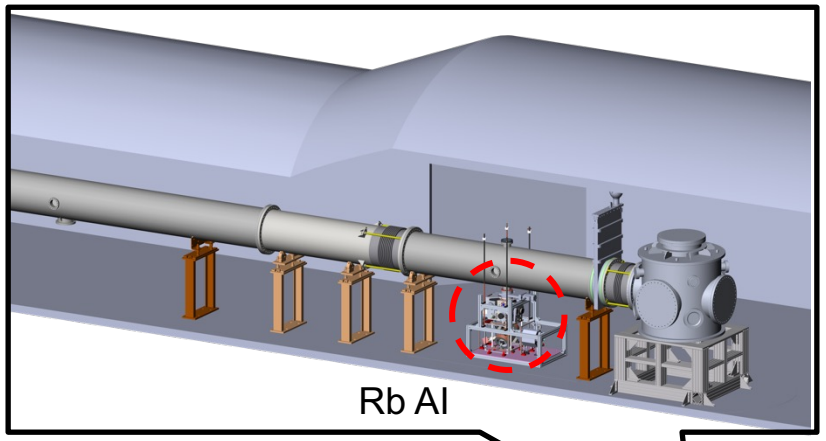


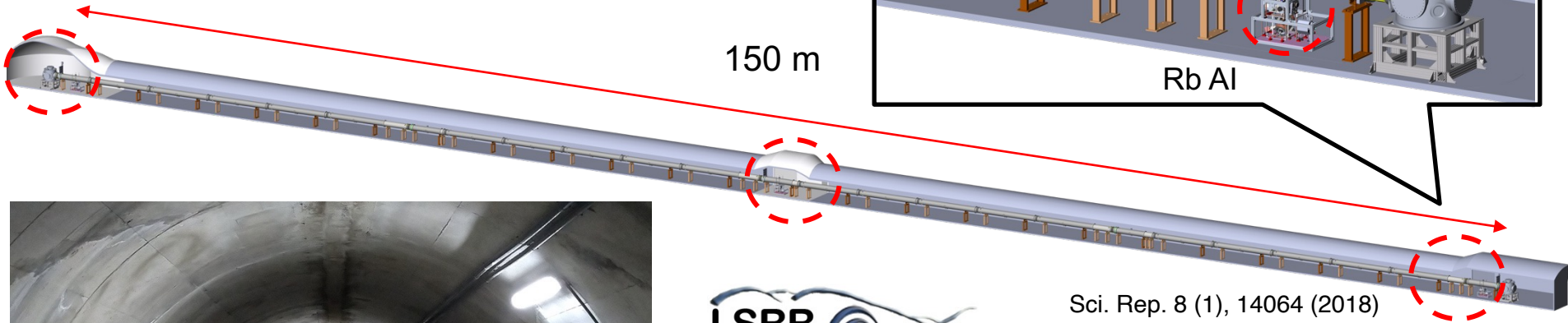
Recent advances of MIGA at LSBB

MIGA, a large-scale gravity antenna

- A Project carried by a French consortium of 17 partners to build a **150 m long array of three Rb interferometers.**

- Develop AI techniques to build future sub-Hz GW detectors and study of Newtonian Noise.
- Develop new methods for characterizing gravity field fluctuations for applications in Geoscience (geology, seismology, hydrogeology…)





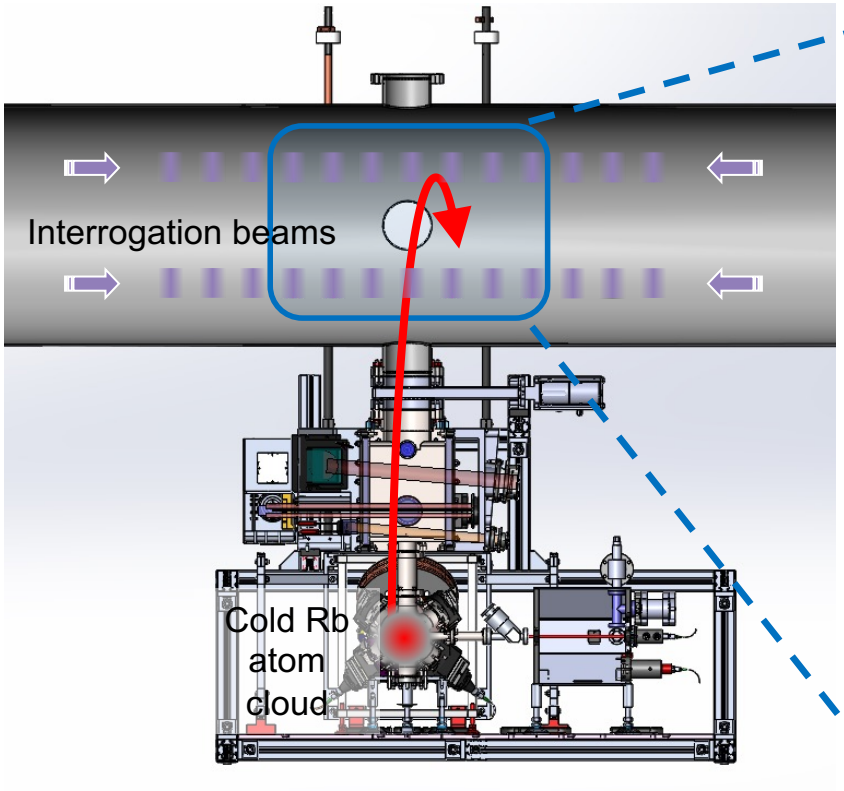


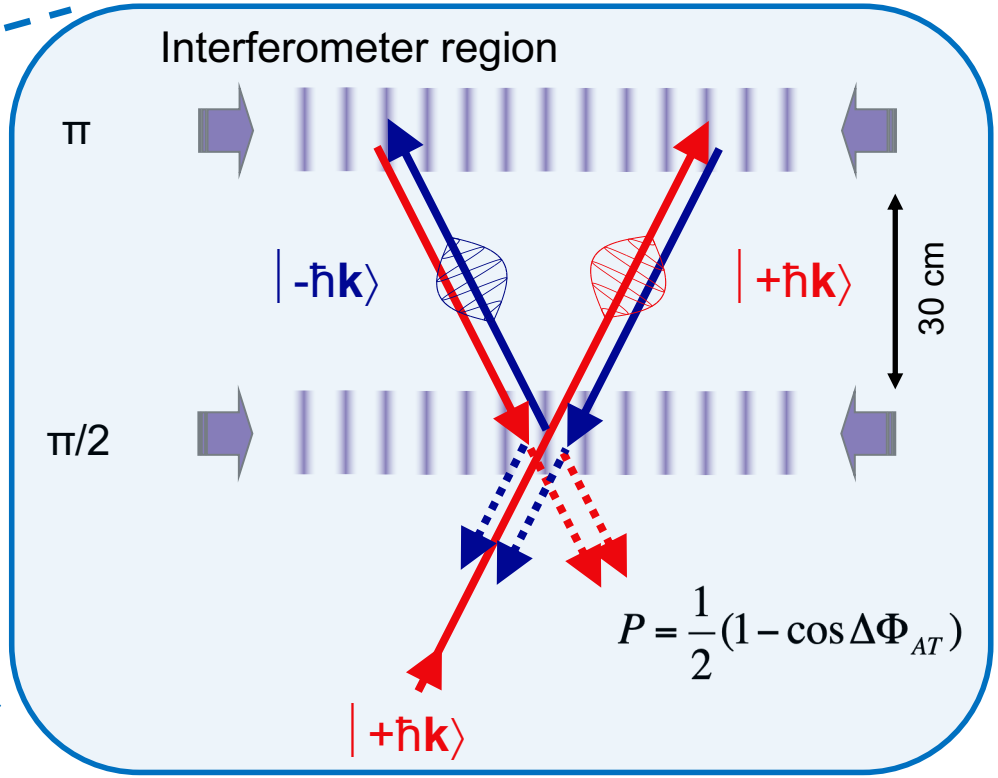
Sci. Rep. 8 (1), 14064 (2018)

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

- An infrastructure now being installed at the LSBB underground Laboratory
- A site with exceptional low noise properties (seismic, magnetic)

Functioning of a MIGA Atom Interferometer



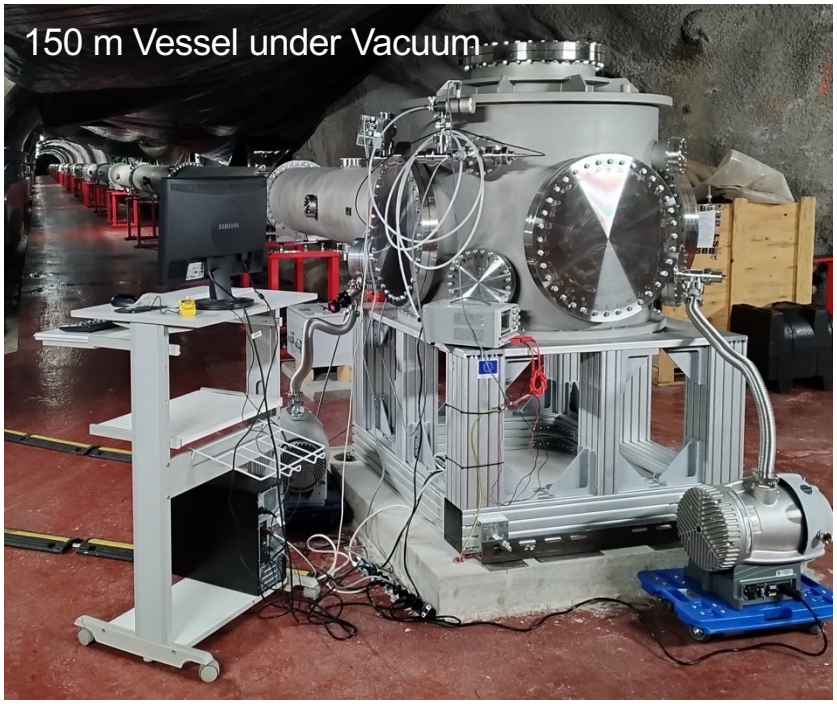


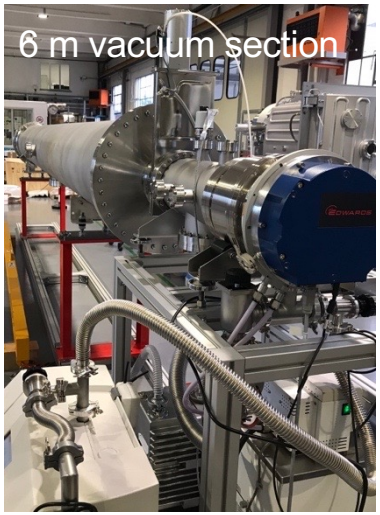
- Rb atom source uses a combination of a 2D and 3D magneto-optic traps.
- After cooling, trapping, the atoms are launched on a parabolic trajectory

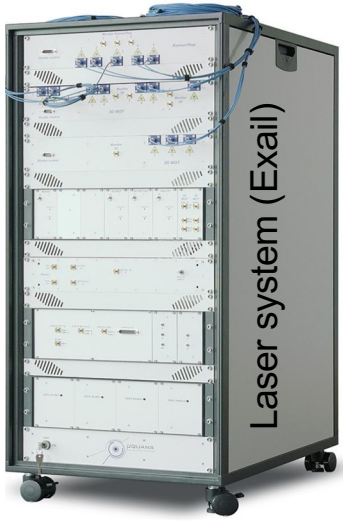
- Manipulation using Bragg diffraction on a set of two horizontal interrogation beams.
- Two atom interferometers with L=150 m (1 mrad of sensitivity, 2T= 500 ms) strain sensitivity of 2.10^{-13} at 2 Hz

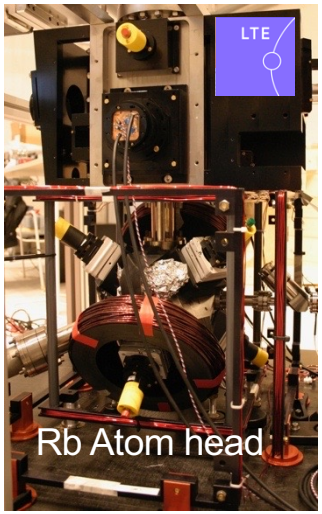
MIGA, status











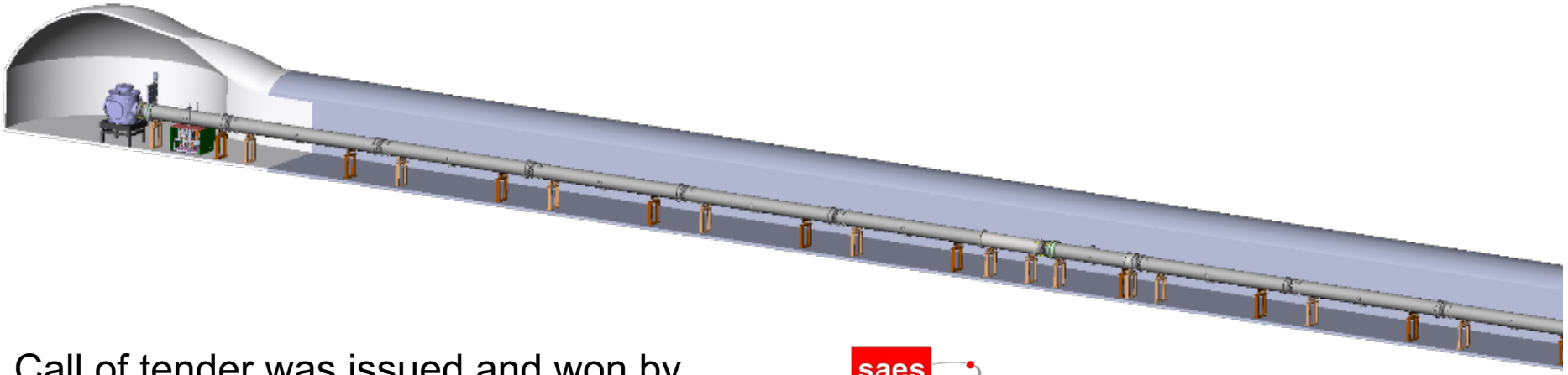


- Two 150 m dedicated galleries were bored at LSBB
- All parts (vacuum, atom heads, lasers) produced and tested.
- Vacuum system completely assembled at LSBB and a few 10^{-9} mbar. Following steps: baking of the system and atom heads connection.
- Cold atom production at LSBB starting.

Specifications of the vacuum vessel

A (very) demanding system:

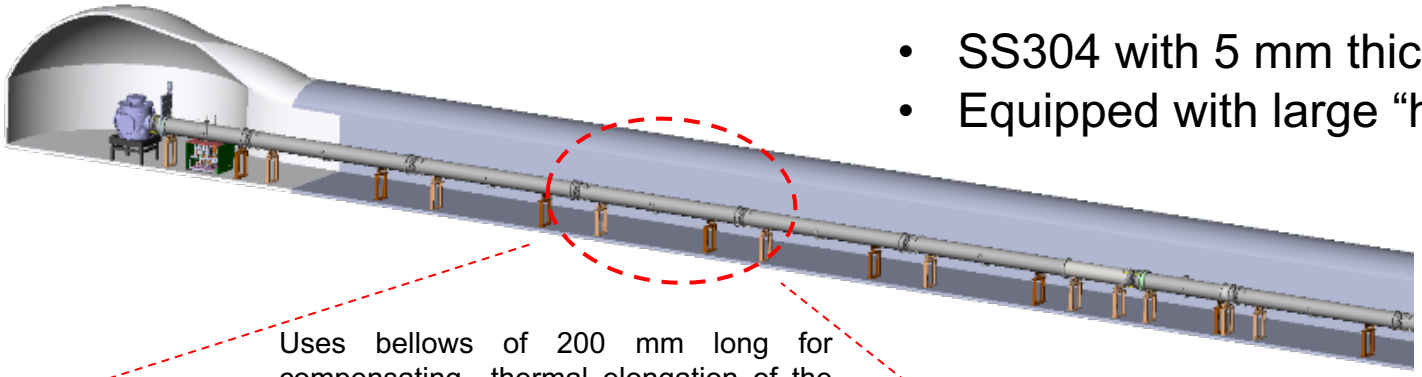
- Large aperture: 50 cm large, 150 m long, total volume of 30 m^3
- Must reach 10^{-9} mbar of residual pressure
  - Baking @100 °C for a few days required
  - Pumping speed in normal operation 10000-20000 l/s
- Being assembled and operated in rough conditions (humidity – cleanliness)



Call of tender was issued and won by SAES for a total of 1 ME

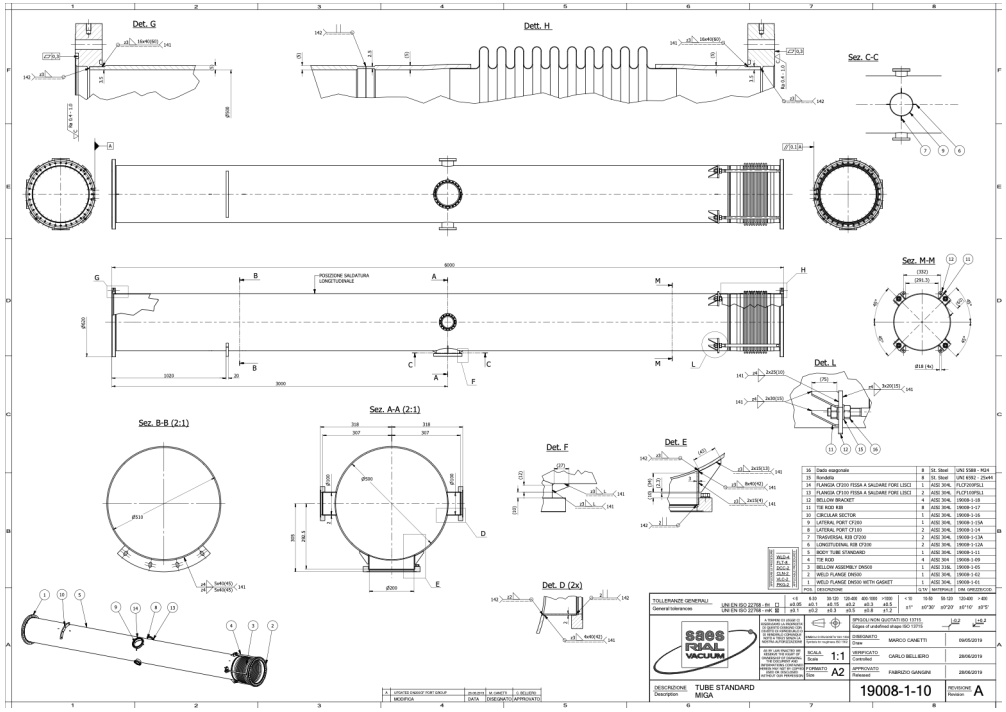
Vacuum vessel

Most of the system composed by “standard” 6 m sections:



- SS304 with 5 mm thickness
- Equipped with large “helicoflex“ flanges

Uses bellows of 200 mm long for compensating thermal elongation of the whole section (around 0,5 cm at 100 °C).



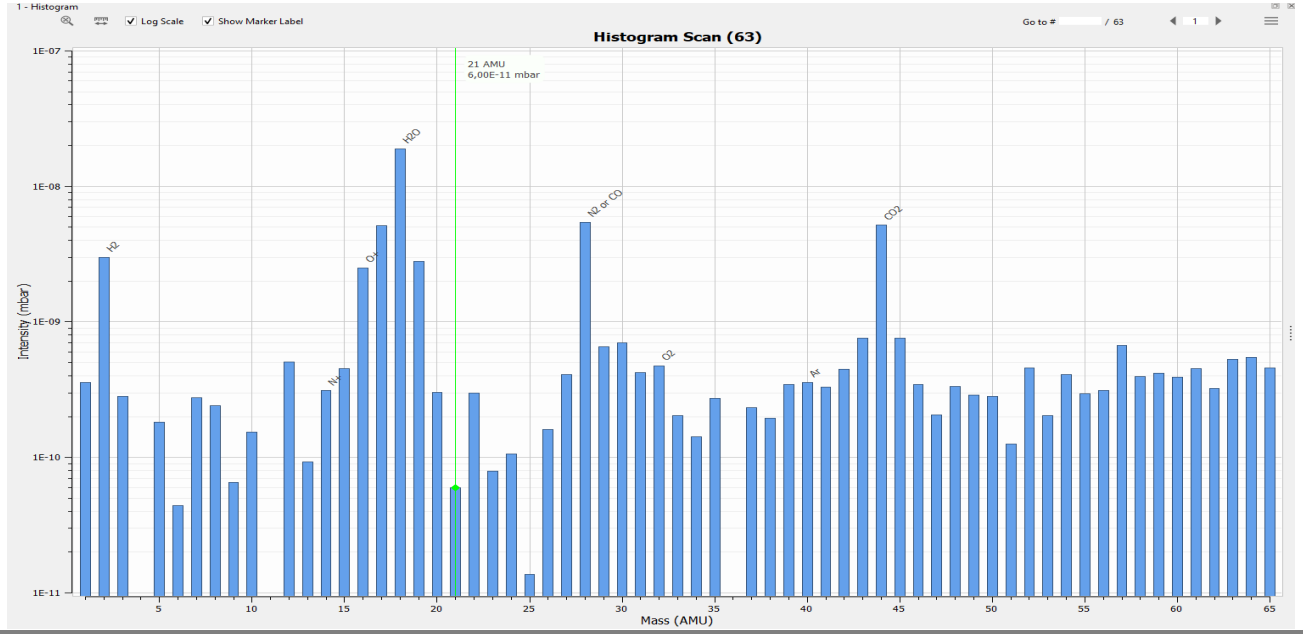


MIGA vacuum system installation

- Installation progressing since end 2023 from support of LP2N and LTE teams. End 2024 we we started forming a local engineering team at LSBB.
- The activity involved installation of towers, tubes, supports, fittings, probes, blank flanges, pumping and venting system), precise tube alignment, vacuum test (RGA analysis, leak tests).
- The first vacuum test were realized successfully beginning of 2024 on 10 m section where we demonstrated to reach a vacuum level of a few 10^{-8} mbar
- System gradually assembled, aligned and tested by about 20-30m sections.
- Now very good performances obtained

$P_0 = 4.10^{-9}$ mbar





- Reach H_2O degazing rate 2.10^{-11} mbar.l.s^{-1}/cm^2,
- **Expected nominal performance before baking**

MIGA, installation

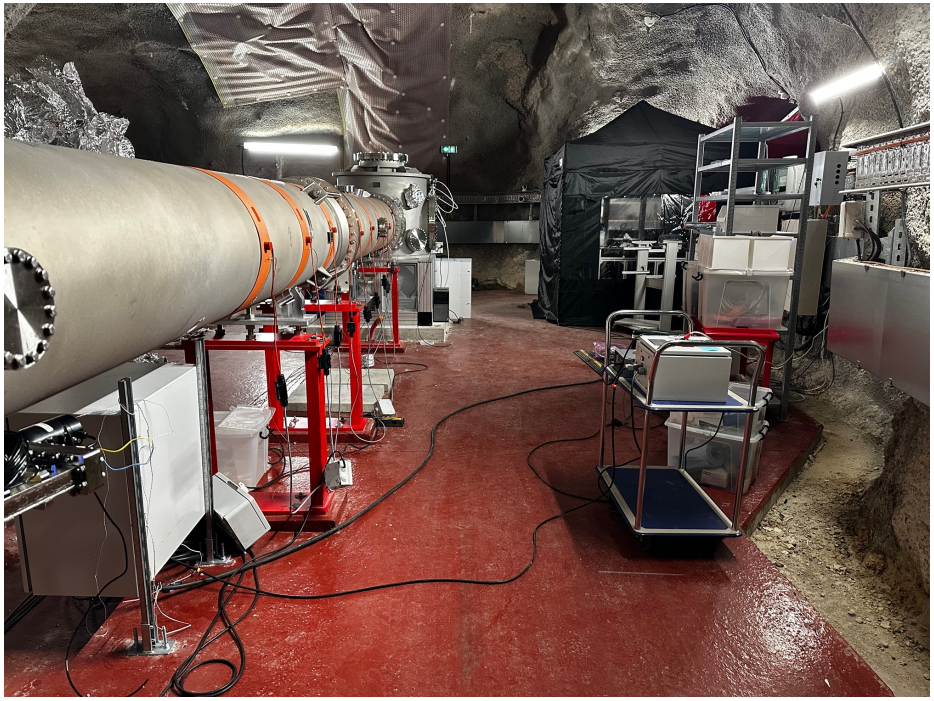






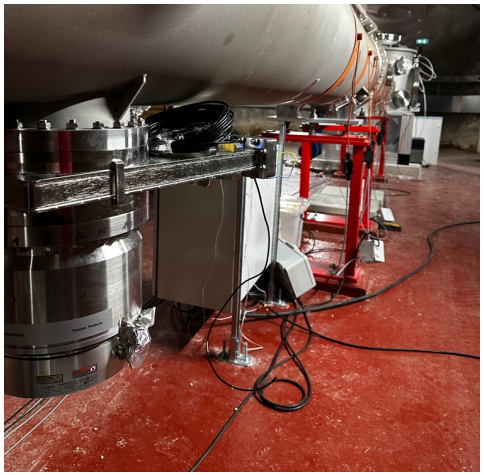


Completed system



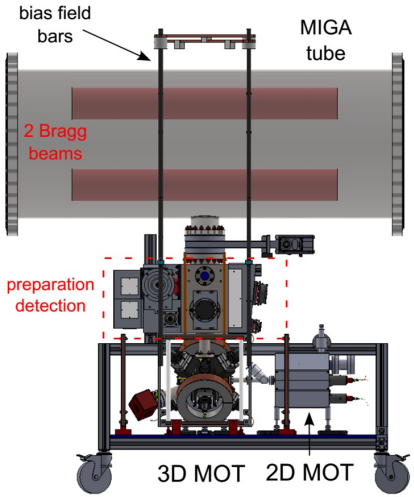


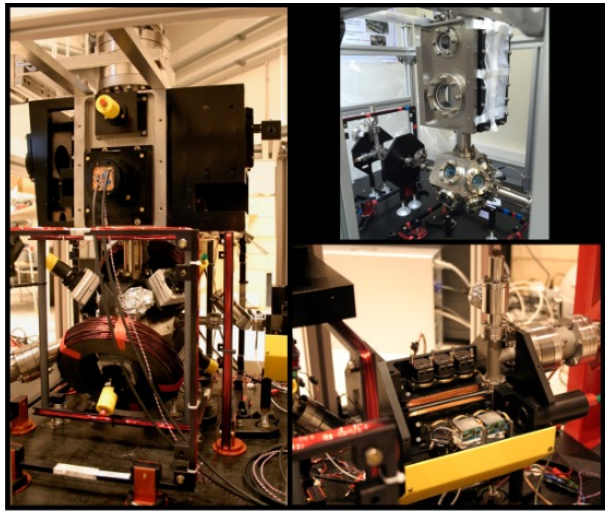




Atom Heads

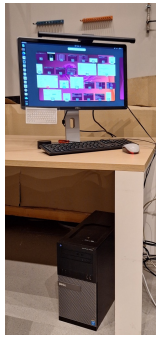
- Q. Beaufils *et al.*, Sci Rep 12, 19000 (2022)

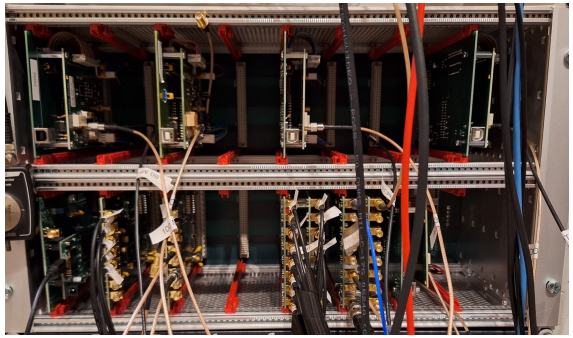




5 system produced and tested at LTE (2 generations)

- D. O.Sabulsky *et al.*, Sci. Rep. 10, 3268 (2020)
- A. Bertoldi *et al.*, RSI, 91, 03320 (2020)







1 FPGA: "brain" of the system, controls all the cards
5 DDS: controls frequencies and powers for laser locking and AOMs
1 DAC: control the voltage amplitude of AOMs
2 TTL: Transistor to Transistor Logic, ON/OFF of shutters

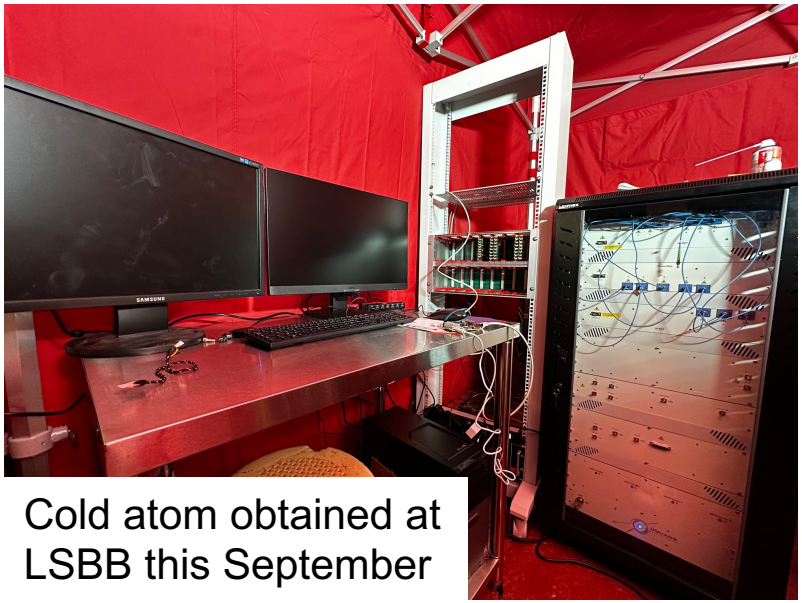
2 generations of ctrl system , 3 generations of Exail fiber lasers (LTE/LP2N)

Two complete systems of last generation delivered at LSBB in Nov 2025

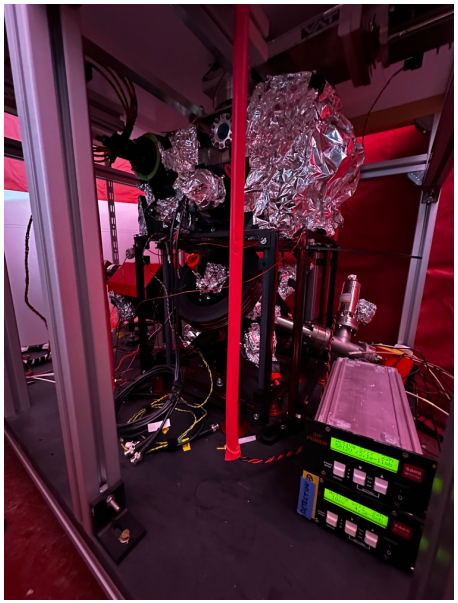
Atom Heads at LSBB

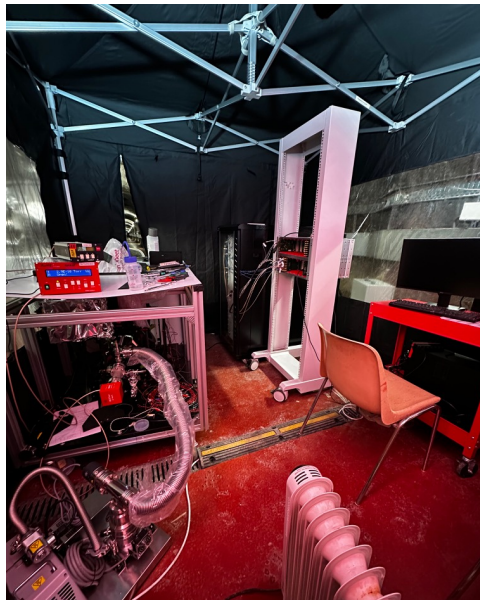






Cold atom obtained at LSBB this September



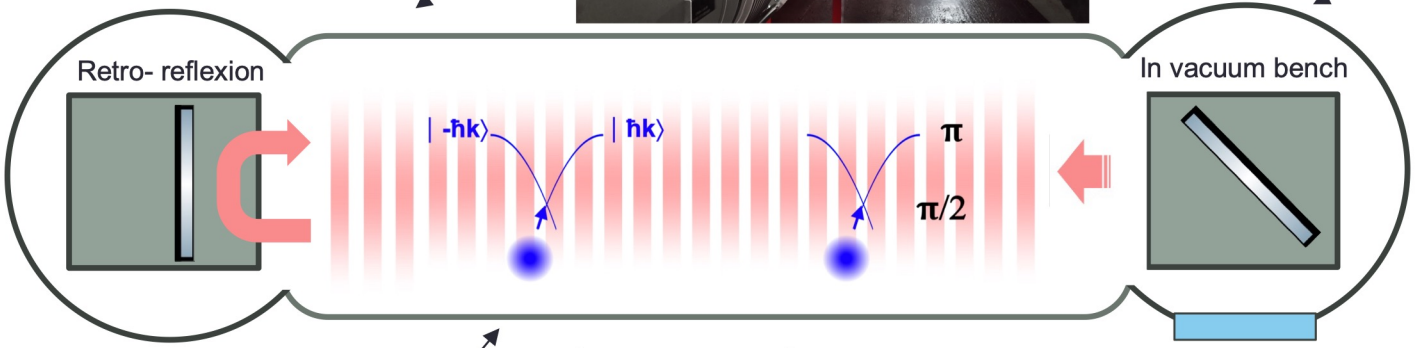


Towards first measurements…

- Objective: first large-scale AI measurements with a simplified configuration



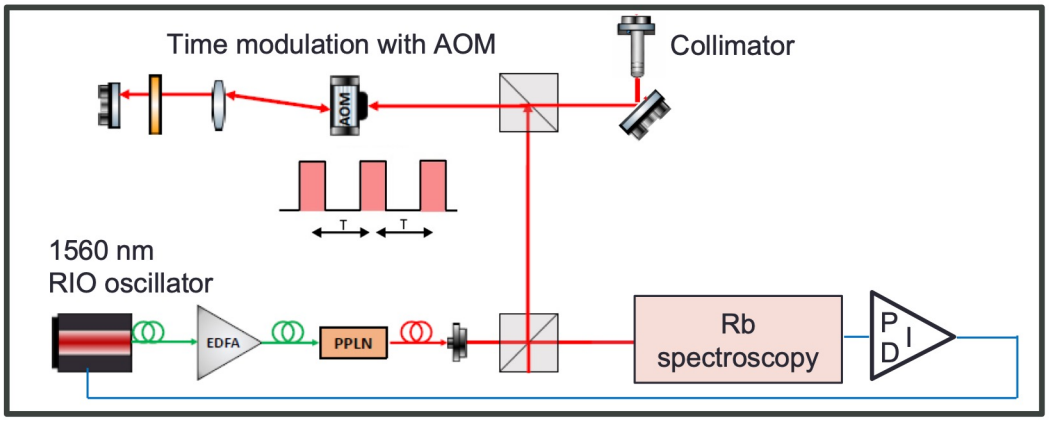






P_{out}=150 mW @780 nm
$2w_0^2$=34 mm

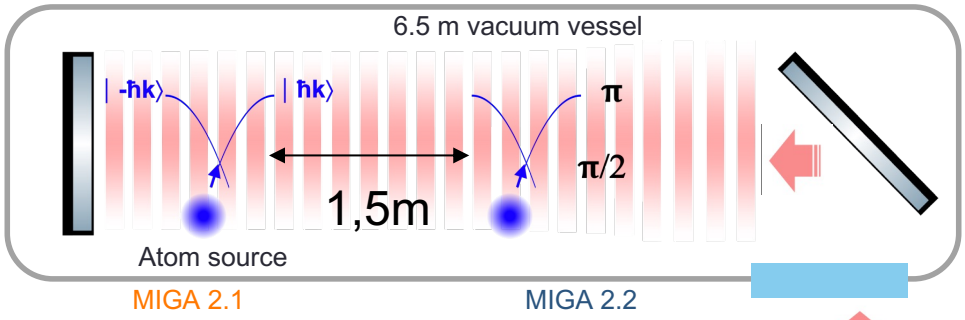
Laser bench

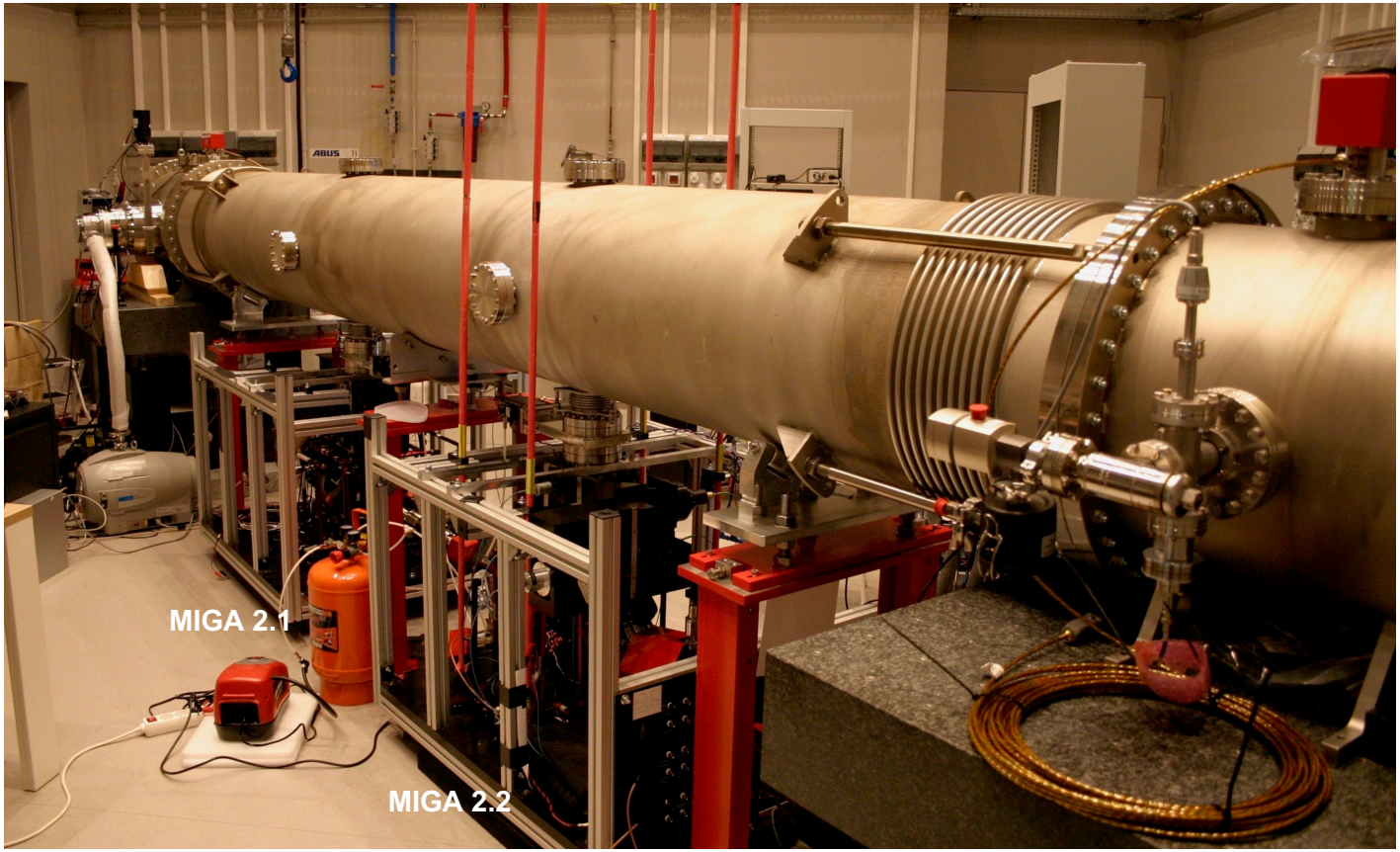


First results of the MIGA gradiometer at LP2N and noise analysis

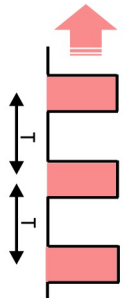
MIGA gradiometer at LP2N

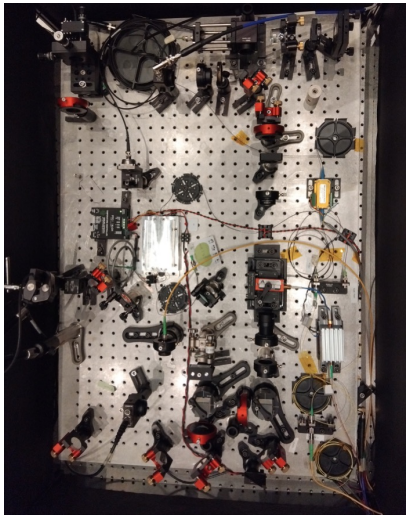
- We realized a complete reduced scale version of MIGA.
- Used to develop all MIGA components (heads, control system, vacuum).
- Now obtaining first gradiometric results we want to further deploy at LSBB.





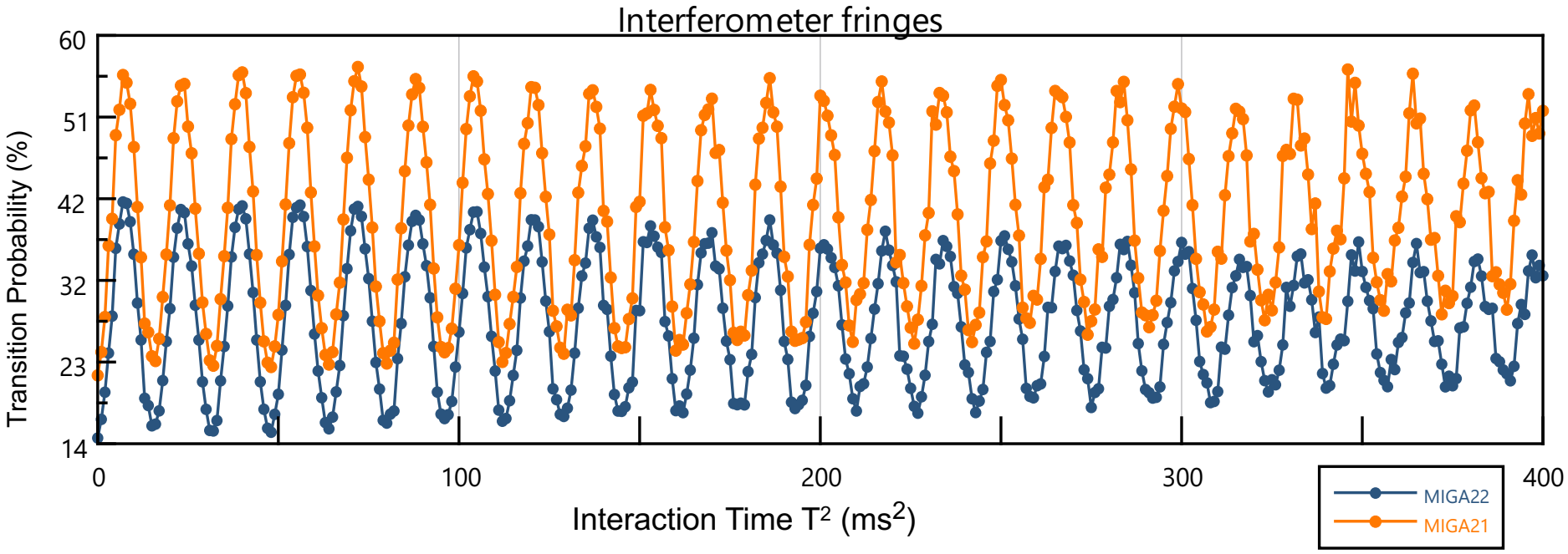
Works with a single retroreflected Bragg Beam interrogation.





MIGA gradiometer results

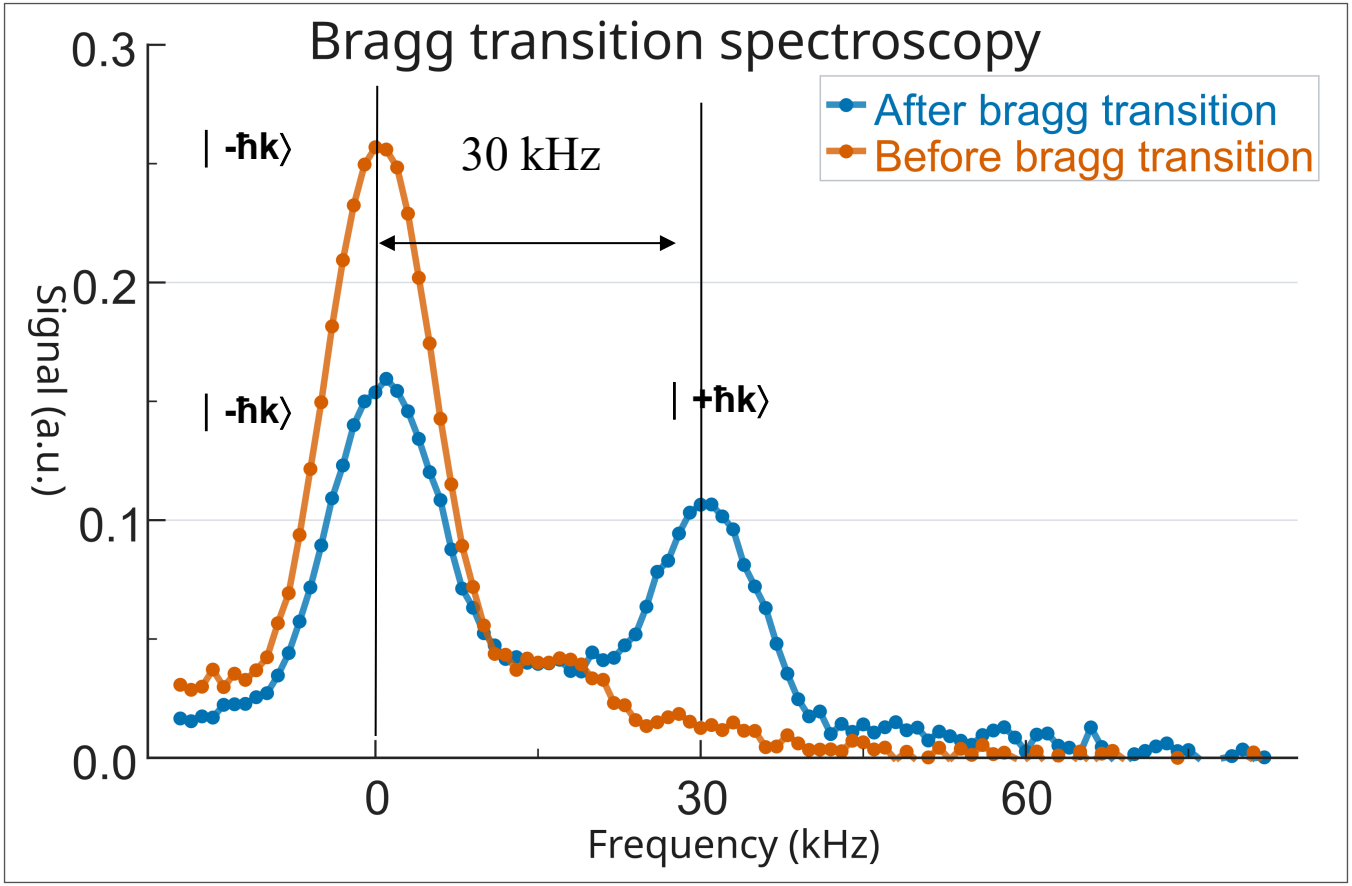
- Demonstrate a complete Pi/2-Pi-Pi/2 for first order Bragg diffraction.
- Tilt of the experiment: Inertial atom phase from the projection of local gravity $\Delta\Phi_{AT}=k\alpha gT^2$
- Atom fringes observed by scanning the interaction time T.



- Fringe contrast 40 % for MIGA 22 and 25 % for MIGA 21

Contrast limitation

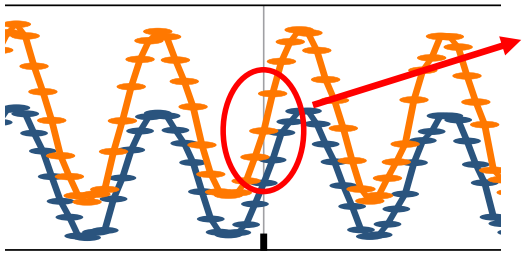
- Limited by the efficiency of the interferometer pulses
- For MIGA 22 (25% constrast) the transfer efficiency of a single Bragg Pi pulse (t=37 us) is 30% to the target state.



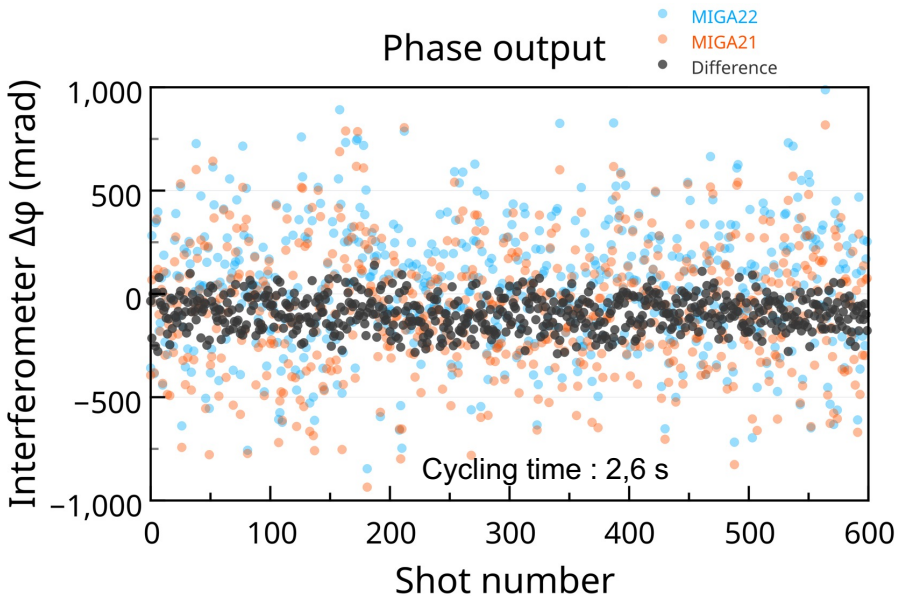
Limits comes from:

- Atoms sources temperature 4-5μK
- Size and spatial inhomogeneity of the Interrogation beam (Gaussian $2w_0^2$=24 mm)

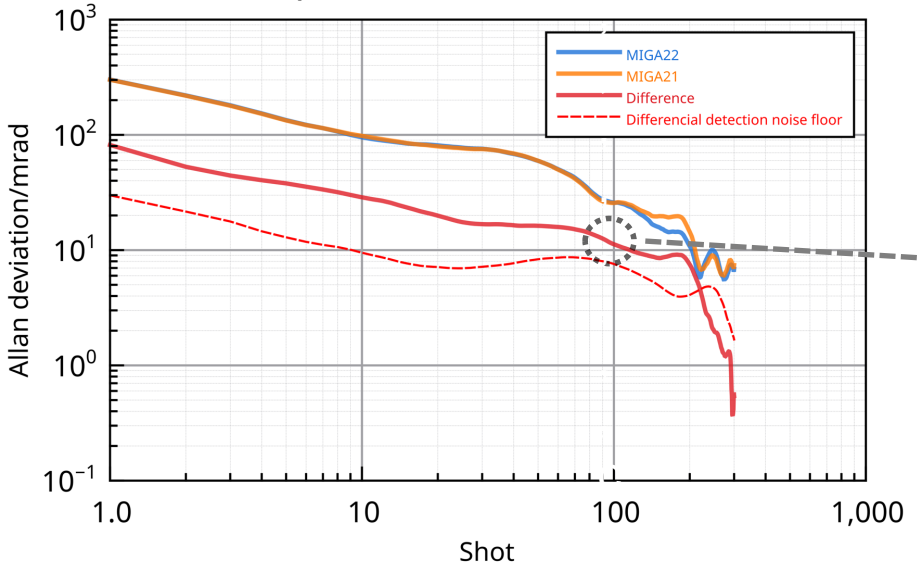
Sensitivity analysis



- We place both interferometers at mid fringe where the system response is linear.
- Acquire successive measures of P and convert them in atom phase using fringe parameters (constrast and offset)



Atom phase noise for T=10 ms

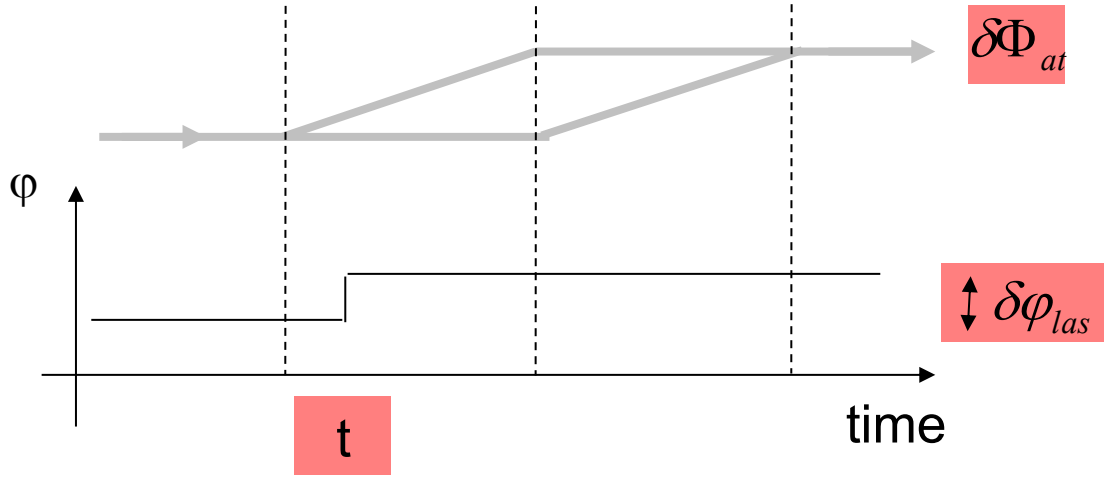


- We use the statistical tool of the Allan Variance that calculate the standard deviation of the measurements as a function of the integration time.
- The gradiometric signal reaches 10 mrad after averaging 100 shots (260 s)
- Equivalent strain sensitivity of $8\ 10^{-10}$
- Not at the estimated differential detection noise

Noise analysis…

Use a tool to calculate response to any given phase fluctuation:

Sensitivity function of the interferometer:



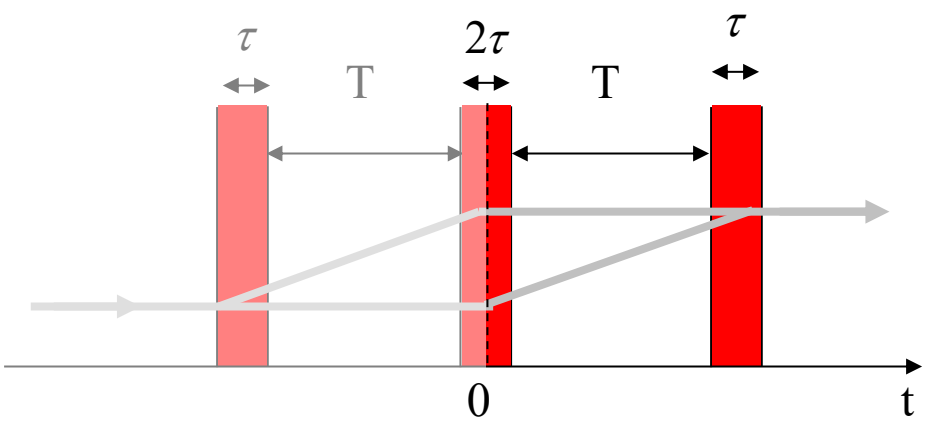
$$g(t) = \lim_{\delta\phi_{las}\to 0} \frac{\delta\Phi_{at}}{\delta\phi_{las}}$$

Atom phase shift at ITF output from any phase fluctuation :

$$\Delta\Phi_{at} = \frac{1}{2}\int g(t)\frac{d\varphi_{las}(t)}{dt}dt$$

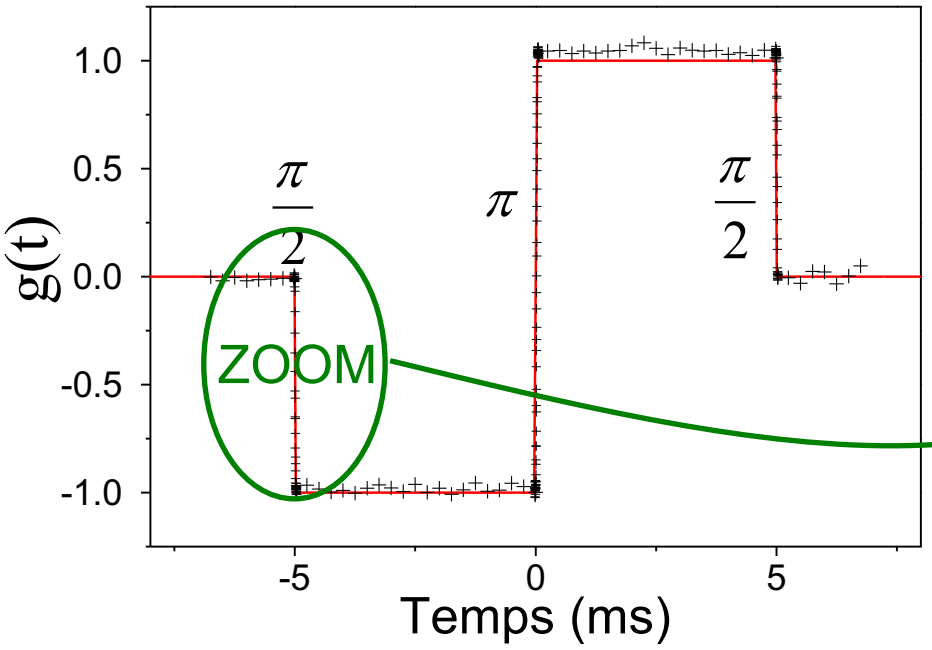
Sensitivity to other effects calculated by conversion in equivalent phase fluctuations (inertial effects, mirrors vibrations, magnetic fluctuations, laser frequency noise…)

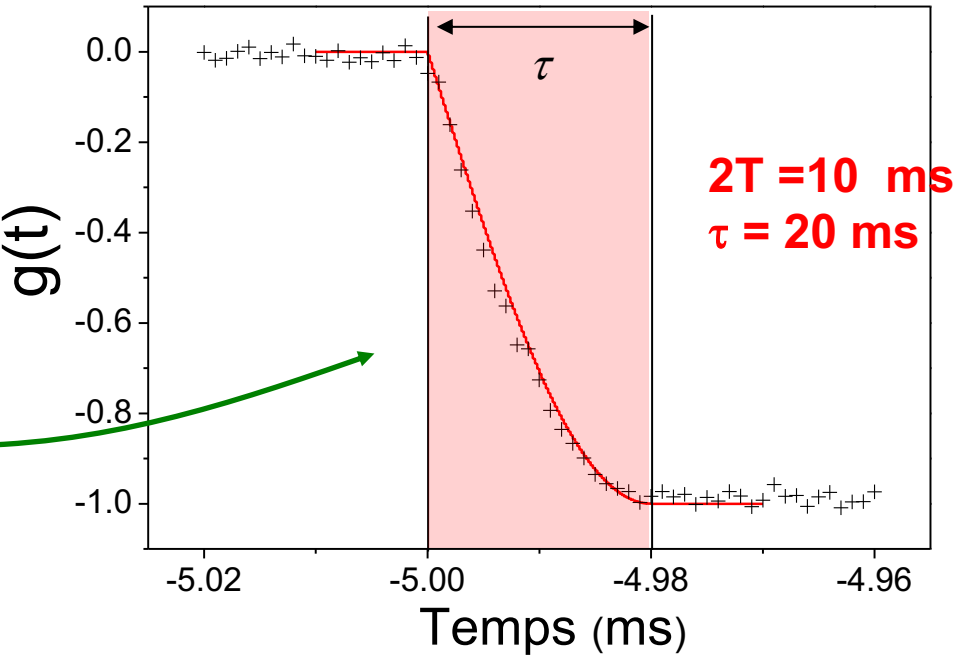
Sensitivity function in time domain:



Odd function

$$g(t)=\begin{cases}\sin(\Omega_R t) & 0<t<\tau\\ 1 & \tau<t<T+\tau\\ \sin(\Omega_R(t-T)) & T+\tau<t<T+2\tau\end{cases}$$





From IEEE Transactions on Instrumentation and Measurement, 57, 6, 1141-1148, (2008)

Sensitivity function in the spectral domain:

In the spectral domain *g* enables to calculate the TF *H(ω)* of the AI :

$$H(\omega) = \omega G(\omega) \quad G(\omega) = TF[g(t)](\omega)$$

Enable to calculate the standard deviation of atom phase fluctuation in presence of a laser phase noise PSD:

$$\sigma^2_{\Phi_{AT}} = \int |H(\omega)|^2 S_{\varphi las}(\omega) \frac{d\omega}{2\pi}$$

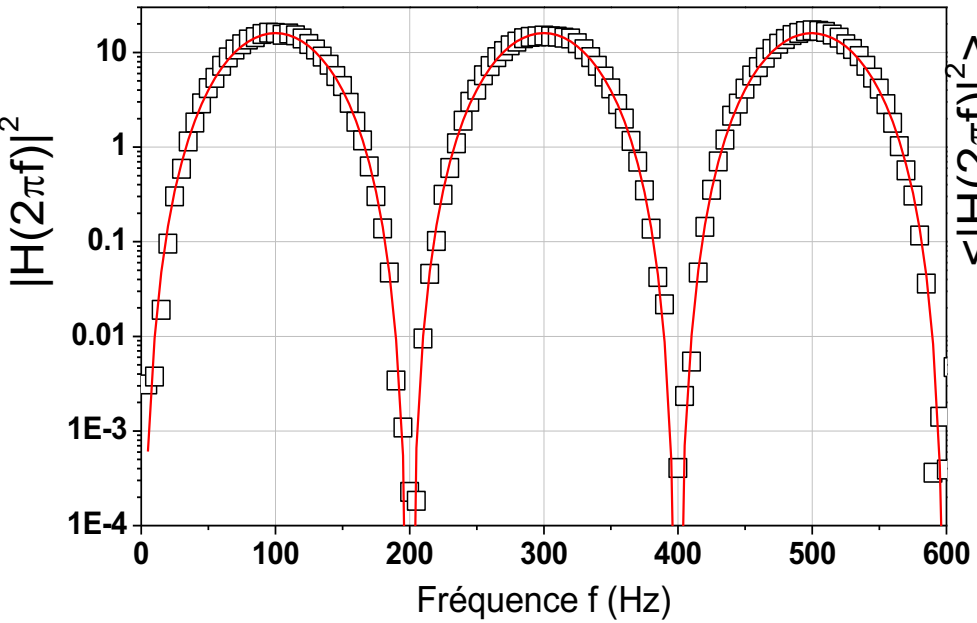
Impact of all noise noise source by external measurement of their PSD and conversion to equivalent phase noise PSD

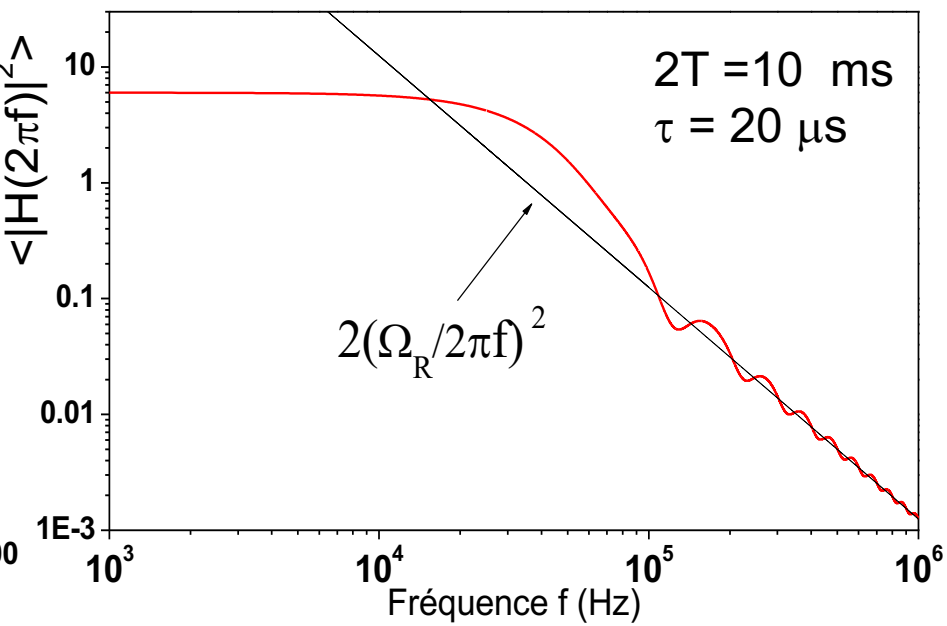
- Magnetic field – measurement from magnetic probes
- Light shift - measurement from interrogation laser intensity
- Miror vibration – seismometer
- Interrogation laser frequency – OFD measurement.

Sensitivity function in the spectral domain:

Low frequency

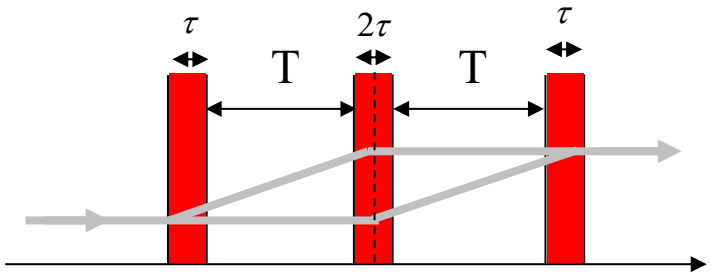
High frequency





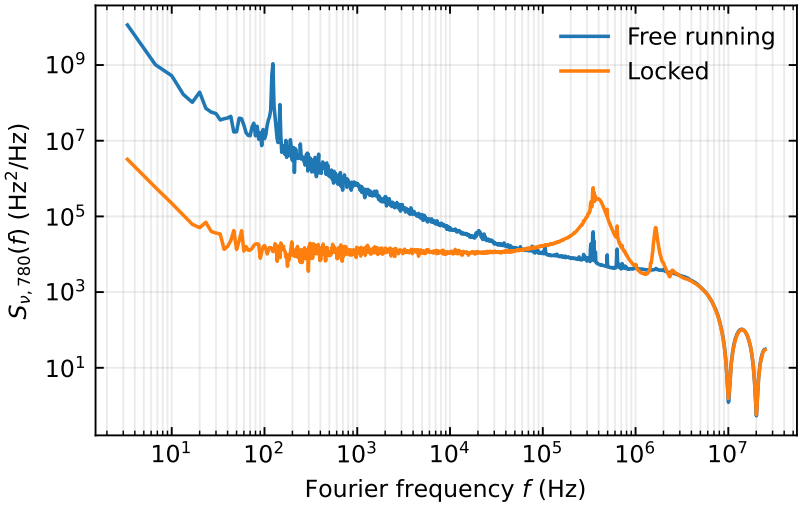
Zeros for the multiples frequencies of $f = \frac{1}{2T}$

Filtering effect linked to the interrogation pulse duration τ

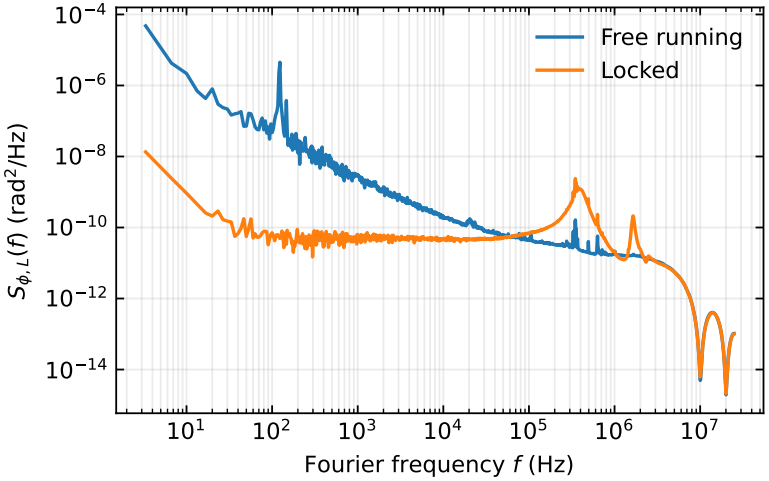


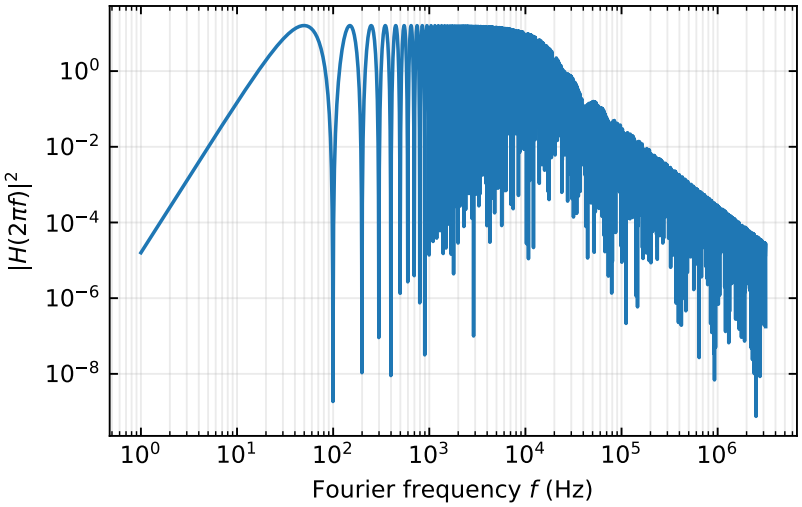
Example: impact of frequency noise

Interrogation laser frequency Noise (measured from OFD)



Conversion to gradiometric laser phase noise





Projected shot to shot Atom phase variation from frequency noise

$$\sigma^2_{\Phi_{AT}(dv)} = \int |H(\omega)|^2 S_{\varphi las}(\omega) \frac{d\omega}{2\pi}$$

$$\sigma_{\Phi_{AT}(dv)} = 2.2 \text{ mrad}$$

Negligible contribution to shot-to-shot gradiometer sensitivity (80 mrad)

To be continued…

Conclusion

- Important progresses done recently. Vacuum system fully operational at a few 10^{-9} mbar. Following steps: atom heads connection baking of the system.
- Cold atom production at LSBB starting.
- Short scale version of MIGA at LP2N now operating and noise analysis progressing
- Speeding up to be on-line by two years deploying the same interrogation configuration at LSBB.



