# Ground-based gravitational wave detection with atom Interferometers: status and perspectives

Remi Geiger, SYRTE, Observatoire de Paris

MIGA collaboration

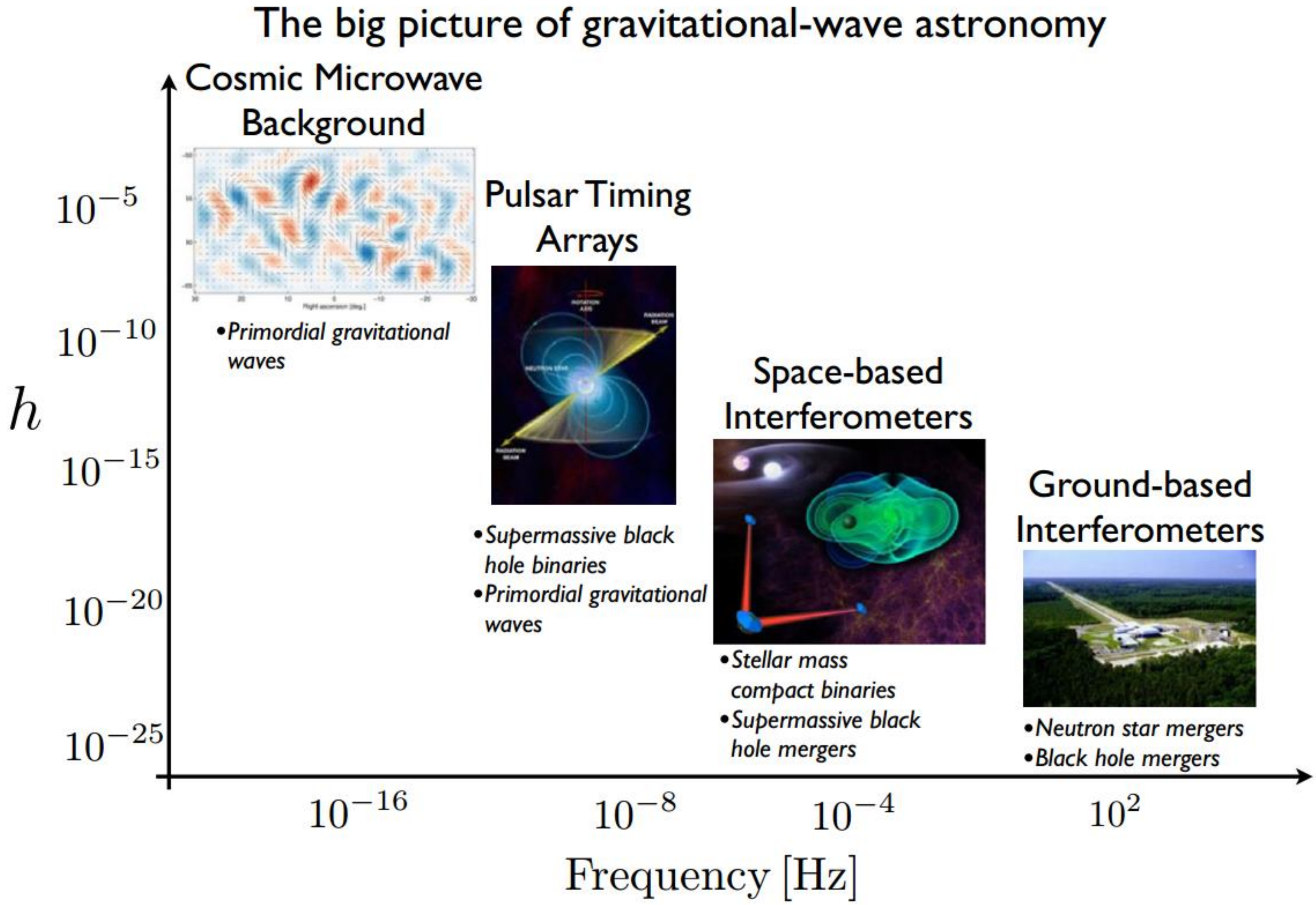
Annual workshop of PhyFOG

Institut d’Astrophysique de Paris, France – May 21st 2019

# Outline

- Gravitational Wave (GW) astronomy: why using atom interferometry ?
- Principle of atom interferometry
- Low frequency GW detection with atom interferometers
- The MIGA instrument.

# GW astronomy

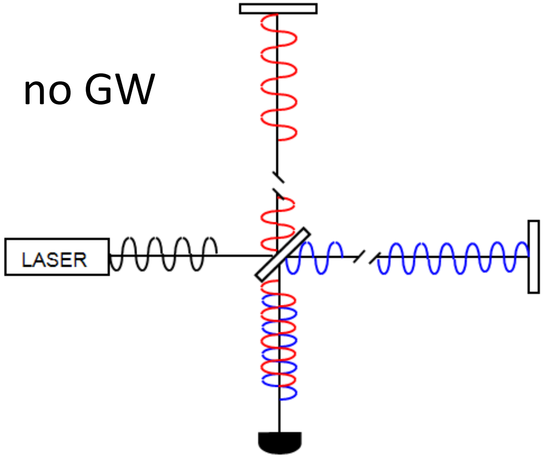


*McLaughlin, GRG 46, 1810 (2014)*

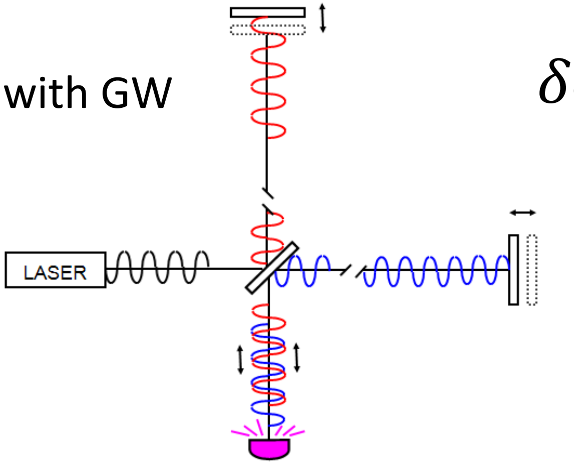
# Detection of GW with laser interferometers

- Quadrupole nature of GW → use a Michelson interferometer
- GW effect : one arm of the interferometer is ‘increased in length’ while the other arm is ‘decreased’ (this interpretation is coordinate dependent)
- The induced phase variation results in a change of the light intensity observed at the interferometer output.

no GW



with GW

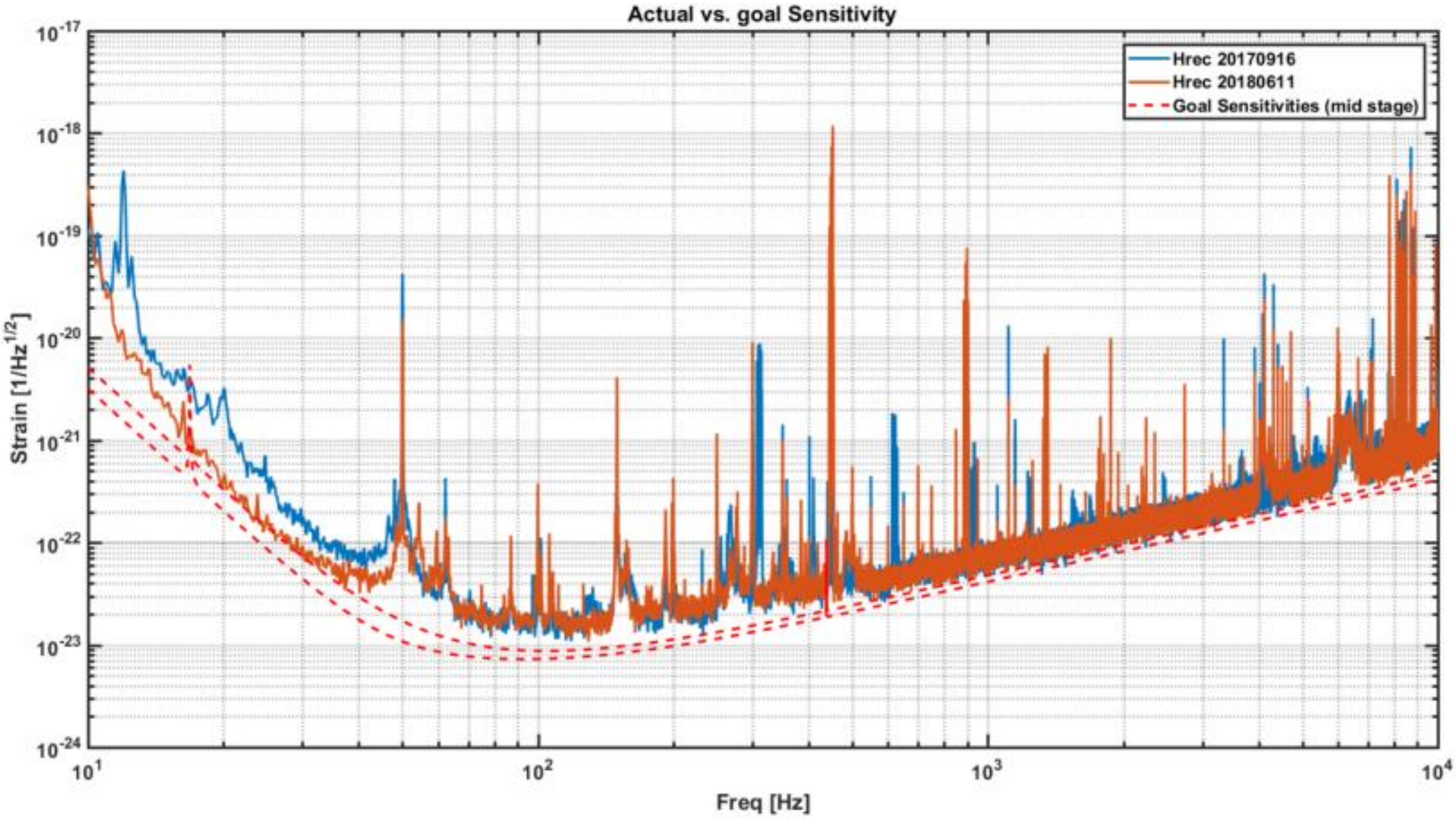


$$\delta\phi = \frac{4\pi\delta L}{\lambda}$$

$$\delta L = \frac{Lh(t)}{2}$$

L=3 km → $\delta L \sim 10^{-19}\ m/\sqrt{Hz}$

# Strain sensitivity curve (VIRGO)



Credit: Nicolas Leroy (LAL, Orsay)

# GW astronomy below 10 Hz

**Motivation**: at frequencies <10 Hz, optical GW detectors are limited by **motion noise**

- Residual seismic noise
- Suspension thermal noise
- Coating thermal noise
- Etc.

More on the noise sources : see, e.g.,

*The VIRGO sensitivity curve - VIR-NOT-PER-1390-51 (2004)*

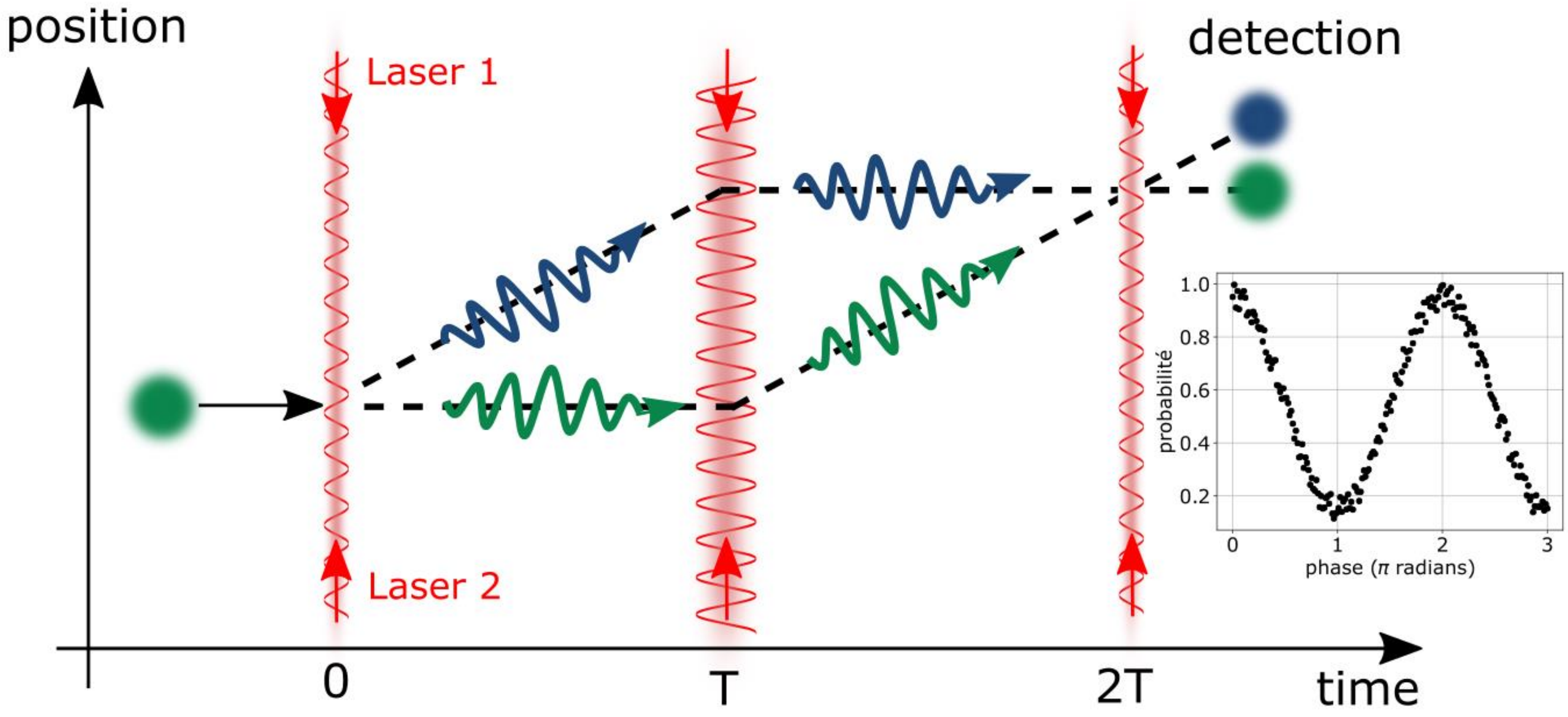
Why not using «  perfectly » free falling test masses to measure the laser phase?

→ **Atom interferometry**

# Principle of Atom Interferometry

# Principle of Atom Interferometry

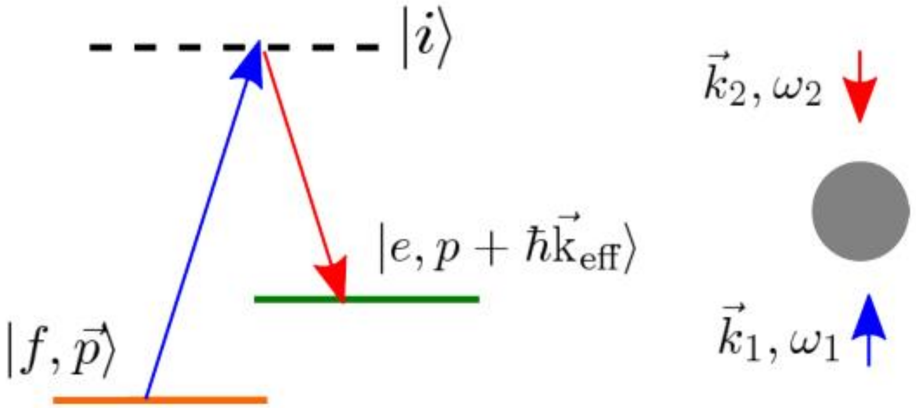
- Analogy with a Mach-Zehnder optical interferometer
- Use laser pulses to coherently split and recombine an atomic wave



Two-wave interference signal : $P = P_0 + A\cos(\Delta\Phi)$

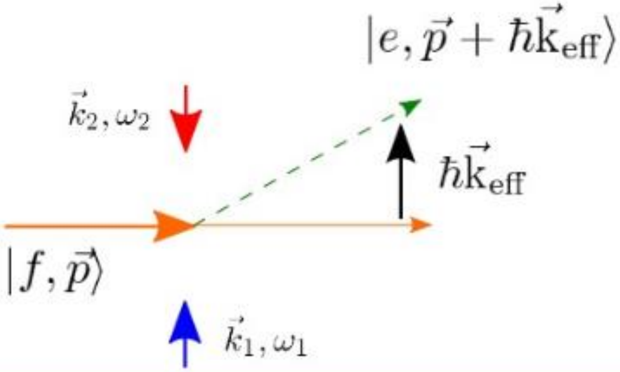
# Two photon transitions

Example : AI with stimulated Raman transition



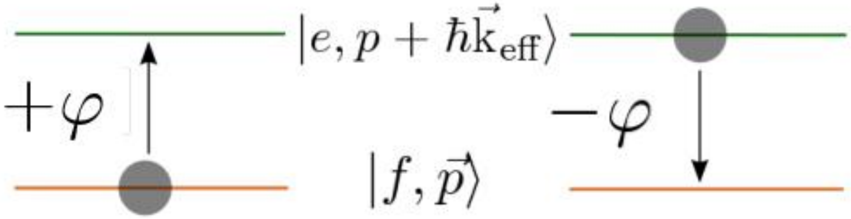
Momentum transfer

$$k_{\mathrm{eff}} = k_1 + k_2$$



Laser phase difference imprinted on the atoms

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



# Interferometer phase

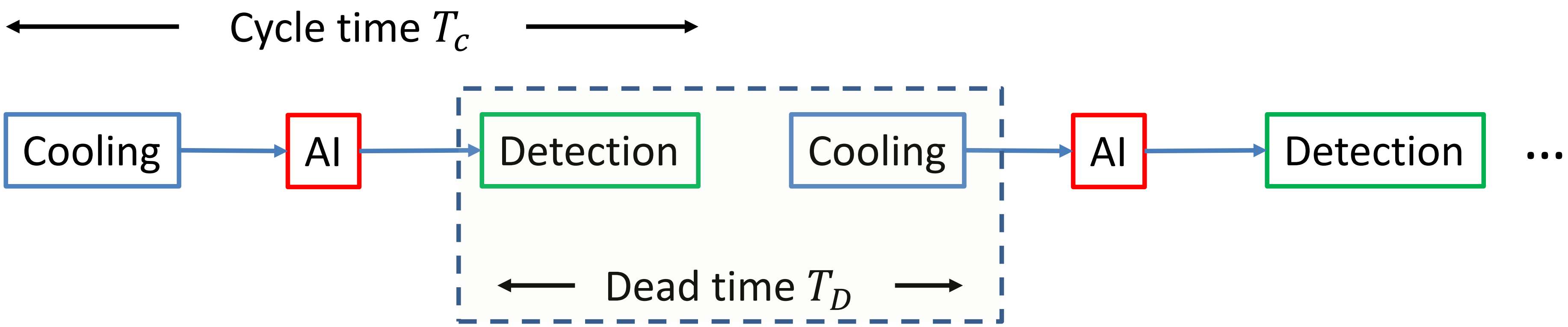
Top path : $\varphi(0) - \varphi(T)$

Bottom path : $\varphi(T) - \varphi(2T)$

$$\longrightarrow \quad \Delta\Phi = \varphi(0) - 2\varphi(T) + \varphi(2T) = \frac{4\pi g T^2}{\lambda}$$

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

# Typical experimental sequence



Cycle time $T_c$

Cooling → AI → Detection → Cooling → AI → Detection …

Dead time $T_D$

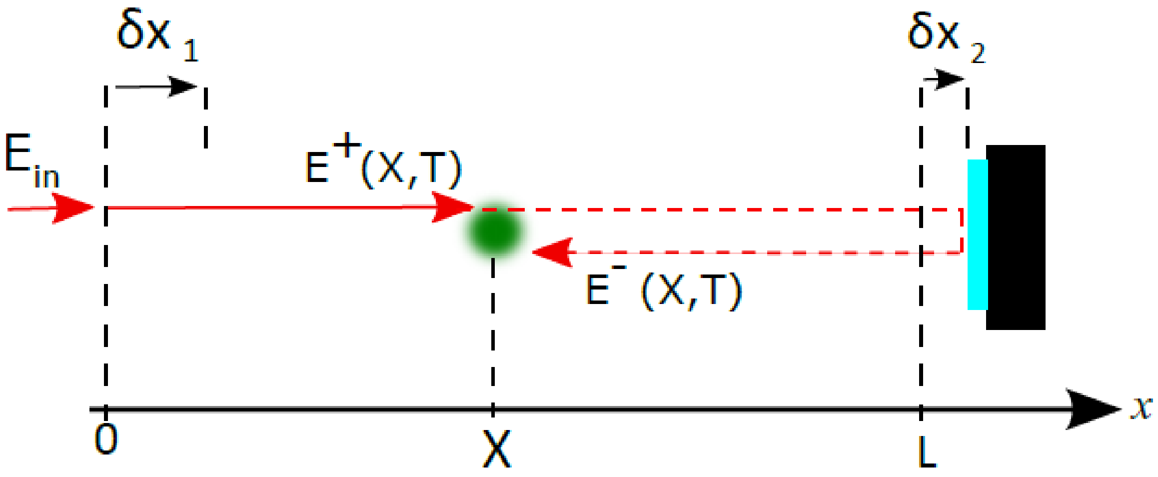
**Typical values** :

- $10^6$ atoms, temperature of 1 µK (rms velocities $\sim cm.s^{-1}$)
- 2T = few 100 ms
- Cycle time ~ 1 s.

# Gravitational Wave detection with an array of atom interferometers

*W. Chaibi et al, Phys. Rev. D 93, 021101(R) (2016)*

# Effect of the GW on the AI



*arxiv: 1611.09911*

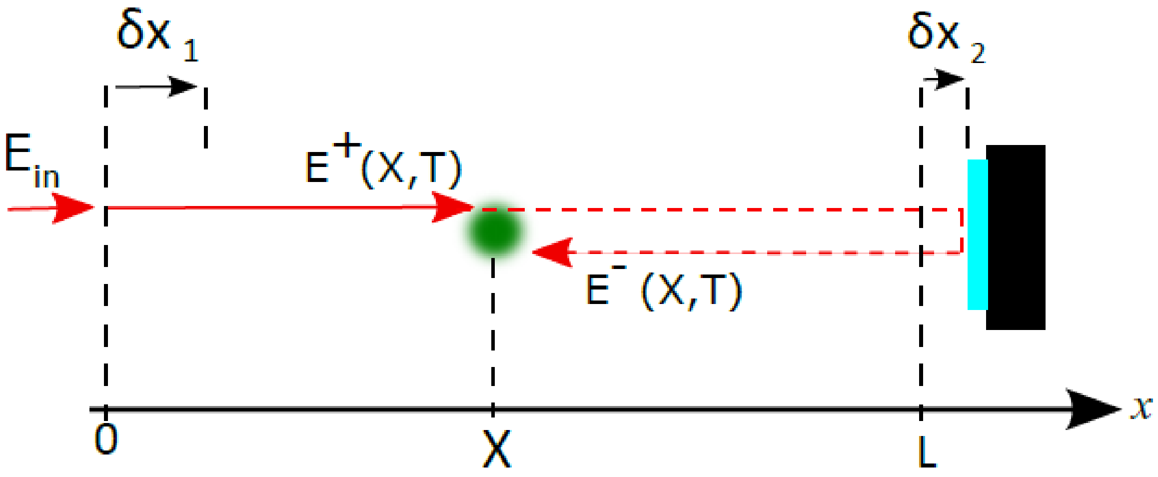
The AI records the relative phase between the 2 counter-propagating lasers:

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

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

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

# Effect of the GW on the AI



*arxiv: 1611.09911*

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

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

The AI measures the variation of $\Delta\phi(t)$ on the time scale of $T$:

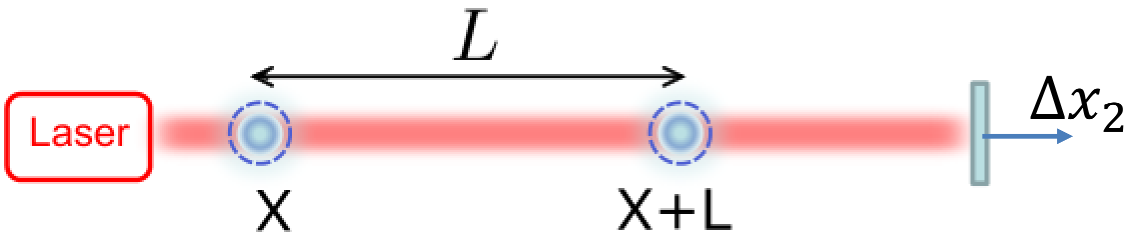
$(k = \frac{2\pi}{\lambda})$

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

Transfer function of the AI

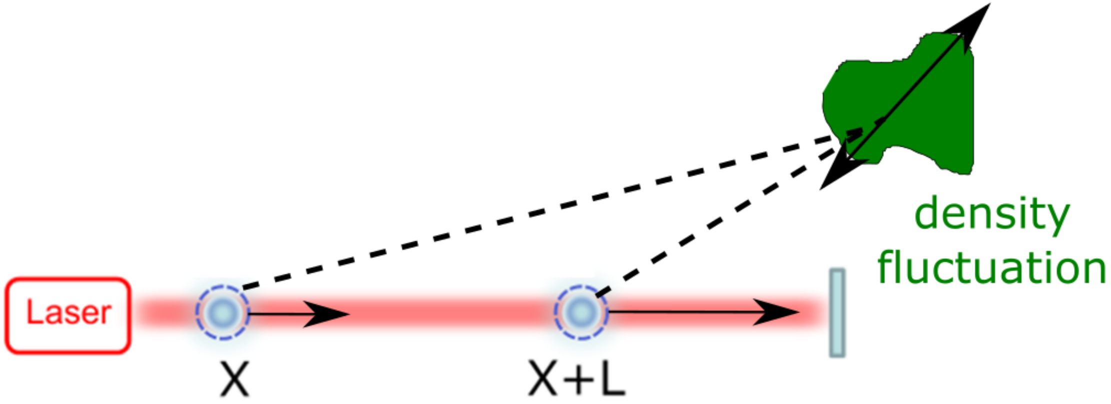
# AI gradiometer

- 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 $\Delta x_2$.

# Gravity gradient noise



- Gradiometer signal = $\phi(X) - \phi(X+L) \sim k\left[L\ddot{h}(t) + a_x(L+X) - a_x(L)\right]$

GW

Gravity gradient

The GW signal cannot be separated from a fluctuating gravity gradient.

→ « Newtonian Noise » (fundamental limit) ; well known in optical GW detectors

→ Limit for observations on ground below few Hz.

# Main sources of NN at frequencies < 10 Hz

- Mass fluctuations in one region of space :

$$\frac{F_x}{m} = G\Delta M(\omega)\frac{\cos\theta}{r^2}$$

*Saulson, PRD (1983)*

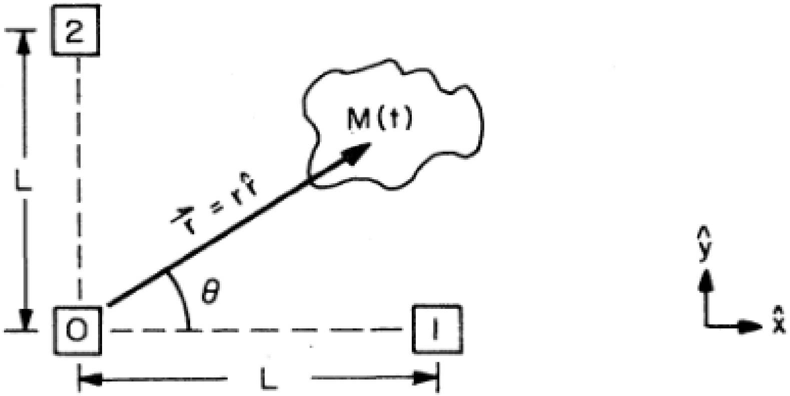


FIG. 1. Interferometer configuration.

| **Seismic NN (Density fluctuations due to ground motion)** | **Infrasound NN (Density fluctuations in the near atmosphere)** |
|---|---|
| Ground motion | Air density fluctuations caused by turbulence |
| Velocity of P-waves | Sound velocity |
| Correlation length ~ few km (at 1 Hz) | 200 m (at 1 Hz) |

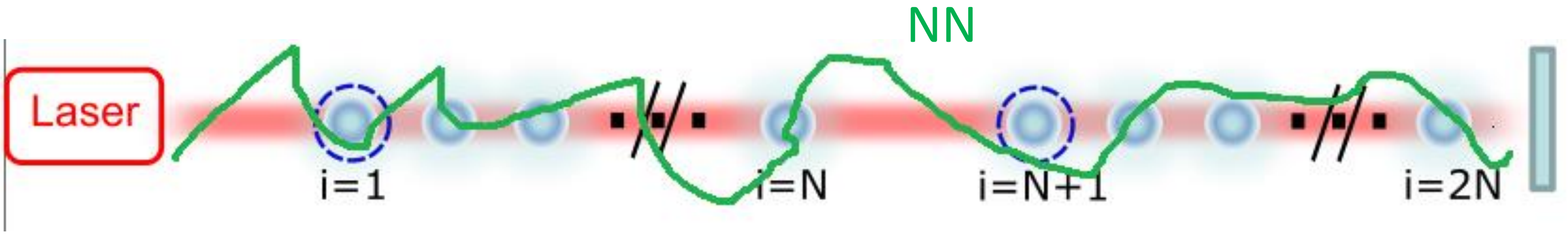
*Detailed review : J. Harms, Living Rev. Relativity, 18, (2015), 3*

# Beating the Newtonian Noise

**General idea** : repeat the gradiometer experiment to average the Newtonian Noise.

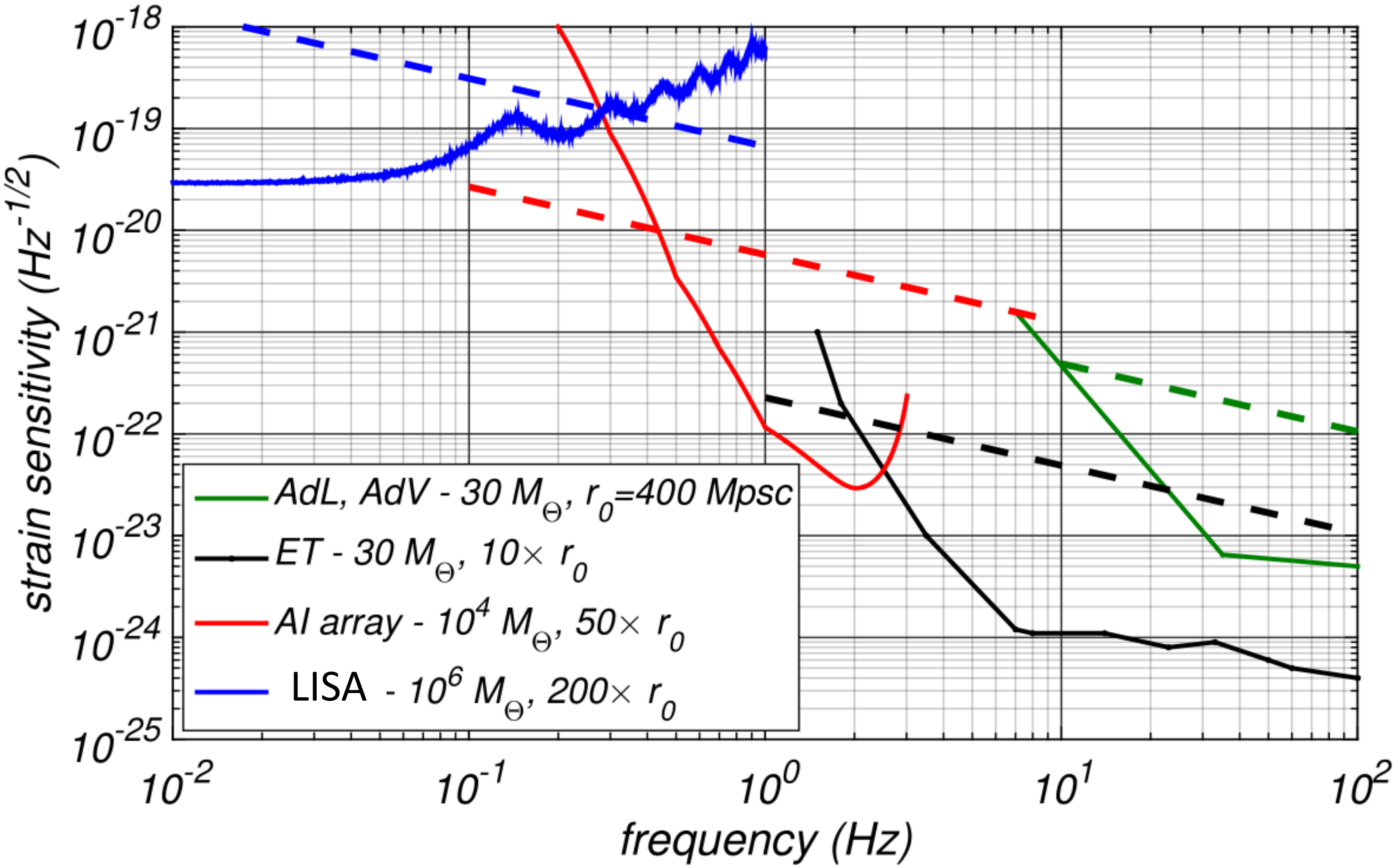
NN characteristic length (few km at most) << GW wavelength

→ average the NN to zero.



$$H_N(t) = \frac{1}{N}\sum_{i=1}^{N} \psi_i(t),$$

# Filling the blind zone



Many sources are predicted in the 0.3-3 Hz frequency band

(see Harms et al, PRD 88, 122003 (2013)).

# The MIGA project :

# Matter wave laser Interferometric Gravitation Antenna

***References***

- *R. Geiger et al, arXiv:1505.07137 (2015)*
- *B. Canuel et al, Scientific Reports **8**, 14064 (2018)*

# The MIGA project

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

1. *Monitoring of underground mass distributions*

   → Applications: geophysics, hydrology

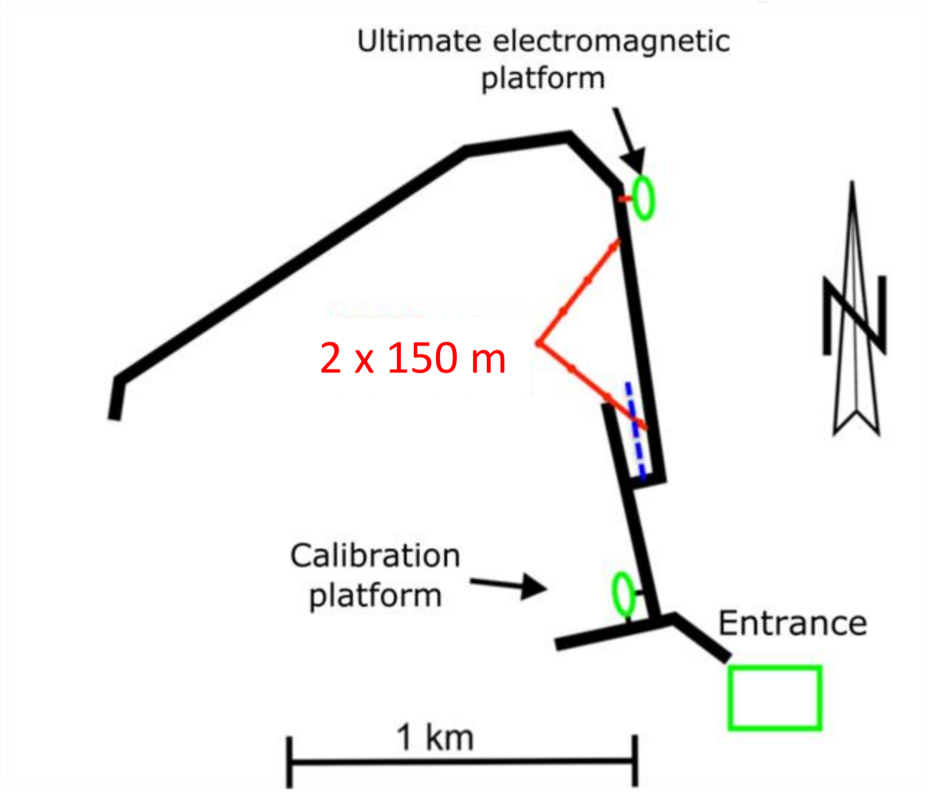
2. *Test setup for applications of AI to gravitational wave (GW) detection*

# Overview of the MIGA project

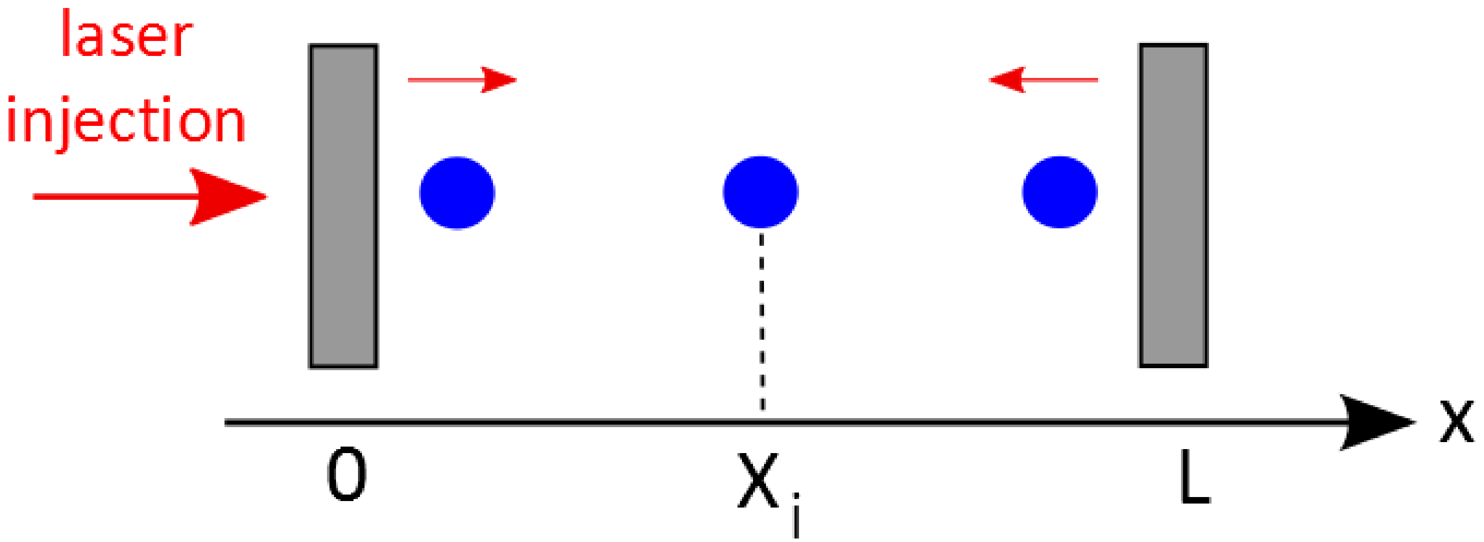
**Implementation site**

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

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



# Orders of magnitude



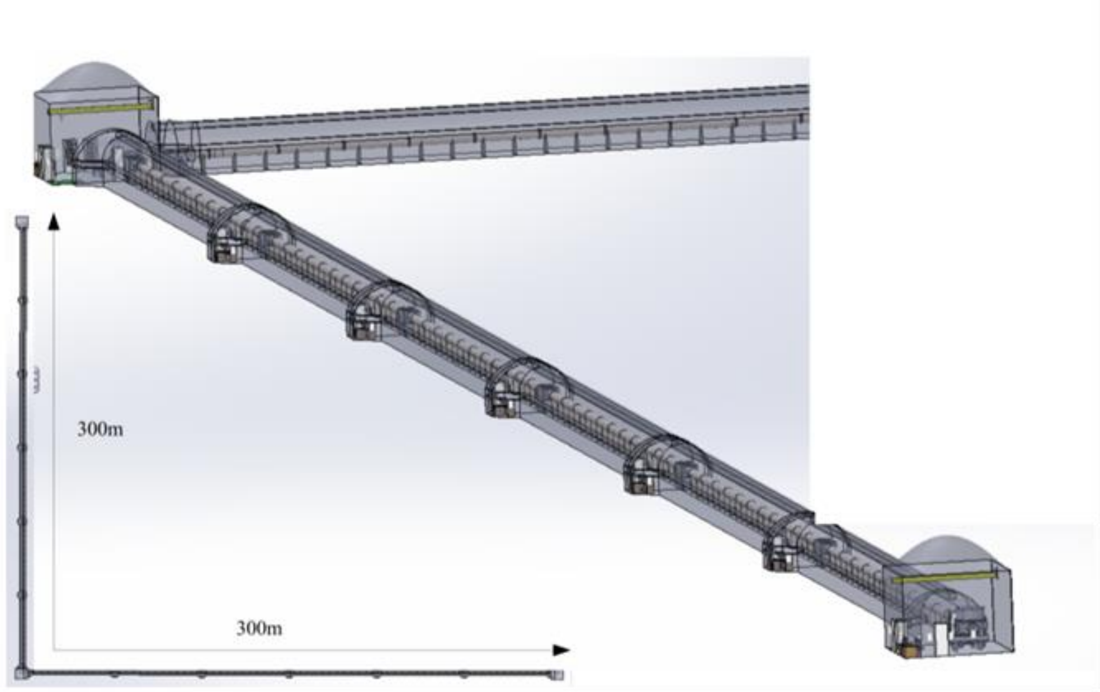
$L = 150\ m$ baseline

Rb 87 atoms: $\lambda = 780\ nm$

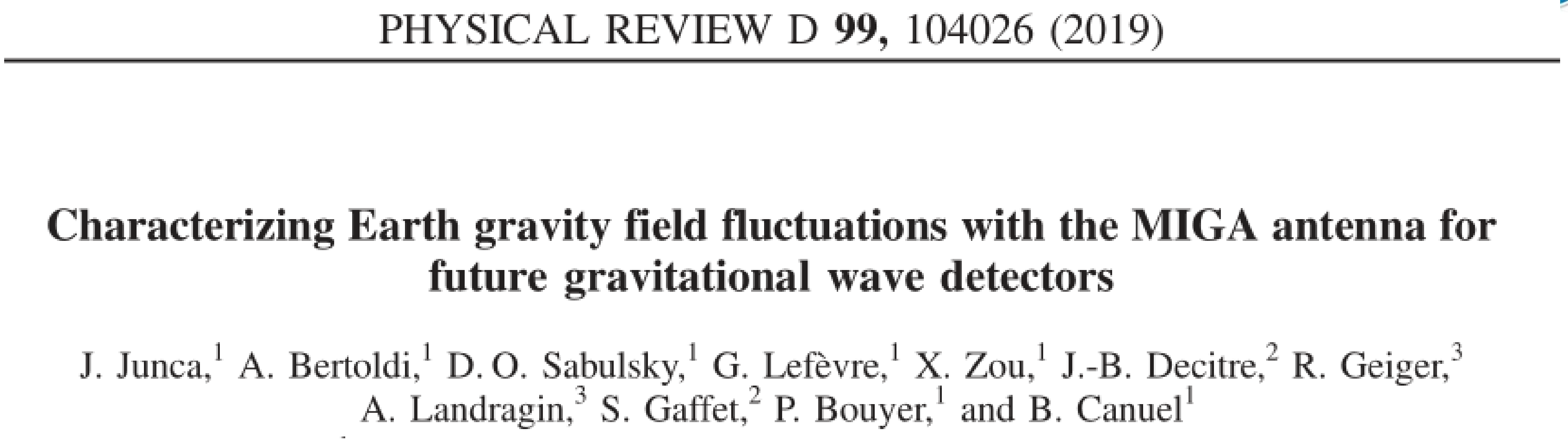
Target strain sensitivity: $10^{-13}\ /\sqrt{Hz}$ (MIGA advanced: $10^{-15}\ /\sqrt{Hz}$ )

# MIGA : status and perspectives

- Atom interferometry units under realization
- Digging of the MIGA galleries at LSBB ongoing → December 2019
- MIGA installation at LSBB in 2020
- MIGA commissioning and data runs: 2021-2023.



# What can we learn with MIGA?



PHYSICAL REVIEW D **99,** 104026 (2019)

**Characterizing Earth gravity field fluctuations with the MIGA antenna for future gravitational wave detectors**

J. Junca,[1] A. Bertoldi,[1] D. O. Sabulsky,[1] G. Lefèvre,[1] X. Zou,[1] J.-B. Decitre,[2] R. Geiger,[3]
A. Landragin,[3] S. Gaffet,[2] P. Bouyer,[1] and B. Canuel[1]

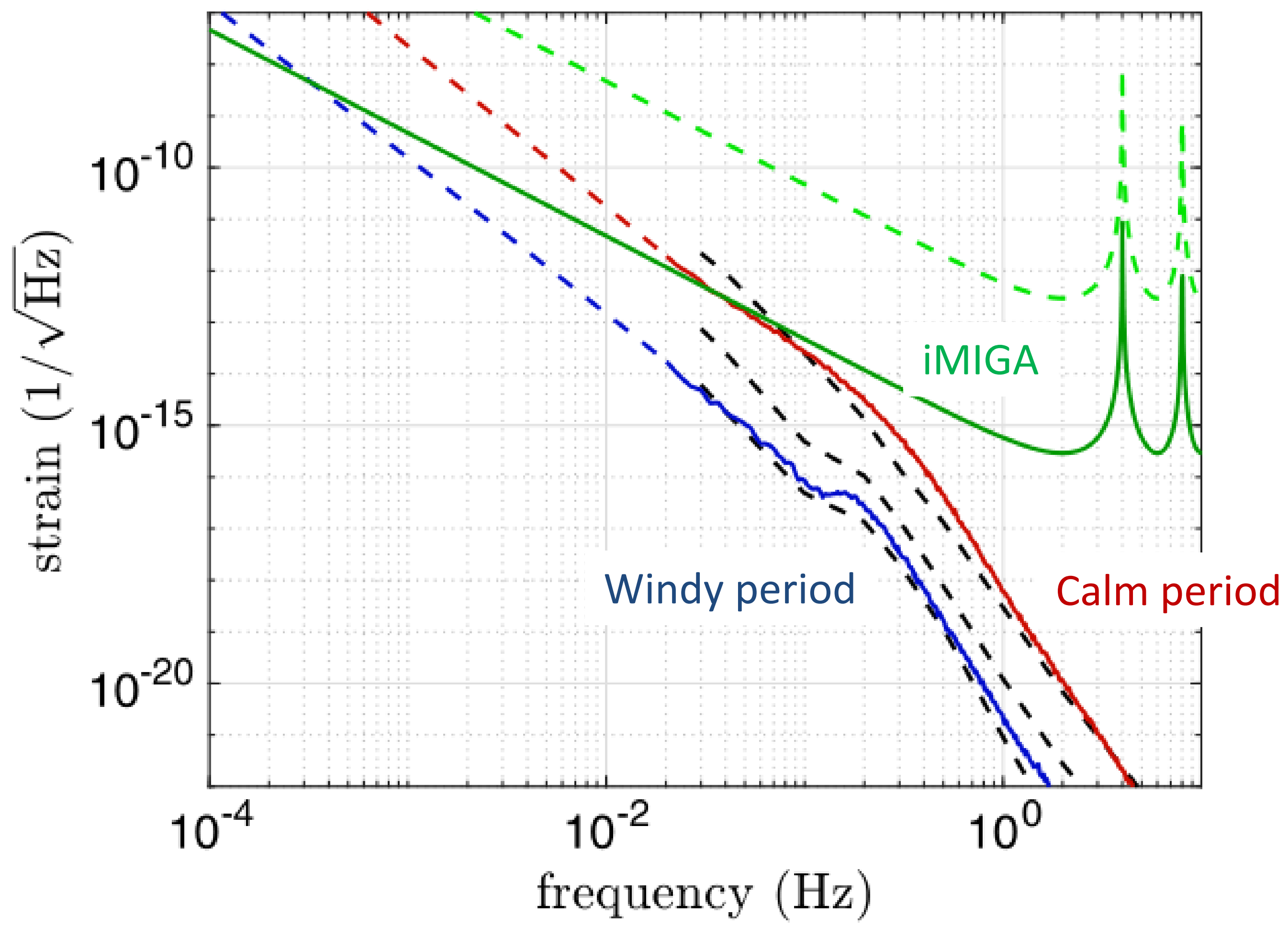
Ideas:

- the gravity gradient noise (GGN) increases at low frequencies
- Atom interferometers feature good long term stability

→ The GGN has more and more influence upon integration

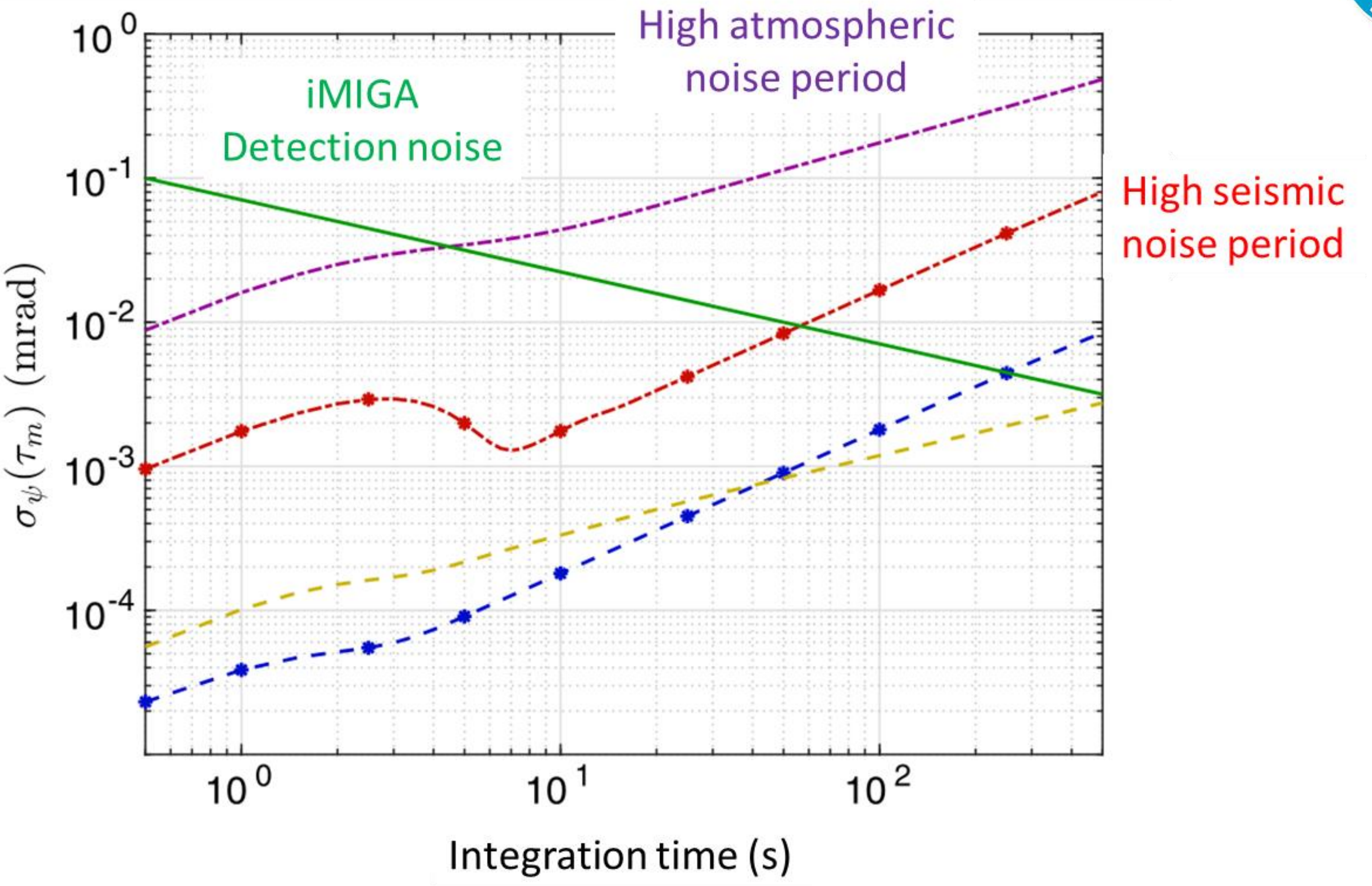
→ Can it be used to get knowledge about the GGN ?

# Testing GGN models with MIGA



*MIGA strain sensitivity to infrasound GGN*

# Testing GGN models with MIGA



→ fluctuations of the atomic phase induced by atmospheric/seismic GGN will be observable by averaging measurements → test of GGN models.

# Conclusions

- **Atom interferometry** : measure an optical phase using free falling atoms
- **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**
- **Challenges** for cold atom physics to reach $\sim 10^{-20}/\sqrt{Hz}$ strain sensitivity

  Contribution to GW astronomy in the ~ 0.3 – 3 Hz band

- **MIGA** : proof of concept + test of Gravity Gradient Noise models.
- Ongoing effort for a design study at the **European level** (ELGAR project).

# Thank you for your attention!


Q. Beaufils


B. Canuel

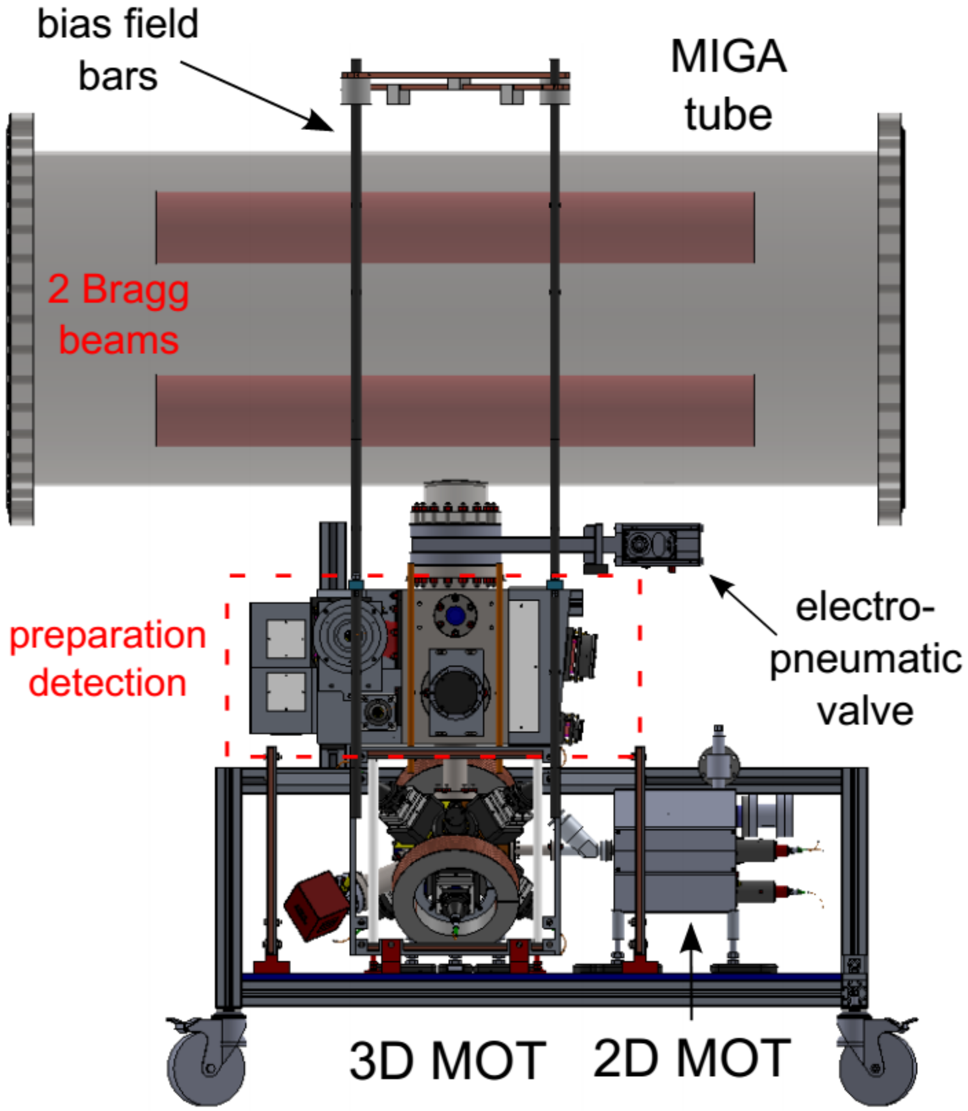
A. Bertoldi

P. Bouyer

S. Gaffet

A. Landragin

# Cold atom source (SYRTE)



# Title

# Title