Hybrid Atom-Optical Interferometry for Gravitational Wave Detection and Geophysics

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for the MIGA consortium

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http://syrte.obspm.fr/tfc/capteurs_inertiels https://sites.google.com/site/migaproject/

Outline

Matter-wave laser Interferometry Gravitation Antenna

1. Aims of the MIGA project
2. MIGA principle and sensitivity
3. Status and perspectives

Aims of the MIGA project

An instrument combining atom and optical interferometry for:

1. **Geophysics** - Precision measurements of the Earth gravity field

- Gravity gradient measurements: $10^{-13}\ s^{-2}/\sqrt{Hz}$ at 1 Hz

(resolution of 1 ton of water 100 m away from the instrument)

→ *Detection of gravitational signals resulting from anomalous mass fluctuations*

→ *Monitoring of water flows in geological reservoirs*

→ *Characterization of the dynamics of hydro-mechanical processes*

Aims of the MIGA project

1. Geophysics - Precision measurements of the Earth gravity field

- Gravity measurements: $10^{-10}\ g/\sqrt{Hz}$
- Gravity gradient measurements: $10^{-13}\ s^{-2}/\sqrt{Hz}$ at 1 Hz

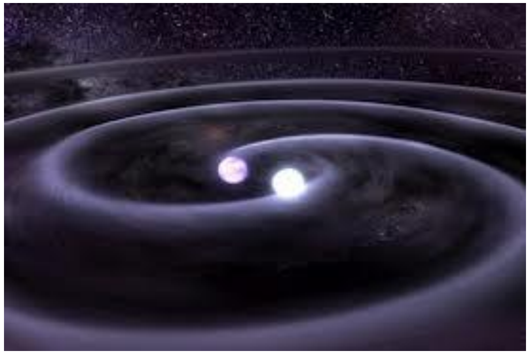
(resolution of 1 ton of water at 100 m from the instrument)

2. **Low frequency Gravitational Wave detection** (0.1 – 10 Hz)

- Different limitations than optical GW detectors (VIRGO, LIGO, …)
- Many interesting astrophysical sources at low frequencies

Compact binaries:

→ *merging White-Dwarfs, neutron stars, black holes*



The MIGA consortium

10 year project (2013 – 2023) involving 15 research institutes & companies

- Atomic Physics & metrology
- Laser & optics
- Relativity & gravitation
- Geosciences

MIGA infrastructure at LSBB (South-East Fr.)

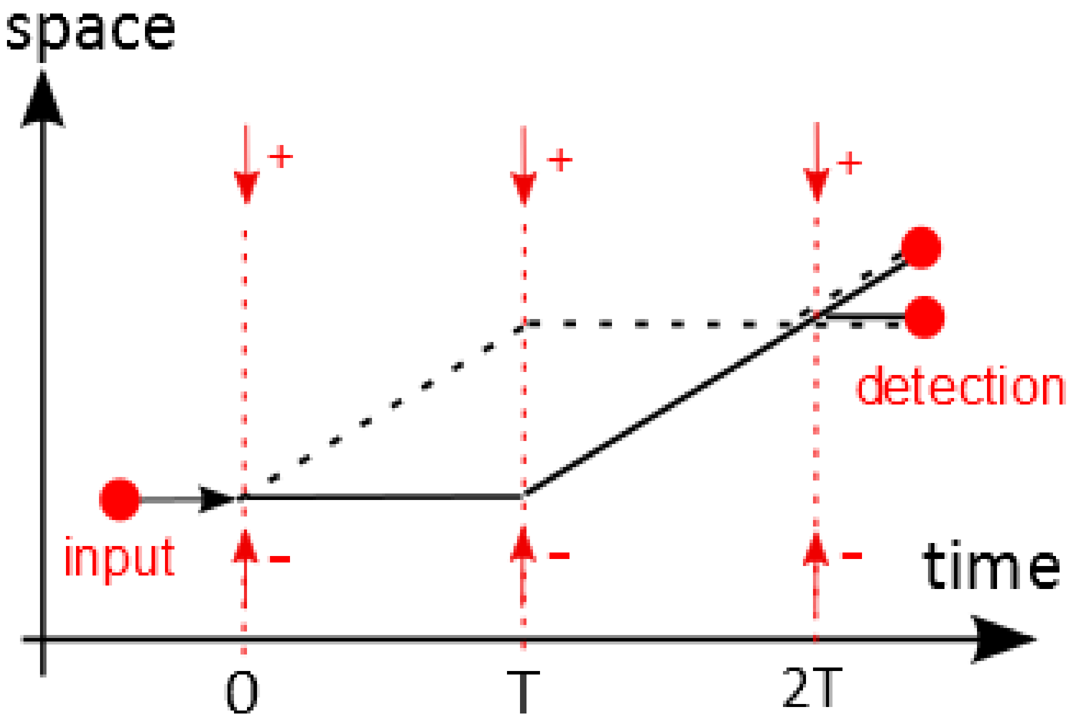
- Low noise underground lab
- Site of geological interest
- 200 m optical cavity, 3 atomic sensors

Principle of the MIGA instrument

Principle of atom interferometry

→ Probe the local phase of a laser beam using free falling atoms

→ Mach-Zehnder like interferometer using conterpropagating lasers



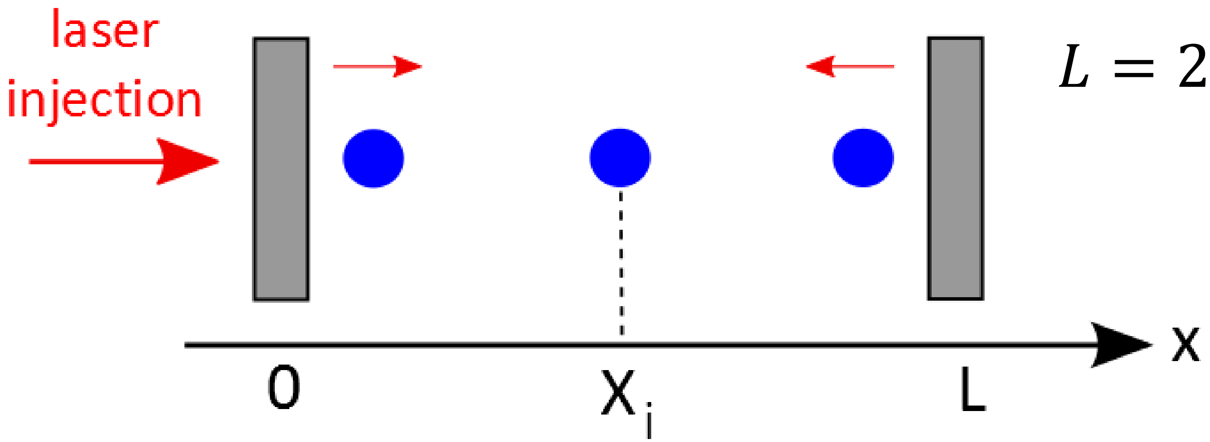
AI output: $P \propto \cos \Delta\Phi$

$$\Delta\phi = 2kT^2 a$$

$$2k = \frac{4\pi}{\lambda} = \frac{4\pi\nu_0}{c}$$

Local accelaration of the laser/atom

Principle & orders of magnitude



$L = 200\ m$ cavity

Rb87 atoms:

$\lambda = 780\ nm$

Interferometer phase shift at position x : $\Delta\phi(x) = 2kT^2 a(x)$

Interrogation time $2T \approx 0.5\ s$; Phase sensitivity = 1/SNR ~ 1 mrad/shot

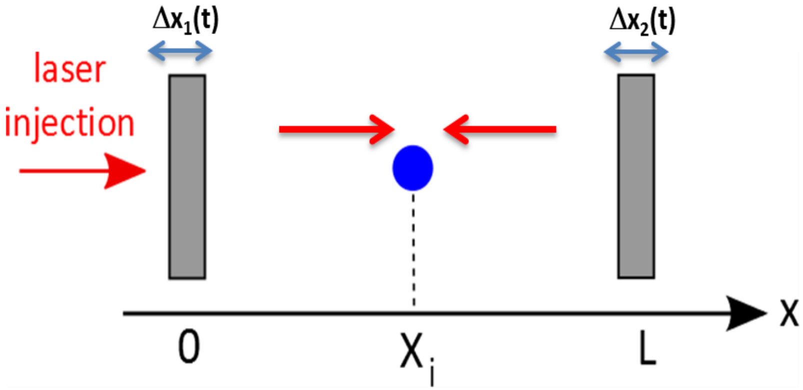
Acceleration sensitivity $\sim 10^{-9}\ m.s^{-2}/\sqrt{Hz}$

Gravity gradient sensitivity $\sim 10^{-13}\ s^{-2}/\sqrt{Hz}$ → resolve 1 ton at 100 m

GW detection

Calculation of the Interferometer phase shift taking into account:

- Laser frequency noise $\delta\upsilon(t)$
- Vibration of the mirrors $\Delta x_1(t)$ and $\Delta x_2(t)$
- Strain due to the gravitational wave h(t)
- Local inertial effects → Gravity noise



$$s_\phi(X) = \frac{4\pi\nu_0}{c}T^2[a_2(L) - a(X)] - \frac{4\pi}{c}(L-X)\left(s_{\delta\nu} + \frac{\nu_0}{2}s_h\right)$$

W. Chaibi, RG, B. Canuel, *in preparation*

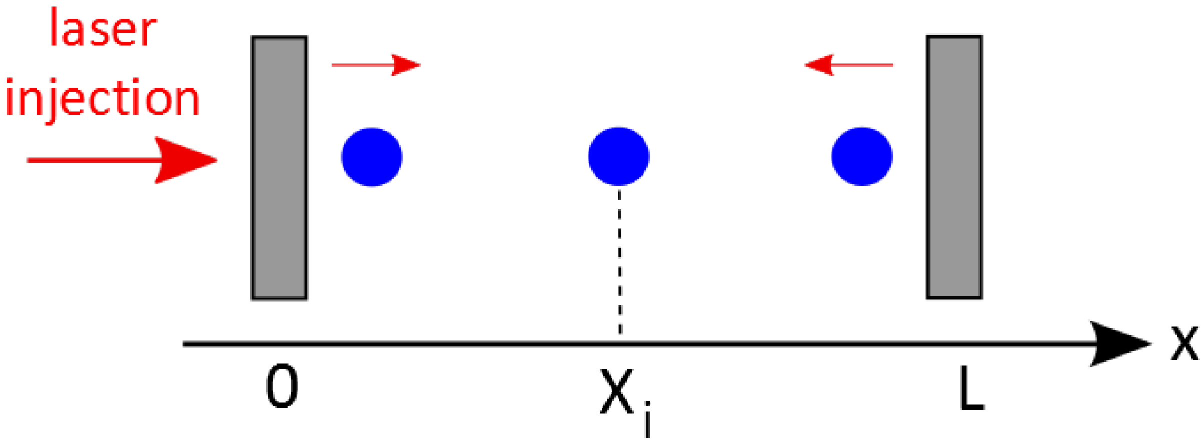
Position noise is common !

→ No need for high vibration isolation

(different from optical GW detectors sensitive to position noise)

GW detection

Insensitive to position noise of the optics !



Differential signal:

$$s_\phi(X_1) - s_\phi(X_2) = \frac{4\pi\nu_0}{c}T^2\left[a(X_2) - a(X_1)\right] - \frac{4\pi}{c}(X_2 - X_1)\left(s_{\delta\nu} + \frac{\nu_0}{2}s_h\right)$$

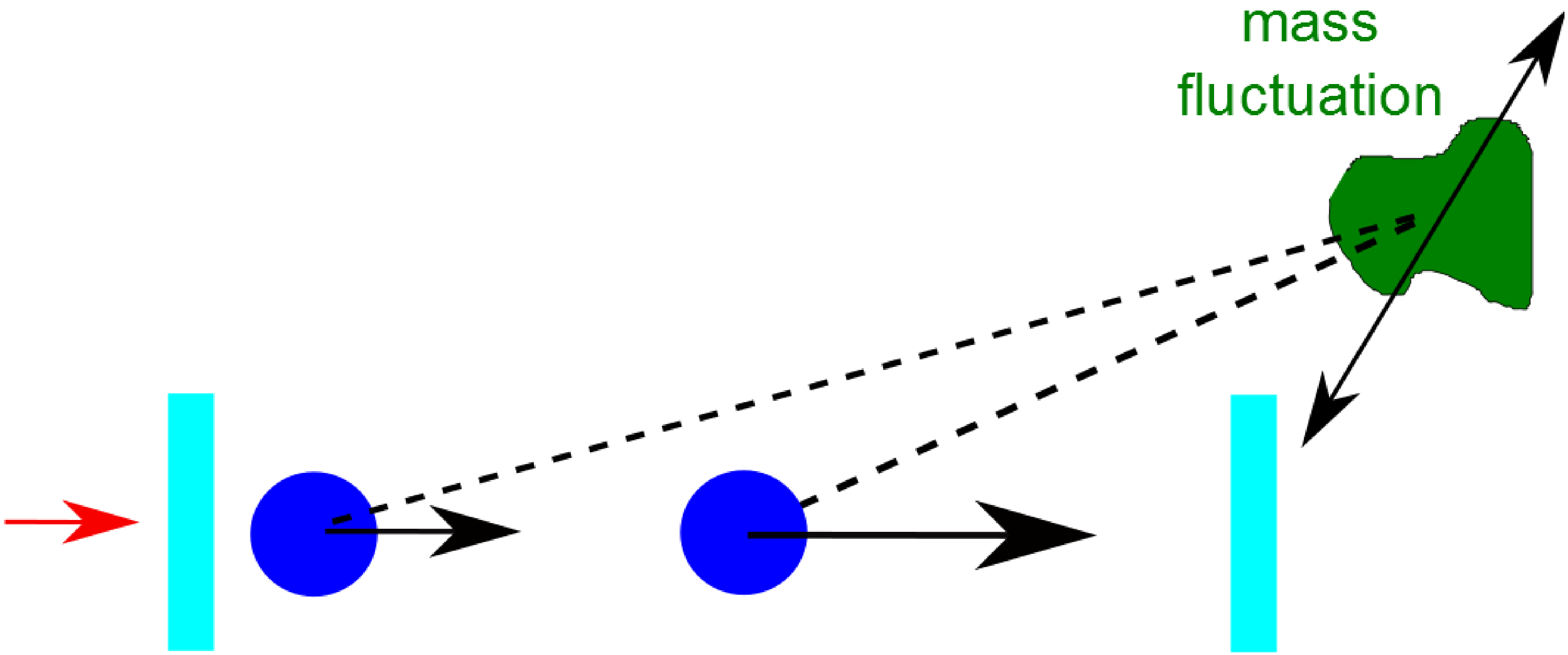
Gravity gradient noise

W. Chaibi, RG, B. Canuel, *in preparation*

Gravity gradient (GG) noise

Fundamental limit to ground-based GW detectors

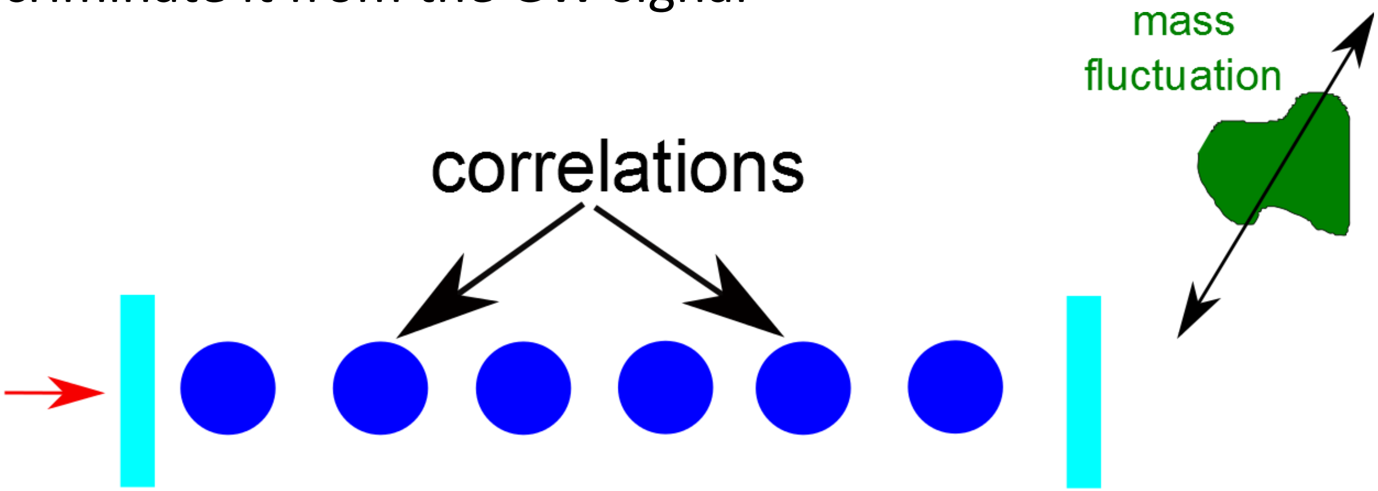
- Gravity gradient noise due to nearby mass fluctuations (tidal effect)
- Big limitation for GW detection below 10 Hz ….



Gravity gradient (GG) noise

Advantage of AI sensors: it is possible to spatially resolve gravity !

- GW have long wavelength ($3 \times 10^8\ m$ @ 1 Hz) while GG have short characteristic length of variation (1 m – few km)
- Correlations between distant sensors provide information on the GG noise and allows to discriminate it from the GW signal



W. Chaibi, RG, B. Canuel, *in preparation*

Typical GW sensitivity

$$h = 1 \times 10^{-19} \sqrt{\frac{10^{10}}{N_{at}} \frac{1000}{N_{\hbar k}} \frac{10^{7} m^{-1}}{k} \frac{10 km}{L}}$$

Many cold atoms

Large physical separation
(Large Momentum Transfer
Beam Splitters)

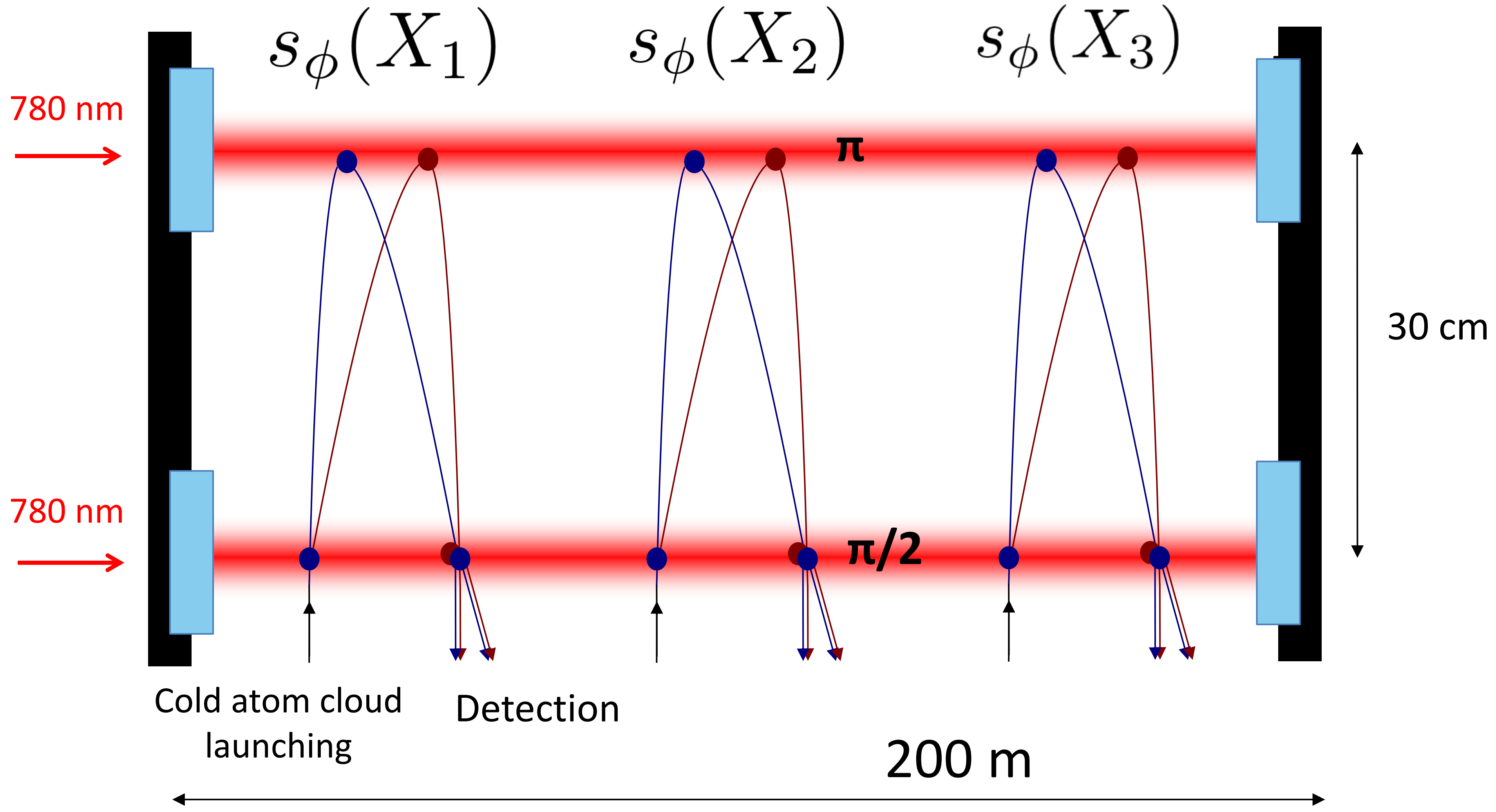
Large scale
antenna

A challenging project for atom optics !

Target of MIGA: 10^{-16} strain sensitivity within 5 years

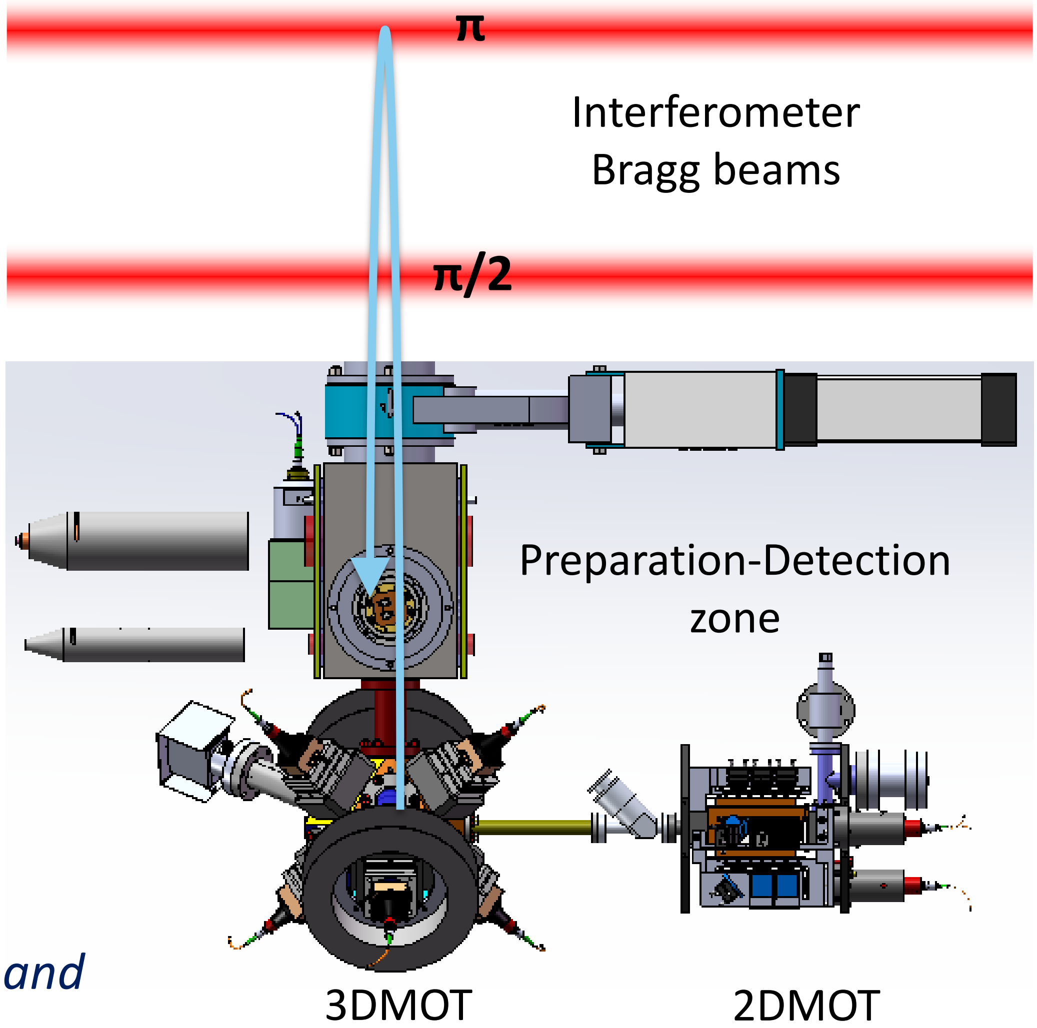
MIGA subsytems: status

MIGA geometry



Cold atom source at SYRTE

- Design similar to cold atom fountains and inertial sensors.
- Rb 87 atoms trapped in a 3D MOT loaded by a 2D MOT.
- 10^8 atoms launched on a vertical trajectory at 4 m/s.
- Sets of Raman transitions to prepare of pure magnetic state and for velocity selection.
- Detection of transition probability by fluorescence of the cloud.



Design by Louis Amand

MIGA other subsytems

- SYRTE (Paris) : cold atom source and detection system
- LP2N (Bordeaux): cavity control, vacuum tube
- ARTEMIS (Nice): cavity mirror suspensions
- µQuans (Bordeaux): laser system
- LSBB (Rustrel): tunnels & site management

LP2N Laboratoire Photonique, Numérique et Nanosciences

ARTEMIS

µQUANS

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

Close perspectives

- Cold atom source assembly & characterization at SYRTE (Oct. 2014)
- AI prototype and suspensions will be available in Oct. 2014 (Bordeaux)

  → 10 m cavity prototype
- Start commissioning of the prototype mid 2015 (Bordeaux)
- Start Gallery preparation beginning of 2015 (LSBB)
- MIGA installation mid 2016 (LSBB)

Conclusion

MIGA: an instrument to study various aspects of gravity

- Geosciences → high stability of AI sensors
- Astrophysics → complement to current detectors

An interdisciplinary collaboration

Many challenges, in particular in atomic physics !

Thank you !

W. Chaibi (Nice)

B. Canuel, A. Bertoldi, P. Bouyer (Bordeaux)

Louis Amand

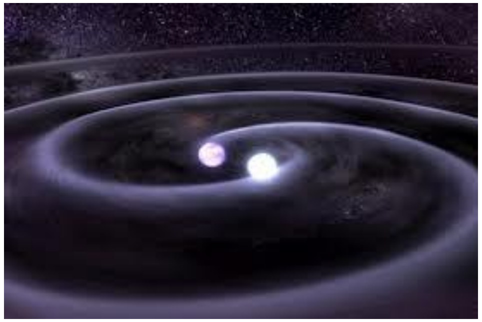
Arnaud Landragin

PhDs and postdocs are welcome !

GW sources in the 0.1 – 10 Hz band

Most probable sources : White Dwarf binaries in the Milky-Way

Neutron star binaries



From J. Harms et al, PRD **88**, 122003 (2013)

$$h = \frac{2(4\pi)^{1/3}}{c^4}\frac{\eta(GM)^{5/3}}{r} f_{\mathrm{GW}}^{2/3} = 2.4\times 10^{-22}\left[\frac{f_{\mathrm{GW}}}{0.01\ \mathrm{Hz}}\right]^{\frac{2}{3}}\frac{\eta}{0.25}\left[\frac{M}{2M_\odot}\right]^{\frac{5}{3}}\frac{10\ \mathrm{kpc}}{r},$$

Amplitude of GW

$$T_{\mathrm{insp}} = \frac{3}{8}T = \frac{5}{256\pi^{8/3}}\frac{c^5}{\eta(GM)^{5/3}} f_{\mathrm{GW}}^{-8/3} = 5.5\times 10^3\ \mathrm{yr}\left[\frac{0.25}{\eta}\right]\left[\frac{M}{2M_\odot}\right]^{-\frac{5}{3}}\left[\frac{f_{\mathrm{GW}}}{0.01\ \mathrm{Hz}}\right]^{-\frac{8}{3}}.$$

Duration of GW

Rate for ~ 1 solar Mass neutron star in Milky Way like galaxies: 1 – 1000 /Myr

J Abadie *et al* 2010 *Class. Quantum Grav.* **27** 173001

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