THE MIGA ANTENNA: NEW PERSPECTIVES FOR HIGH PRECISION GRAVITY MEASUREMENTS

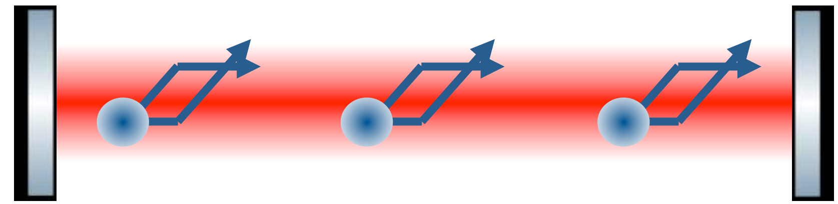
B. Canuel, LP2N,IOGS/CNRS/Univ. Bordeaux
LSBB,CNRS/UAPV/UNS/OCA/AMU
for the MIGA consortium

Outline

- Introduction
- New generation of low frequency GW detectors with AI and GGN
- The MIGA antenna and LSBB environment.
- Future GW detector geometries enabling GGN reduction
- Conclusion

MIGA Project

Build a new instrument combining matter-wave and laser interferometry



- <u>Gravitational wave physics</u>
  - Demonstrator for future sub-Hz ground based GW detectors
- <u>Geoscience</u>
  - Gravity sensitivity of 10^{-10} g/Sqrt(Hz) @ 2Hz
  - Gradient sensitivity of 10^{-13} s^{-2}/Sqrt(Hz) @ 2Hz: geology, hydrogeology…

A Large research infrastructure hosted in a low noise laboratory

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

- A 200 m horizontal optical cavity coupled with 3 AI
- Possible evolutions towards 2D or 3D instrument on site

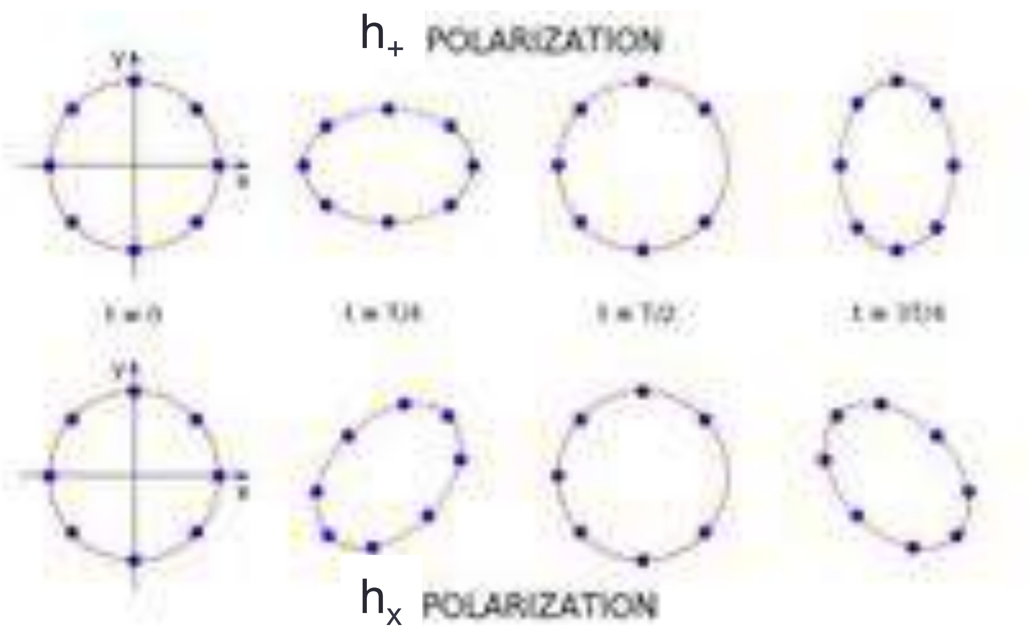
New generation of low frequency GW detectors with AI and GGN

Einstein: mass + acceleration = GRAVITATIONAL WAVES

GW: transverse space-time distortions propagating at the speed of light,
2 independent polarizations
GW alternately squeeze and stretch space in perpendicular directions.

$$\mathbf{h}(z,t) = e^{i(\omega t - kz)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Effect of plus and cross polarized GW on a ring of free falling test masses



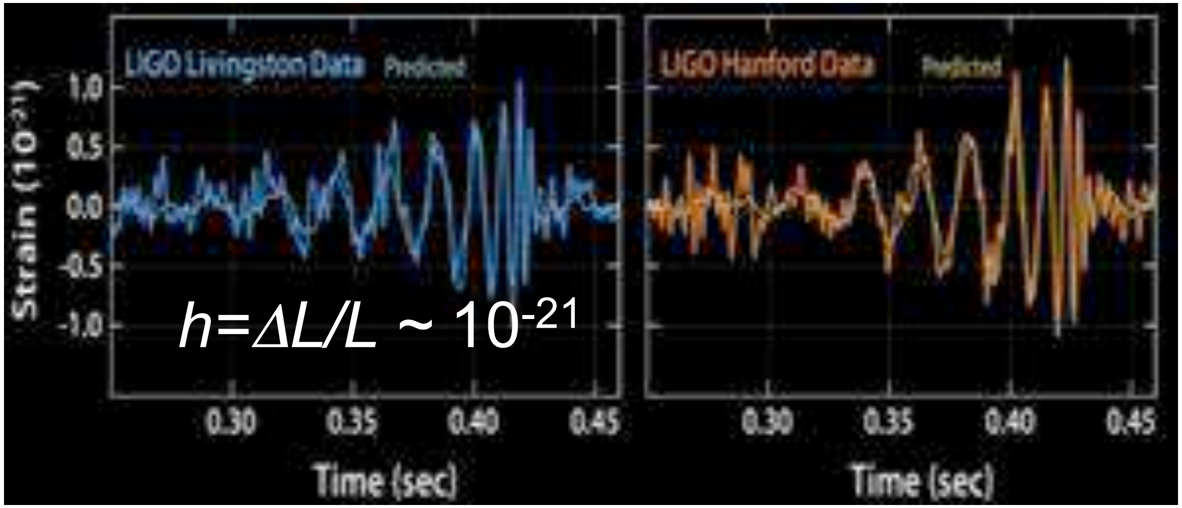
Gravitational wave strengths are characterized by the dimensionless amplitude h:

h = dL/L (dL is the variation of distance between 2 masses separated by a length L)

The sensitivity of detectors is fundamentally proportional to its length.

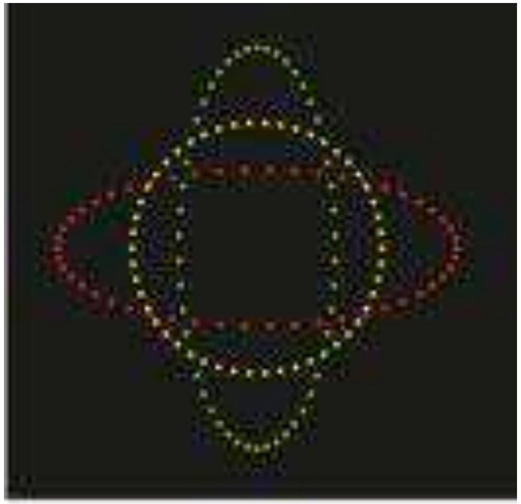
Gravitational Wave detection…

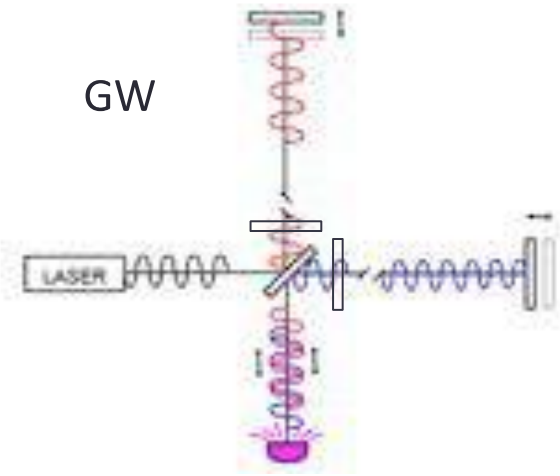
- First direct observation 14/09/2015
- Coalescence of a black hole binary system (36 $M_\odot$+29 $M_\odot$)
- Open the way towards « gravitational astronomy »

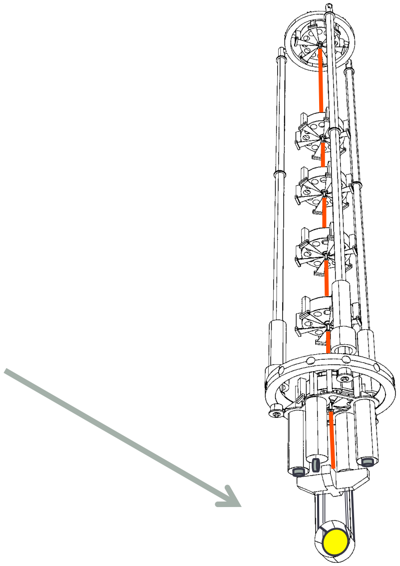


LIGO Scientific Collaboration and Virgo Collaboration, PRL 116, 061102 (2016)

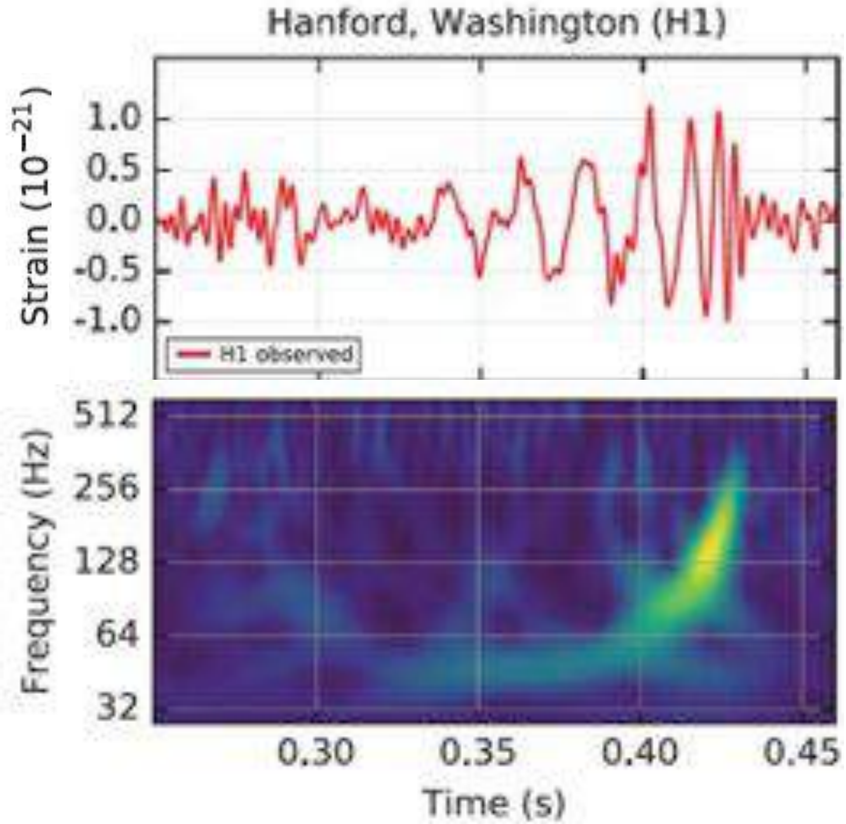
Interferometric detectors

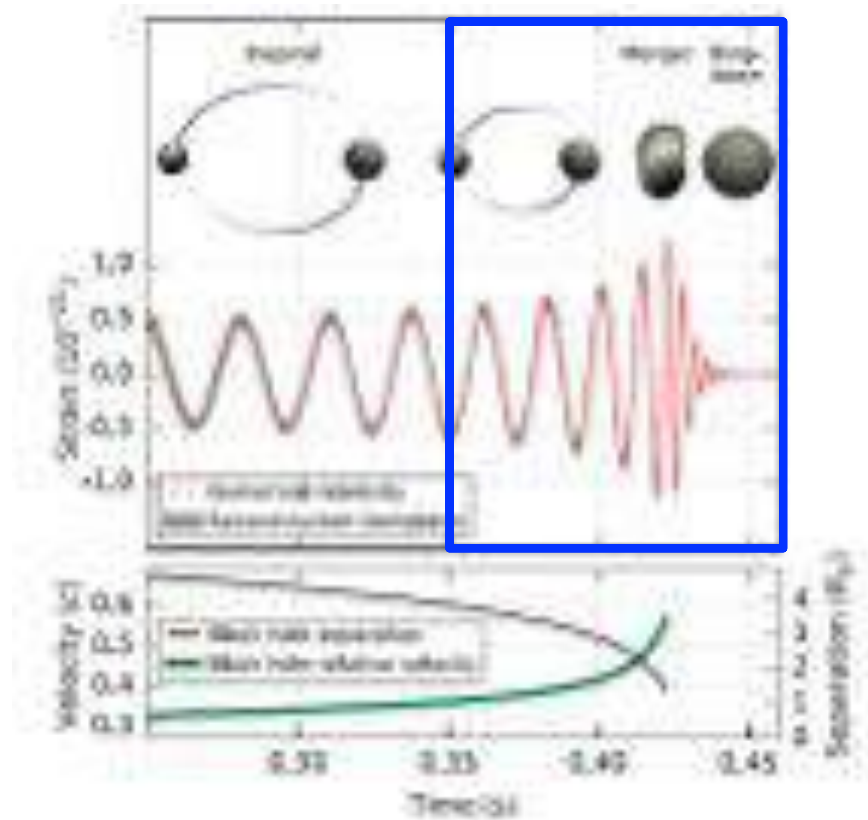






Overcoming the limitations of state-of-the-art GW detectors



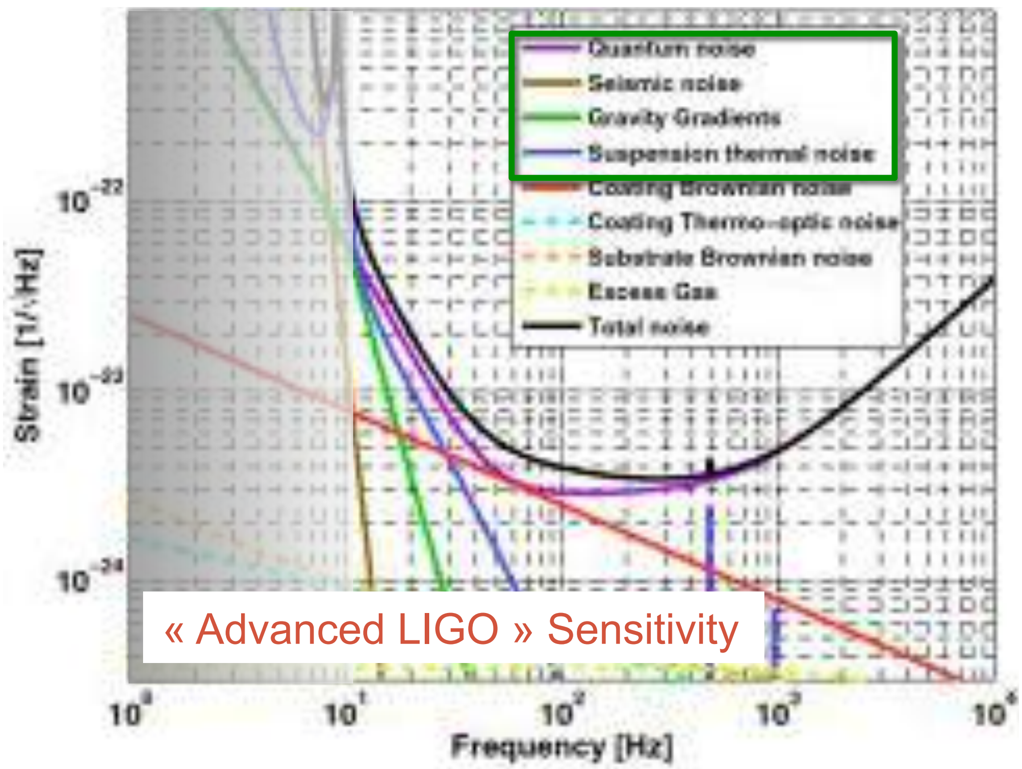


- State-of-the-art GW detectors sense the ultimate evolution phase of binary systems
- A transient of a few hundreds of ms which corresponds to system coalescence

With low frequency detectors (f<1Hz)

- Observation of the same sources on quasi continuous timescales $T \propto f_{GW}^{-8/3}$

A new astronomy is possible with low frequency detectors

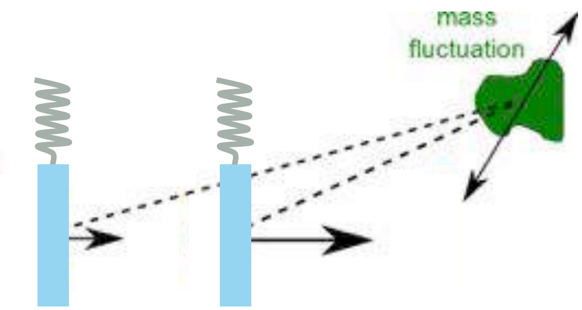


Limitations for f<10 Hz:

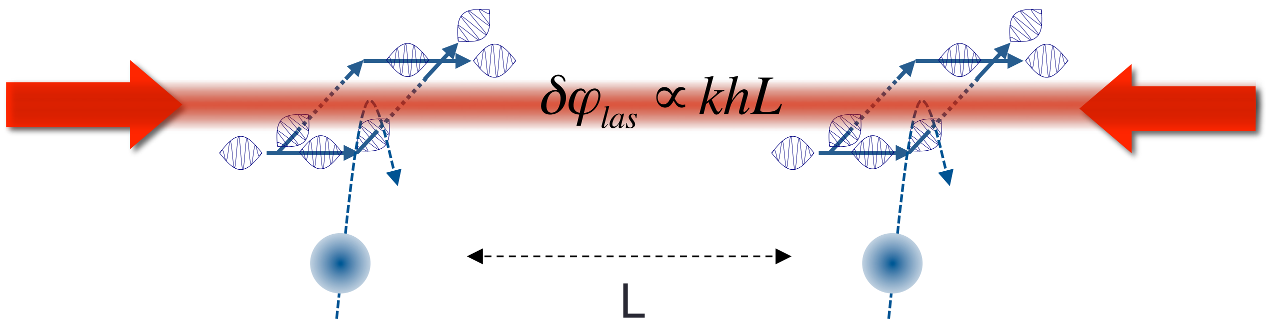
- Radiation pressure noise
- Imperfections of Mirror suspensions
- « Gravity gradient » noise

« Gravity Gradient » noise

Fluctuations of the Earth gravity field



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



PHYSICAL REVIEW D 78, 122002 (2008)

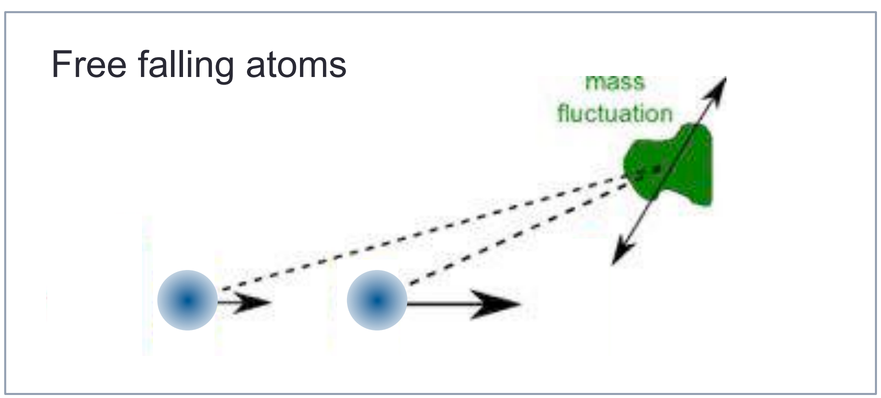
Atomic gravitational wave interferometric sensor

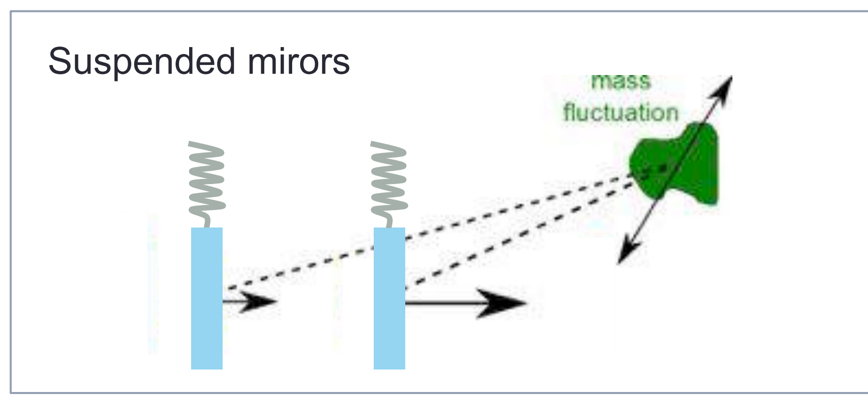
Savas Dimopoulos,[1,*] Peter W. Graham,[2,†] Jason M. Hogan,[1,‡] Mark A. Kasevich,[1,§] and Surjeet Rajendran[1,2,∥]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*SLAC, Stanford University, Menlo Park, California 94025, USA*
(Received 28 August 2008; published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

Enable to overcome:

- Limitations related to suspension systems.
- Radiation pressure noise.

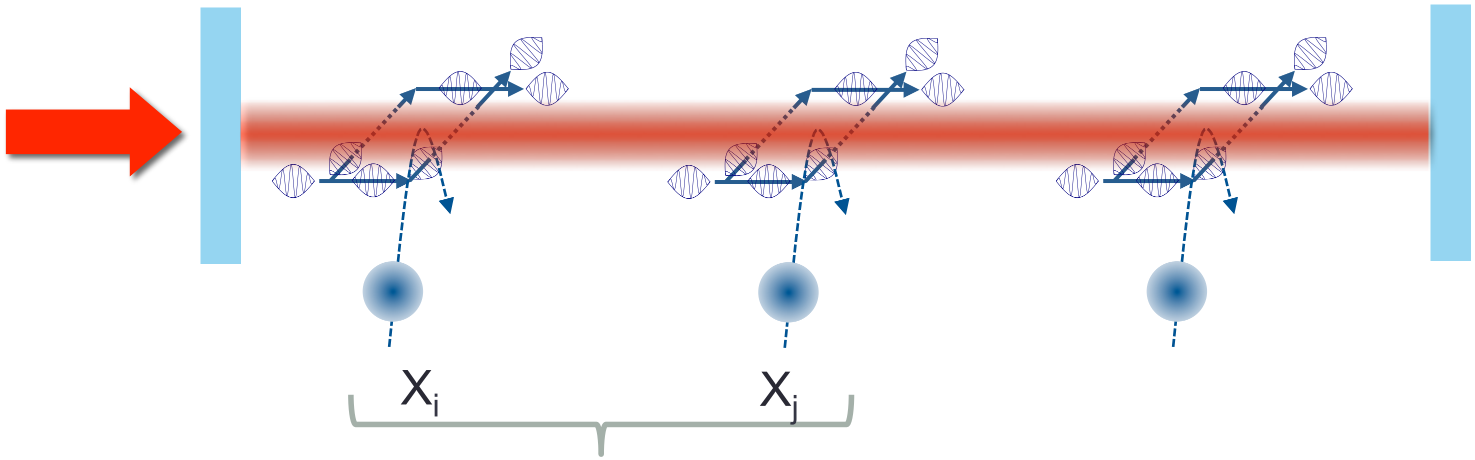
Sensitivity to Gravity Gradient Noise is the same !





Networks of AIs for Gravity Gradient Noise cancellation

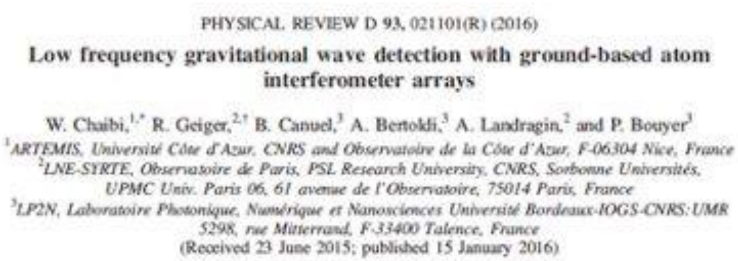
Example of the MIGA Geometry



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

- Effet 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



PHYSICAL REVIEW D 93, 021101(R) (2016)

Low frequency gravitational wave detection with ground-based atom interferometer arrays

W. Chaibi,[1,*] R. Geiger,[2,†] B. Canuel,[3] A. Bertoldi,[3] A. Landragin,[2] and P. Bouyer[3]
[1]*ARTEMIS, Université Côte d'Azur, CNRS and Observatoire de la Côte d'Azur, F-06304 Nice, France*
[2]*LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France*
[3]*LP2N, Laboratoire Photonique, Numérique et Nanosciences Université Bordeaux-IOGS-CNRS:UMR 5298, rue Mitterrand, F-33400 Talence, France*

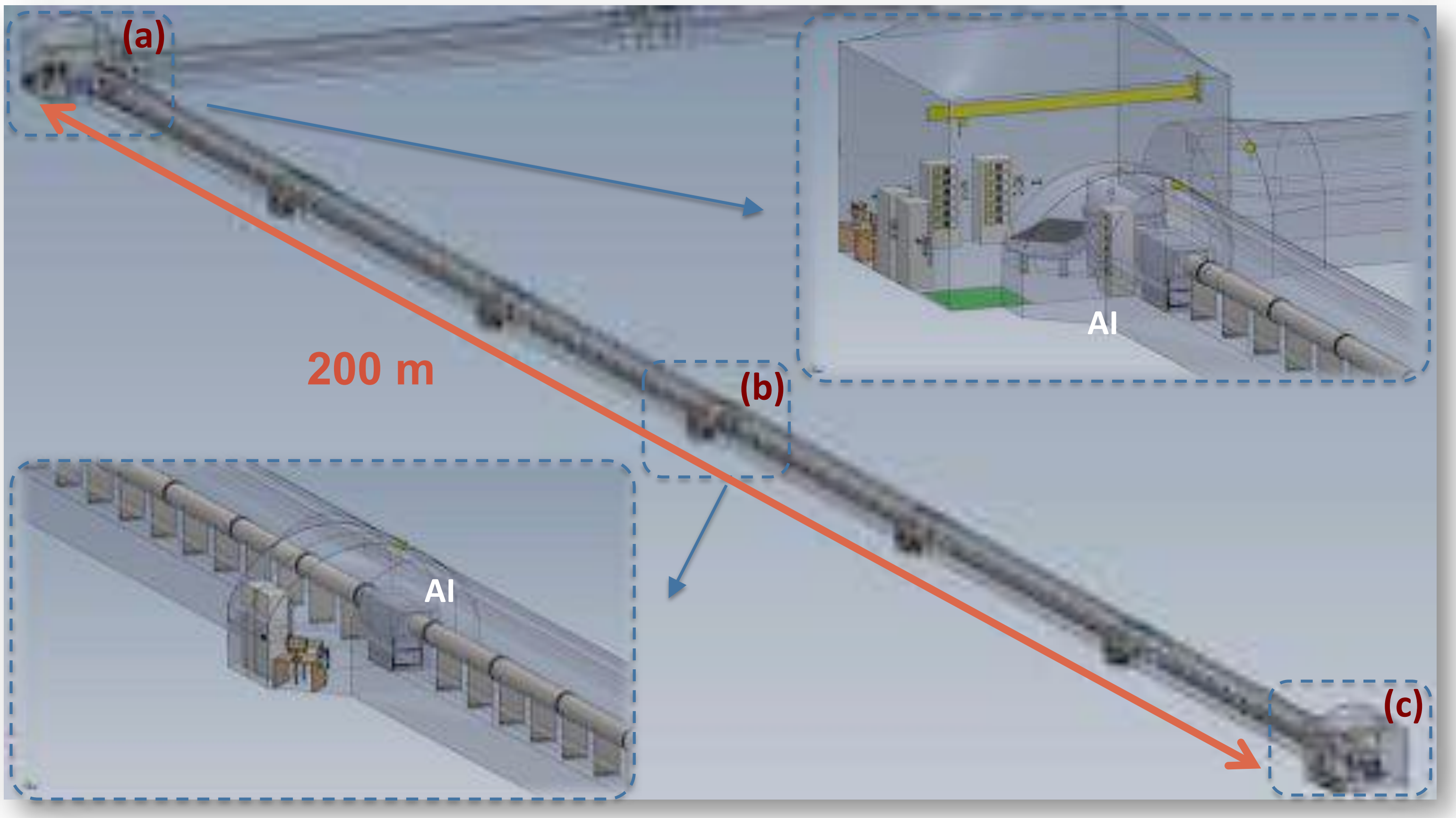
(Received 23 June 2015; published 15 January 2016)

- Low frequency (10^{-2}-10 Hz) GW detection limited by detection noise
- Measures of the local gravity field = Geoscience

The MIGA antenna and LSBB site.

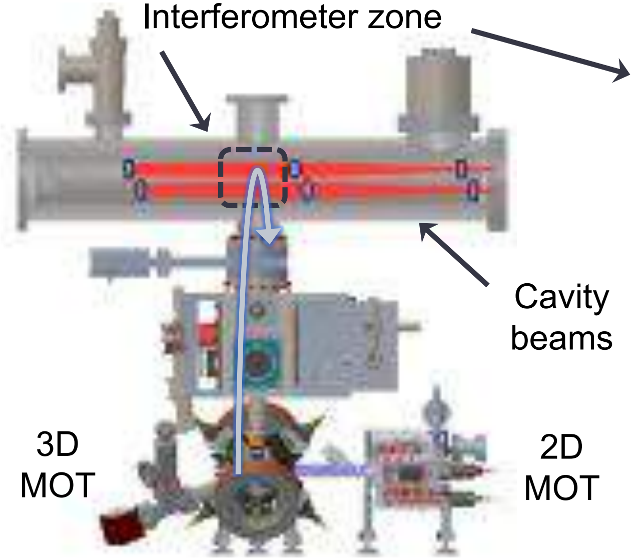
The MIGA Instrument

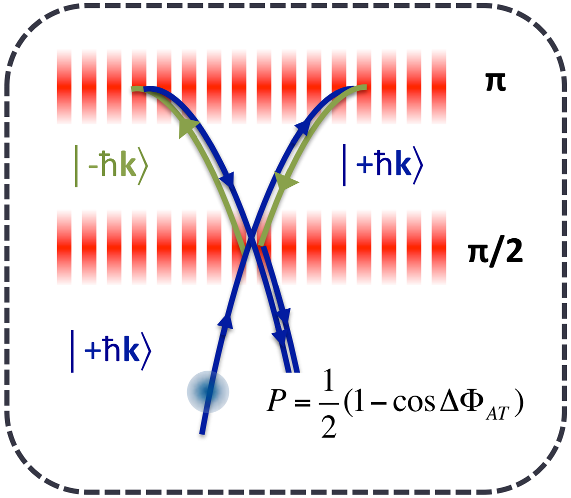
- An array of AI installed in a low noise underground laboratory (LSBB)

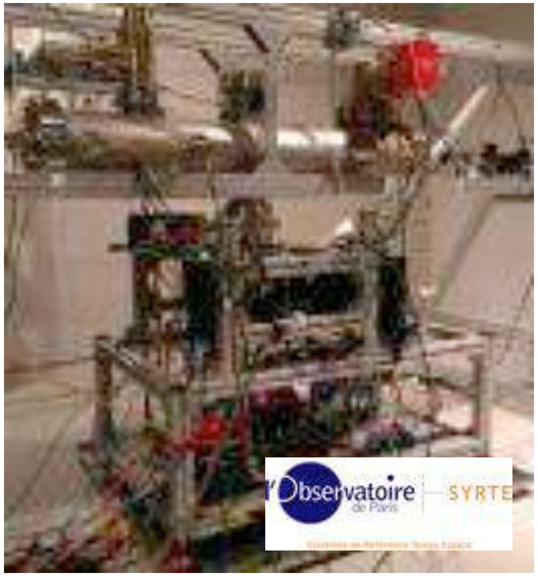


Study coupling at low frequency between Geophysics and GW signals.

Study new measurements methods for geophysics
Access to gravity gradients and higher orders ->3D mapping of local gravity







Rb 87 atoms trapped in a 3D MOT loaded by a 2D MOT.

Two other AIs in production to start assembling a reduced size antenna (10 m)

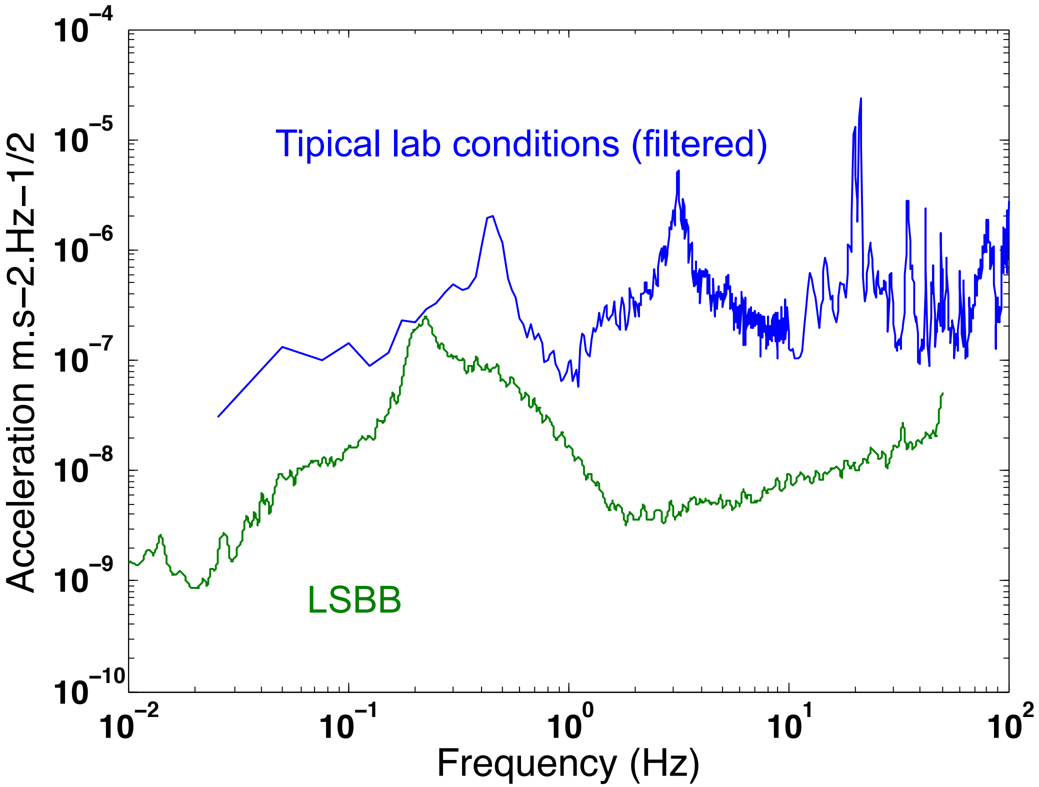
MIGA: Status 2/2

- A dismissed military facility
- Former command centre for nuclear force

- Infrastructure works will start end 2017
- MIGA installation: mid 2019

LSBB, a low noise site for MIGA

Environmental noise may prevent to reach detection noise (quantum noise) easily.
Usual suspects: **seismic** and magnetic noise



RMS noise on AI measurements induced by seismic noise:

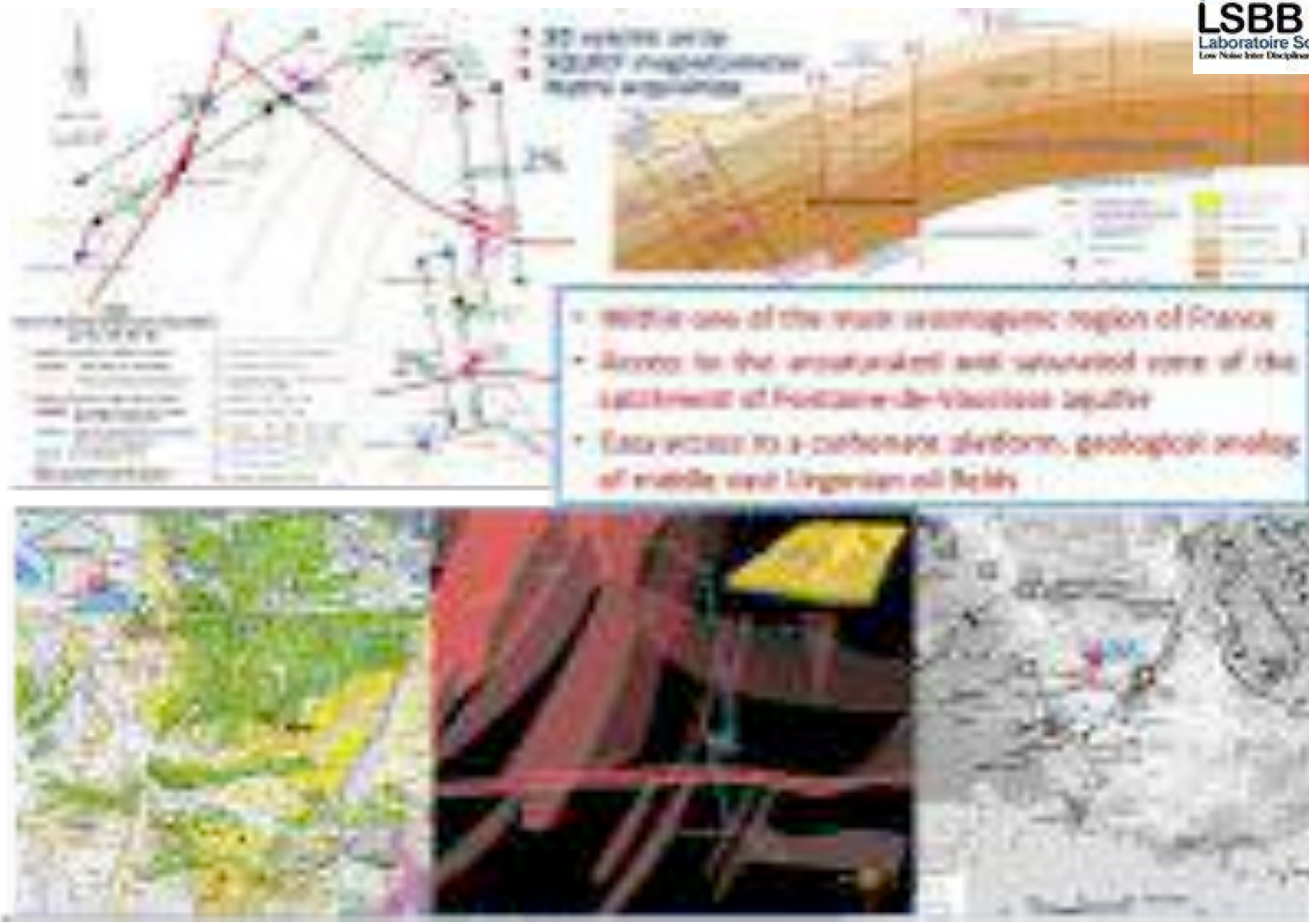
σ_ϕ=640 mrad → σ_ϕ=60 mrad

Underground operation enables AI to reach optimal performances

See T. Farah, et al., Gyroscopy Navig. ***5****, 266 (2014).*

≈ 5 10^{-10} g = 0.5 µGal

LSBB, a site of geological interest

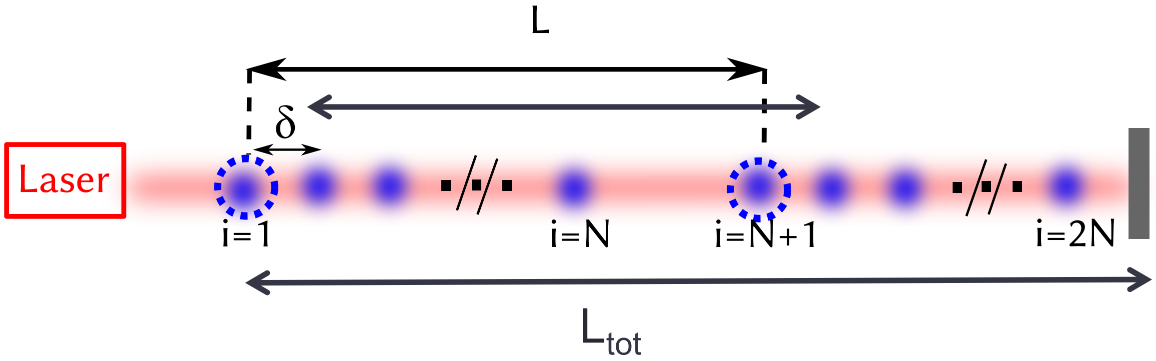


MIGA: Access to gravity gradient&higher orders, long term fluctuations

Future detector geometries enabling GGN reduction.

Further MIGA: future GW detectors enabling GNN cancellation

Dense arrays of Atom Interferometers could be used as future GW detectors



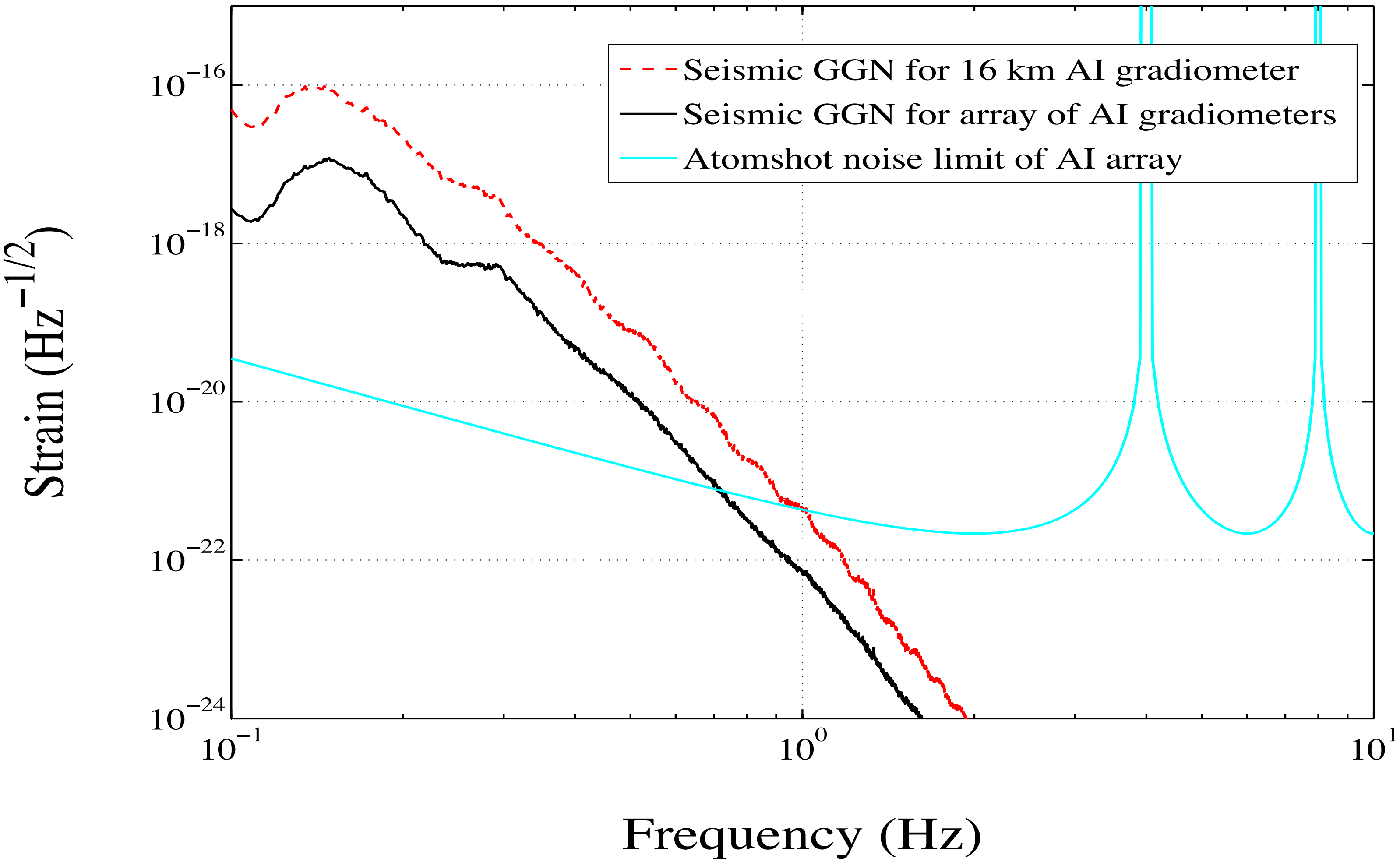
- L_{tot}=32 km
- N=80 gradiometers
- baseline L = 16 km

- Gravitational Wave signal can be extracted using a spatial averaging method
- N Correlated gradiometers enable to average the GGN over several realizations

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

- The geometry of the detector (δ,L) is chosen with respect to the spatial correlation properties of the GGN.

GGN reduction with an AI network



- Gain of about factor 10 in the 100 mHz 1 Hz band
- Space for improvement using all spatial information of the network (use different baseline L in the numerical treatment)

Conclusion

- MIGA will be a new infrastructure for a large community
- Study new measurements methods for geophysics
- Opens perspectives for low frequency GW detection, future of GW astronomy

GGN is a strong limit for earth based detectors

- Arrays of AIs can be configured to reject GGN