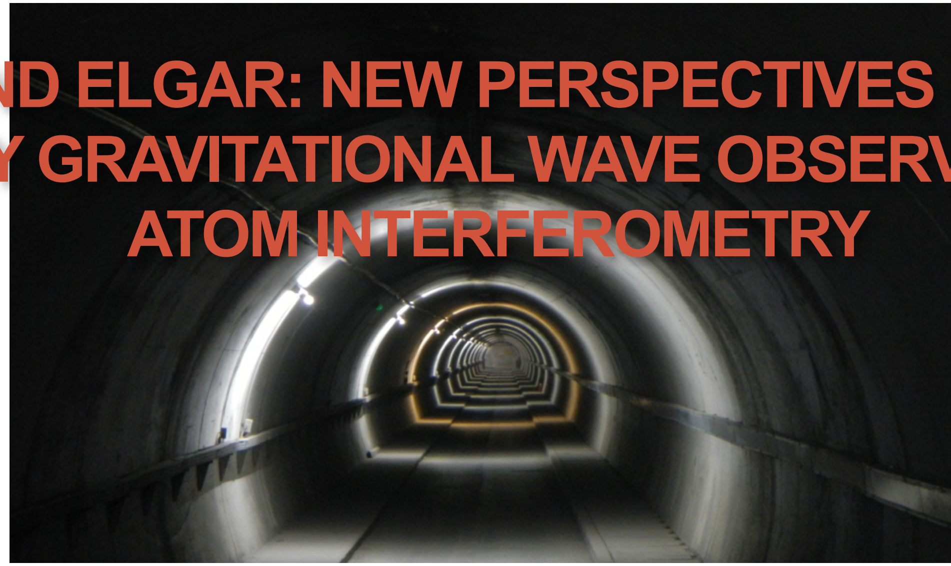
MIGA AND ELGAR: NEW PERSPECTIVES FOR LOW FREQUENCY GRAVITATIONAL WAVE OBSERVATION USING ATOM INTERFEROMETRY



INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech
CNRS
UNIVERSITÉ BORDEAUX 1 Sciences Technologies
CEA DE LA RECHERCHE À L'INDUSTRIE
Université PARIS DIDEROT PARIS 7
l'Observatoire de Paris
Université Nice Sophia Antipolis
ALPhA NOV Centre Technologique Optique et Lasers
LNE Le progrès, une passion à partager
UPMC SORBONNE UNIVERSITÉS
ENS ÉCOLE NORMALE
UNIVERSITÉ PARIS SUD Comprendre le monde, construire l'avenir®
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UNIVERSITÉ MONTPELLIER
IRD Institut de recherche pour le développement
LAPHIA Laser & Photonics in Aquitaine
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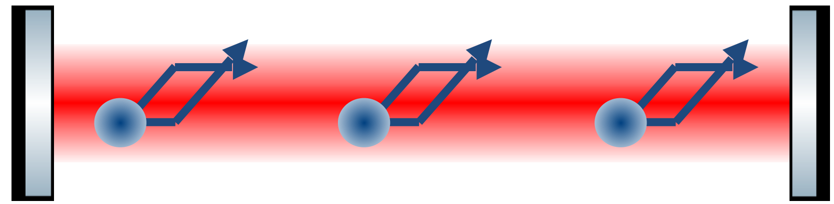
INVESTISSEMENTS D'AVENIR

A new large instrument combining matter-wave and laser interferometry



- Gravitational wave physics
  - Demonstrator for future sub-Hz ground based GW detectors
- Geoscience
  - 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

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

Design of a large-scale instrument with **interdisciplinary applications** based on recent advances in atomic interferometry: MIGA is the first of a new generation of **detectors** both built **underground** and using **quantum manipulation of atoms** for **geosciences**, **seismology** and **fundamental physics**.

Coordination of experts in **fundamental physics, geosciences and astronomy**.

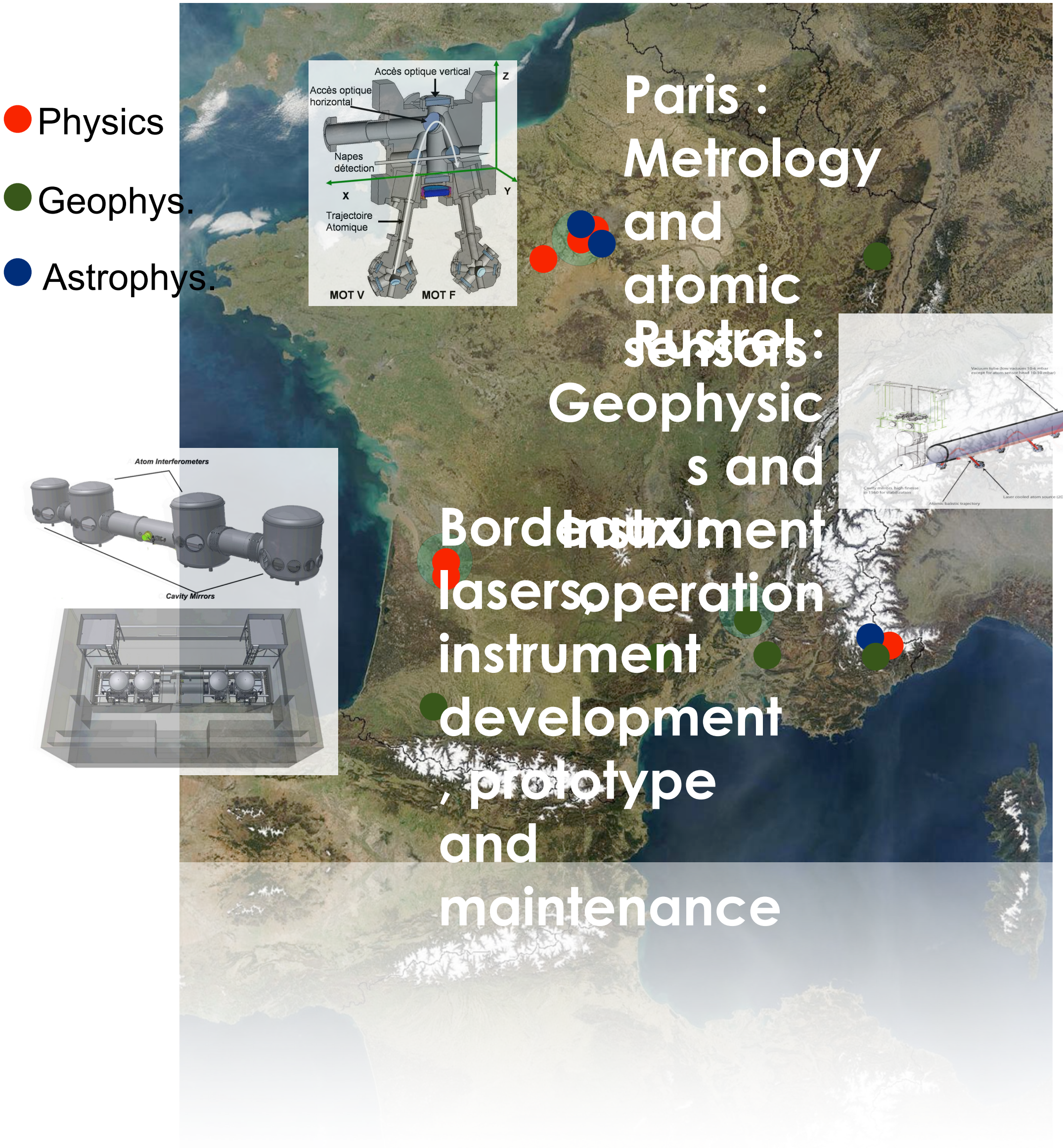
A first generation of research facility enabling high-precision tests to be carried out by different communities.

An important step towards a **low-frequency gravitational strain sensor** with an interest in the detection of **gravitational waves** and also geophysics.

Physics

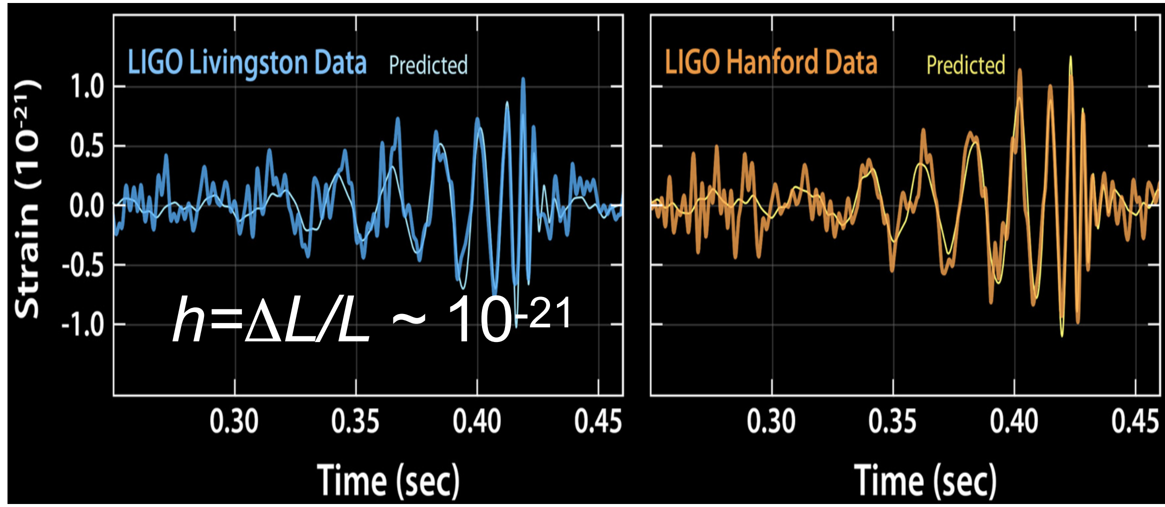
Geophys.

Astrophys.



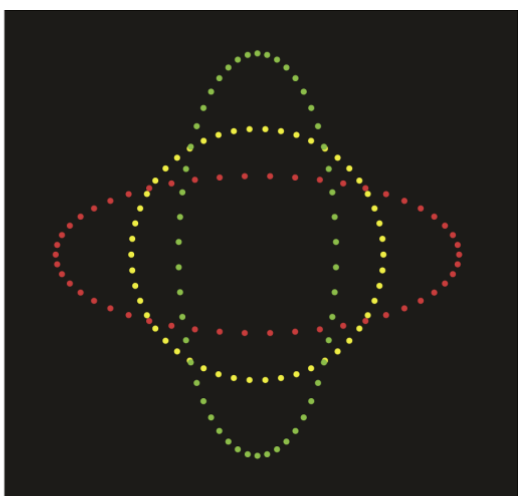
Gravitational Wave detection

- 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 »

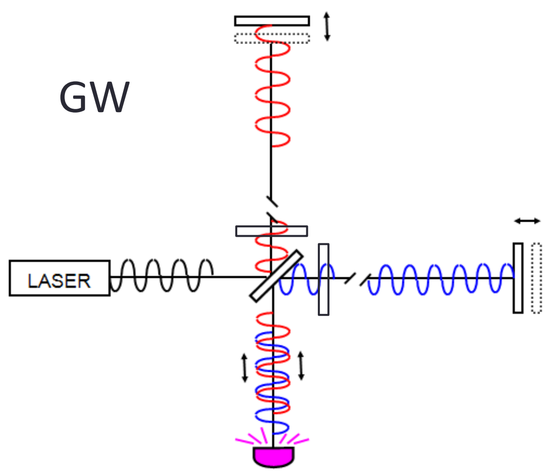


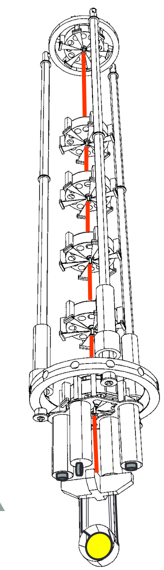
LIGO Scientific Collaboration and Virgo Collaboration, PRL 116, 061102 (2016)

Interferometric detectors

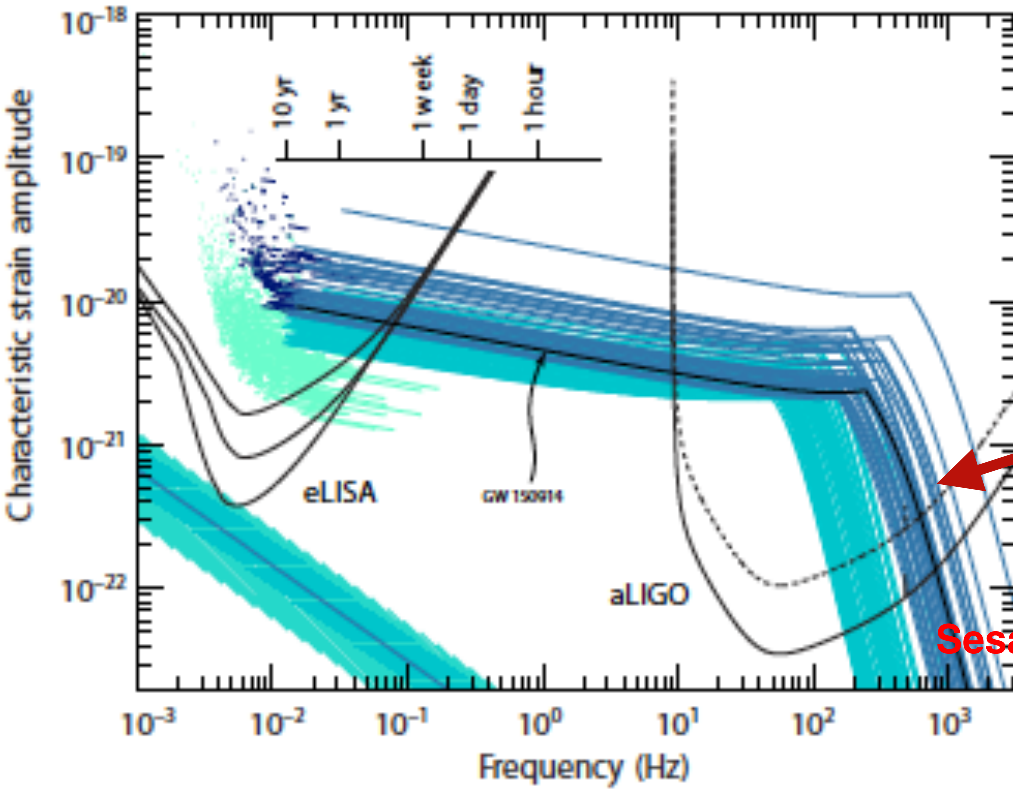


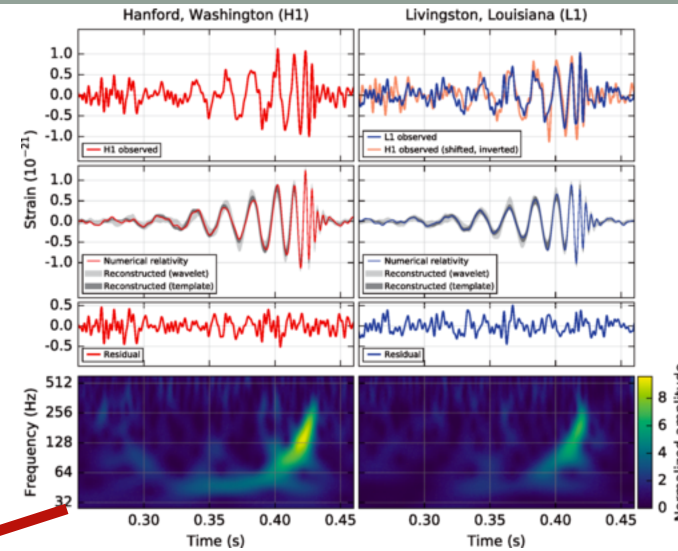
GW





Can we extend the frequency band of state-of-the-art GW detectors?





Sesana, arxiv.org/1602.06951

State-of-the-art GW detectors sense the ultimate evolution phase of binary systems

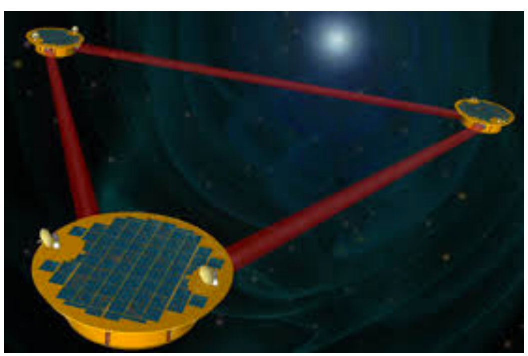
- A transient of a few hundreds of ms which corresponds to system coalescence

With low frequency detectors (f<1Hz)

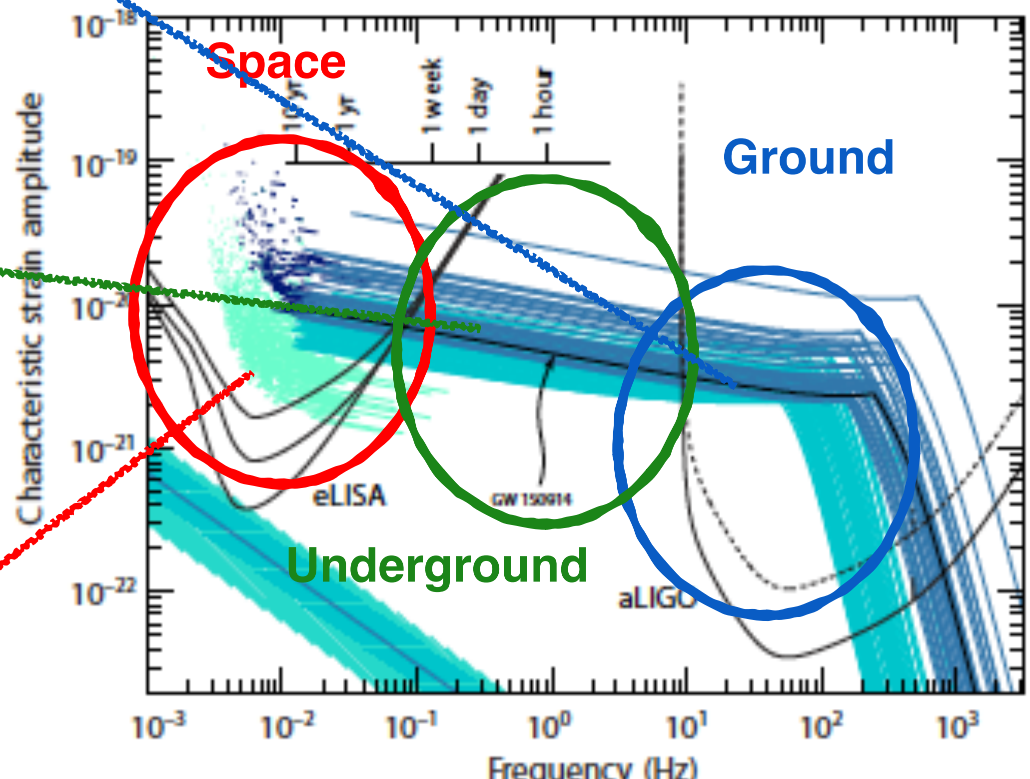
- Observation of the same sources on quasi continuous timescales $T \propto f_{GW}^{-8/3}$

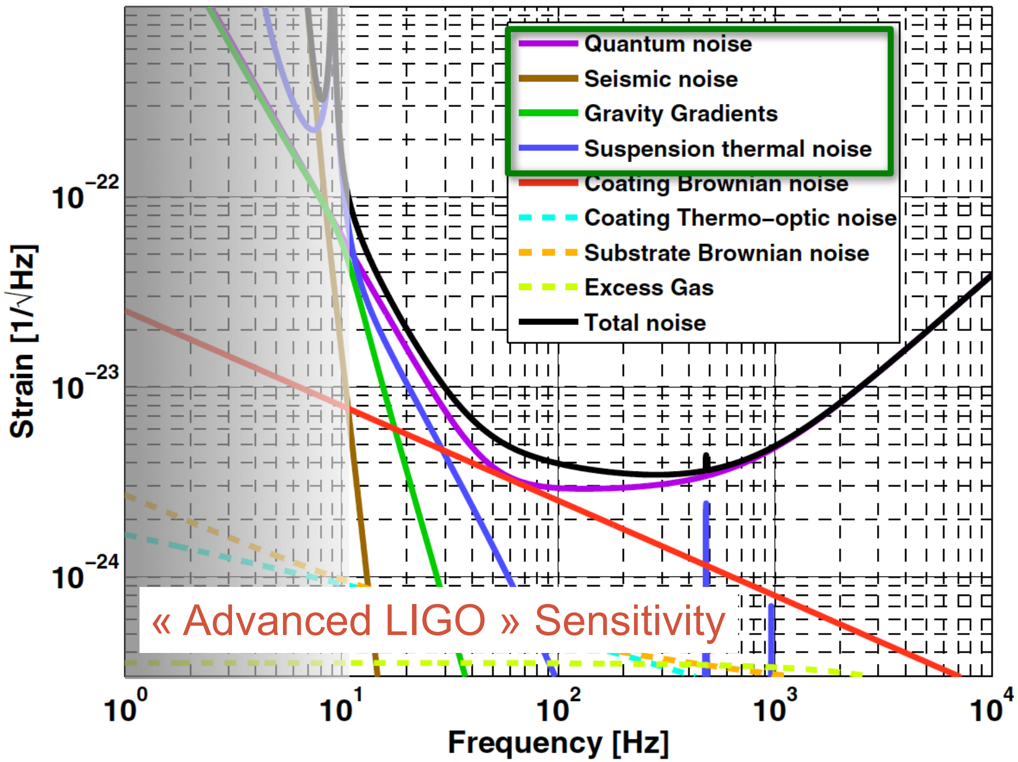
A new astronomy is possible with low frequency detectors

Can we extend the frequency band of state-of-the-art GW detectors?



- **New observables**
- **New sources**



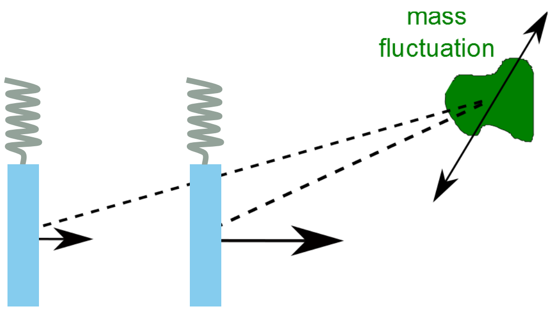


Limitations for f<10 Hz:

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

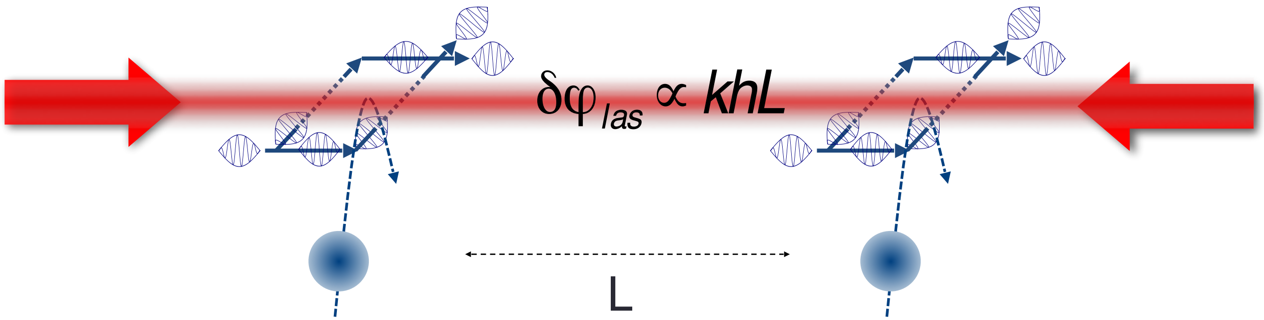
« Gravity Gradient » noise

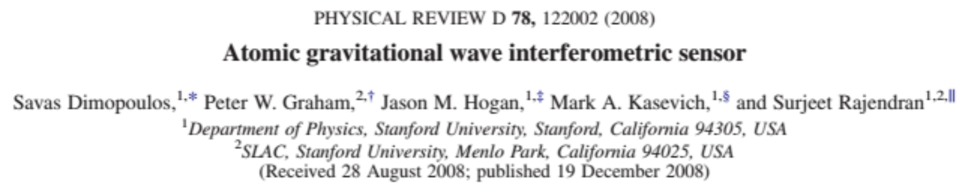
Fluctuations of the Earth gravity field



Cold atoms for GW detection ?

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




PHYSICAL REVIEW D 78, 122002 (2008)

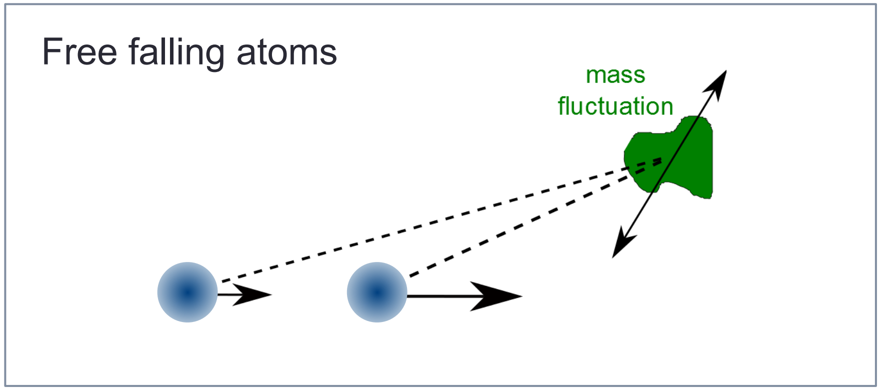
Atomic gravitational wave interferometric sensor

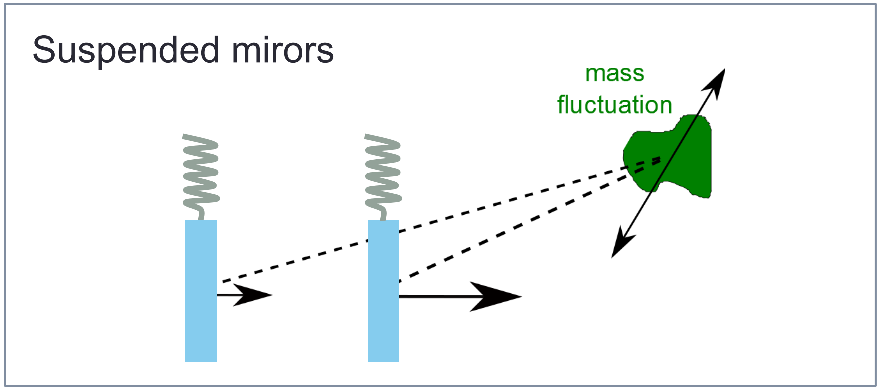
Savas Dimopoulos,[1,*] Peter W. Graham,[2,†] Jason M. Hogan,[1,‡] Mark A. Kasevich,[1,§] and Surjeet Rajendran[1,2,‖]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*SLAC, Stanford University, Menlo Park, California 94025, USA*
(Received 28 August 2008; published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

Enable to overcome:

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

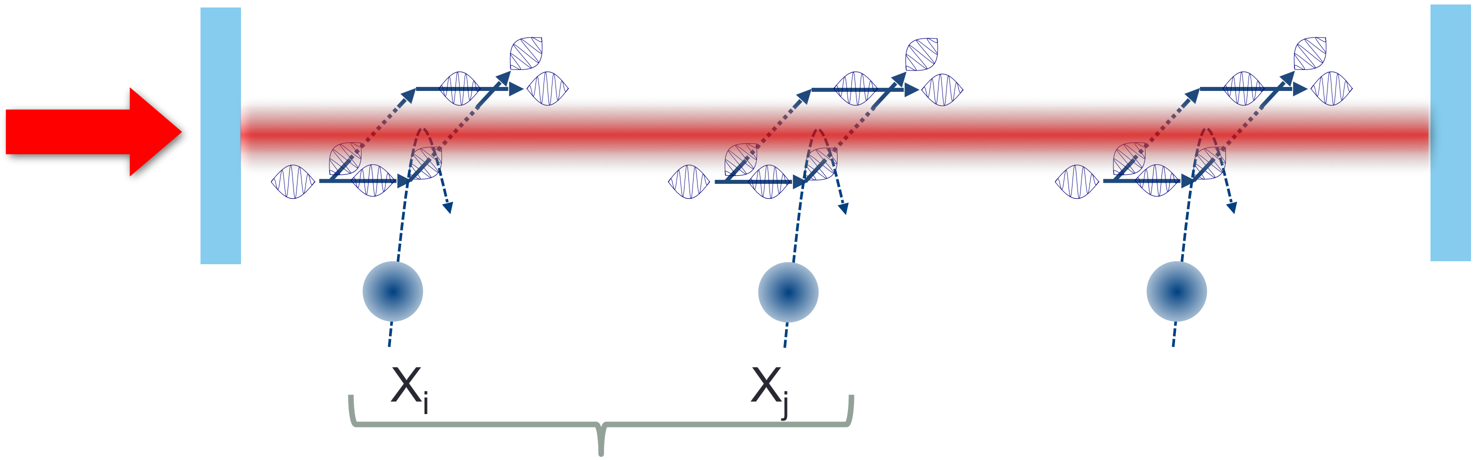
Sensitivity to Gravity Gradient Noise is the same !





Networks of AIs for Gravity Gradient Noise cancellation

Example of the MIGA Geometry



$$\Delta\phi_{at}^{i}-\Delta\phi_{at}^{j}\ \begin{cases} \bullet\ \text{Effet GW} & \propto kh(X_i - X_j) \\ \bullet\ \text{Gravity gradient} & \propto 2kT^2\left[a(X_i) - a(X_j)\right] \end{cases}$$

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]
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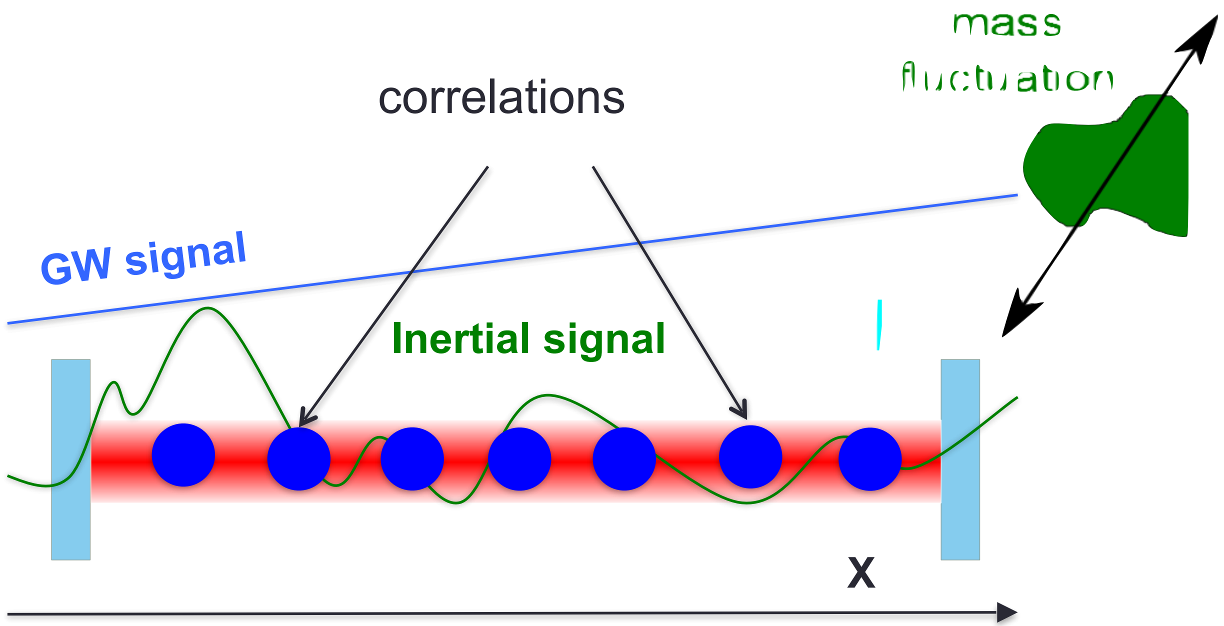
[2]*LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France*
[3]*LP2N, Laboratoire Photonique, Numérique et Nanosciences Université Bordeaux-IOGS-CNRS:UMR 5298, rue Mitterrand, F-33400 Talence, France*
(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**

Use of AI offers possibility to spatially resolve gravity

- ➡GW have long wavelength 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**



Networks of AIs for Gravity Gradient Noise cancellation

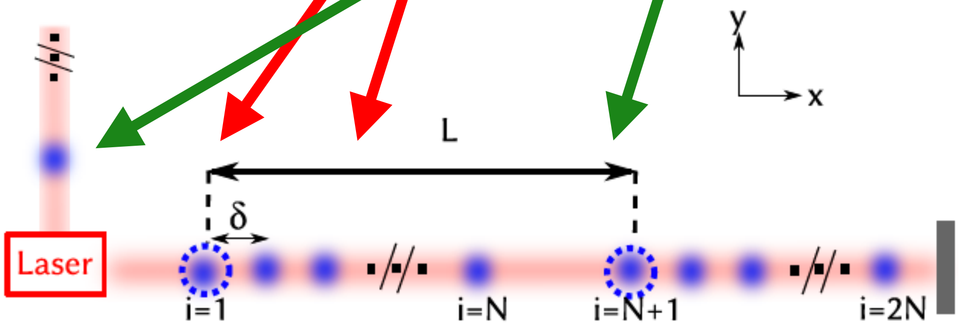
➡ **Strain sensitivity**

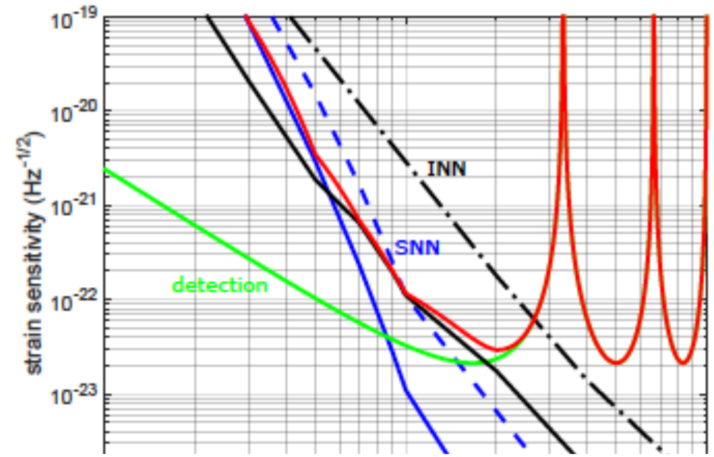
$$S_h(\omega) = \frac{S_a(\omega)}{\omega^4 L^2} + \frac{4S_\epsilon(\omega)}{16NL^2(2nk)^2\sin^4(\omega T/2)}.$$

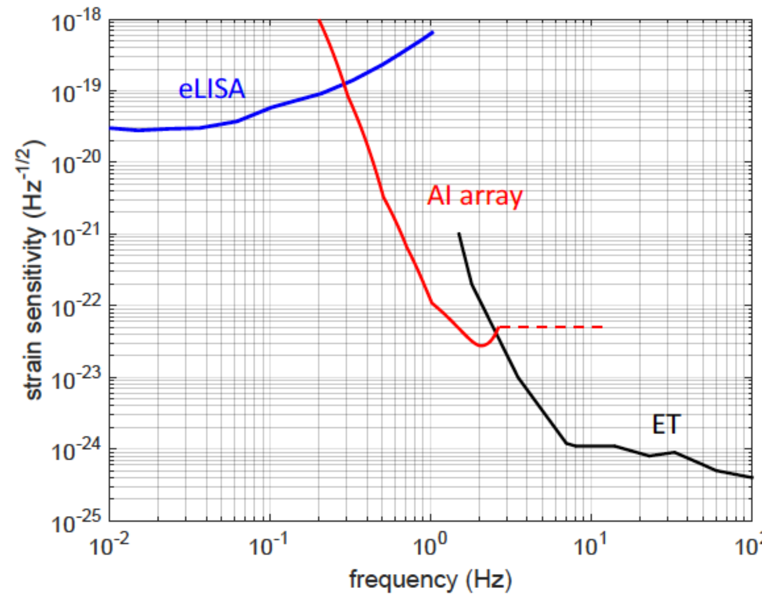
➡ **Shot noise**

$$S_a(\omega) = \frac{1}{N^2}\sum_{i,j=1}^{2N}\left(\mathcal{C}_\parallel(X_i,X_j,\omega) + \mathcal{C}_\perp(X_i,Y_j,\omega)\right)$$

➡ **Seismic noise**



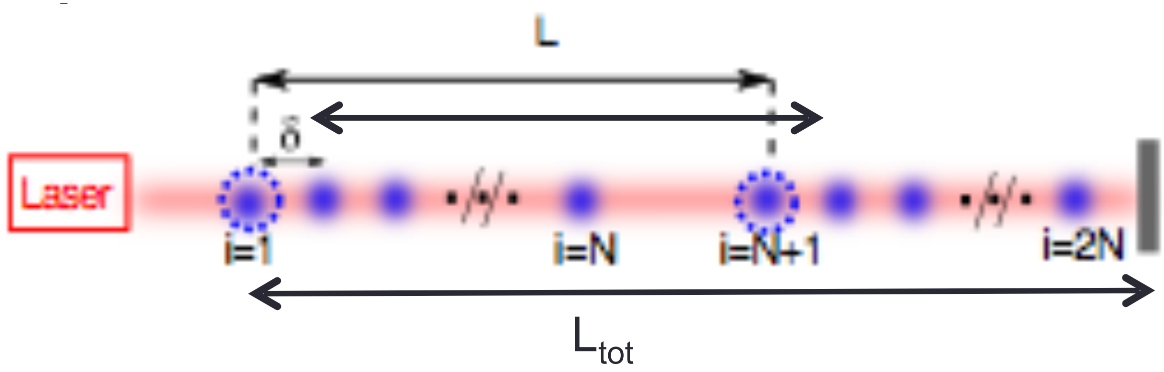




W. Chaibi, et al. Phys. Rev. D 93, 021101(R), 2016

Next generation Matter-wave antenna can reach sensitivity

Dense arrays of Atom Interferometers could be used as future GW



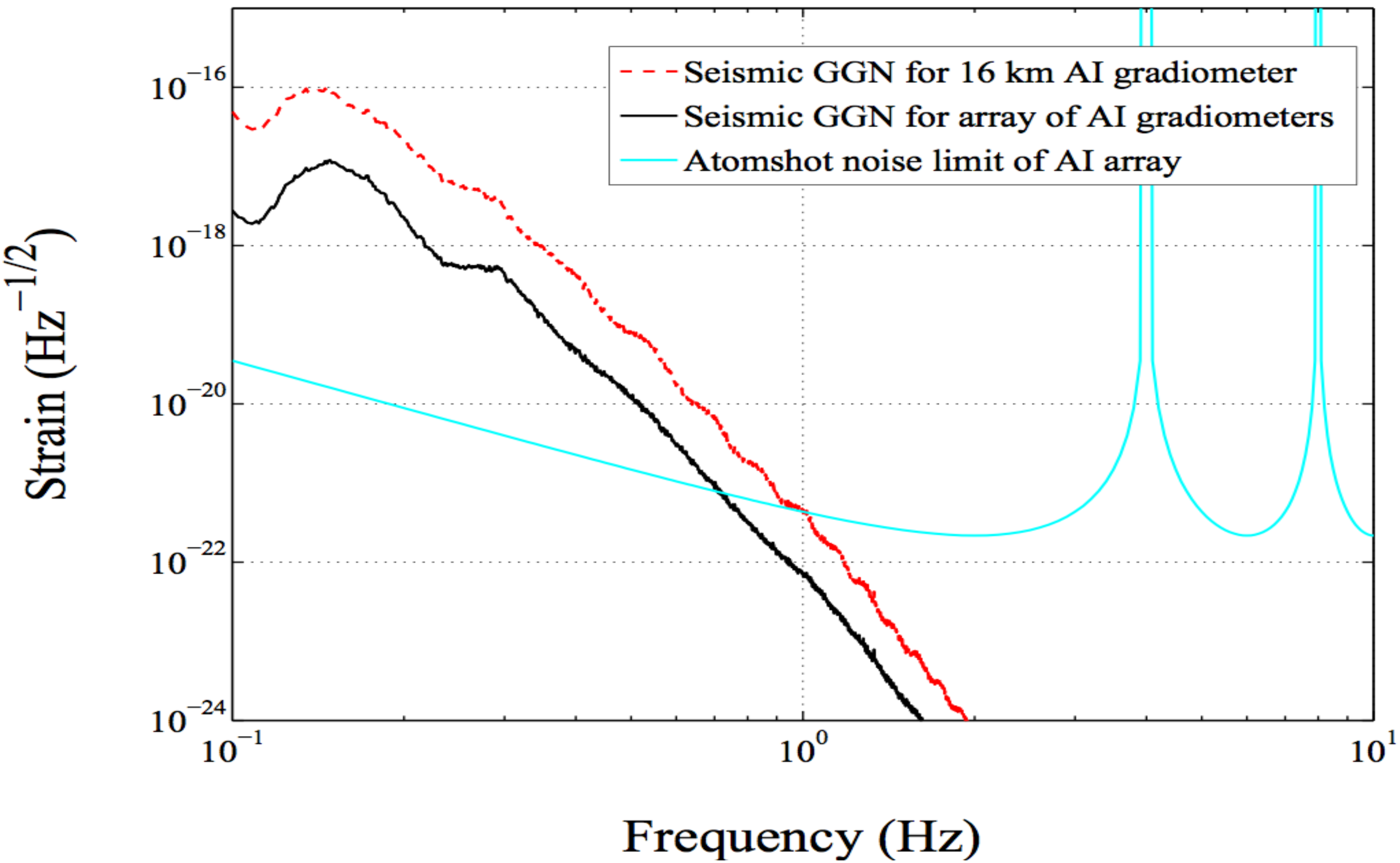
- L_{tot}=32 km
- N=80 gradiometers
- baseline L = 16 km

- 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

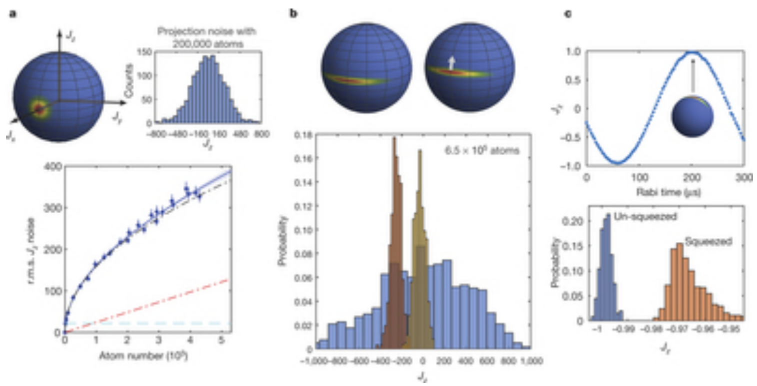


- Gain of about factor 10 in the 100 mHz 1 Hz band
- Space for improvement using all spatial information of the network (use different baseline L in the numerical treatment)

Tools for next generation Matter-wave antenna

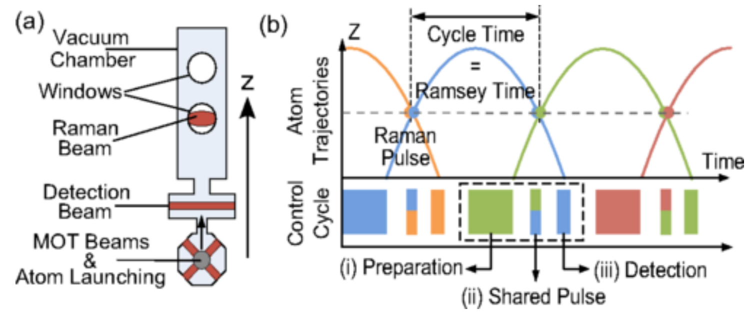
Measurement noise 100 times lower than the quantum-projection limit using entangled atoms

Nature 529, 505–508



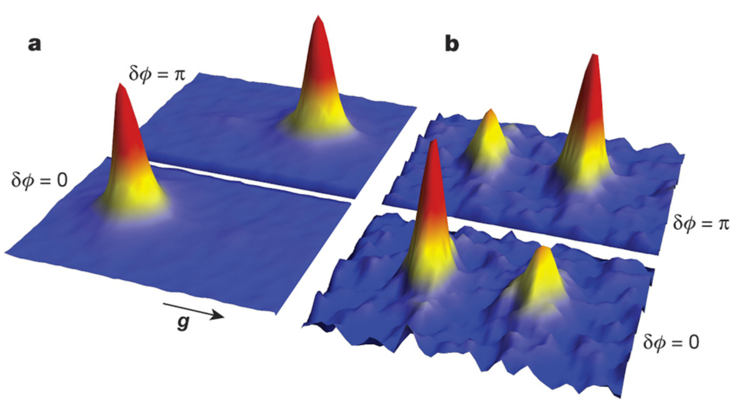
Stability enhancement by joint phase measurements in a single cold atomic fountain

Phys. Rev. A 90, 063633



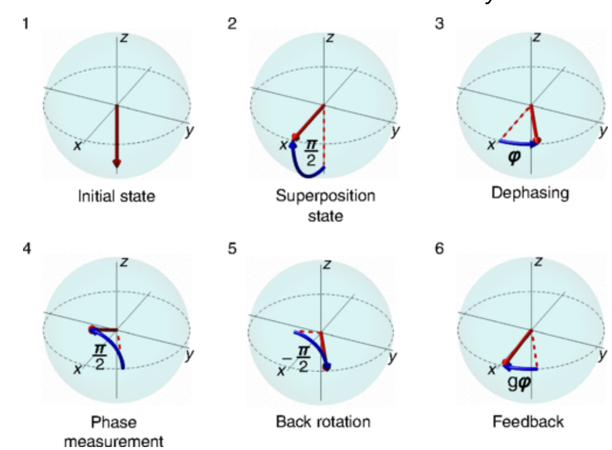
Quantum superposition at the half-metre scale

Nature 528, 530–533



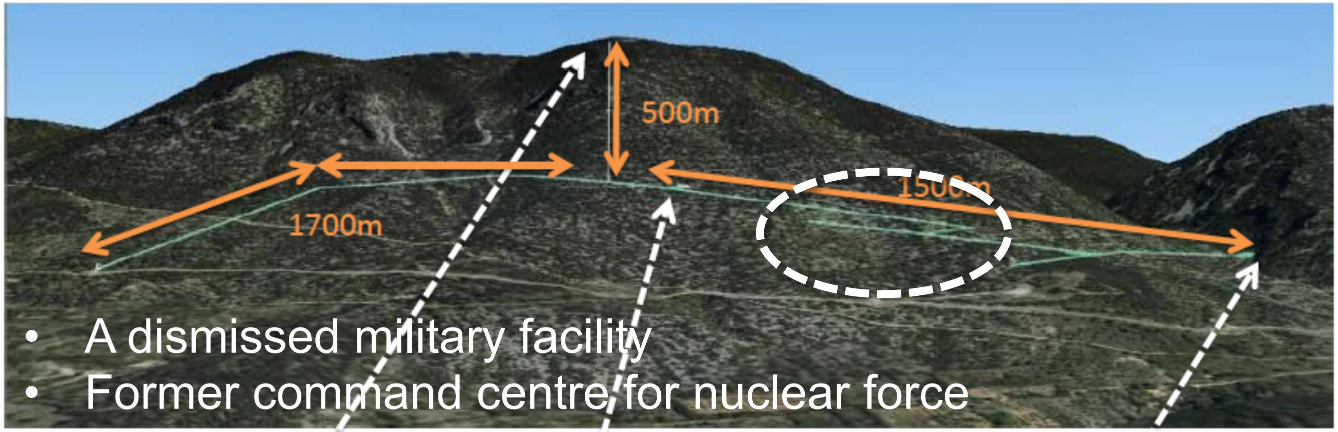
Phase Locking a Clock Oscillator to a Coherent Atomic Ensemble

Phys. Rev. X 5, 021011

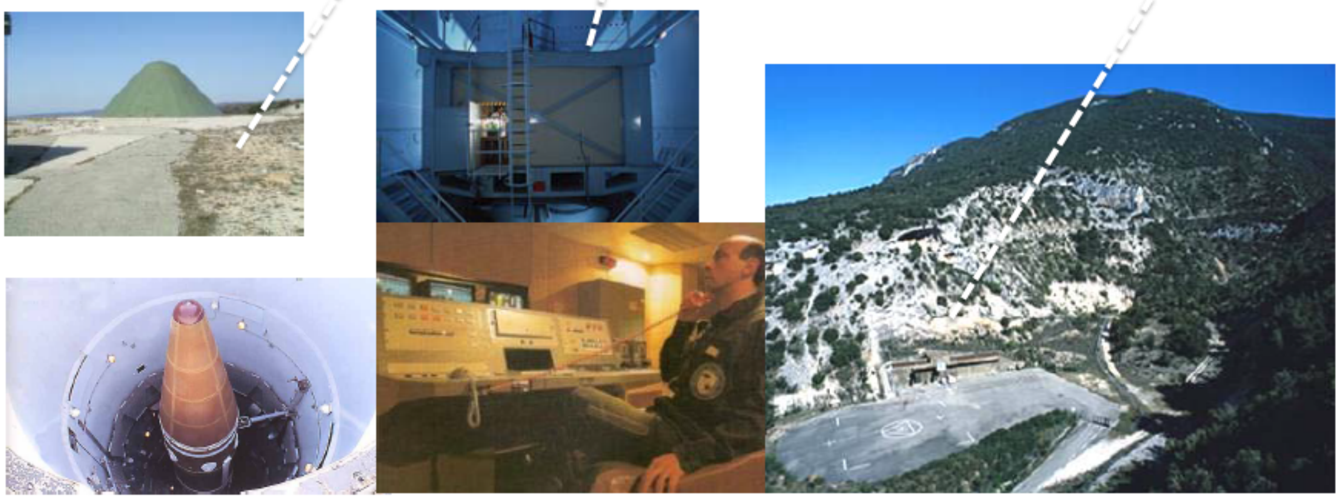


Underground site (LSBB) for MIGA

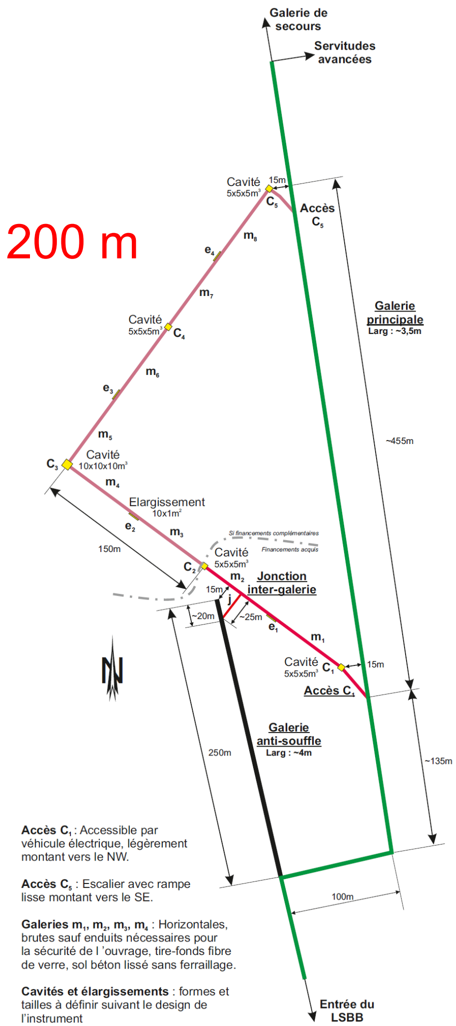
MIGA at the LSBB site



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

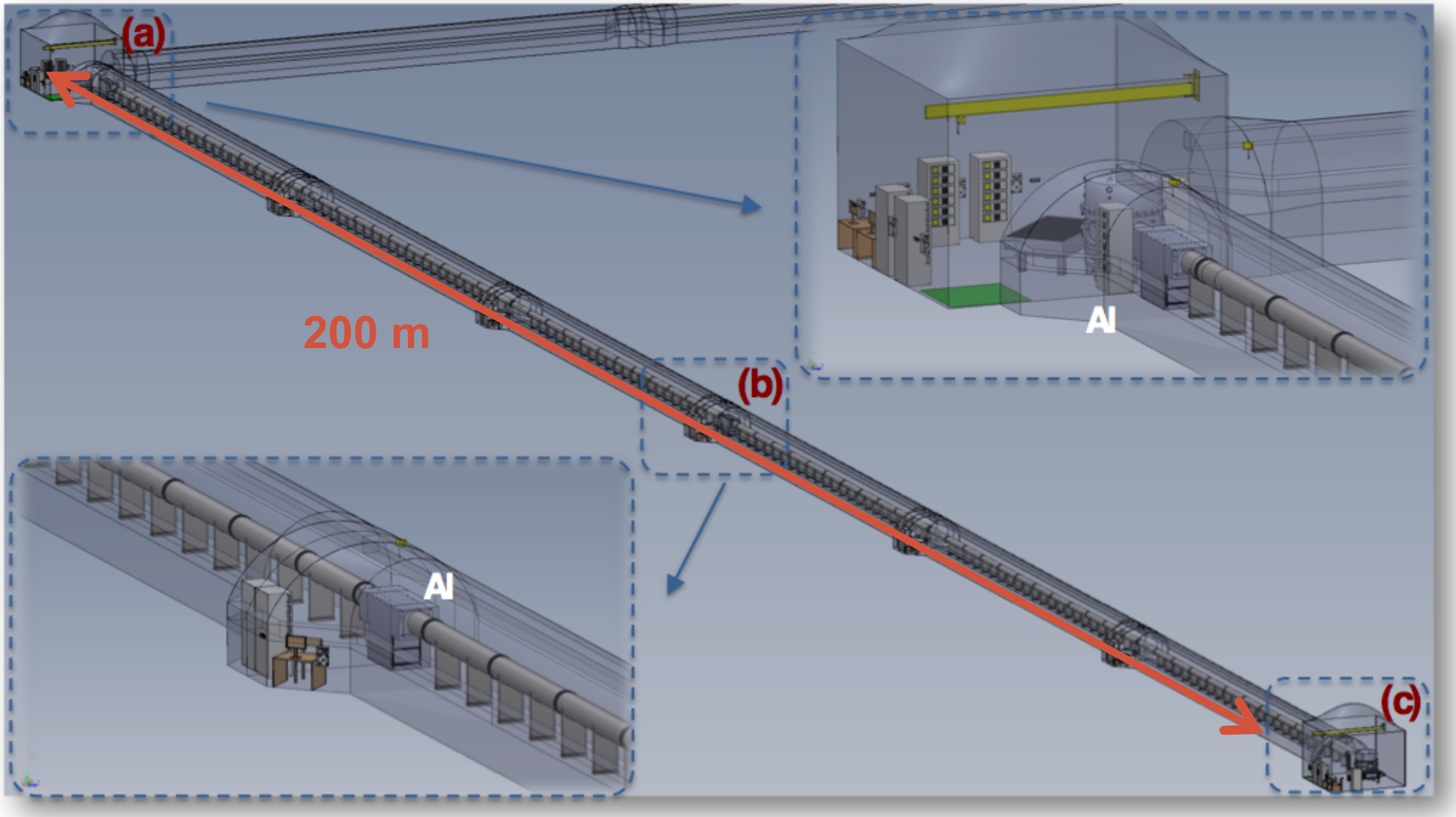


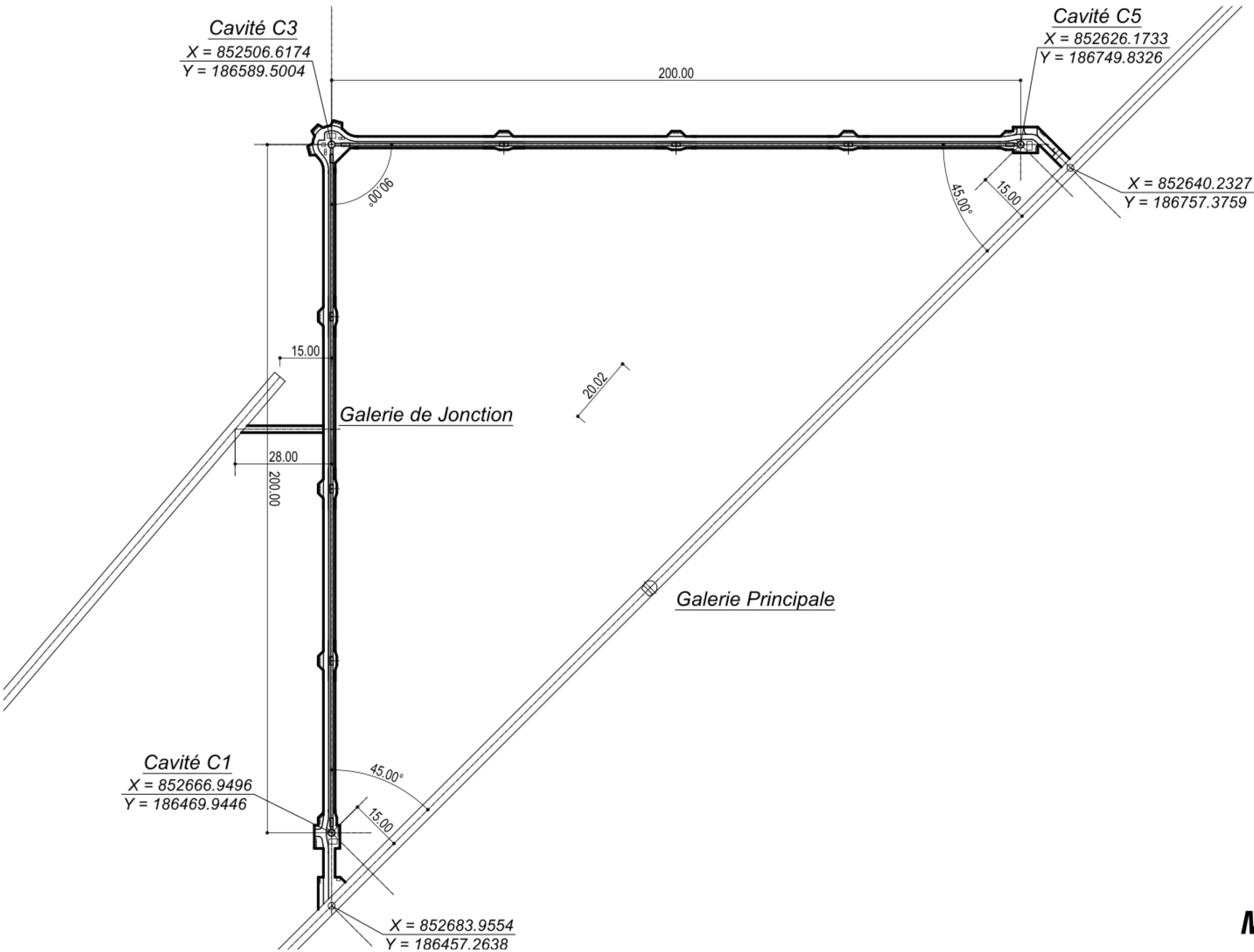
200 m



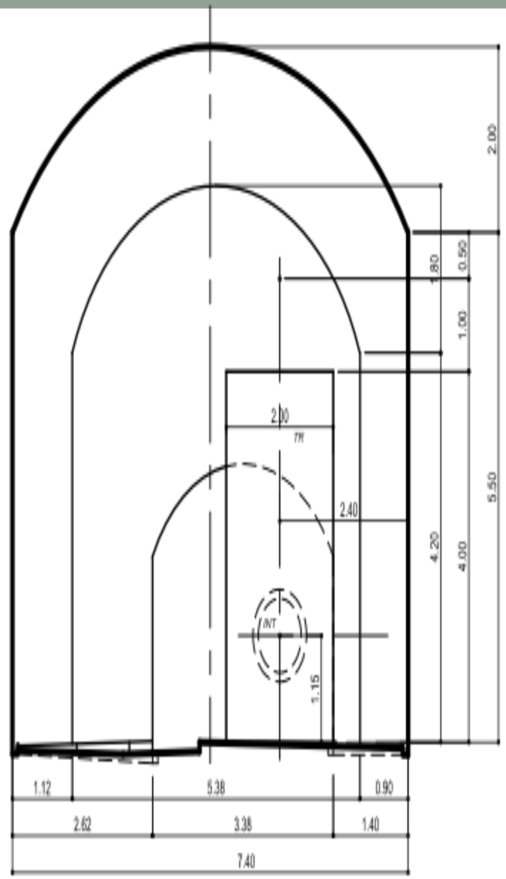
- Infrastructure works will start end 2017
- MIGA installation: mid 2019

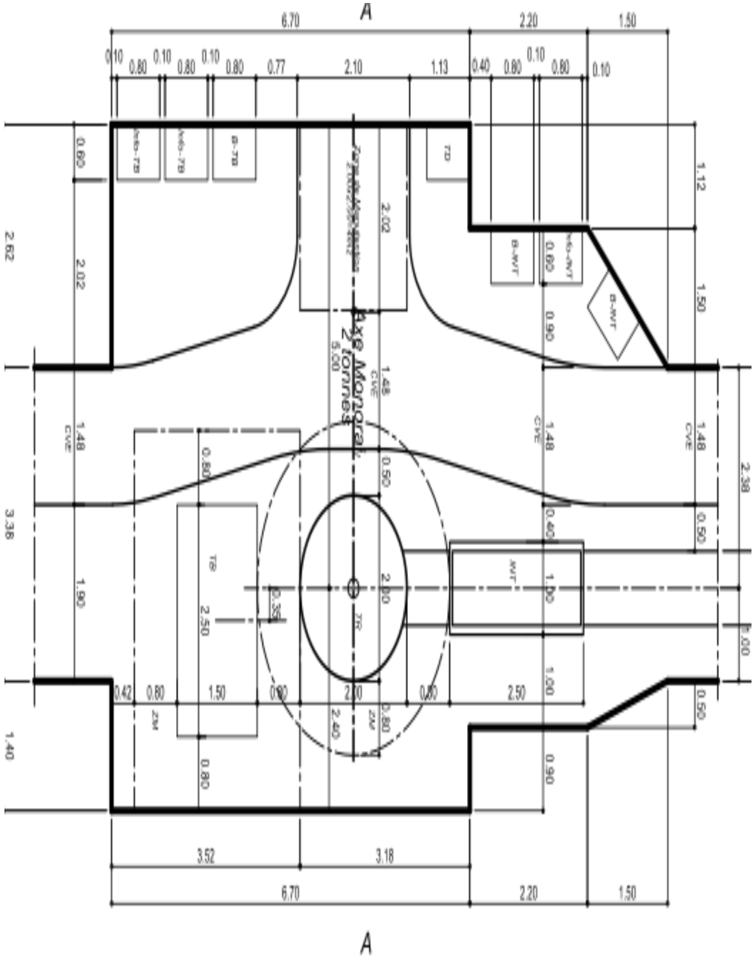
The MIGA Instrument

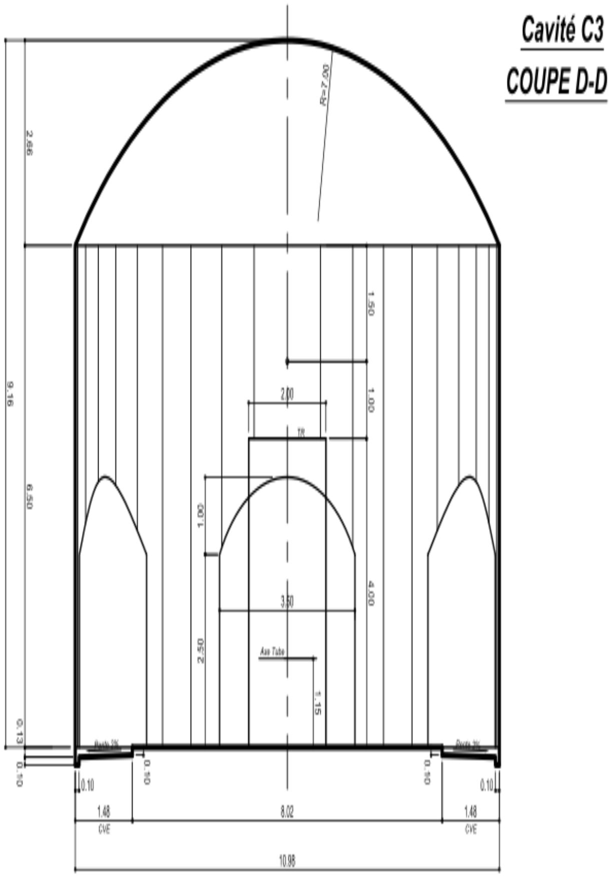



Cavité C3
X = 852506.6174
Y = 186589.5004
200.00
Cavité C5
X = 852626.1733
Y = 186749.8326
X = 852640.2327
Y = 186757.3759
90.00°
45.00°
15.00
15.00
20.02
Galerie de Jonction
28.00
200.00
Galerie Principale
Cavité C1
X = 852666.9496
Y = 186469.9446
45.00°
15.00
X = 852683.9554
Y = 186457.2638

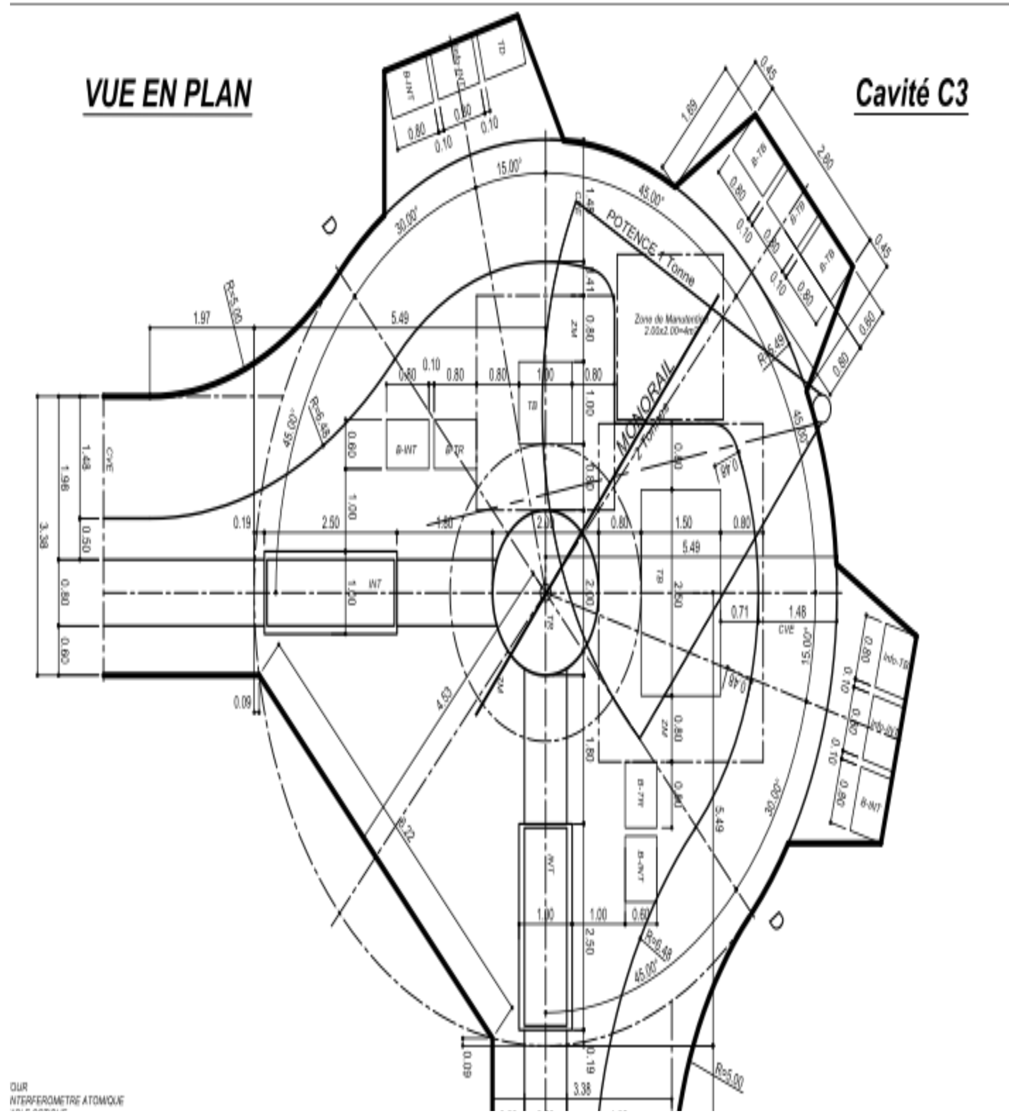
MIGA







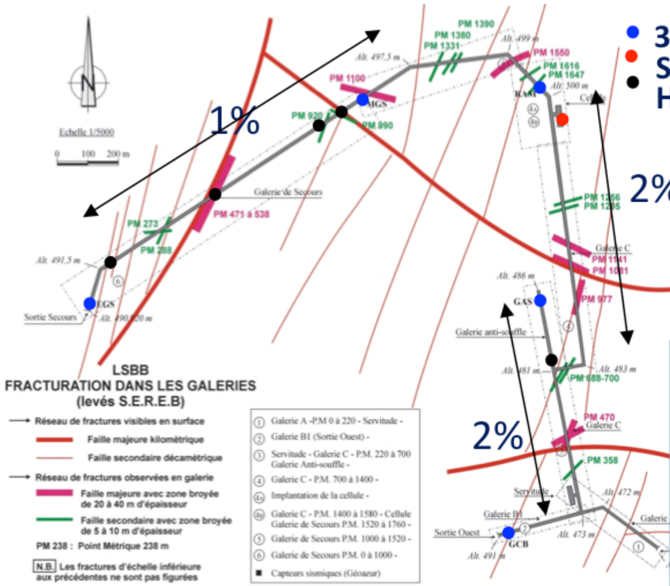
Cavité C3
COUPE D-D

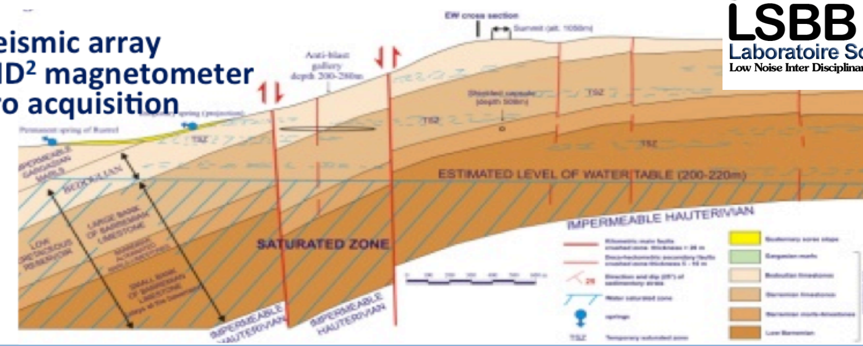


VUE EN PLAN
Cavité C3
POTENCE 1 Tonne
MONORAIL
Zone de Manutention

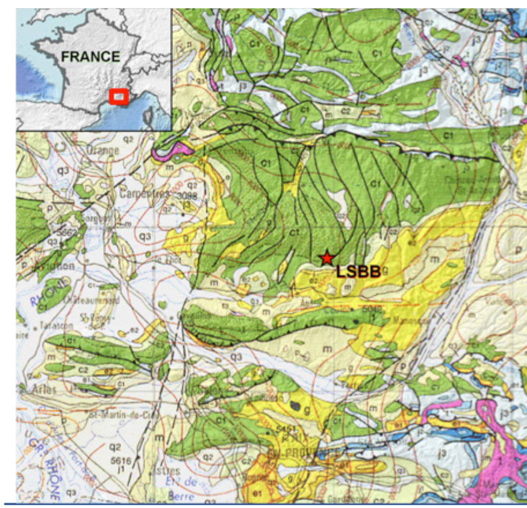
LSBB, a site of geological interest

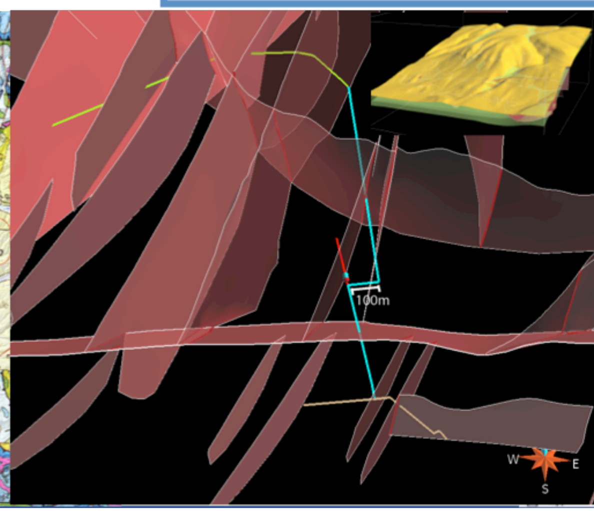
LSBB
Laboratoire Souterrain à Bas Bruit
Low Noise Inter Disciplinary Underground Science & Technology

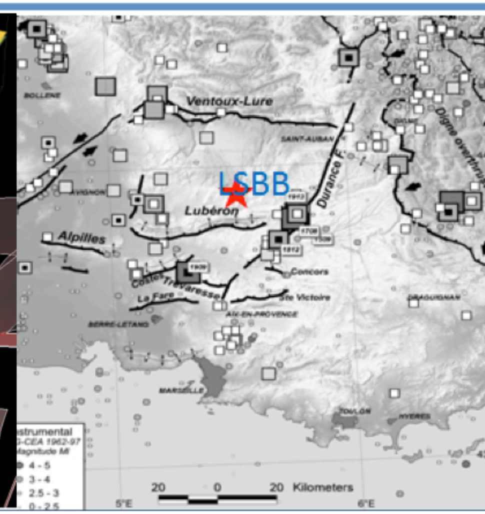




- Within one of the main seismogenic region of France
- Access to the unsaturated and saturated zone of the catchment of Fontaine-de-Vaucluse aquifer
- Easy access to a carbonate platform, geological analog of middle east Urgonian oil fields

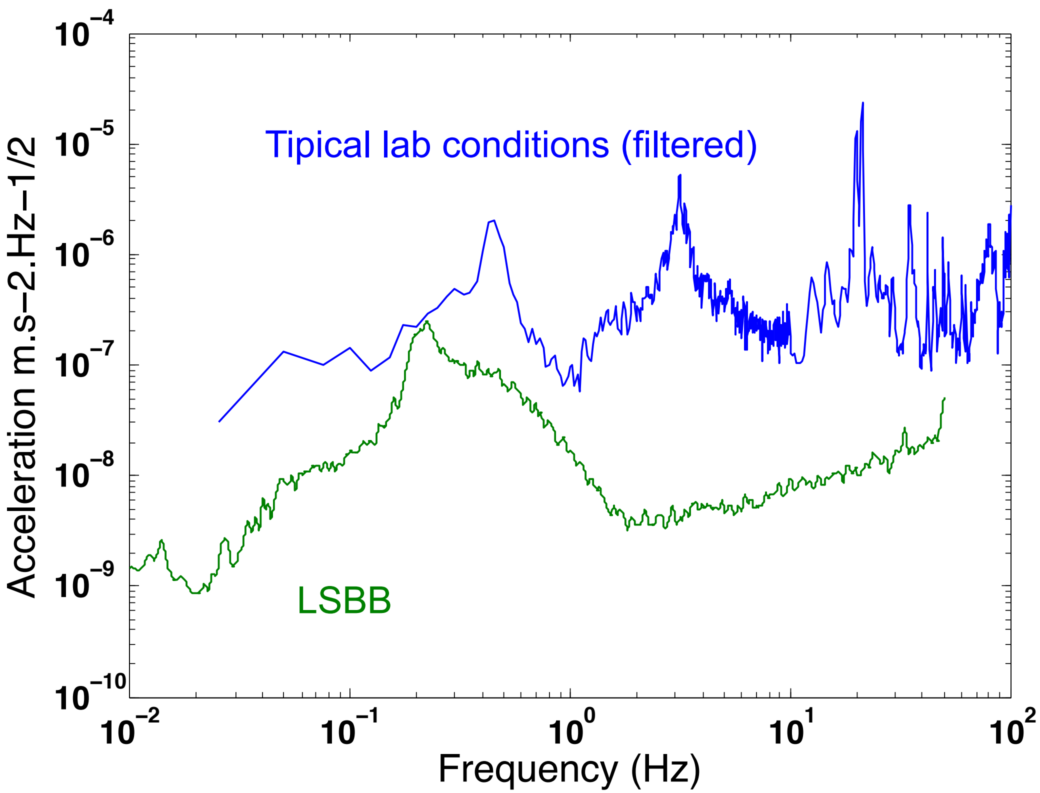






MIGA: Access to gravity gradient & higher orders, long term fluctuations

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:

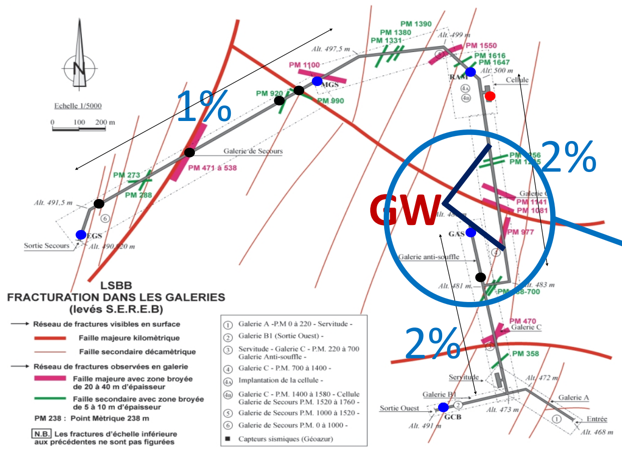
σ_ϕ=640 mrad → σ_ϕ=60 mrad

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

Collaboration with TOTAL to predict escalated site



Core analysis and wall imaging

Geological modeling

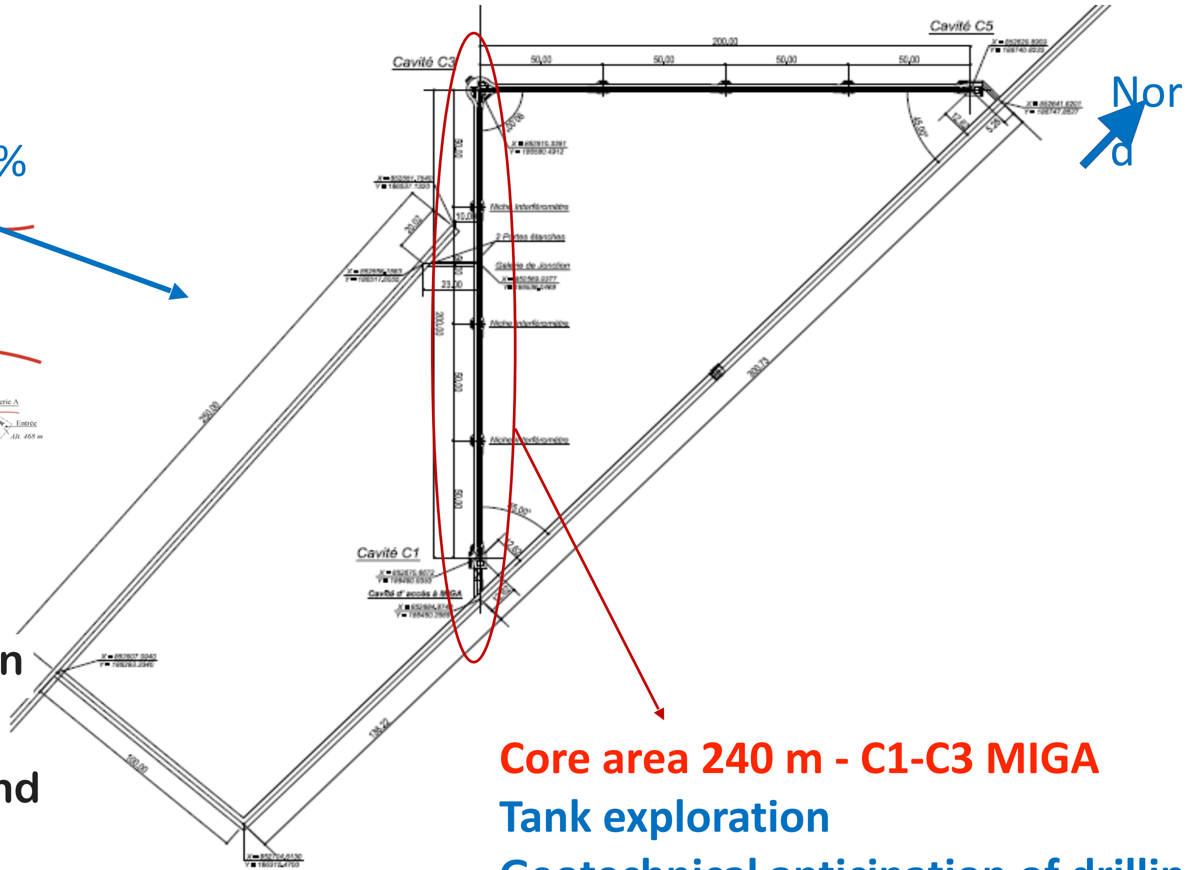
Carbonated reservoir prediction

Environment

hydro-geological analysis around

MIGA

Seismic models



Core area 240 m - C1-C3 MIGA

Tank exploration

Geotechnical anticipation of drilling

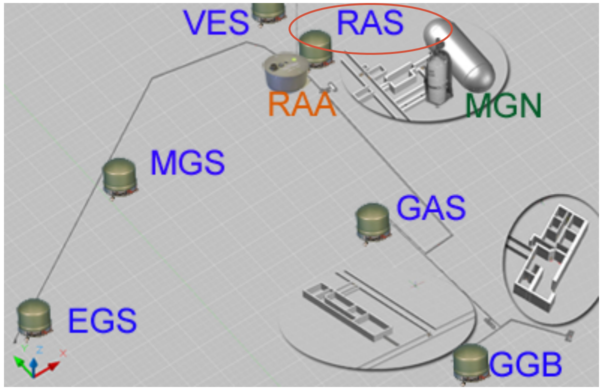
Projection of GGN for MIGA

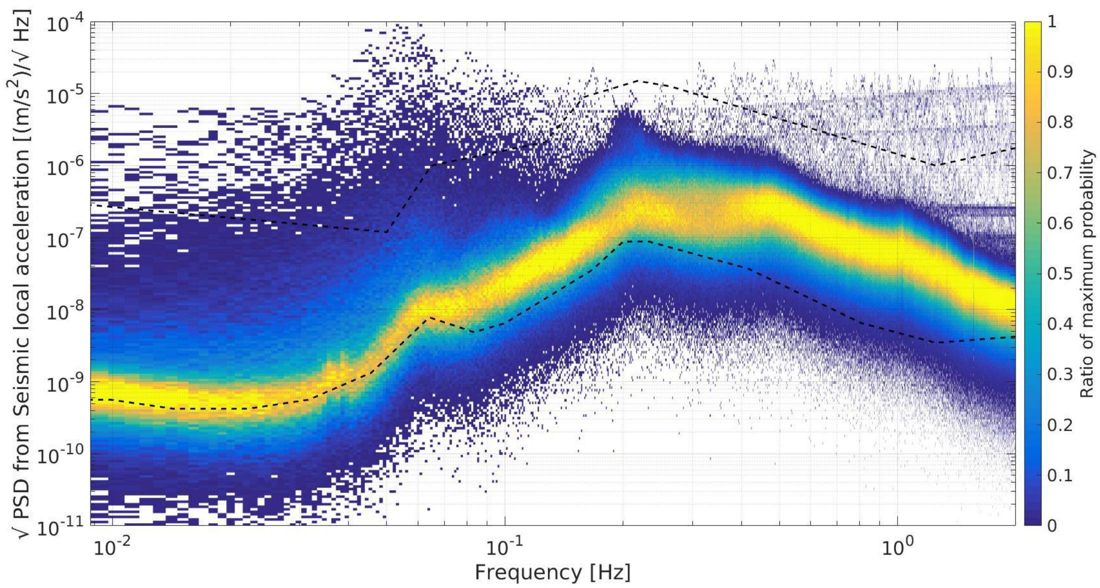
Sources Gravity Gradient noise on detector site **(10^{-2}-10 Hz)**

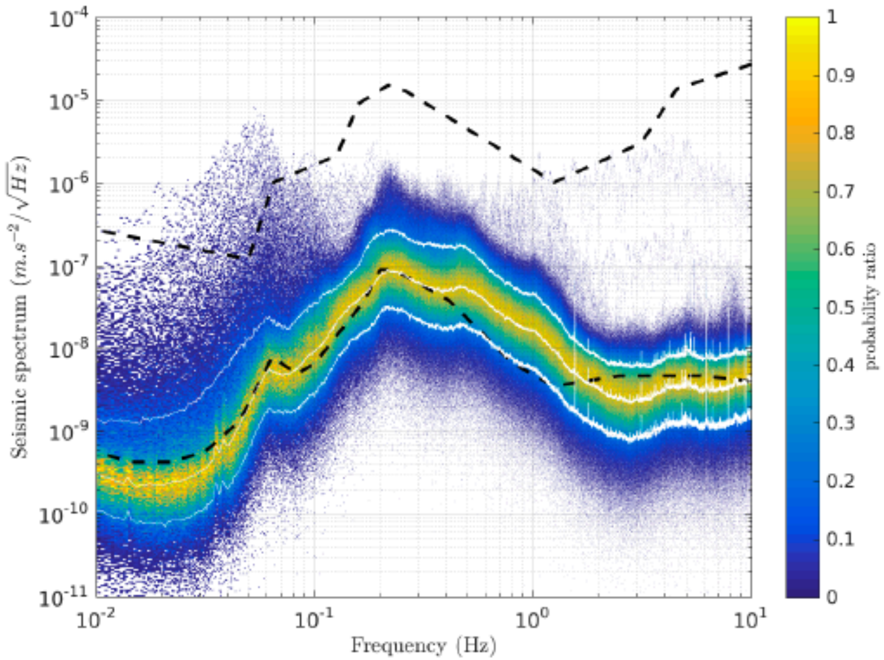
- Seismic GGN
- Atmospheric GGN
- Other : geophysical properties (hydrology), linked to human activity

Seismic GGN for MIGA at LSBB

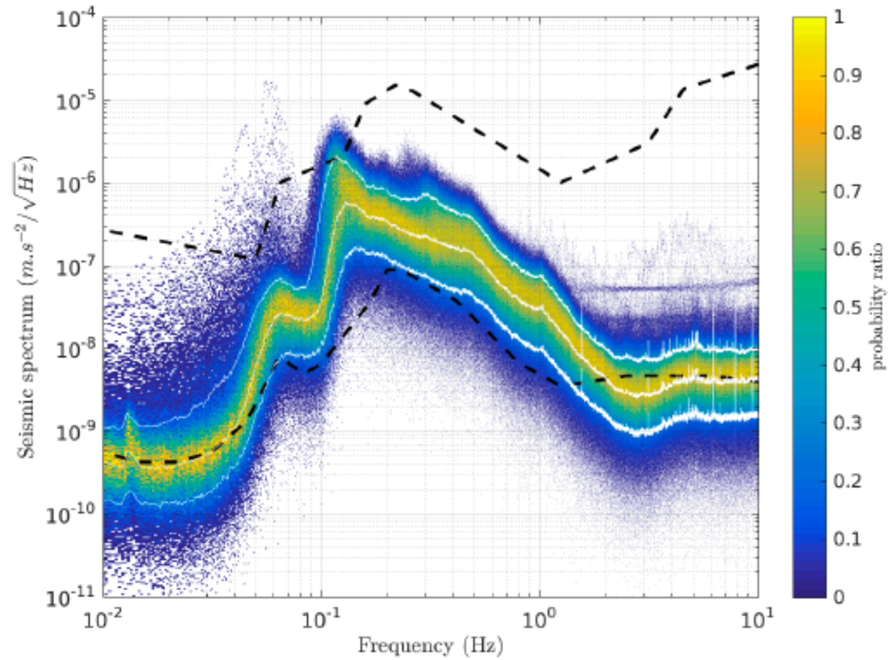
- STS-2 sensor





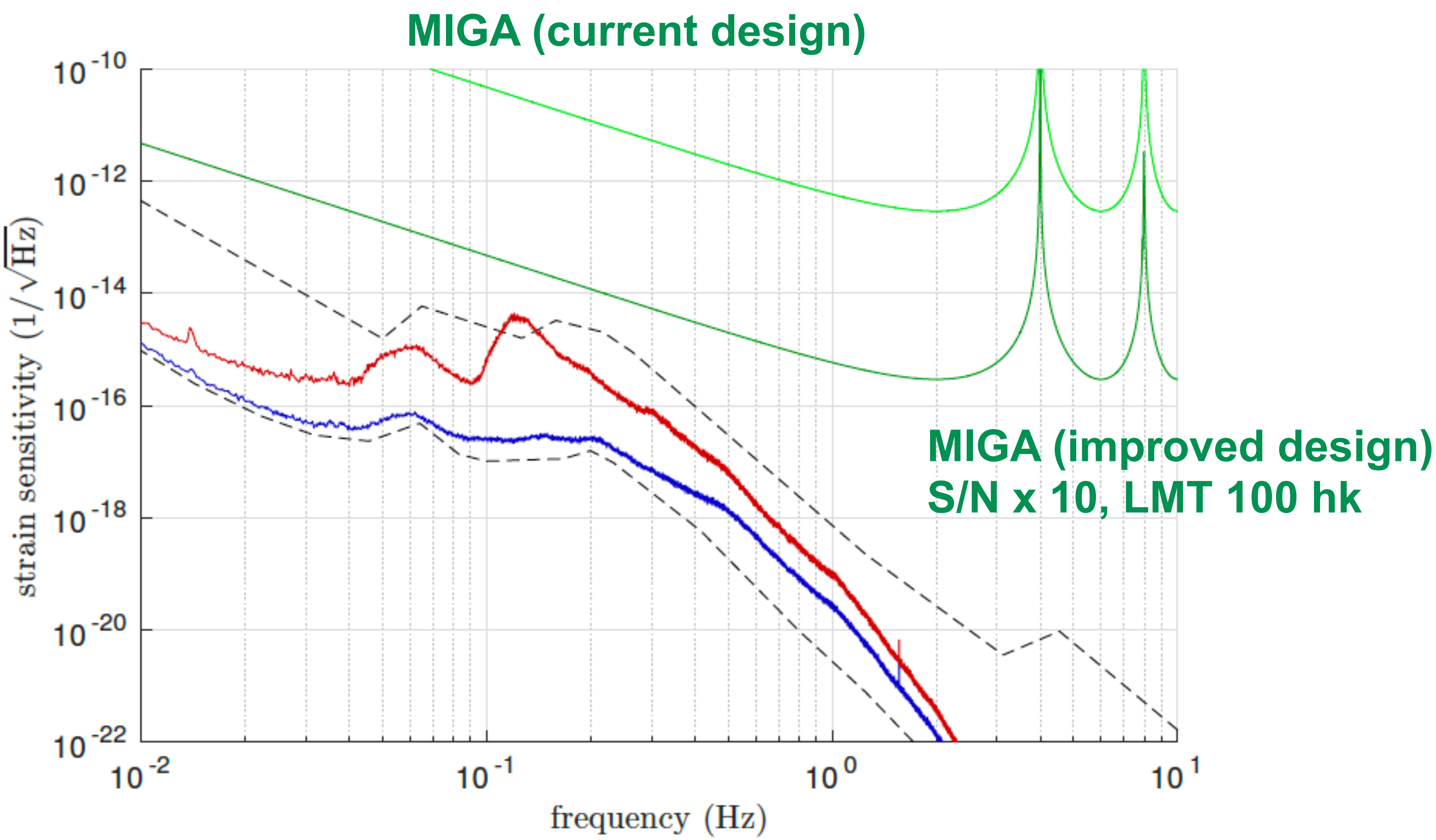


(a) on a "quiet" month (august)



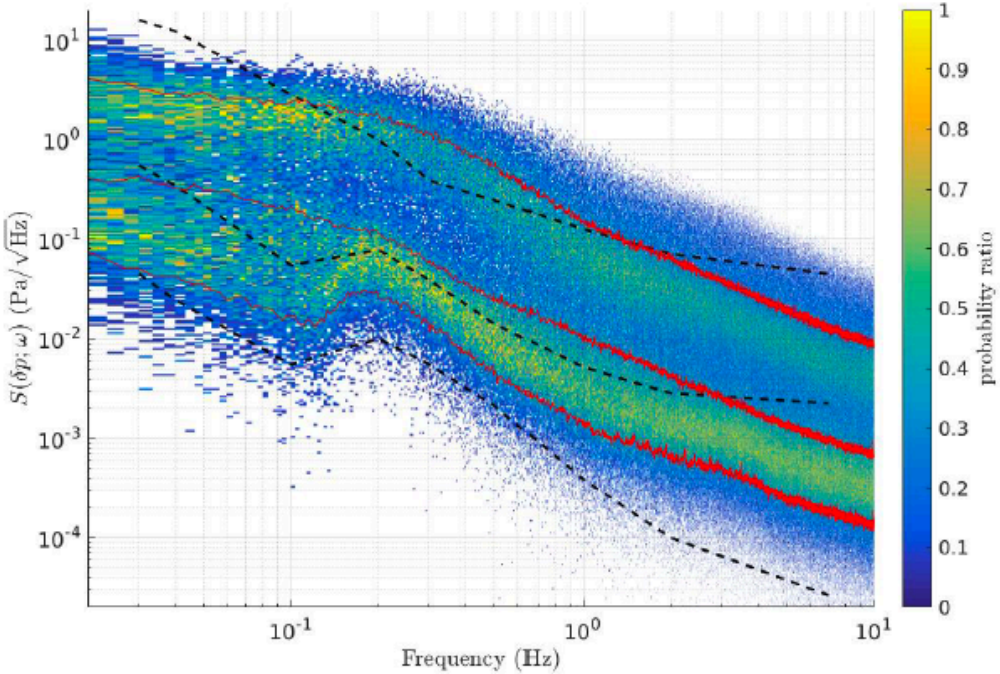
(b) on a "noisy" month (February)

Projection for seismic noise



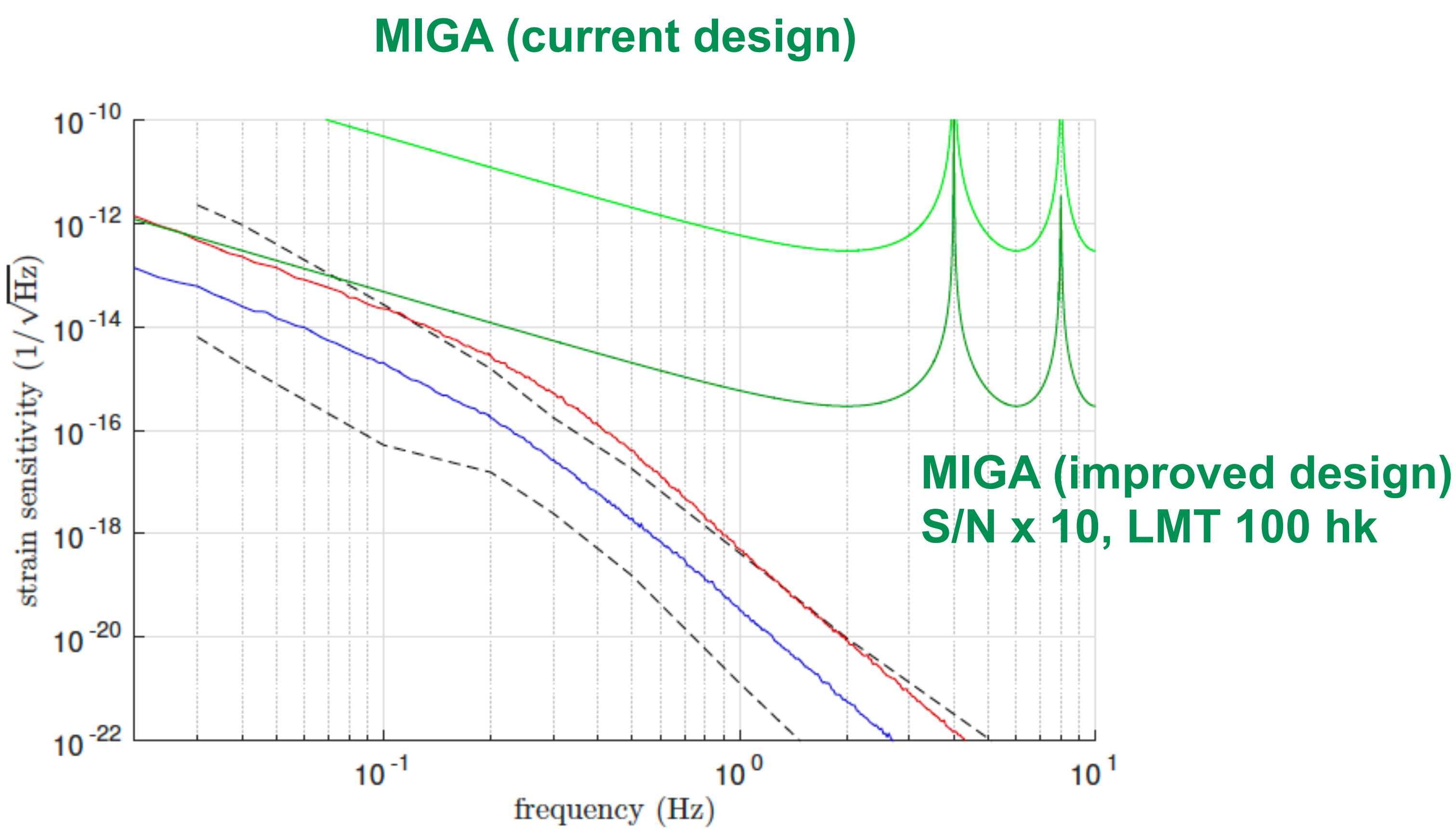
MIGA strain sensitivity. In blue (resp. red) seismic GGN projection from Lsbb 50th percentile of a quiet week (resp. 90th percentile of a noisy week), in dashed black from Peterson model data, in green detection noise for MIGA in its initial configuration (light green) and for an improved version (dark green).

Projection for infrasound noise



Histogram of the outside pressure variations 500 m above the future MIGA gallery with 10th, 50th and 90th percentile in red and Bowman low, mid and high model in dashed black.

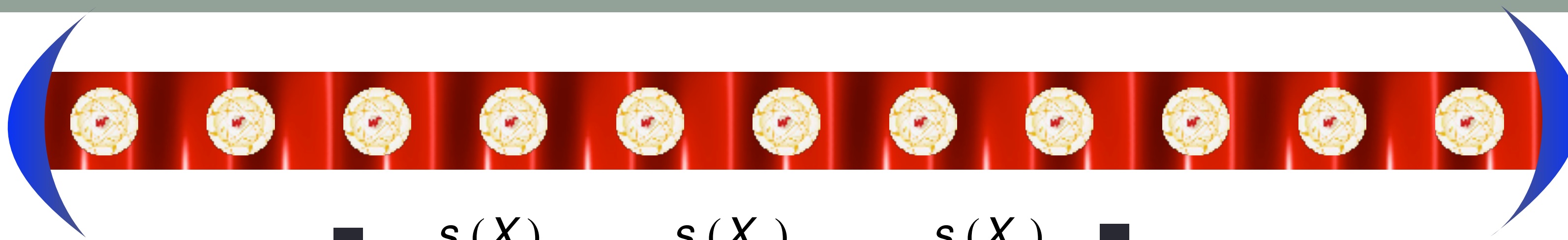
Projection for infrasound noise

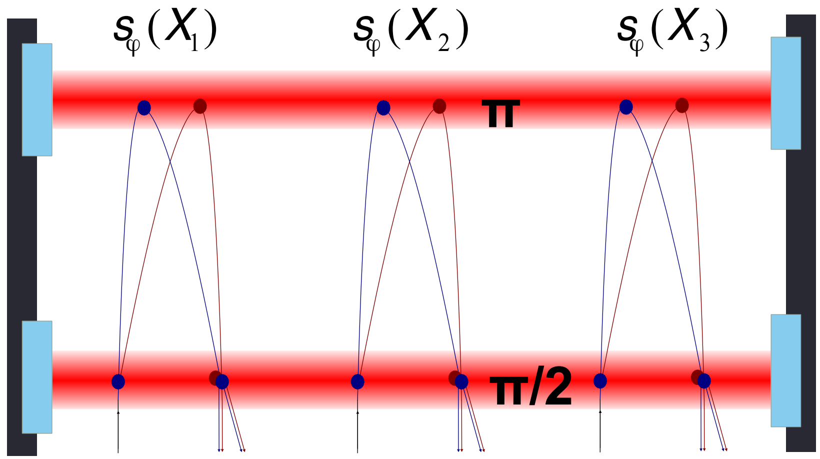


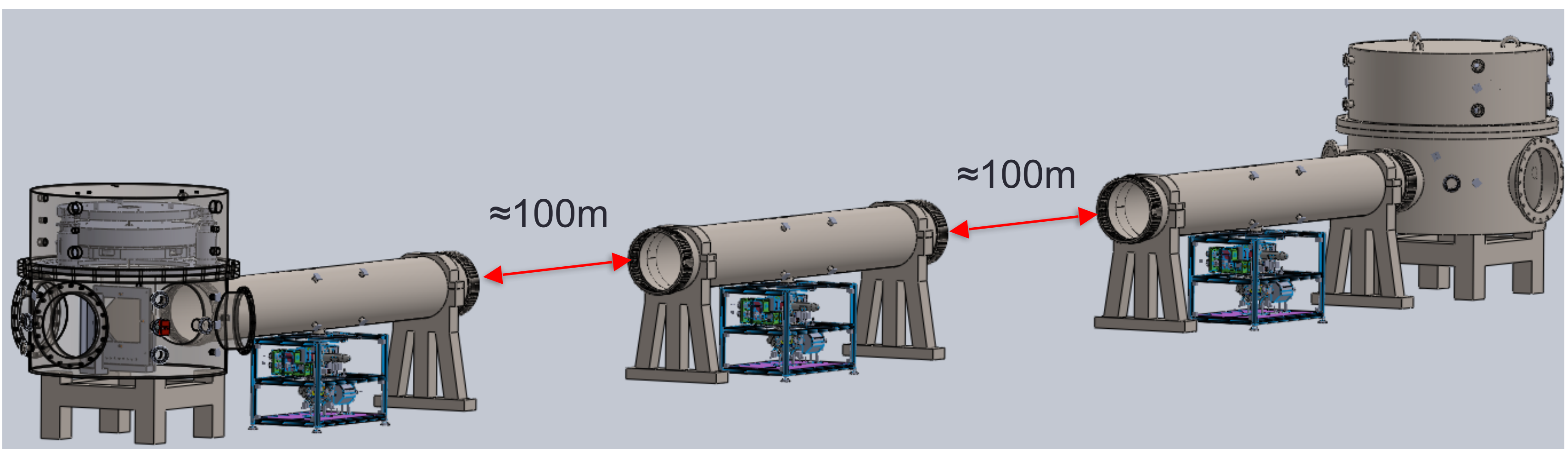
MIGA strain sensitivity for the infrasound GGN, with data from Bowman model (dashed black) and from data gathered on site at the Lsbb (50th percentile in blue and 90th percentile in red).

MIGA status and perspectives

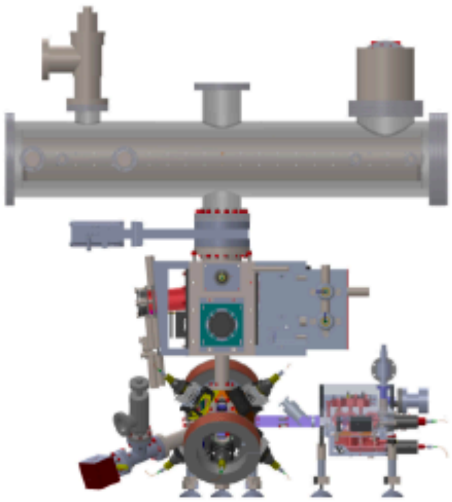
The MIGA antenna



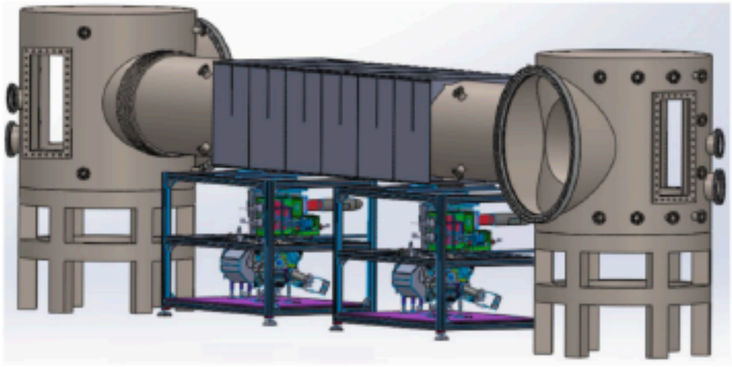




Accelerometer



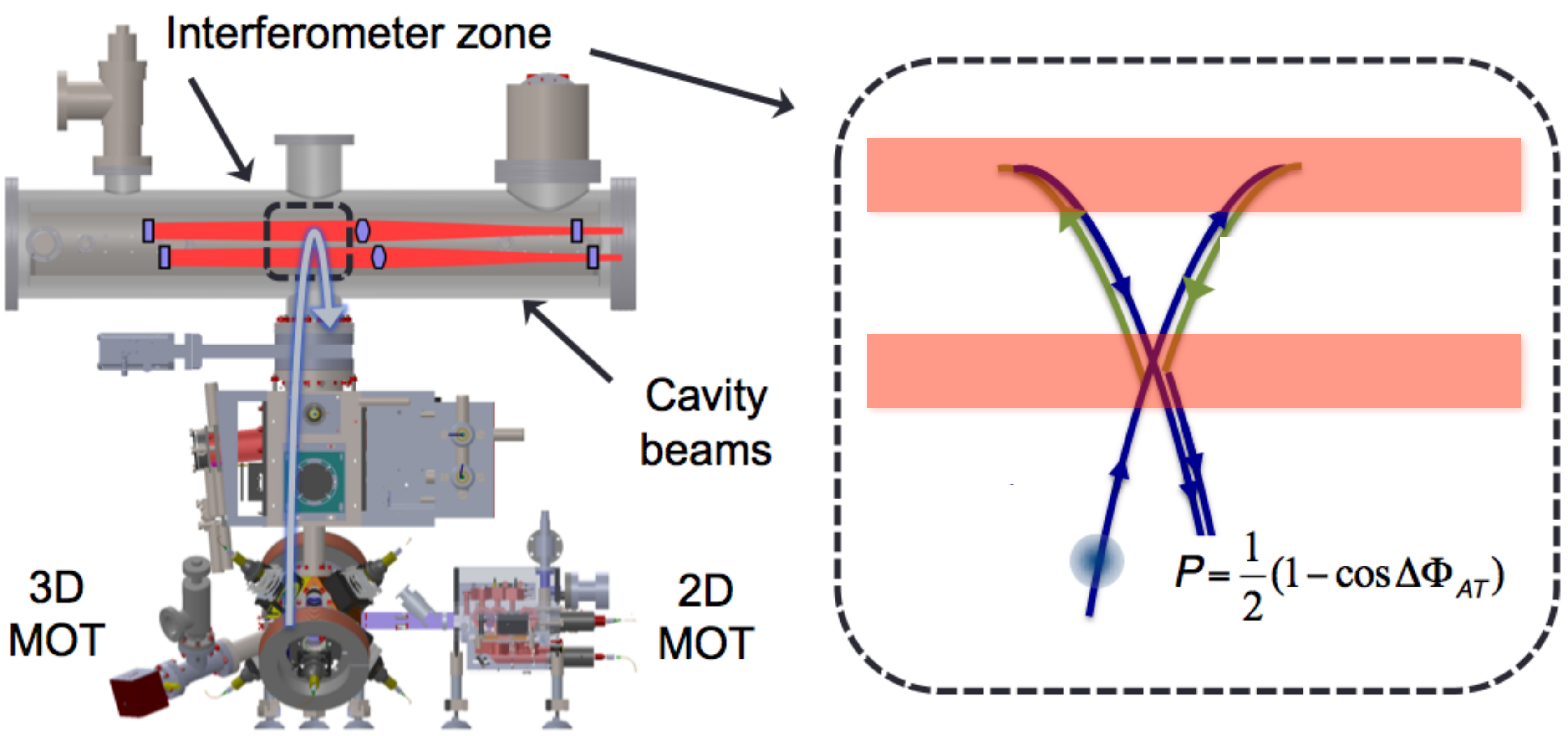
Gradiometer

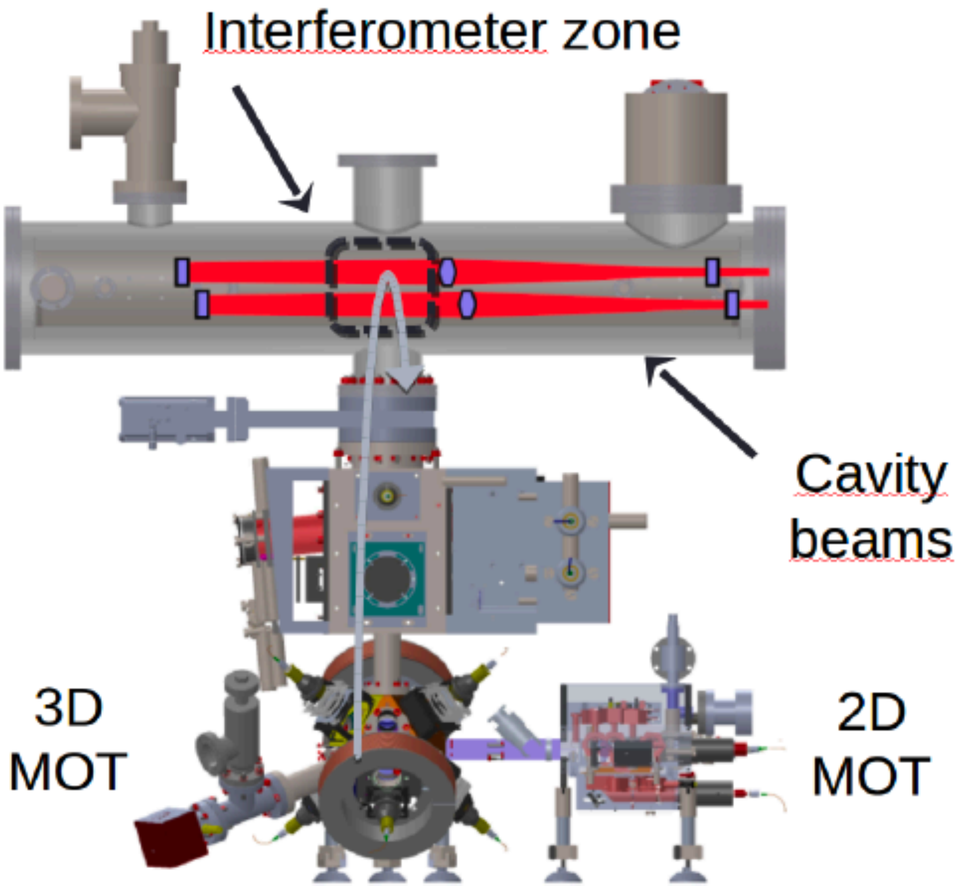


- One cold atom source
- two parallel 80 cm long cavities
- Study cavity enhanced Bragg pulses

- Two cold atoms sources
- Two parallel 5.7 m long cavities
- Study of differential measurements (gradiometer)
- Testing the equipment

Accelerometer set up



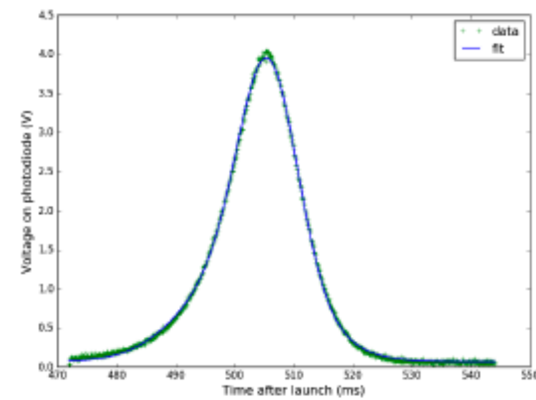


^{87}Rb ~10^{-10} mbar

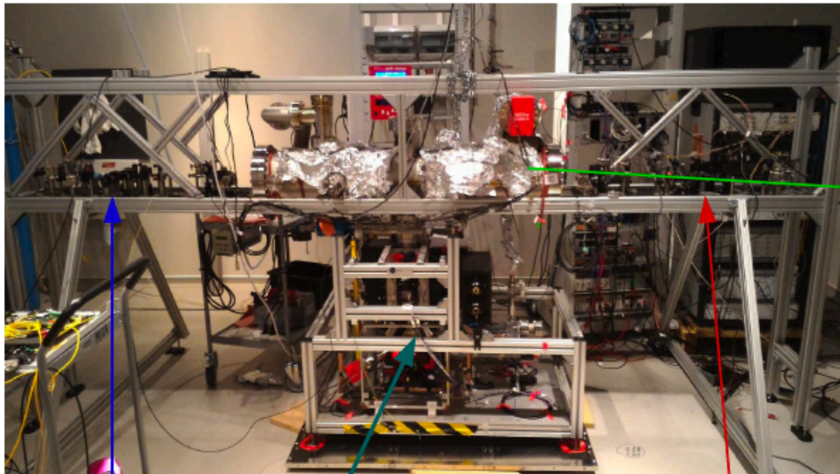
Fountain configuration

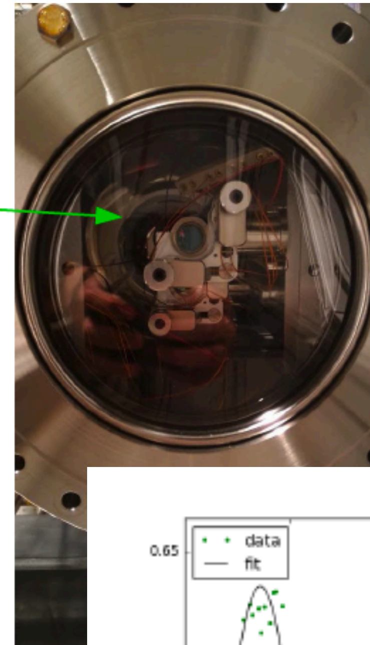
l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace

- Loading a 3D Magneto-optical trap (MOT) with a 2D MOT
- Preparation : velocity an magnetic selection with Raman beams
- Interferometry with intracavity Bragg pulses
- Detection by fluorescence with sheet of lights



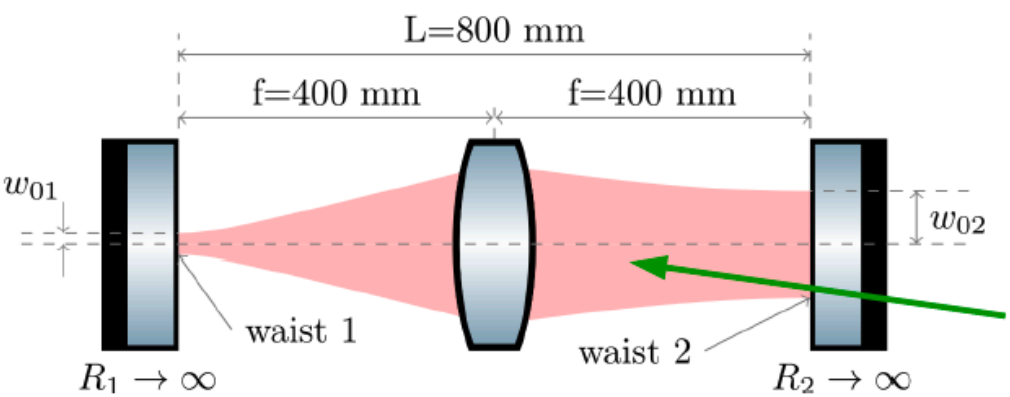
T ~ 4 μK

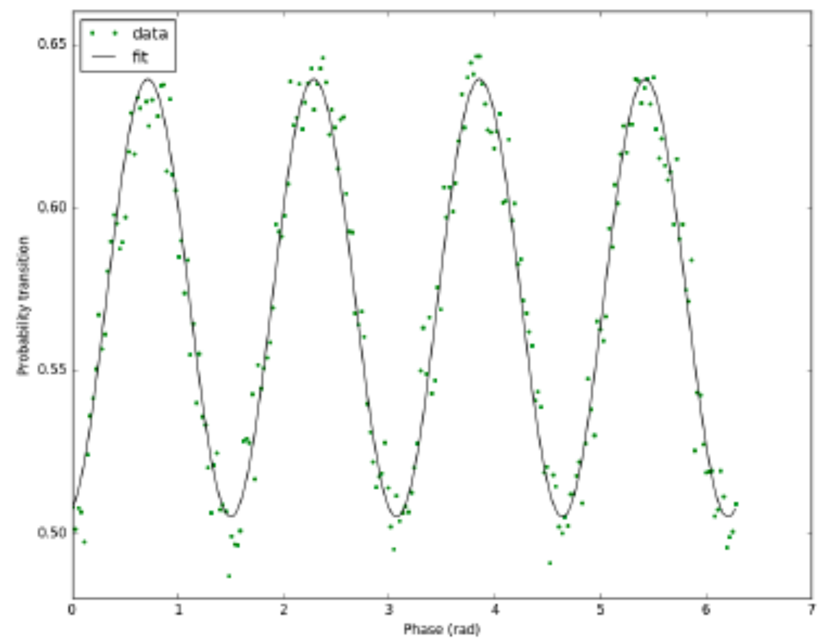




1560 nm injection bench

780 nm injection bench





2012

2013

2014

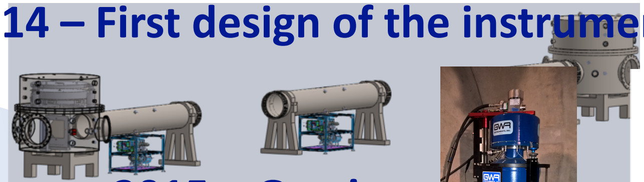
2015

2016

2017

2018

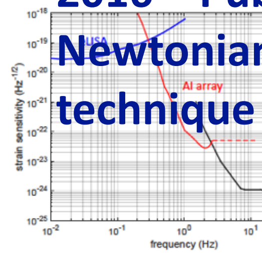
2019



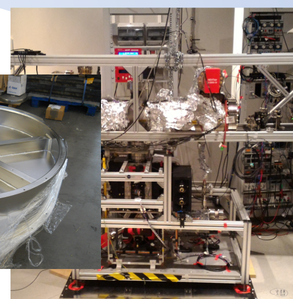
2014 – First design of the instrument

2013 - Project manager hired from VIRGO

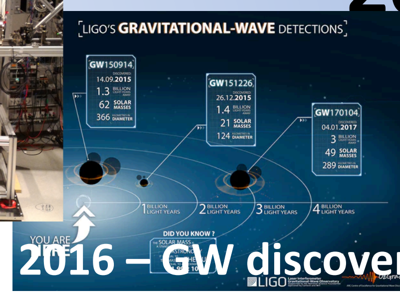
2015 – Gravimeter



2016 – Publication (PRD) of the Newtonian Noise suppression technique



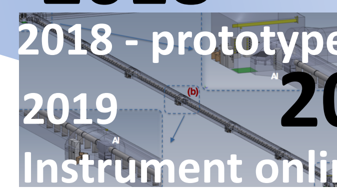
2015 – First suspension and sensor prototype



2016 – GW discover

2017 – Gallery preparations

2017 – 3 sensors ready



2018 - prototype

2019 Instrument onlin

After MIGA : ELGAR

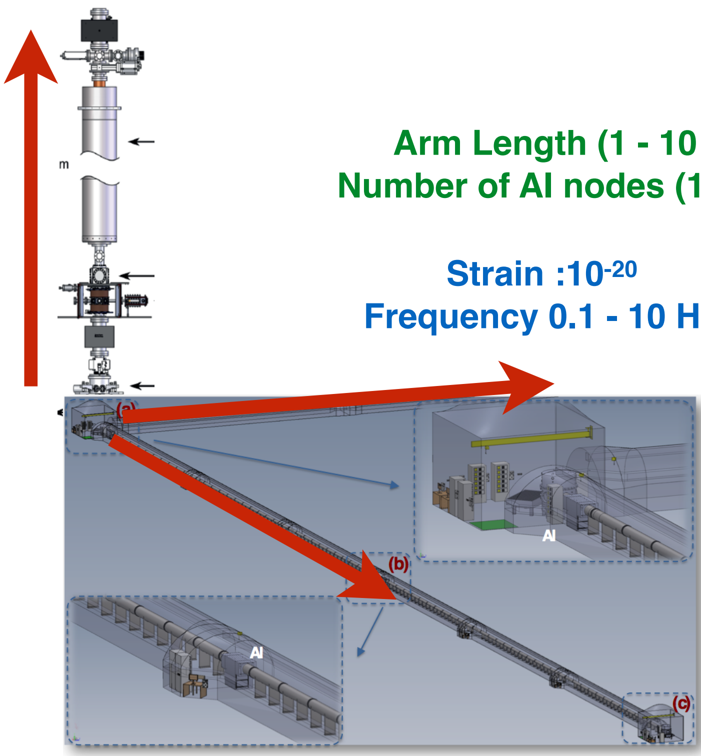
European Laboratory for Gravitation and Atom-interferometric Research (ELGAR)

Sync with other GW observation instruments

3D antenna configuration

Arm Length (1 - 10 km)
Number of AI nodes (10 - 100)

Strain :10^{-20}
Frequency 0.1 - 10 Hz



“full band analysis”, gravitational noise analysis improvement, joint data management and analysis

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