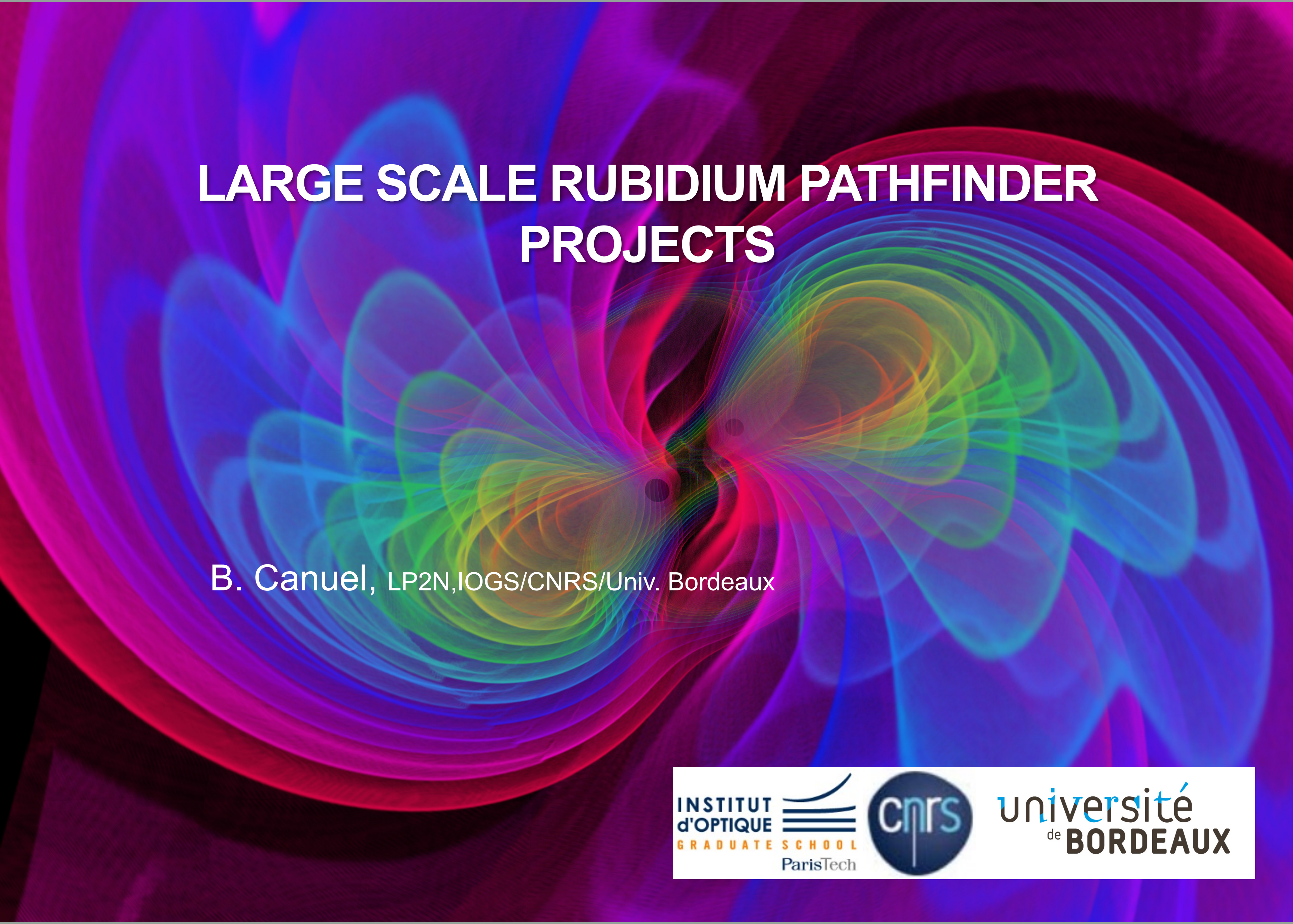


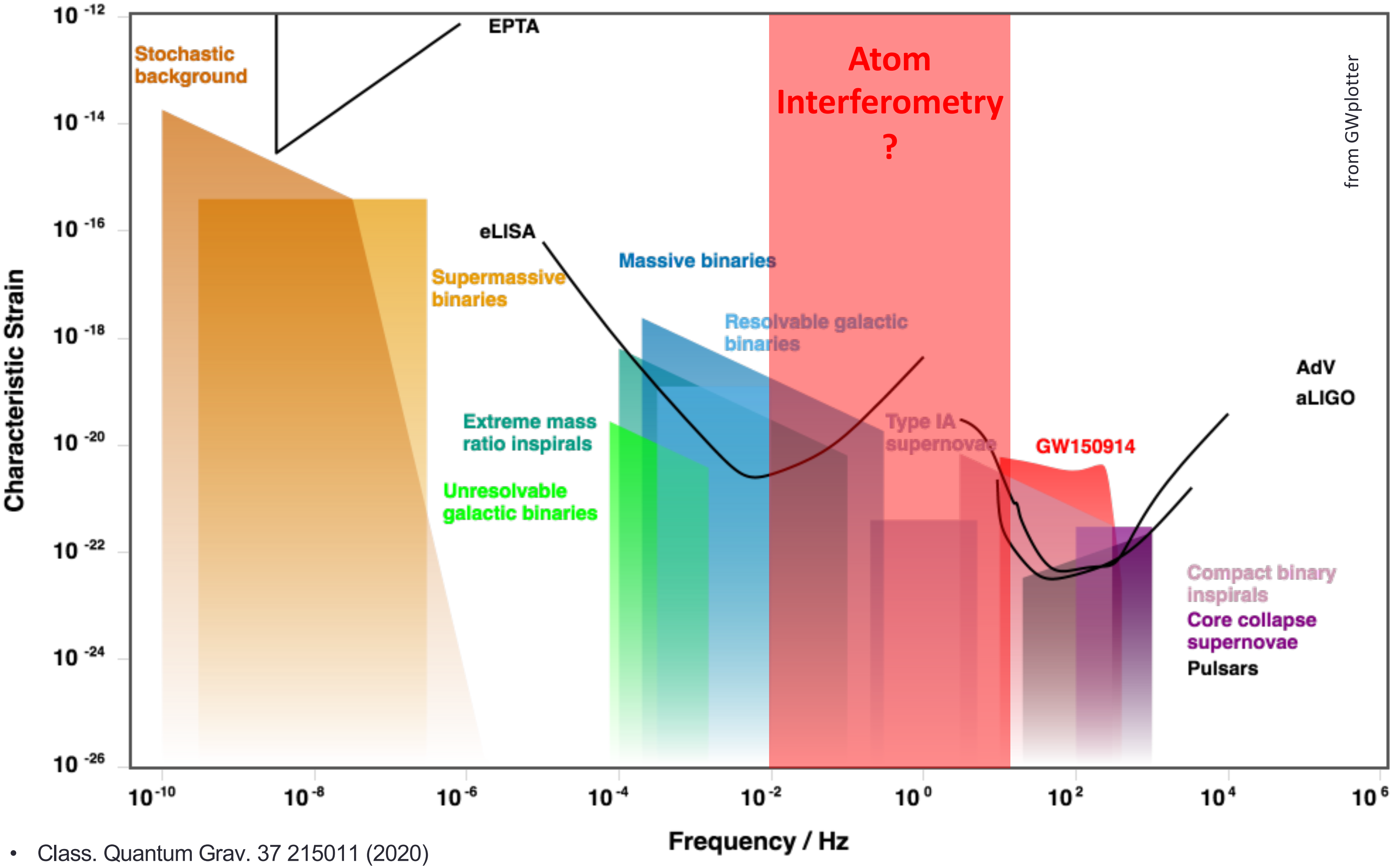
LARGE SCALE RUBIDIUM PATHFINDER PROJECTS

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

Outline

- Low frequency GW detectors with AI
- Large prototypes and initiatives.
    - MIGA
    - ELGAR
    - ZAIGA

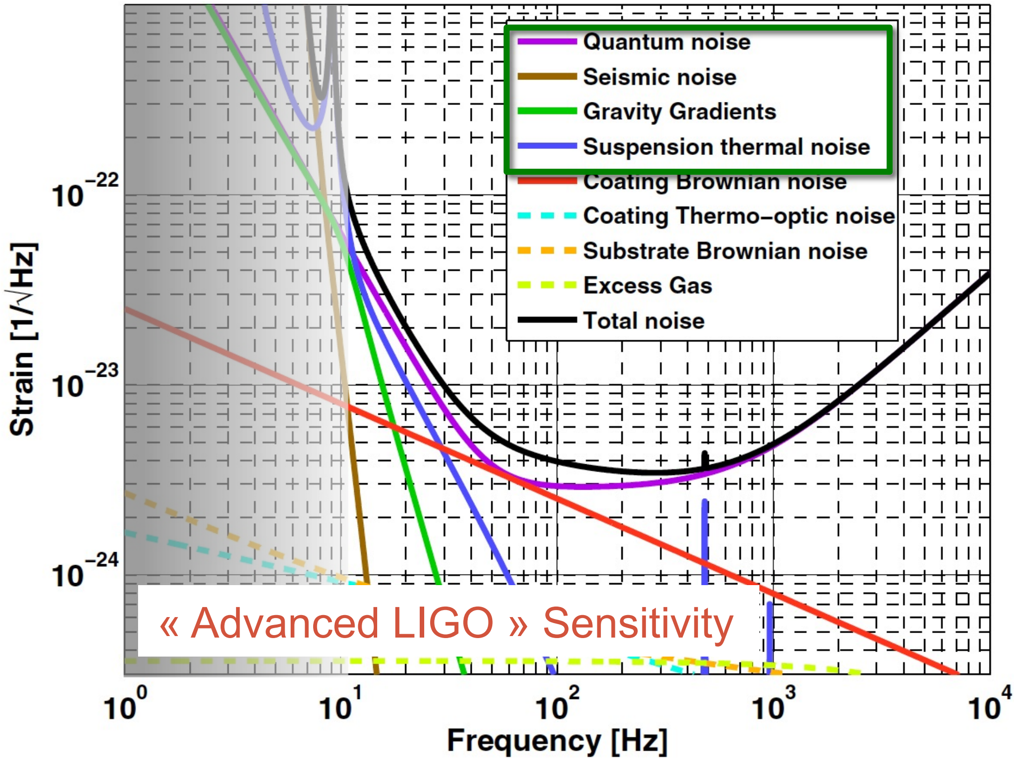
Low frequency GW detectors



- Class. Quantum Grav. 37 215011 (2020)
- Class. Quantum Grav. 35 054004 (2018)
- Phys. Rev.Lett. 116, 231102 (2016)
- Phys. Rev. D, 88 122003 (2013)

New results in GW astronomy : precision gravity and cosmology tests, new possibility of multi-messenger astronomy, observation of heavier binary systems, ...

How to extend the frequency band of state-of-the-art GW detectors?



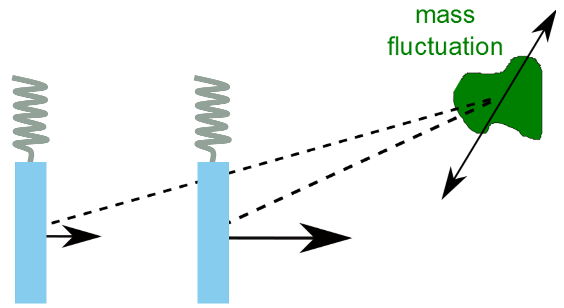
« Advanced LIGO » Sensitivity

Limitations for f<10 Hz:

- Residual seismic noise
- « Gravity gradient » noise

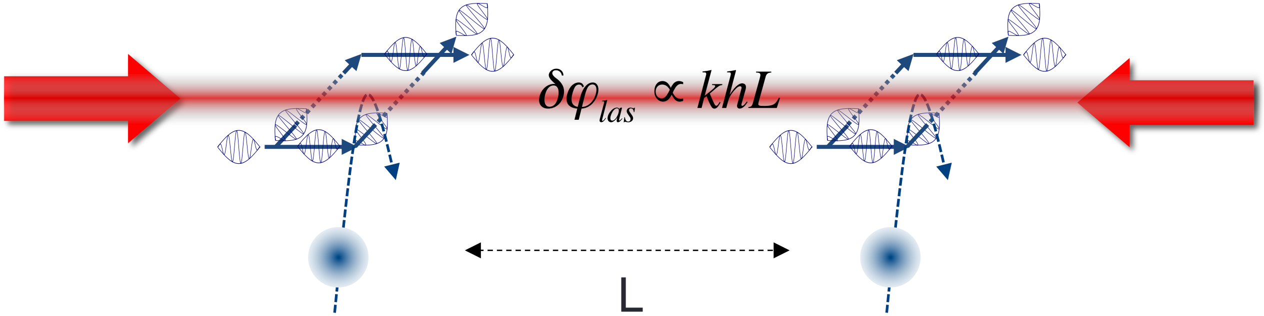
« Gravity Gradient » noise

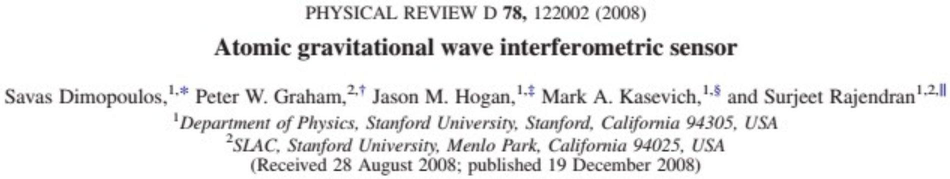
Fluctuations of the Earth gravity field



Cold atoms for GW detection ?

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




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

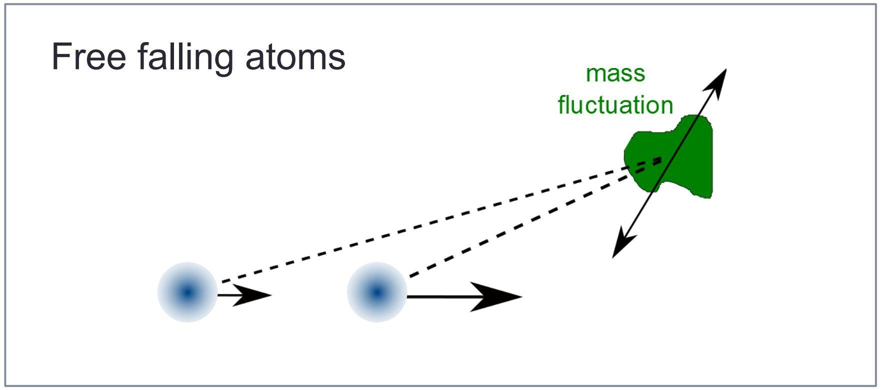
Atomic gravitational wave interferometric sensor

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)

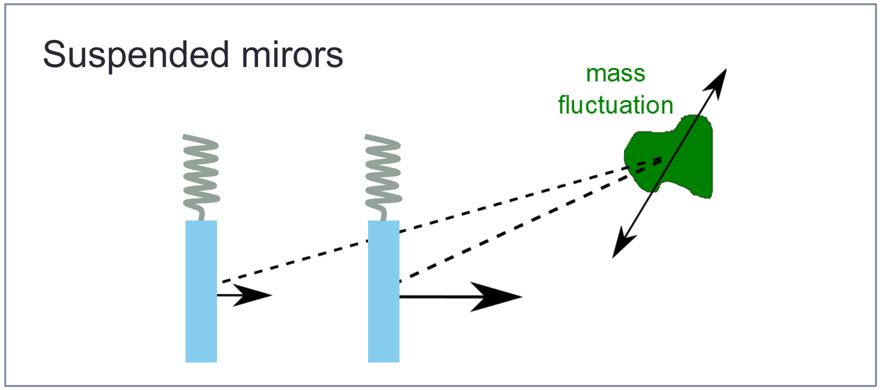
Strong immunity to seismic noise

Sensitivity to Gravity Gradient Noise is the same !

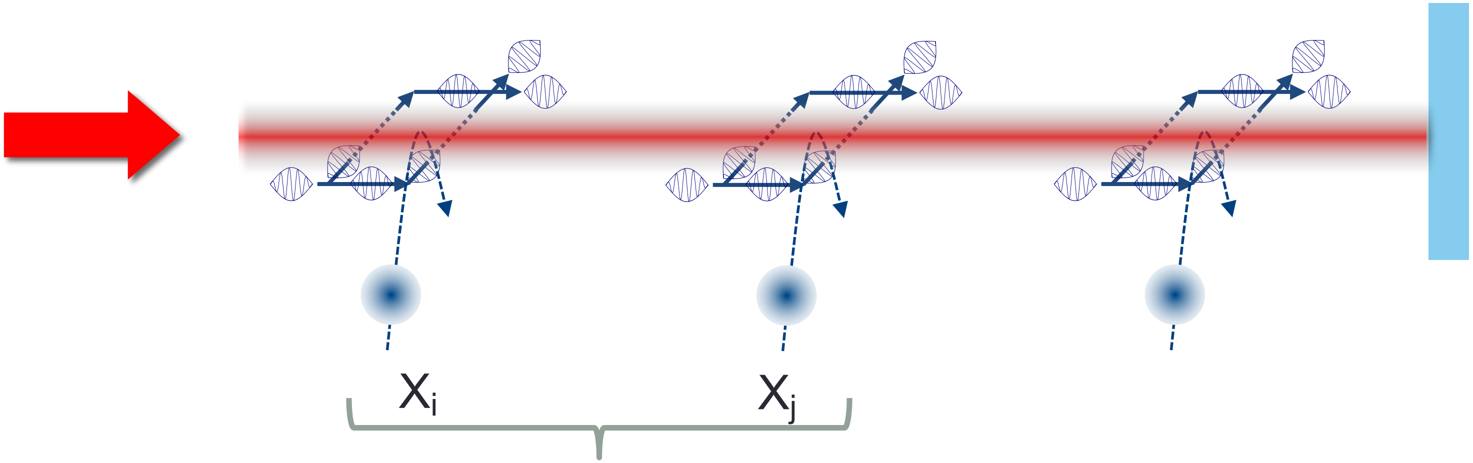
Free falling atoms



Suspended mirors



Networks of AI sensors for GGN reduction



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

- 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

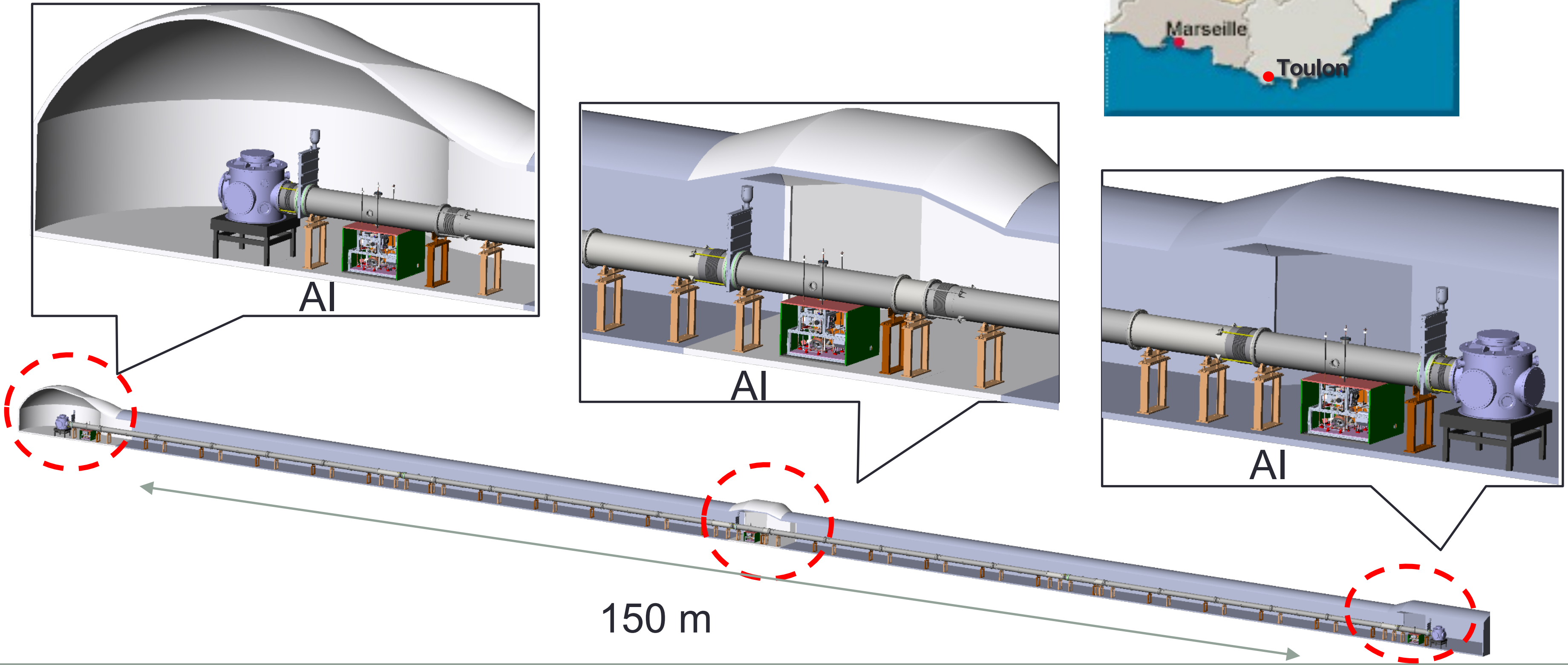
- Low frequency (10^{-2}-10 Hz) GW detection limited by detection noise

Large prototypes and initiatives

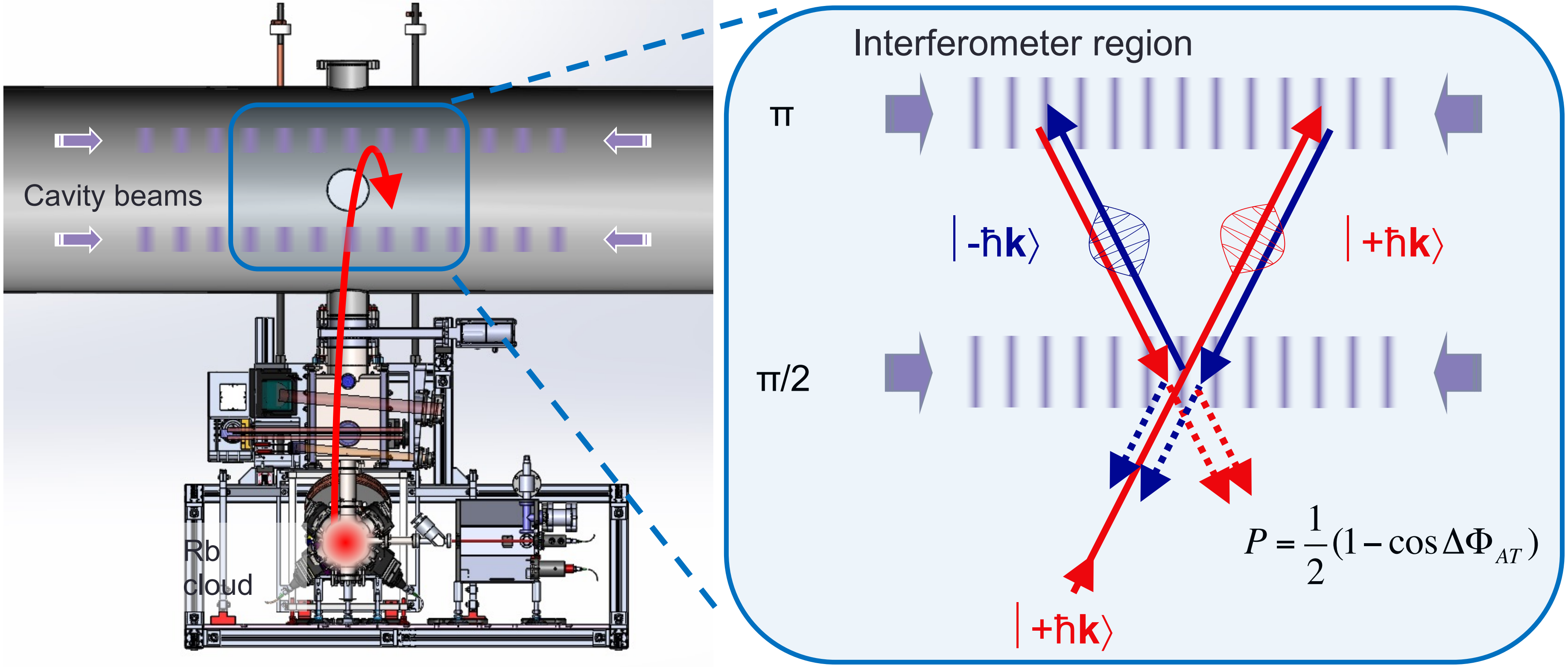
The MIGA Instrument

- A French research program carried out by 15 partners and institute
- An array of Rb AI installed in a low noise underground laboratory (LSBB)

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



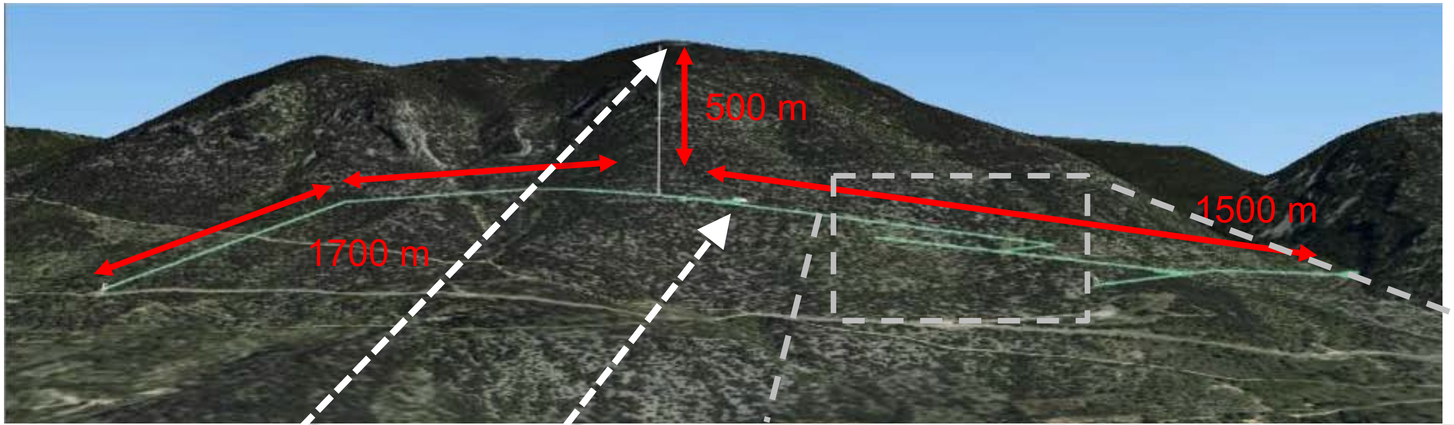
Functioning of a MIGA Atom Interferometer



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

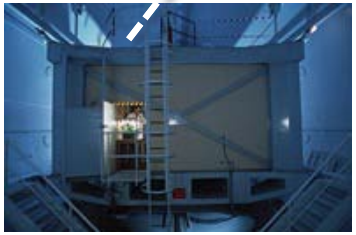
- Rb atom source uses a combination of a 2D and 3D magneto-optic traps.
- After cooling, trapping, the atoms are launched on a parabolic trajectory
- Manipulation using Bragg diffraction on a set of two horizontal cavity beams.

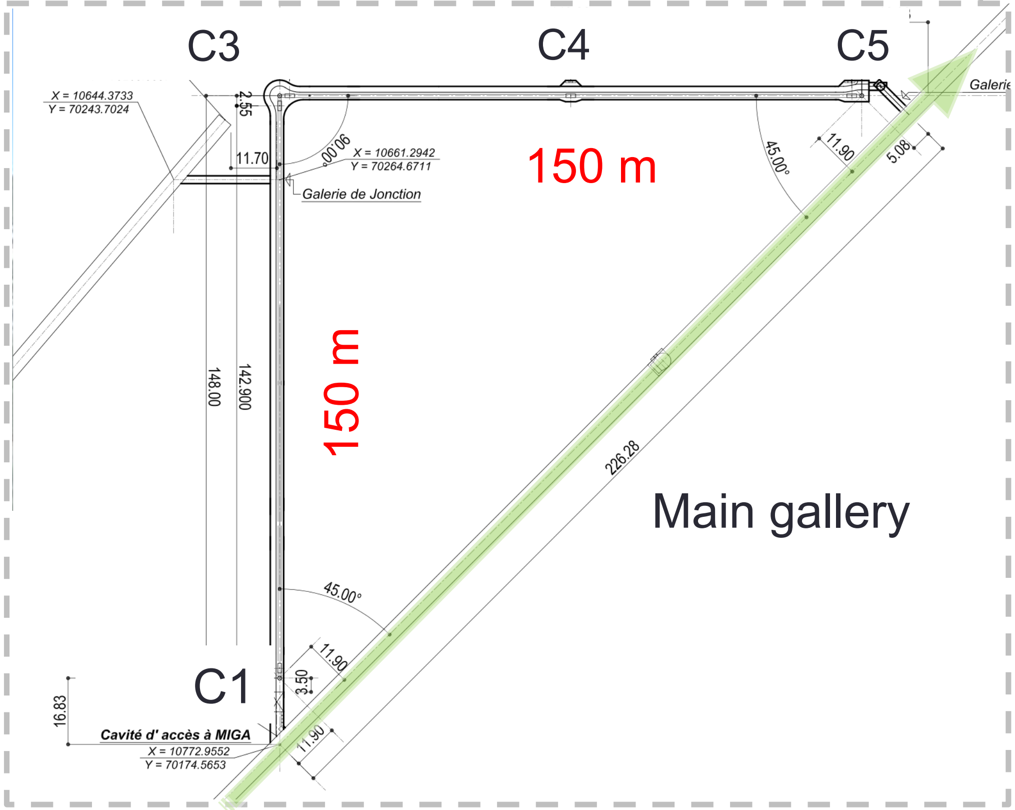
MIGA infrastructure



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

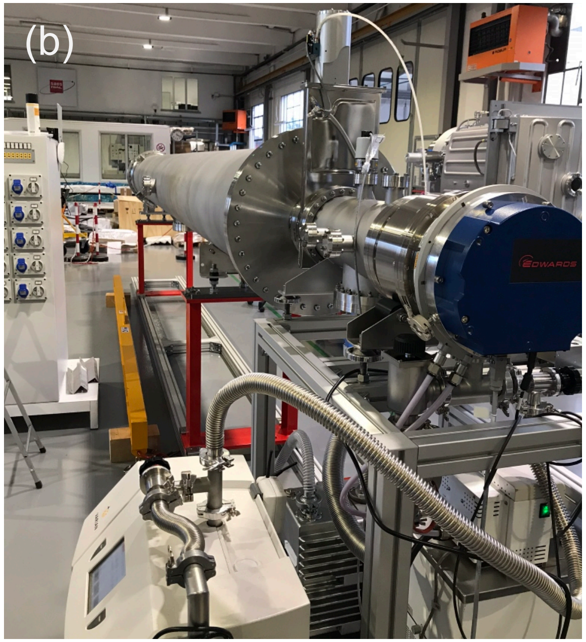
- A dismissed military facility
- Former command centre for nuclear force

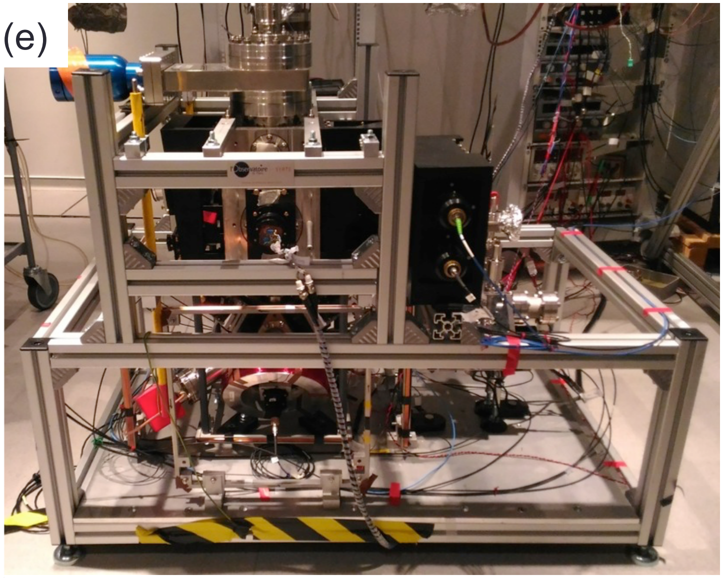




- Two new perpendicular galleries of 150m dedicated to MIGA

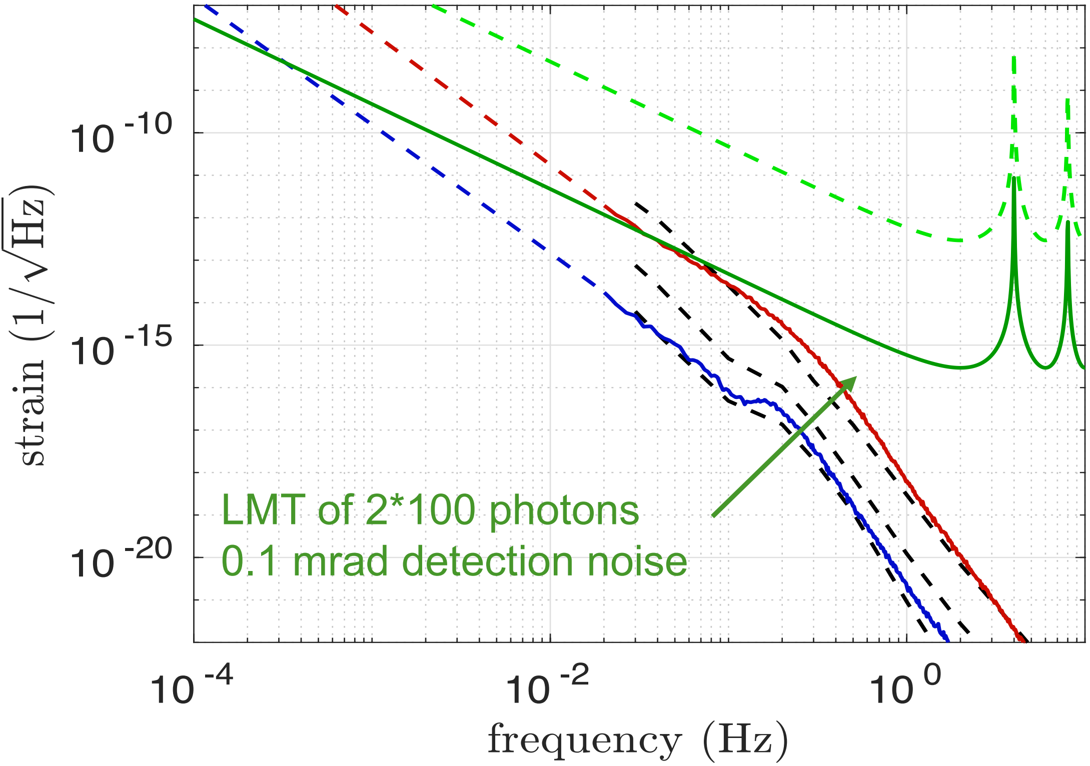
The MIGA Instrument





MIGA Status and prospects

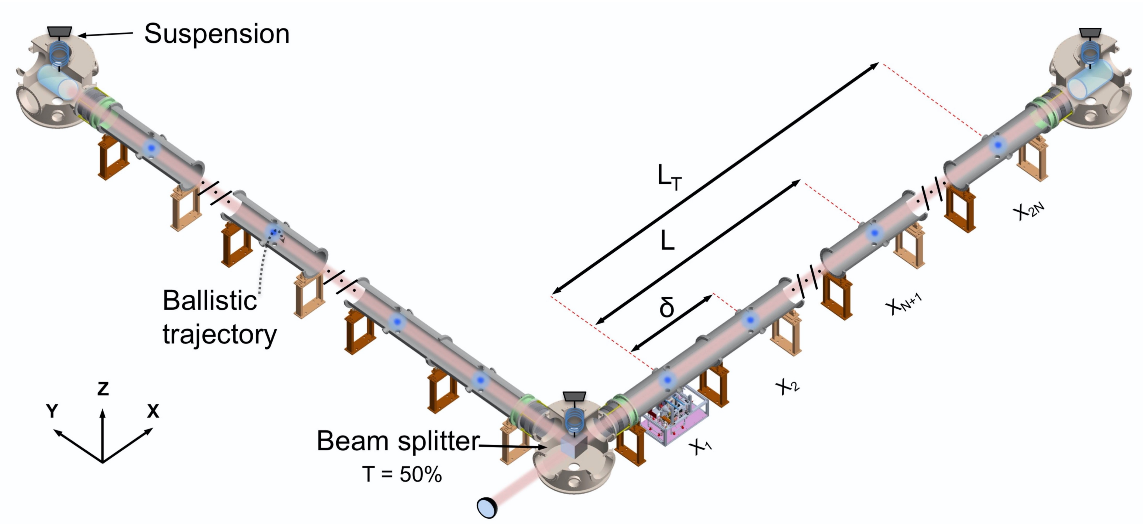
- Vacuum system being assembled
- Planning to connect the atom heads beginning of 2022



- Initial strain sensitivity 2.10^{-13} at 2 Hz.
- Study advanced measurement strategies & atom manipulation techniques
- Fill the sensitivity gap for GW detection
- Advanced studies of GGN

ELGAR - a European Laboratory for Gravitation and Atom-interferometric Research

- Build an underground infrastructure based on large scale AI, to study space-time and gravitation with the primary goal of detecting **GWs in the infrasound band** (0.1 Hz-10 Hz).
- Opens multi-band GW astronomy: new sources, precision gravity/cosmology tests….
- ELGAR initiative is sustained since 2014 by an active research group that now gathers about 60 scientists from more than 20 labs over 6 EU countries.
- Relies on large national initiatives for quantum technologies: MIGA (FR), VLBAI (GER), MAGIA (IT), UK National Quantum Technology Hub.

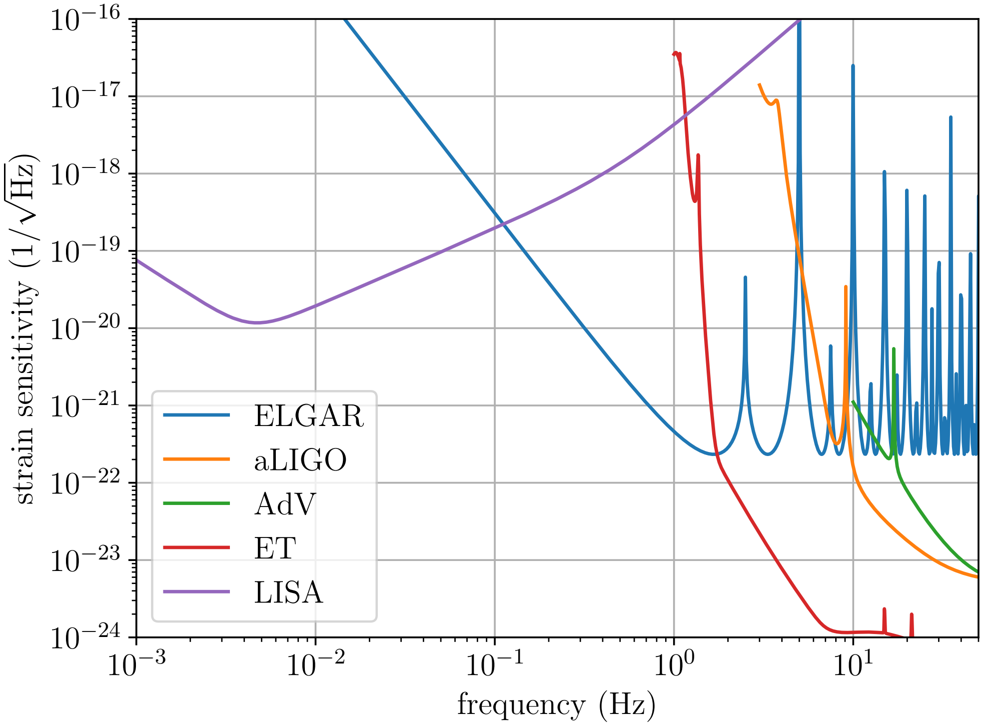


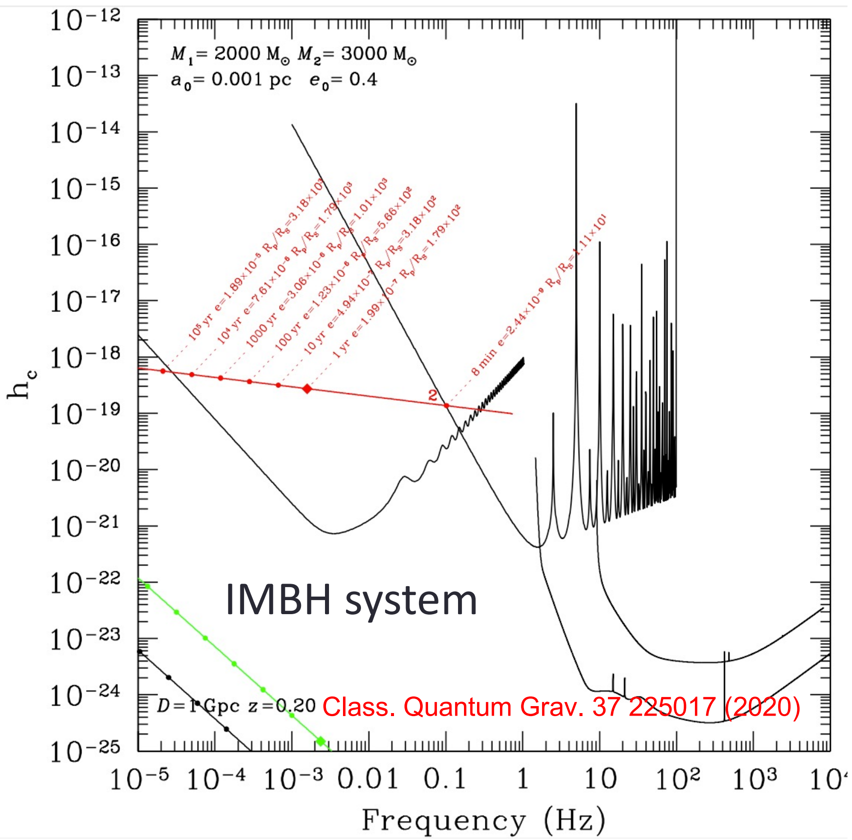
Based on array of Atom gradiometers that reduces the contribution of Gravity Gradient Noise

Atomic source	
Species	^{87}Rb
Loading source	2D+ MOT
Equivalent atomic flux[a]	$1 \times 10^{12}\,\mathrm{s}^{-1}$
Ensemble type	ultracold source
Expansion velocity ($T_{\mathrm{eff}} \approx 100$ pK)	$100\,\mu\mathrm{m\,s}^{-1}$
Vertical launching velocity	$4\,\mathrm{m\,s}^{-1}$
Cloud size[b]	16 mm
Detector	
Single gradiometer	
Configuration	Double loop, four pulses
Interrogation time	$4T = 800$ ms
Atom optics	Sequential Bragg
Momentum transfer	$2n = 1000\ \hbar k$
Baseline	$L = 16.3$ km
Peak strain sensitivity (at 1.7 Hz)	$4.1 \times 10^{-21}\,\mathrm{Hz}^{-1/2}$
Full detector	
Number of gradiometers per arm	$N = 80$
Gradiometer separation	$\delta = 200$ m
Total baseline	$L_T = 32.1$ km
Peak strain sensitivity (at 1.7 Hz)	$3.3 \times 10^{-22}\,\mathrm{Hz}^{-1/2}$

ELGAR

ELGAR sensitivity





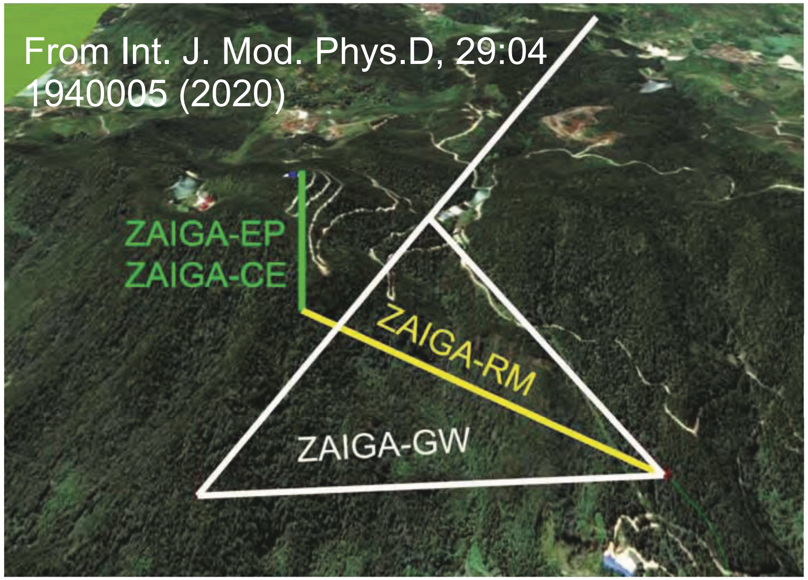
IMBH system

Class. Quantum Grav. 37 225017 (2020)

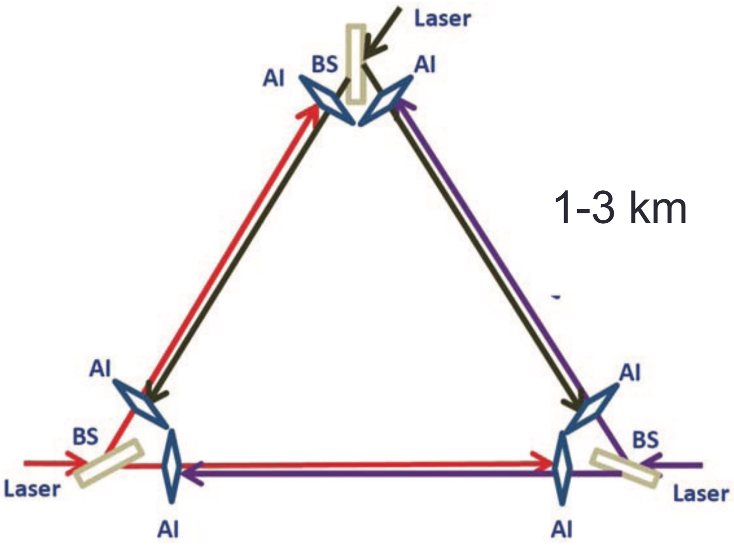
- Proposed as ”design study” for H2020-INFRADEV-2017-1 & INFRADEV-01-2019-2020
- Support from ANR in 2018
- Preliminary design: Class. Quantum Grav. 37 225017 (2020)
- Future : subsystems design: ArXiv:2007.04014 [physics.atom-ph] (2020), roadmap ?, DS or IA call ?

ZAIGA -Zhaoshan long-baseline Atom Interferometer Gravitation Antenna

- Large-scale infrastructure based on laser ranging techniques and cold atom sensors for multiple purposes:
  - Mid-band GW detection using atom interferometry
  - Test the equivalence principle
  - Measurement of the gravitational redshift using optical clocks
  - Improved tests of general relativity using a long baseline atom gyroscope

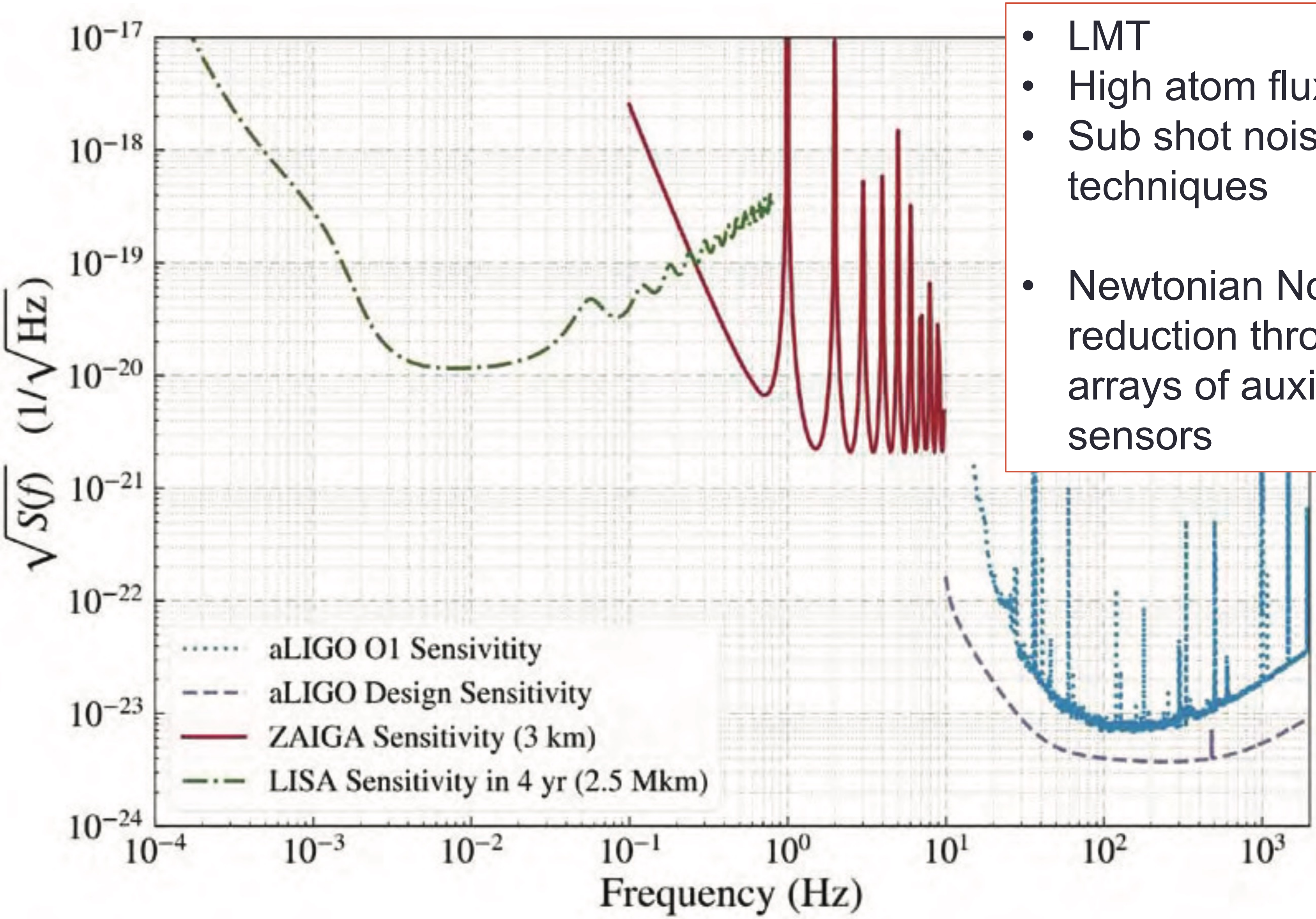

From Int. J. Mod. Phys.D, 29:04 1940005 (2020)

ZAIGA facility below the Zhaoshan mountain, 80 km south-east of Wuhan (China)



ZAIGA-GW instrument

ZAIGA GW sensitivity



- LMT
- High atom flux
- Sub shot noise techniques

- Newtonian Noise reduction through arrays of auxiliary sensors

From Int. J. Mod. Phys.D, 29:04 1940005 (2020)

Conclusion

- Large scale pathfinder projects EU and international scale for precision measurements with AI.
- Strong large national initiatives for future advanced quantum sensors.
- Build future observatories for the study of space-time and gravitation.
  - Primary goals: GWs / scalar DM.
  - Secondary goals: General relativity, Geophysics …