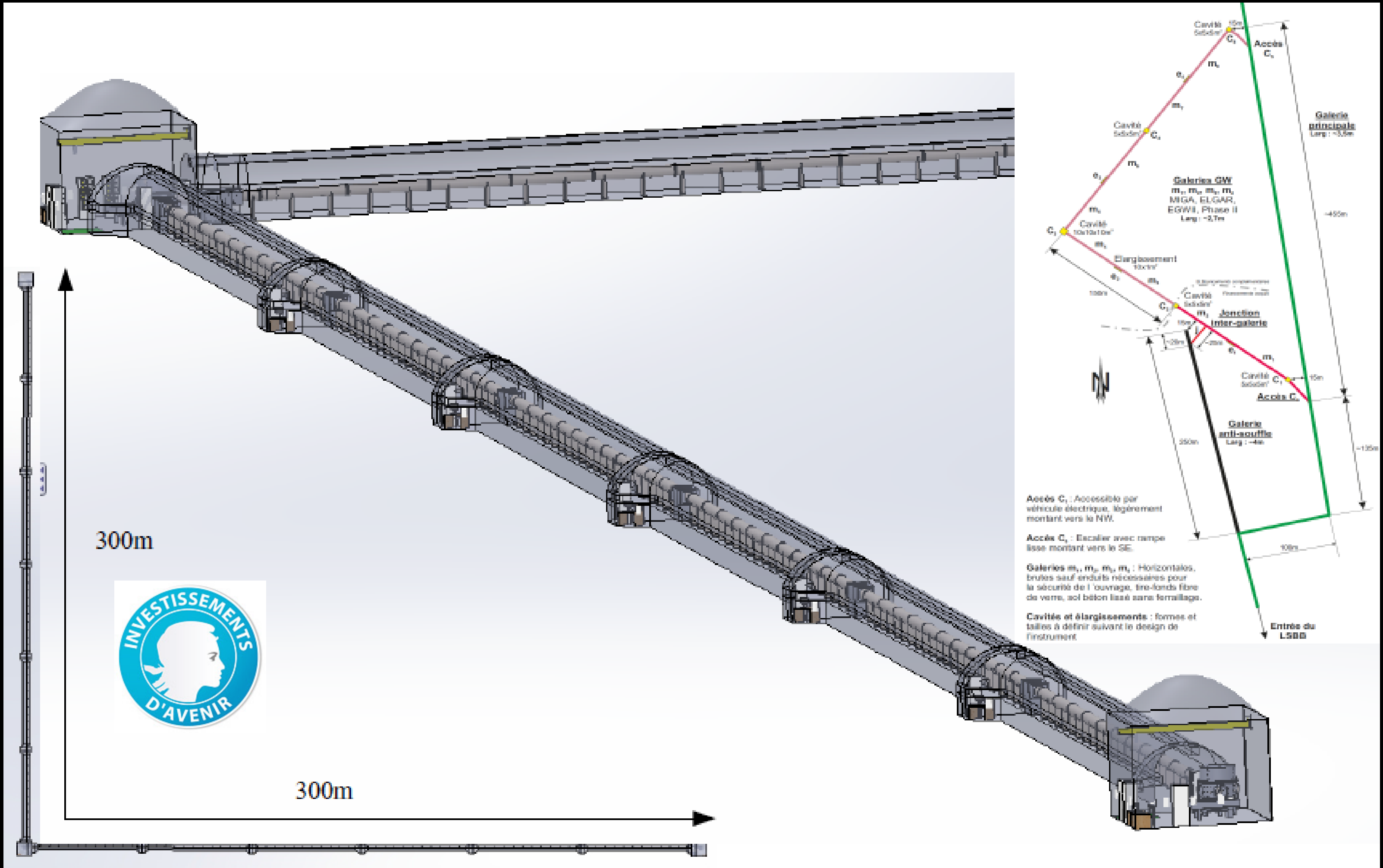
The MIGA atom interferometry gravitational antenna for infrasound GW detection

A. Bertoldi — LP2N, IOGS, CNRS (Bordeaux)
for the MIGA consortium



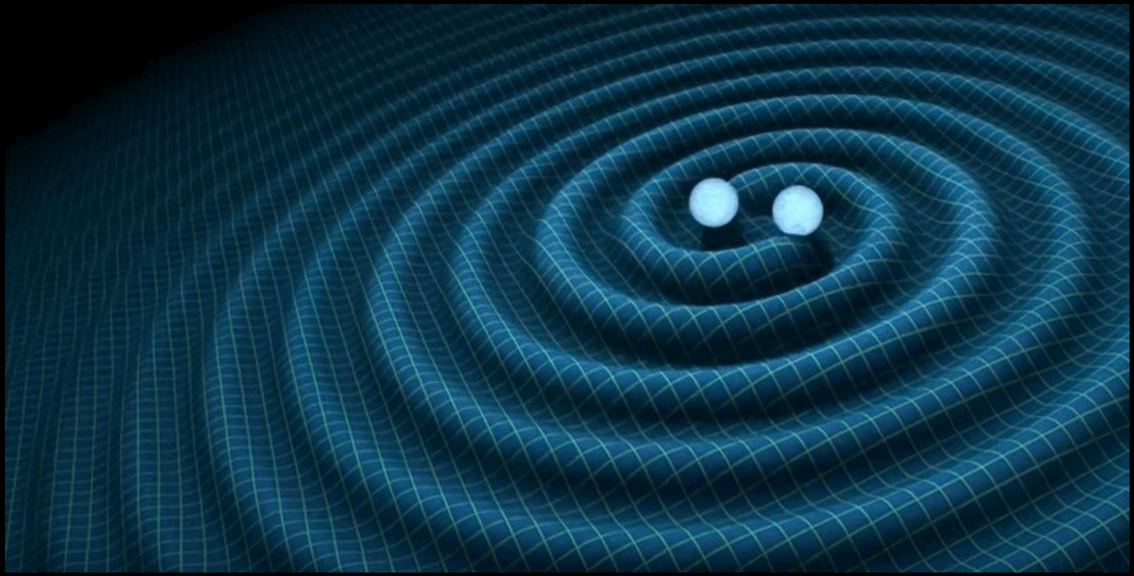
Accès C_1 : Accessible par véhicule électrique, légèrement montant vers le NW.

Accès C_5 : Escalier avec rampe lisse montant vers le SE.

Galeries m_1, m_2, m_3, m_4 : Horizontales, brutes sauf enduits nécessaires pour la sécurité de l'ouvrage, fine-fonds fibre de verre, sol béton lissé sans ferraillage.

Cavités et élargissements : formes et tailles à définir suivant le design de l'instrument

GW detection with Atom Interferometry



- cold neutral atoms in free fall are ideal probes on geodetics (identical, no calibration required, massive)
- AI tool to measure geodetics
- Feasible single baseline measurement
- Can discriminate GGN and GW

Outline

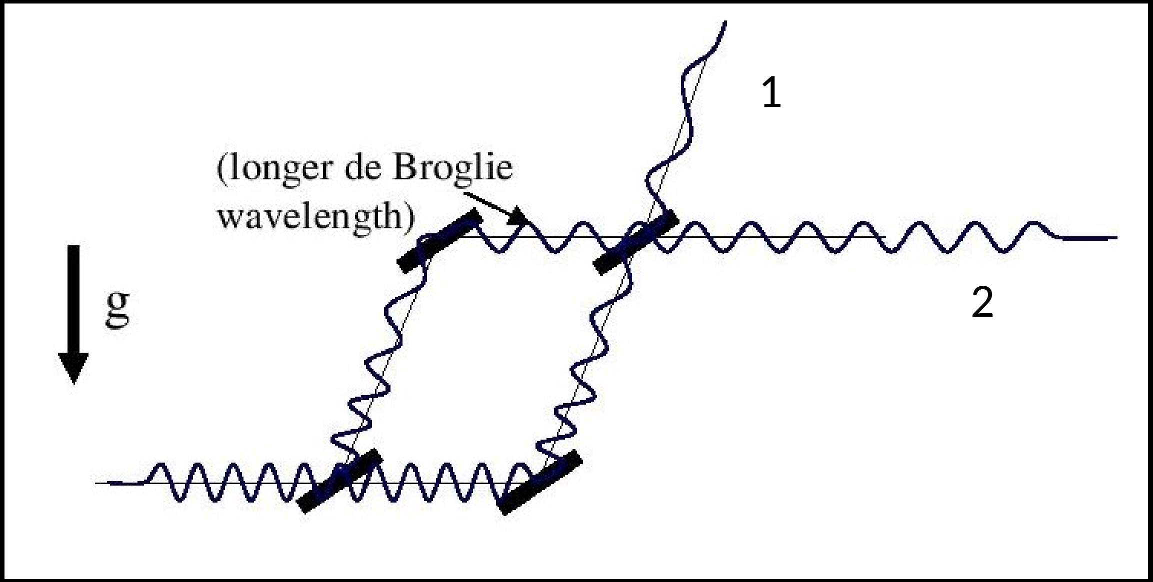
Introduction to Atom Interferometry

MIGA – **M**atter-wave laser **I**nterferometer **G**ravitation **A**ntenna

AI and GGN rejection

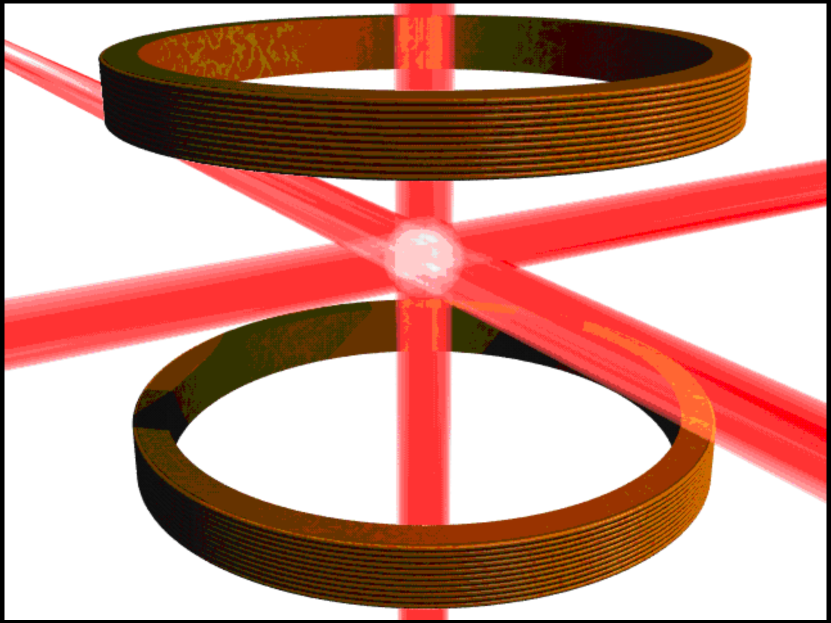
Atom Interferometry

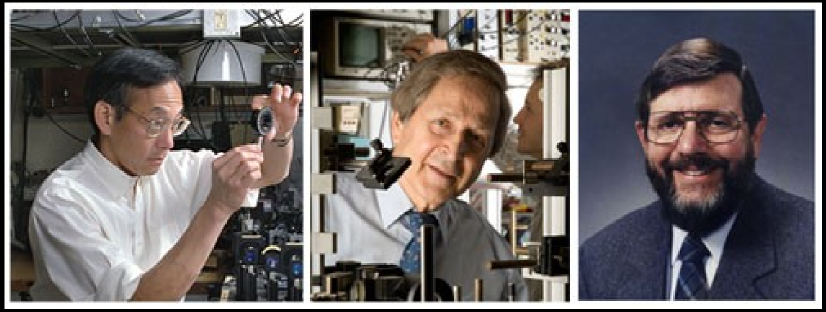
de Broglie wavelength: $\lambda = h/(mv)$



Measurements of inertial effects ($\Delta g/g = 3\times10^{-9}$, rotation 1 nras/s stab.), gravity gradient and curvature, fundamental constants (G, h/m), constraints PPN, tests GR, search dark energy…

Cold atoms





Nobel 1997: laser cooling & atom trapping
– S. Chu, C. Cohen-Tannoudji, W. Phillips

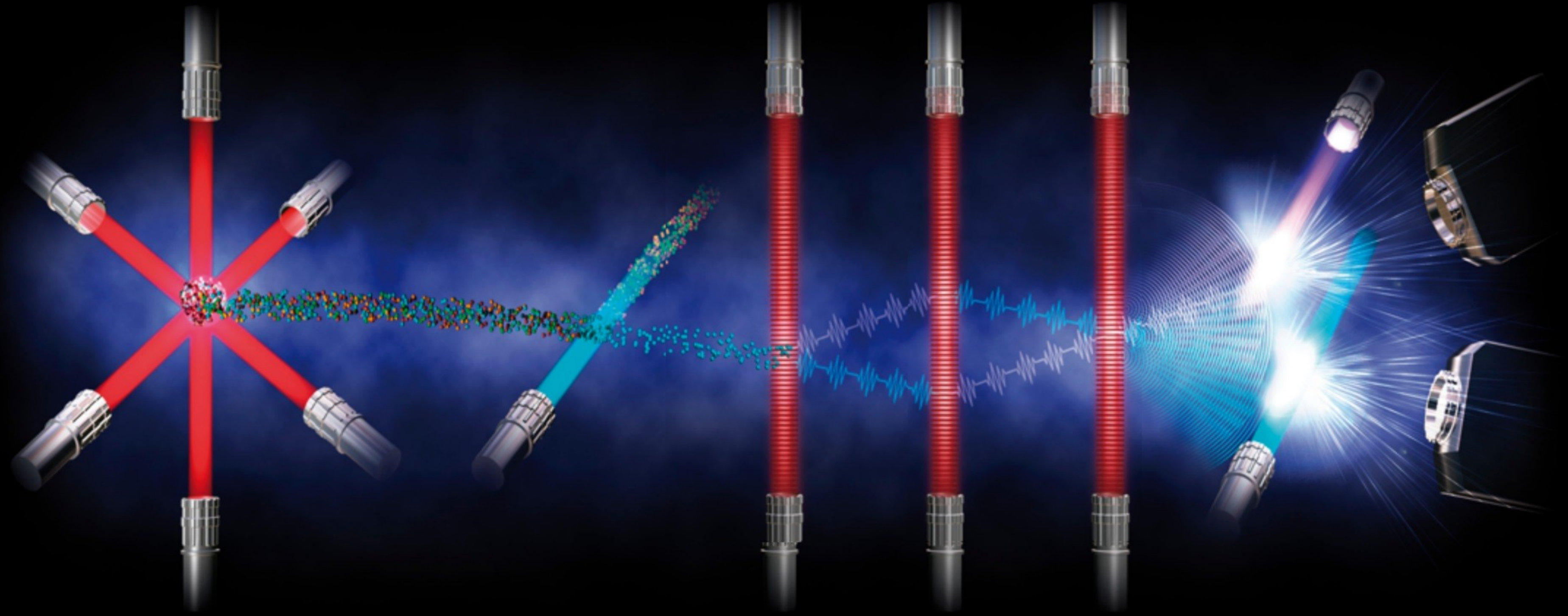
Nobel 2001:	Bose Einstein Condensate (E. Cornell, C. Weimann, W. Ketterle)
Nobel 2005:	coherence, laser based spectroscopy & comb
Nobel 2012:	measuring & manipulate individual quantum systems

Coherent manipulation

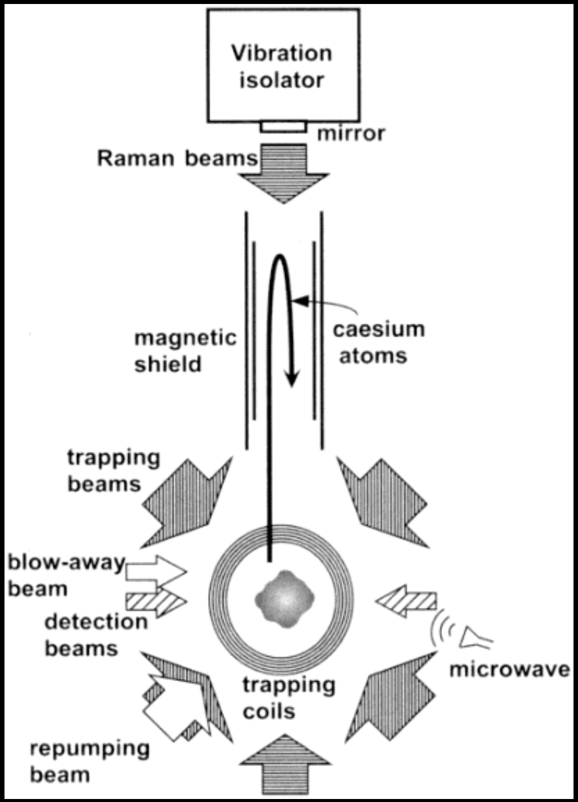
de Broglie wavelength: $\lambda = h/(mv) \sim 1\mu m$

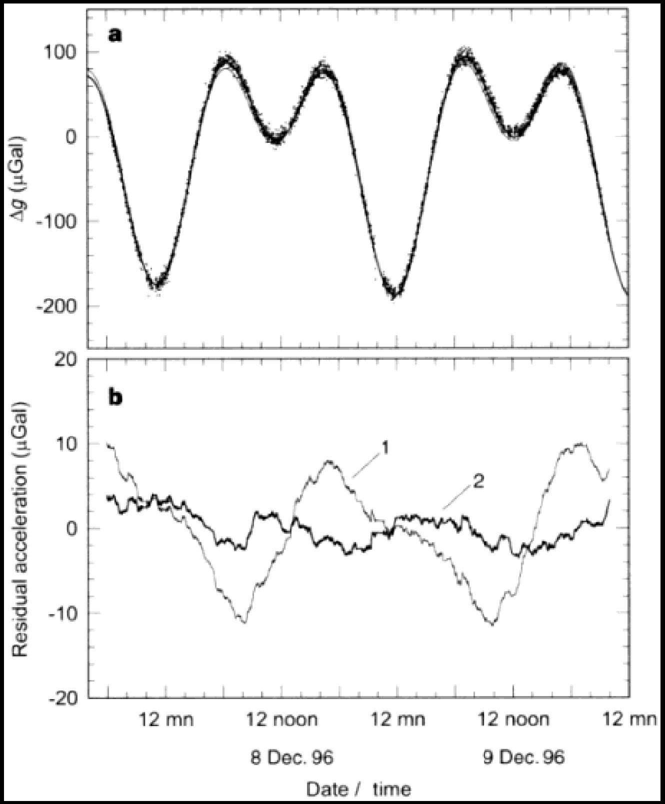
T ~ 1 μK → v ~ 1 cm/s

diffraction gratings with e.m. waves



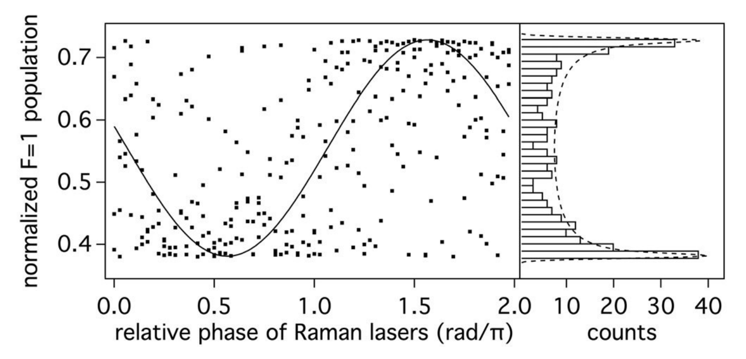
Absolute atom gravimeter

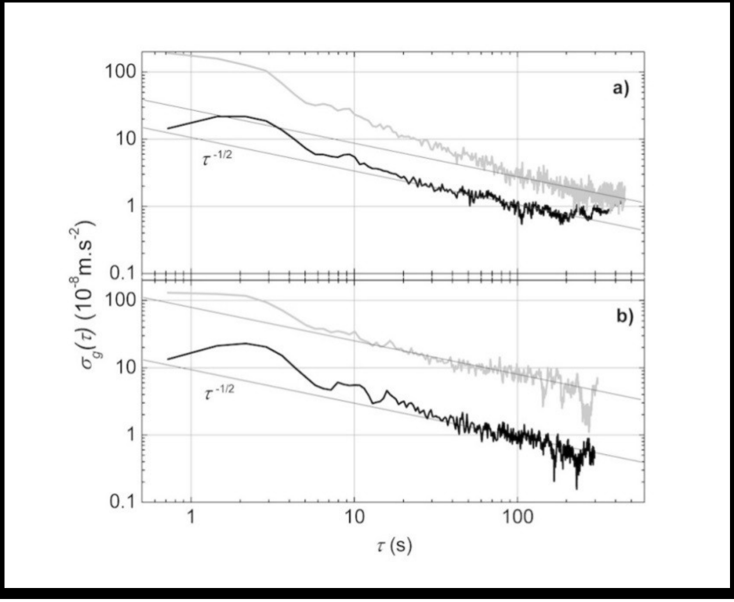


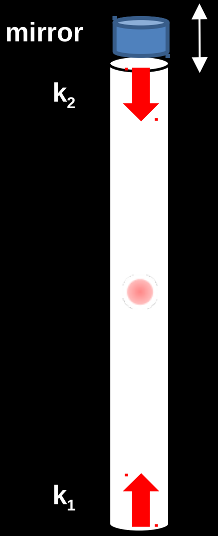


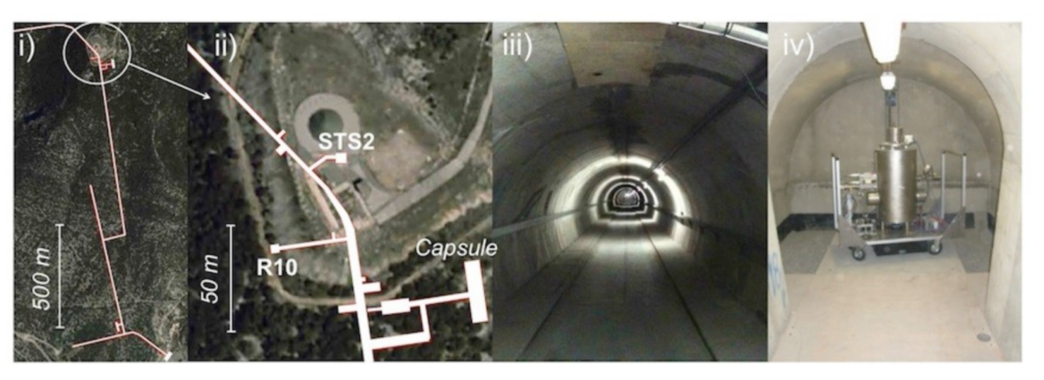
Peters *et al*., Nature **400**, 849 (1999) **$\Delta g/g = 3\times10^{-9}$**

Measuring gravity @ LSBB



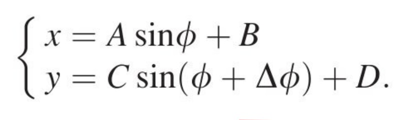




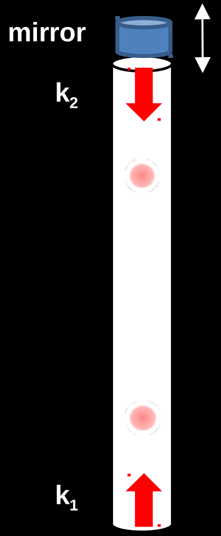


Farah *et al.*, Gyr. and Navig. **5**, 266 (2014)

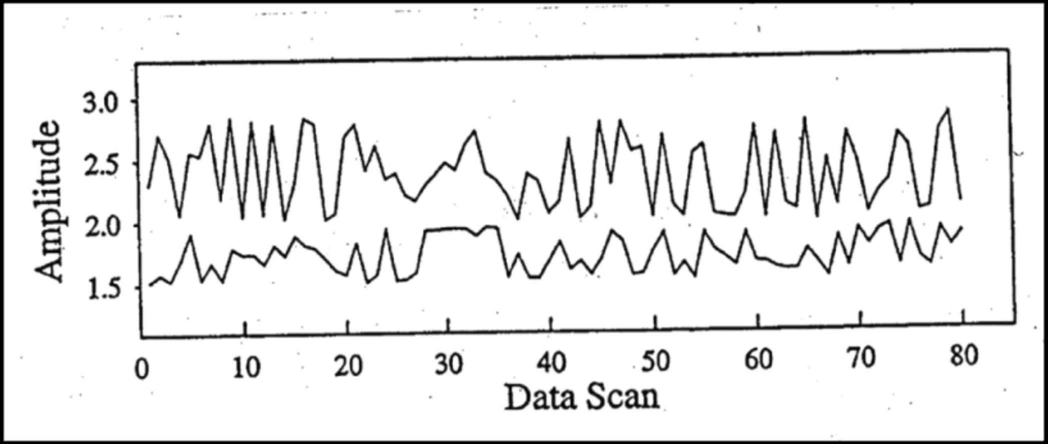
Gradiometry with AI

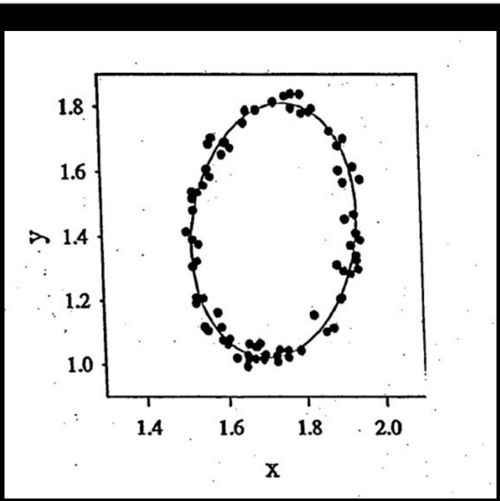


$$\begin{cases} x = A\sin\phi + B \\ y = C\sin(\phi + \Delta\phi) + D. \end{cases}$$



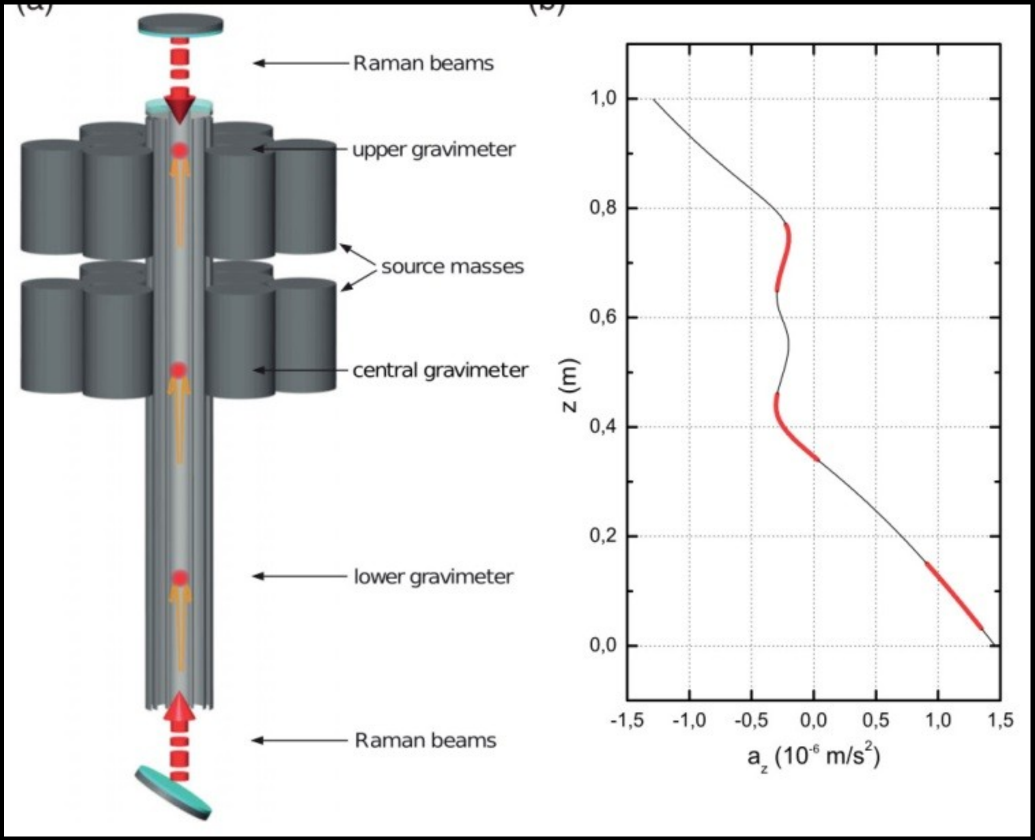
$\partial_z g \sim 10^{-9}$ g m^{-1} Hz$^{-1/2}$





Kasevich *et al.*, US20050027489 Patent

Measurement of curvature - 1

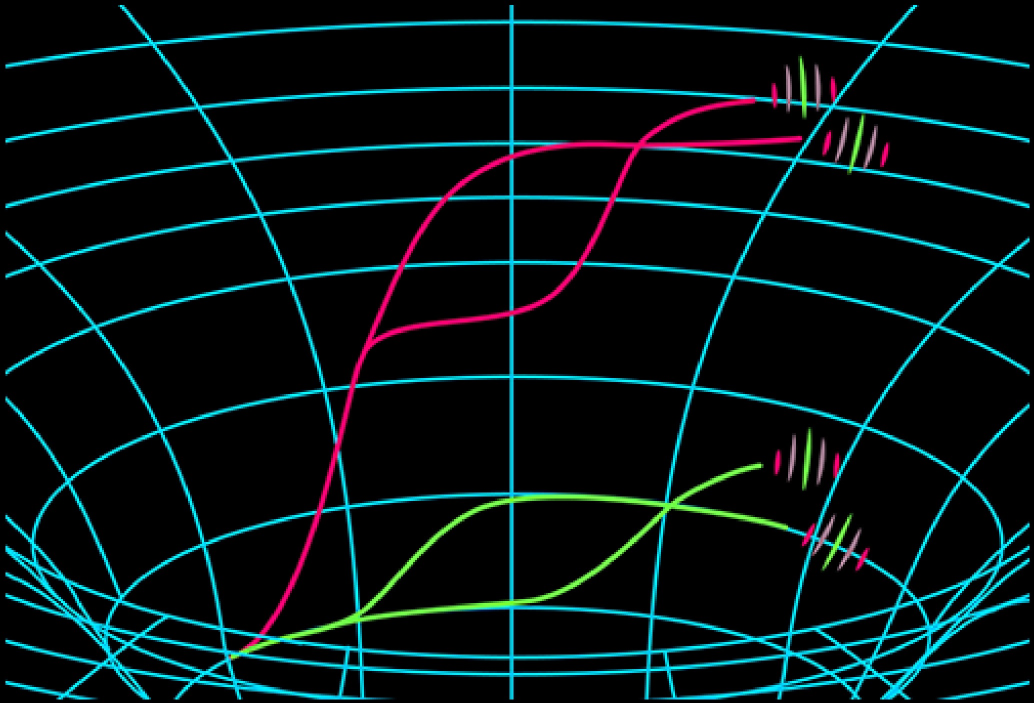


cloud distance ~30 cm

$\zeta = (1.399 \quad 0.003) \times 10^{-5}\ \mathrm{s}^{-2}\ \mathrm{m}^{-1}$

Rosi et al, PRL 114, 013001 (2015)

Measurement of curvature - 2



from Physics 10, 47 (2017)

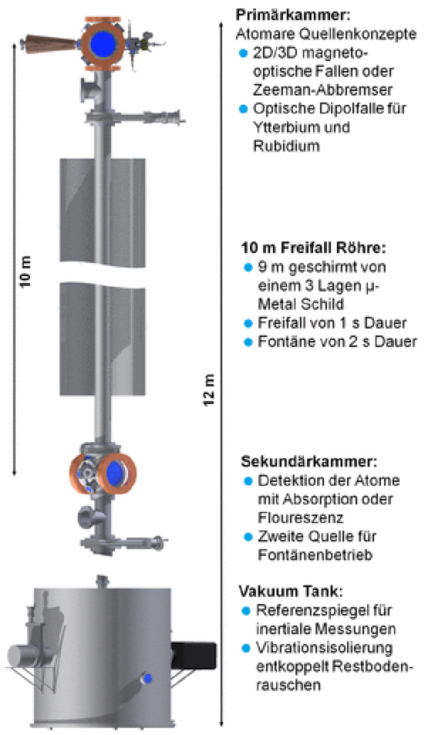
Curvature effect on the wavefunction of individual atoms

Asenbaum et al, PRL 118, 183602 (2017)

Very Large Baseline AI

Stanford – US

Wuhan – China



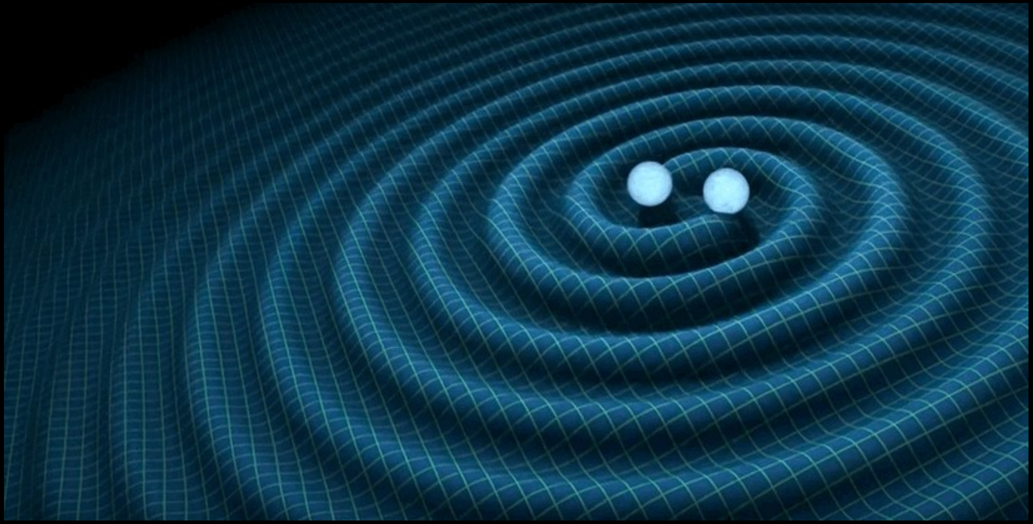
Hannover – Germany

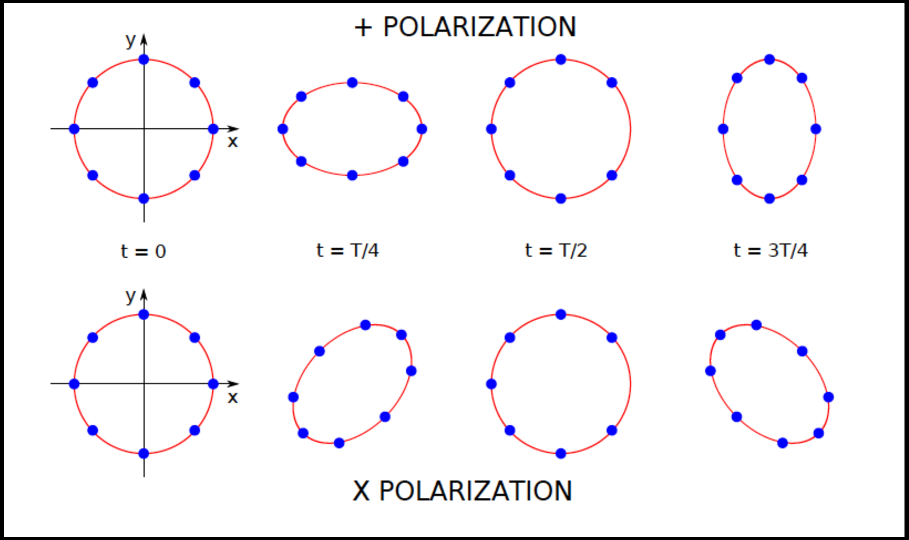
Proposals of ground and space projects
with even longer baselines,
to test GR, matter neutrality, dark
matter/energy…

Gravitational Waves

In GR accelerated mass → GW

- speed of light propagation
- 2 polarizations





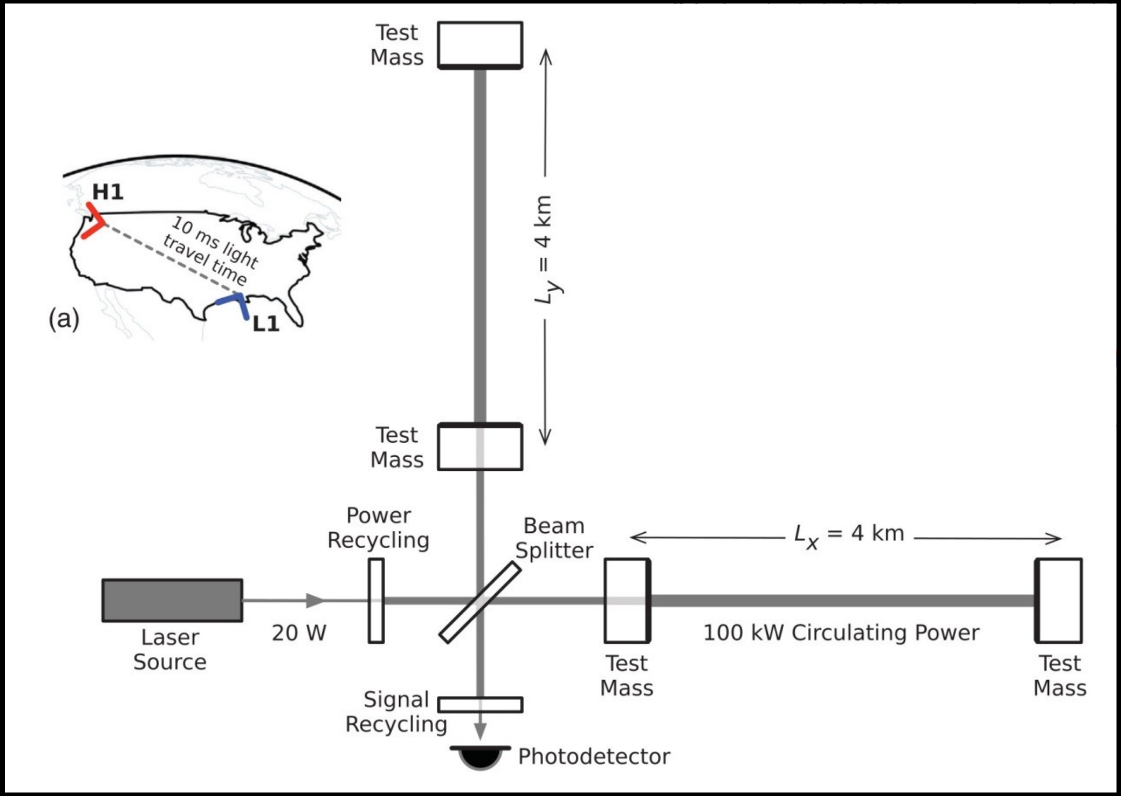
GW changes separations between geodetics

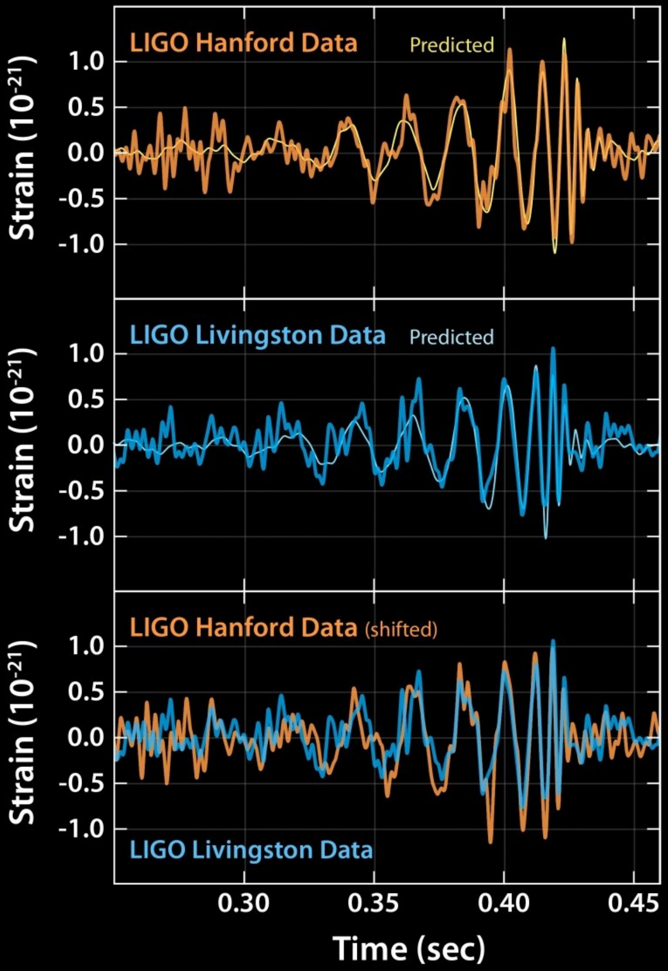
$$h = \delta L / L$$

$$\mathbf{L\ (1+h\ \sin(\omega t))}$$

Optical Interferometry for GW detection

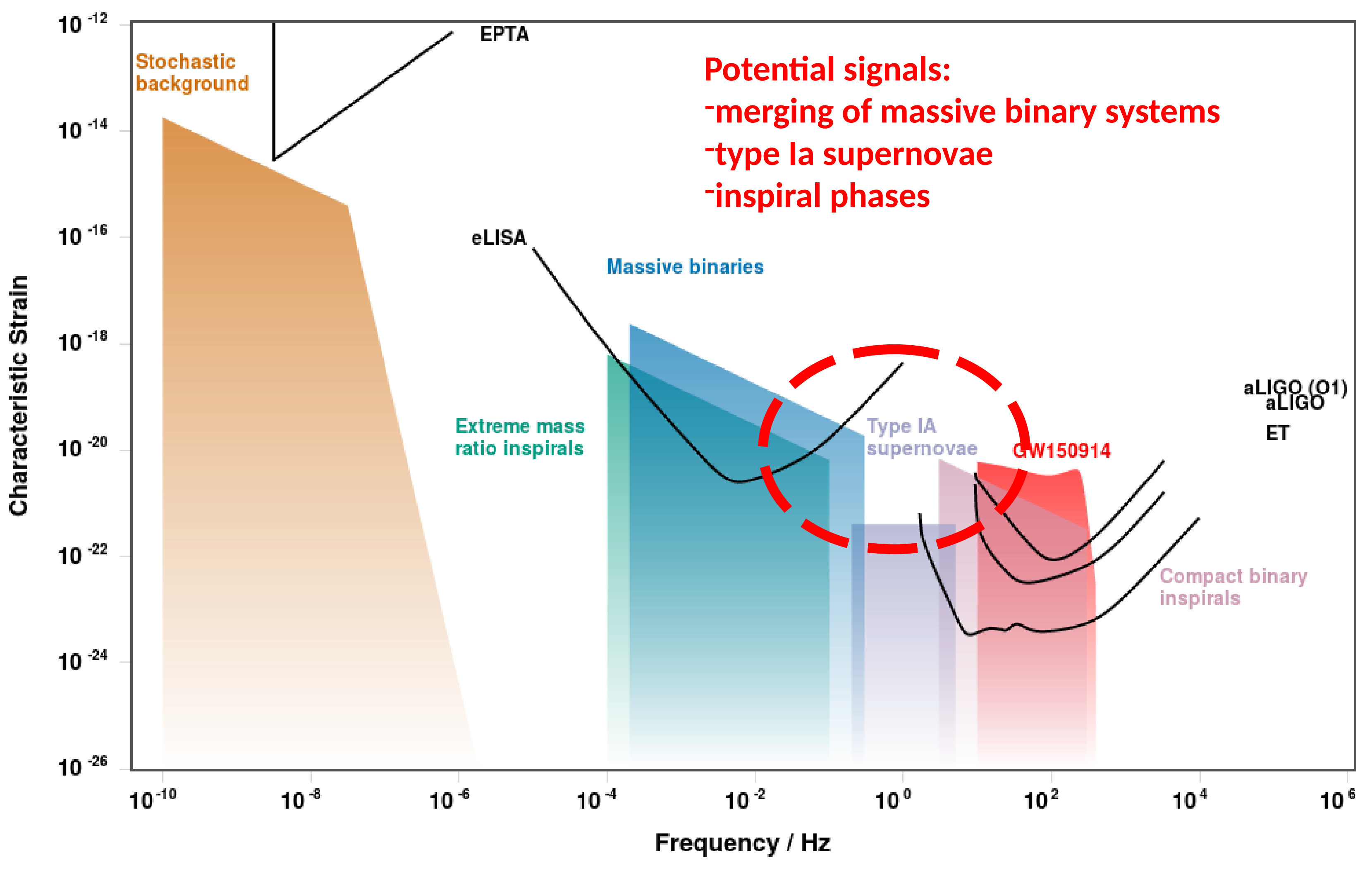
Giant Michelson interferometers





First detection: PRL 116, 061102 (2016)

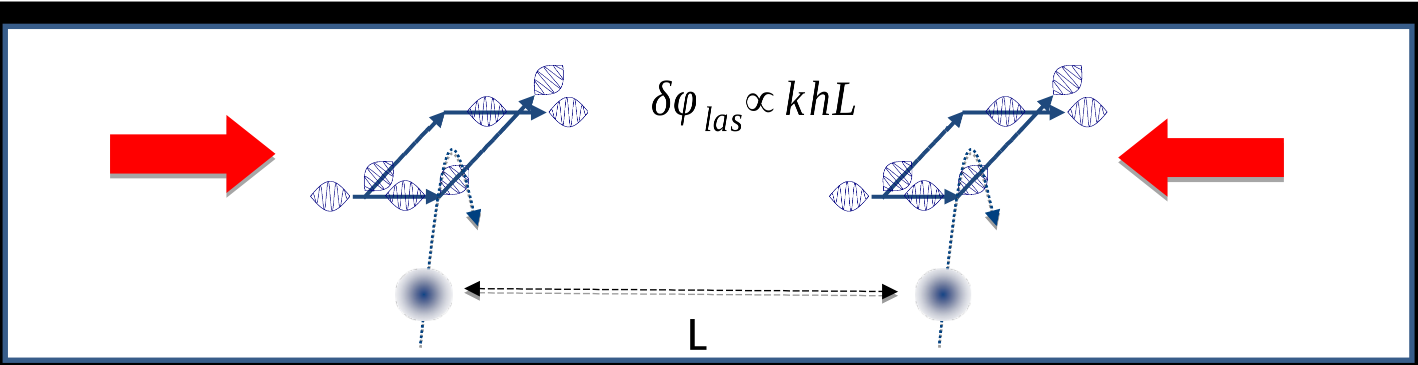
GW detectors sensitivities

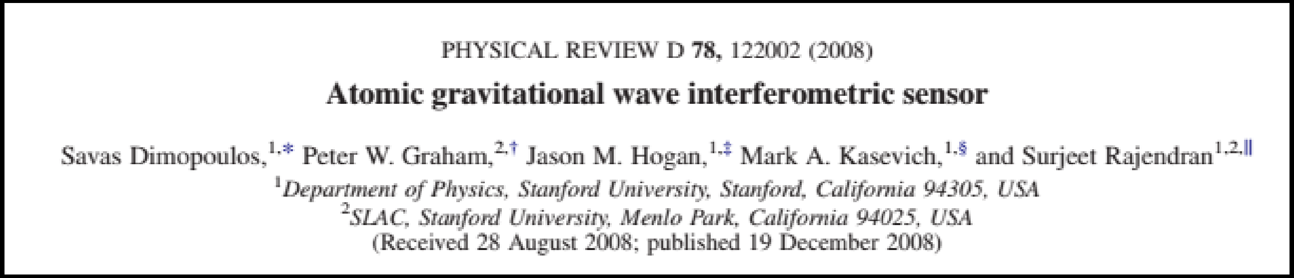


Potential signals:
- merging of massive binary systems
- type Ia supernovae
- inspiral phases

GWplotter from Moore, Cole and Berry

AI and GW detection

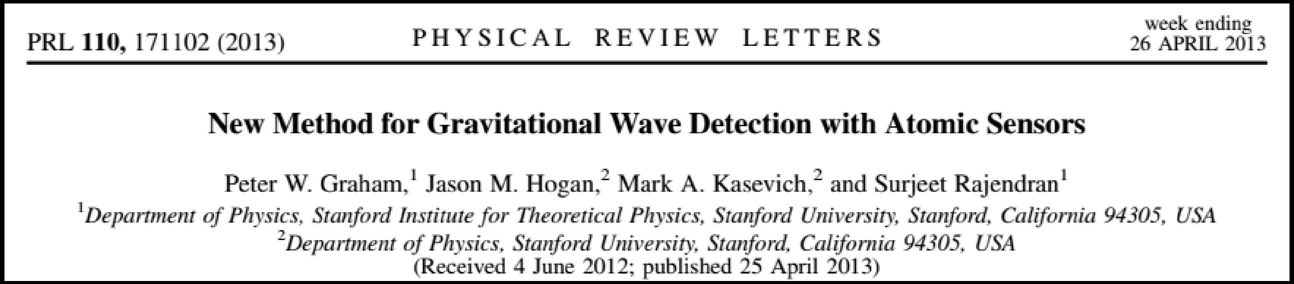




PHYSICAL REVIEW D **78,** 122002 (2008)

Atomic gravitational wave interferometric sensor

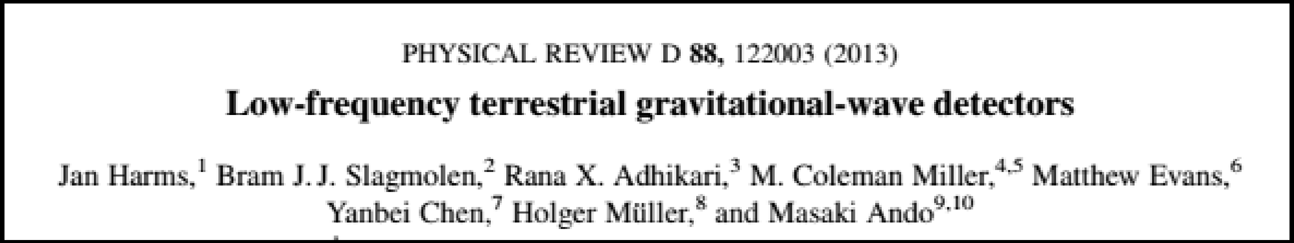
Savas Dimopoulos,[1,*] Peter W. Graham,[2,†] Jason M. Hogan,[1,‡] Mark A. Kasevich,[1,§] and Surjeet Rajendran[1,2,‖]
[1] *Department of Physics, Stanford University, Stanford, California 94305, USA*
[2] *SLAC, Stanford University, Menlo Park, California 94025, USA*
(Received 28 August 2008; published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



PRL **110,** 171102 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

New Method for Gravitational Wave Detection with Atomic Sensors

Peter W. Graham,[1] Jason M. Hogan,[2] Mark A. Kasevich,[2] and Surjeet Rajendran[1]
[1] *Department of Physics, Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*
[2] *Department of Physics, Stanford University, Stanford, California 94305, USA*
(Received 4 June 2012; published 25 April 2013)

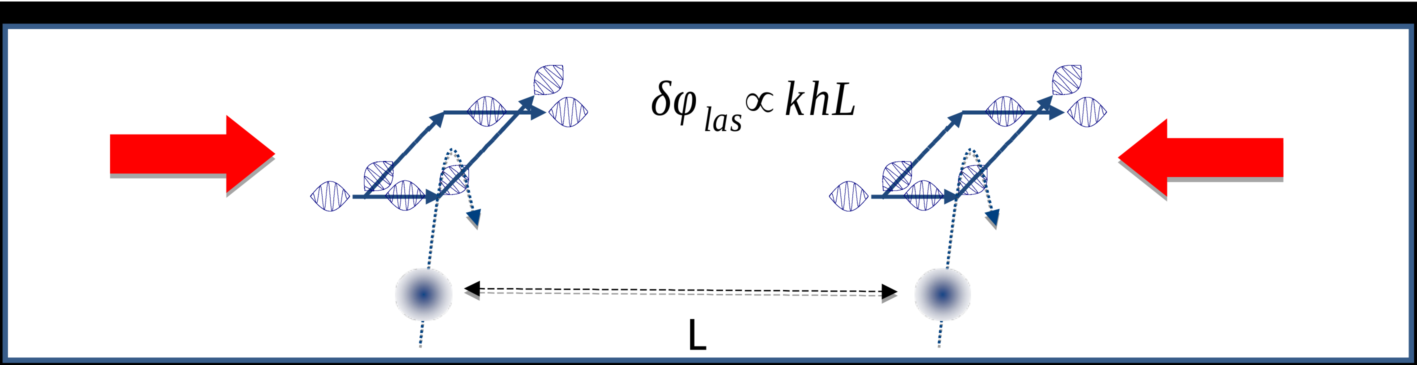


PHYSICAL REVIEW D **88,** 122003 (2013)

Low-frequency terrestrial gravitational-wave detectors

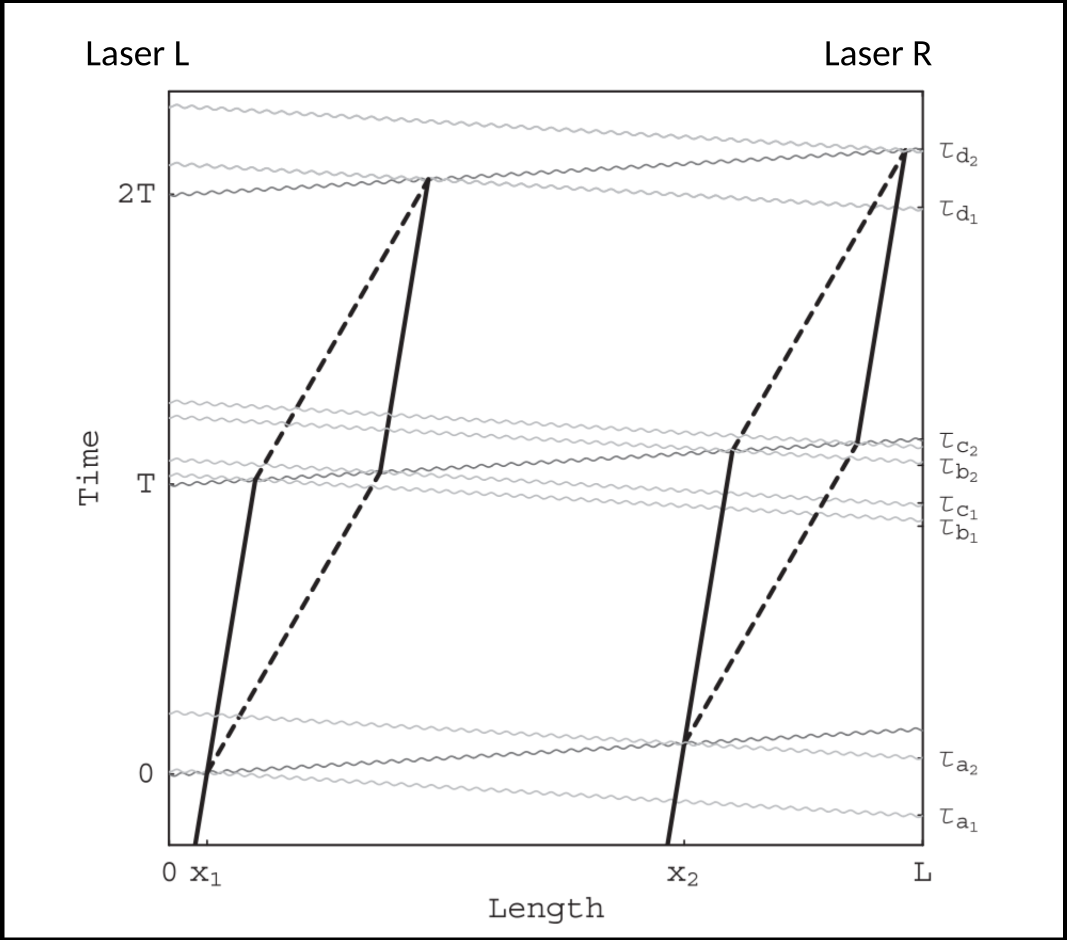
Jan Harms,[1] Bram J. J. Slagmolen,[2] Rana X. Adhikari,[3] M. Coleman Miller,[4,5] Matthew Evans,[6]
Yanbei Chen,[7] Holger Müller,[8] and Masaki Ando[9,10]

AI and GW detection



- Free falling atoms insensitive to vibrations (decoupled)
- Optical ruler subject to seismic noise
- Noise mitigation via differential measurement (GG)
- Atoms do not feel radiation pressure
- **Use optical transitions to avoid laser technical noise**
- **GGN reduction**

Gravity gradient measurement and noise



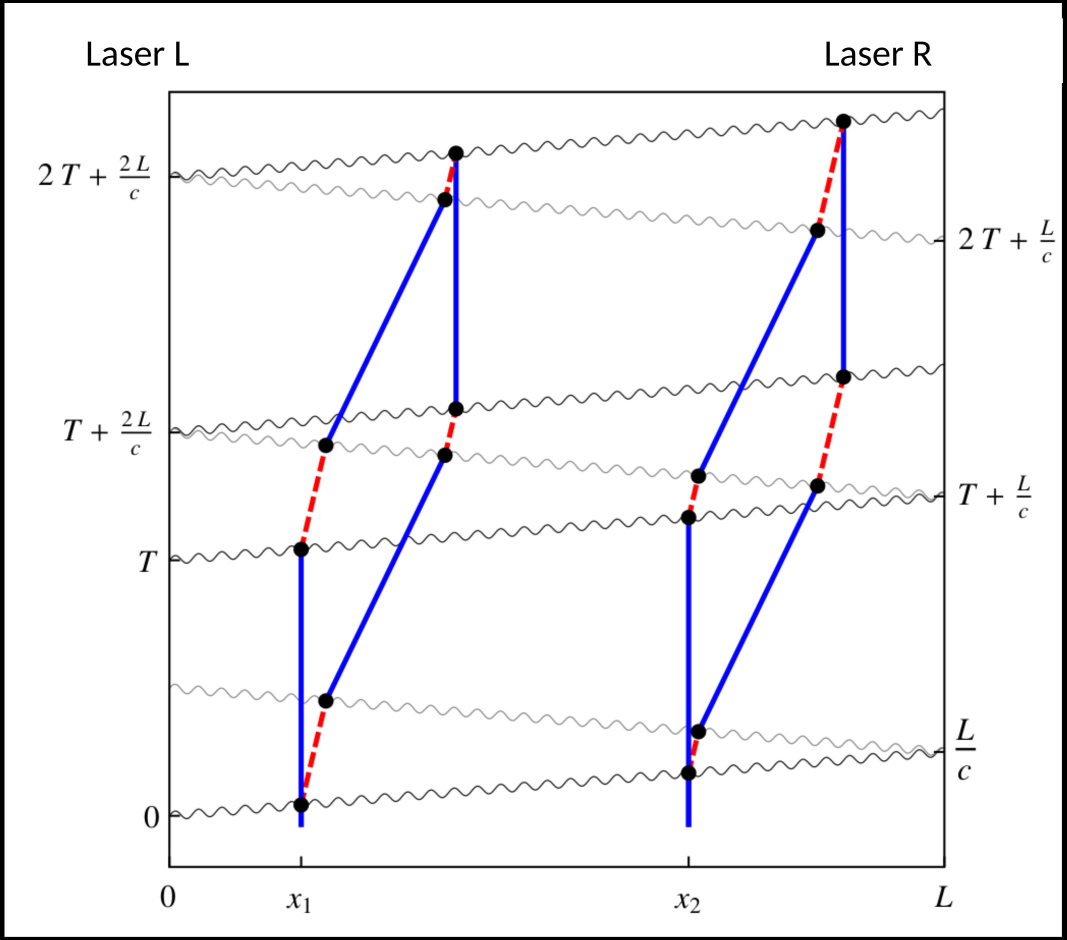
GW signal in the differential atomic phase

Noise Laser L common mode; noise Laser R given by travel time delay

→ ultra-stable laser, Michelson-Morley multi-arm configuration

Graham et al, PRL 110, 171102 (2013)

Single photon AI



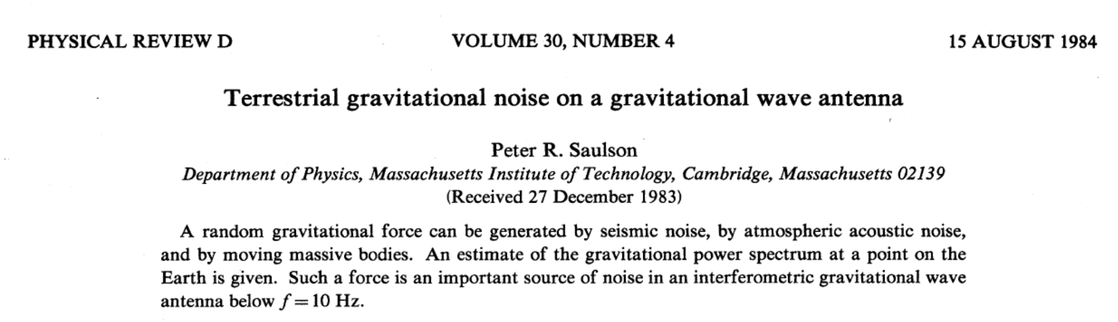
(Single photon) optical transitions used for atomic clocks

→laser noise Common Mode, and requirement mitigation

Graham et al, PRL 110, 171102 (2013)

GGN sensitivity

Gravity Gradient Noise is a fundamental limit for ground based GW detectors with two test masses



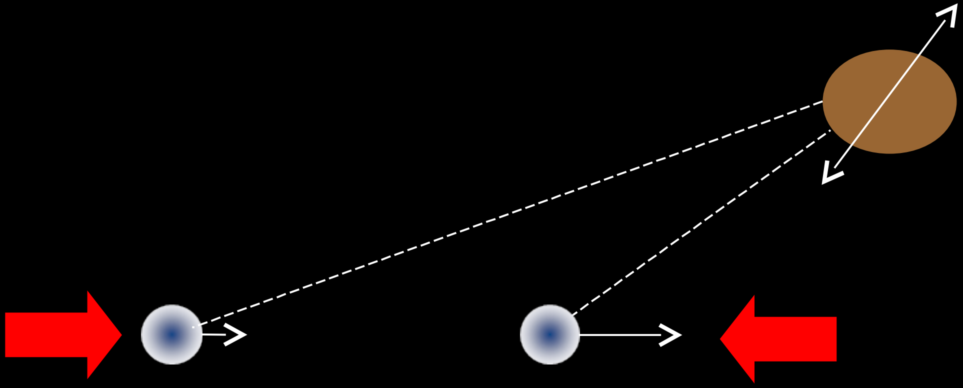
PHYSICAL REVIEW D VOLUME 30, NUMBER 4 15 AUGUST 1984

Terrestrial gravitational noise on a gravitational wave antenna

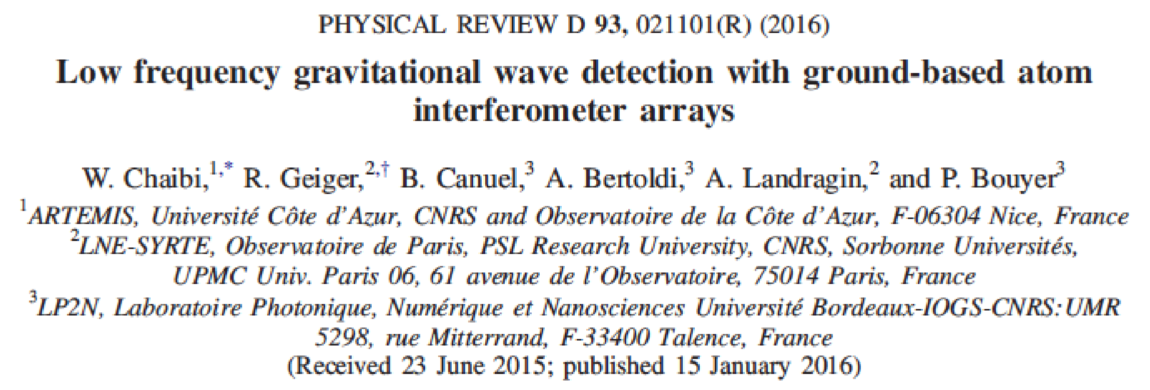
Peter R. Saulson
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 27 December 1983)

A random gravitational force can be generated by seismic noise, by atmospheric acoustic noise, and by moving massive bodies. An estimate of the gravitational power spectrum at a point on the Earth is given. Such a force is an important source of noise in an interferometric gravitational wave antenna below $f = 10$ Hz.



GGN sensitivity



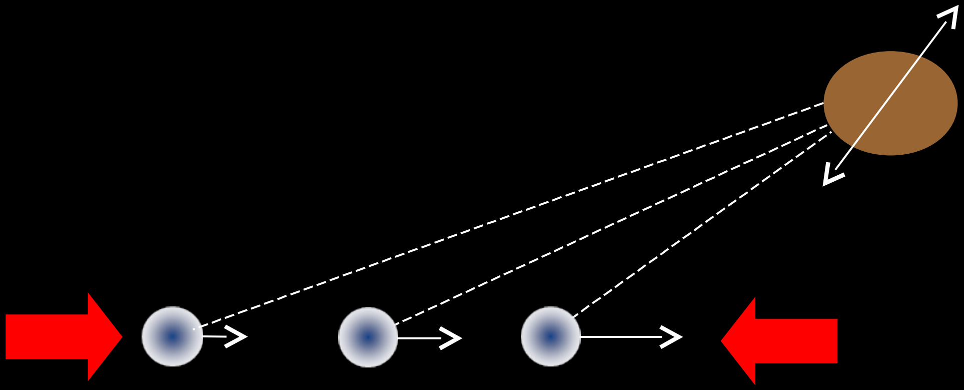
PHYSICAL REVIEW D 93, 021101(R) (2016)

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)

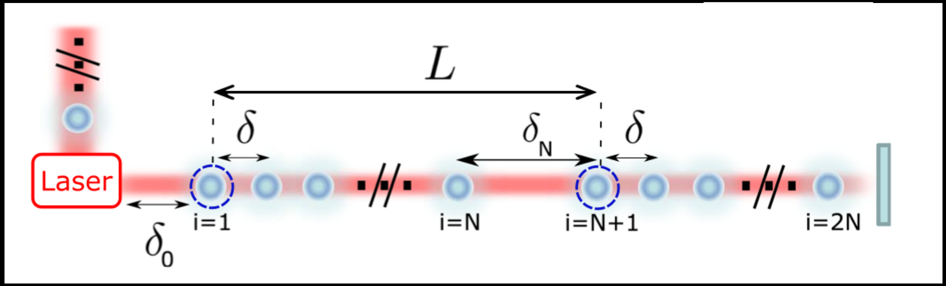


$$\phi_{at}^{i}-\phi_{at}^{j} = kh\,(x_i-x_j) + 2kT^2\,[\,a(x_i) - a(x_j)\,]$$

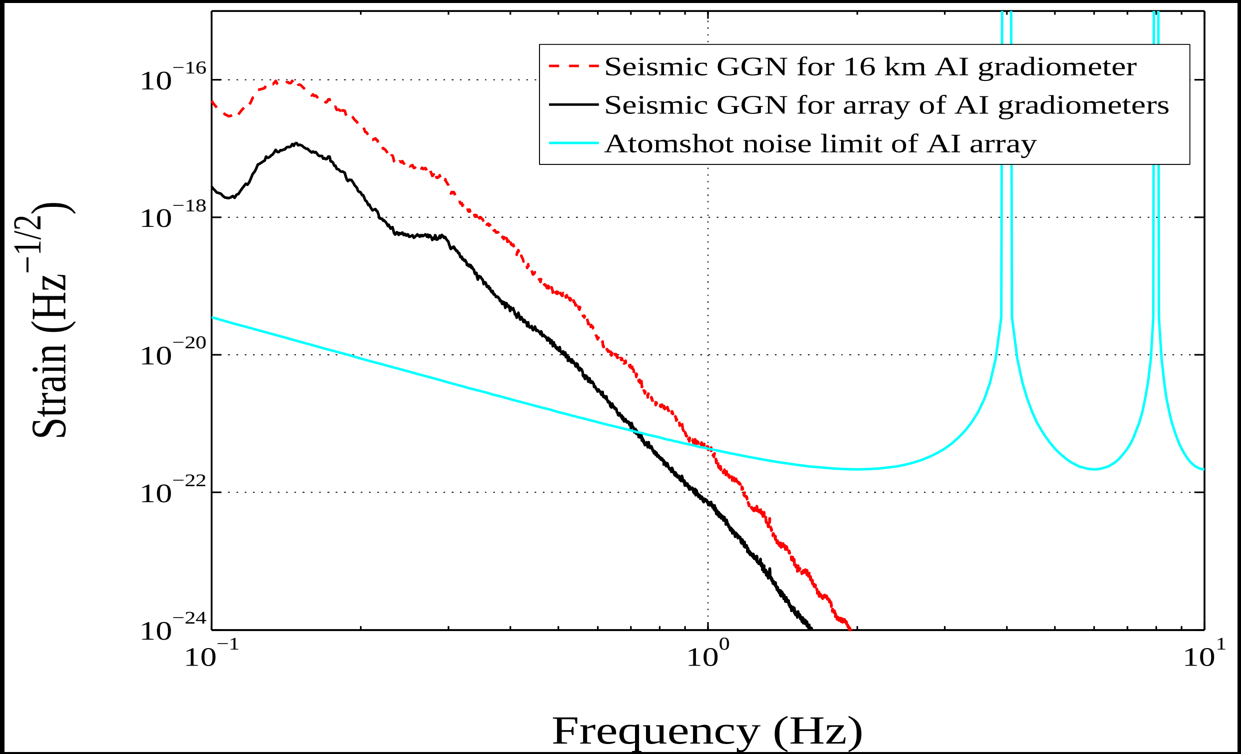
GW

Gravity gradient

GGN reduction with AI array



80 gradiometers, L=16 km
PRD 93, 021101(R) – 2016



Spatial averaging to reduce GGN and allow for GW extraction

10× gain in the
100 mHz – 10 Hz band

Detector geometry optimized in relation to GGN spatial correlation properties

MIGA – Matter wave laser Interferometer Gravitation Antenna

MIGA project

French “Equipement d’Excellence” Initiative
17 partners

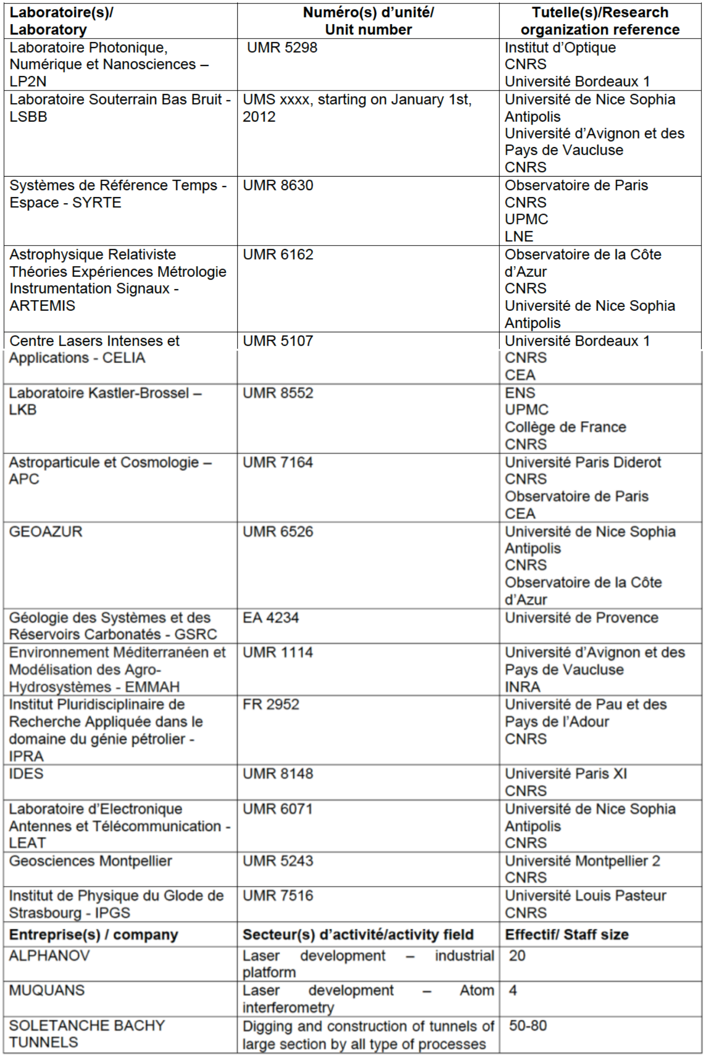
Gravitational wave physics

Demonstrator for sub-Hz ground based GW detectors

Geoscience

Gravity sensitivity of 10^{-10} g/√Hz @ 2Hz

Gradient sensitivity of 10^{-13} s^{-2}/ √ Hz @ 2Hz



Laboratoire(s)/ Laboratory	**Numéro(s) d’unité/ Unit number**	**Tutelle(s)/Research organization reference**
Laboratoire Photonique, Numérique et Nanosciences – LP2N	UMR 5298	Institut d’Optique CNRS Université Bordeaux 1
Laboratoire Souterrain Bas Bruit - LSBB	UMS xxxx, starting on January 1st, 2012	Université de Nice Sophia Antipolis Université d’Avignon et des Pays de Vaucluse CNRS
Systèmes de Référence Temps - Espace - SYRTE	UMR 8630	Observatoire de Paris CNRS UPMC LNE
Astrophysique Relativiste Théories Expériences Métrologie Instrumentation Signaux - ARTEMIS	UMR 6162	Observatoire de la Côte d’Azur CNRS Université de Nice Sophia Antipolis
Centre Lasers Intenses et Applications - CELIA	UMR 5107	Université Bordeaux 1 CNRS CEA
Laboratoire Kastler-Brossel – LKB	UMR 8552	ENS UPMC Collège de France CNRS
Astroparticule et Cosmologie – APC	UMR 7164	Université Paris Diderot CNRS Observatoire de Paris CEA
GEOAZUR	UMR 6526	Université de Nice Sophia Antipolis CNRS Observatoire de la Côte d’Azur
Géologie des Systèmes et des Réservoirs Carbonatés - GSRC	EA 4234	Université de Provence
Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes - EMMAH	UMR 1114	Université d’Avignon et des Pays de Vaucluse INRA
Institut Pluridisciplinaire de Recherche Appliquée dans le domaine du génie pétrolier - IPRA	FR 2952	Université de Pau et des Pays de l’Adour CNRS
IDES	UMR 8148	Université Paris XI CNRS
Laboratoire d’Electronique Antennes et Télécommunication - LEAT	UMR 6071	Université de Nice Sophia Antipolis CNRS
Geosciences Montpellier	UMR 5243	Université Montpellier 2 CNRS
Institut de Physique du Glode de Strasbourg - IPGS	UMR 7516	Université Louis Pasteur CNRS
Entreprise(s) / company	**Secteur(s) d’activité/activity field**	**Effectif/ Staff size**
ALPHANOV	Laser development – industrial platform	20
MUQUANS	Laser development – Atom interferometry	4
SOLETANCHE BACHY TUNNELS	Digging and construction of tunnels of large section by all type of processes	50-80

MIGA – principal partners

LP2N (Bordeaux)
cavity design, vacuum system, project management

SYRTE (Paris)
cold atom source, detection system

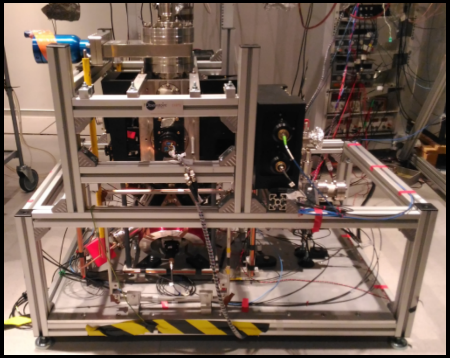
ARTEMIS (Nice)
cavity mirror suspensions

µQuans (Bordeaux)
laser systems

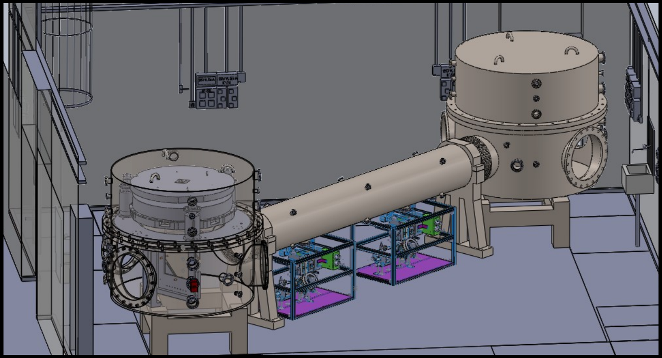
LSBB (Rustrel)
tunnels & site management, geophysics expertise

MIGA – experimental activity

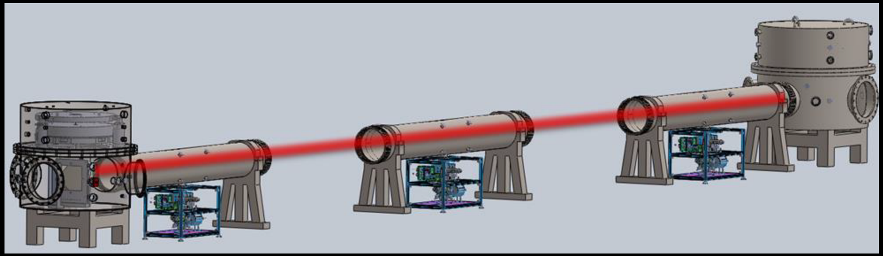
- validation of cavity enhanced AI with free-falling atomic sensors (2016-17)



- prototype 10m horizontal gradiometer @LP2N (2018-19)

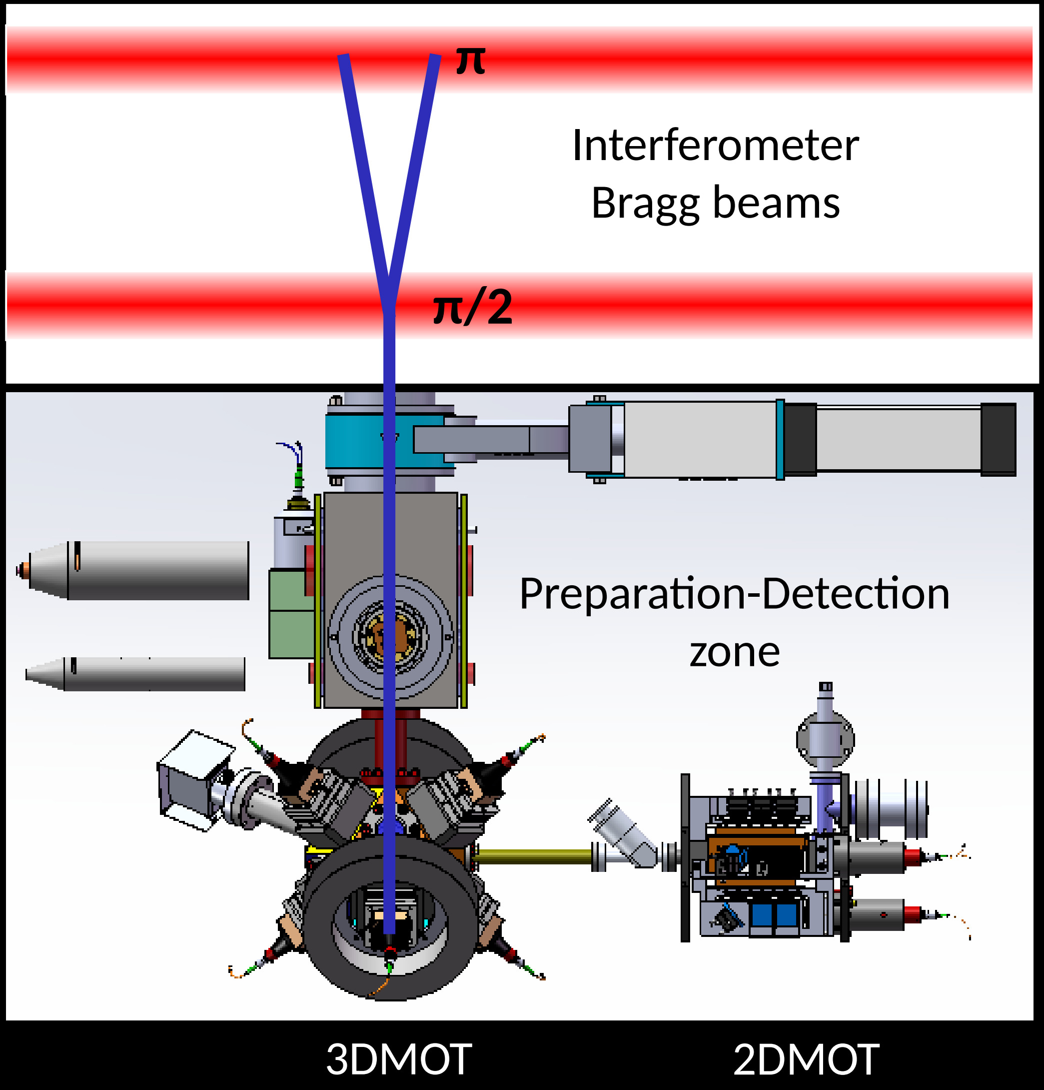


- 300m VLBAI array at LSBB (2019—)

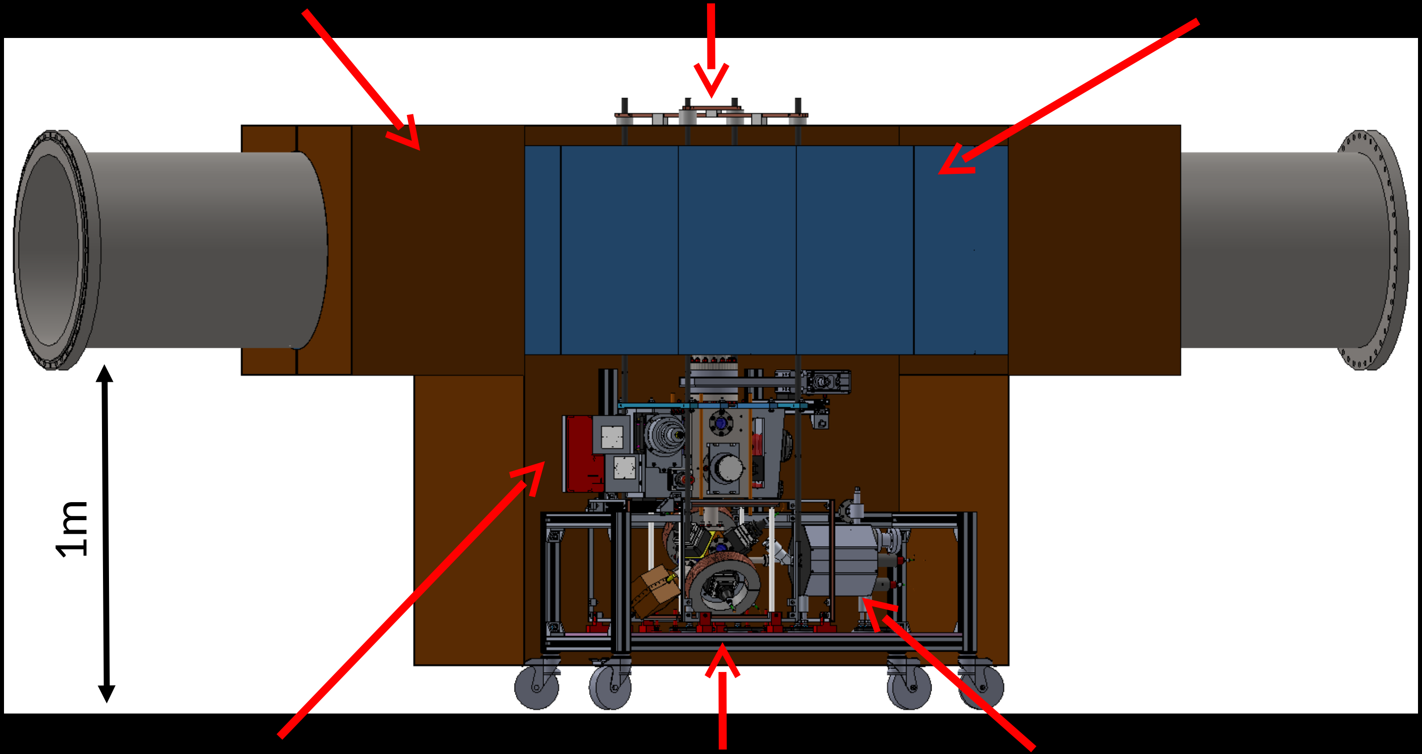


Cold atom fountain

- ^{87}Rb atoms cooled and trapped in 2D / 3D MOT
- 10^8 atoms launched vertically at 4 m/s
- Raman transitions to prepare of pure magnetic state and velocity selection
- Detection of transition probability by fluorescence over 10^6 atoms



Atomic sensor



Sensor magnetic shield

Bias magnetic field

Tube magnetic shield

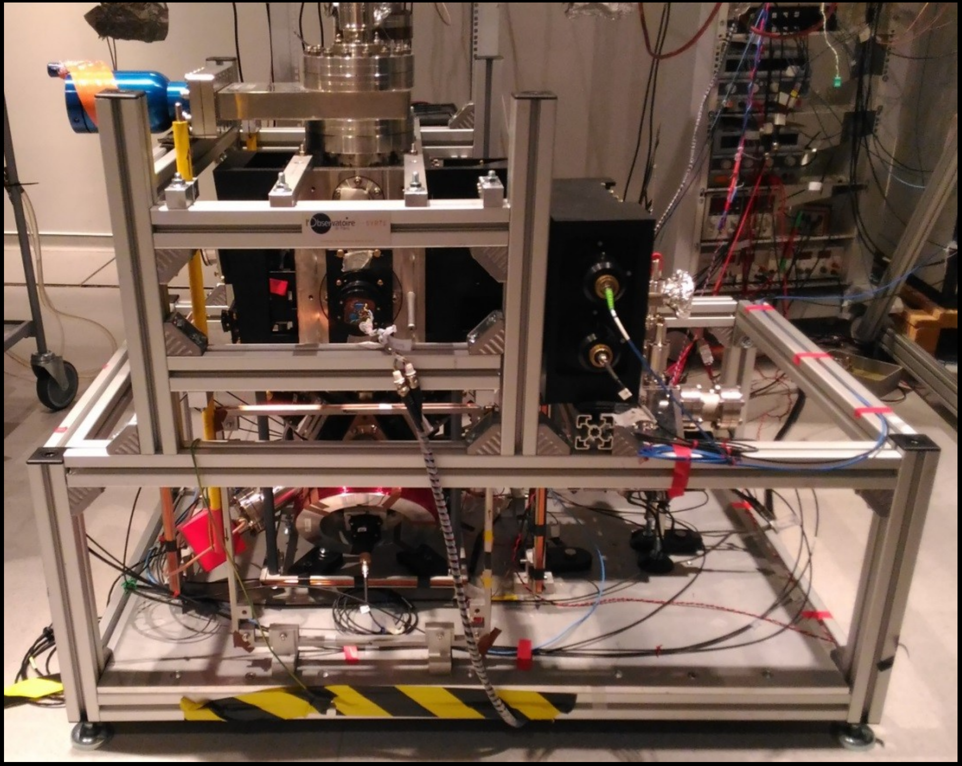
Preparation and detection

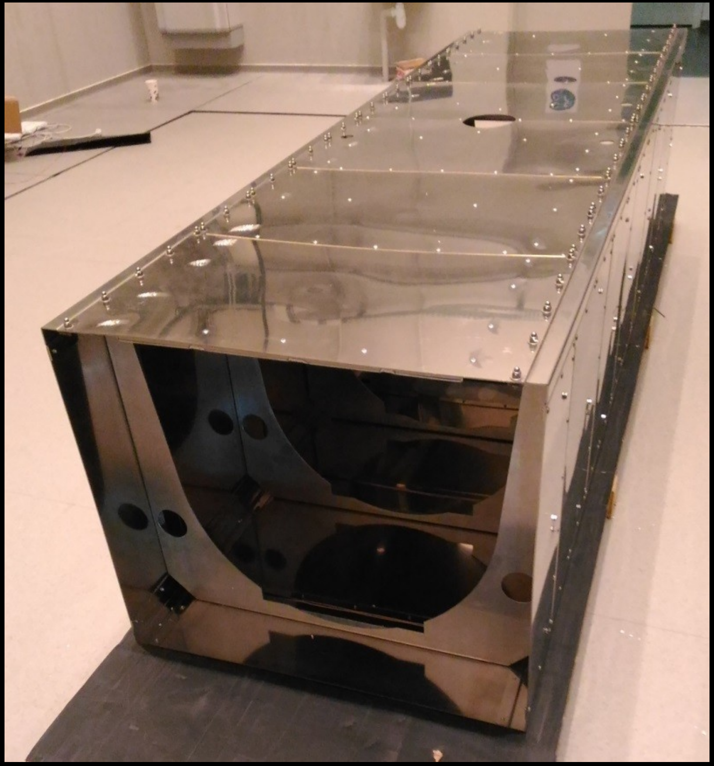
3D MOT

2D MOT

Atomic gravimeter

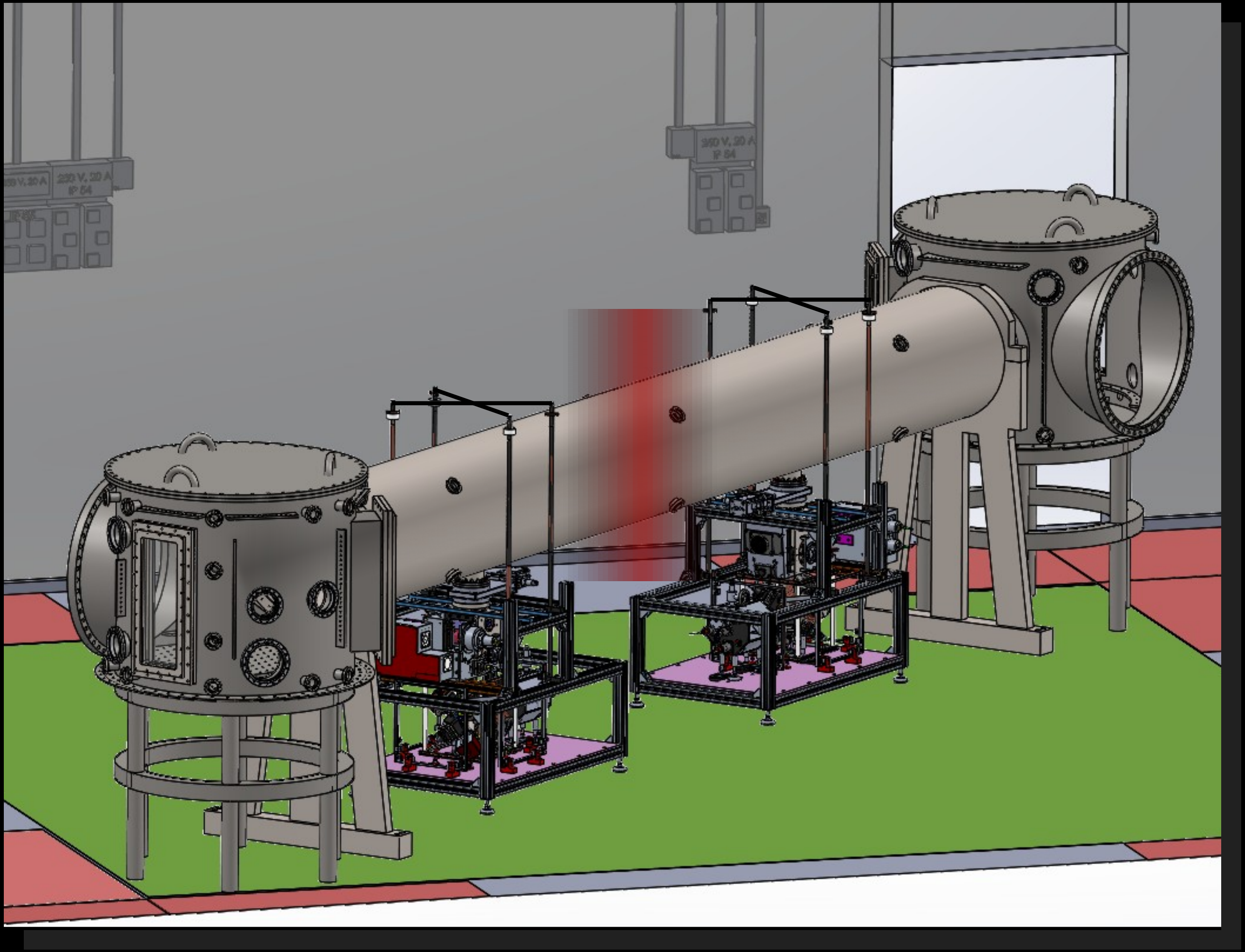
- ✓ Cold ^{87}Rb atom cloud (2D MOT, 3D MOT) prepared and launched vertically
- ✓ Interrogation cavities characterized
- ✓ Vacuum setup, magnetic shield, and control system tested



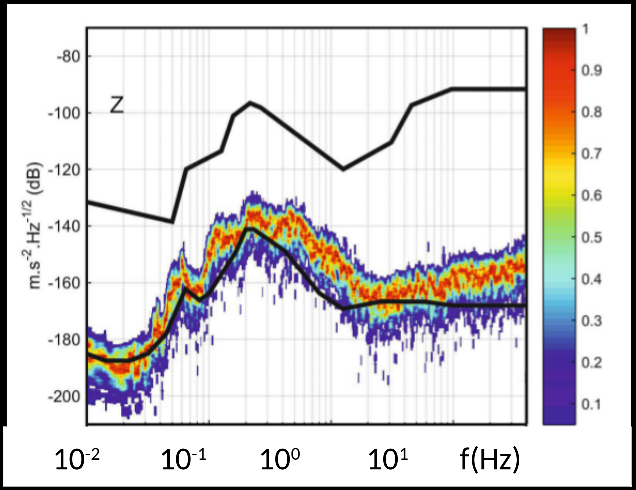


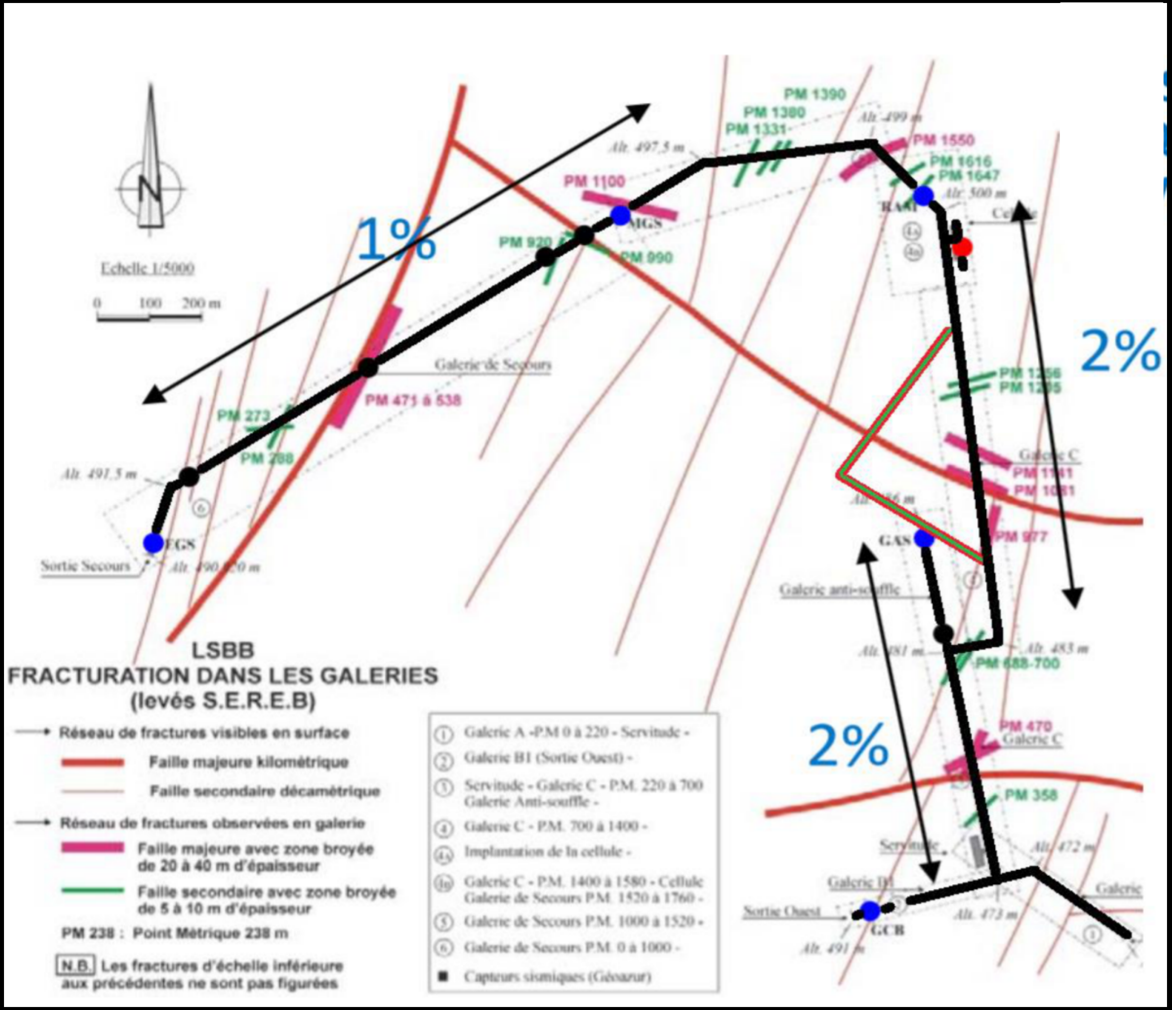
10m gravity-gradiometer

- ✓ Two atom sensors and laser systems realised
- ✓ Vacuum system designed



Laboratoire Souterrain à Bas Bruit (LSBB)

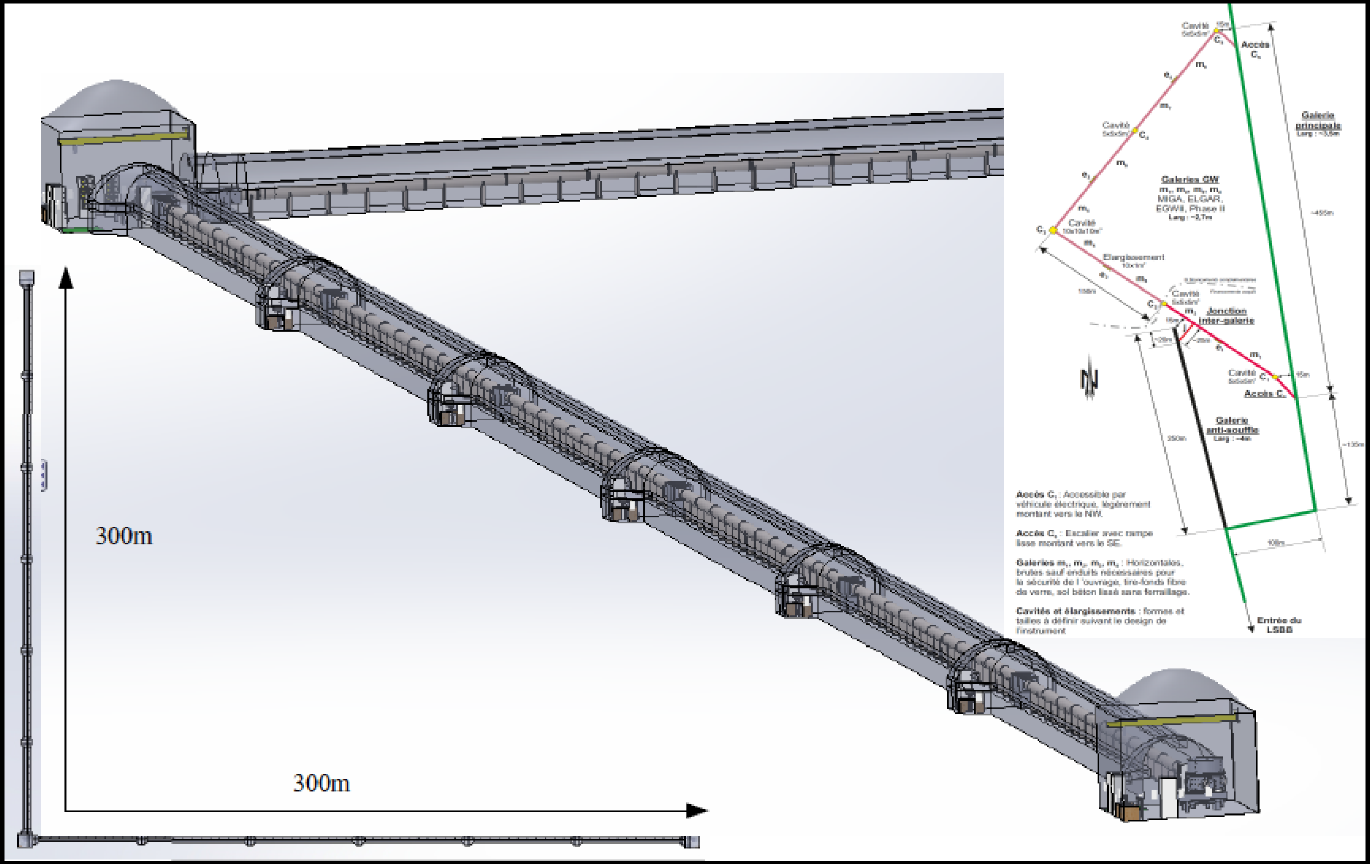




MIGA @ LSBB (Rustrel – France) arXiv:1703.02490

Two dedicated tunnels of 300 m

- Continuous operation without perturbation
- Need for horizontal interrogation
- Orthogonal configuration to remove laser noise



Accès C_1 : Accessible par véhicule électrique, légèrement montant vers le NW.

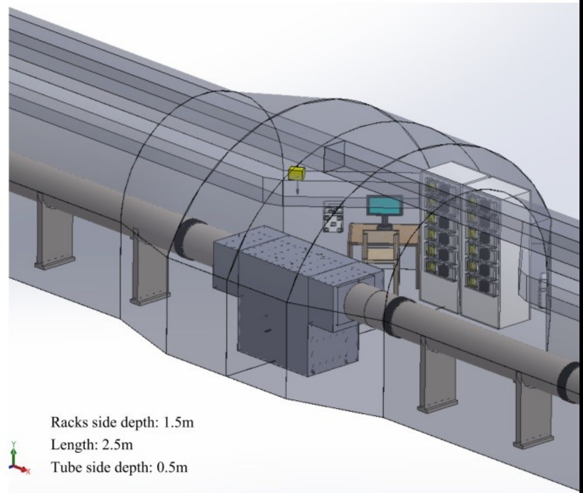
Accès C_2 : Escalier avec rampe lisse montant vers le SE.

Galeries m_1, m_2, m_3, m_4 : Horizontales, brutes sauf enduits nécessaires pour la sécurité de l'ouvrage, tire-fonds fibre de verre, sol béton lissé sans ferraillage.

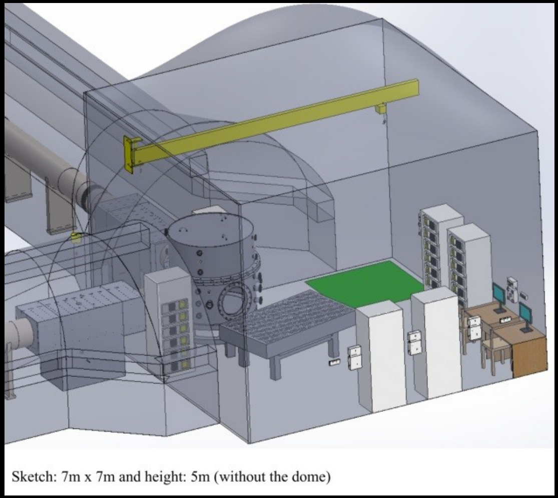
Cavités et élargissements : formes et tailles à définir suivant le design de l'instrument.

MIGA @ LSBB (Rustrel – France) arXiv:1703.02490

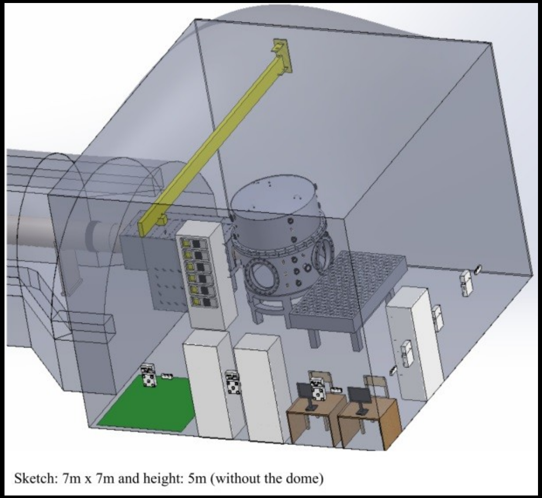
Definition of requirements (volume, access, instrumentation, services, environment – temperature, humidity)



Atom Interferometer niche

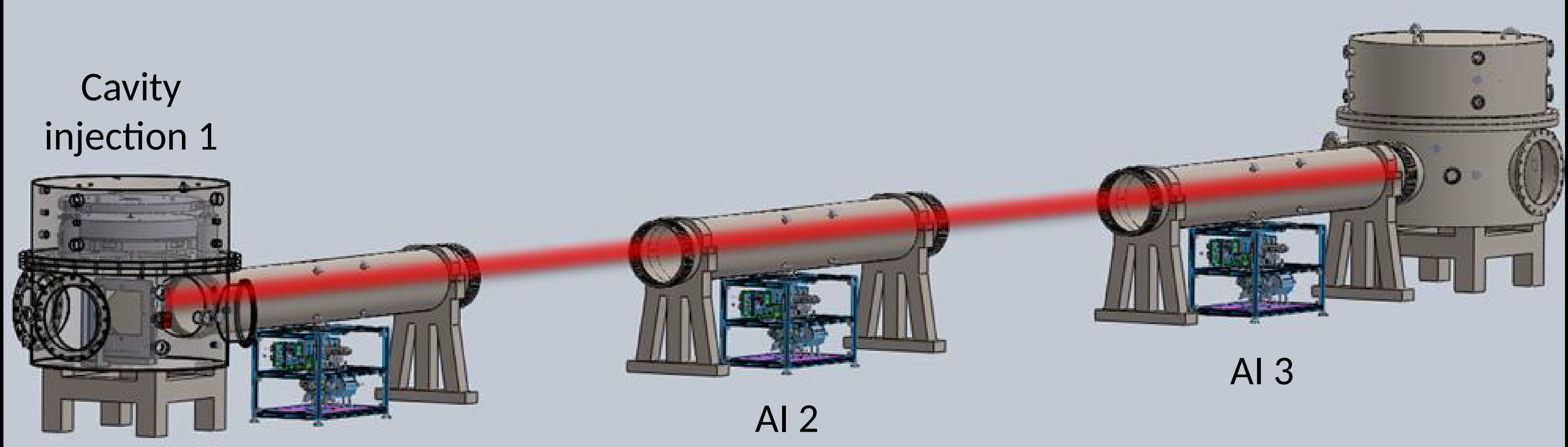


Central cavity

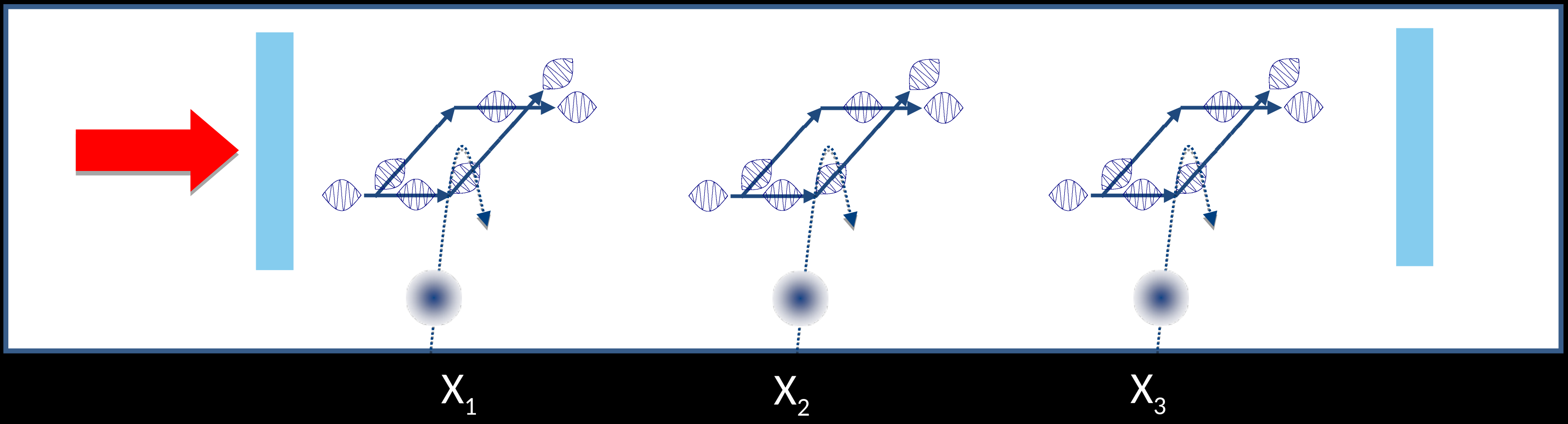


Extreme cavity

One arm of MIGA



MIGA



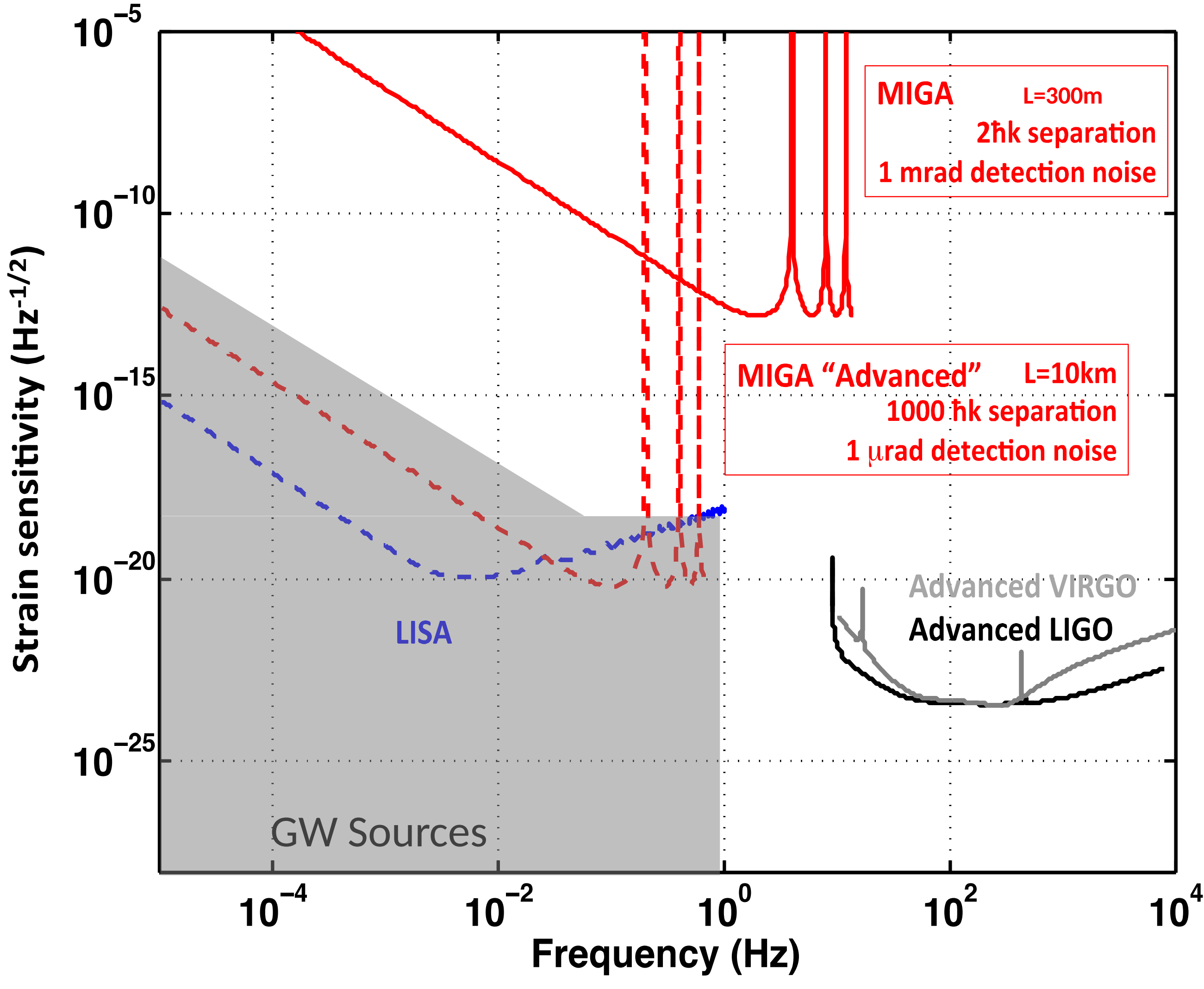
$$\phi_{at}^{i}-\phi_{at}^{j} = kh\,(x_i-x_j) + 2kT^2\,[\,a(x_i) - a(x_j)\,]$$

GW

Gravity gradient

- Low frequency GW measurement
- Measurement of the local gravity field → Geoscience

MIGA – GW sensitivity



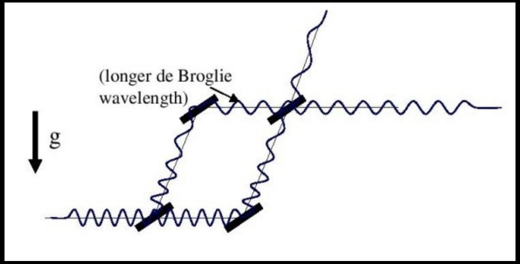
MIGA – upgrades

- Substitute Raman/Bragg transitions with single photon ones
- Trapped Atom Interferometry to increase interrogation time
- Measurement-and-correction interrogation schemes, interleaved schemes to increase sensitivity
- Engineer quantum noise to boost sensitivity (spin squeezing)

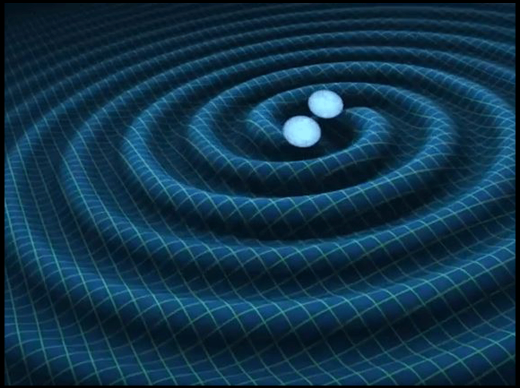
	MIGA	done	required
Momentum Separation:	2hk	$10^2(10^3?)$ hk	1000hk
Geometric separation:	3.5 mm	54 cm	~1 m
Detection sensitivity:	QPN	QPN-20dB	QPN-20dB
# atoms:	10^6	10^7	10^8
Separation:	300 m	10 m	10 km

Conclusions

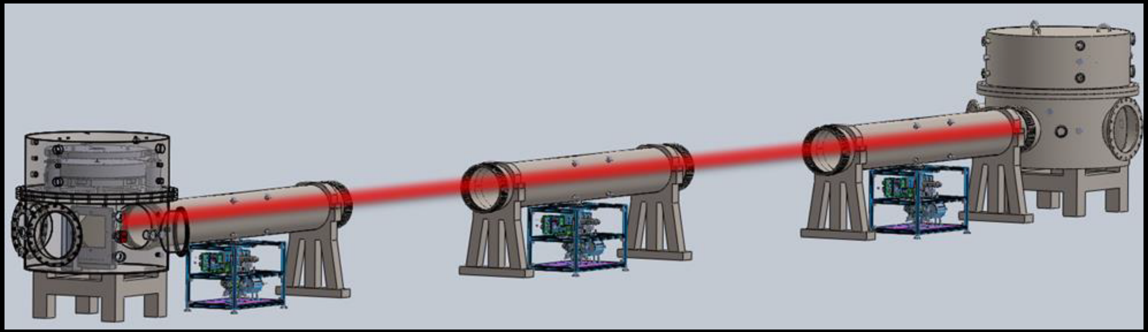
Atom Interferometry



AI as a new approach to GW detection, key features



MIGA for GW detection and geophysics, status of the experiment



Stuff @ LP2N and MIGA Consortium

P. Bouyer	
A. Bertoldi	
B. Canuel	
M. Prevedelli	Inv. Prof.
G. Lefèvre	PhD stud.
M. Essayeh	M2 stud.

Past members:

I. Riou	PhD stud
S. Pellisson	postdoc
J. Gillot	postdoc

Spatial correlation NN

PRD 93, 021101(R) – 2016

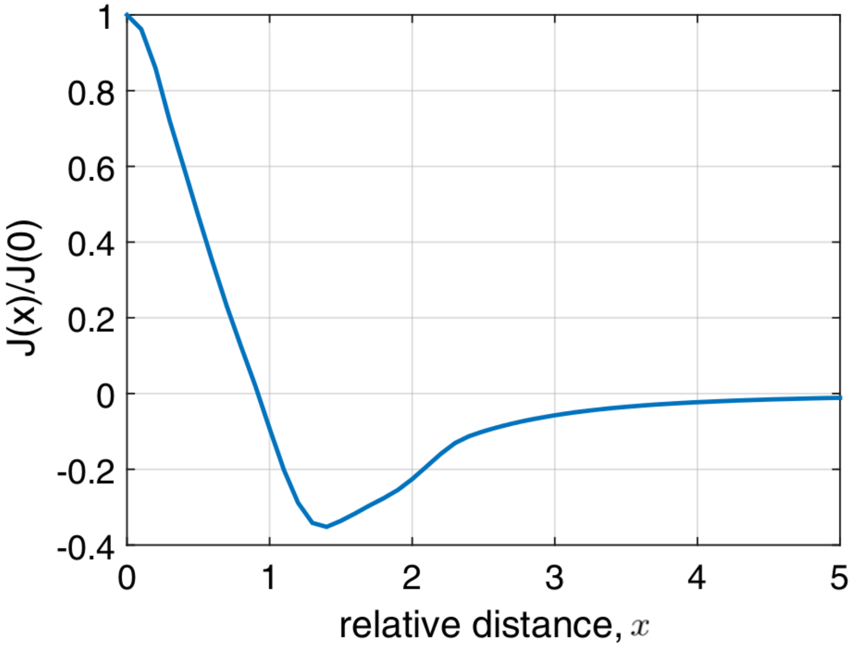


FIG. 2. Spatial behavior of the normalized NN correlations between two distant points separated by the relative distance $x = |X_j - X_i|/\mathcal{L}_\rho(\omega)$, where $\mathcal{L}_\rho(\omega)$ is the NN correlation length. The anticorrelation is a consequence of mass conservation between adjacent cells of fluctuating density.

NN reduction using AI array

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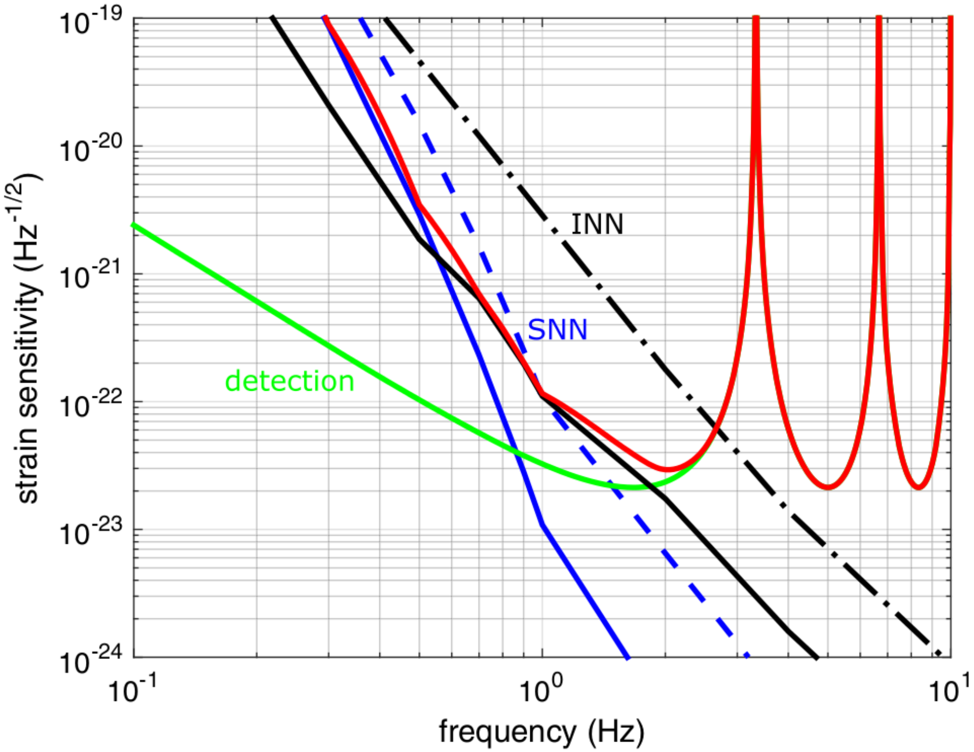

FIG. 3. Strain sensitivity curve for an AI array with $N = 80$, $\delta = 200$ m, $\delta_0 = \delta_N = 500$ m, $L = 16.3$ km and $L_a = 32.6$ km. The AI phase noise is -140 dB rad^2/Hz with the interrogation time $T = 0.3$ s, and $n = 1000$ LMT beam splitters. Green: Detection noise. Dotted-dashed black (dashed blue): INN (SNN) for two test masses separated by the baseline L. Solid black line (blue): Residual INN (SNN) after NN rejection with the AI array. Red: Overall sensitivity curve.

INN: Infrasound NN
SNN: Seismic NN

Compact large mode cavity AI arXiv:1701.01473