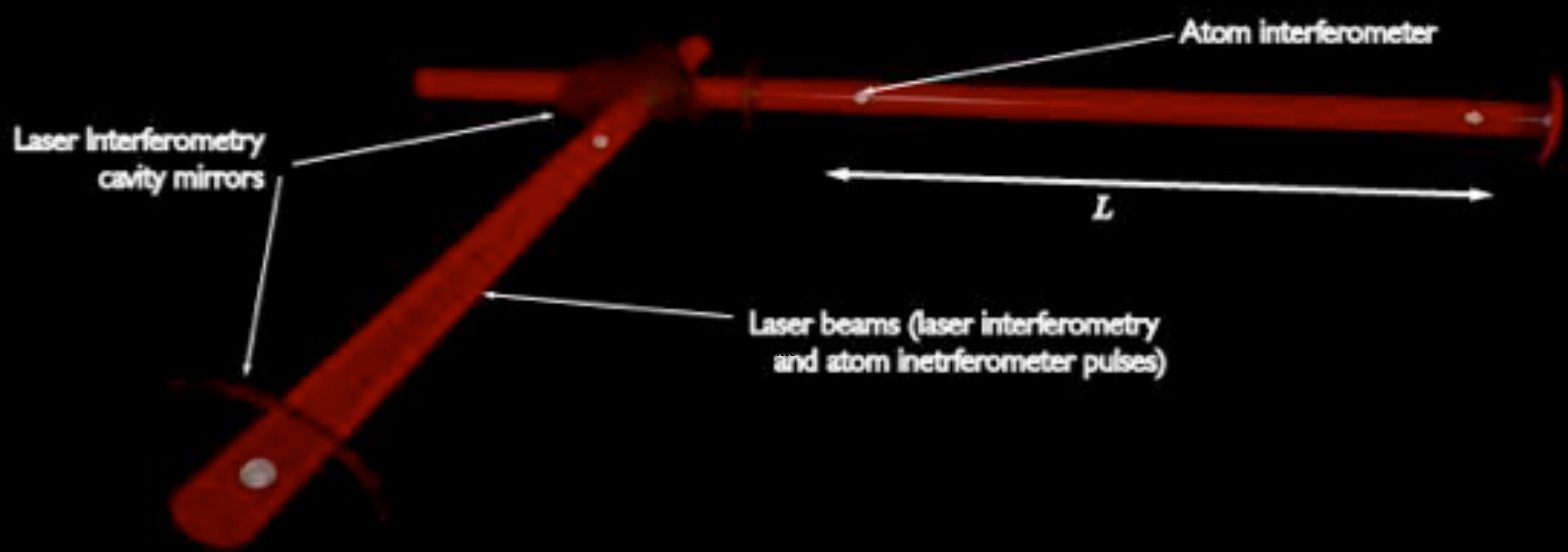
Underground matter-wave interferometer based gravitation antenna

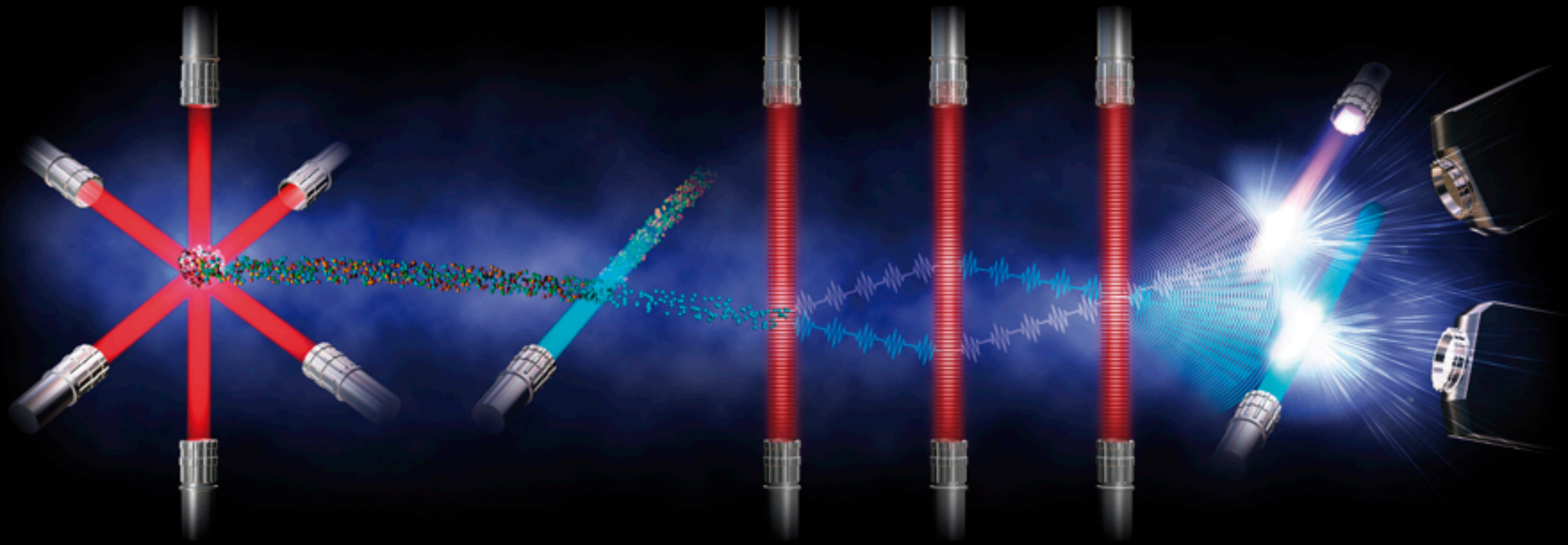


P. Bouyer

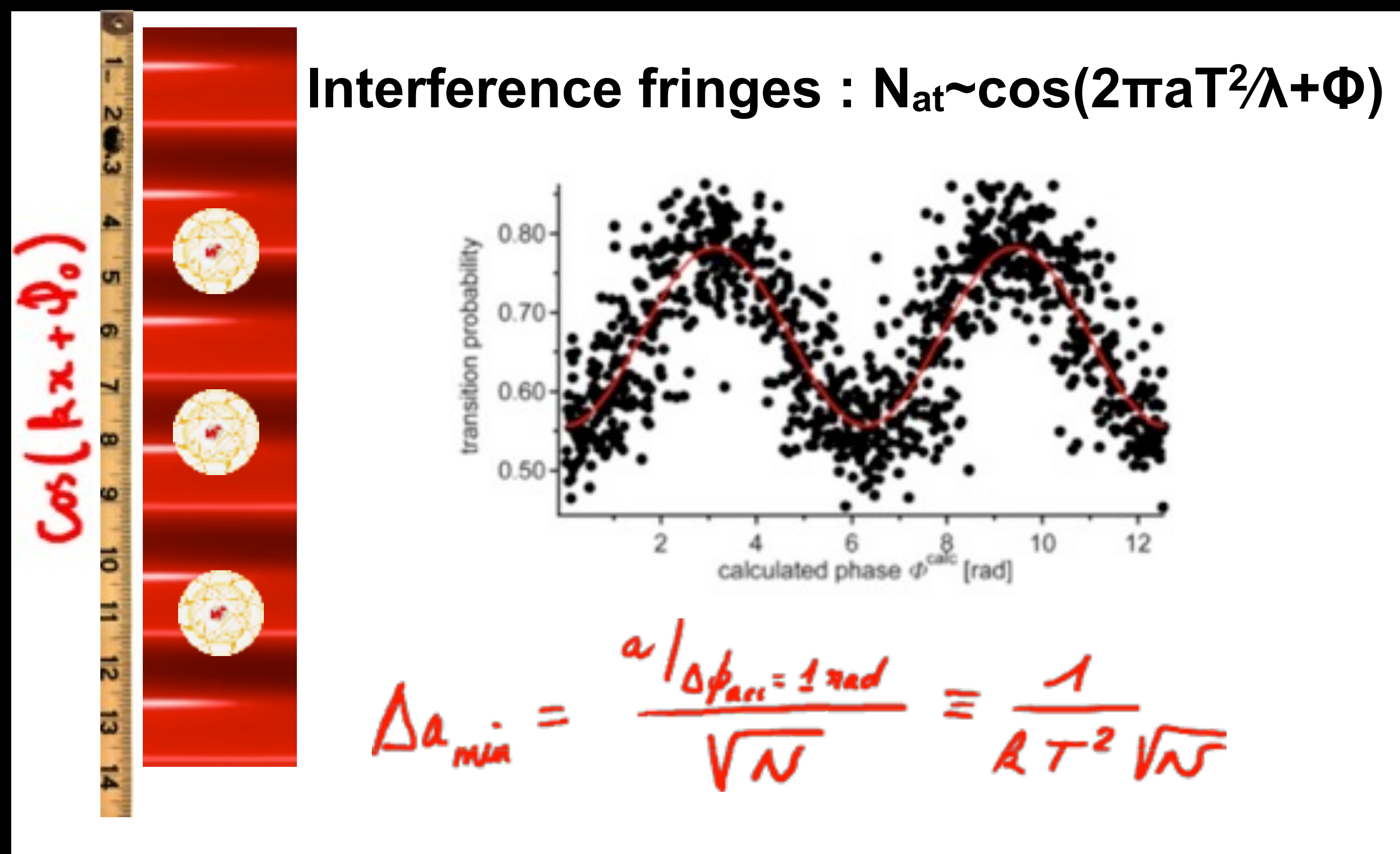
Laboratoire Photonique, Numérique et Nanoscience, Bordeaux, France

on behalf of the MIGA partners

Using atom Interferometry ...



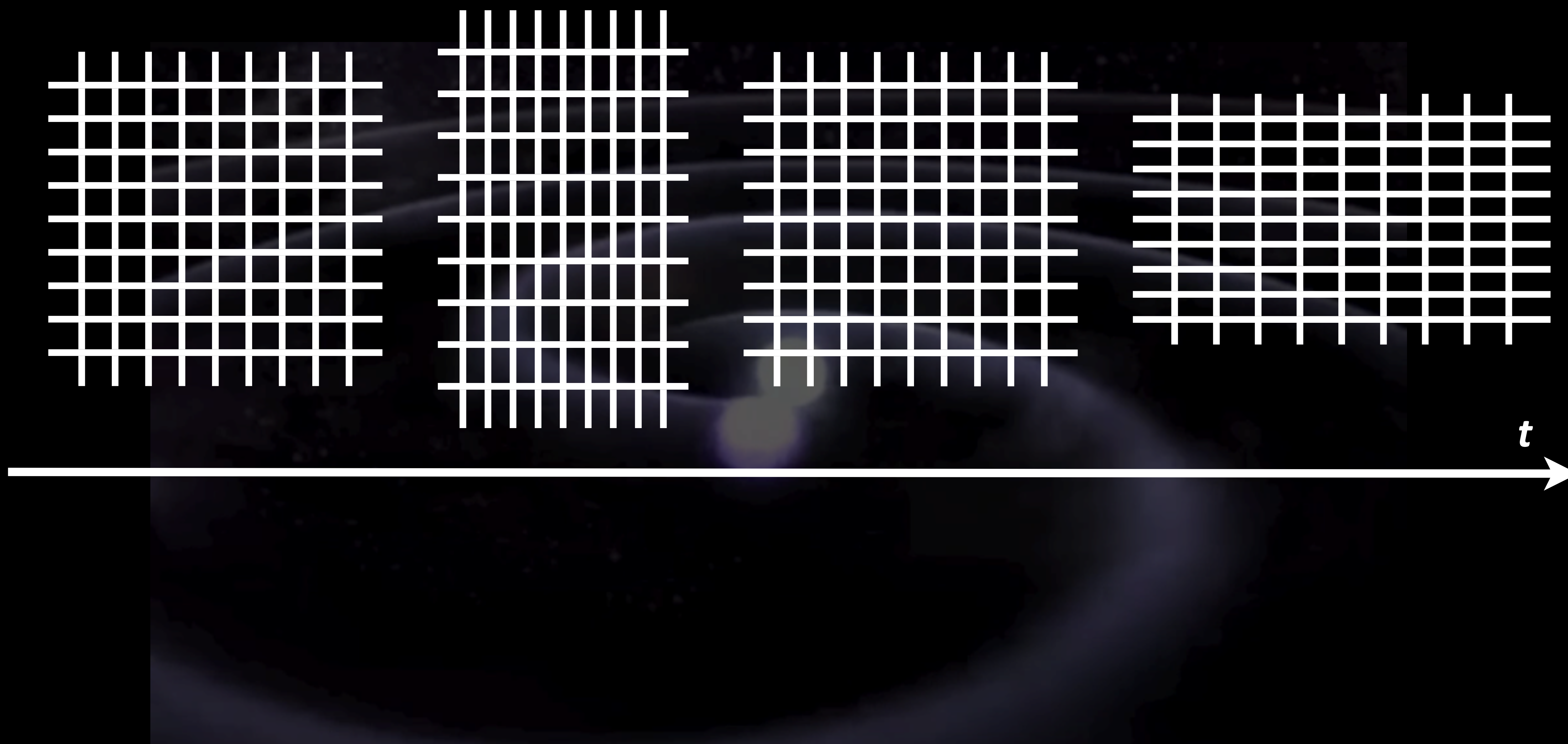
Using atom Interferometry ...



... to detect gravitational waves

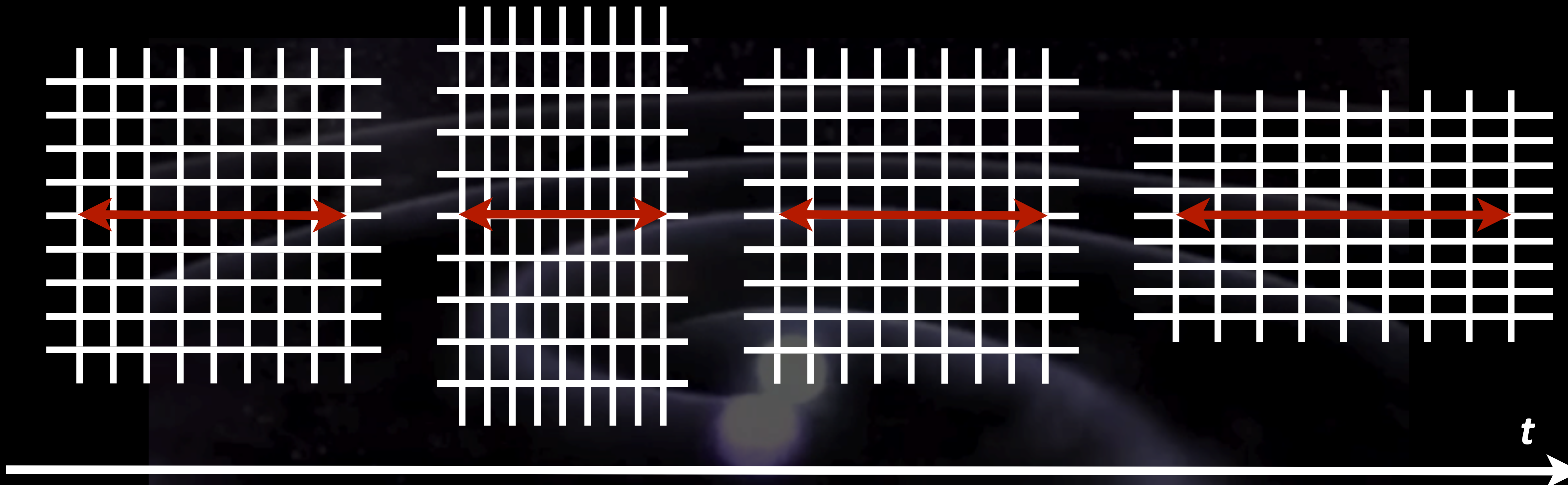
Gravity waves will distort space time

example of a linearly polarized GW



Gravity waves will distort space time

example of a linearly polarized GW



the time light will take to travel between 2 points anchored to the reference frame will be modulated

Gravity waves will distort space time

example of a linearly polarized GW

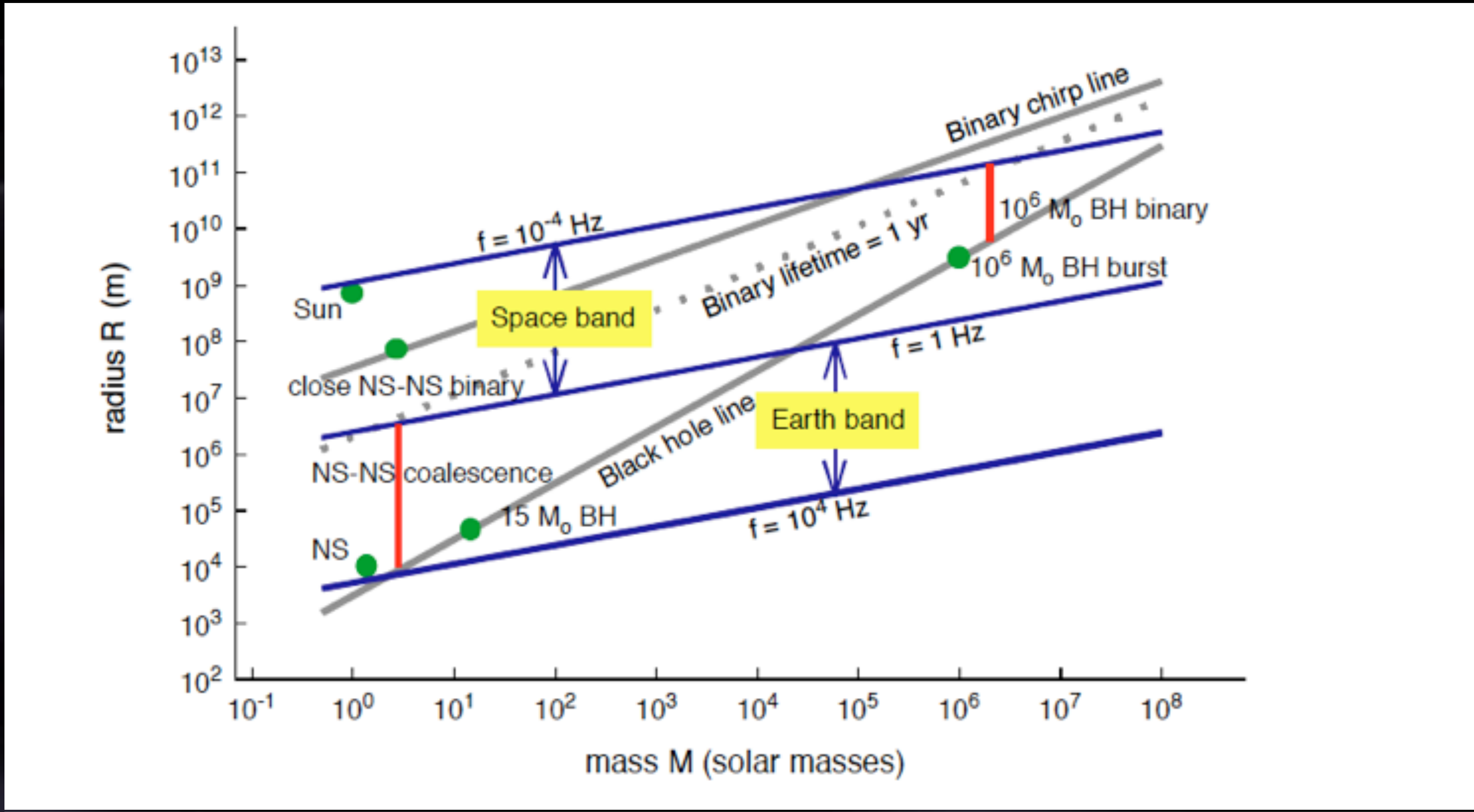
the time light will take to travel between 2 points anchored to the reference frame will be modulated

strain h (modulation amplitude) is very small on the earth ($\approx 10^{-20}$)

frequency Ω of the gravitational wave spans over a large range (mHz to kHz)

$$L/2[1+h.\sin(\Omega t)]$$

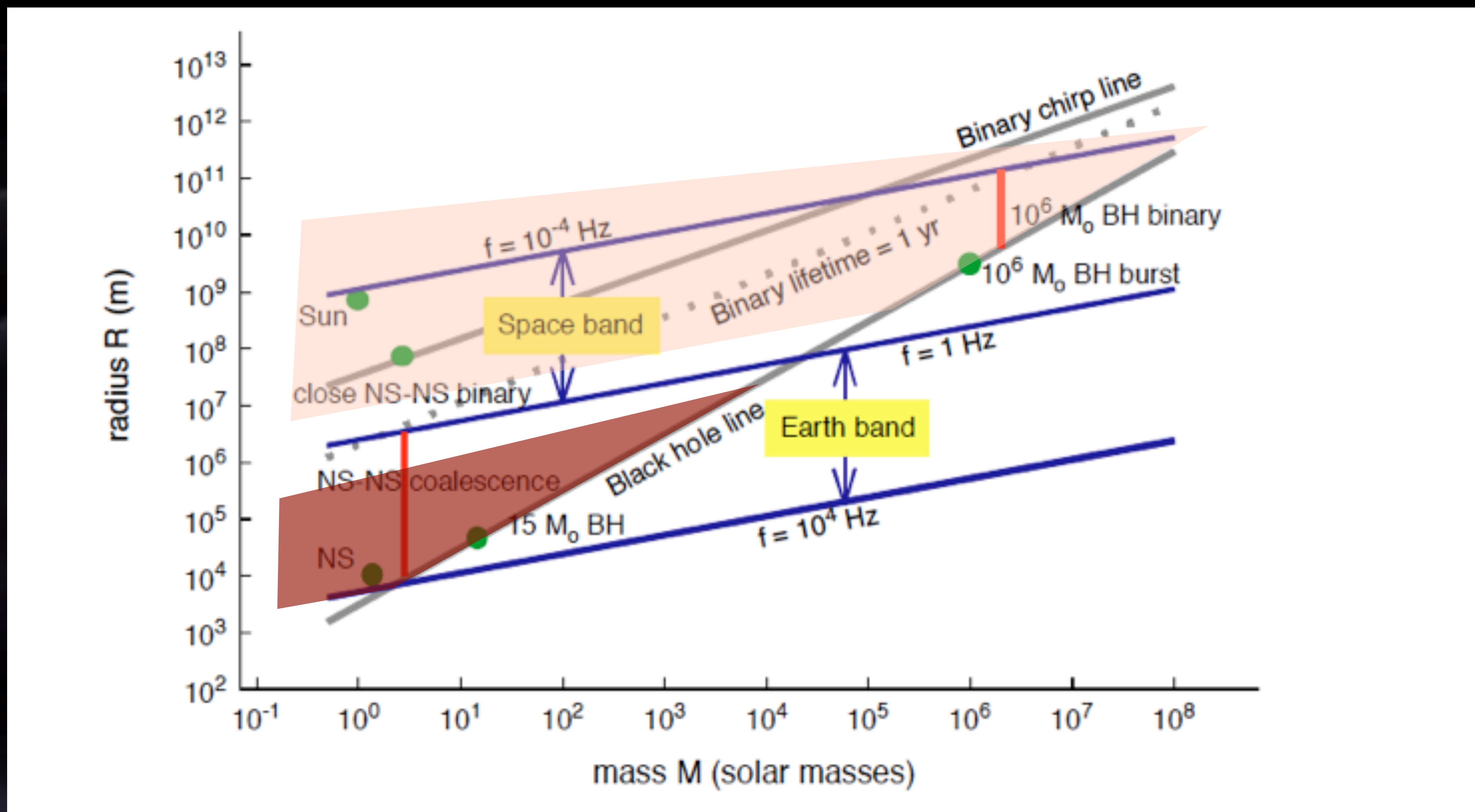
$L/2[1+h.\sin(\Omega t)]$



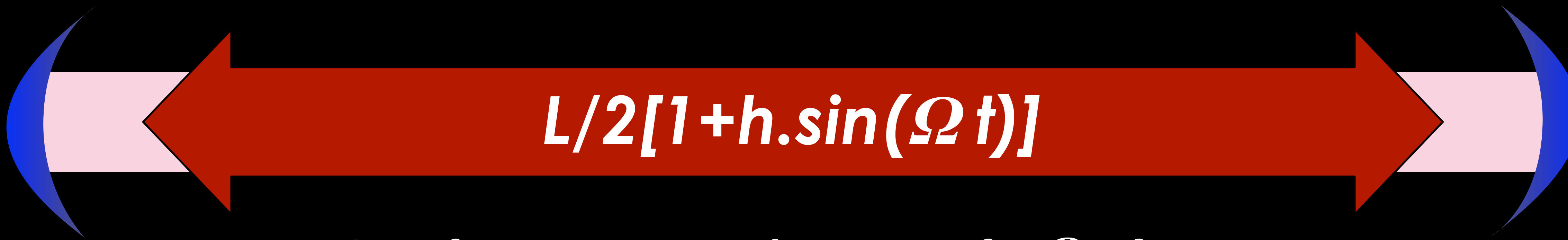
From Schultz, Class. Quantum Grav. 13 (1996) A219–A238

$L/2[1+h.\sin(\Omega t)]$

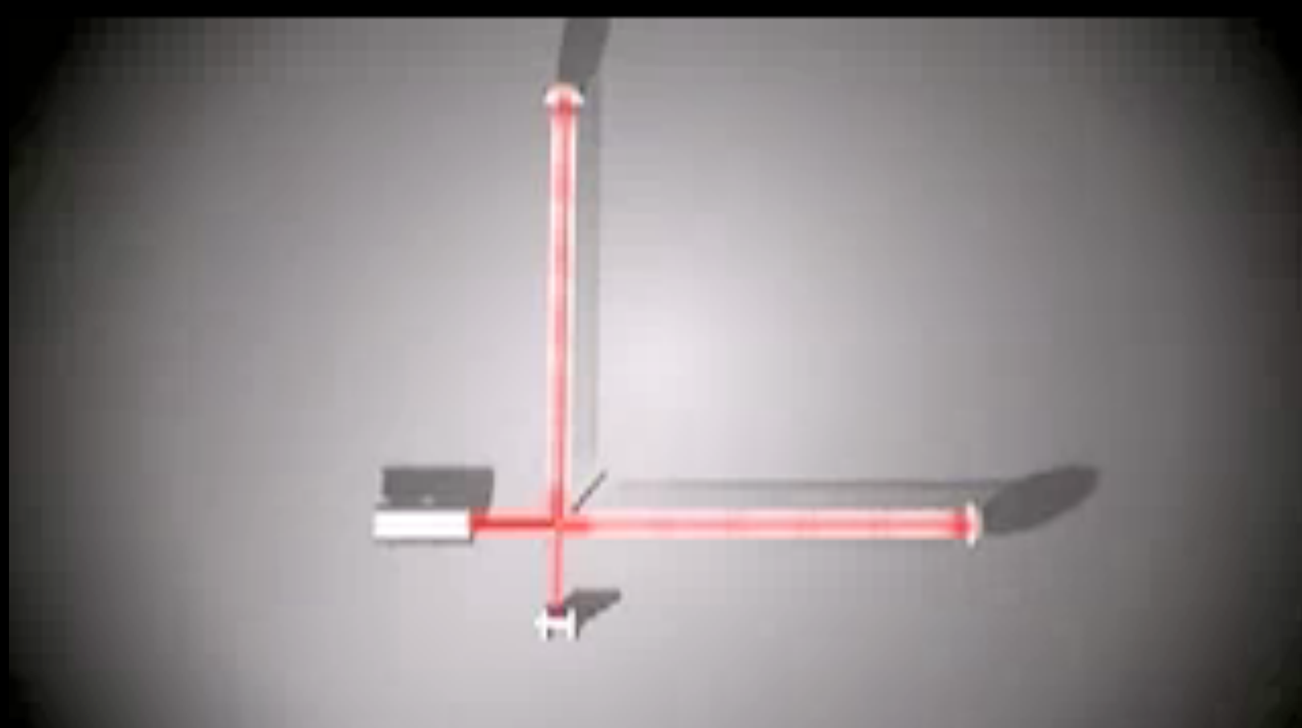
Laser interferometers can detect GW for Ω > few Hz.



From Schultz, Class. Quantum Grav. 13 (1996) A219–A238



Laser interferometers can detect GW for Ω > few Hz.

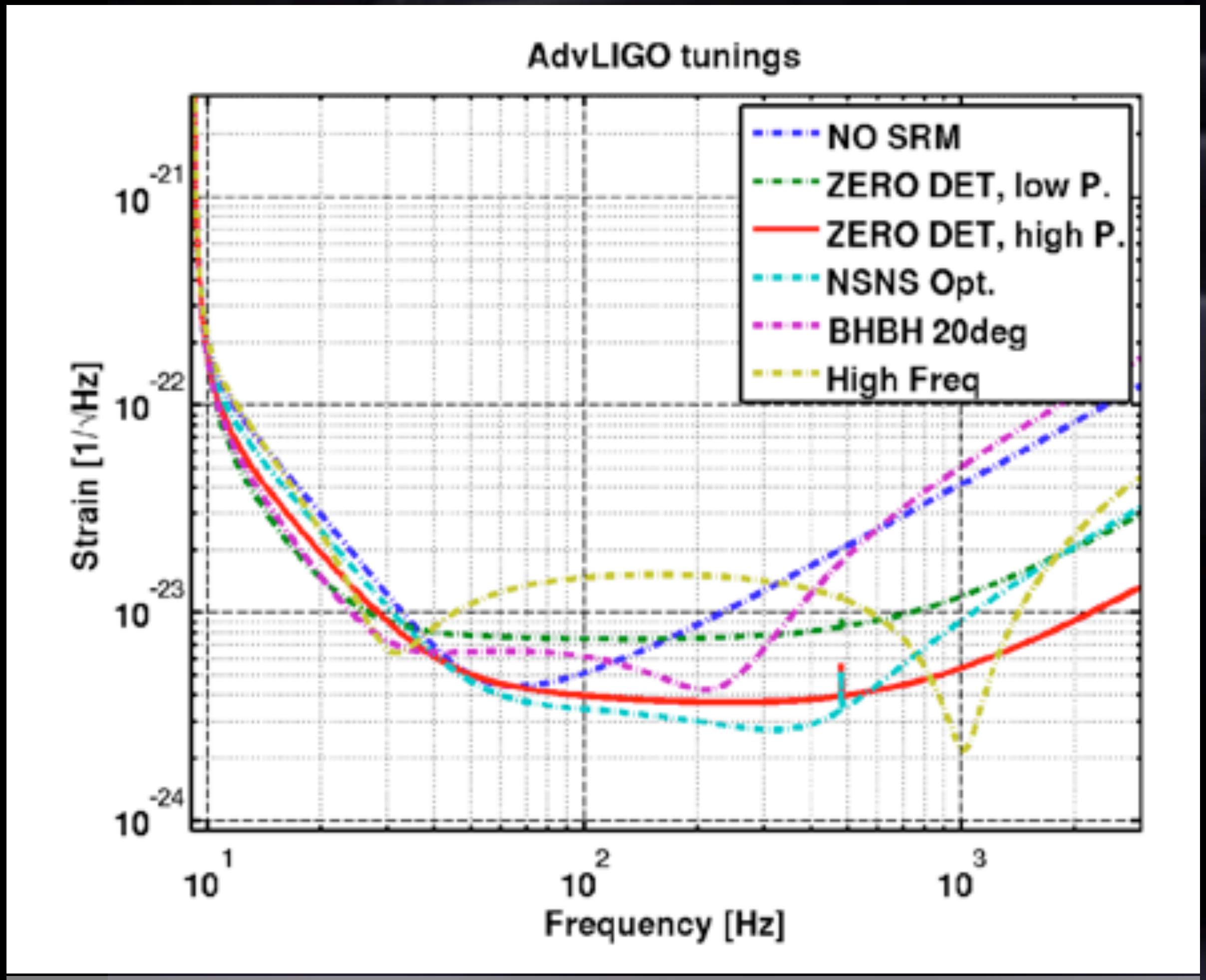


Laser readout of distance between 2 proof masses in free fall (2 mirrors).

Mirrors must be «isolated» from ground by high performance suspensions

2 arms (Michelson type) interferometer.

Laser interferometers can detect GW for Ω > few Hz.



Laser readout of distance between 2 proof masses in free fall (2 mirrors).

Mirrors must be «isolated» from ground by high performance suspensions

2 arms (Michelson type) interferometer.

Low frequency sensitivity limited to few Hz because of seismic noise.

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Correlated measurement by coupling atoms and cavity mirrors

Position → $x \sim L(1 + h\sin(\omega t))$

Acceleration → $a \sim hL\omega^2 \sin(\omega t)$

Correlated measurement by coupling atoms and cavity mirrors

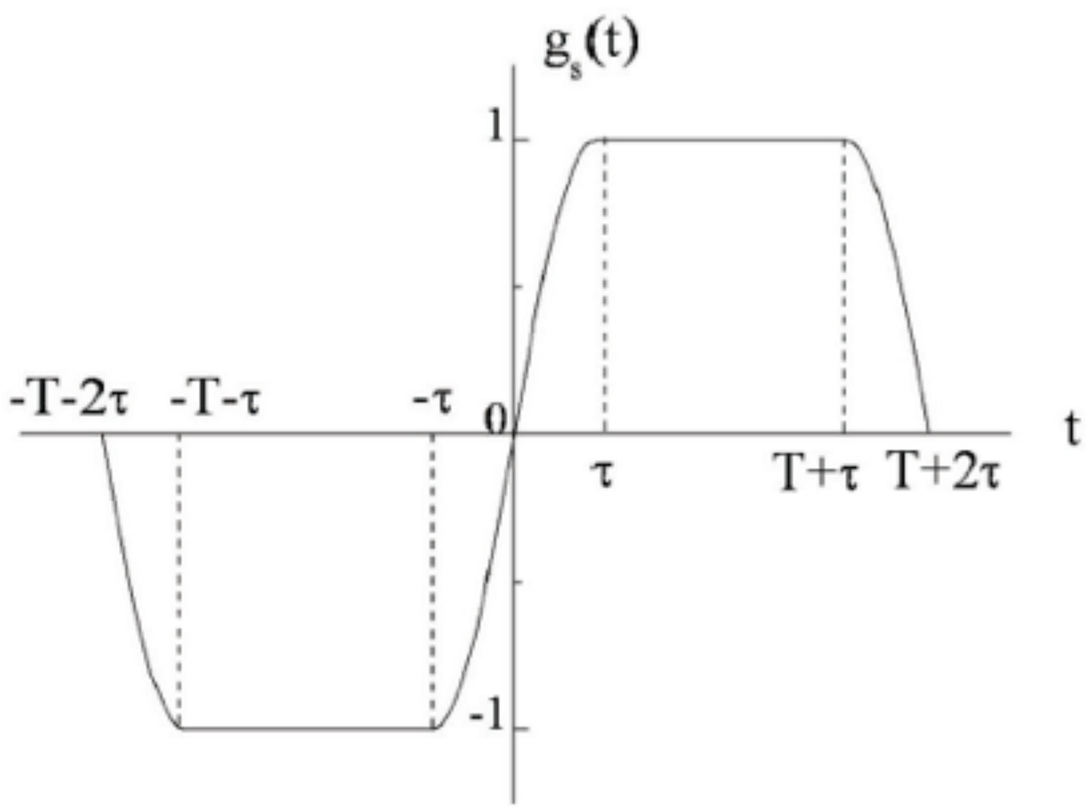
Position → $x \sim L(1 + h\sin(\omega t))$

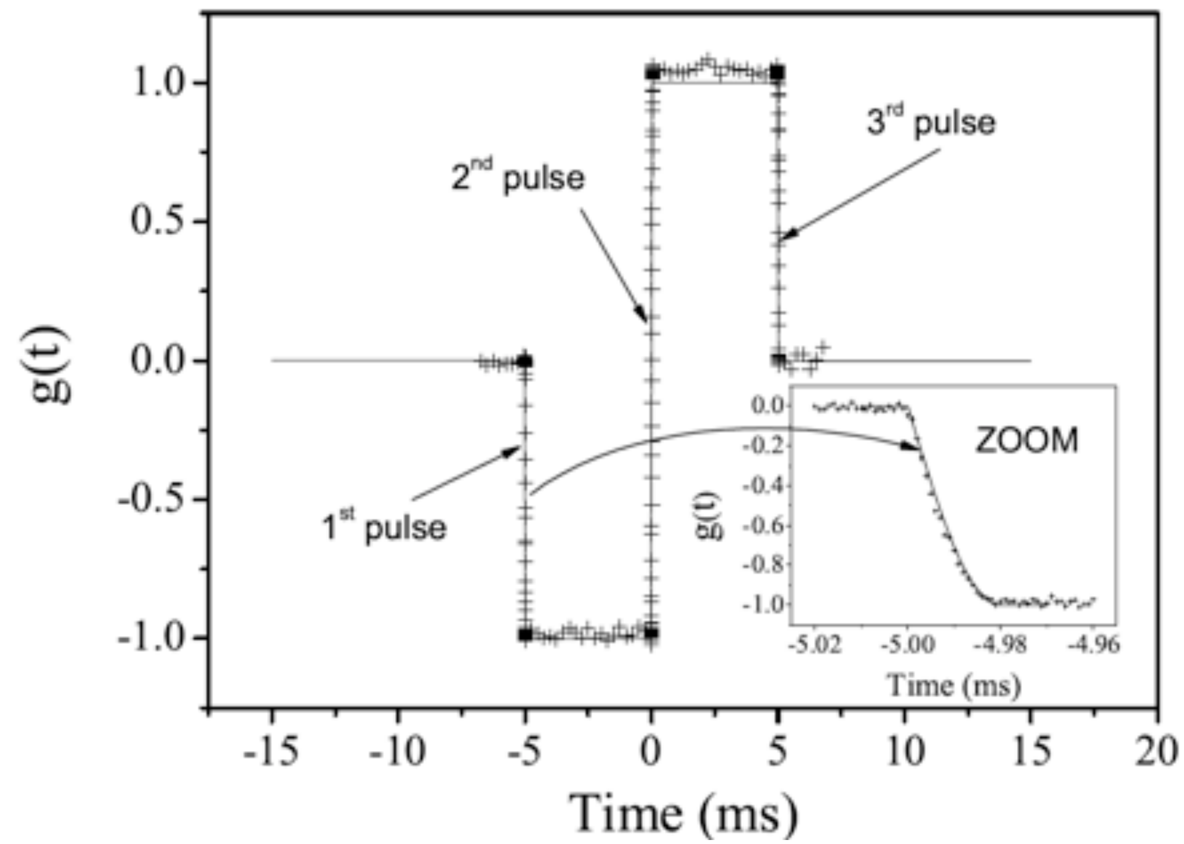
Acceleration → $a \sim hL\omega^2 \sin(\omega t)$

$$\Delta\phi = kaT^2 \sim khL\omega^2 \sin(\omega t)T^2$$

$$\Delta\phi = kaT^2 \sim khL\omega^2 \sin(\omega t)T^2$$

The sensitivity function is a natural tool to characterize the influence of the noise of the environment on the the interferometric phase.



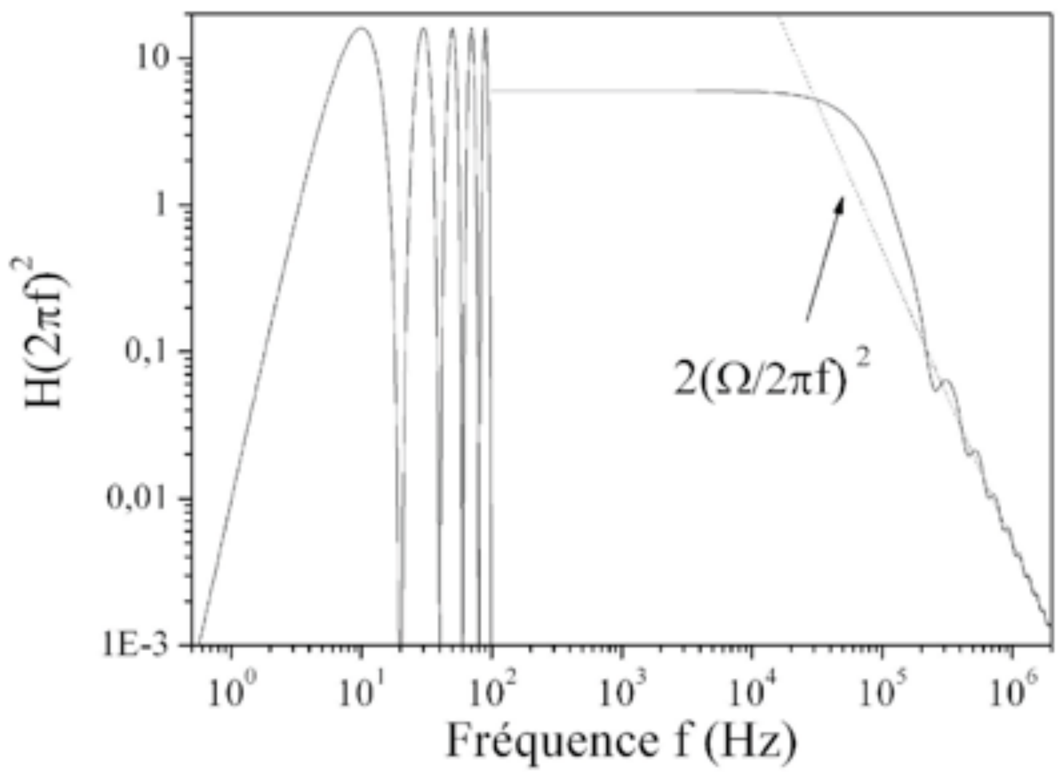


$$g(t) = \begin{cases} \sin(\Omega_R t) & 0 < t < \tau_R \\ 1 & \tau_R < t < T + \tau_R \\ -\sin(\Omega_R(T-t)) & T + \tau_R < t < T + 2\tau_R \end{cases}$$

$$\delta\Phi = \int_{-\infty}^{+\infty} g_s(t)d\phi(t) = \int_{-\infty}^{+\infty} g_s(t)\frac{d\phi(t)}{dt}dt$$

Interferometer transfer function (acts as a filter)

- Introduce the transfer function $H(\omega) = |\omega G(\omega)|$

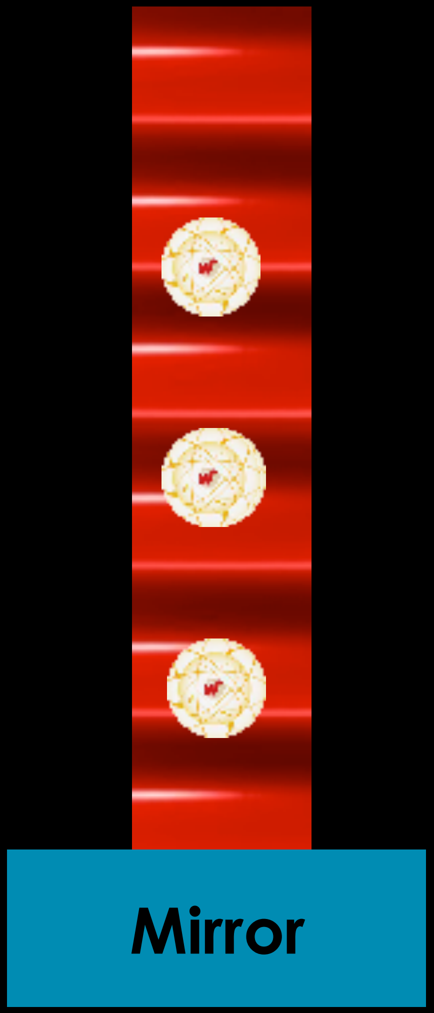


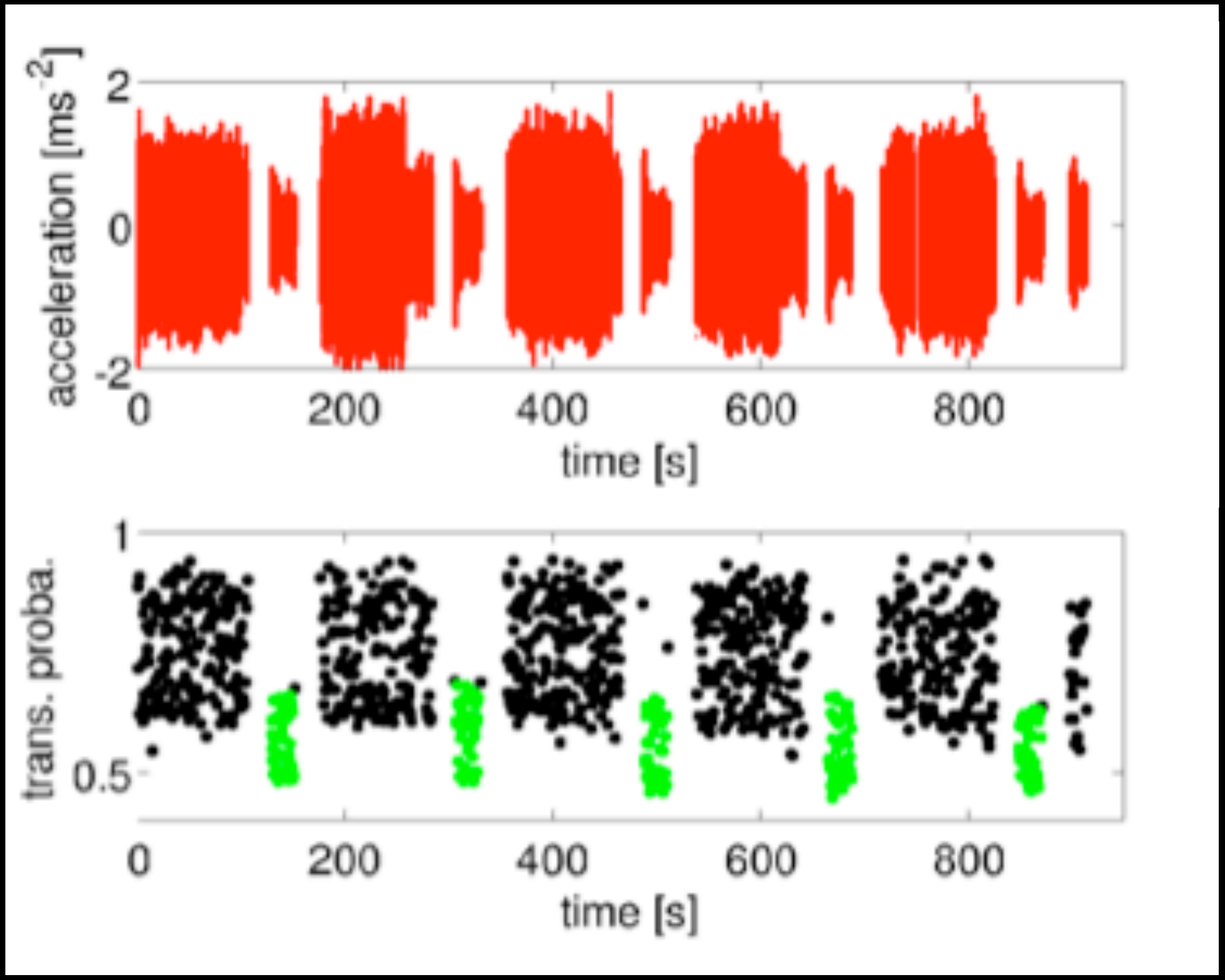
- Error induced by phase noise

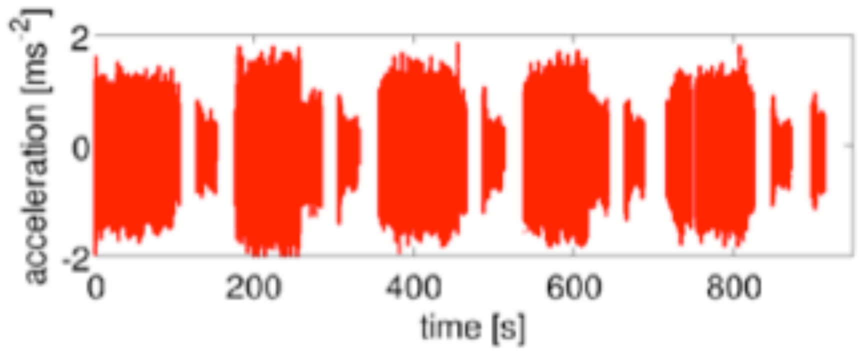
$$\sigma_\Phi^2 = \int_0^{+\infty} |\omega G(\omega)|^2 S_\phi(\omega) \frac{d\omega}{2\pi}$$

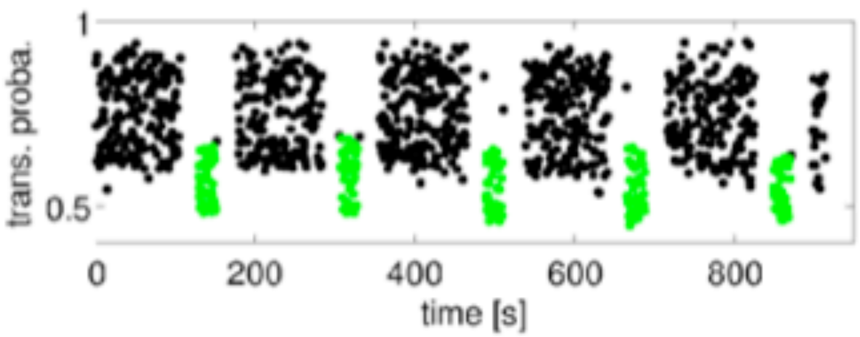
- Can compute sensitivity function for all contributions

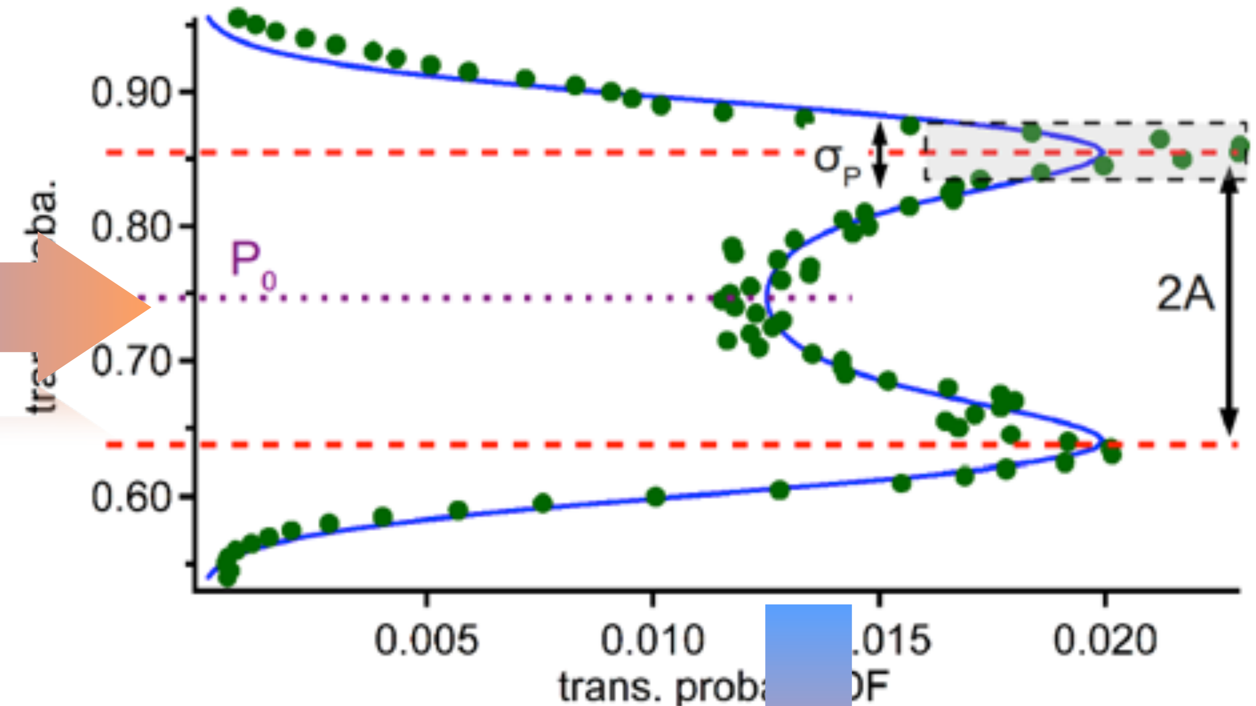
One example of correlated measurement

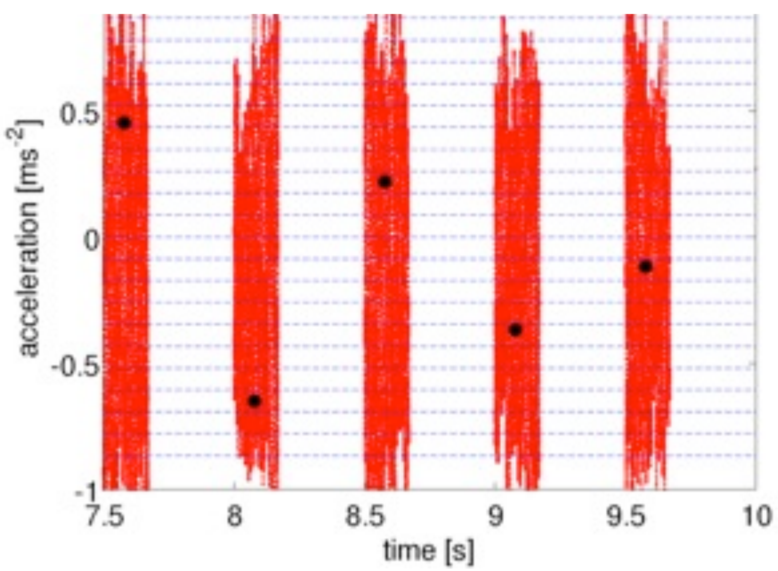

Mirror


acceleration [ms^{-2}]
2
0
-2
0
200
400
600
800
time [s]
trans. proba.
1
0.5
0
200
400
600
800
time [s]



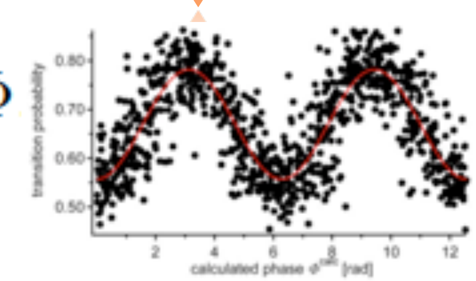






$$\Phi = a_{\mathrm{m}} \times kT^2$$

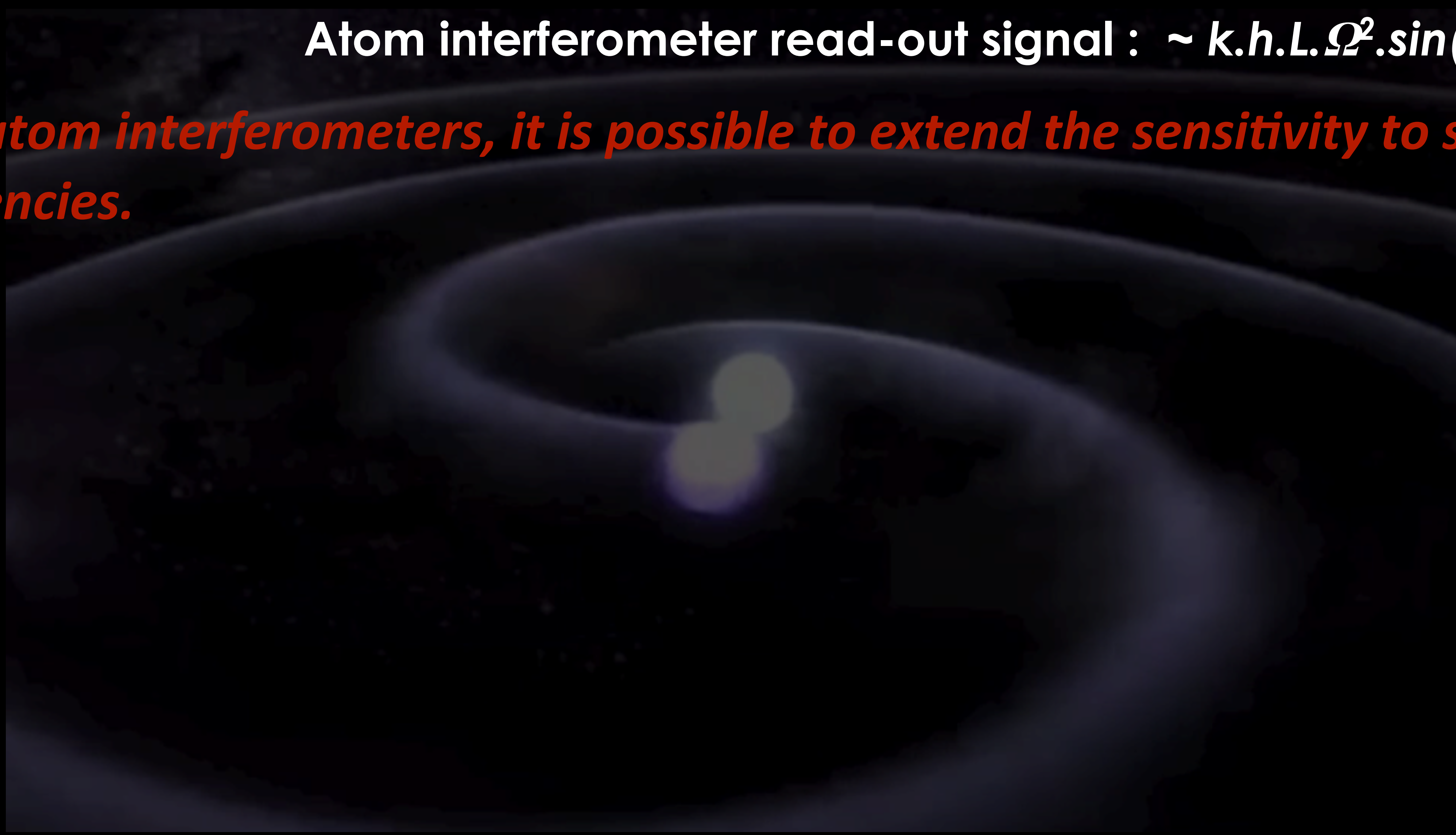
$$P^{\mathrm{AI}}(\Phi) = P_0 - A\cos\Phi$$



$$\mathrm{SNR} = A/\sigma_P$$

$$P_0 = 0.747,\, 2A = 0.261 \text{ and SNR} = 4.7$$

Laser cavity read-out signal : ~ $h.L.\sin(\Omega t)$

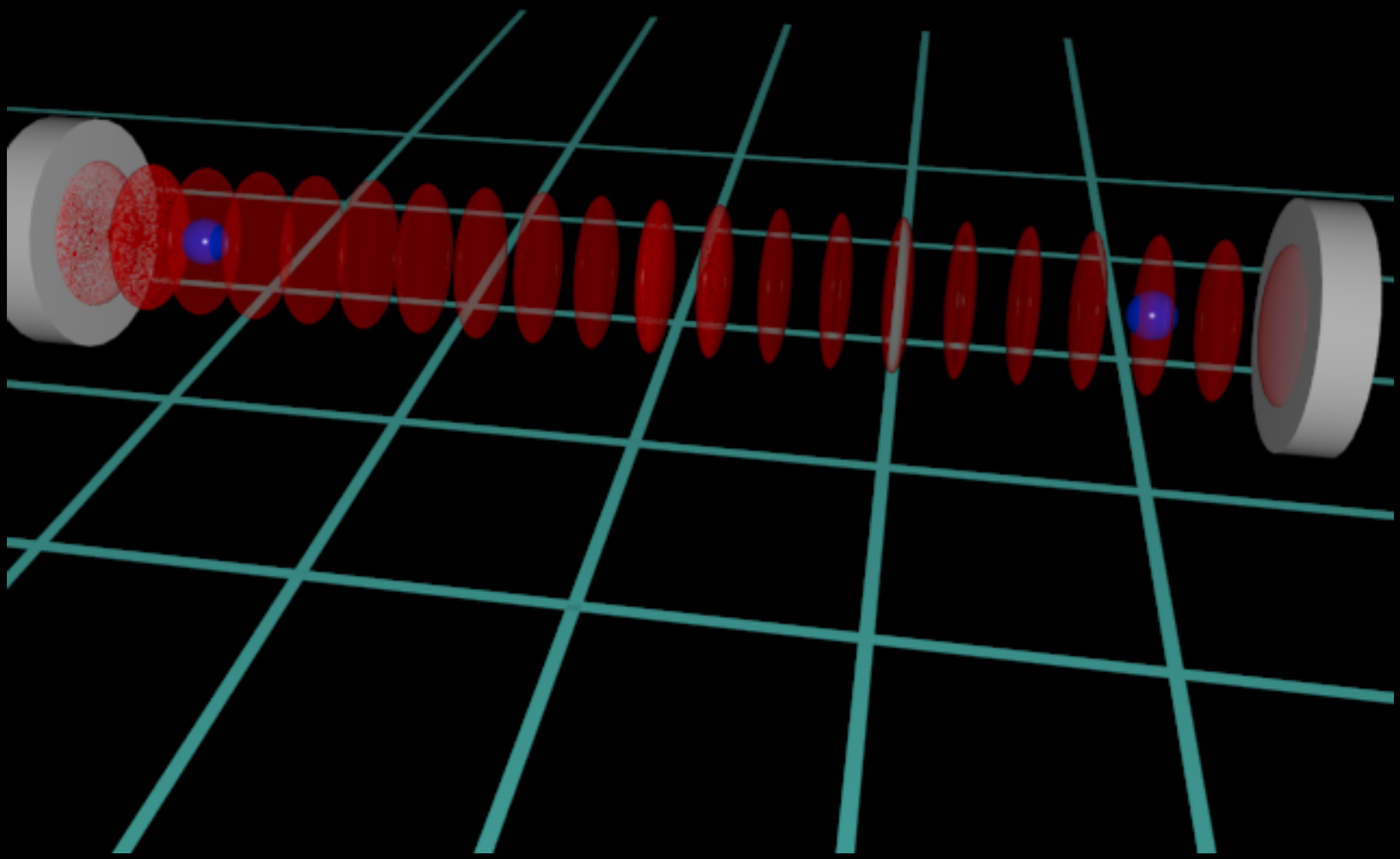


Atom interferometer read-out signal : ~ $k.h.L.\Omega^2.\sin(\Omega t)$

With atom interferometers, it is possible to extend the sensitivity to sub Hz frequencies.

How to readout GW signal

Laser locked to cavity and used for light pulse atom interferometry



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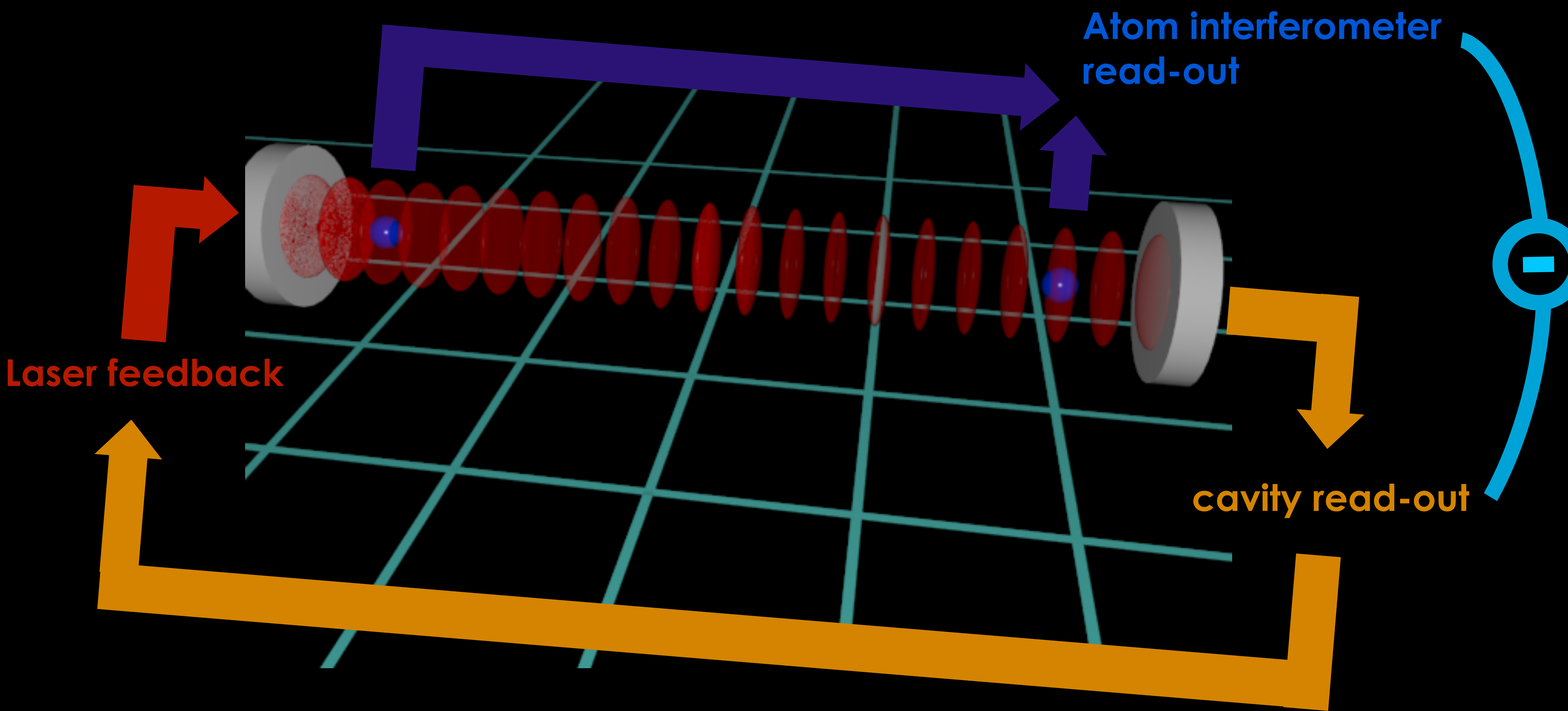
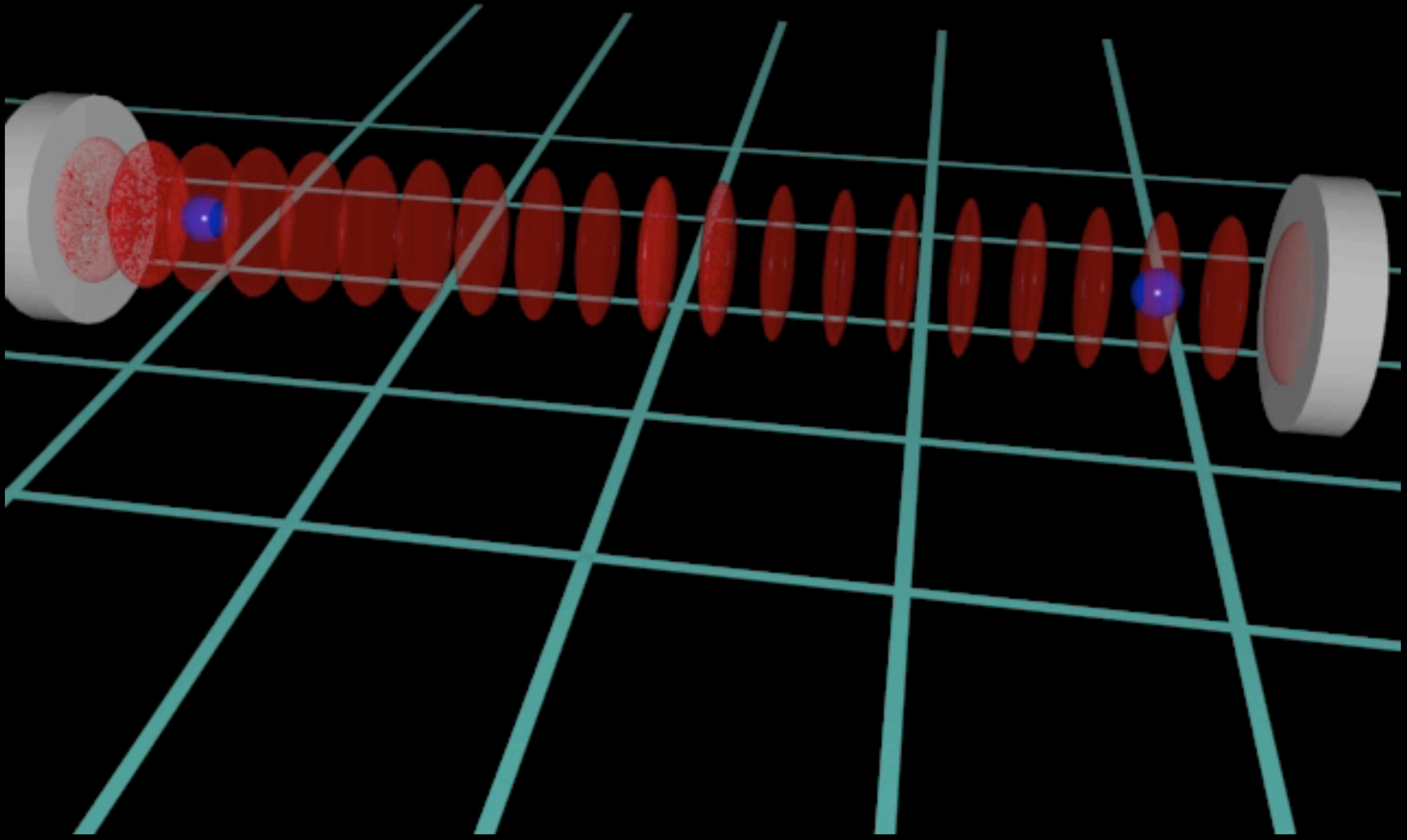


Effect of gravitational wave : *L.h.sin(Ω t)*

Laser cavity read-out signal : $\partial(k^{-1}) \sim L.h.\sin(\Omega t)$

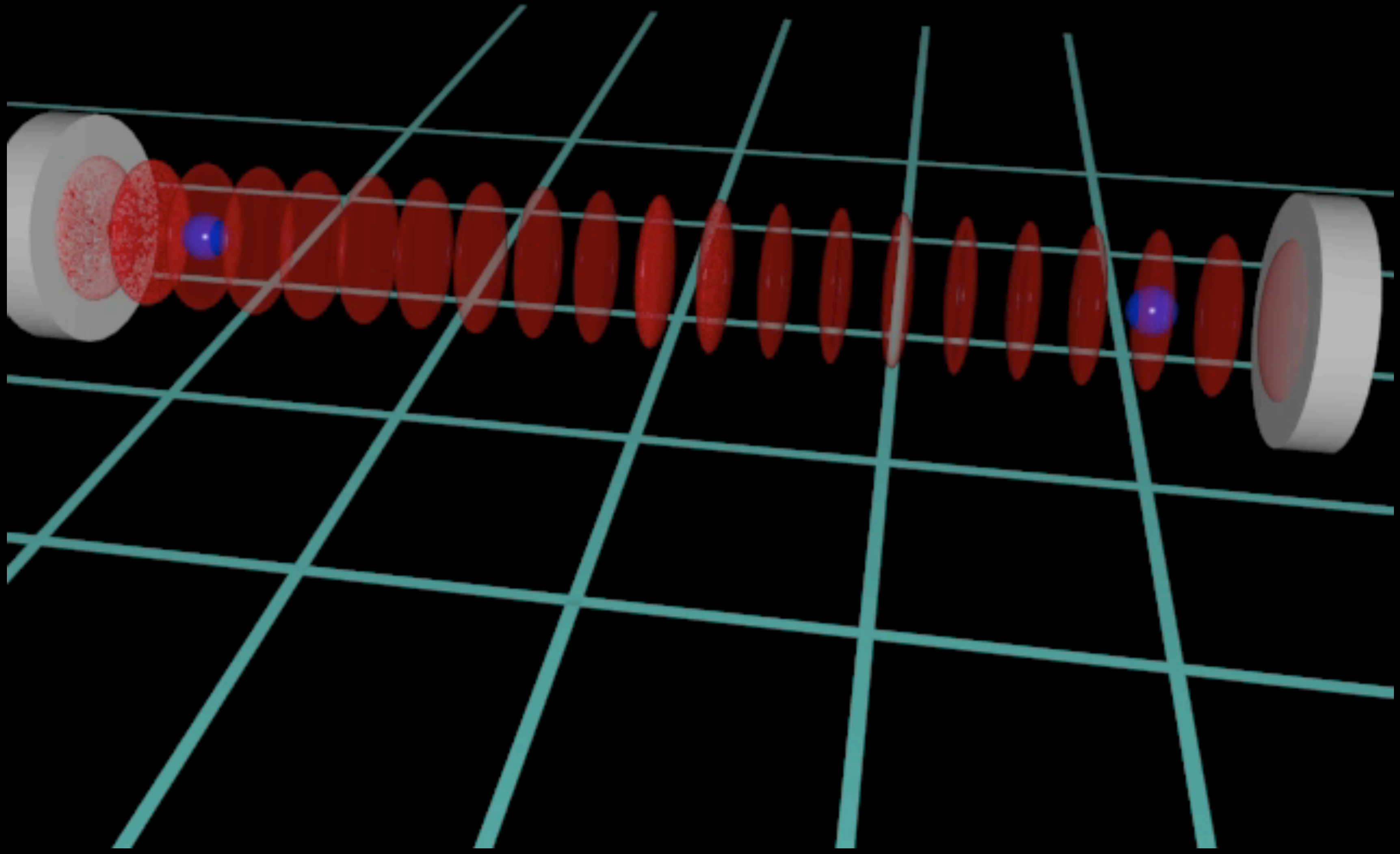
Atom interferometer read-out signal : ~ 0



Effect of seismic noise : 0

Laser cavity read-out signal : $\partial(k^{-1}) \sim A.sin(\Omega t)$

Atom interferometer read-out signal : $\sim A.sin(\Omega t)$

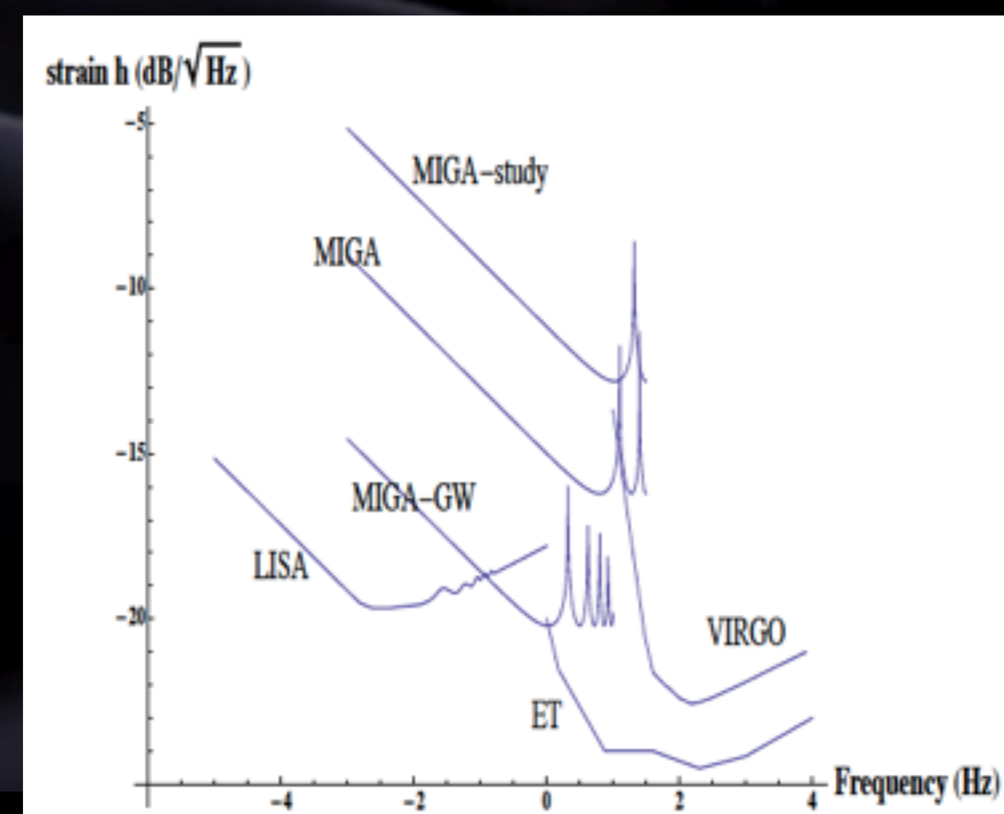


By correlating atom interferometers and cavity readout, it is possible to extend the sensitivity to sub Hz frequencies.

MIGA-study: current state-of development technology for compact sensors
.3 second interrogation time, L = 100 m, 4 recoil light pulse splitter, atomic shot noise limited phase shift sensitivity of 100 µrad

MIGA: shortterm enhanced design performances
.5 second interrogation time, L=1 km, 100 recoil.

MIGA-GW: ambitious design performance
3 second interrogation time, L=10 km, 1000 recoil, 1 µrad atomic phase shift sensitivity



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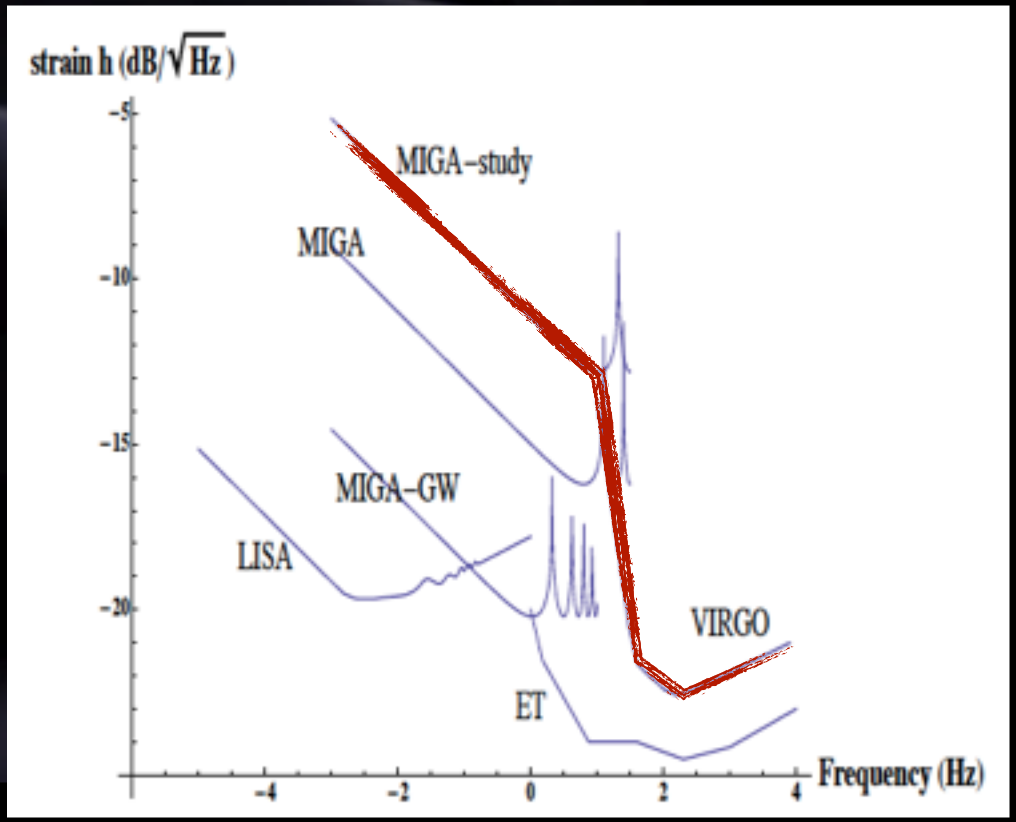

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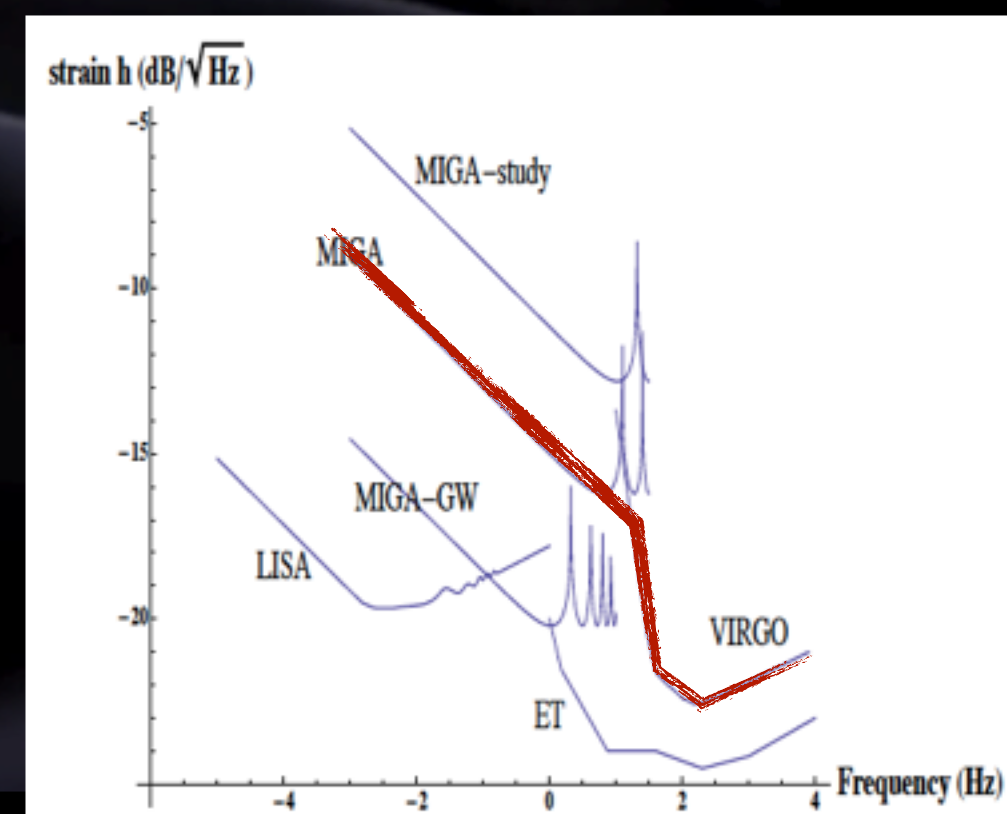

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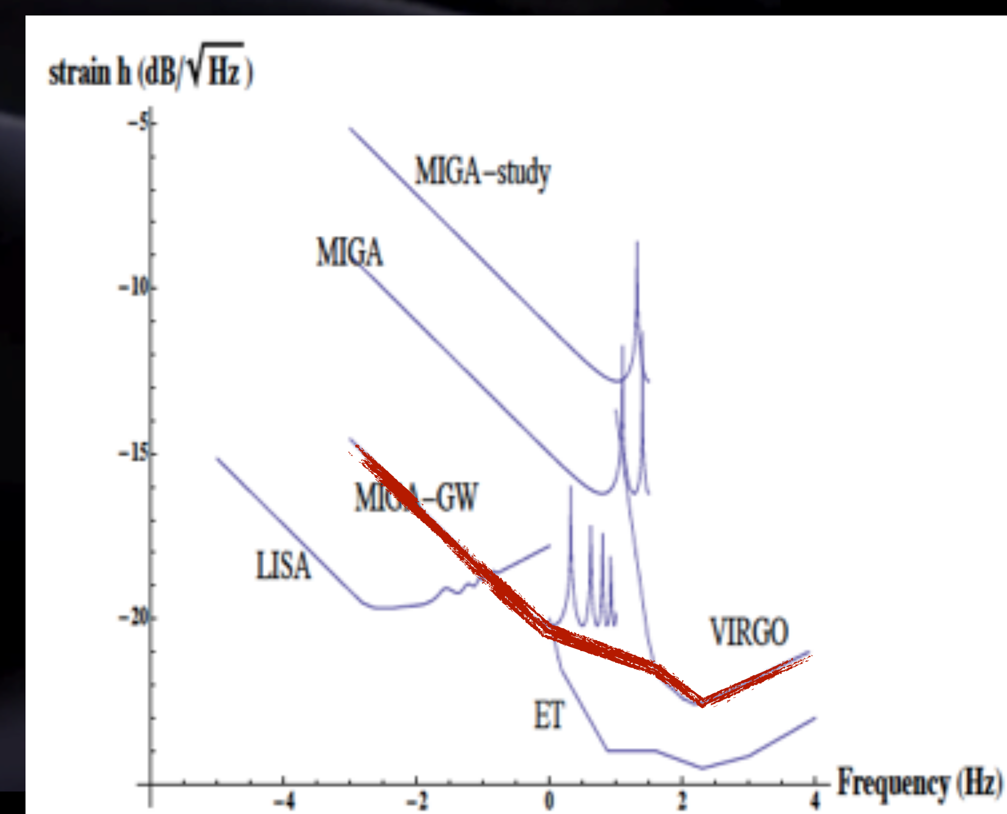
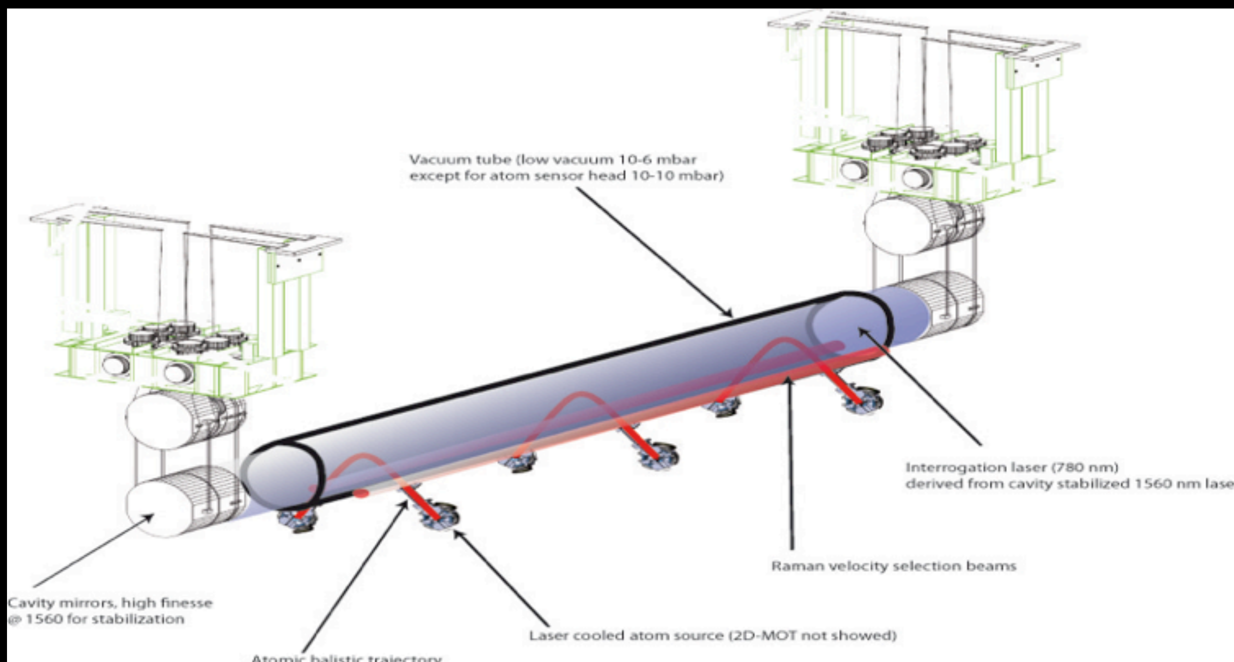


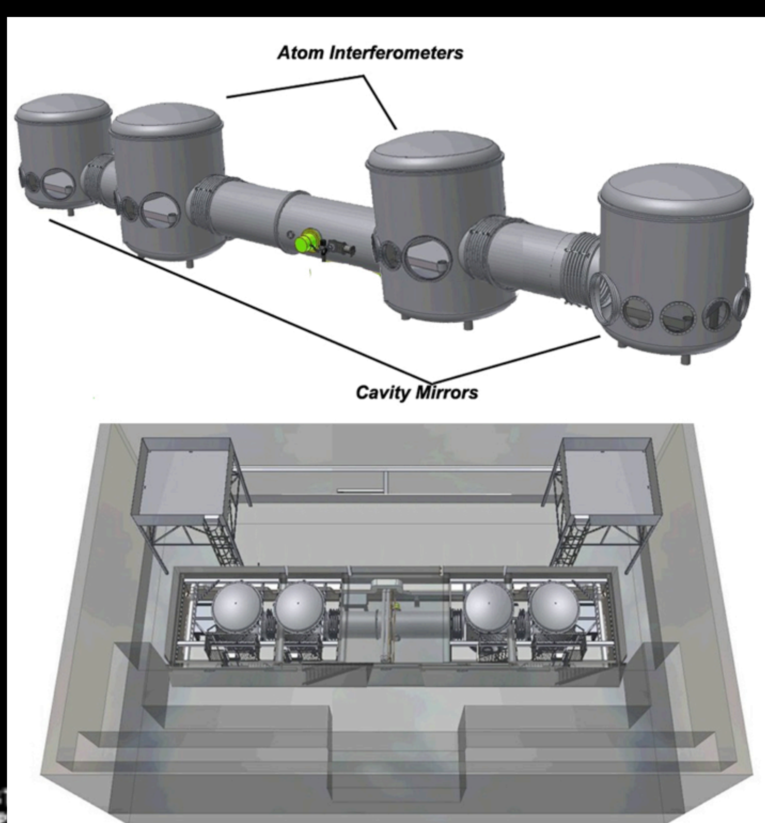
Funded instrument EQUIPEX 2011 : France

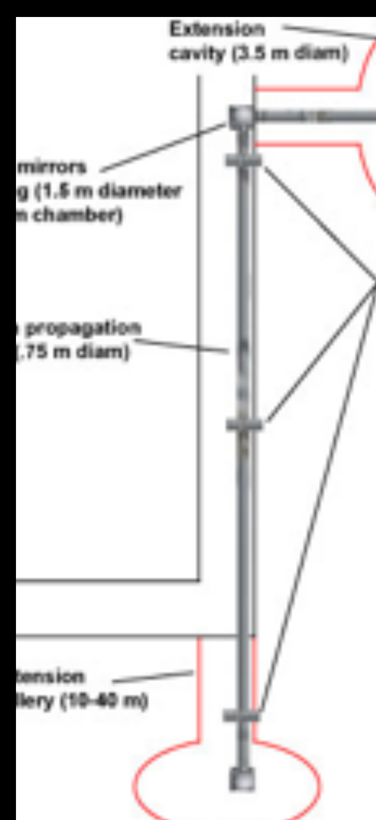
First “small” version : 400-600 m



15 institutes - 3 compagnies

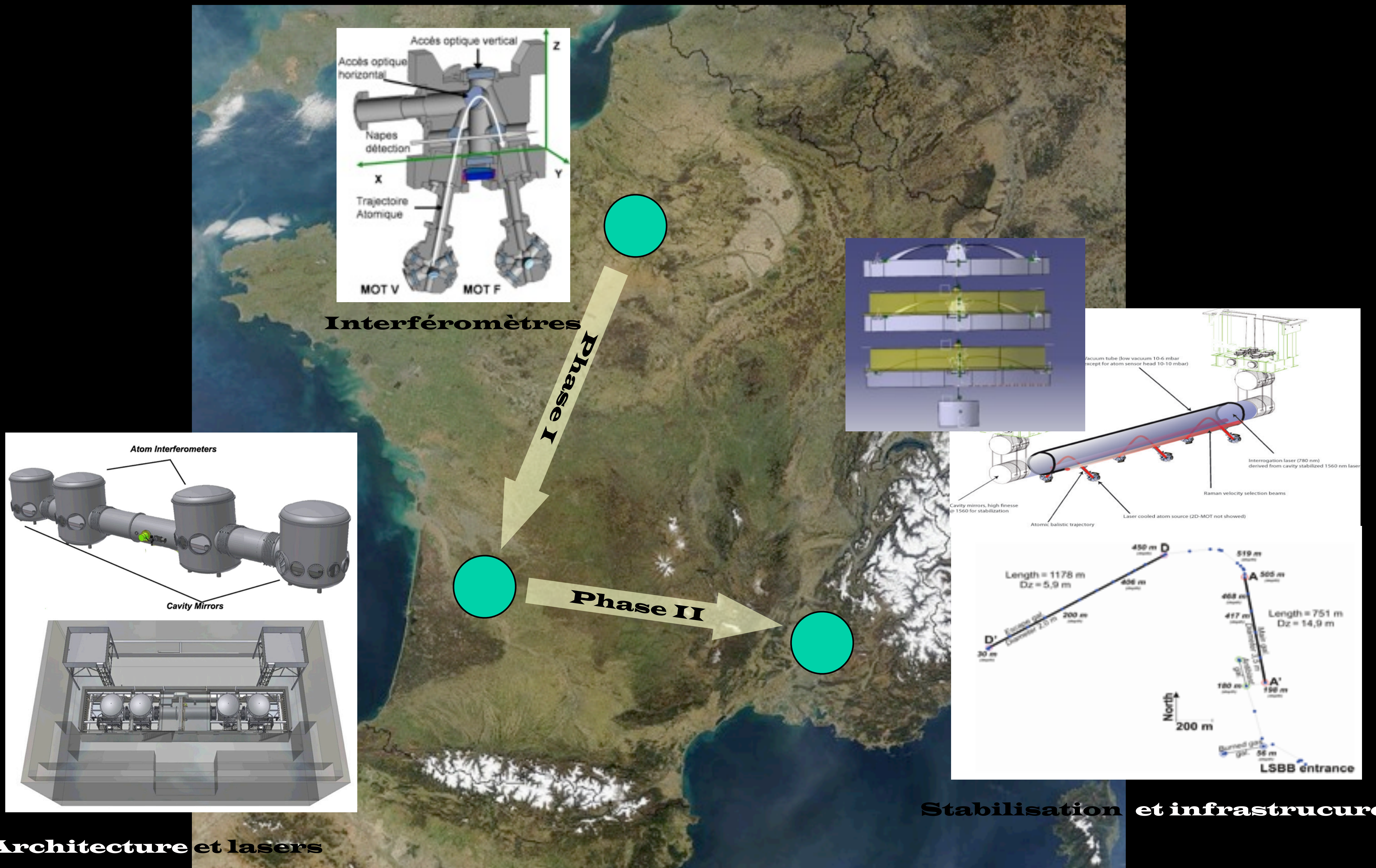
Laboratoire(s)/ Laboratory	Numéro(s) d'unité/ Unit number	Tutelle(s)/Research organization reference
Laboratoire Photonique, Numérique et Nanosciences – LP2N	UMR 5298	Institut d'Optique CNRS Université Bordeaux 1
Laboratoire Souterrain Bas Bruit - LSBB	UMS xxxx, starting on January 1st, 2012	Université 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 Globe 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





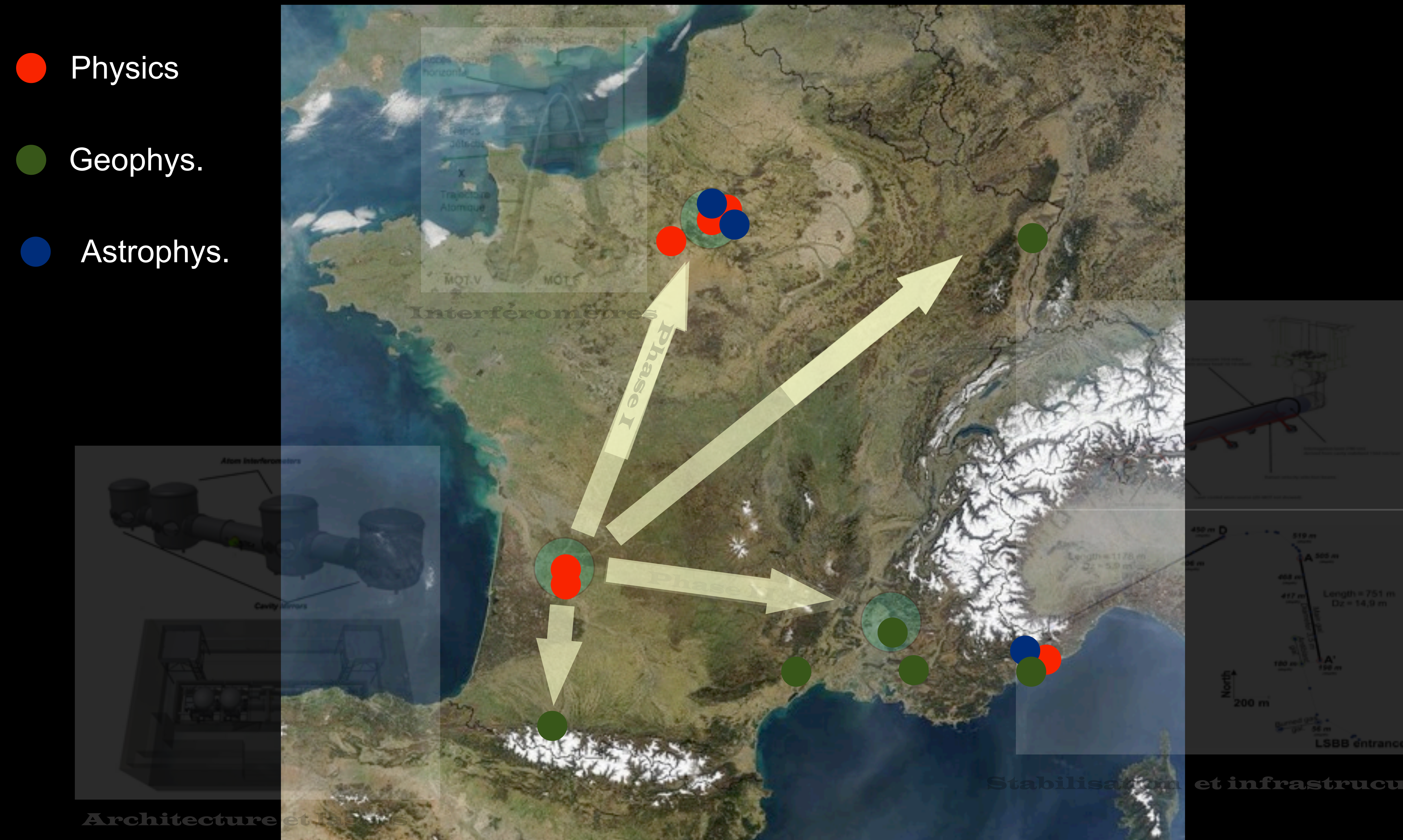
EQUIPEX Organization

3 Science centers in France involved in the instrument development



Multidisciplinary organization

Large network of users, from fundamental physics to geophysics



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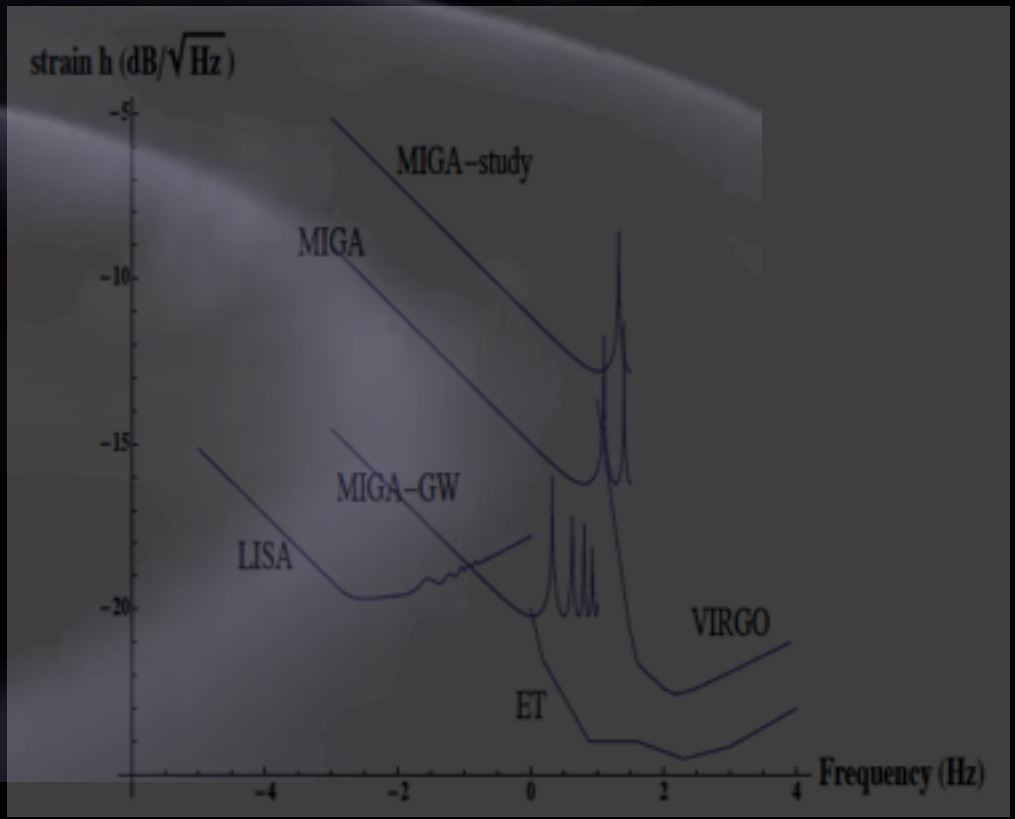
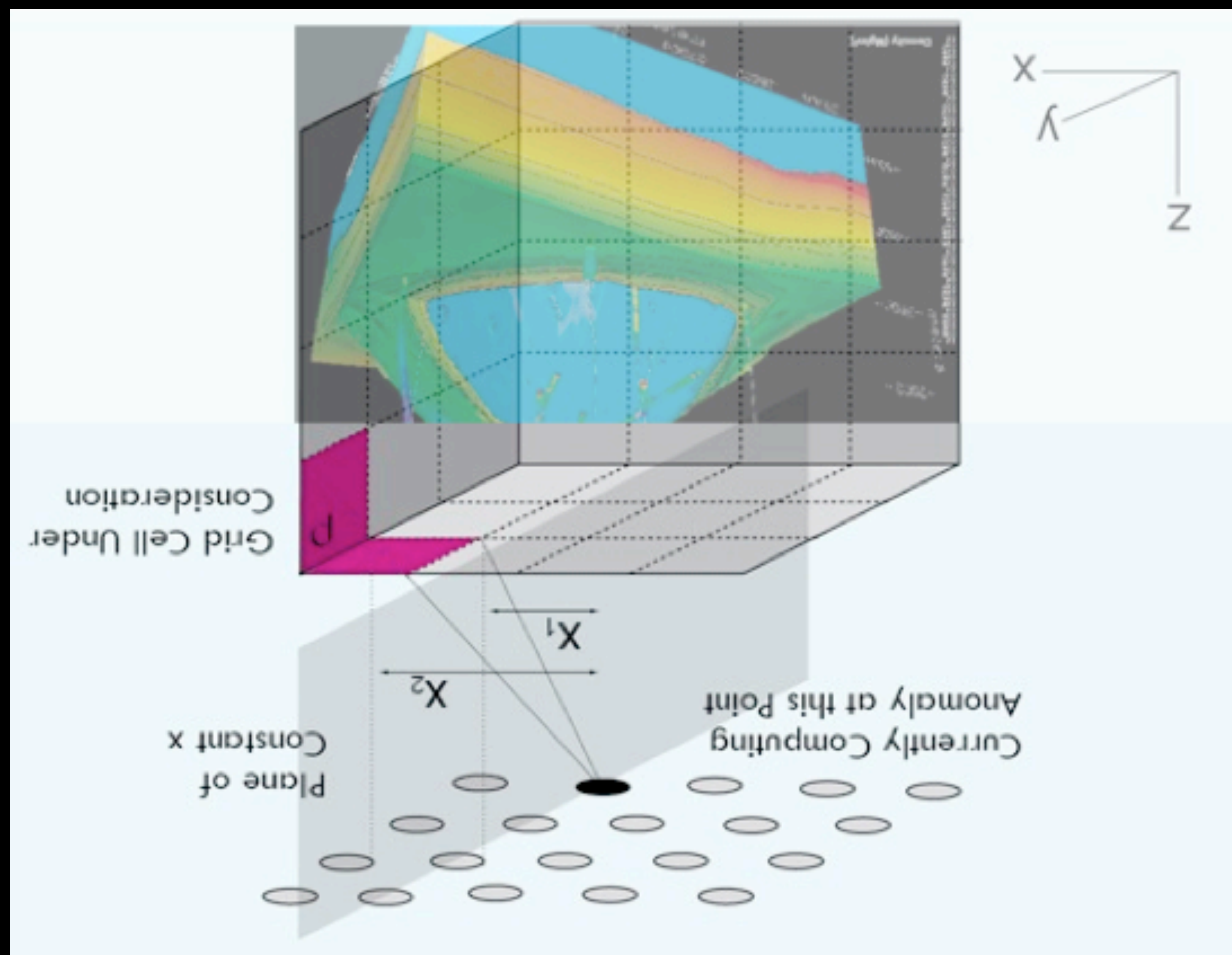
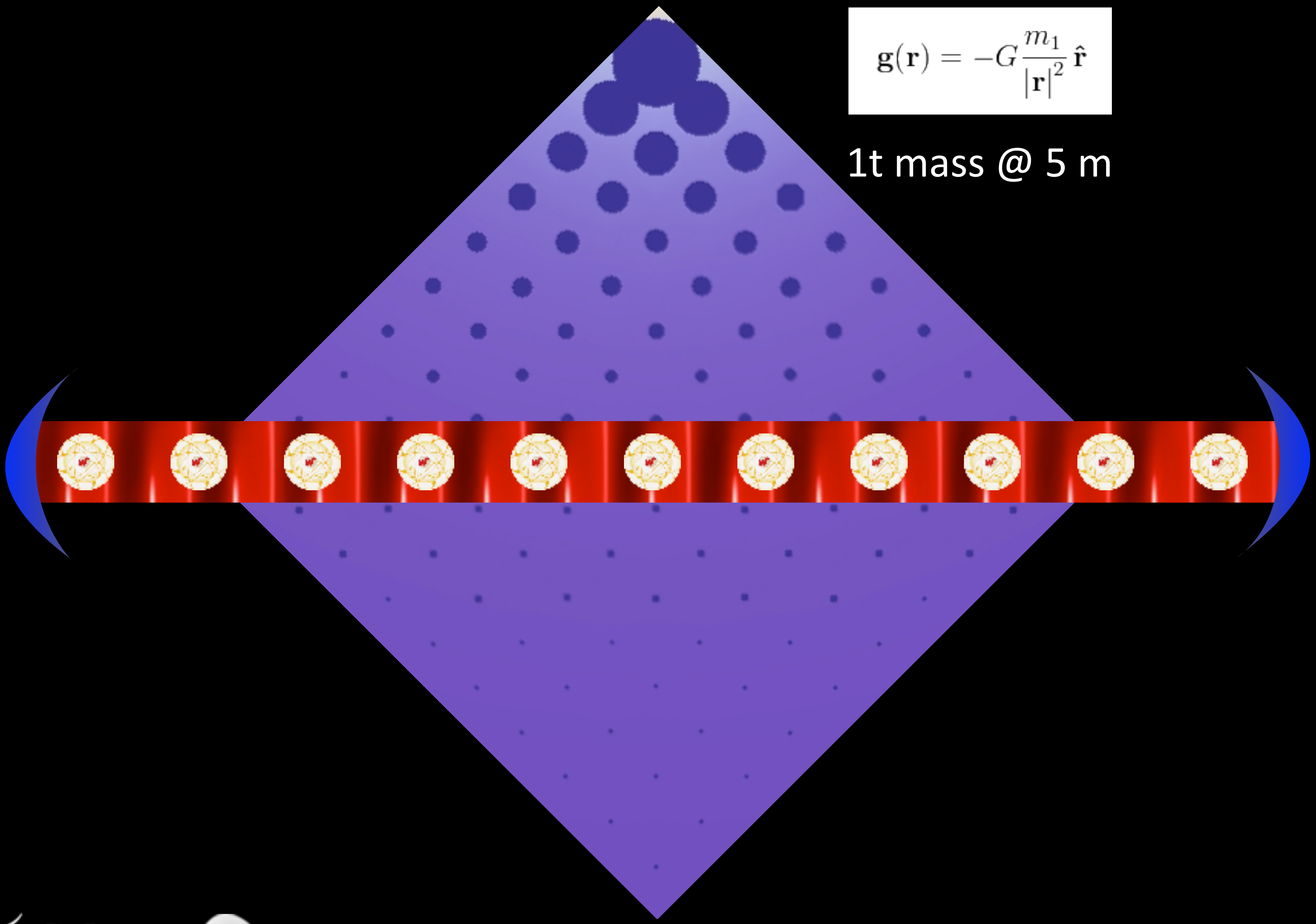


Gravity monitoring for underground survey





$$\mathbf{g}(\mathbf{r}) = -G\frac{m_1}{|\mathbf{r}|^2}\,\hat{\mathbf{r}}$$

1t mass @ 5 m

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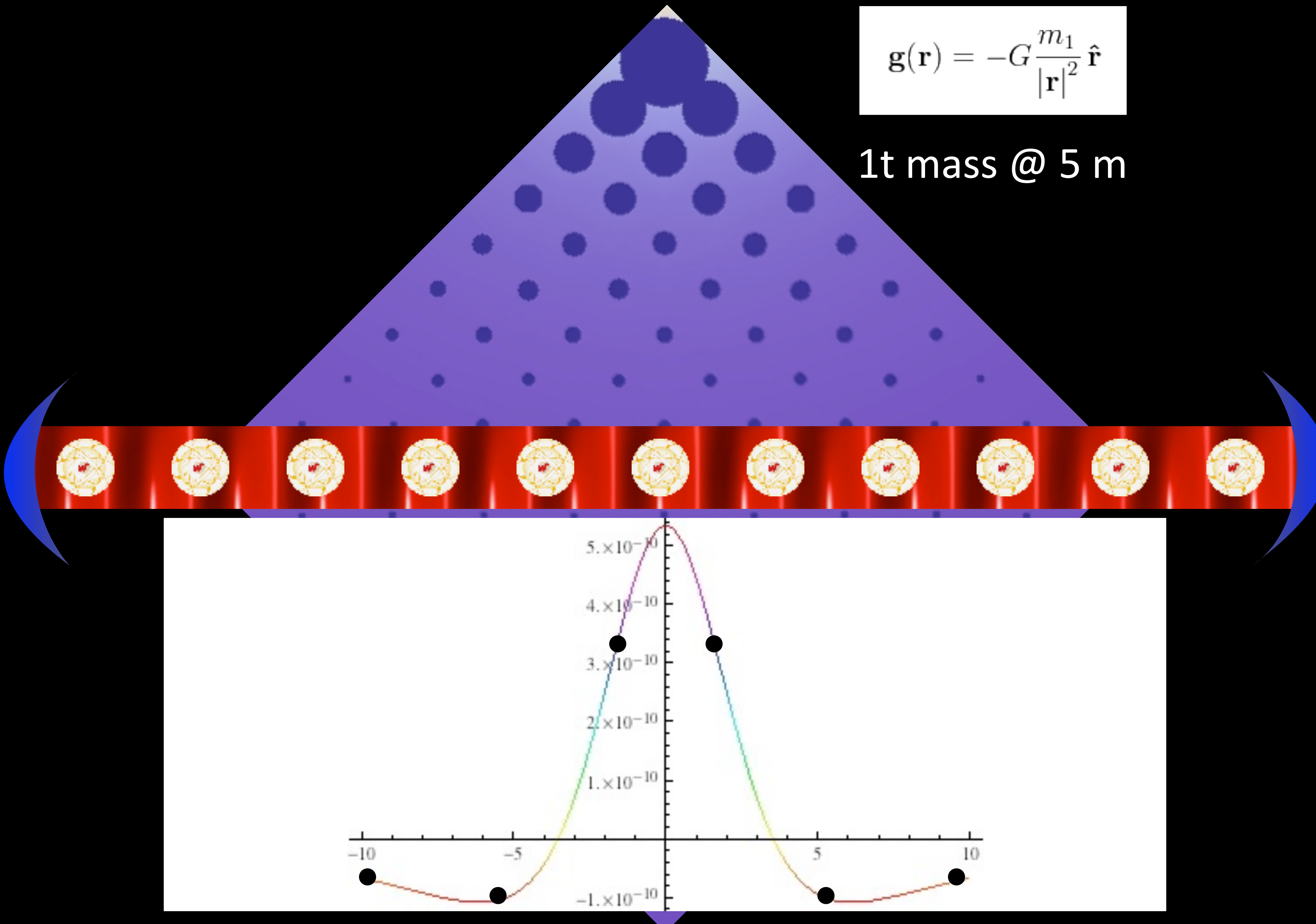

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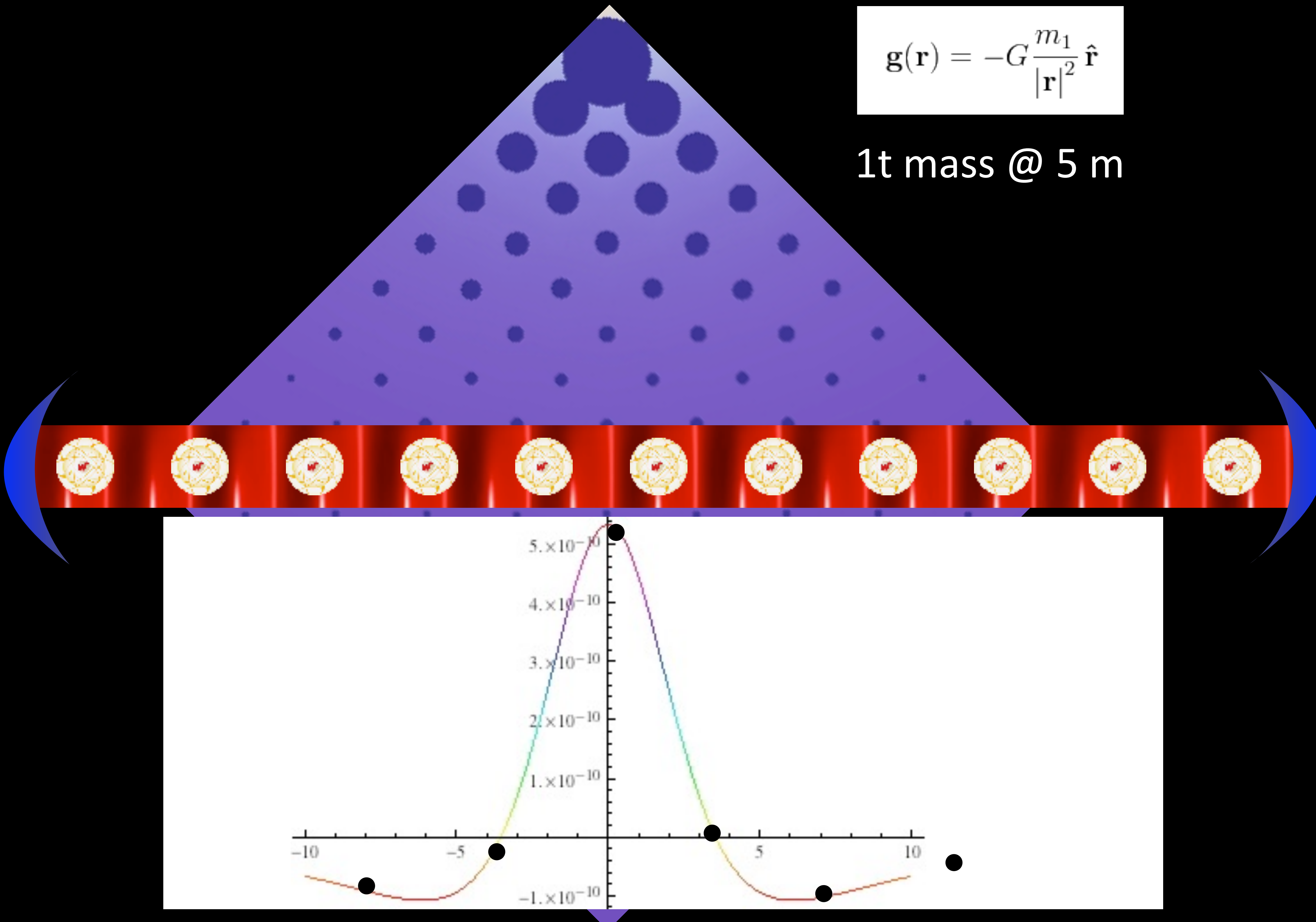


Example of geophys. application

- Hydrology (thesis T. Jacob, geoscience Montpellier)

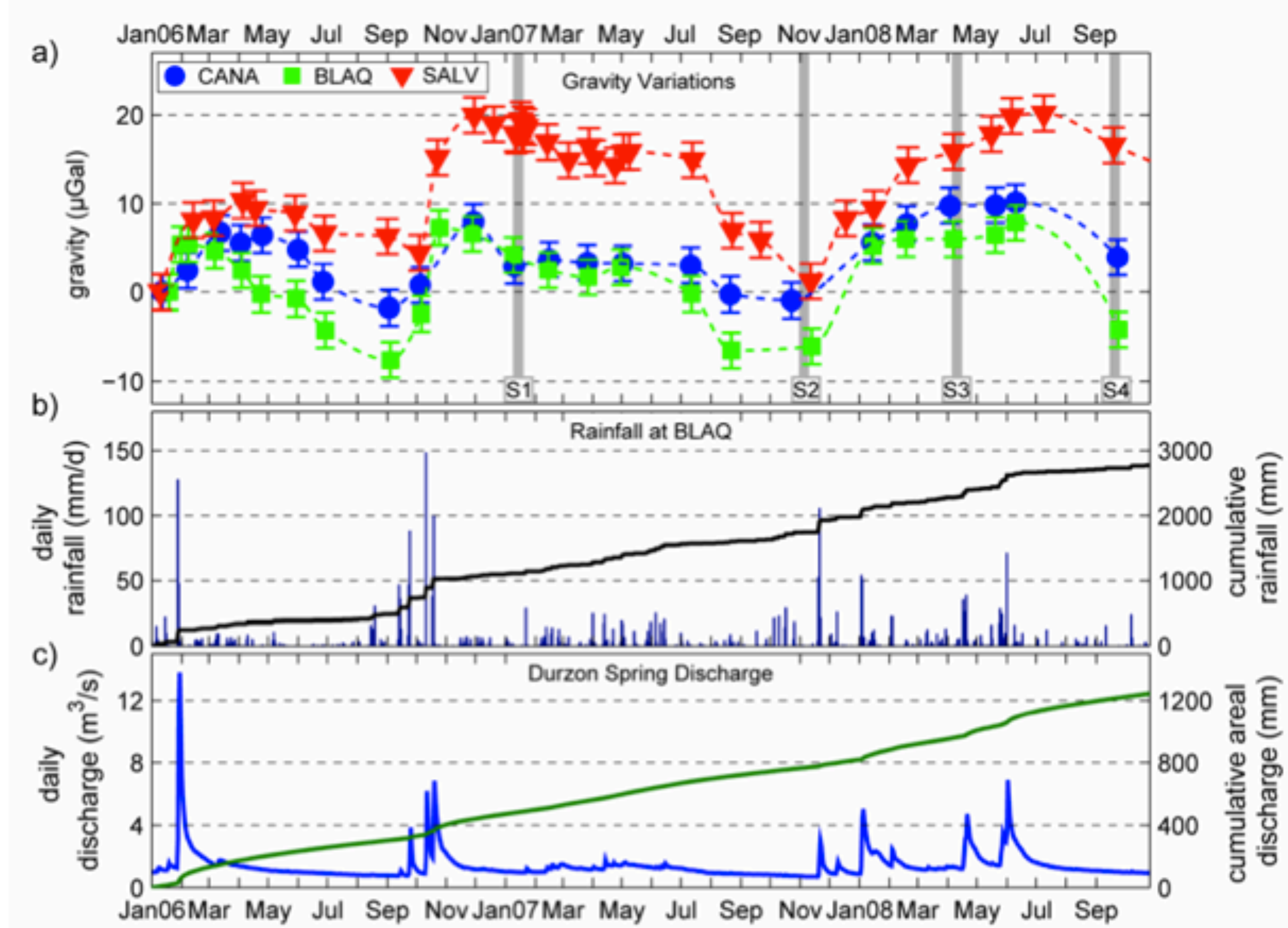
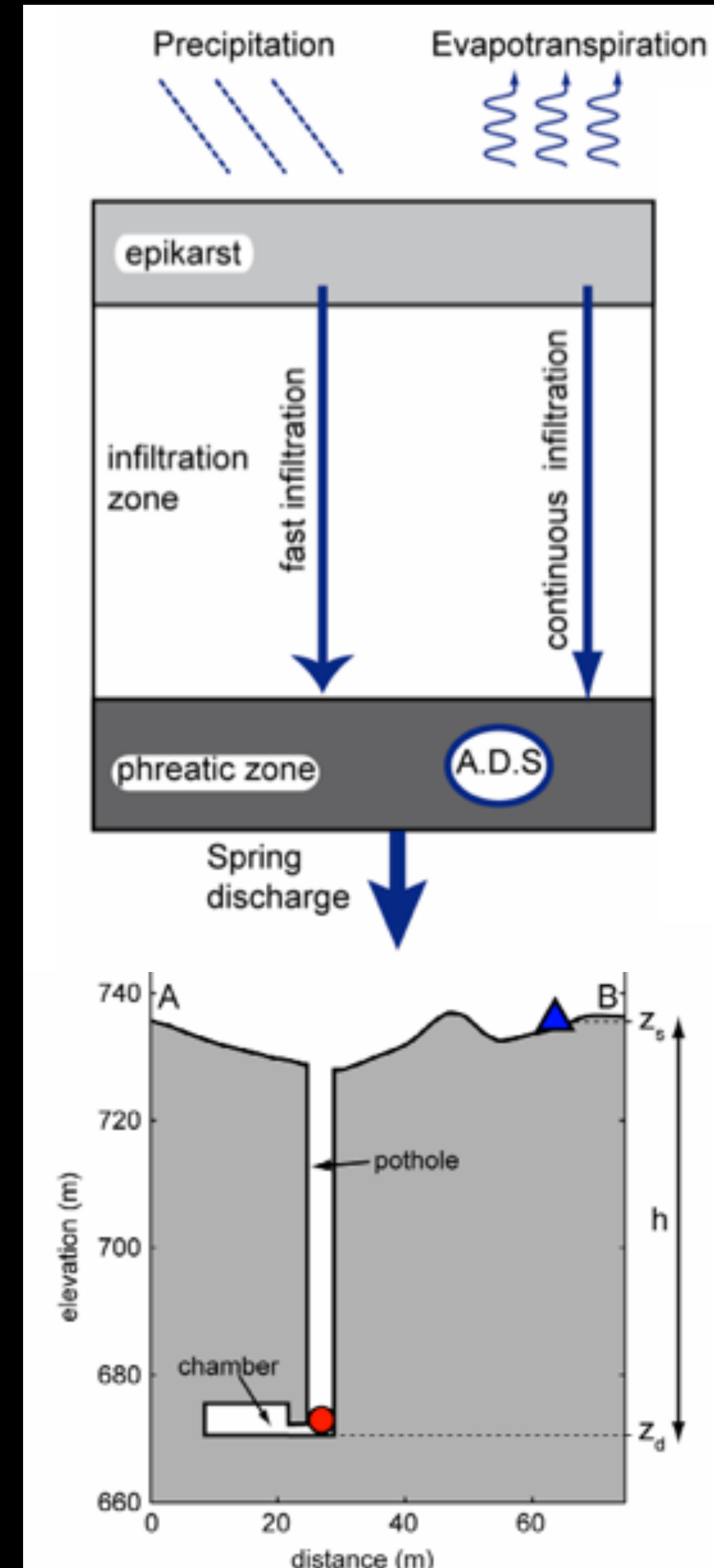


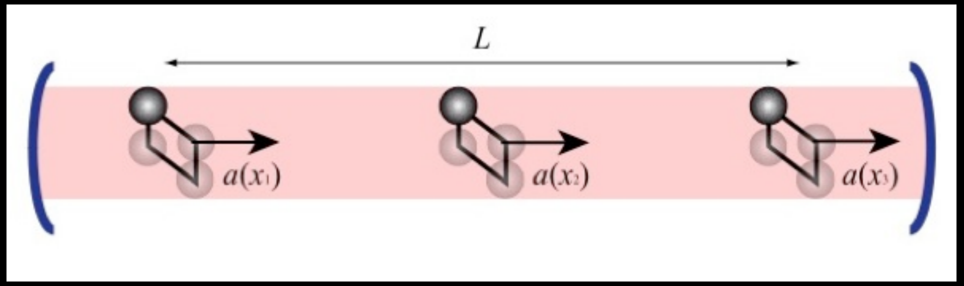
Figure 7.2 : a) Absolute gravity variations at site CANA, BLAQ and SALV, corrected for regional hydrology (see text for explanations). Survey periods S1 to S4 are indicated by vertical grey bars. b) Daily and cumulative rainfall measured at BLAQ, c) Daily Durzon spring discharge (blue line) and cumulative areal discharge (green line).



Implementation of MIGA-EQUIPEX in the underground laboratory in Rustrel, France

MIGA sensitivity to gradients	10^{-13} s^{-2} at 2 Hz
MIGA sensitivity to strain	10^{-14} dB/√Hz at 2 Hz
MIGA sensitivity to gravity	10^{-10} g at 2 Hz
Atom number per interferometer	10^{6} atom per atomic source at 100 nK
Atom temperature (rms velocity)	100 nK (1 mm/s)
Cooling laser power per interferometer	1 Watt
Cavity finesse	min. 100
Beam waist in cavity	min. 300 mm
Cavity laser power	50 Watts
Cavity laser frequency noise	PSD < 10^{-3} Hz^2/Hz between 10 Hz and 100 kHz
Vibration isolation frequency range	> 1 Hz
Vibration isolation level	< 10^{-2} at 1Hz and above.
Advanced MIGA sensitivity to strain	10^{-16} dB/√Hz at 1 Hz (improved detection) 10^{-21} dB/√Hz at .1 Hz (improved detection, levitation methods)

- One horizontal galleries with 300 m length



- Possibility of second orthogonal and third vertical gallery
- MIGA arms could be «connected» via ultra-high stability laser link

Thank you

you are welcome to joint us in Bordeaux