MIGA, a large scale gravity antenna using quantum technology

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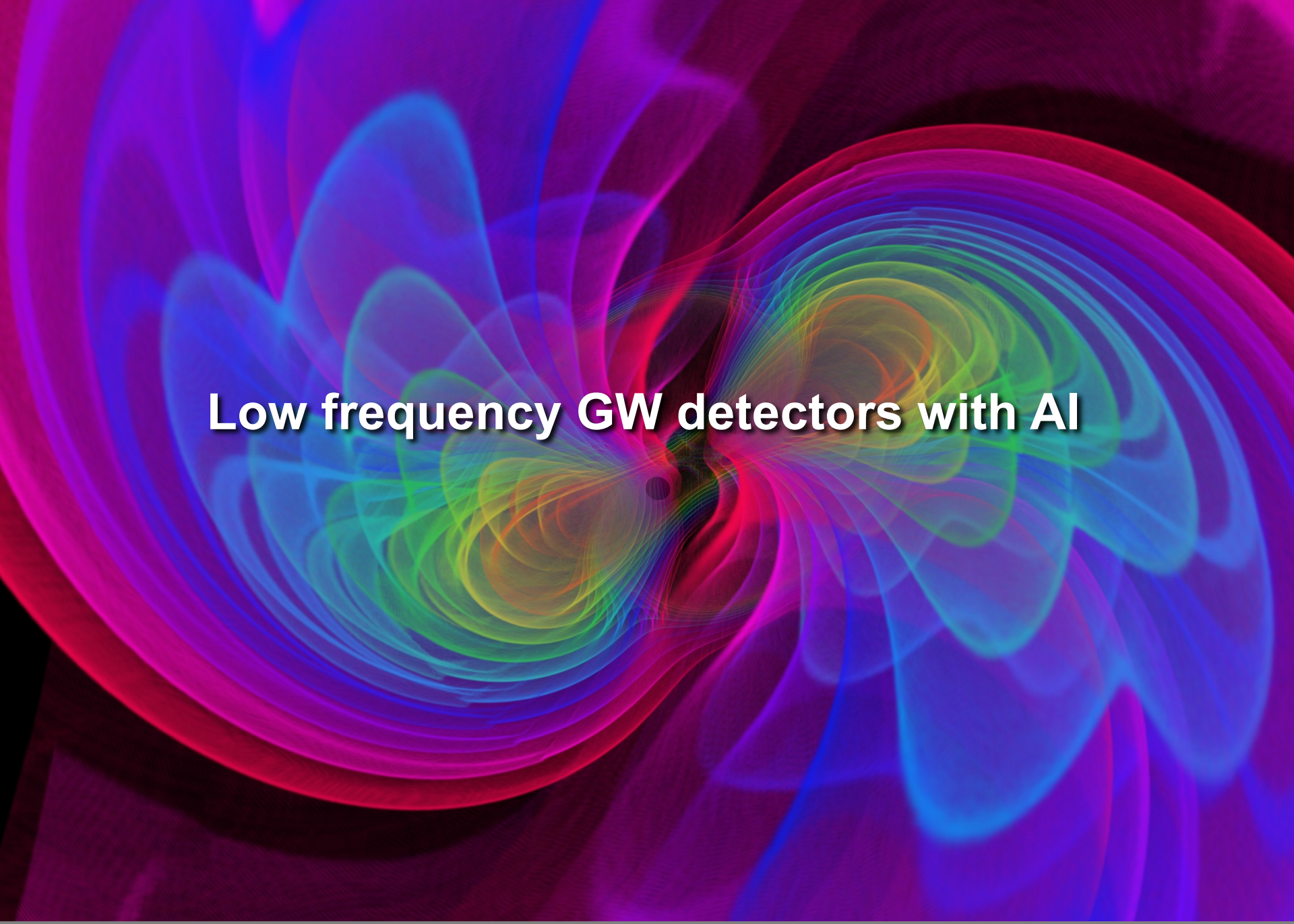
for the MIGA consortium

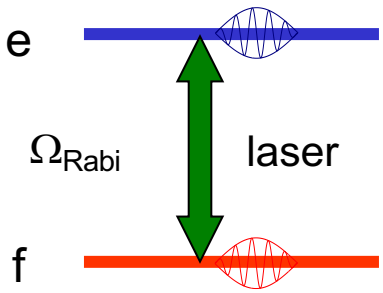
Outline

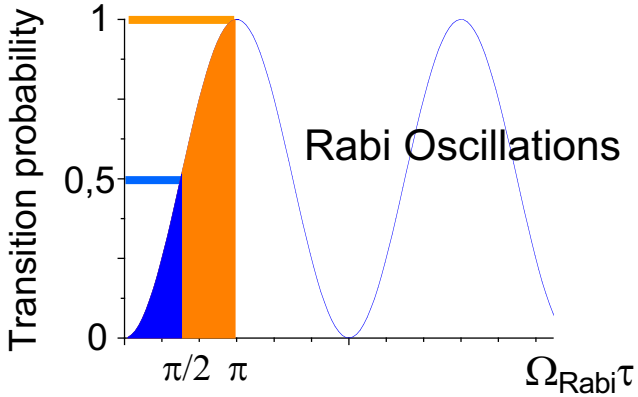
- Low frequency GW detectors with Atom Gradiometers
- The MIGA antenna
  - Infrastructure-vacuum system-Atom sources
  - Atom interferometry in cavity

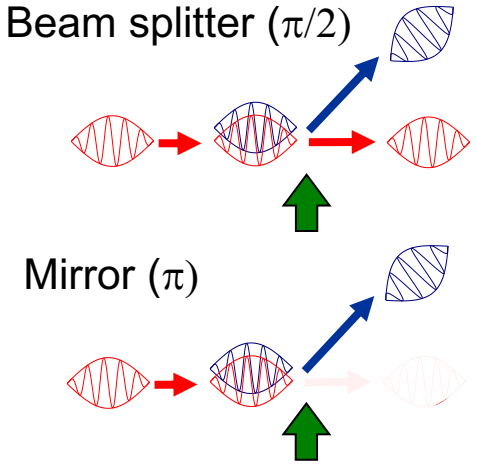

Low frequency GW detectors with AI

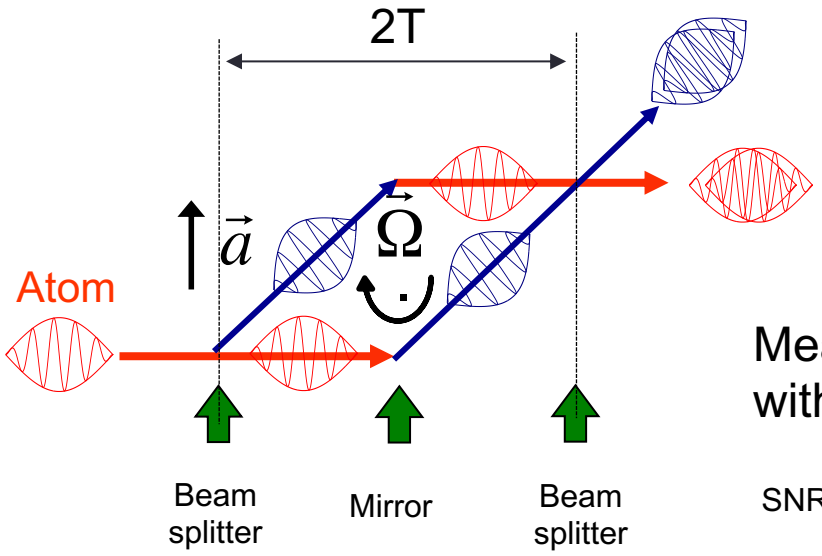
Atom interferometry

De Broglie wave associated to atoms: $\lambda_{dB} = h / p$







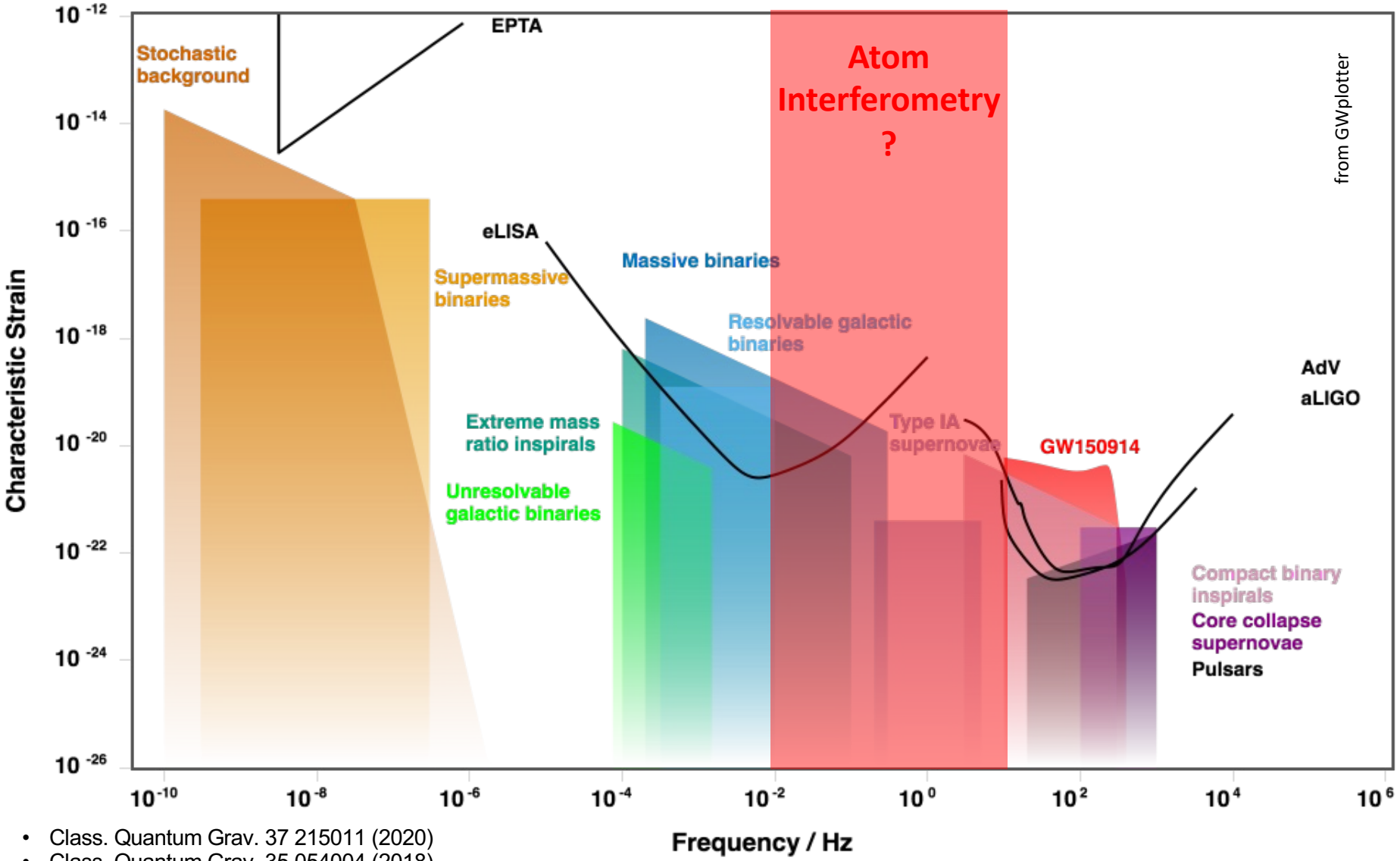


$$P = \frac{1}{2}(1 + \cos \Delta\Phi_{AT}) \downarrow \propto \varphi_l$$

Measures the evolution of the MW with respect the laser field.

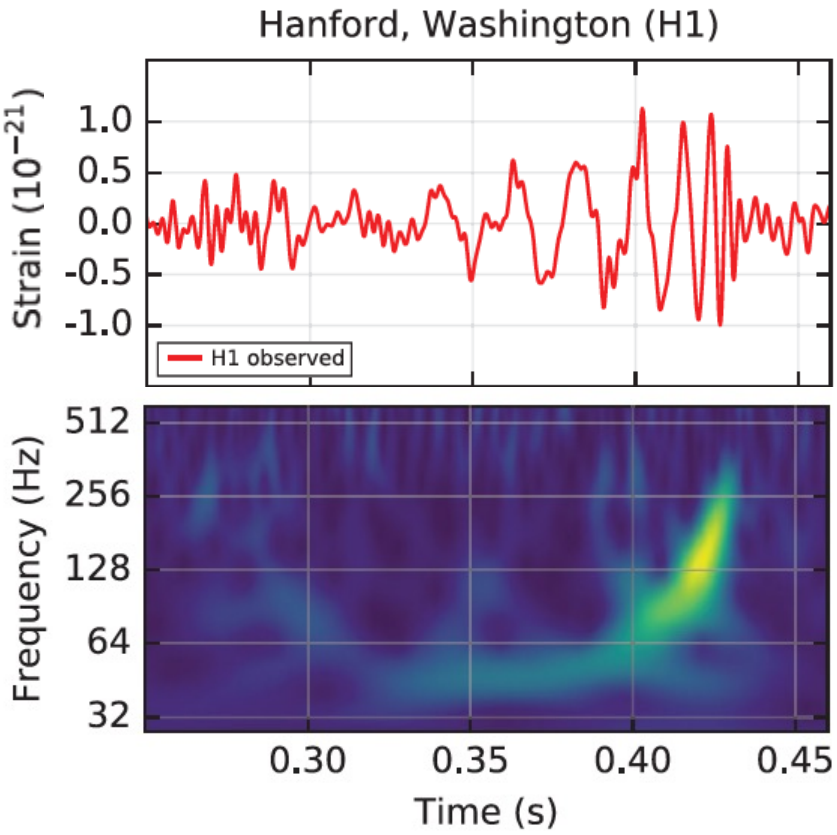
SNR 1 mrad, 2T=0.5 s, λ=780 nm $\delta a_{min} \approx 10^{-10}$ g

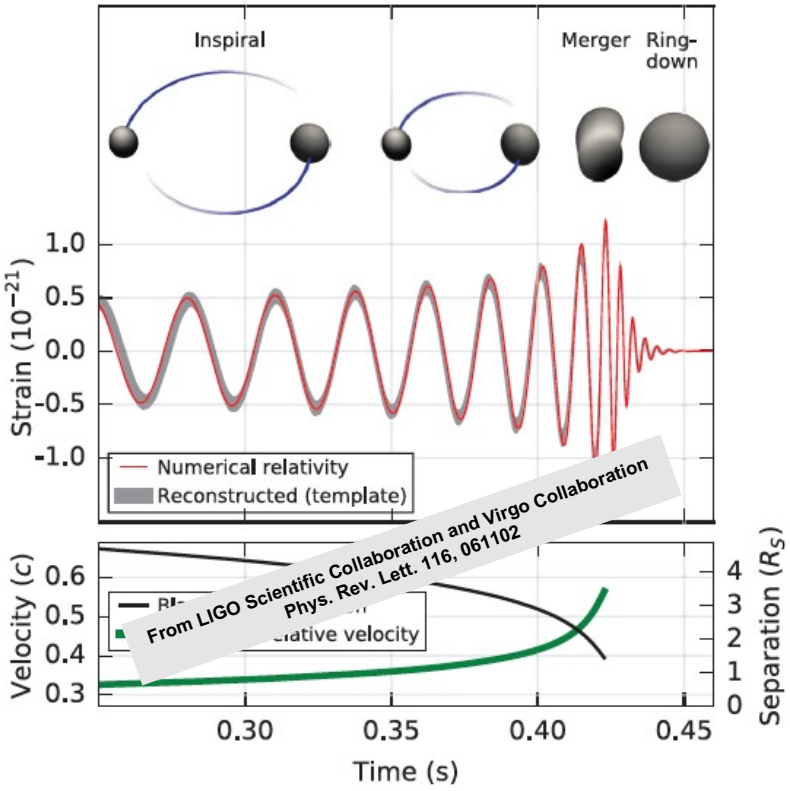
Low frequency GW detectors



- 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 physics with sub Hz GW detection

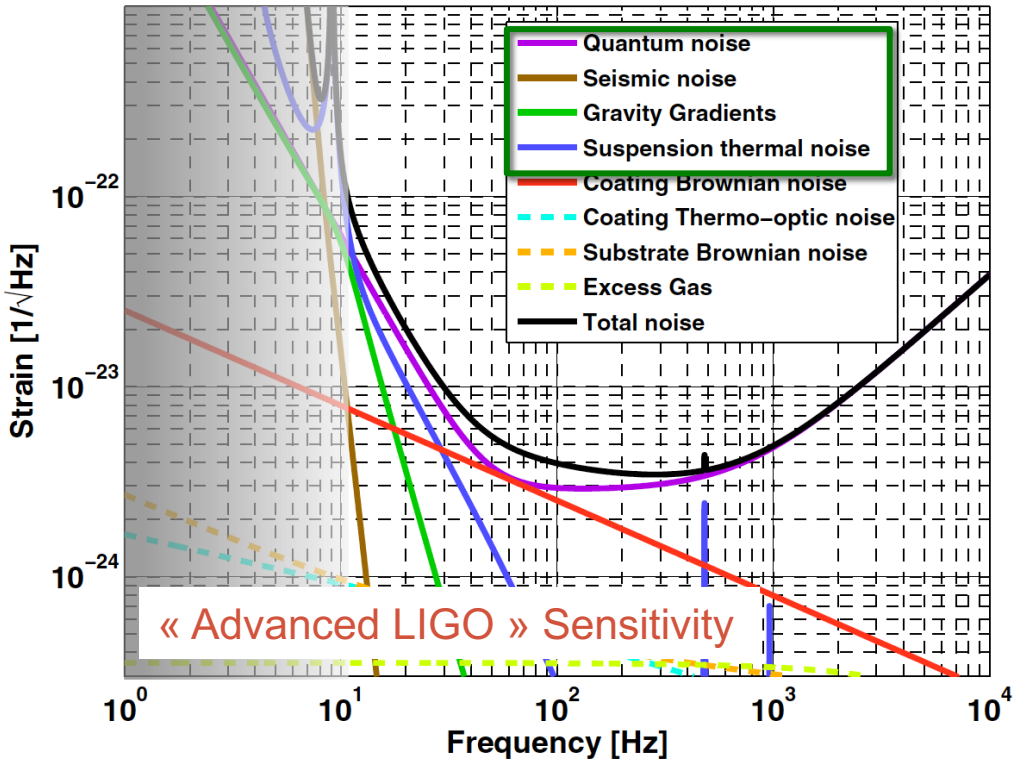




With low frequency detectors (f<1Hz)

- Observation of the same sources on quasi continuous timescales
- 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 towards low frequency?

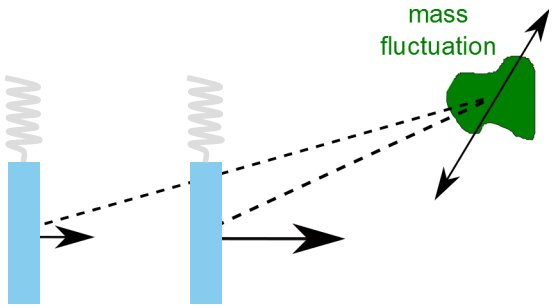


Limitations for f<10 Hz:

- Residual seismic noise
- « Gravity gradient » noise

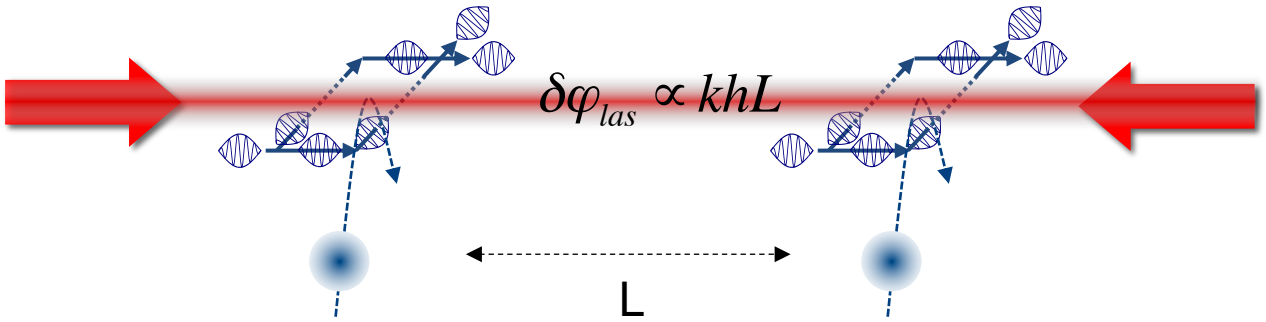
« Gravity Gradient » noise

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

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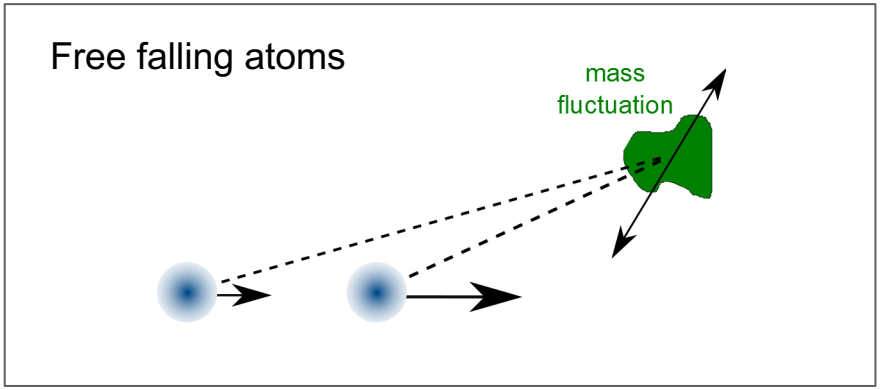
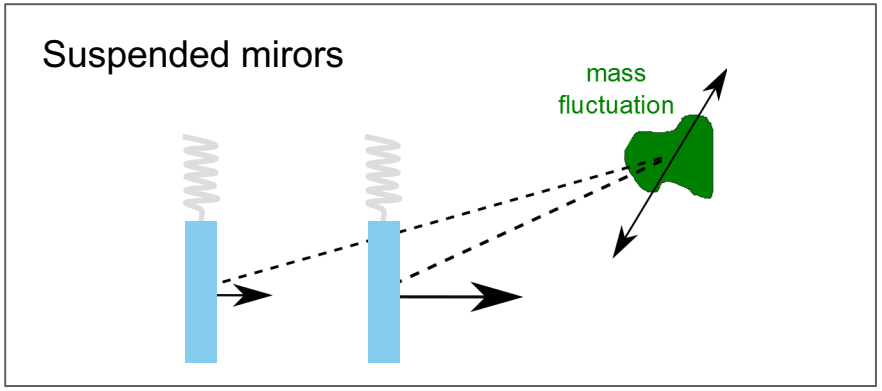
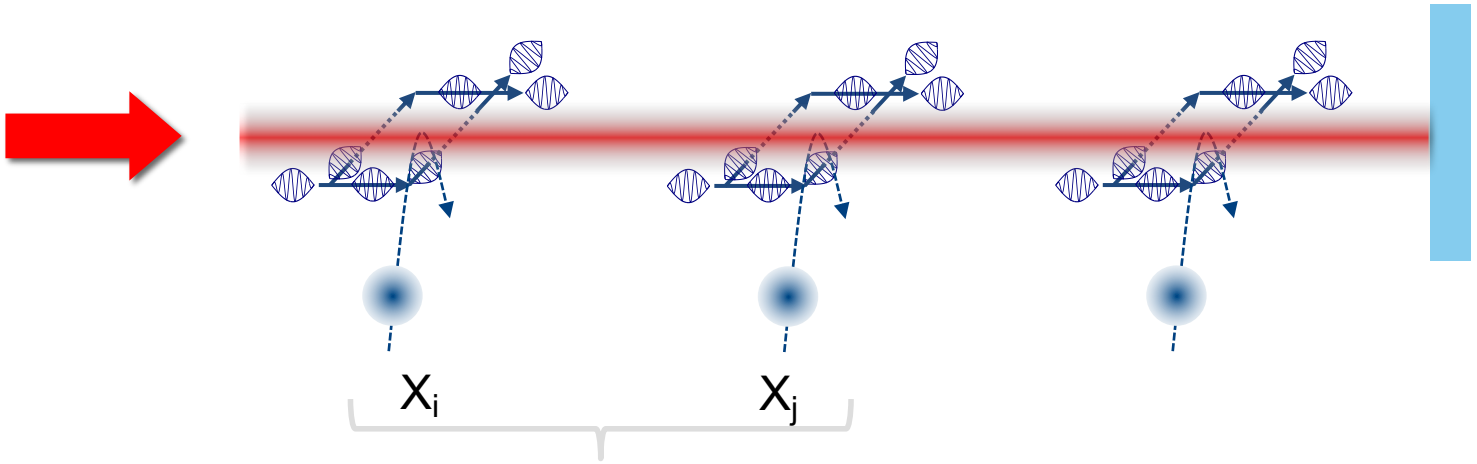
(Received 28 August 2008; published 19 December 2008)

Strong immunity to seismic noise
Sensitivity to Gravity Gradient Noise is the same !





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

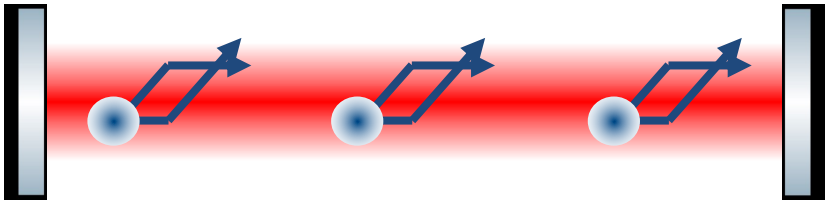
Phys. Rev. D **93**, 021101(R)

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

The MIGA antenna

- Infrastructure-vacuum system-atom sources
- Atom interferometry in cavity

Build a new instrument combining matter-wave and laser interferometry



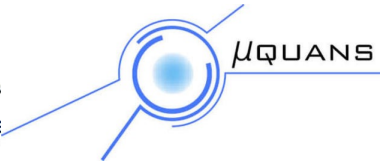
- Gravitational wave physics
  - Demonstrator for future sub-Hz ground based GW detectors
- Geoscience
  - Gravity sensitivity of 10^{-10} g/Sqrt(Hz) @ 2Hz
  - Gradient sensitivity of 10^{-13} s^{-2}/Sqrt(Hz) @ 2Hz: geology, hydrogeology…

A Large research infrastructure hosted in a low noise laboratory

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

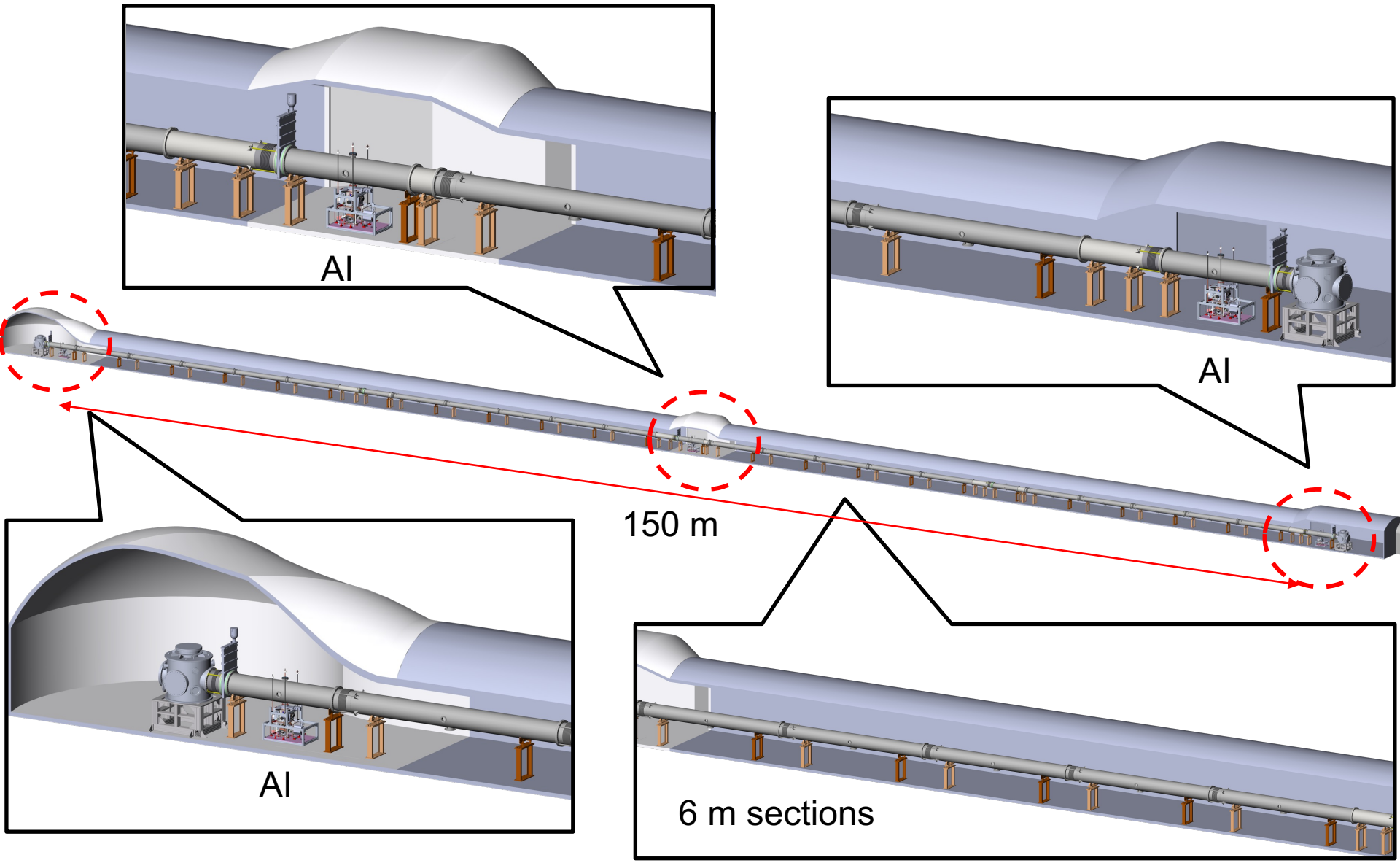
- A 150 m horizontal optical cavity coupled with 3 AI
- Possible evolutions towards 2D geometry

Partners labs

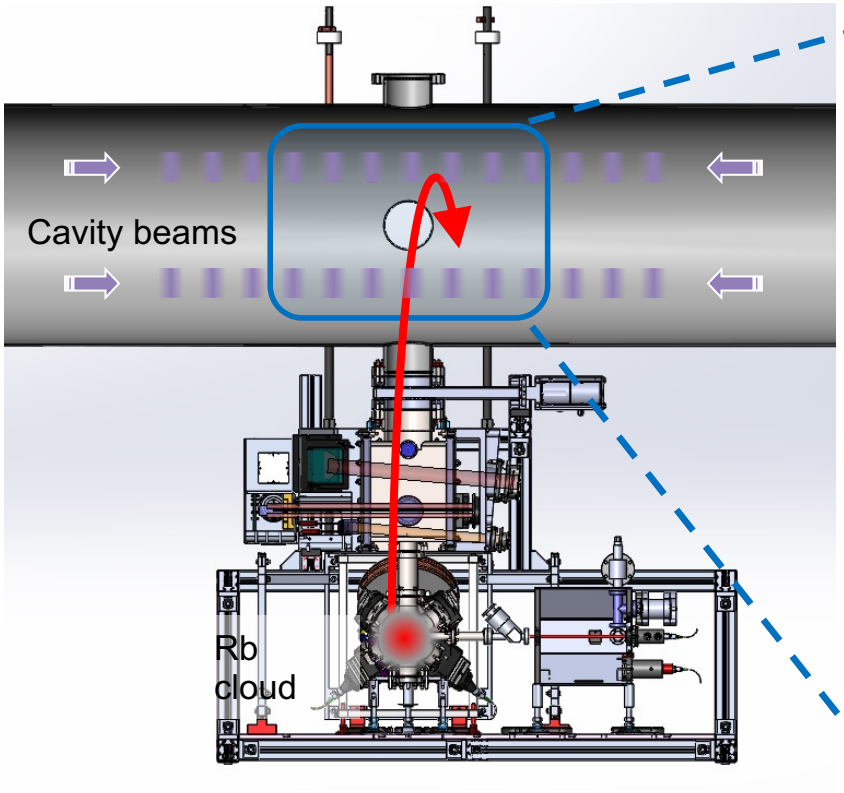


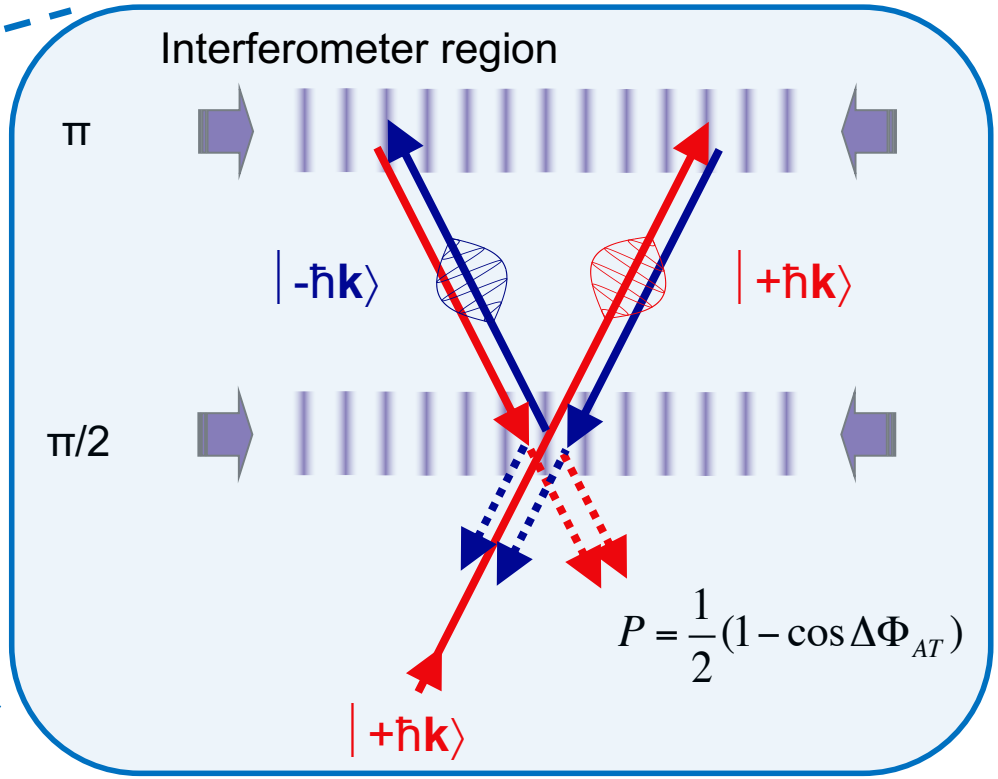
French “Equipement d’Excellence” Initiative
17 partners

The MIGA antenna



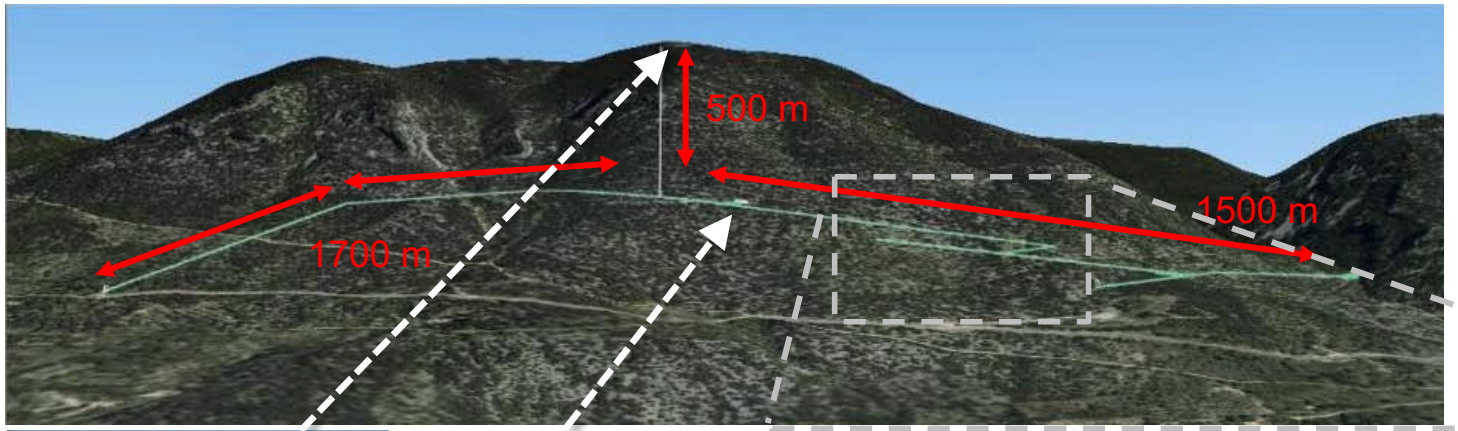
Functioning of a MIGA Atom Interferometer





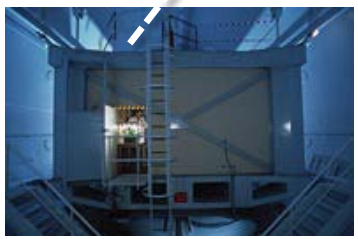
- Rb atom source uses a combination of a 2D and 3D magneto-optic traps.
- After cooling, trapping, the atoms are launched on a parabolic trajectory
- Manipulation using Bragg diffraction on a set of two horizontal cavity beams.

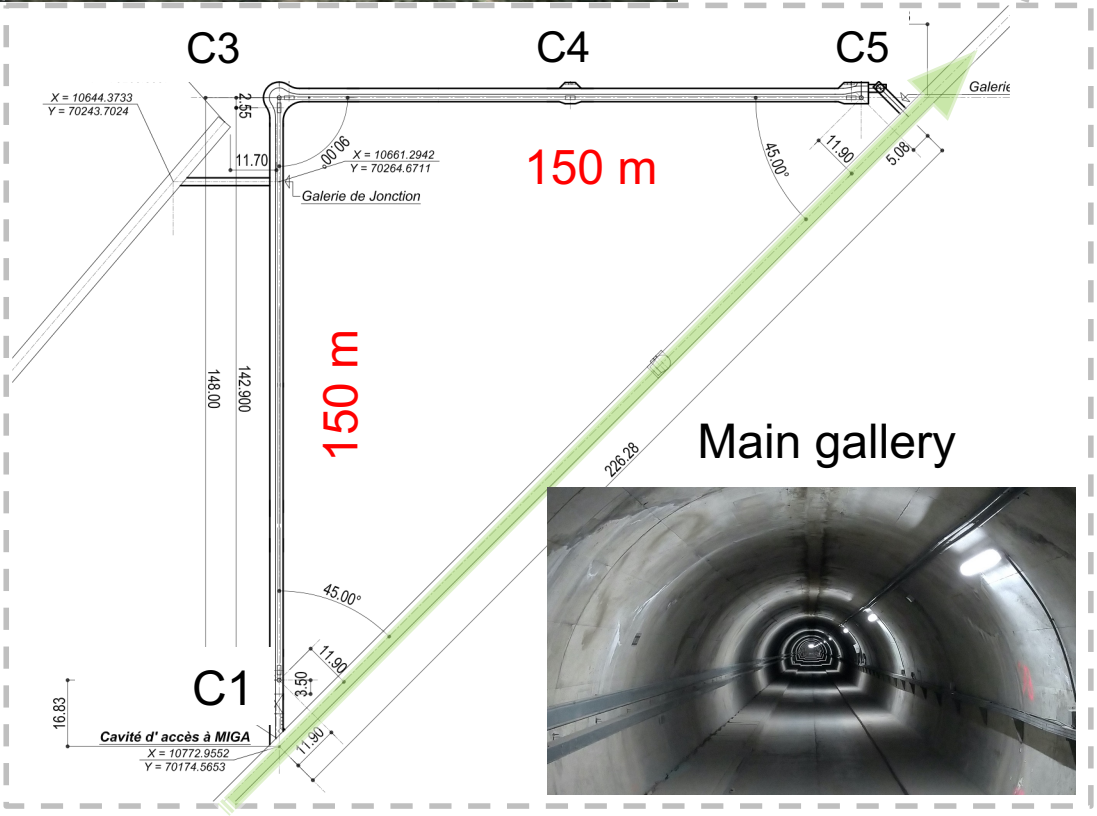
MIGA infrastructure



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

MIGA galleries at LSBB

MIGA galleries at LSBB



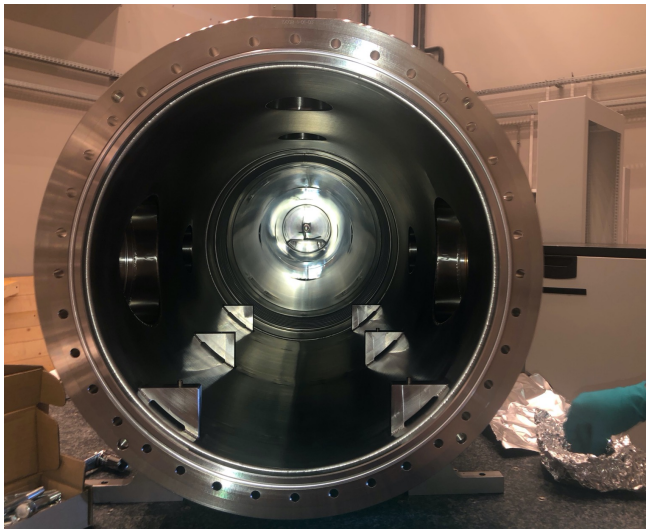



Vacuum vessel

- Large aperture: 50 cm large, 150 m long, total volume of 30 m^3
- Must reach 10^{-9} mbar of residual pressure after Baking @200 °C with Pumping speed in normal operation 10000-20000 l/s
- Assembled and operated in rough conditions (humidity – cleanliness)

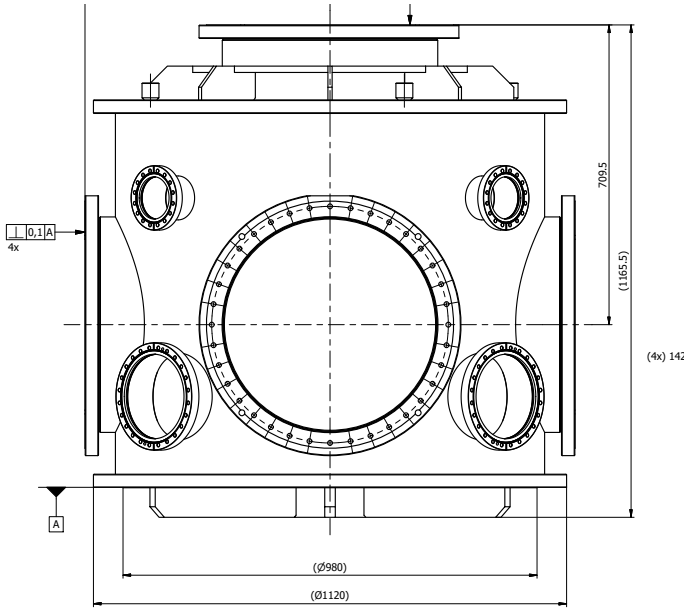
Most of the system composed by “standard” 6 m sections:

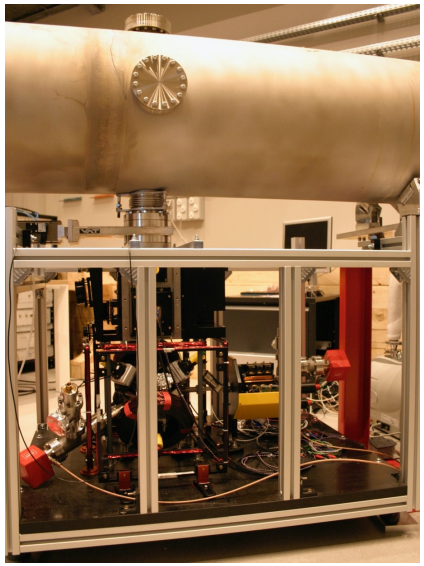
- SS304 with 5 mm thickness
- Uses “helicoflex“ flanges
- Every piece tested in factory to prove the ultimate pressure level (a few 10^{-10} mbar) before acceptance and shipping.



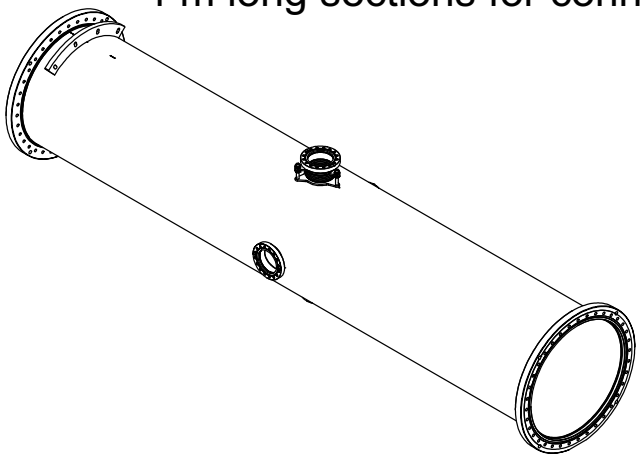
Vacuum vessel

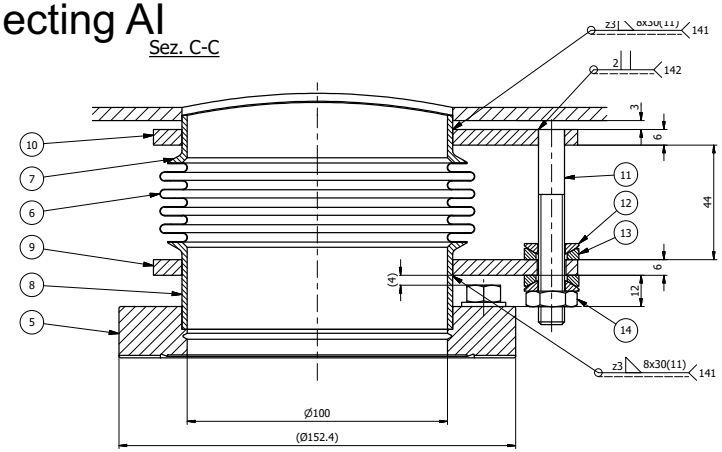
Towers hosting benches for cavity optics





4 m long sections for connecting Al

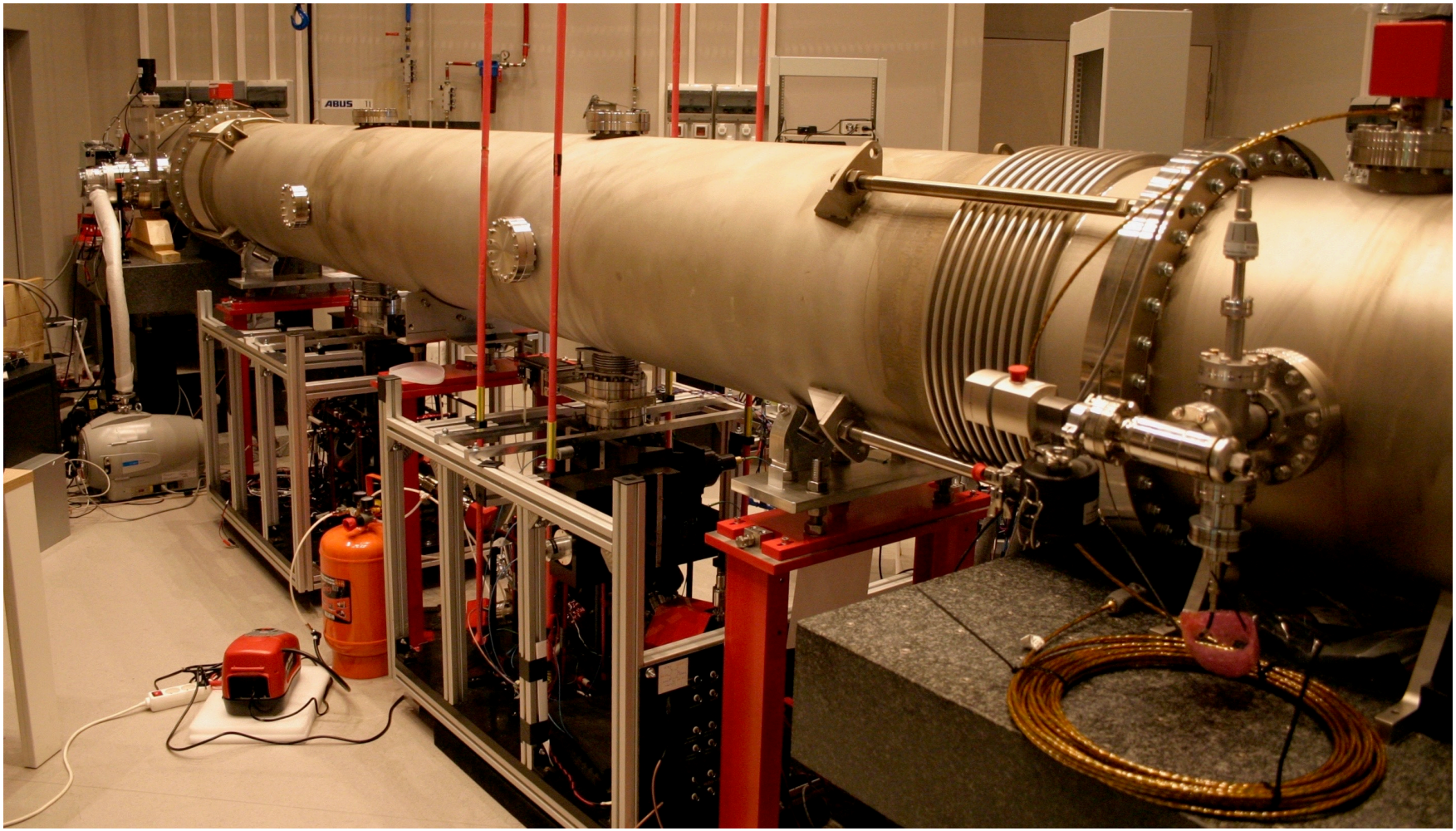




Bellows designed for optimal alignment of atom trajectories

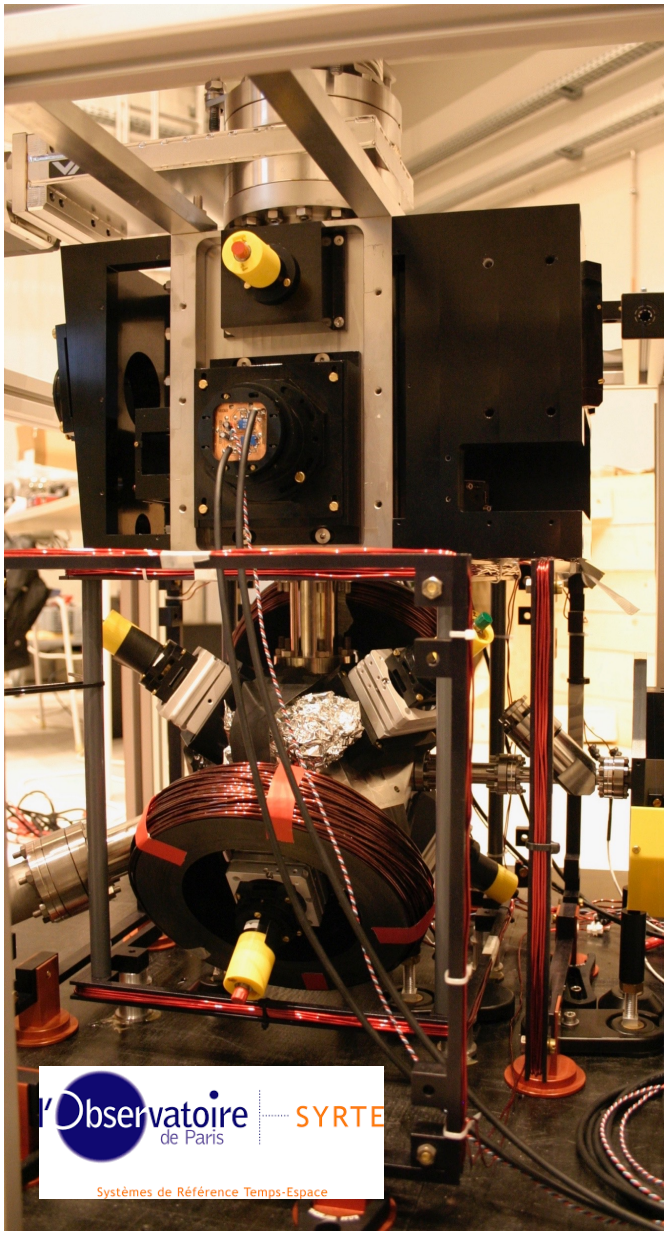
Vacuum tests

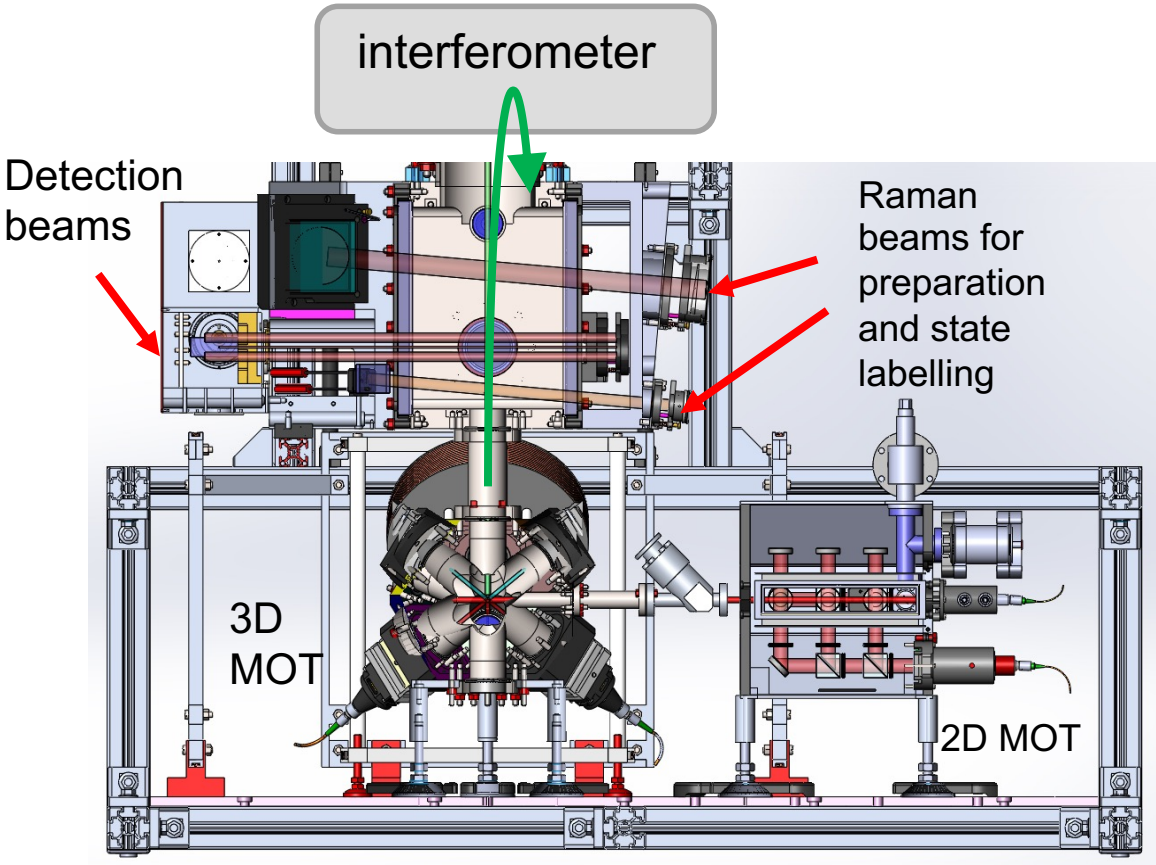
- Parts produced, tested and delivered to LSBB
- Completed all the pumping/baking procedure for MIGA



- A short-sized version to study advanced atom manipulation techniques for MIGA improvement .

The Rb atom sources





- 2D-3D magneto-optic traps 5x10^8 atoms/s of Rb at $2\ \mu K$.
- On their way up: stage of preparation using a set of Raman beam (velocity selection and pure magnetic state): 10^7 atoms/s of Rb at T = $150\ nK$
- On their way up down: detection of the transition probability in two steps: State labelling converting momentum-to-internal state and fluorescence detection.

Laser system of atom heads

- Dedicated fiber laser system developed with Muquans to realize all functions for cooling/preparation/detection.
- Based on Telecom Technologies: robust, stable and remotely controllable to cope with rough conditions of LSBB

8. Raman/Repump; 2U

7. 3D MOT; 2U

6. 2D MOT; 2U

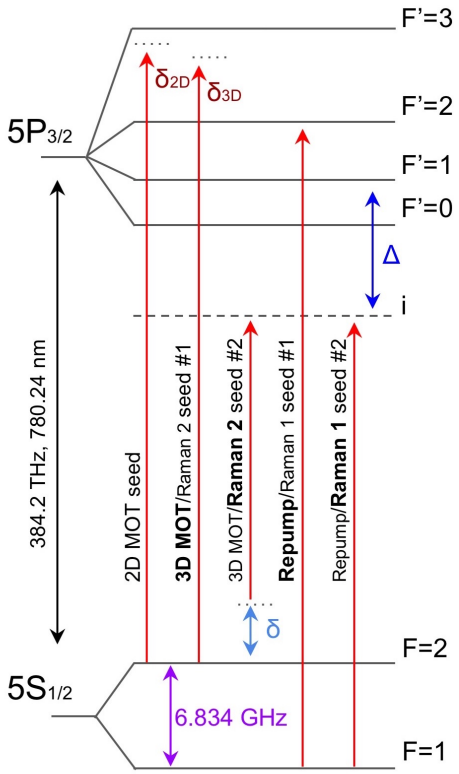
5. Seed Lasers; 3U

4. Microwave Synth.; 2U

3. RF/ Heating; 3U

2. EDFA supplies; 3U

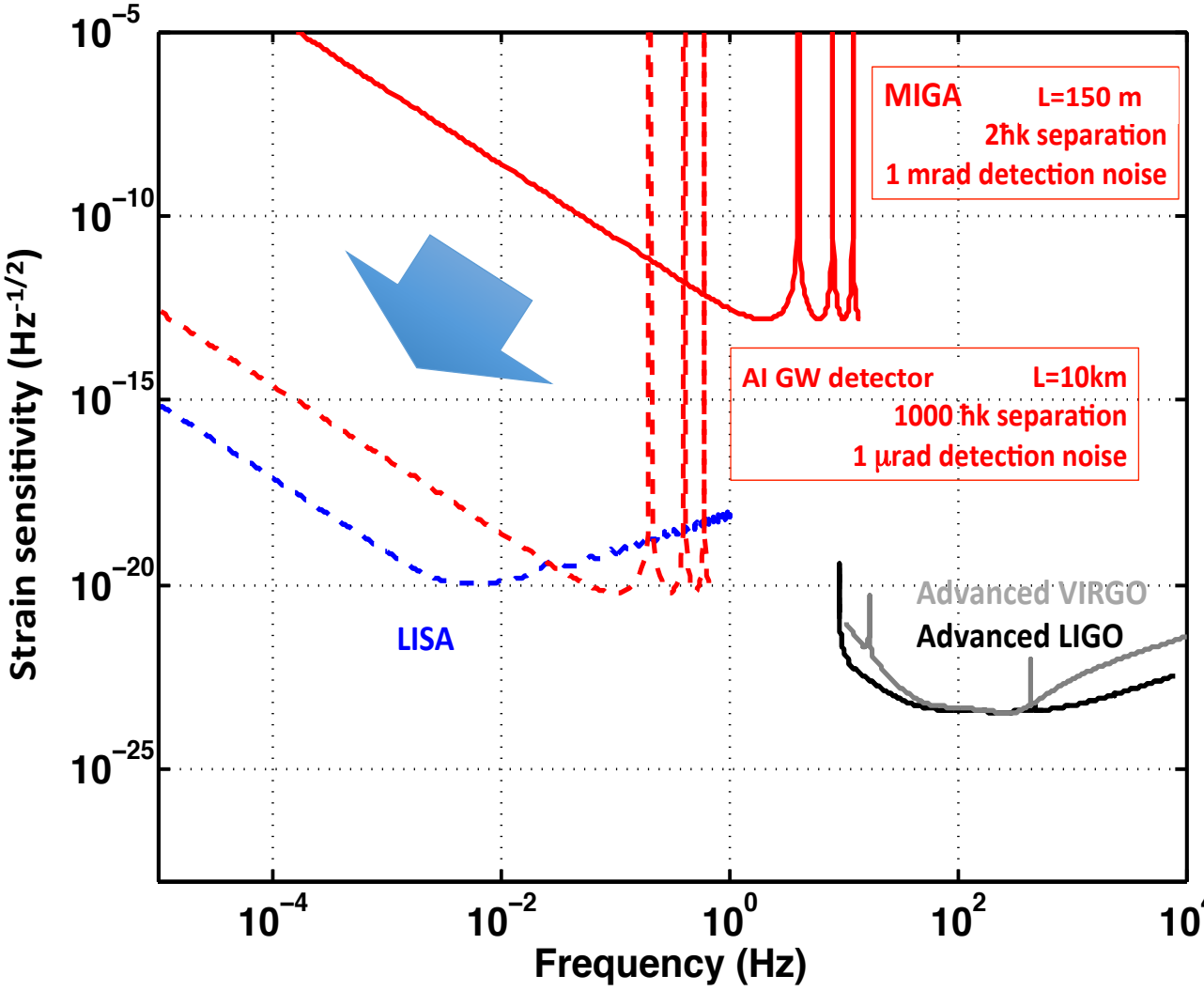
1. Power Supply; 2U



MIGA installation

- Vacuum system being assembled.
- 6 month for assembly and commissioning to reach target pressure.
- Planning to connect the atom heads by 2022.

- Atom shot noise limited strain sensitivity of initial MIGA 2.10^{-13}@ 2 Hz



Challenge for atom optics
- « LMT » techniques
- High atom flux 10^{12}/s

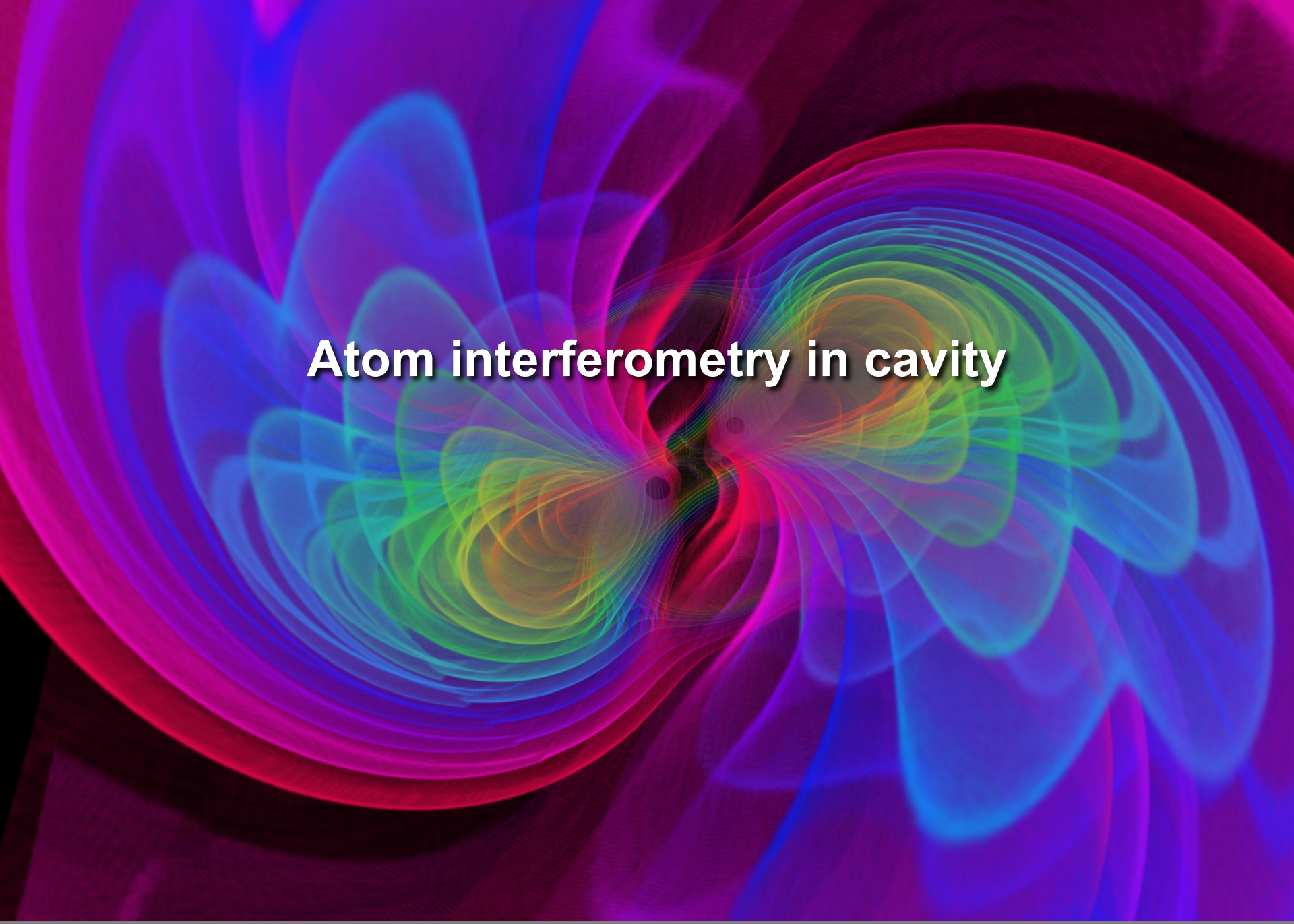
and

Technical noise reduction:
- Frequency noise
- Residual seismic noise
- Magnetic noise
- Wavefront, scattering ….

and

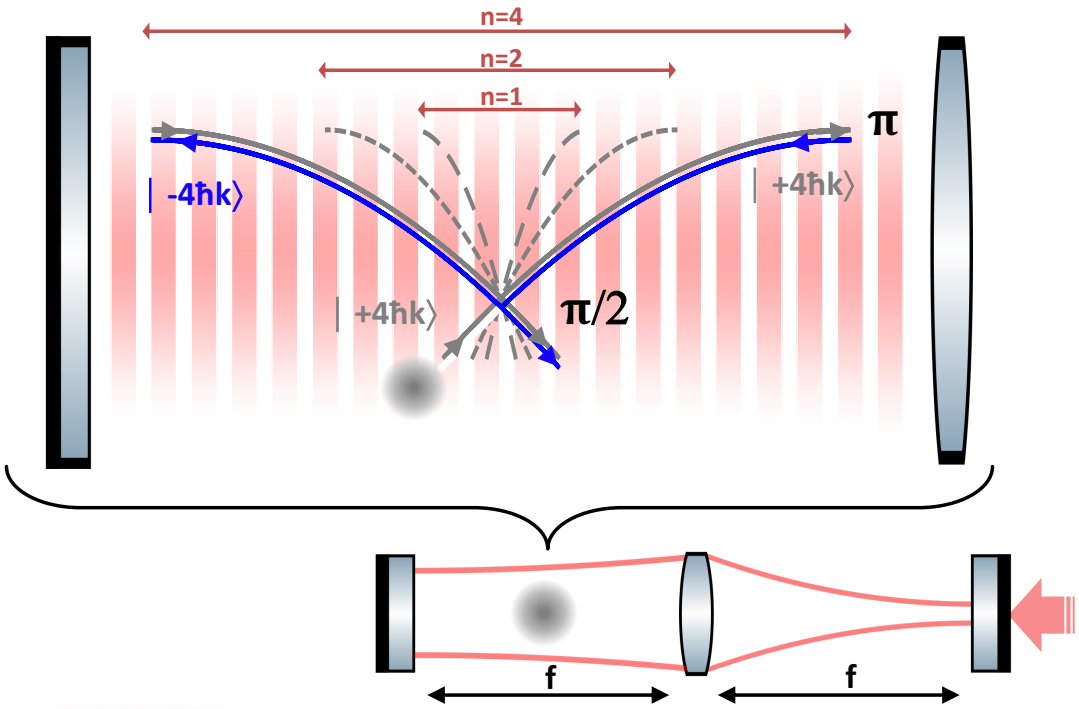
- Requires Advanced GGN rejection scheme

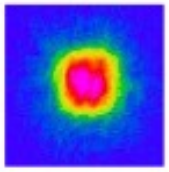
Phys. Rev. D 93, 021101(R) (2016)


Atom interferometry in cavity

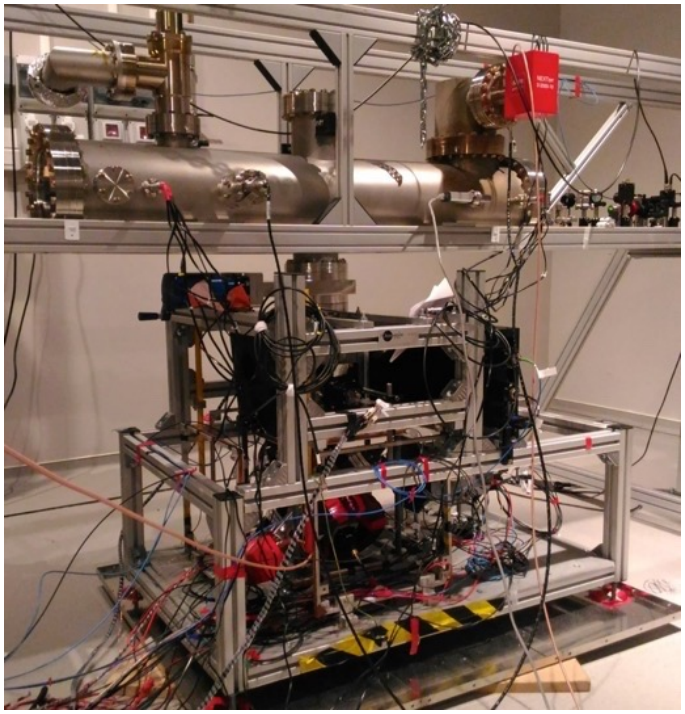
Atom interferometry in cavity

- Test atom cavity interrogation on a reduced scale of 80 cm using a MIGA Rb source.
- Uses degenerate resonator geometry enabling a large resonating mode.





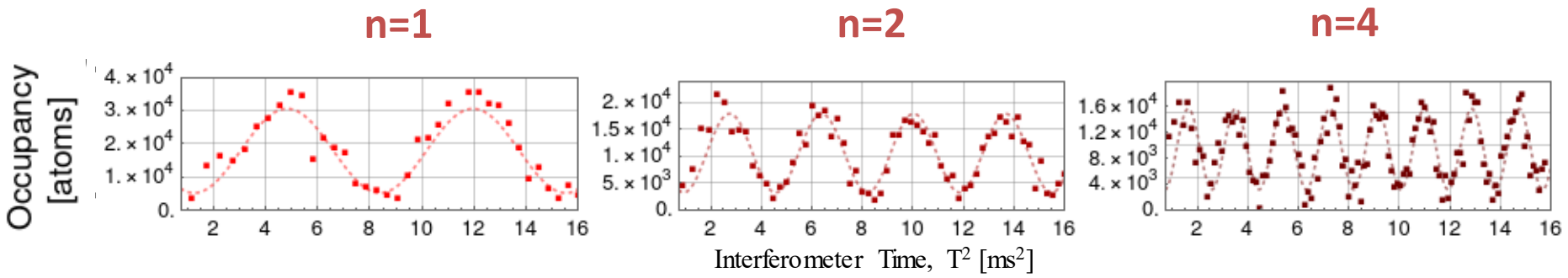
Resonant field diameter 4 mm

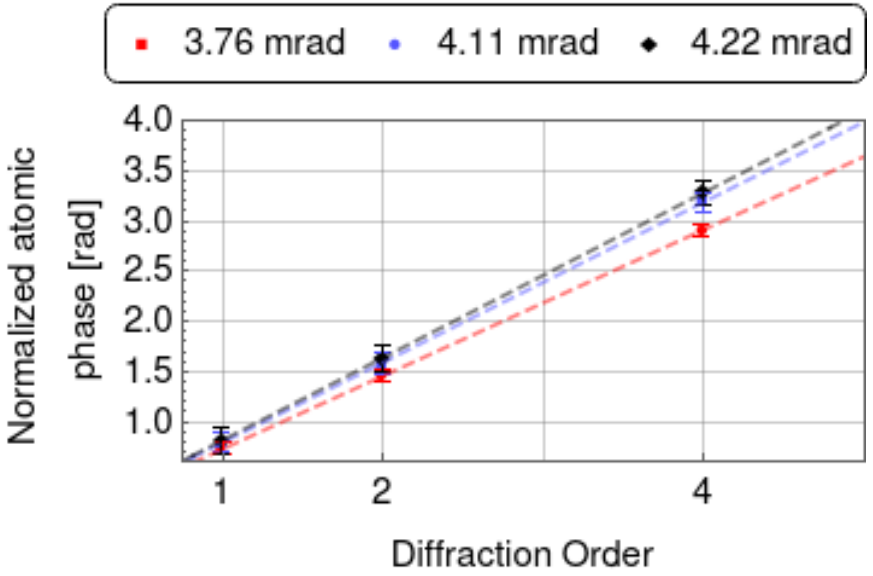


- Study of advanced atom manipulation techniques.
- Cavity build up help to reach high order Bragg diffraction: increase the separation of matter waves – ie sensitivity.

Atom interferometry in cavity

- Demonstrate in cavity atom interferometry up to n=4
- Tilt of the experiment: Inertial atom phase from the projection of local gravity $\Delta\Phi_{AT}=2n\alpha gT^2$
- Atom fringes observed by scanning the interaction time T.





- Linear increase of the scale factor as function of n.
- Opens perspective for MIGA sensitivity improvement

Conclusion

- Atom Gradiometers are promising for Low frequency GW detection and multi-band GW astronomy.
  - Dark matter searches
  - Tests of general relativity (EP, Lens-Thirring...)
  - Study of geophysical processes at global or local scale.
- Actions to push further the limitations : Atom manipulation, Sources, Metrology, GGN
- MIGA antenna under installation, online in 2023 …