Terrestrial Very Long Baseline atom interferometry

- setting the technolgy scene

E.M.R.

with input from Buchmüller, Canuel, Kovachi/Hogan, Kasevich, Tino an

Zhan groups

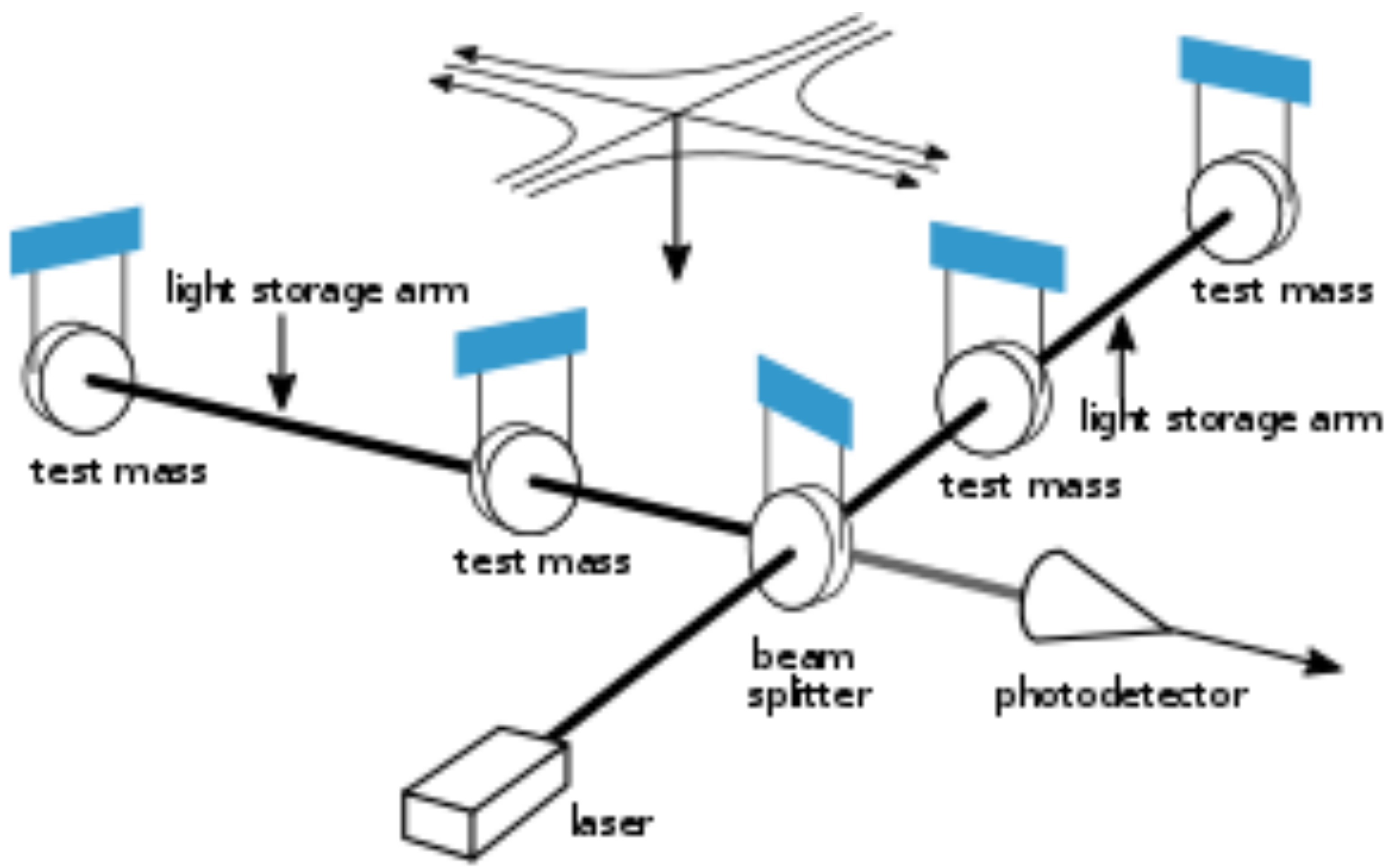
S. Abend, N. Gaaloul, D. Schlippert

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

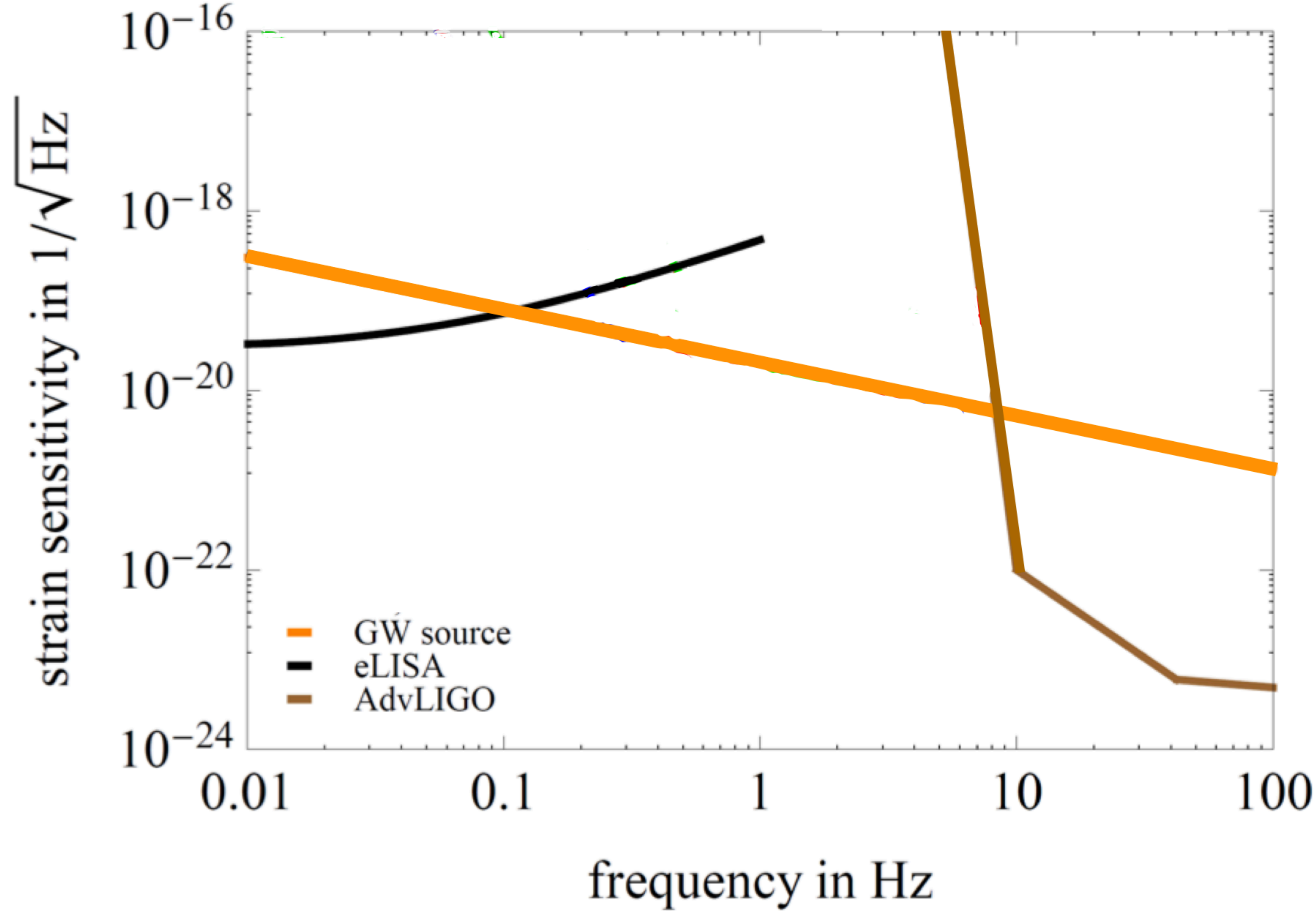
aufgrund eines Beschlusses des Deutschen Bundestages

Schematic of a gravitational wave detector based on light interferometry

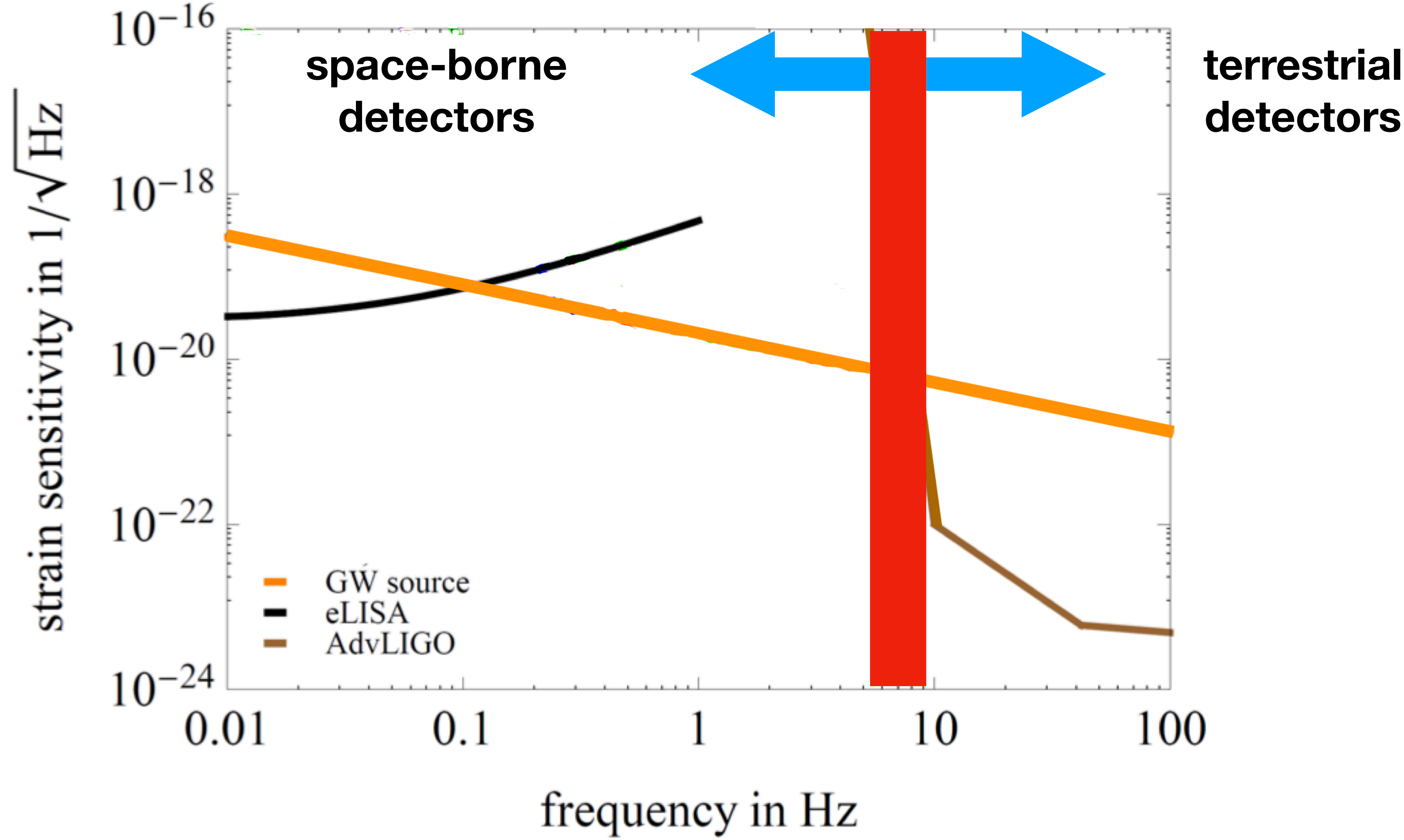


en.wikipedia.org/wiki/Gravitational-wave_observatory

Strain sensitivity of light-interferometric gravitational wave detectors



Spectral range of terrestrial detectors is limited by test mass suspension



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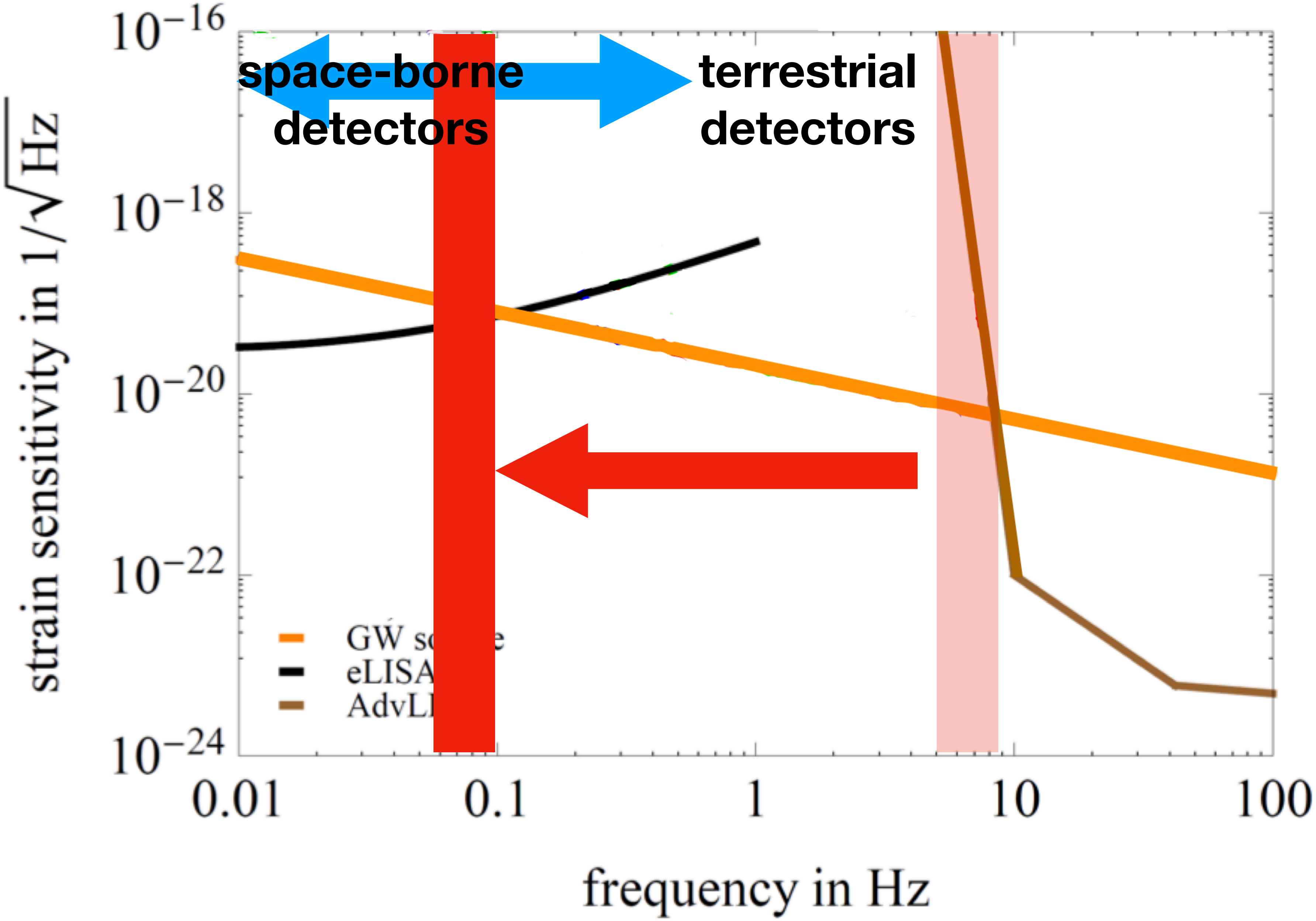
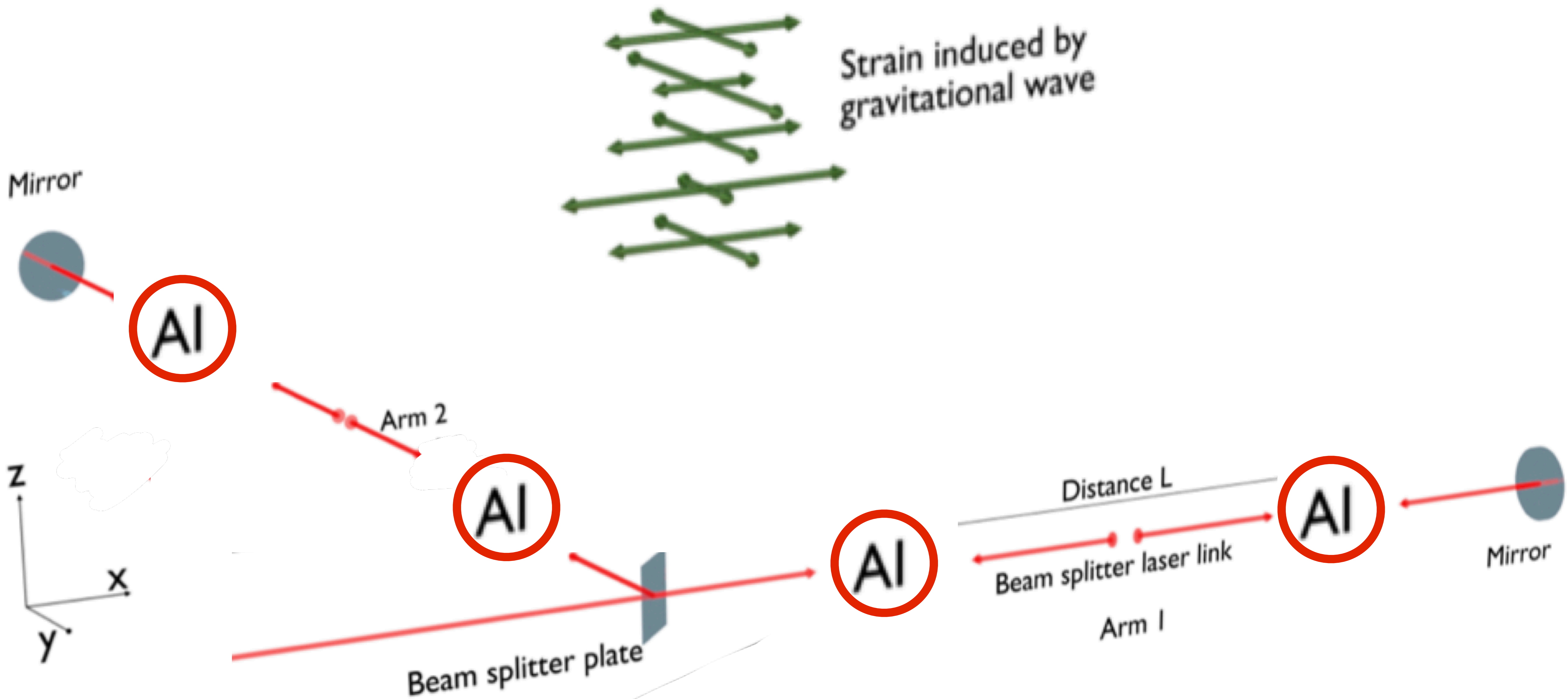
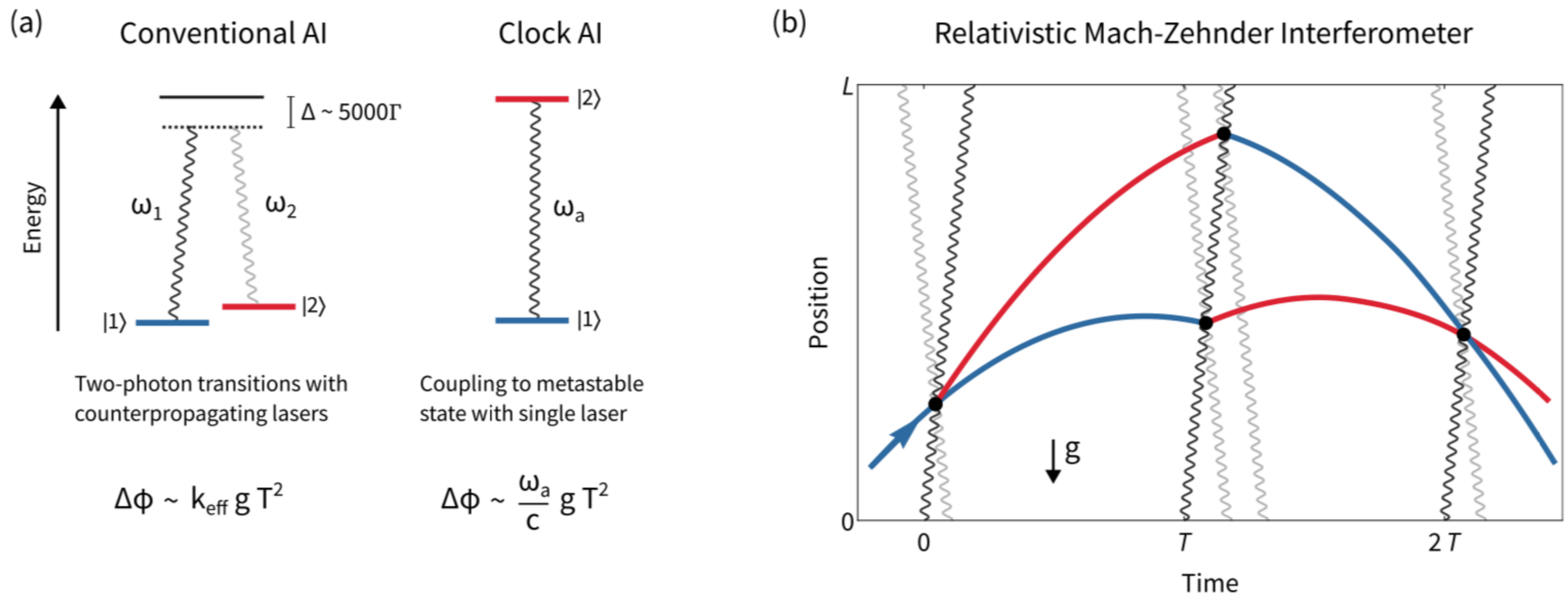


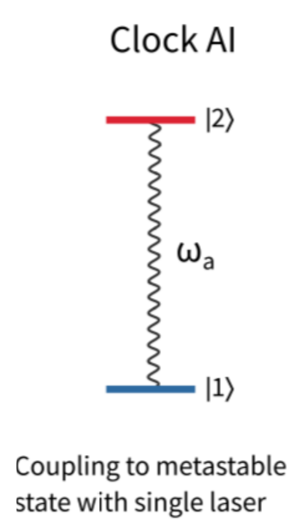
can one extend terrestrial detectors into the infrasound range ?

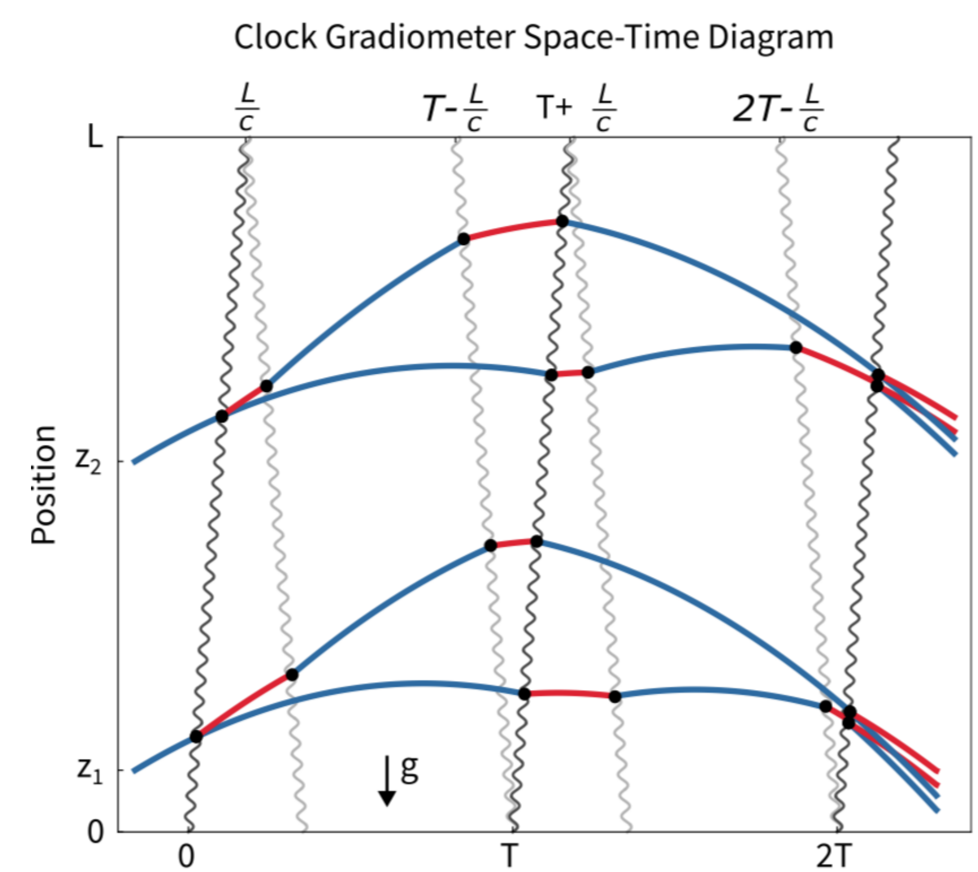
Schematic of a gravitational wave detector based on atom interferometry



Light pulse atom interferometry (AI)

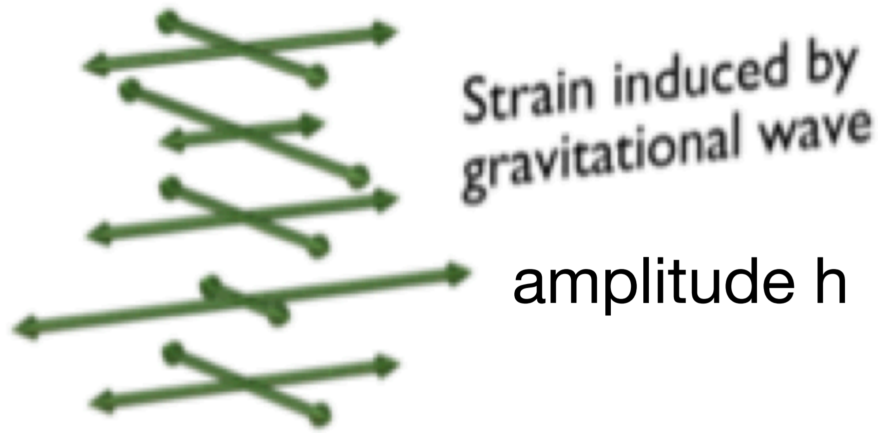






ideally sensitivity scales with momentum transfer of multiple photon recoils n k

horizontal Light pulse atom interferometry (AI)



amplitude h

gravitational wave induced phase

$$\delta\Phi_{GW} \sim n\ k\ h\ L\ f(\omega,T)$$

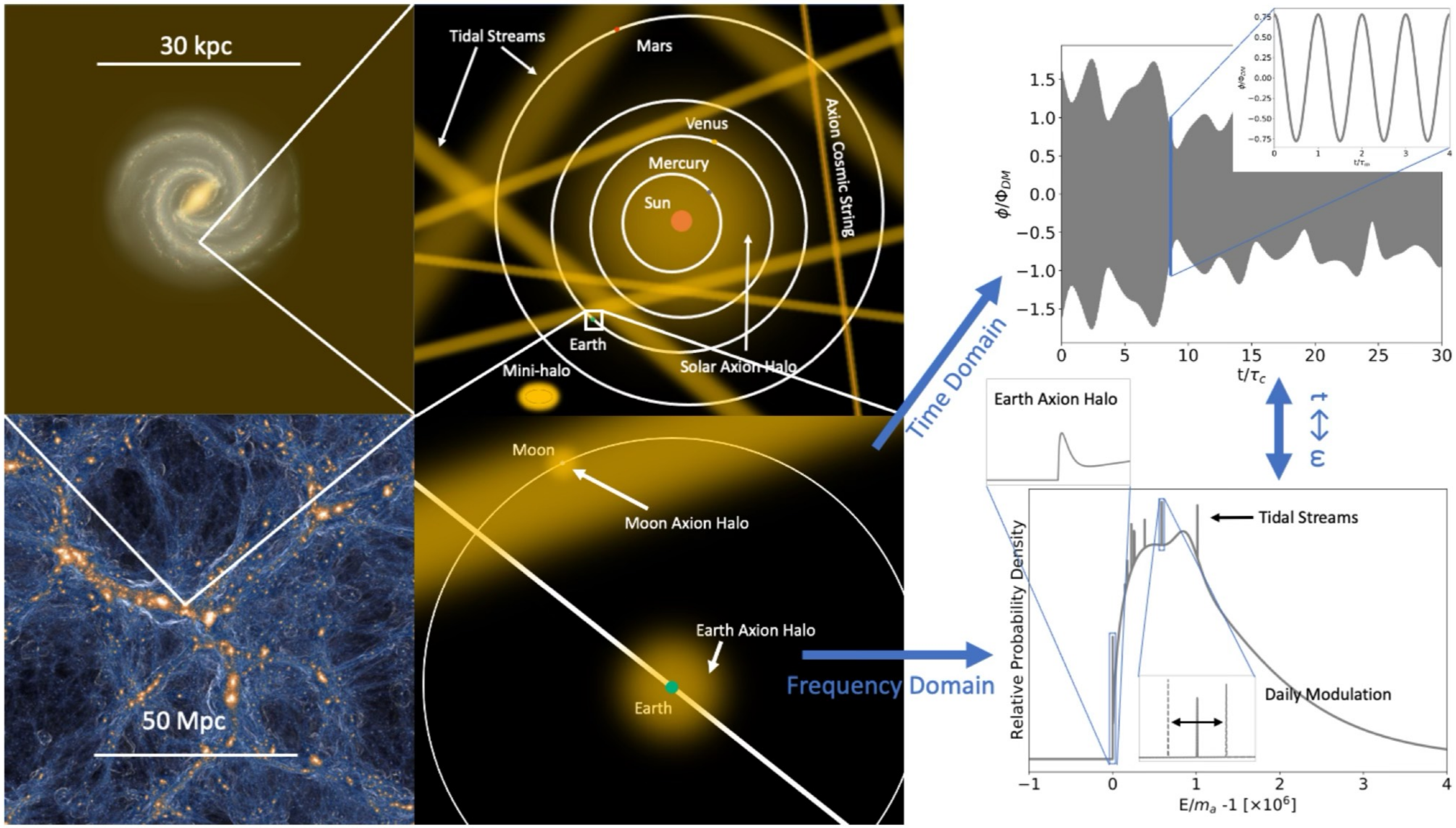
momentum transfer
multiple (n)
photon recoils k

acceleration induced phase

$$\delta\Phi_{Grav} \sim n\ k\ T^2\ \Delta a\ f(\omega, L)$$

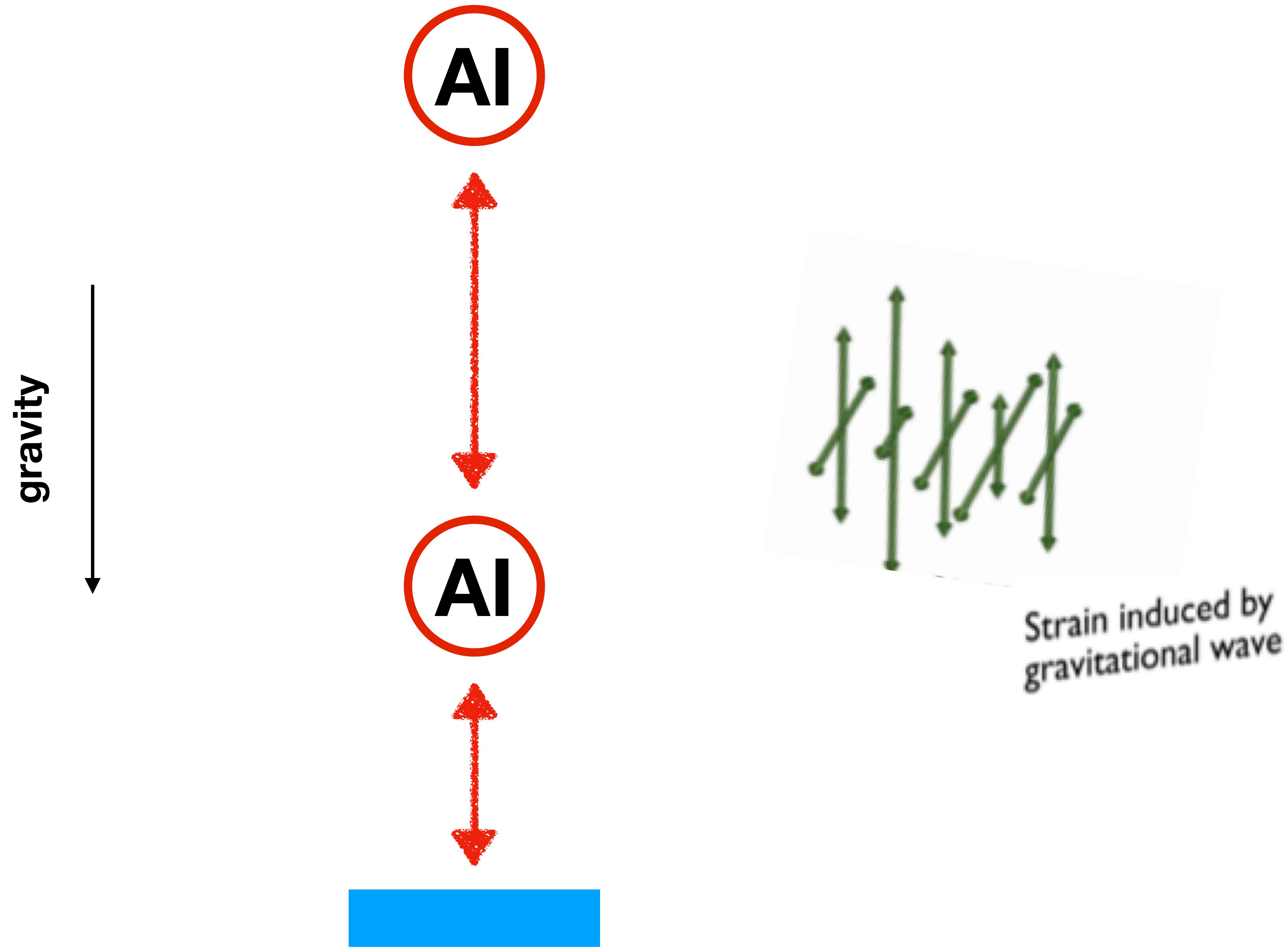
differential
acceleration Δa

coupling of light dark matter axions/axion-like particles



arXiv:2203.14923v3 [hep-ex]

vertical light pulse atom interferometry (AI)

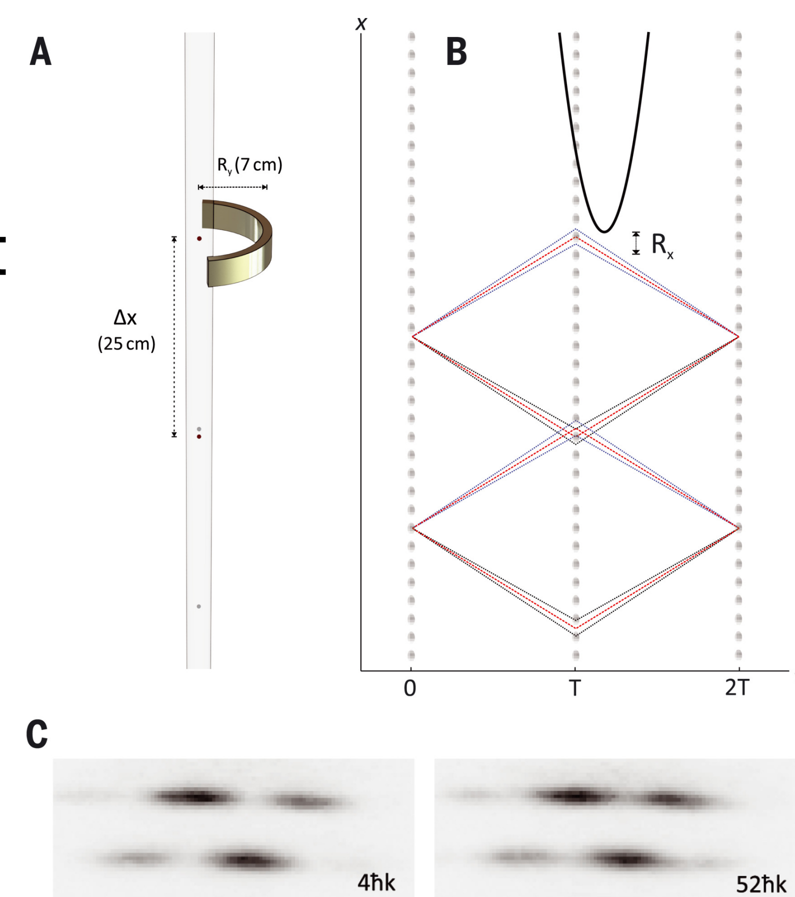


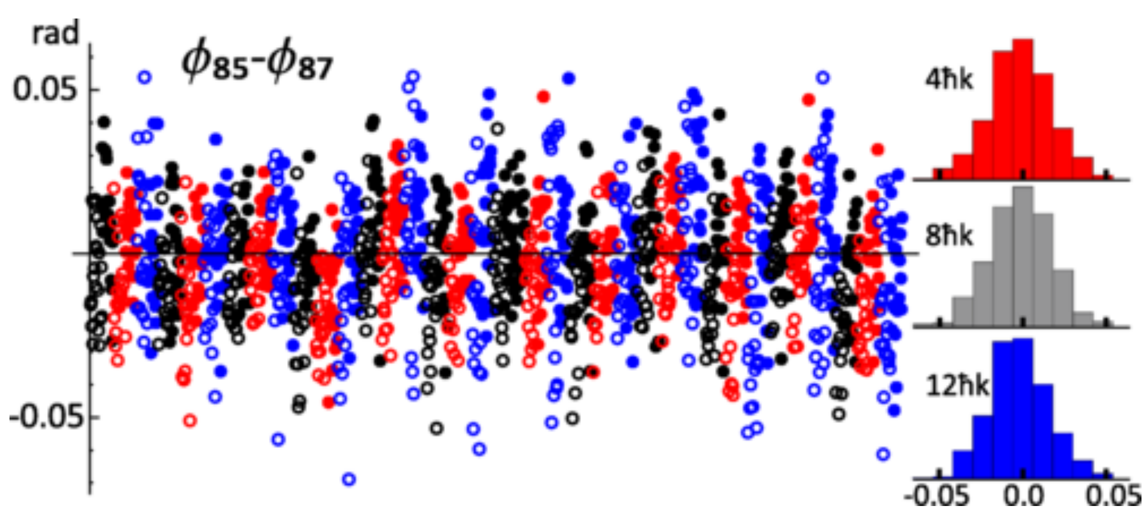
pioneering
vertical very-long light pulse atom interferometry (AI)

Stanford tower
Wuhan tower

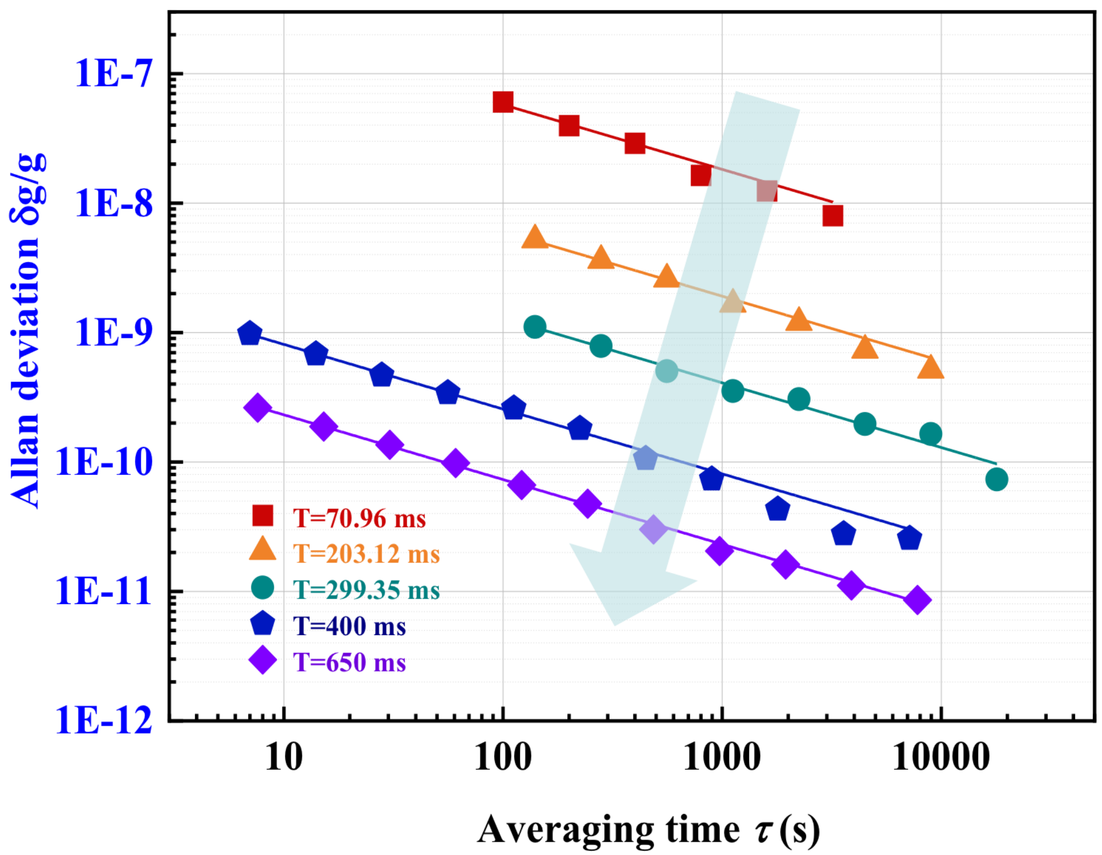
Stanford Tower

- Started in early 2000s
- Recent results
    - differential acceleration of Rb-85/Rb-87 EP test: $\eta=[1.6\pm1.8(\text{stat})\pm3.4(\text{syst})]\times10^{-12}$
    - Measurement of gravitational Aharanov-Bohm effect
    - Gradiometer sensitivity: 5 x $10^{-10}/s^2$ per shot (differential acceleration resolution 1.1 x 10^{-11} g per shot, 1.4 x 10^{-12} g after 70 shots)





Wuhan Tower



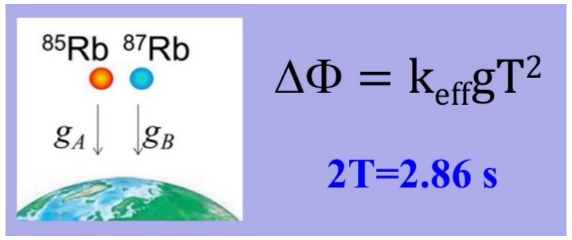
2015
4WDR method **8E-9**
L. Zhou, S.T. Long et al. *Phys. Rev. Lett.* **115**, 013004 (2015)

2018
Coriolis effect compensation **5.1E-10**
W. T. Duan, C. He et al. *Chin. Phys. B* **29**, 070305(2020)

2020
AC Stark shift Optimization **7.3E-11**
L. Zhou, C. He et al. *Phys. Rev. A* **104**, 022822 (2021)

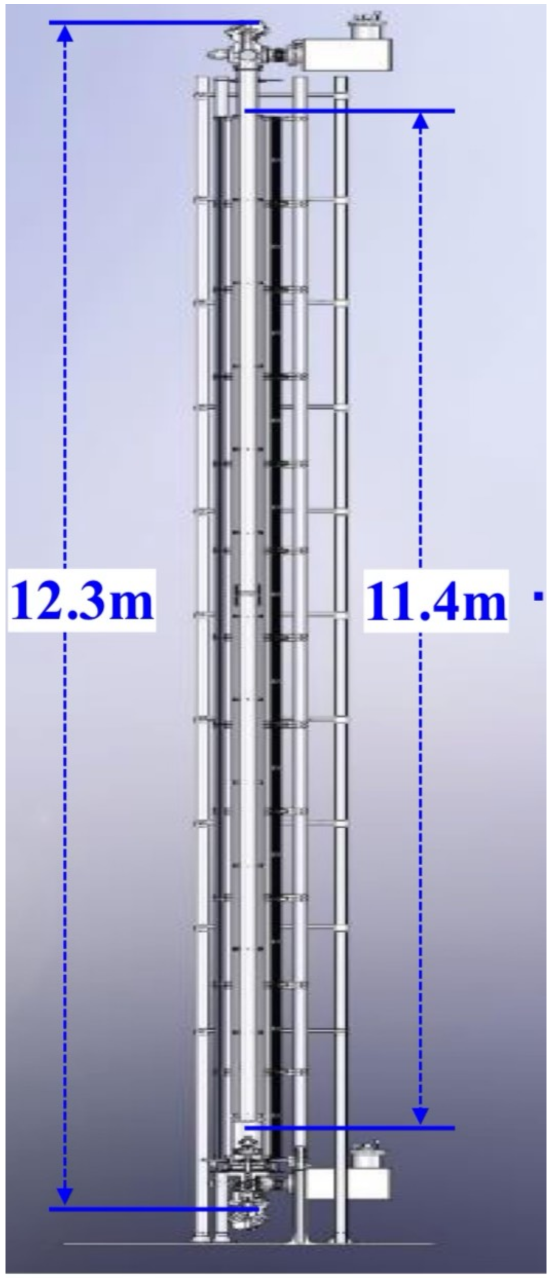
2022
Shear phase readout **2.5E-11**
L. Zhou, S. T. Yan et al. *Frot. Phys.* **10**, (2022)

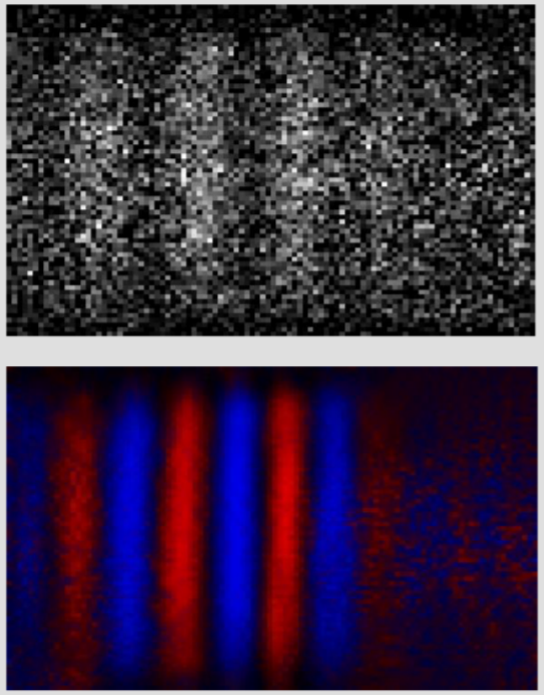
2023
Gravity gradient compensation **8.6E-12**

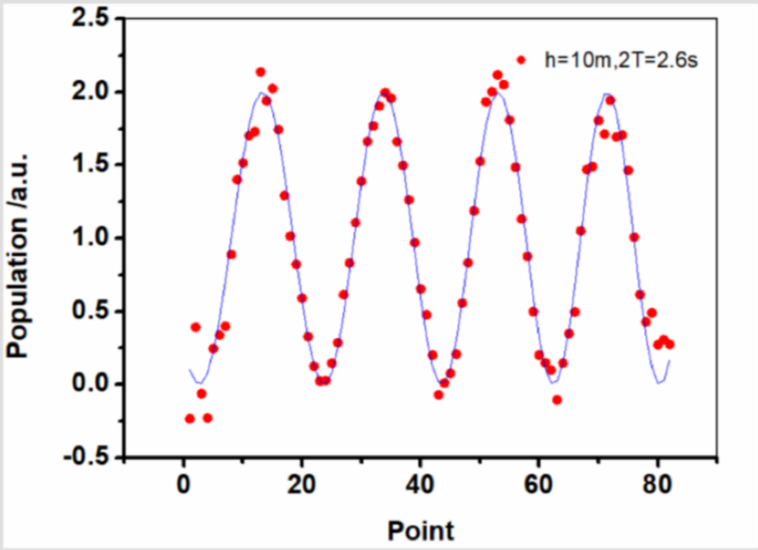


$\Delta\Phi = k_{eff} g T^2$

2T=2.86 s

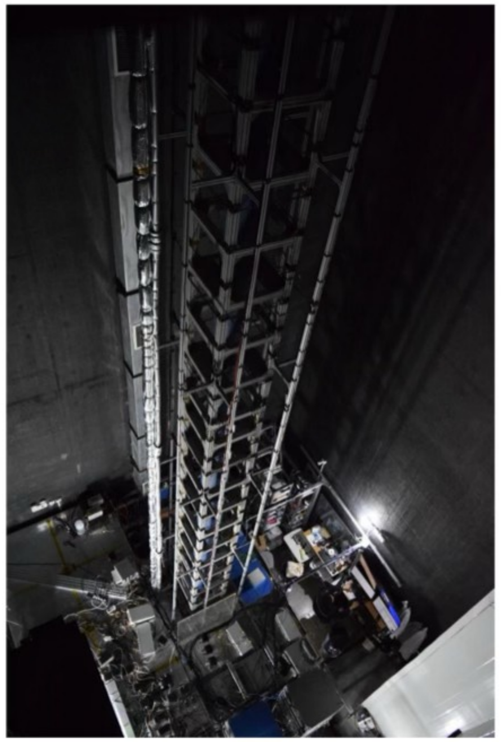






Principal component analysis

$\delta g/g = 4.5\times10^{-11}$/shot



Magnetic shield

pioneering
vertical light pulse atom interferometry (AI)

Stanford tower
Wuhan tower

nearly 20 years of operation demonstrated state-of-the-art resolution in differential acceleration measurements $\delta g/g \sim 10^{-11}$ single shot

Benefiting from upgrades, in the next five years, we can expect two order of improvement and may see 10^{-14} after integration of 100 experiments

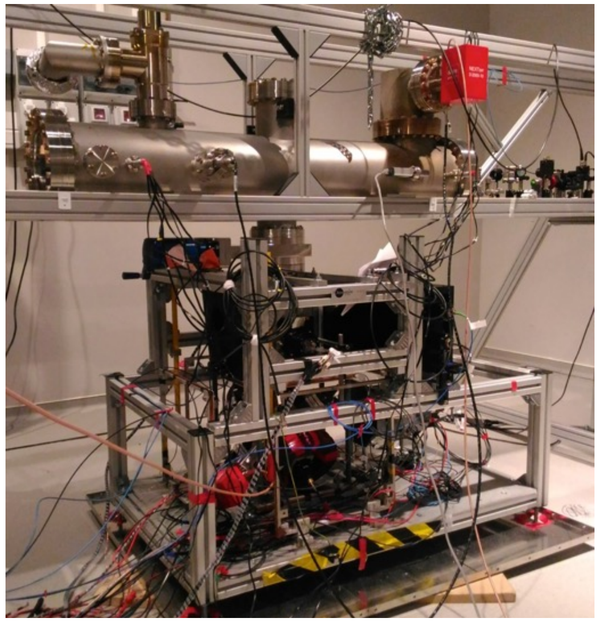
pioneering
horizontal very-long light pulse atom interferometry

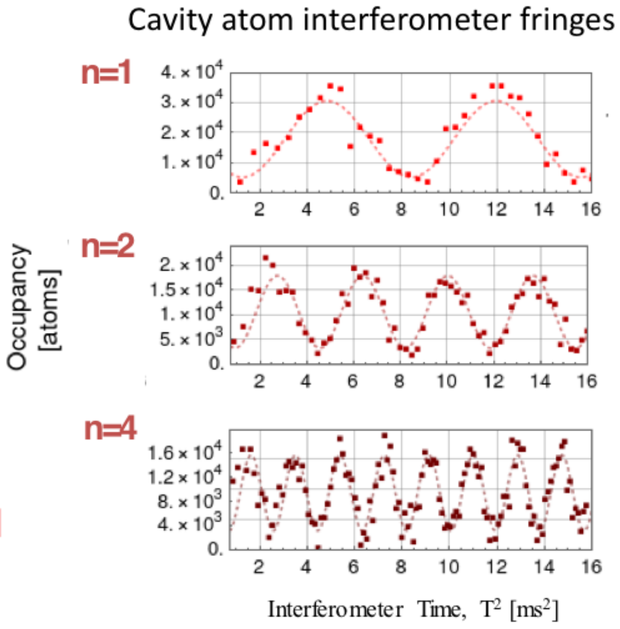
Bordeaux prototypes

horizontal light pulse atom interferometry (AI)

MIGA prototypes: from 1 to 6 m

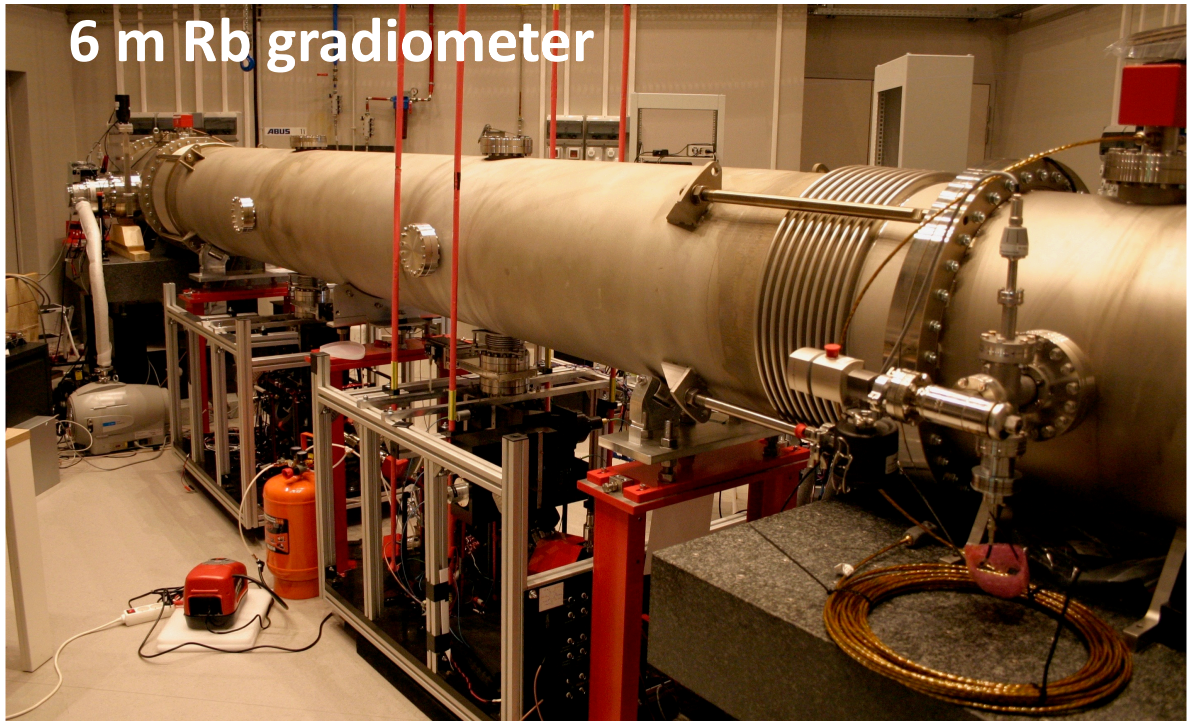
- Demonstration a horizontal multi-photon cavity atom interferometer driven via Bragg diffraction ($8\hbar$k momentum transfer)
- Development of enhanced cavity interrogation pulse exploiting the ring mode structure of a marginally stable resonator.





Studies now being extended on an atom gradiometer, short size version of the MIGA antenna with the scope to:

- Develop new LMT methods based on composite cavity pulses to reach hundreds of $\hbar$k momentum transfer.
- Elaborate of new schemes for GW detection and dark Matters studies based on cavity gradiometry.



novel
vertical very-long light pulse atom interferometry

Hannover VLBAI
in realisation
Stanford MAGIS-10
Cambridge AION-10

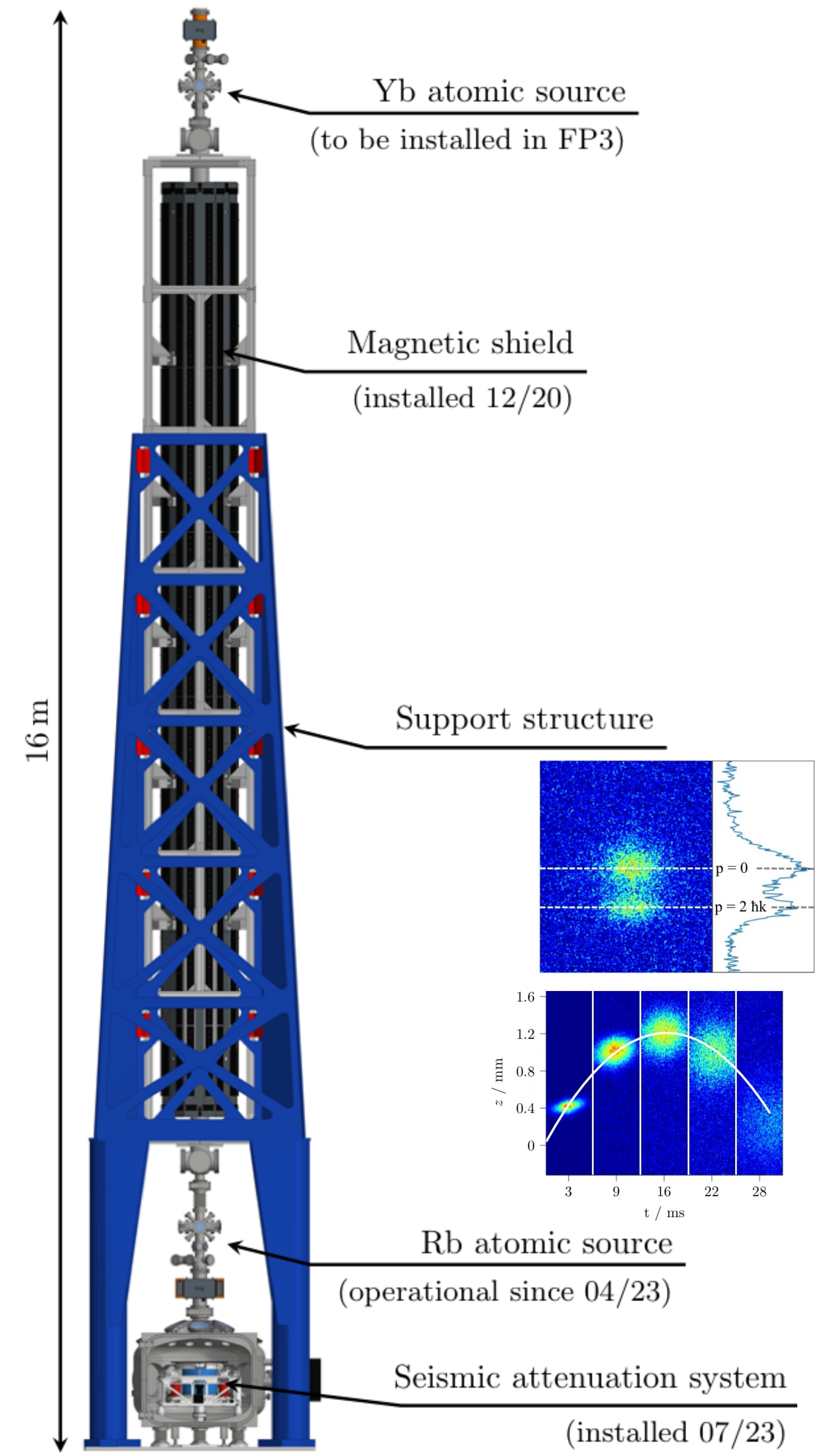
novel vertical light pulse atom interferometry (VLBAI)

quantum-gravity interface for matter waves (EP tests / quantum clock experiments, …)

methods for gravitational wave detection

features

- fast source of ultra-cold atoms (Bose-Einstein condensates)
- scalable magnetic shield
- vibration isolation
- alkaline and alkaline earth atoms (Rb/Yb)



Stanford 10 m Sr Prototype

- Leverage Stanford 10 m Sr prototype and MAGIS-100 as development platforms

- Improved large momentum transfer (LMT) atom optics
  - Higher power laser systems
  - Robust quantum control techniques (for example: Floquet atom optics, quantum optimal control approaches)
  - Resonant operation mode
  - 3-photon atom optics to enable use of bosonic Sr-88

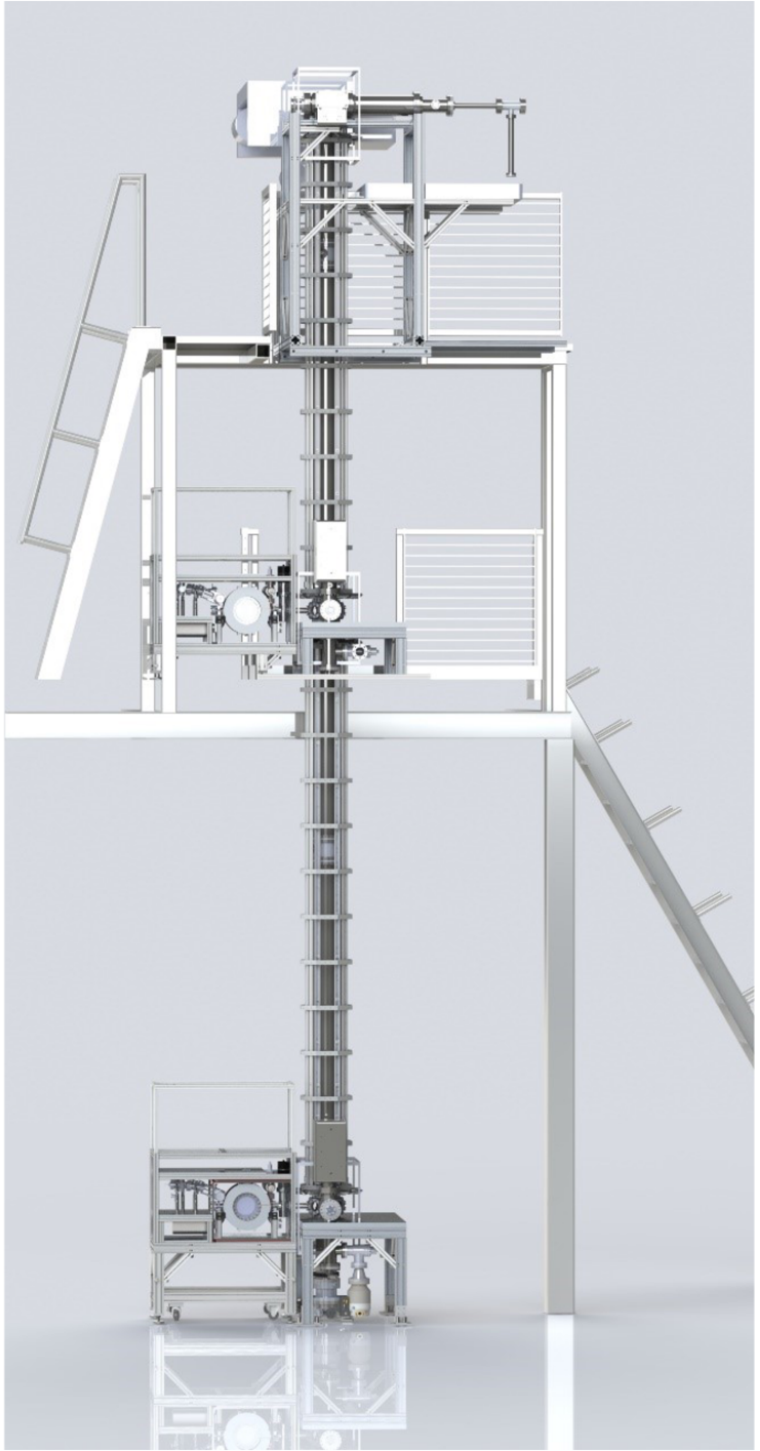
- Improved phase resolution
  - Higher cold atom flux
  - Spin squeezing
  - Advanced atom lensing techniques

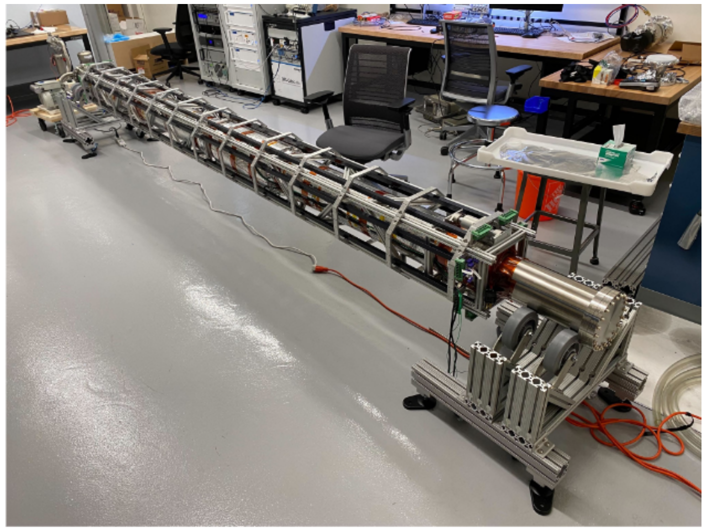
- Multiplexed interferometers

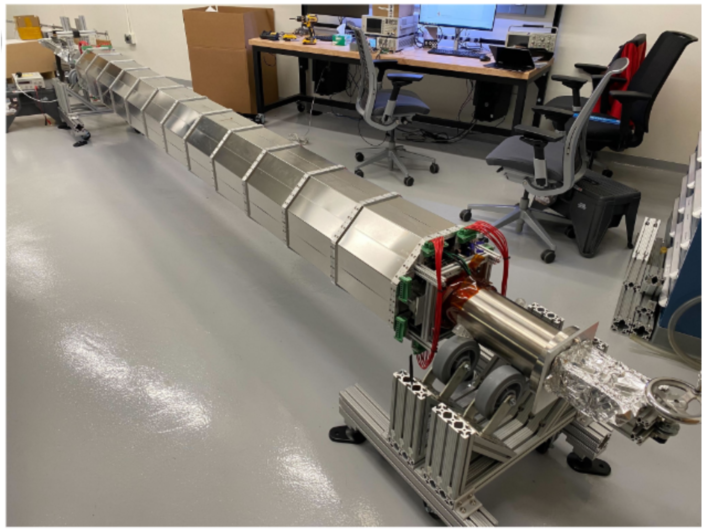
- Background noise suppression strategies (for example: gravity gradient noise)

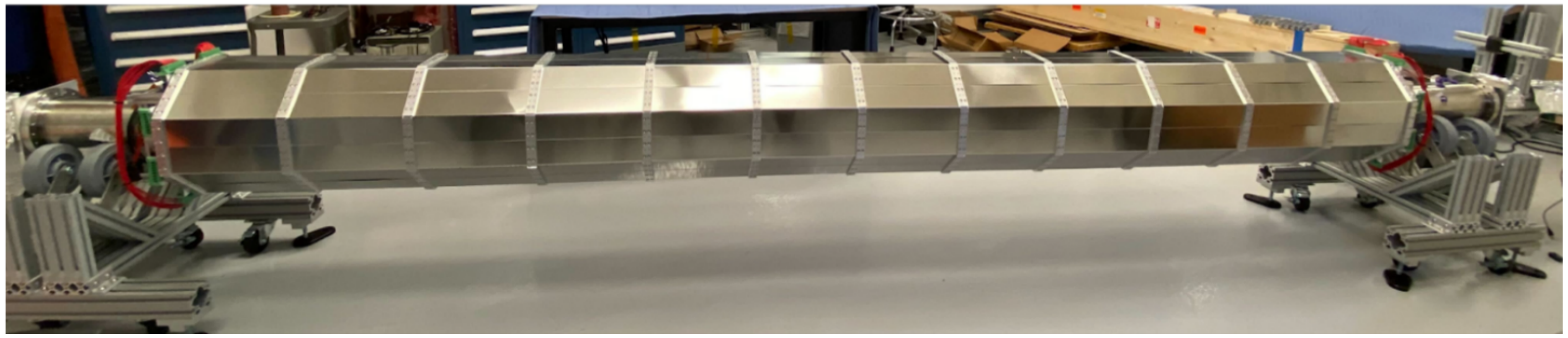
Experiment	(Proposed) site	Baseline L (m)	LMT atom optics n	Atom sources	Phase noise $\delta\phi$ (rad/$\sqrt{\text{Hz}}$)
Sr prototype tower	Stanford	10	10^2	2	10^{-3}

Stanford 10 m Sr Prototype

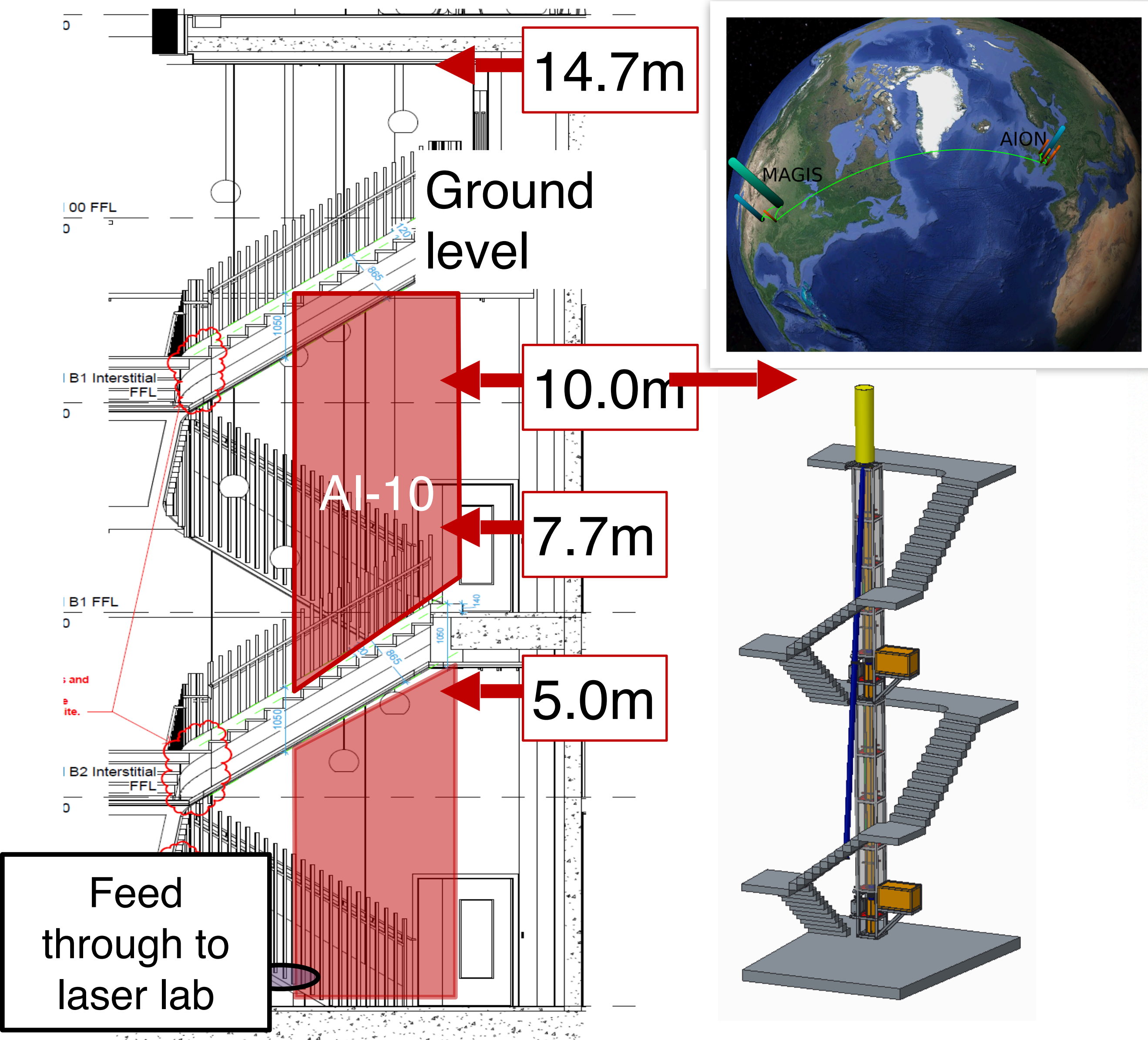








novel
vertical light pulse atom interferometry (AION)



L. Badurina et al., *AION: An Atom Interferometer Observatory and Network*, *JCAP* **05** (2020) 011, [arXiv:1911.11755]

Project executed in national partnership with **UK National Quantum Technology Hub in Sensors and Timing, Birmingham, UK,** and international partnership with **The MAGIS Collaboration and The Fermi National Laboratory, US**

To push the state-of-the-art single photon Sr Atom Interferometry, the AION project builds dedicated Ultra-Cold Strontium Laboratories in: **Birmingham, Cambridge, Imperial College, Oxford, and RAL**
The laboratories are expected to be fully operational in summer 2023.

AION-10 - apart of a 4 stage road map

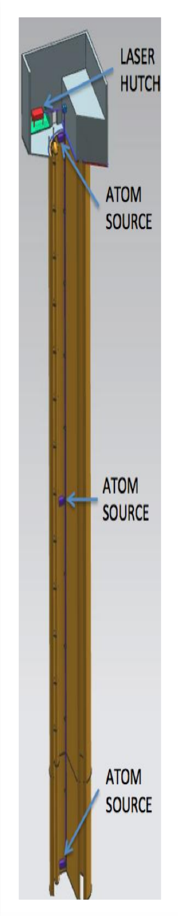
- **Stage 1:** to build and commission the 10 m detector, develop existing technology and the infrastructure for the 100 m.
- **Stage 2:** to build, commission and exploit the 100 m detector and carry out a design study for the km-scale detector.
  - AION was selected in 2018 by STFC as a high-priority medium-scale project.
  - AION will work in equal partnership with MAGIS in the US to form a “LIGO/Virgo-style” network & collaboration, providing a pathway for UK leadership.

Stage 1 is now funded with about £10M by the QTFP Programme and other sources and Stage 2 could be placed at national facility in Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).

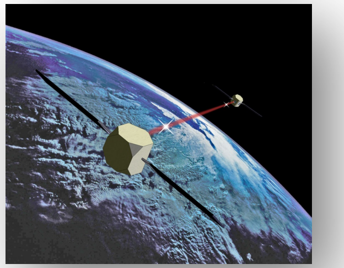
L ~ 10m

L ~ 100m

L ~ 1km

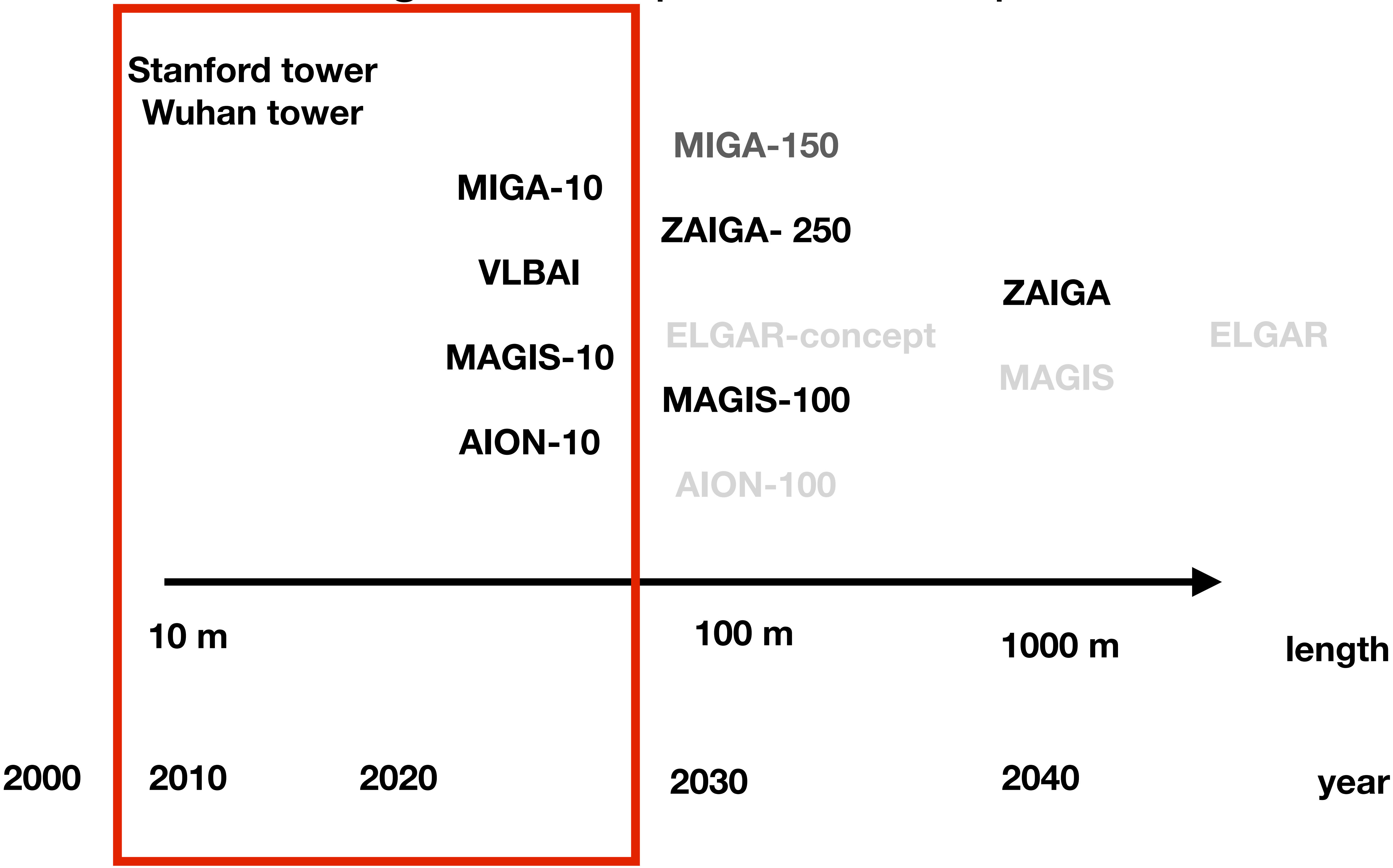


- **Stage 3:** to build a kilometre-scale terrestrial detector.
- **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - AION has established science leadership in AEDGE, bringing together collaborators from European and Chinese groups (e.g. MIGA, MAGIA, ELGAR, ZAIGA).

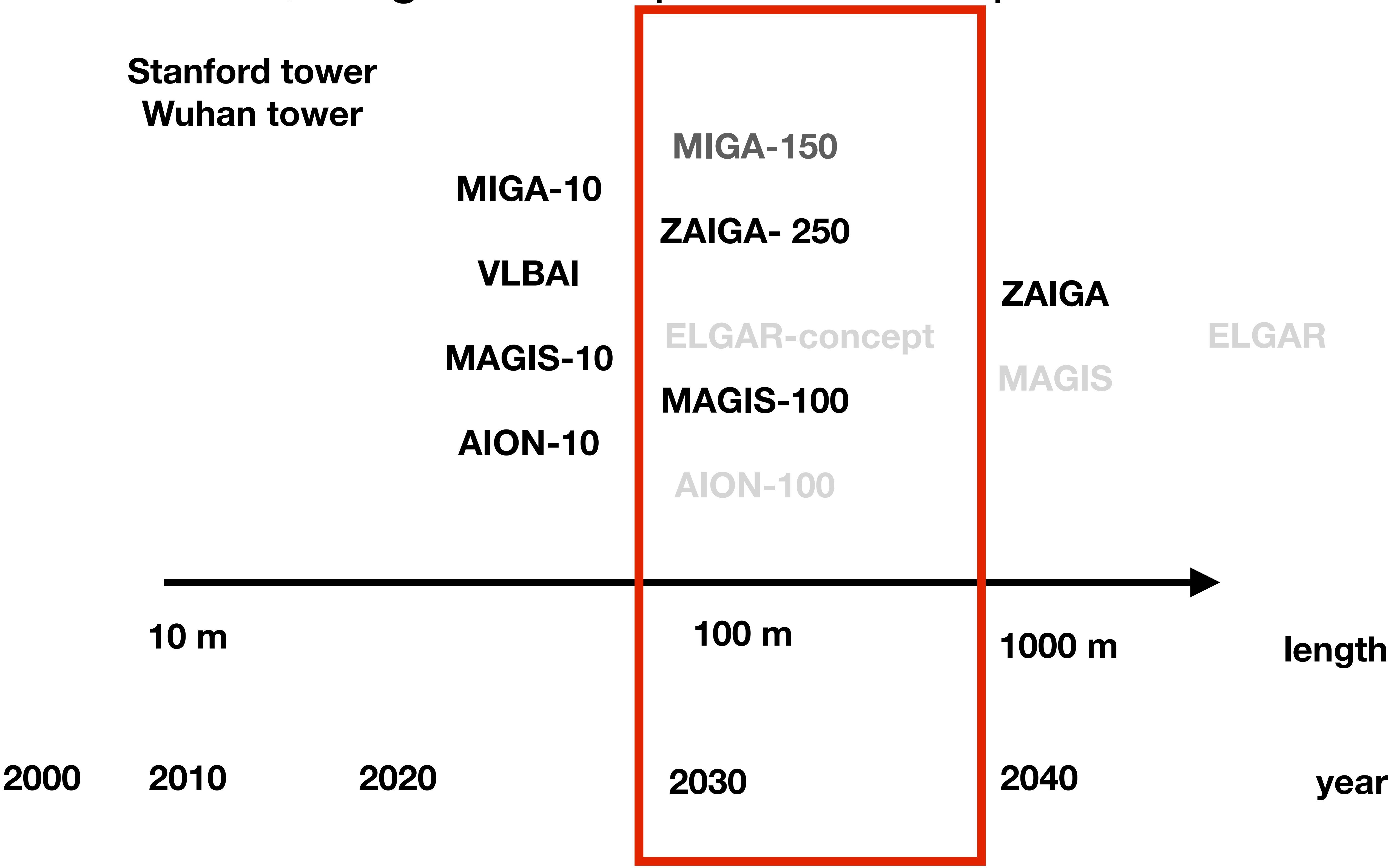


Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

terrestrial very long baseline atom interferometers activities, length and implementation period



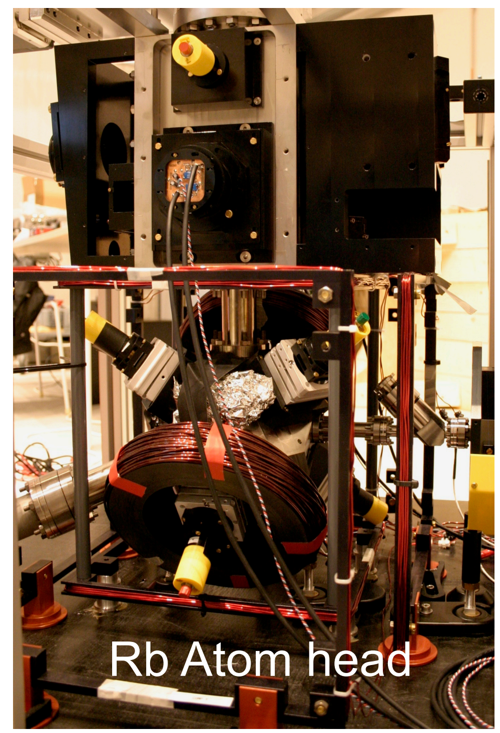
terrestrial very long baseline atom interferometers activities, length and implementation period

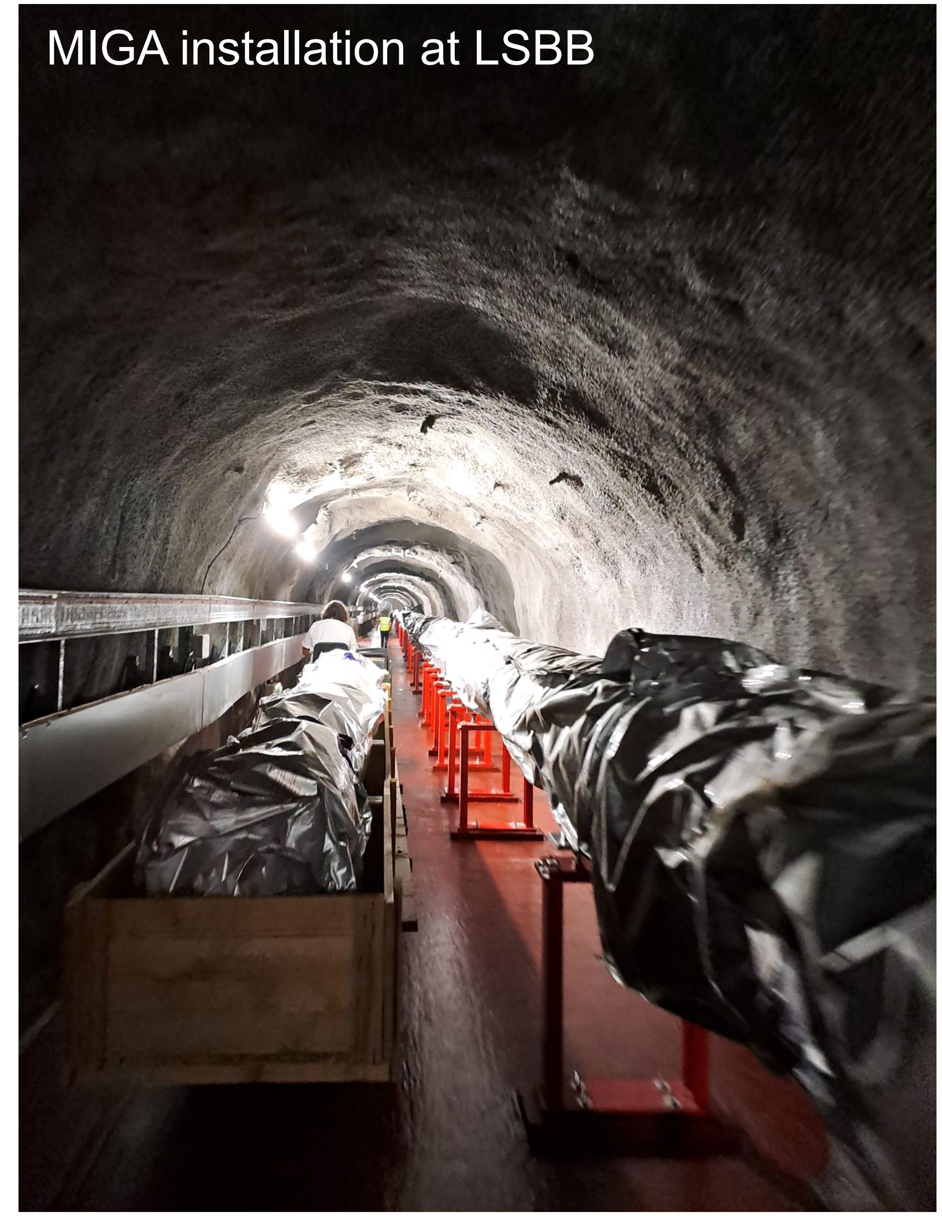


very-long light pulse atom interferometry beyond 10m length

MIGA-150 (horizontal)
MAGIS-100 (AION -100)
ZAIGA -250

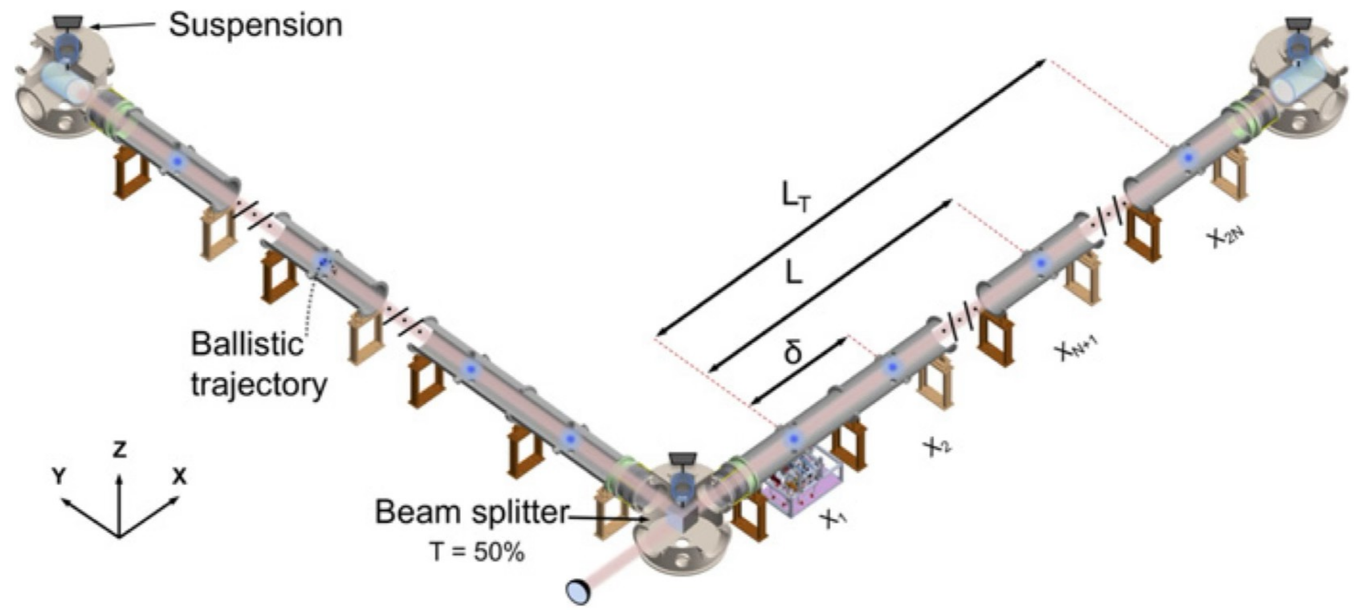
MIGA - 250 Status

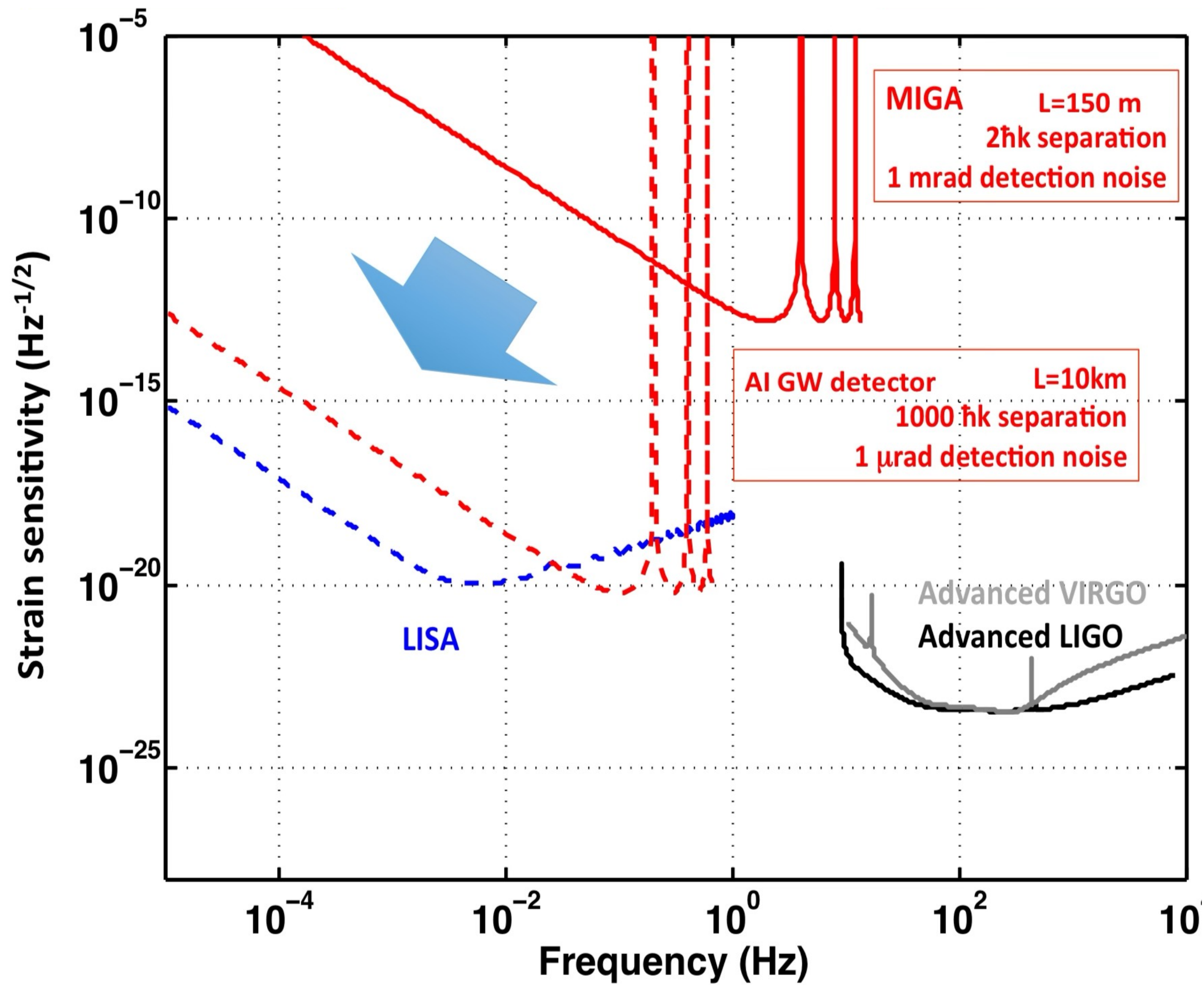




- Two 150 m dedicated galleries were bored at LSBB
- All parts (vacuum, atom head&lasers) produced and tested.
- Vacuum system now being assembled, 75 % achieved. Antenna operational by 2025.

MIGA - 150 plan

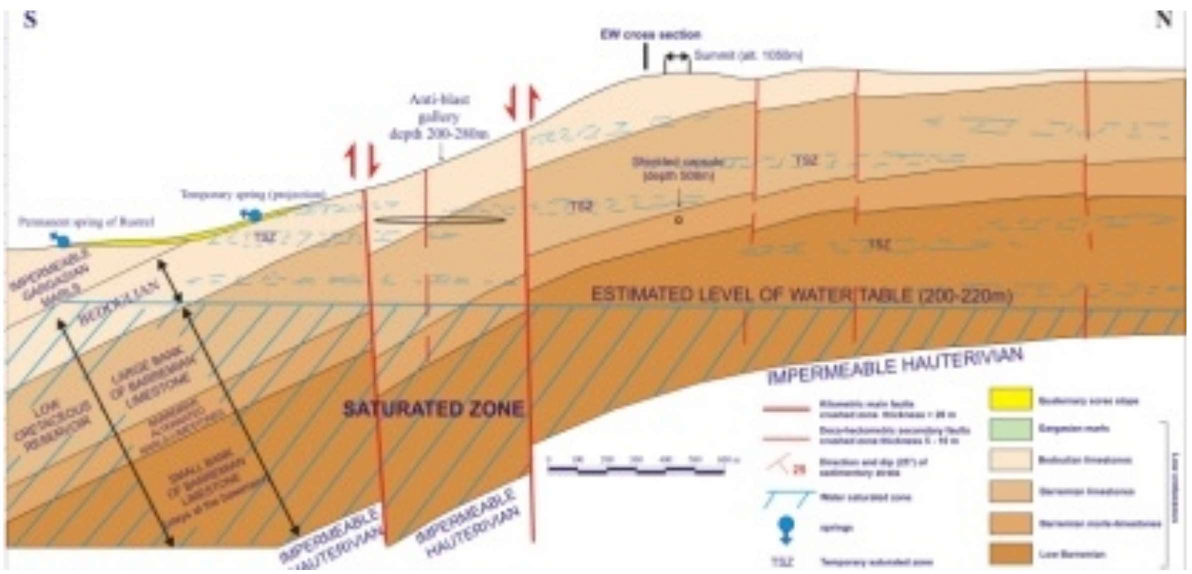




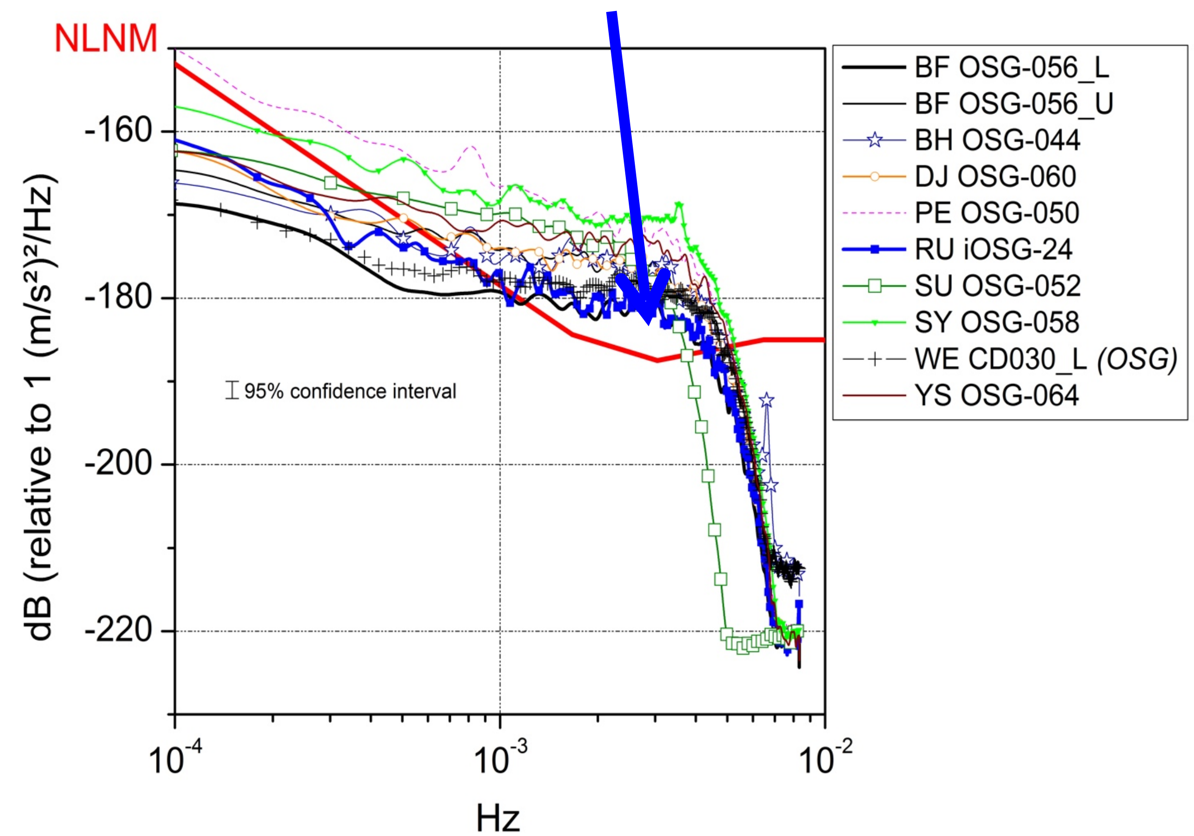
Science with MIGA

Short term :

- Gravity cartography/Mass transfer in 2D
- Newtonian noise modelisation
- Correlation with a vertical 500 m superconducting gradiometer
- Hydrogeology

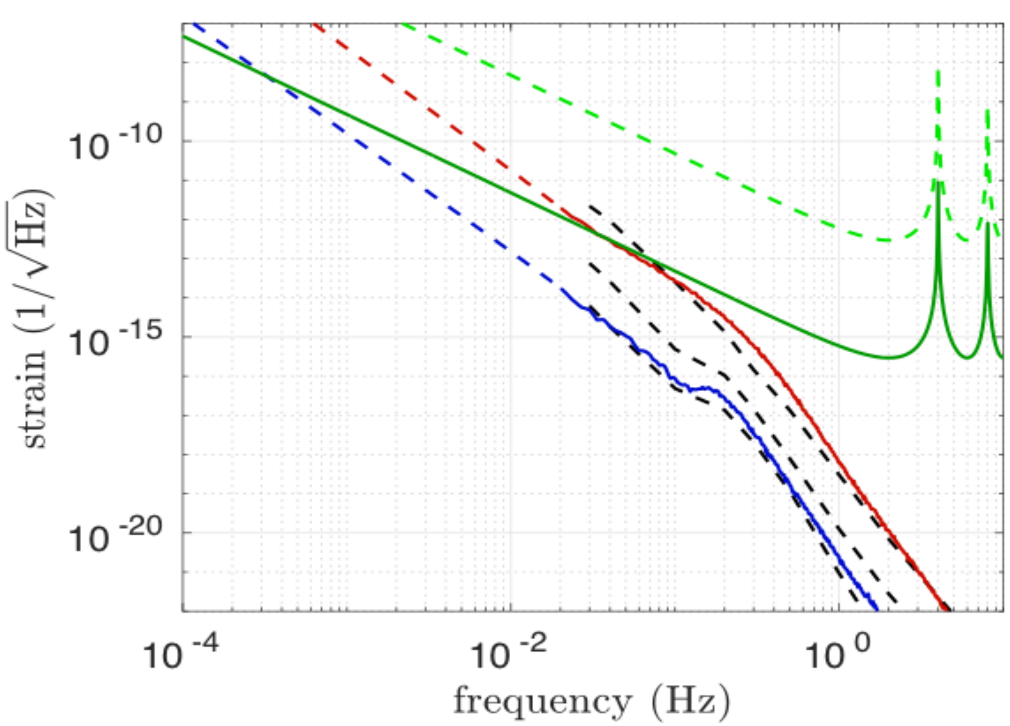


IOSG-24@LSBB: one of the quietest site in the world



Statistical Noise levels: iOSG-24 vs. worldwide SGs and NLNM

Medium term with improved sensitivity:



Fundamental Physics:

- Newtonian Noise direct measurement
- Test of general relativity
- Dark matter studies

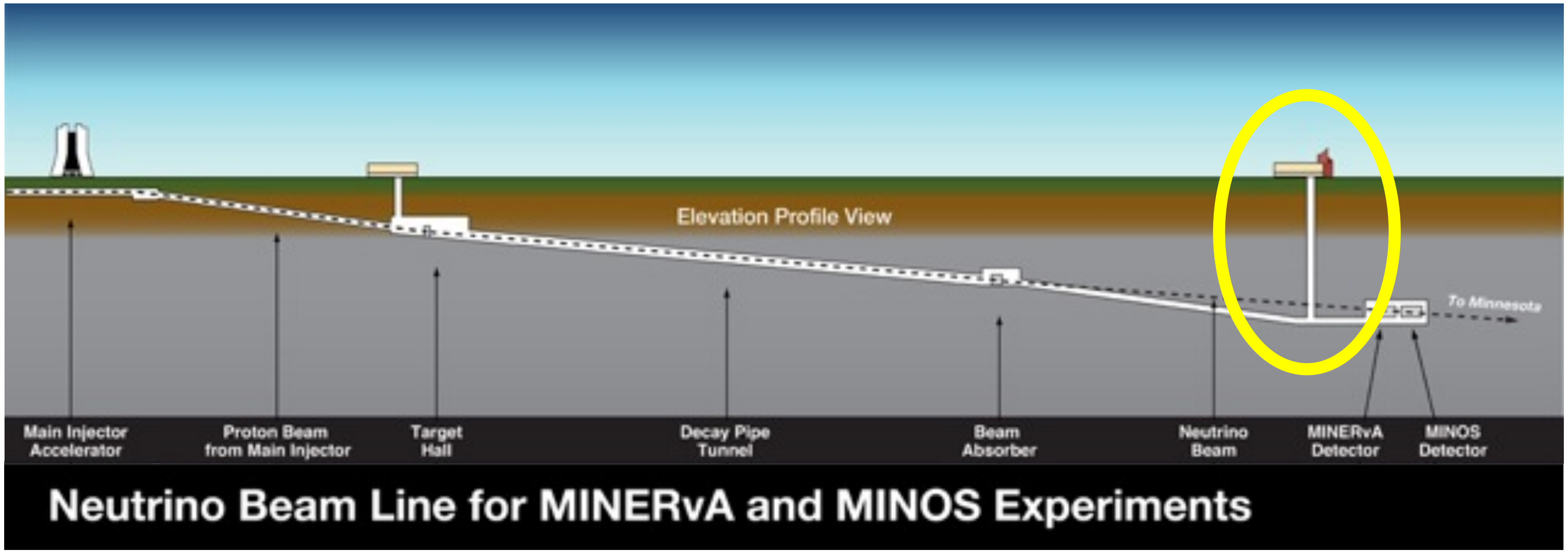
Geophysics:

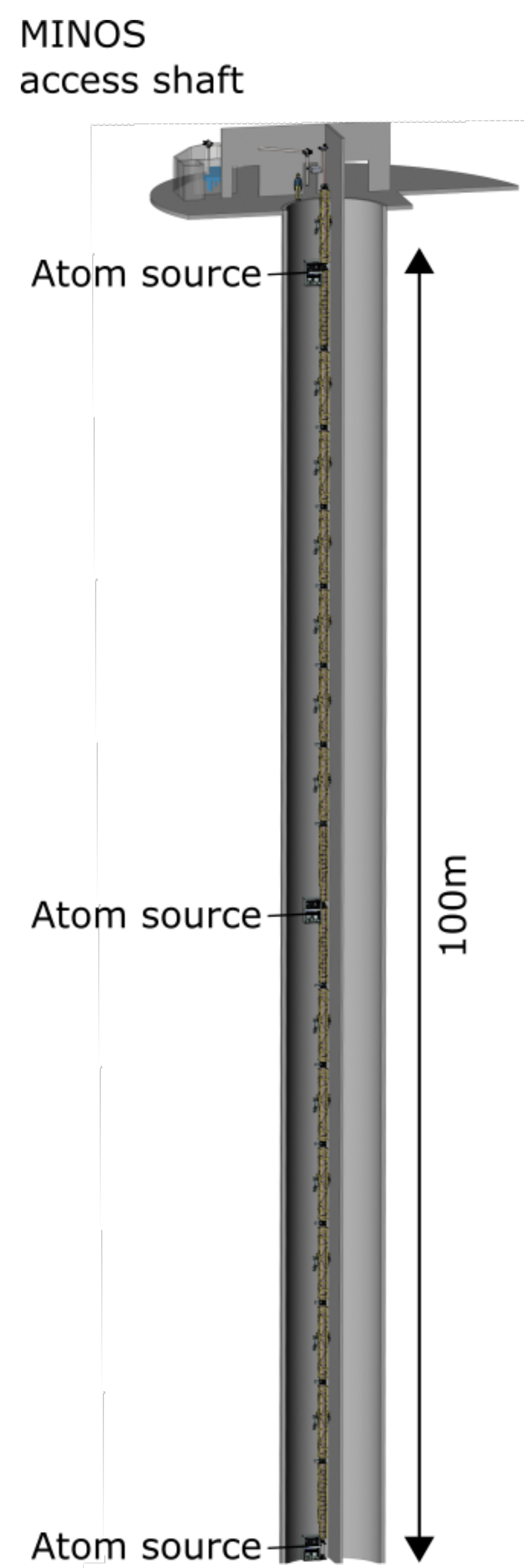
- Study of seismic gravity precursors
- Rotational seismology

MAGIS-100 detector at Fermilab

MAGIS-100

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



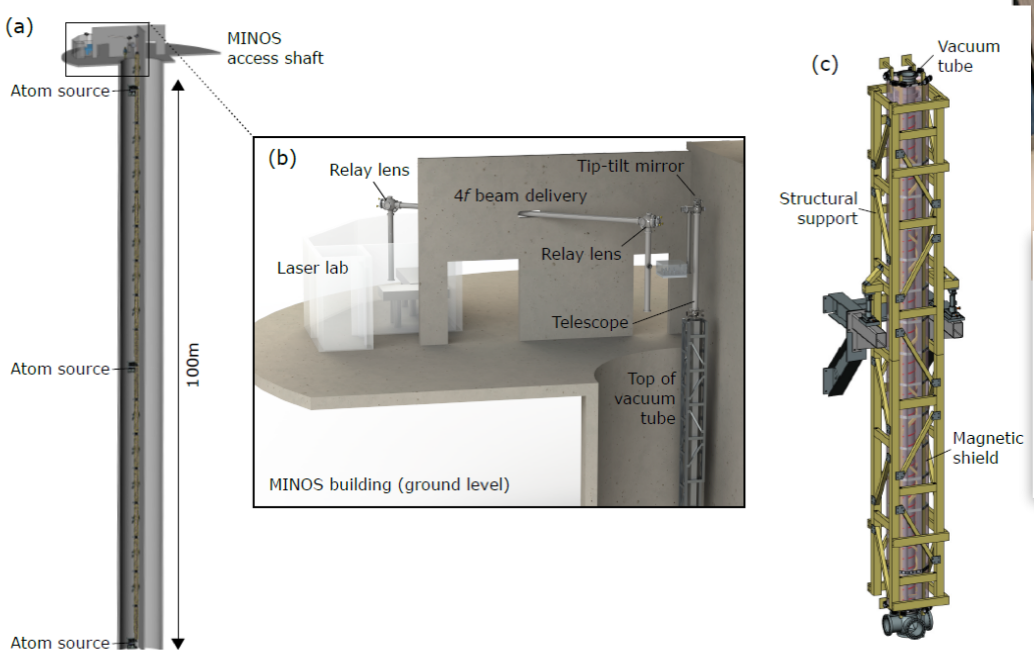


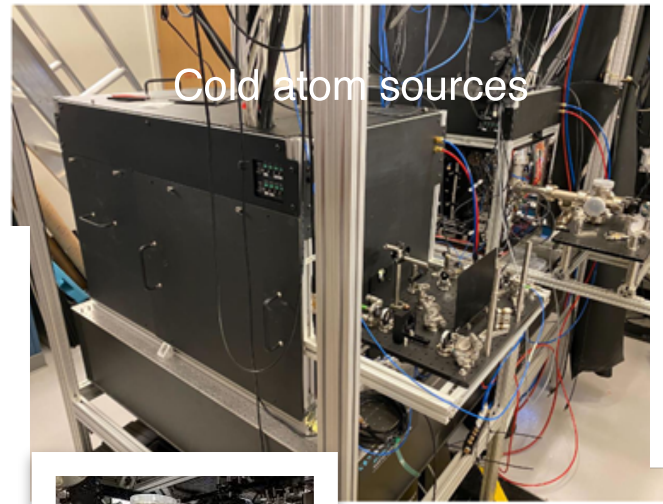
- 100-meter-tall atom interferometry apparatus
- Quantum mechanics at very large scales
- Search for wavelike dark matter
- Prototype for mid-band gravitational wave detection

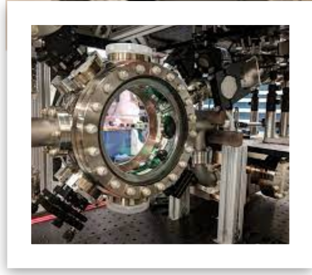
Jefferson Lab · Stanford · Fermilab · Northwestern University · ODU · University of Liverpool · Northern Illinois University · Johns Hopkins University · University of Cambridge · University of Oxford · SLAC

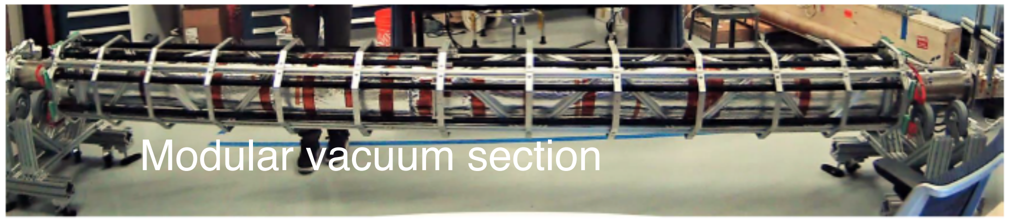
MAGIS-100 Experiment

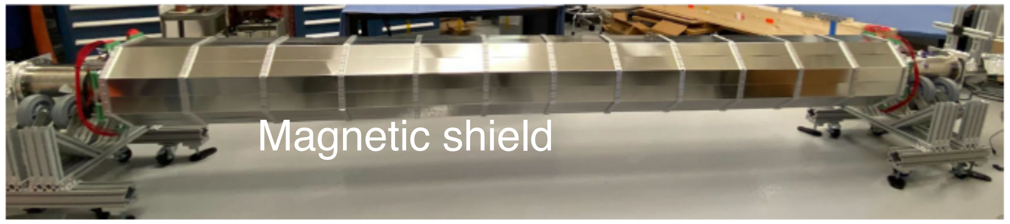
MAGIS-100

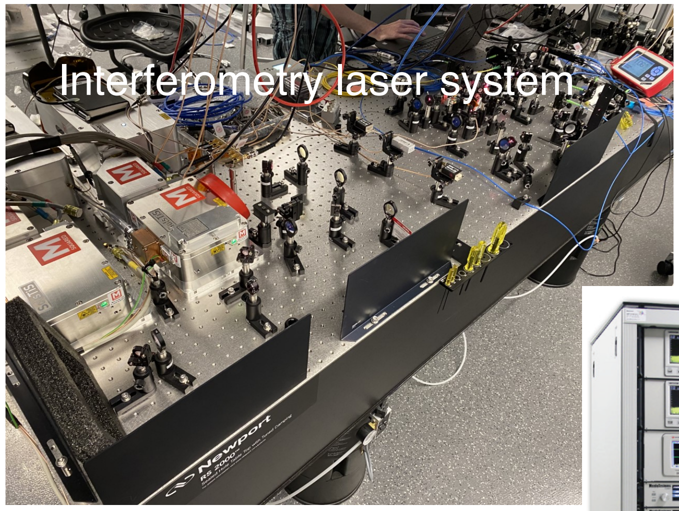










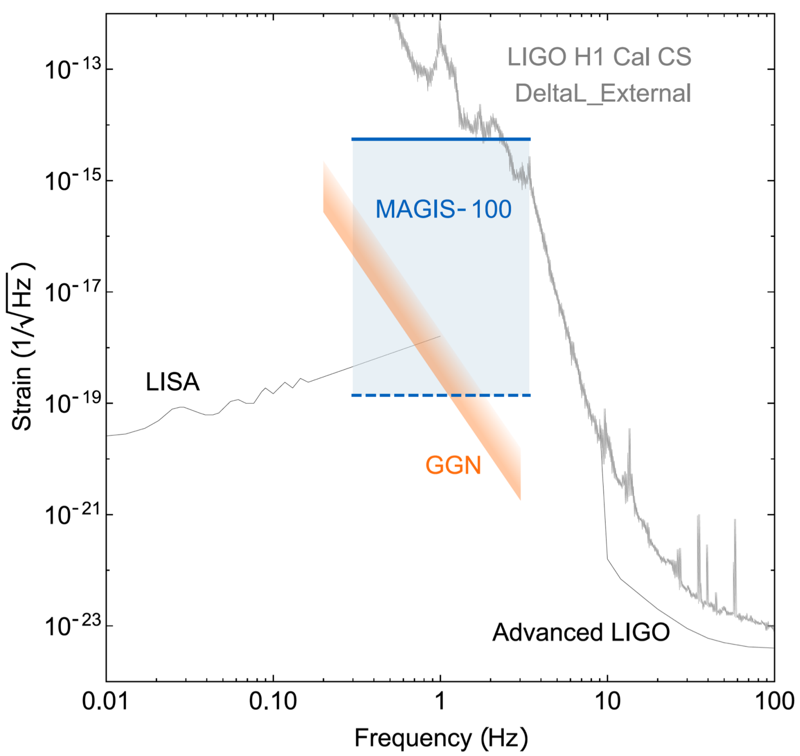


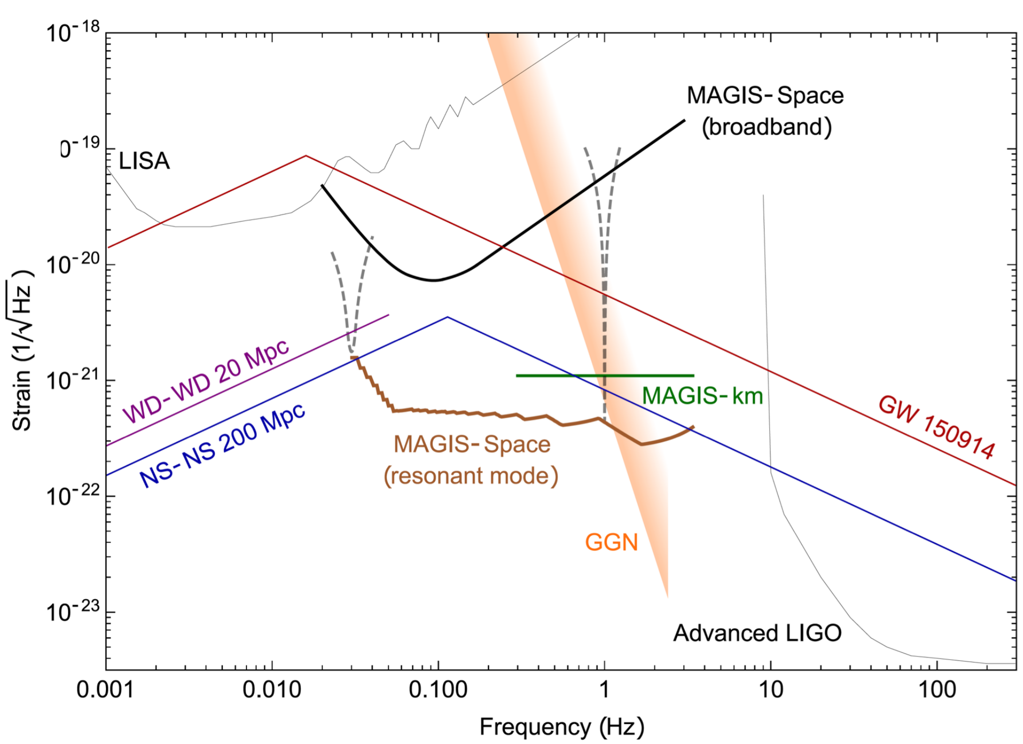
Frequency Comb

- 17 modules, each with magnetic shielding, vacuum pipe, current-carrying wires for generating bias magnetic field
- Laser lab at top of shaft (currently undergoing construction)
- Three Sr atom sources over 100 m baseline, local optical lattices can launch atoms from each source
- High-power laser system with agile frequency control, spatially filtered beam mode, and precisely controlled pointing via tip-tilt mirrors
- Construction and testing of subsystems underway

Sensitivity Goals

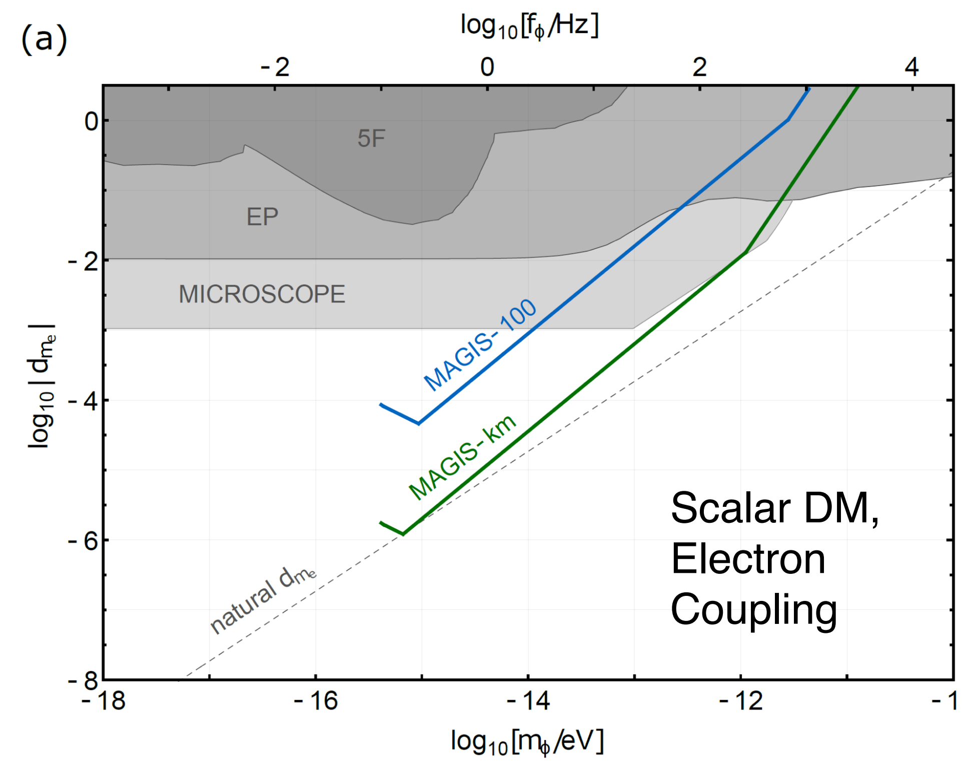
Gravitational Waves

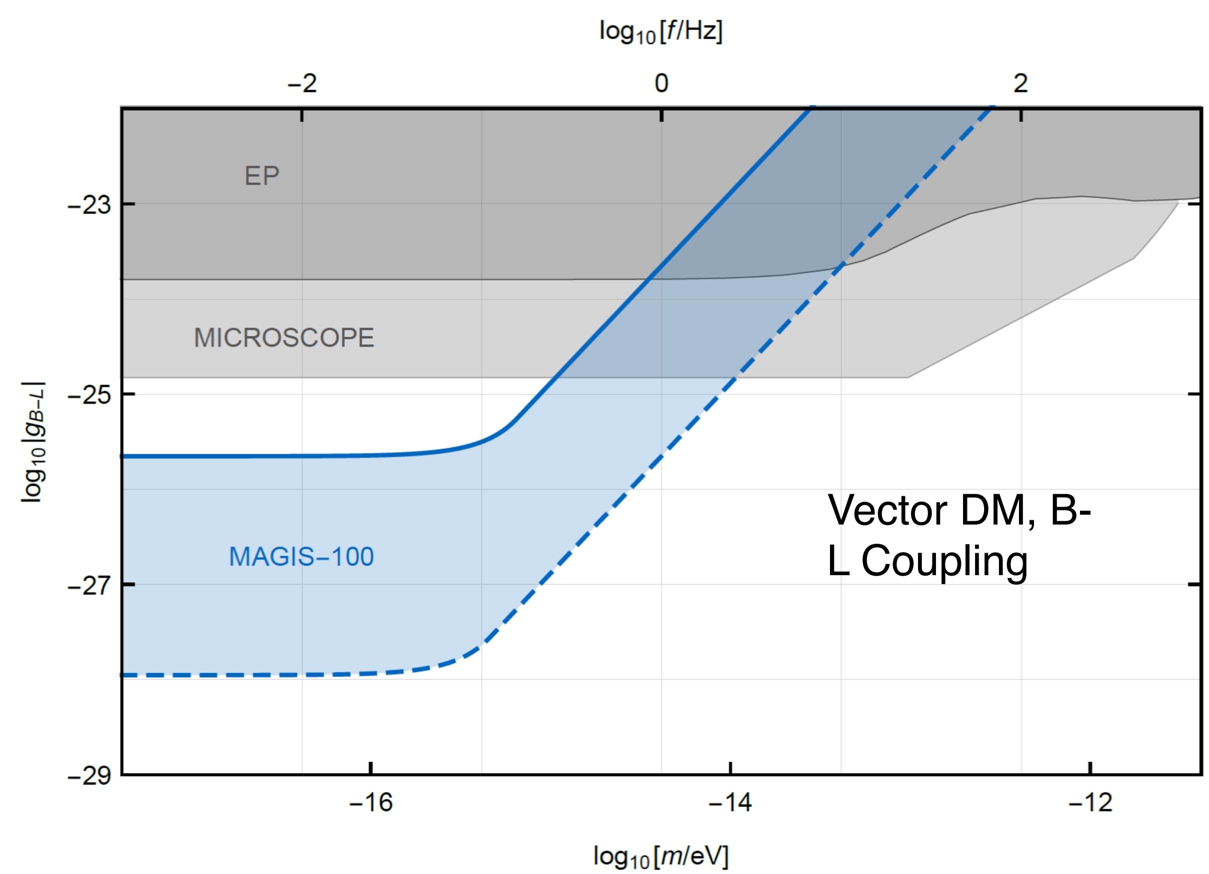




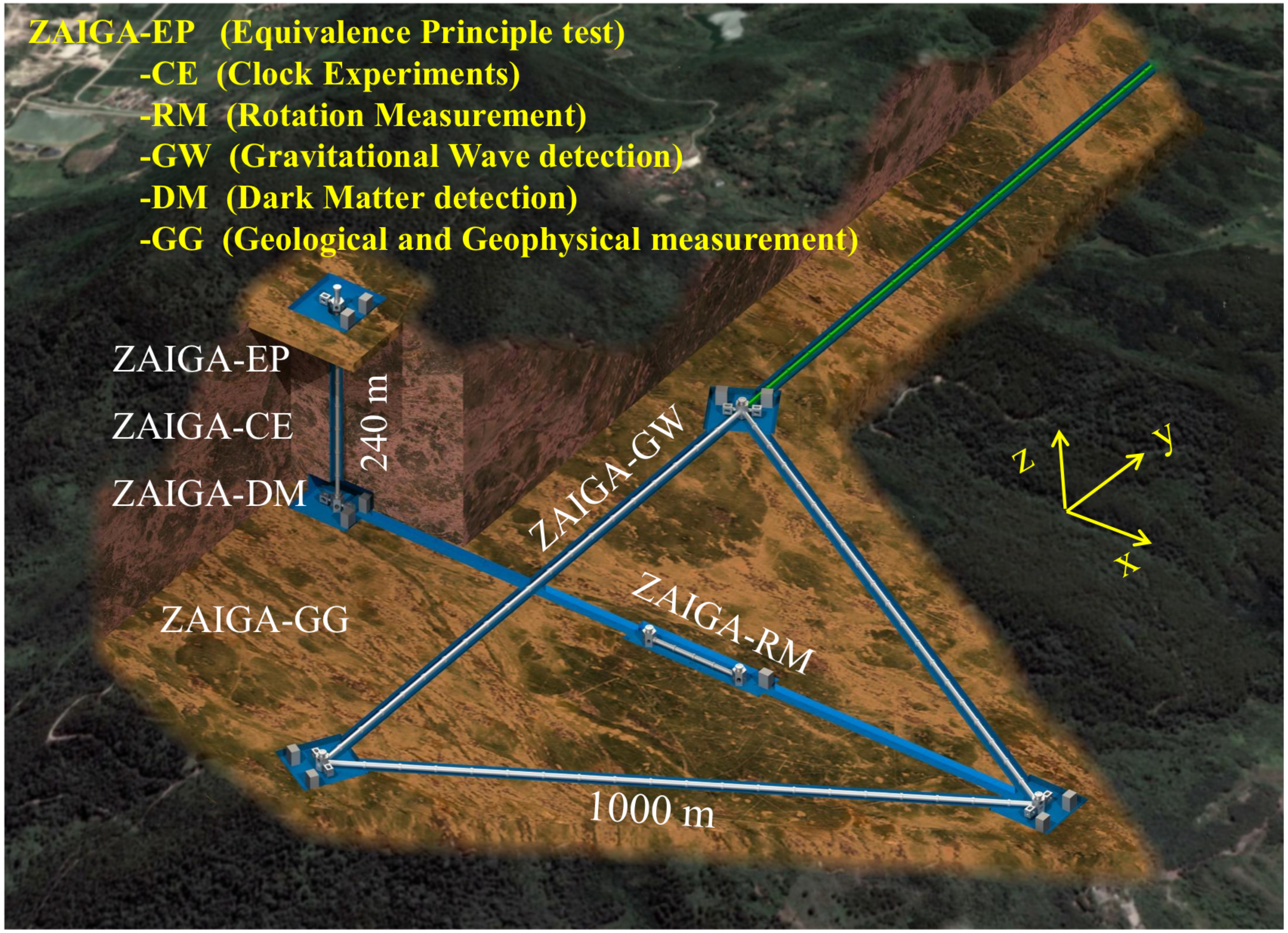
Abe et al., Quantum Sci. Technol. 6 044003 (2021)

Dark Matter





Plan and Design



A platform to test gravity theory with large scale atomic interferometers, gyros and optical clocks

- Equivalence Principle test
  — 10-m AIs, 240-m AI
- Clock Experiments
  — Sr clocks
- Rotation Measurement
  — 20-m gyros
- Gravitational Wave detection
  — AI array (⊥, //)、clocks
- Dark Matter detection
  — AI array (⊥, //)、clocks
- Geological and Geophysical measurement
  — gravimeters, seismometers

Currently, Phase I（240 m shaft + 1.4 km tunnel）is funded, and preliminary design is under way.

Mingsheng Zhan *et al.*, *Intl. J. Mod. Phys. D* **29**,1940005 (2020); arXiv:1903.09288

Research Roadmap

ZAIGA

Building abilities

Item	Goal
AI baseline (Falling time)	240 m (T ≥ 6 s)
Atom species for AI	^{85}Rb ^{87}Rb ^{87}Sr ^{88}Sr
Gravity measurement	1×10^{-12} g
Rotation measurement	8×10^{-12} rad/s
Stability of Sr/Yb clock	2×10^{-18}
Local gravity monitoring	1 μGal

Scientific Tests

Item	Goal
WEP test	$\eta \sim 10^{-13}$
Redshift test	$\alpha \sim 10^{-5}$
Lense-Thirring effect	$\sim 10^{-14}$ rad/s
Dark matter probe	$d \sim 10^{-4}$ @ 1 Hz
GW detection	$s \sim 10^{-19}$ @ 1 Hz

DM & GW

Item	Goal
Dark matter probe	$d \sim 10^{-6}$@ 1 Hz
GW detection	$s \sim 10^{-21}$ @ 1 Hz

Phase I
2022 - 2027

240 m Vertical AI
20 m Gyros
10 m Dual Rb/Sr AI
2E-18 Optical Clocks

Phase II:
2027 - 2035

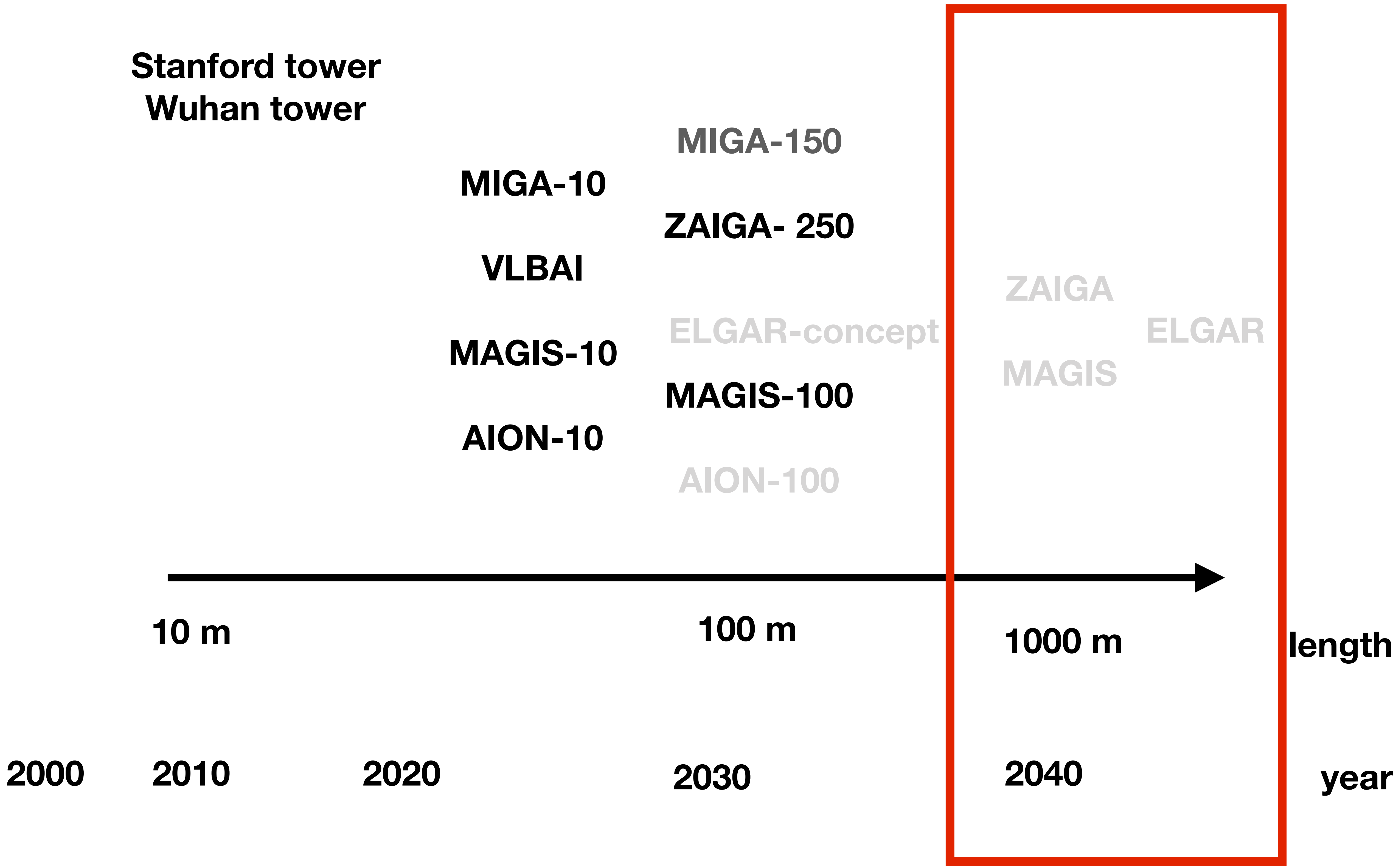
240 m Vertical AI array
Δ1000 m Horizontal AI array

Phase III
2035 -

≥ 3000 m Horizontal AI

ZAIGA

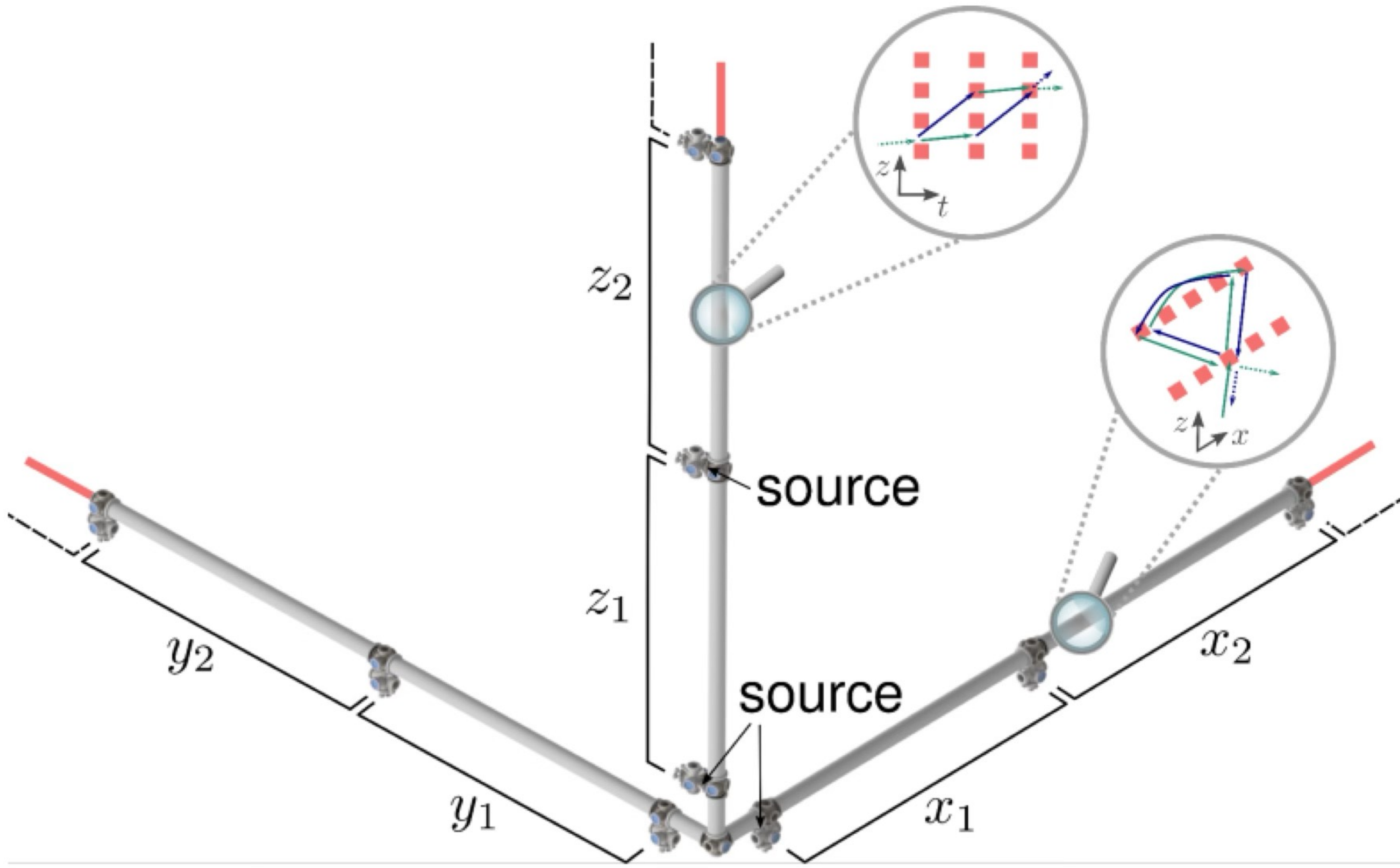
terrestrial very long baseline atom interferometers activities, length and implementation period



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

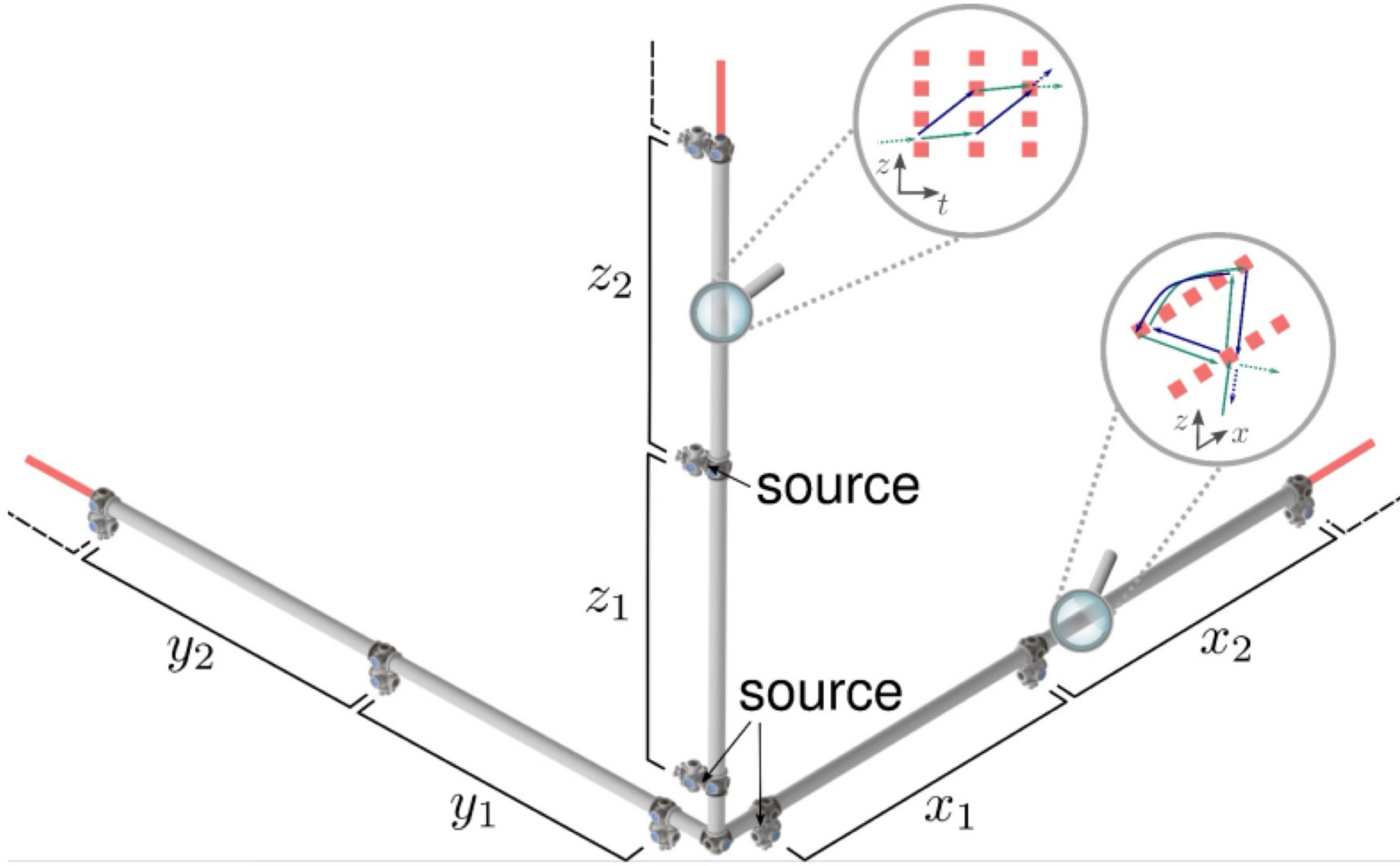
	Organisation		
	Legal name	Short name	Country
1	**Gottfried Wilhelm Leibniz Universität Hannover**	**LUH**	**DE**
2	Centre National De La Recherche Scientifique	**CNRS**	FR
3	Idryma Technologias Kai Erevnas	**FORTH**	GR
4	Istituto Nazionale Di Fisica Nucleare	**INFN**	IT
5	Institut D'estudis Espacials De Catalunya Fundacion	**IEEC**	ES
6	University of Birmingham	**UOB**	UK
7	Deutsches Zentrum für Luft- und Raumfahrt e.V.	**DLR**	DE
8	Imperial College	**ICL**	UK
9	Universität Ulm	**UULM**	DE
10	Technische Universität Darmstadt	**TUDa**	DE
11	University of Southampton	**SOTON**	UK
12	European Gravitational Observatory	**EGO**	IT
13	Universiteit van Amsterdam	**UVA**	NL
14	Université de Toulouse	**UT3**	FR
15	Humboldt Universität zu Berlin	**UBER**	DE
16	King’s College London	**KCL**	UK
17	University of Oxford	**UOXF**	UK
18	University of Cambridge	**UCAM**	UK
19	Ferdinand-Braun-Institut gGmbH Leibniz Institut für Höchstfrequenztechnik	**FBH**	DE
20	Instituto de Física de Altas Energias	**IFAE**	ES

ELGAR



The design of a **new infrastructure, to complement and enlarge the detection bandwidth of planned and existing laser-based GW antennae on Earth and in space**, ensuring a smooth integration of the new infrastructure within the existing landscape.

ELGAR



The design of a new infrastructure, to complement and enlarge the detection bandwidth of planned and existing laser-based GW antennae on Earth and in space, ensuring a smooth integration of the new infrastructure within the existing landscape.

The coordination of European research in the field to optimise efficiency, results and impacts.
A plan to ensure the sustainability of the infrastructure at the crossing between fundamental physics, GW physics and geophysics.

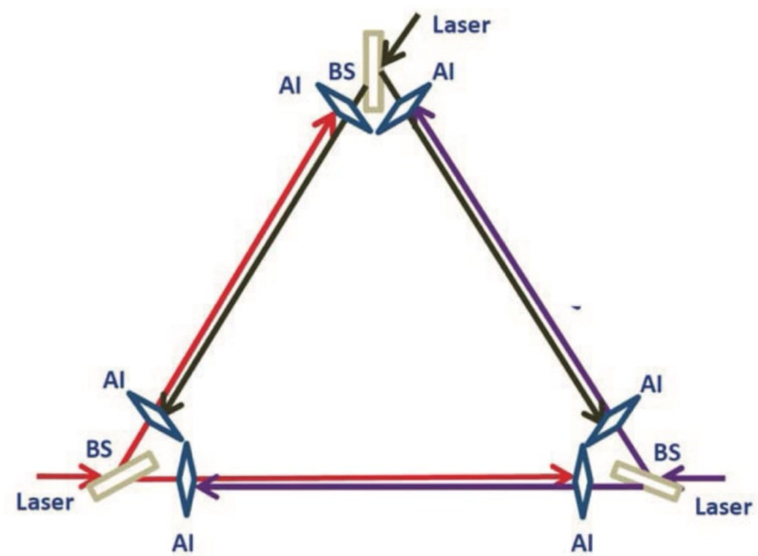
Exploitation of ELGAR's capacity to probe new models of DM and test fundamental physics.

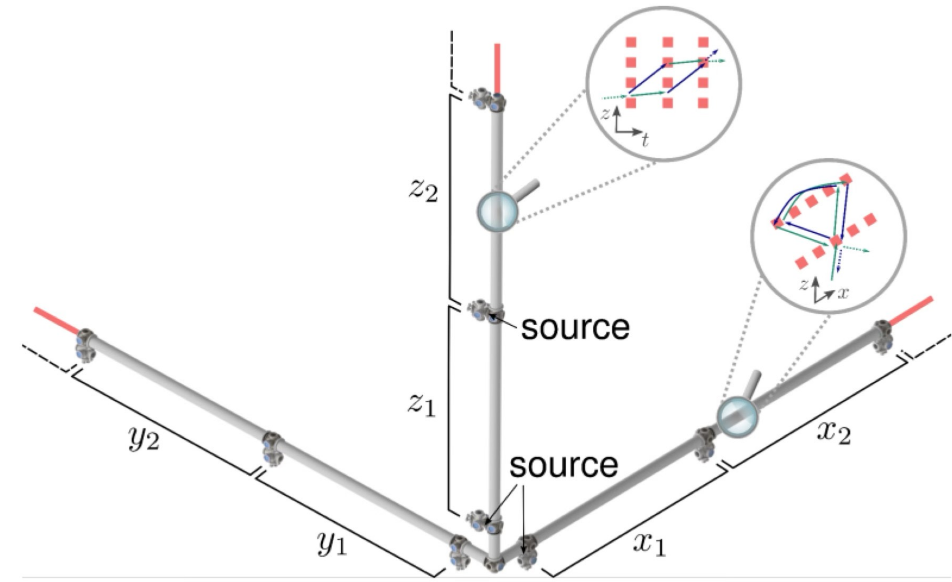
A contribution to long-range plans and roadmaps for such infrastructure with decision-makers at the national level (e.g., RI funding and policy bodies), at European level (e.g., ESFRI, EU framework programmes) and internationally.

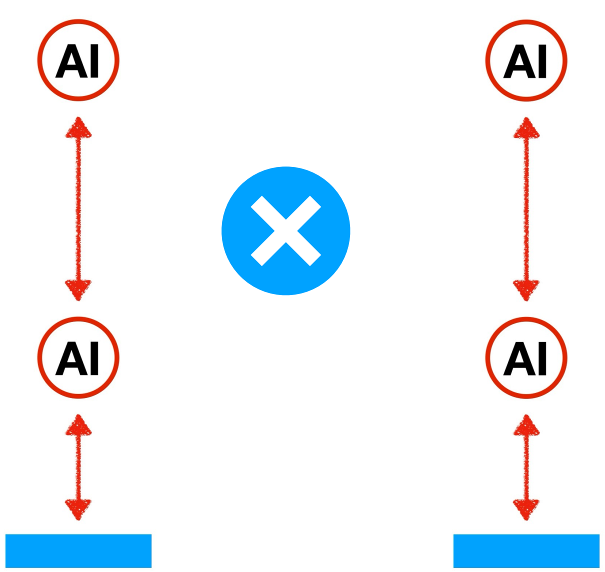
Correlation of VLBAIs

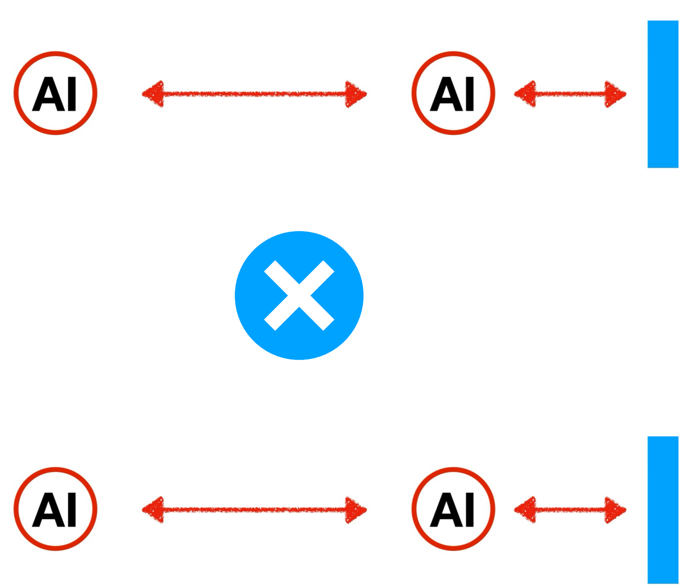
correlation of arms of one detector

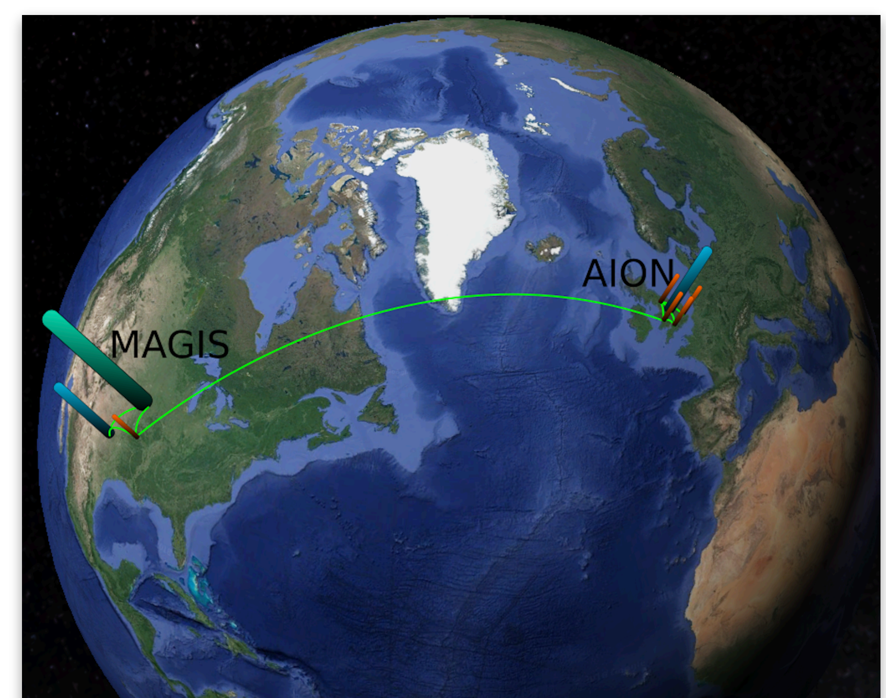
correlation of several deteors (on one site / several sites)











ELGAR

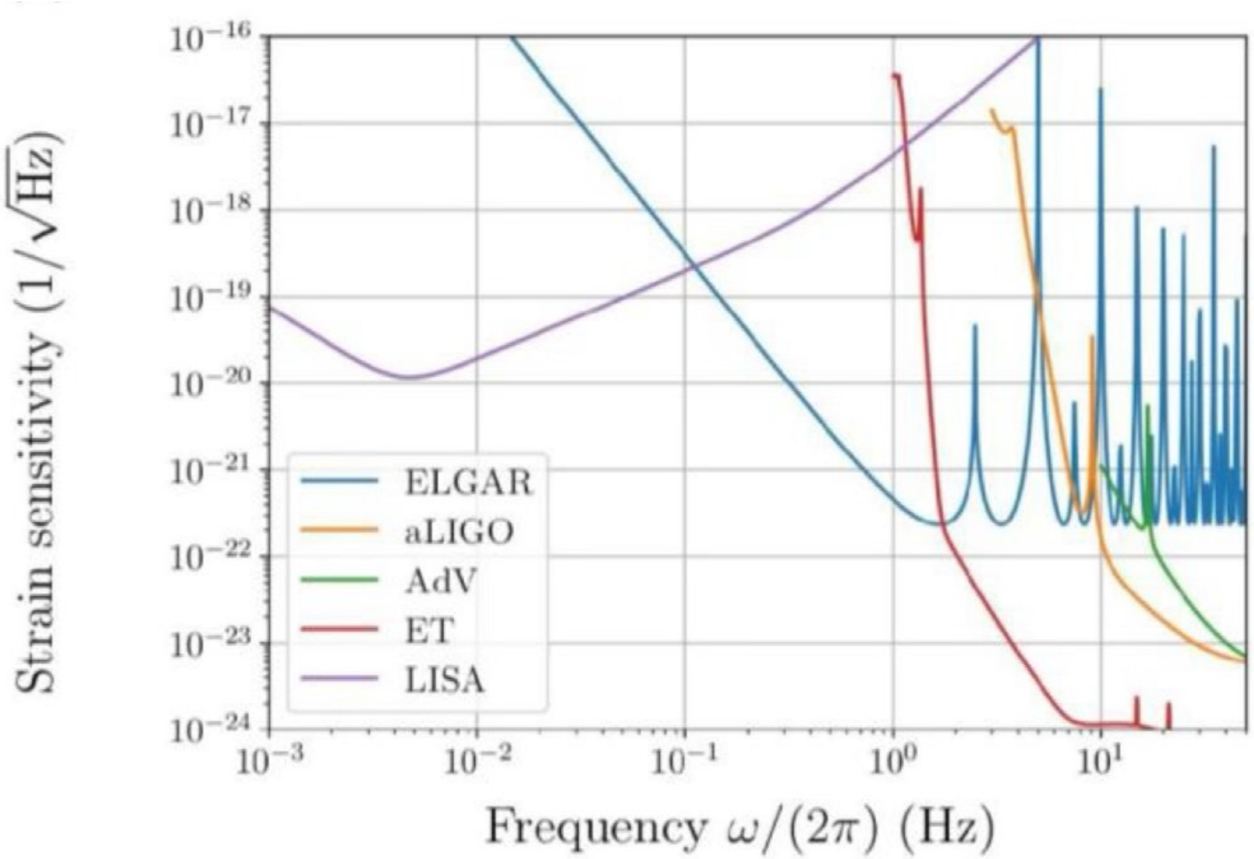


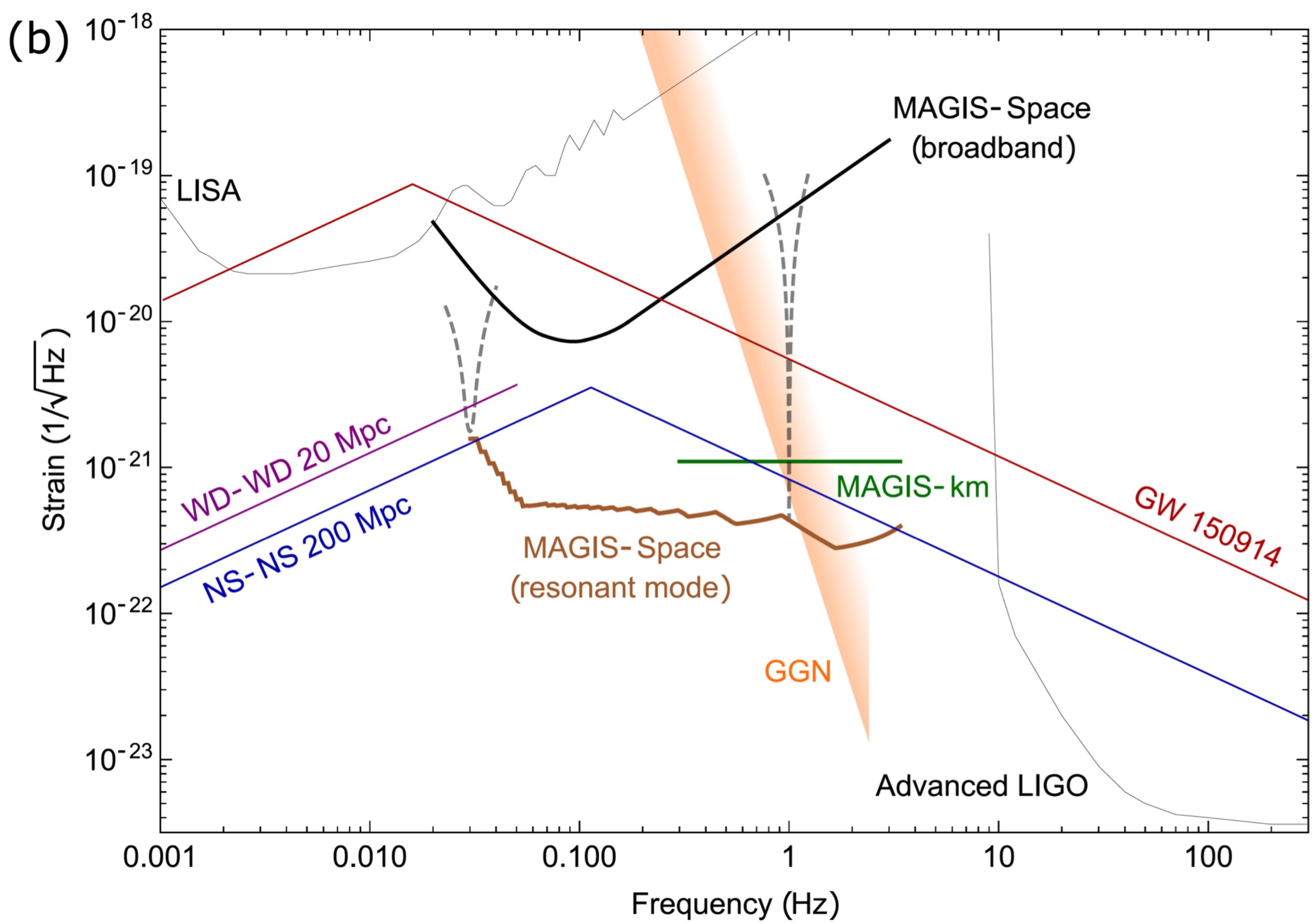
Table 1. Parameters of the ELGAR detector to reach a strain sensitivity of $10^{-22}\ \text{Hz}^{-1/2}$ at the peak frequency of 1.7 Hz limited by atom shot noise.

Atomic source	
Species	^{87}Rb
Loading source	2D + MOT
Equivalent atomic flux[a]	$1\times10^{12}\ \text{s}^{-1}$
Ensemble type	Ultracold source
Expansion velocity ($T_{\text{eff}}\approx 100$ pK)	$100\ \mu\text{m}\,\text{s}^{-1}$
Vertical launching velocity	$4\ \text{m}\,\text{s}^{-1}$
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)	$4.1\times10^{-21}\ \text{Hz}^{-1/2}$
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)	$3.3\times10^{-22}\ \text{Hz}^{-1/2}$

[a] $1\times10^{10}\ \text{s}^{-1}$ + 20 dB squeezing (in variance) or $1\times10^{12}\ \text{s}^{-1}$.
[b] Assuming 10 interleaved interferometers, 1×10^{9} atoms and 20 dB squeezing.

Scaling of vertical VLBAIs (MAGIS/AION, ELGAR?)

Experiment	(Proposed) site	Baseline L (m)	LMT atom optics n	Atom sources	Phase noise $\delta\phi$ (rad/$\sqrt{\text{Hz}}$)
Sr prototype tower	Stanford	10	10^2	2	10^{-3}
MAGIS-100 (initial)	Fermilab (MINOS shaft)	100	10^2	3	10^{-3}
MAGIS-100 (final)	Fermilab (MINOS shaft)	100	4×10^4	3	10^{-5}
MAGIS-km	Homestake mine (SURF)	2000	4×10^4	40	10^{-5}
MAGIS-space	Medium earth orbit (MEO)	4×10^7	10^3	2	10^{-4}



Science applications of TVLBAI

Atom interferometry: Large momentum transfer techniques

Atom sources: Scaling atom number and temperature

Squeezing for atom interferometry

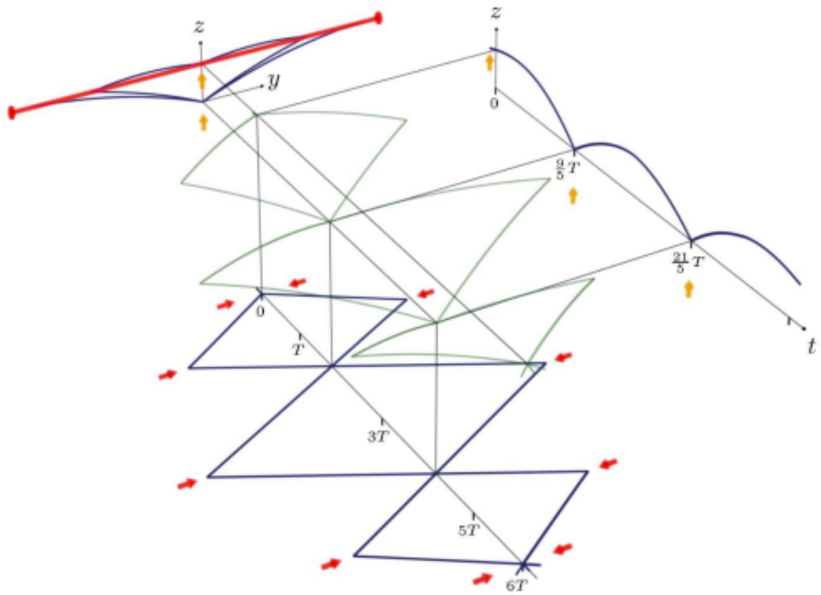
Atom interferometry: Metrology & Systematics

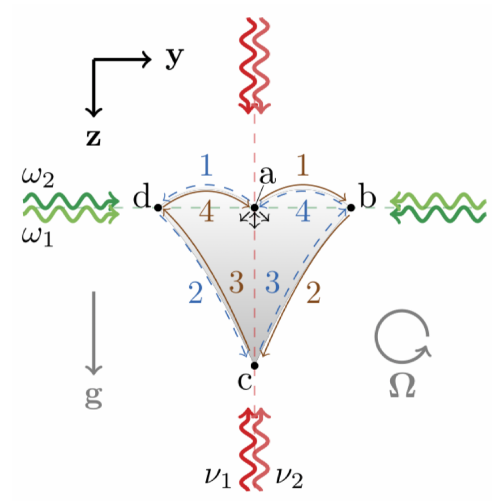
Engineering Challenges for a large-scale AI

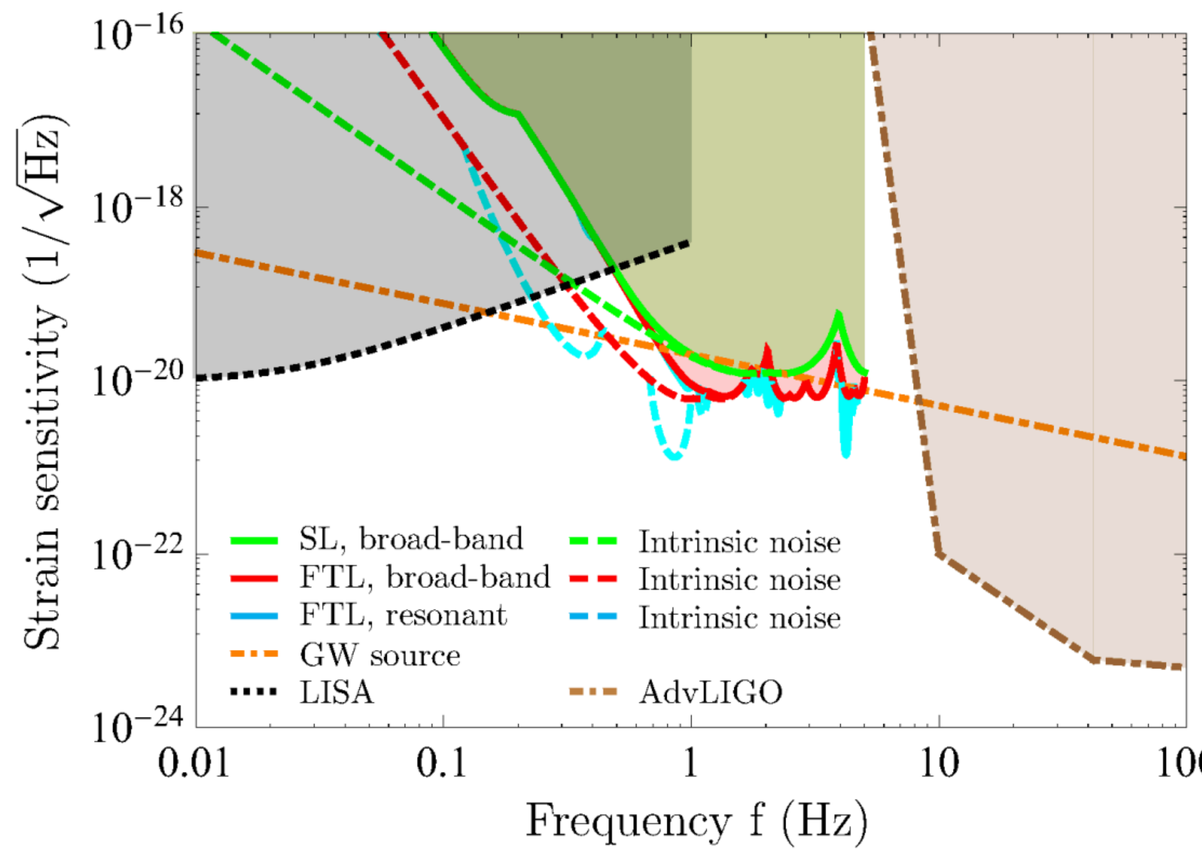
Synergies of Cold Atom and Laser Interferometry GW Experiments

"Towards a Proto-Collaboration "

Large momentum transfer techniques
Multi-loop geometry proposed for GWD/ELGAR

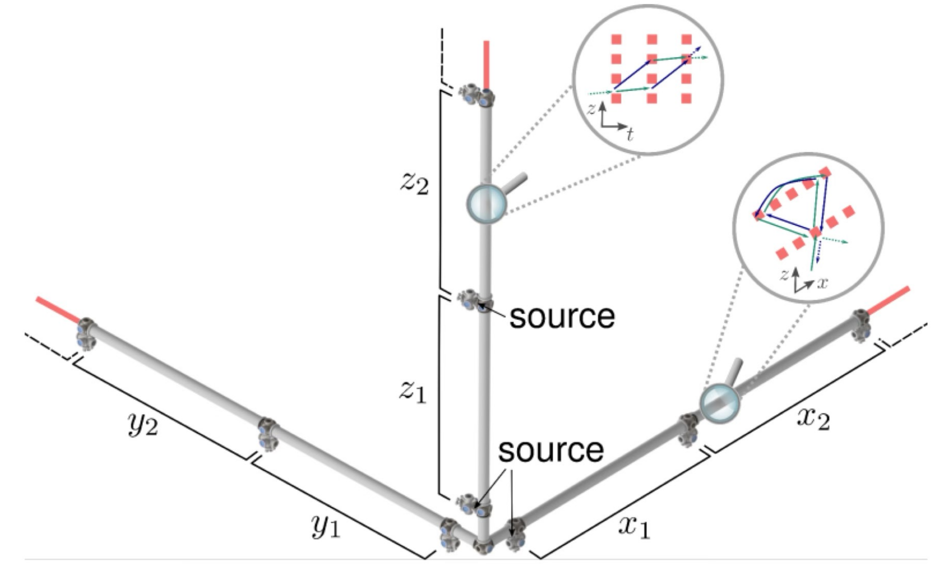






Anticipated parameters:

- Effective wave vector: $K \sim 2000 \cdot 2\pi/(780\ \mathrm{nm})$ for Rb87
- Free evolution time: T = [0.21 s, 0.27 s, 0.3 s]
- Cycle rate: 10 Hz
- Phase noise: σ_ϕ = 1 µrad $\mathrm{Hz}^{-1/2}$
- Baseline: L = 10 km



Ground based

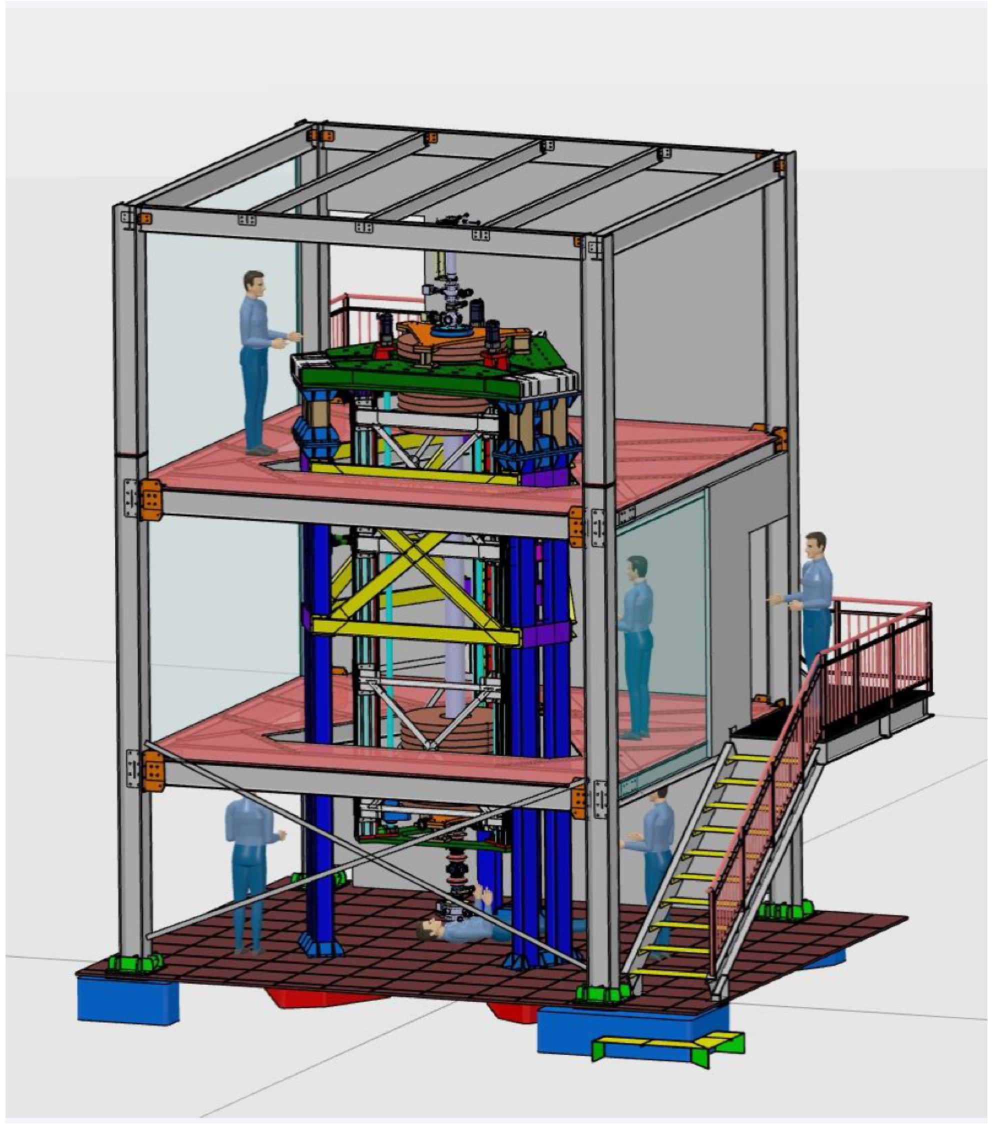
[C. Schubert, D. Schlippert, S. Abend, E. Giese, A. Roura, W. P. Schleich, W. Ertmer, and E. M. Rasel, Scalable, symmetric atom interferometer for infrasound gravitational wave detection, arXiv:1909.01951]

Space based

[Jason M. Hogan, David M. S. Johnson, Susannah Dickerson, Tim Kovachy, Alex Sugarbaker, Sheng-wey Chiow, Peter W. Graham, and Mark A. Kasevich, Babak Saif, Surjeet Rajendran, Philippe Bouyer, Bernard D. Seery, Lee Feinberg, and Ritva Keski-Kuha, An Atomic Gravitational Wave Interferometric Sensor in Low Earth Orbit (AGIS-LEO), arXiv:1009.2702]

Atom interferometry: Metrology & Systematics

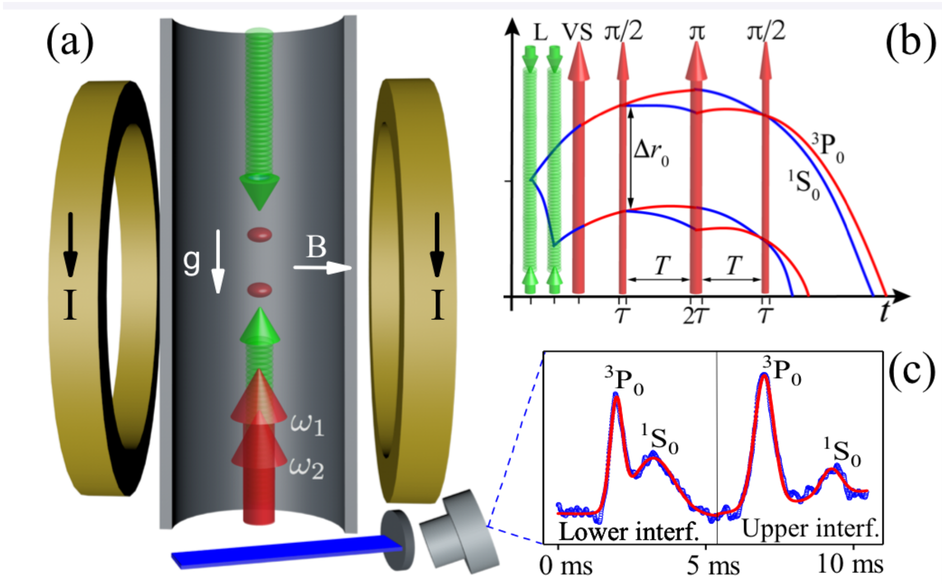
MEGANTE

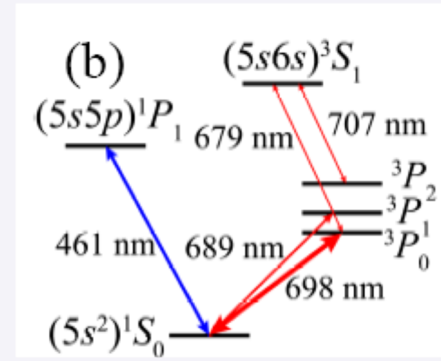


- Height 8 m, basement 5x4 m^2
- Independent foundations (reduced vibration noise)
- Interferometer region length: 4.5 m

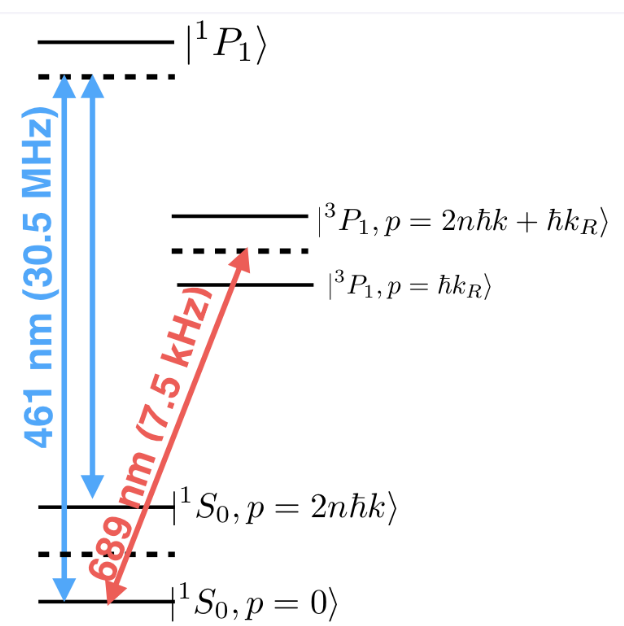
(MEASuring the Gravitational constant with Atom interferometry for Novel fundamental physics TEsts)

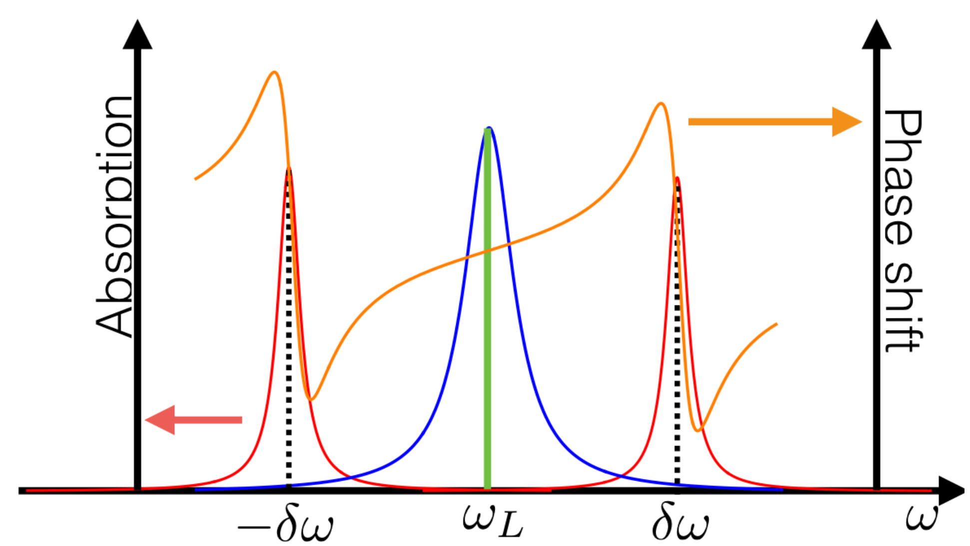
Squeezed momentum states generated from Sr clock states





- ^{88}Sr isotope
- B=300 G -> Δν=20 μHz
- Rabi frequency Ω ~ 1kHz





Frequency splitting from Doppler effect

$$\delta\omega = 2\pi n \times 28.6\ \mathrm{kHz}$$

Condition for dispersive regime:

$$\delta\omega \gg \Gamma$$

terrestrial very long baseline atom interferometers activities, length and implementation period

Stanford tower
Wuhan tower

MIGA-150

MIGA-10

ZAIGA- 250

VLBAI

ZAIGA

ELGAR-concept

ELGAR

MAGIS-10

MAGIS

MAGIS-100

AION-10

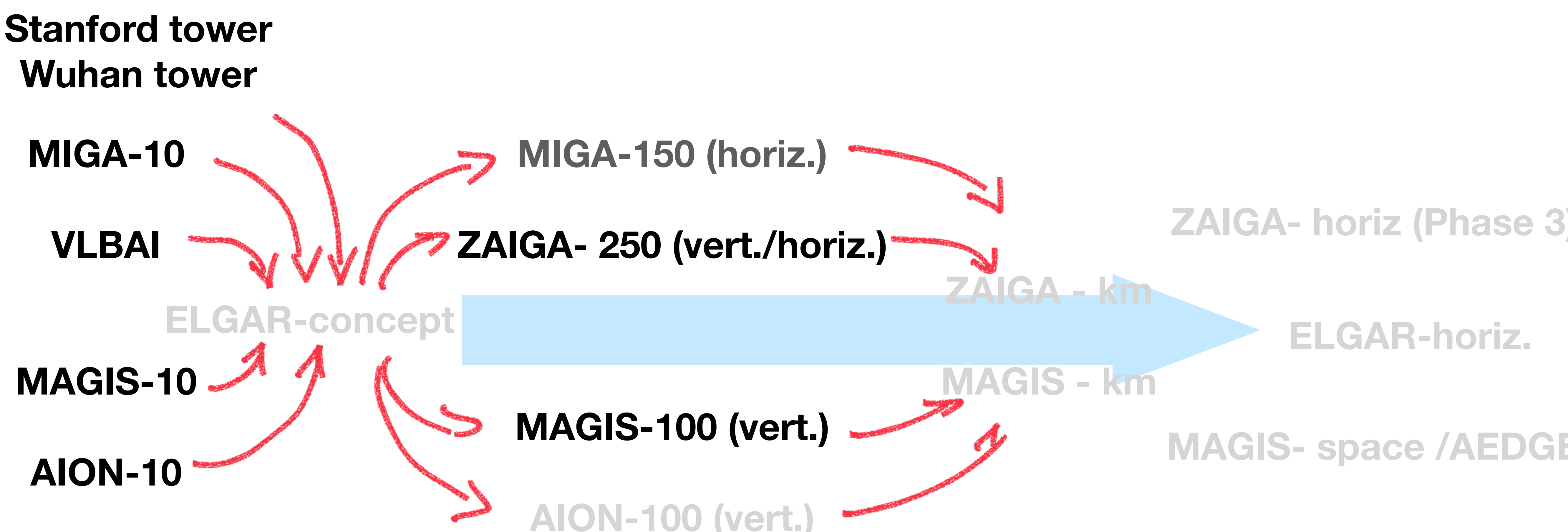
AION-100

10 m **100 m** **1000 m** **length**

2000 **2010** **2020** **2030** **2040** **year**

long term strategy for road map

for a new infrastructure, to complement and enlarge the detection bandwidth of planned and existing laser-based GW antennae on Earth and in space



How could a roadmap for bridging the sensitivity gap look-like ?

How long vertical detectors can be ?

How many photon recoils be transferred in horizontal detectors ?

technically and strategic questions

How could a roadmap for bridging the sensitivity gap look-like?

Which kind of km-size detector should be realized ?

Is the development of MIGA-150 and AION-100 assured ?

Relation between MIGA-150, AION-100 and ELGAR ?

…

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Atom sources: Scaling atom number and temperature

Squeezing for atom interferometry

Atom interferometry: Metrology & Systematics

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Synergies of Cold Atom and Laser Interferometry GW Experiments

"Towards a Proto-Collaboration "

Terrestrial Very Long Baseline atom interferometry

- setting the technolgy scene

E.M.R.

Gottfried Wilhelm Leibniz Universität Hannover - iMAR Navigation
QGyro
Quanten-Inertialsensorsystem

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

TerraQ
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