UK
Quantum Technology Hub
Sensors and Timing

Quantum Sensor Technology

IoP 2022 - Joint APP/HEPP Conference
Rutherford Appleton Laboratory

Kai Bongs
University of Birmingham
05.04.2022

University of Birmingham | University of Glasgow | Imperial College London | University of Nottingham UK | CHINA | MALAYSIA | University of Southampton | University of Strathclyde | University of Sussex

British Geological Survey Expert | Impartial | Innovative | NPL National Physical Laboratory | UK National Quantum Technologies Programme

UK National QT Hub in Sensors and Timing
Funders, Partners and Collaborators

Total project value since 2014: £180M (£60M EPSRC, £120M collaborative projects with industry)

UK
Quantum Technology Hub
Sensors and Timing

UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

Selected Quantum Sensor Applications

Sensing into the ground

Underground risk in infrastructure projects
→ **0.5% GDP**

Sensing brain function

Dementia: 1% GDP
ADHD: 1% GDP

Sensing small objects in the air

29M drones by 2021

Sensing position and movement

~7% GDP

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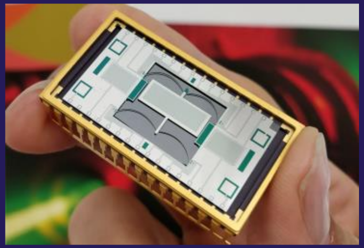
Quantum Technology Hub
Sensors and Timing

The World Economic Forum has recognised **Quantum Sensing** as one of the top 10 emerging technologies for 2020

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

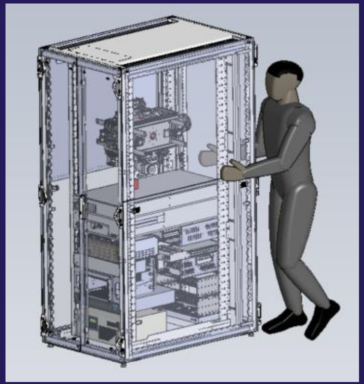
Quantum Sensor Demonstrators – Ready for Deployment

Gravity Gradiometer
450 E/rt(Hz), 35E in 3 min



Wee-g
gravimeter
5ng/√Hz

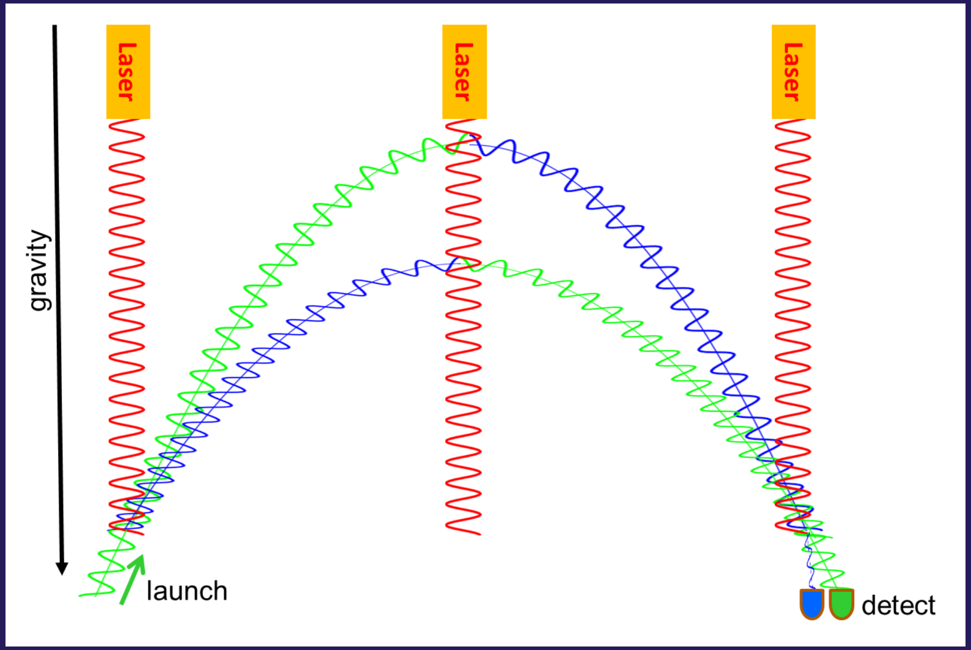
Magnetometer
pT/rt(Hz)



Accelerometer
0.25ng/√Hz, 2μg
(TBC)

Low Phase Noise
Optical Oscillator with
Conversion to RF

Brief Introduction to Atom Interferometry

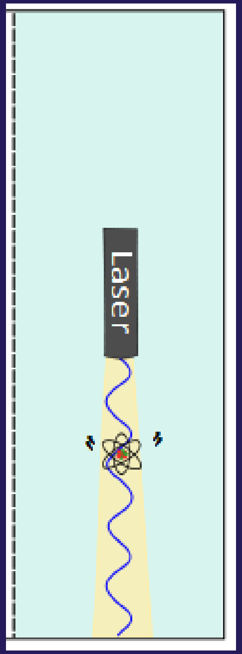


$$\Delta\phi = k_z T^2 g_z = \pi \frac{\Delta z}{\lambda}$$

➔ Dropping object next to laser ruler

Advantages over classical instruments:

- Ideal test mass (no fabrication tolerances or ageing)
- "Absolute" measurement (no drift)
- Can be very sensitive



However, this only helps with the "calibration loops", not the measurement time itself

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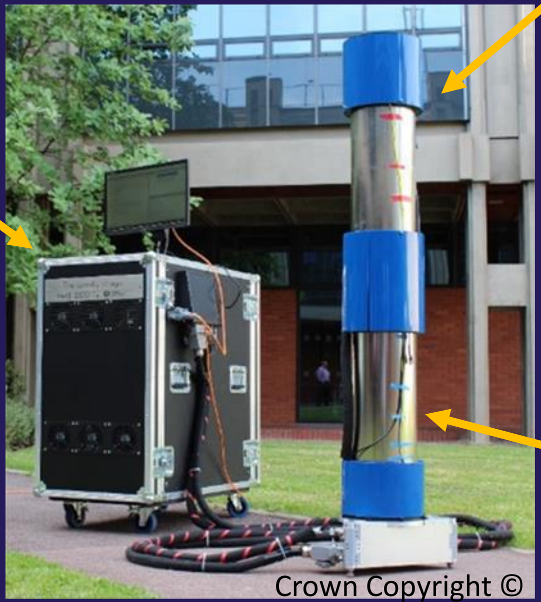
Real-World Trials: Learning the Systematics

Environmentally robust laser systems with telecoms components



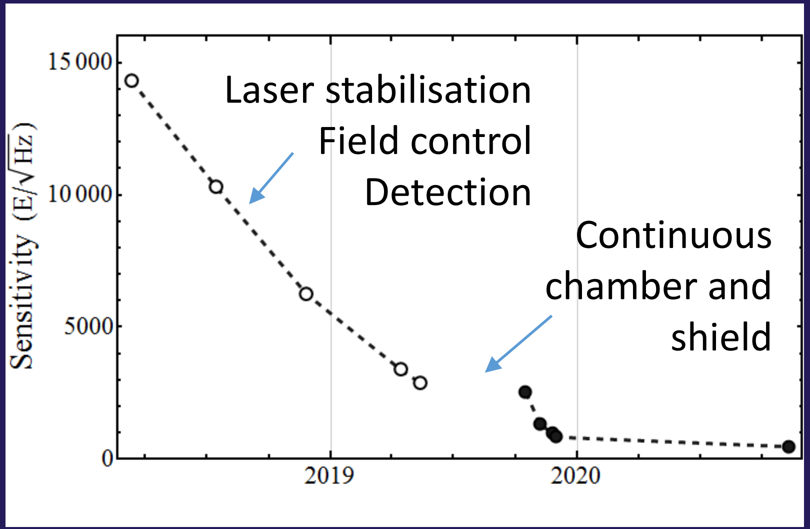
Patent app. US 16/772517, EU 18822463.8

Two beams along single axis

- Alignment Robustness
- Suppression of unwanted sidebands

Continuous vacuum chamber and shield

- Suppression of refractive index fluctuations
- Optimised mag. shielding



Current status: 450 E/rt(Hz), 35E in 3 min

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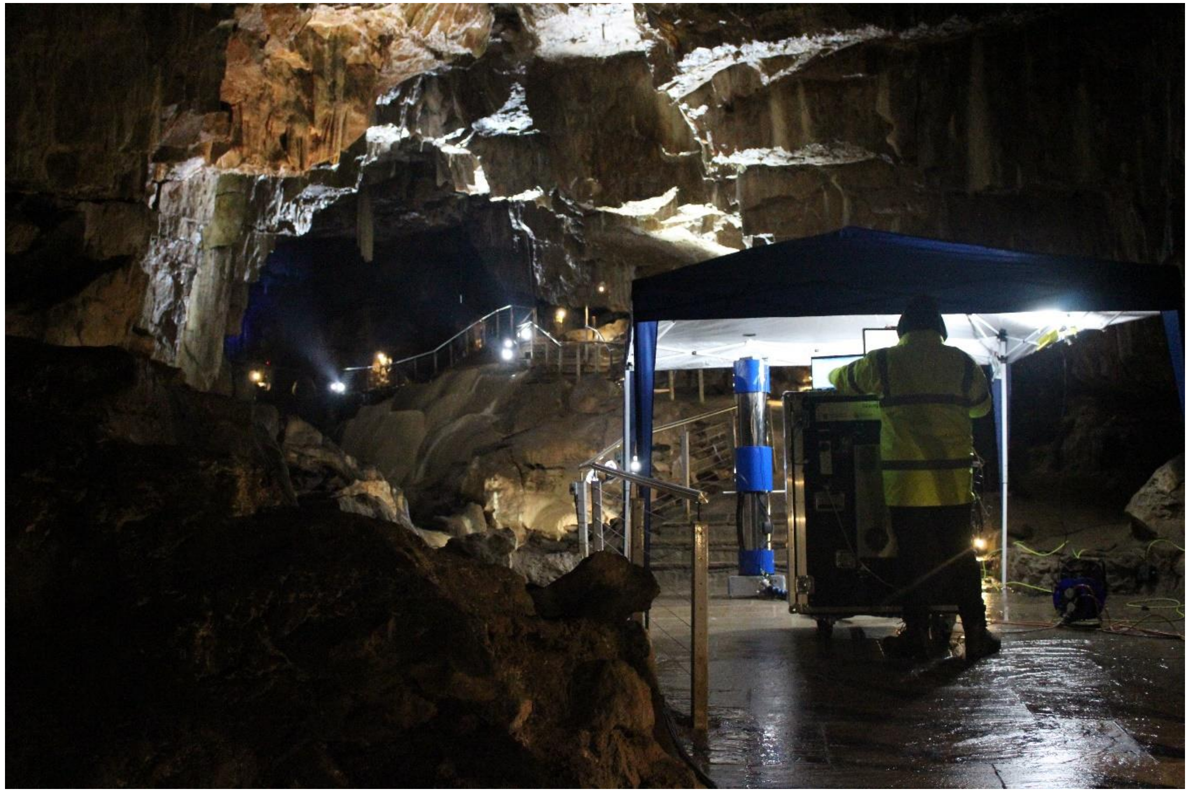
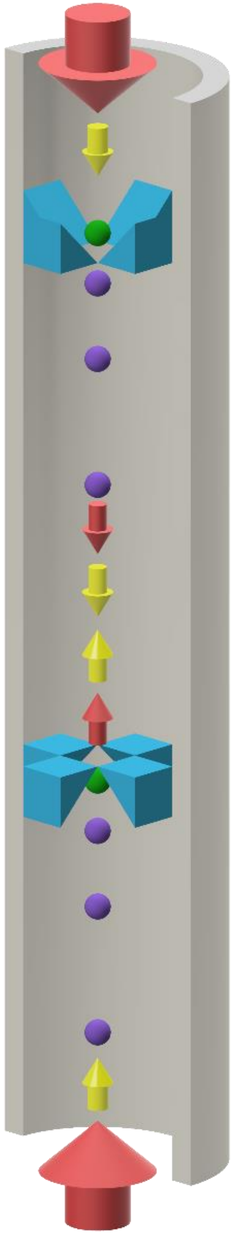
Hourglass gravity gradiometer

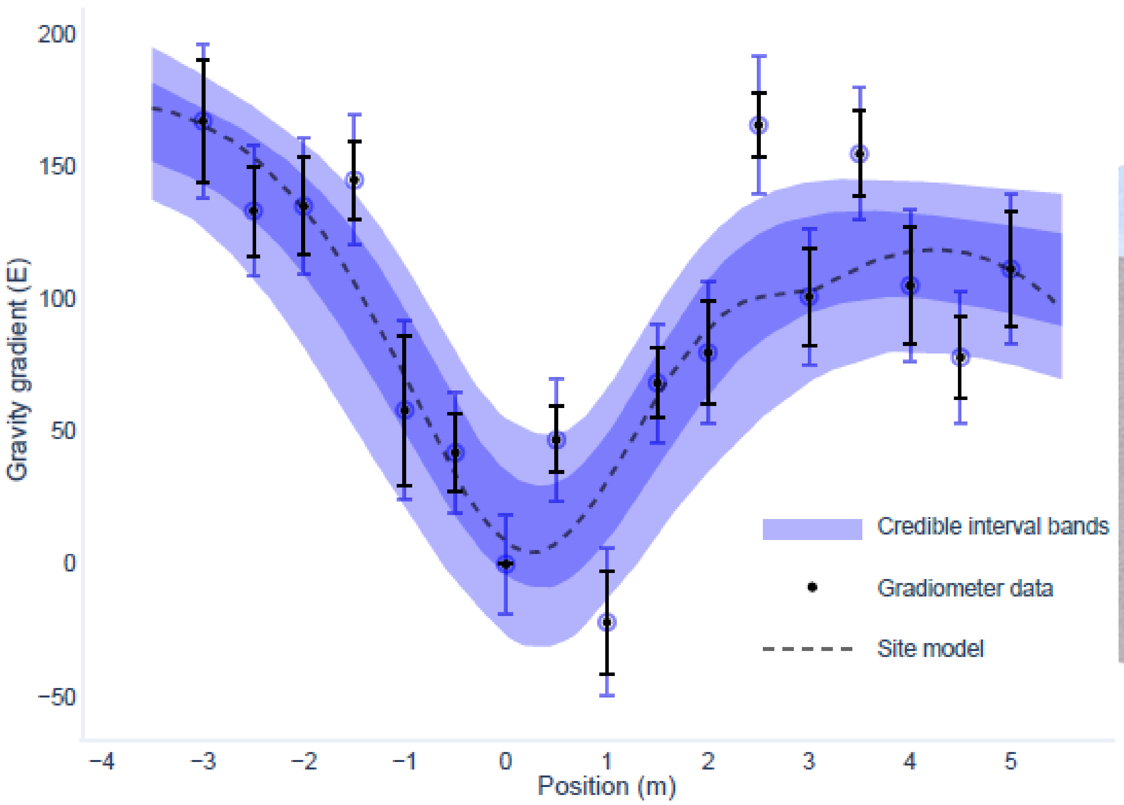
- Novel robust design from Birmingham (patent pending)
- Overcomes challenges for operation in the field

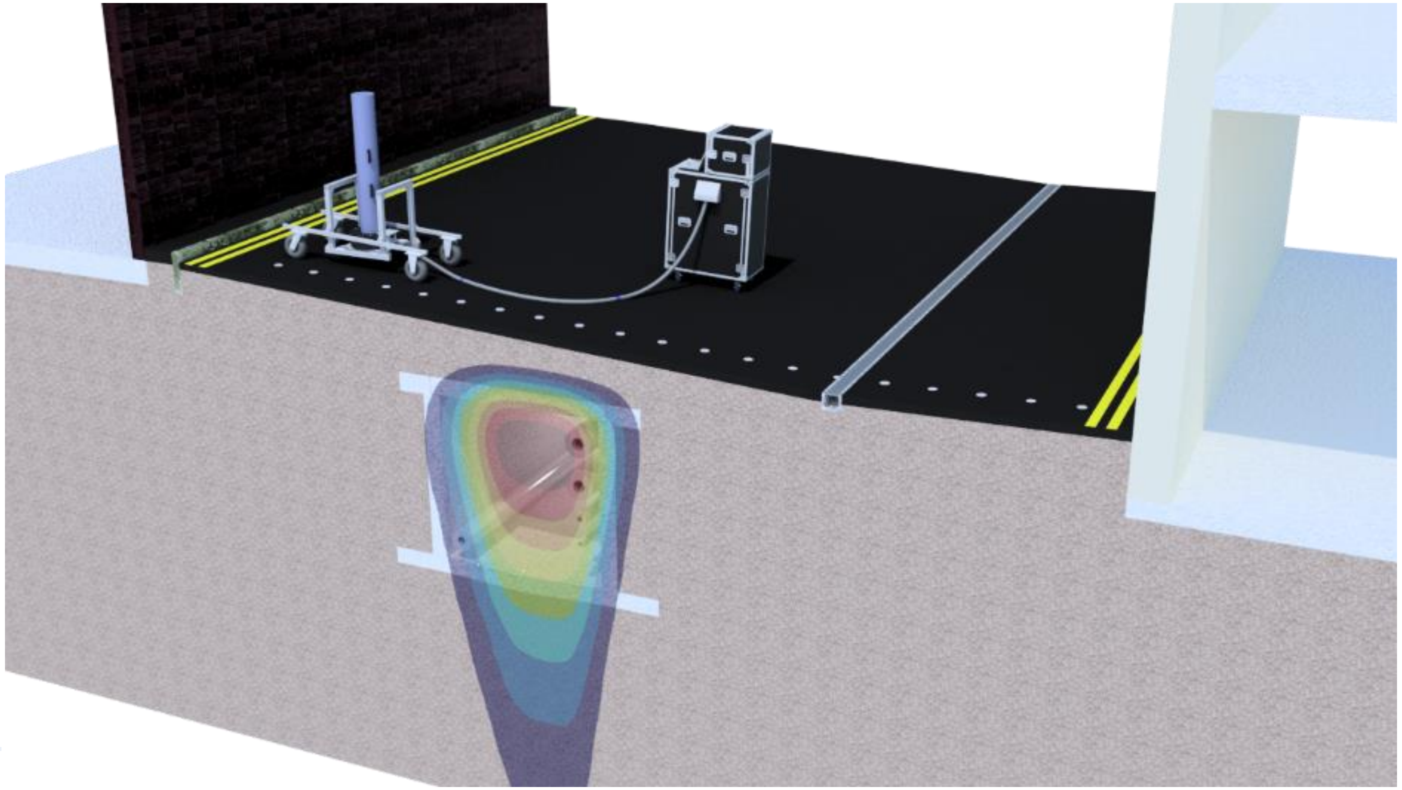


World first detection for quantum gradiometry

- Survey over tunnel

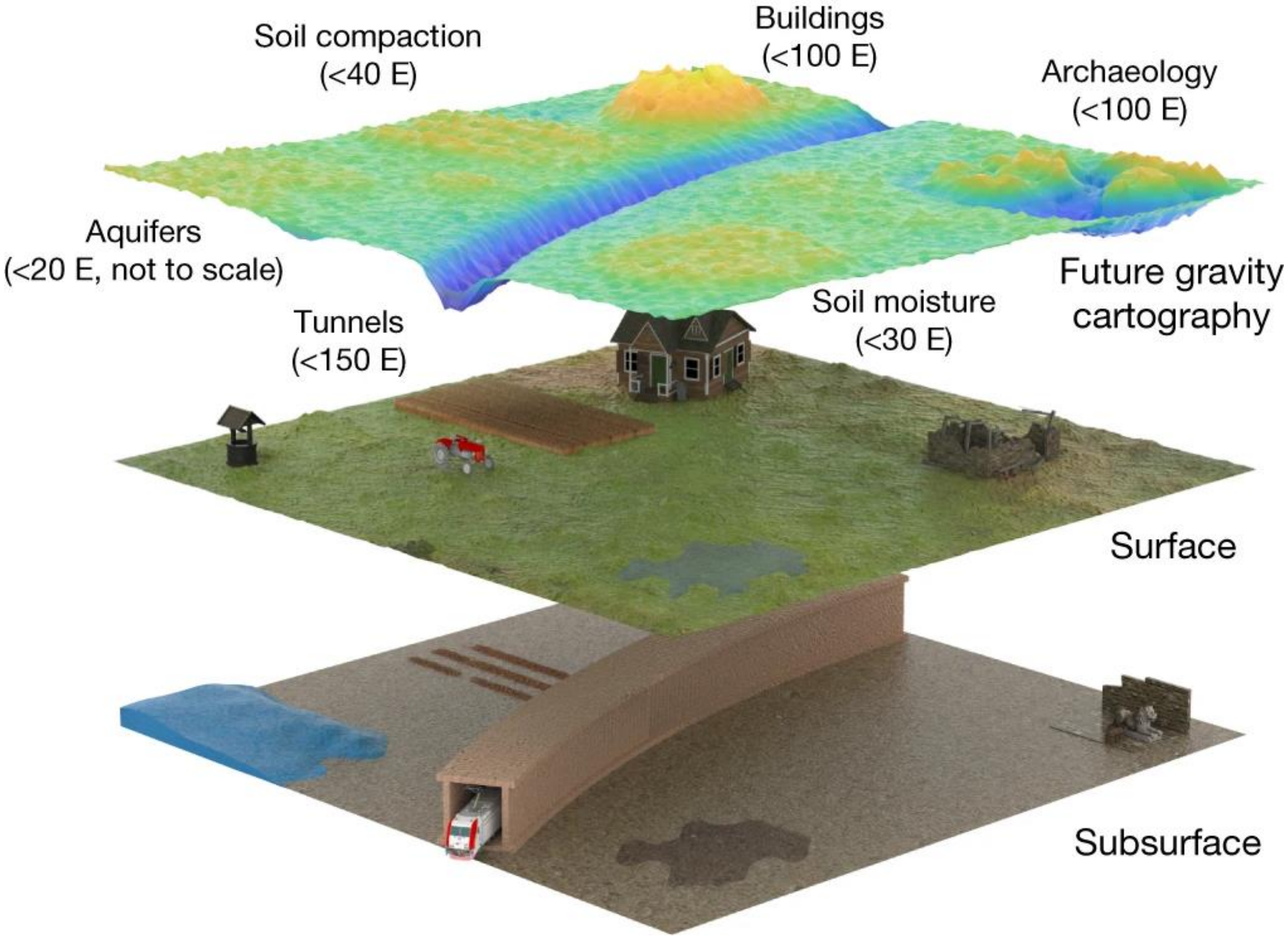




Tunnel centre localised to: ±0.19 m, horizontal; -0.59/+2.3 m, vertical

Enabling Gravity Cartography

- Relevant to a range of applications, including:
  - Water monitoring
  - Infrastructure
  - Archaeology
  - Agriculture
  - Navigation



Article | Open Access | Published: 23 February 2022

Quantum sensing for gravity cartography

Ben Stray, Andrew Lamb, Aisha Kaushik, Jamie Vovrosh, Anthony Rodgers, Jonathan Winch, Farzad Hayati, Daniel Boddice, Artur Stabrawa, Alexander Niggebaum, Mehdi Langlois, Yu-Hung Lien, Samuel Lellouch, Sanaz Roshanmanesh, Kevin Ridley, Geoffrey de Villiers, Gareth Brown, Trevor Cross, George Tuckwell, Asaad Faramarzi, Nicole Metje, Kai Bongs & Michael Holynski

Nature **602**, 590–594 (2022) | Cite this article

University of Birmingham
School of Physics and Astronomy
School of Engineering

RSK

Teledyne e2v Everywhereyoulook™

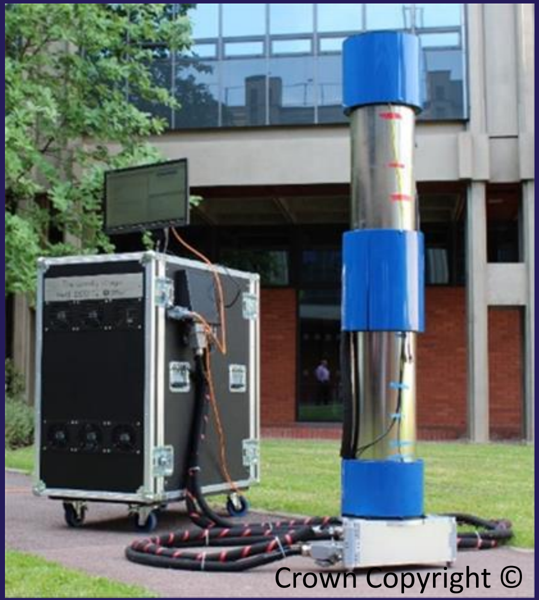
dstl

UK Quantum Technology Hub Sensors and Timing

Funding: dstl; UKRI Engineering and Physical Sciences Research Council; UKRI Innovate UK

The QT Hub Journey: Reducing SWAP-C and Moving Platforms

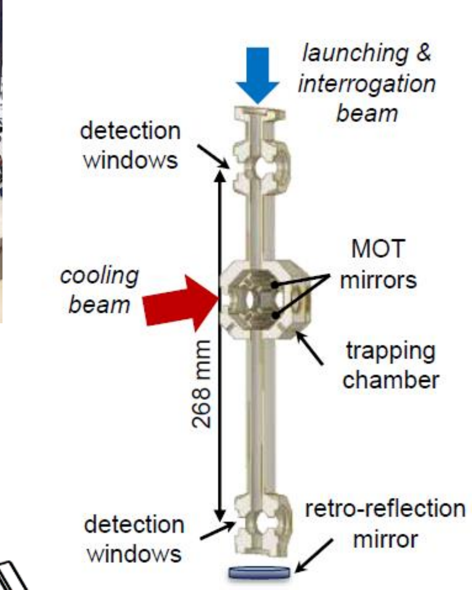
Gravity Imager 1 (GI1)

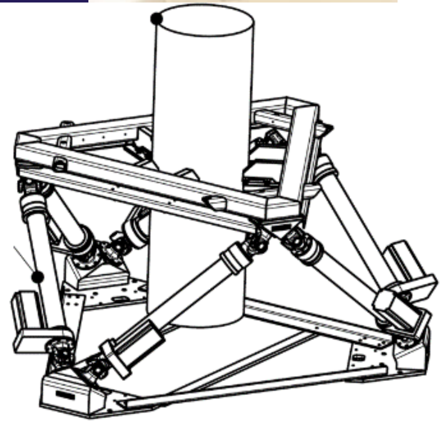


Flying Cold Atoms

Gravity Imager 3

Optics Express **26**, 6542 (2018).
Patent app.
US 16/633922,
EU 18752226.3





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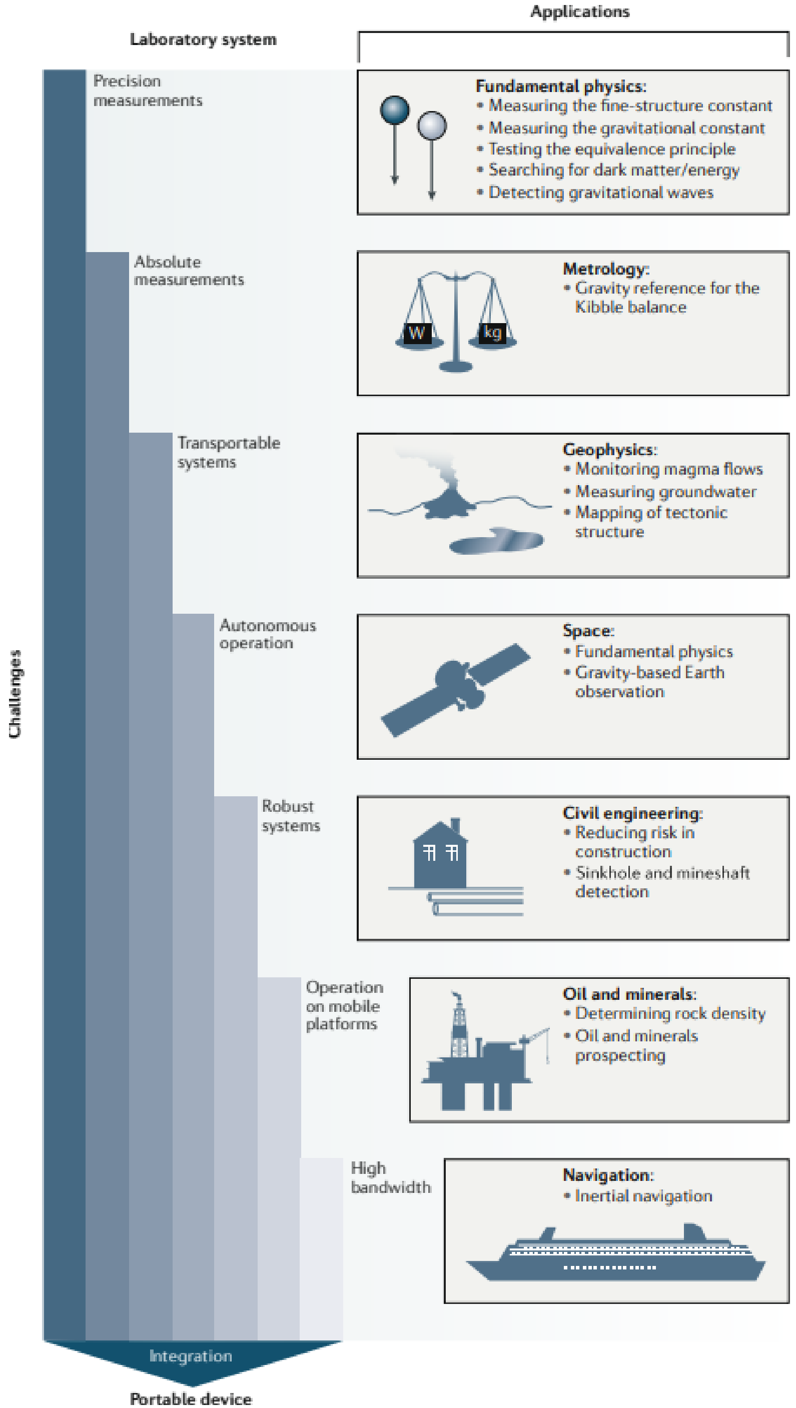


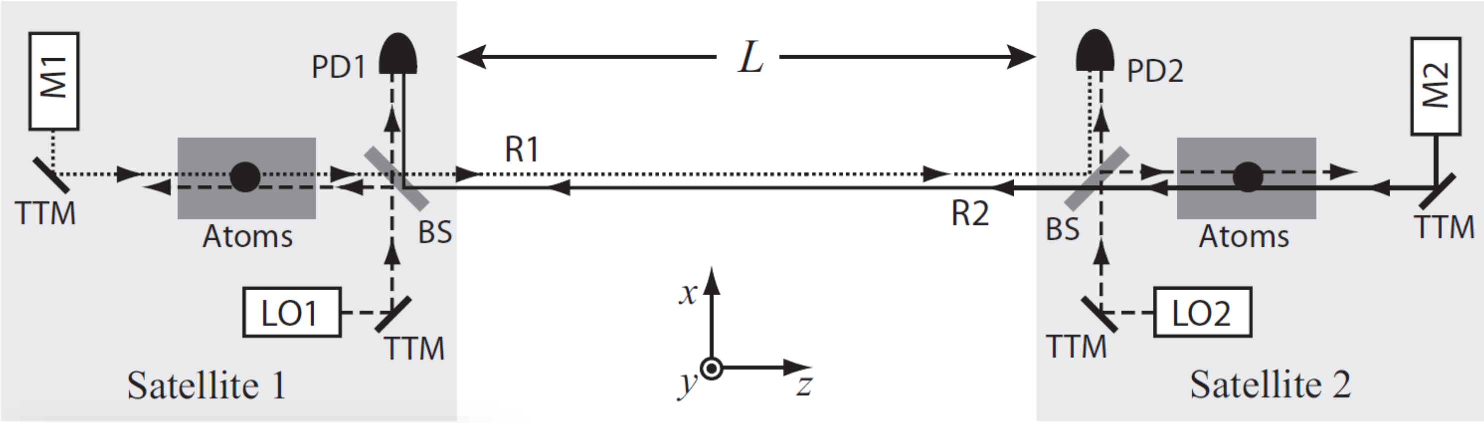
nature reviews physics

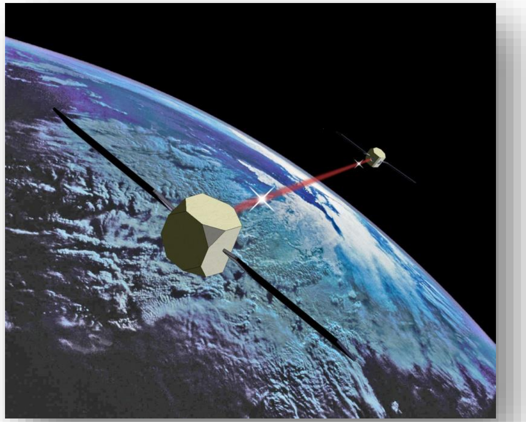
Perspective | Published: 28 October 2019

Taking atom interferometric quantum sensors from the laboratory to real-world applications

Kai Bongs, Michael Holynski, Jamie Vovrosh, Philippe Bouyer, Gabriel Condon, Ernst Rasel, Christian Schubert, Wolfgang P. Schleich & Albert Roura

Nature Reviews Physics **1**, 731–739 (2019) | Cite this article





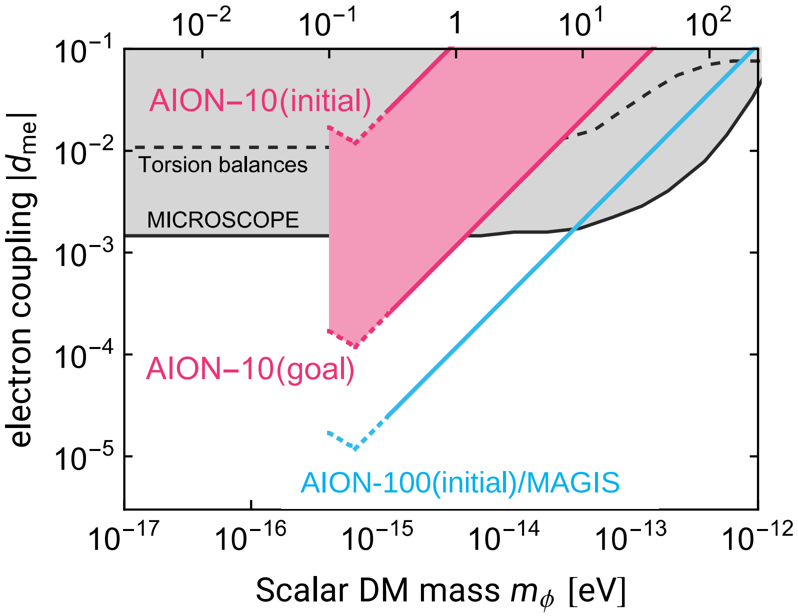
AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration

Oliver Buchmueller, Imperial College London

AION & AEDGE

OPPORTUNITIES FOR ULTRA-COLD ATOM TECHNOLOGY DEVELOPMENT FOR SPACE

Main AION Physics Goals: Dark Matter and Gravitational Waves



Scientific Leadership in phenomenology already established:

The AION Physics Case:

AION Collaboration, AION: An Atom Interferometer Observatory and Network, arXiv:1911.11755. [accepted for publication in JCAP]

AEDGE

Y. El-Neaj, …, O. Buchmueller *et al.* AEDGE: Atomic Experiment for Dark Matter And Gravity Exploration in Space, arXiv:1908.00802, *EPJ Quantum Technol.* 7, 6 (2020).
[Submitted to ESA Voyage2050 call]

Working with leading theorists:

J. Ellis, M. Haehnelt, C. McCabe,
J. March-Russell (AION), C. Burrage, …

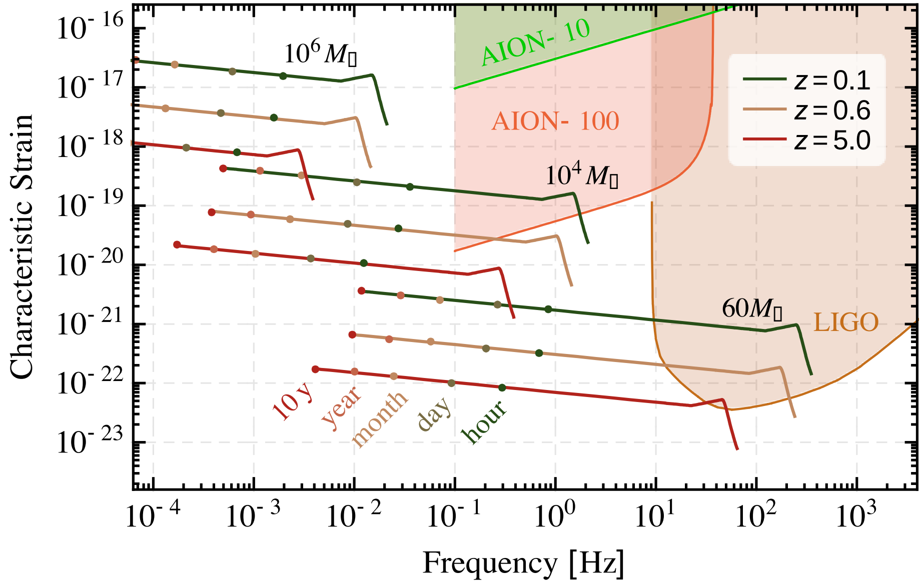
Main Physics Goals:

➢ Search for Ultra-Light Dark Matter

- Explore new parameter space and complement other searches.
- Focus on Scalar DM with Vector and Peudoscalar DM also under study.

➢ Gravitational Waves in mid-frequency band

- Explore frequencies between LISA and LIGO/VIRGO, KAGRA and Einstein Telescope
- Targets: Black hole mergers, phase transitions and cosmic string collisions



Atomic Experiment for Dark Matter and Gravity Exploration

EPJ Quantum Technology 7, 1-27 (2020);

Particle and Cold Atom physicists
Informal Workshop – 130 participants
CERN, July 22/23 2019

Organizers:
Kai Bongs(CA), Philippe Bouyer(CA), Oliver Buchmueller(PP), Albert De Roeck(PP), John Ellis(PP, Theory), Peter Graham (CA, Theory), Jason Hogan (CA), Wolf von Klitzing(CA), Guglielmo Tino(CA), and AtomQT
PP=Particle Physics
CA=Cold Atoms

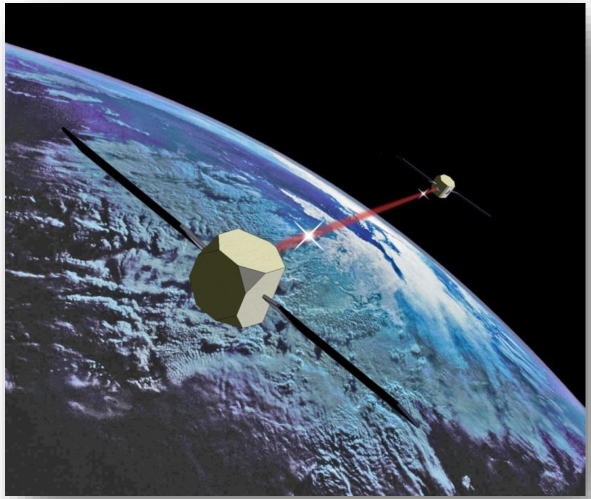


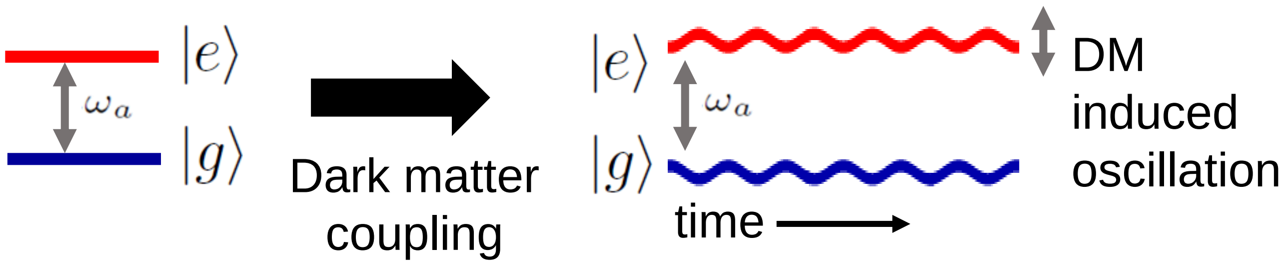
Image: Jason Hogan

ESA Voyage 2050 White Paper

Follow-on to AION, ELGAR, MAGIS, MIGA,…
Heritage from SOC, BECCAL, LISA-PF,…

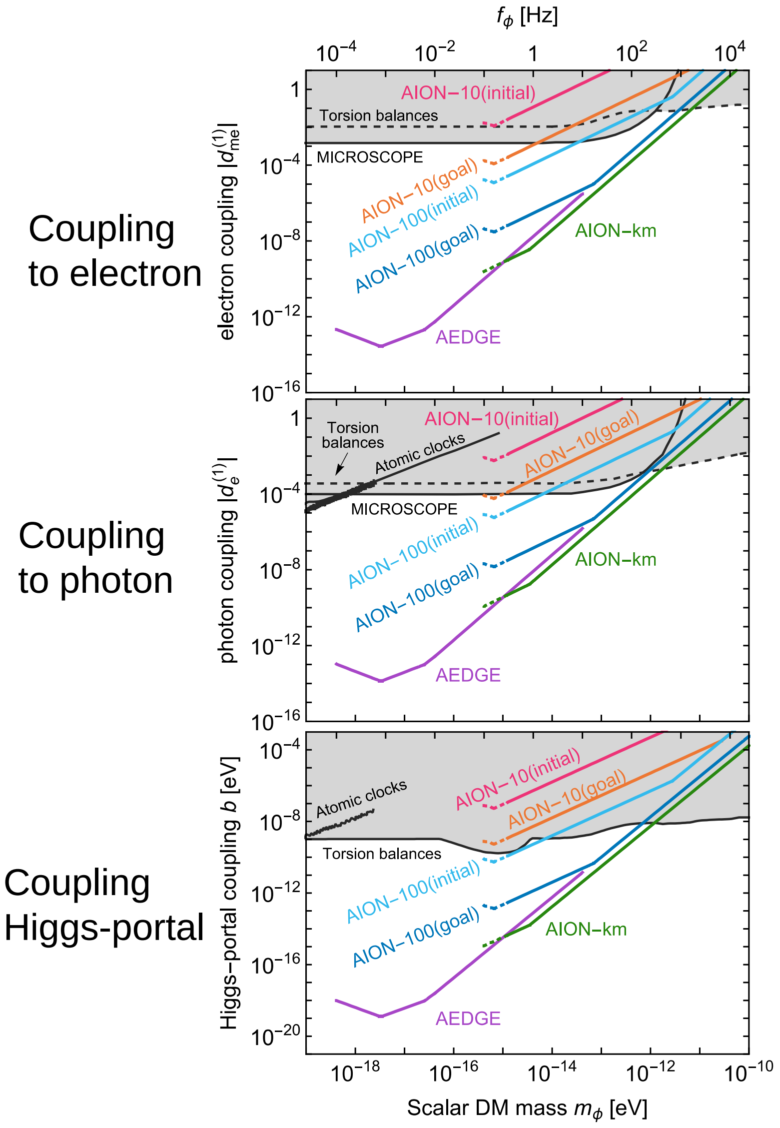
AEDGE – Ultralight Dark Matter

Dark Matter influencing the value of fundamental constants



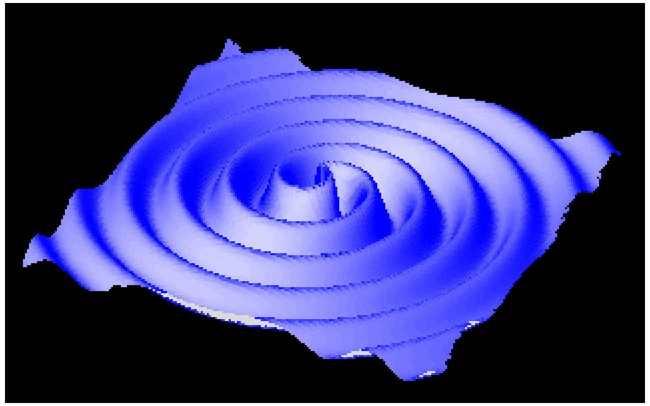
Based on: Arvanitaki et al., PRD **97**, 075020 (2018).

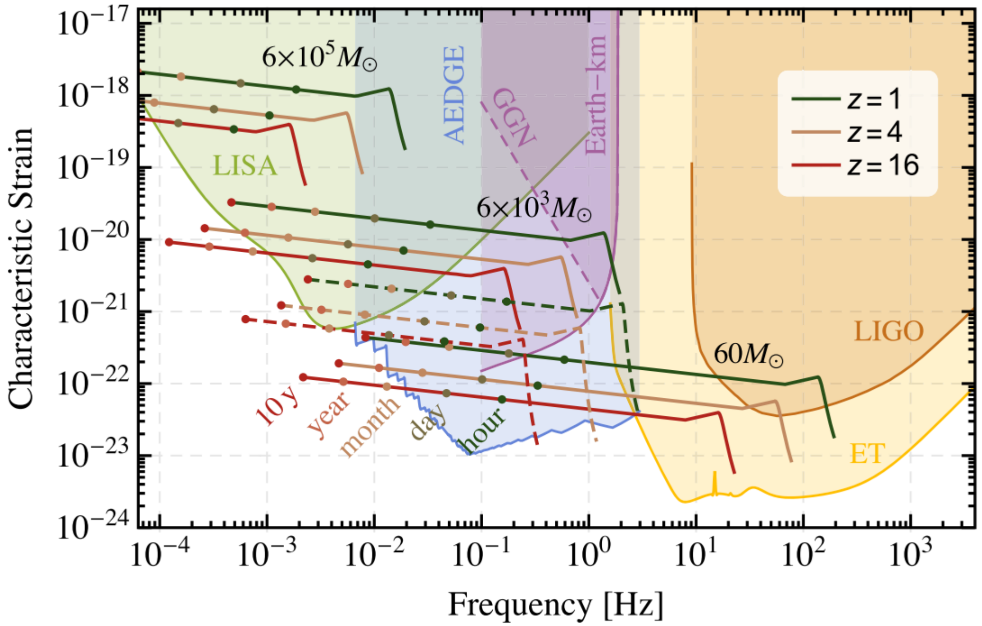
Signal: difference in local clock frequencies



AEDGE – Mid-Frequency Gravitational Waves

GW modulating space-time





Signal due to GW influencing travel time of photons

Mid-band science

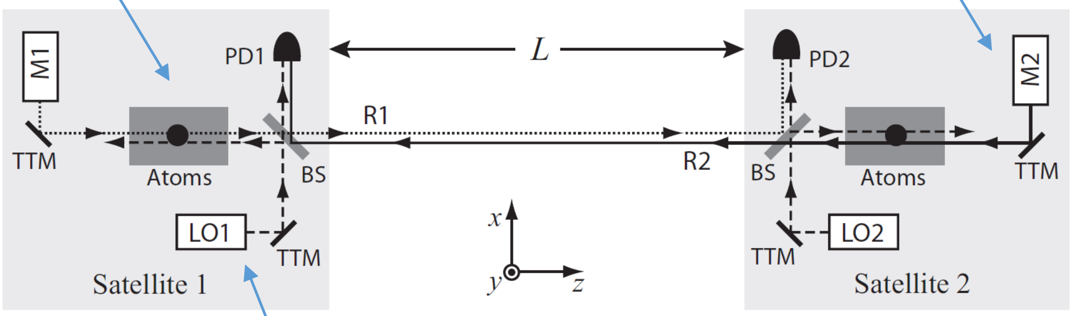
- Detect sources BEFORE they reach the high frequency band
- Optimal for sky localization: predict when and where events will occur

AEDGE – Heritage and Technology Journey

Heritage

Atom interferometer technology
(e.g. QUANTUS, BECCAL,…)

Optical clock laser technology
(e.g. SOC)



Scheme: Jason Hogan, et al.

Optical link phase locking technology
(e.g. LISA-PF)

Technology Roadmap:
De-risking in ground-based
large scale atom interferometers
(10m, 100m, 1km)

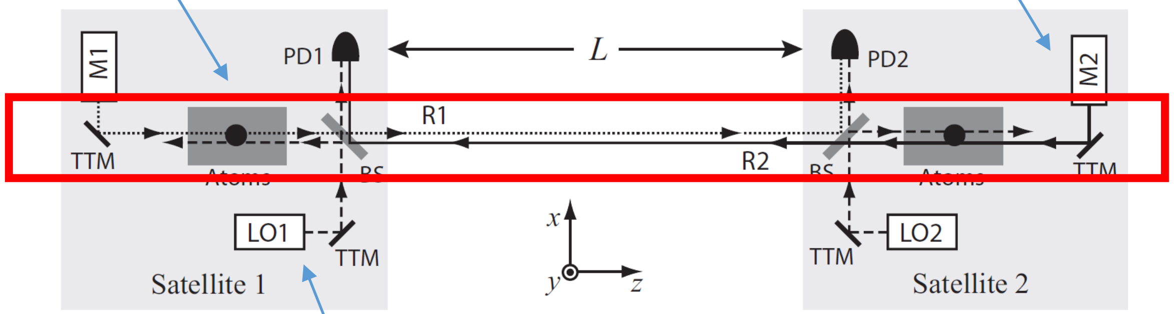
Journal of Cosmology and Astroparticle Physics 05, 011 (2020)

AEDGE – Heritage and Technology Journey

Heritage

Atom interferometer technology
(e.g. QUANTUS, BECCAL,…)
Common laser link

Optical clock laser technology
(e.g. SOC)



Scheme: Jason Hogan, et al.

Optical link phase locking technology
(e.g. LISA-PF)

Technology Roadmap:
De-risking in ground-based
large scale atom interferometers
(10m, 100m, 1km)

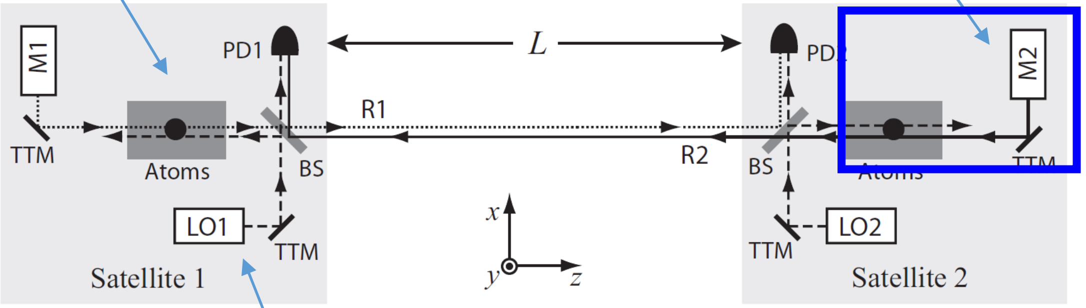
Journal of Cosmology and Astroparticle Physics 05, 011 (2020)

AEDGE – Heritage and Technology Roadmap

Heritage

Atom interferometer technology
(e.g. QUANTUS, BECCAL,…) ✓

Optical clock laser technology
(e.g. SOC)
Environmentally stable clock atom



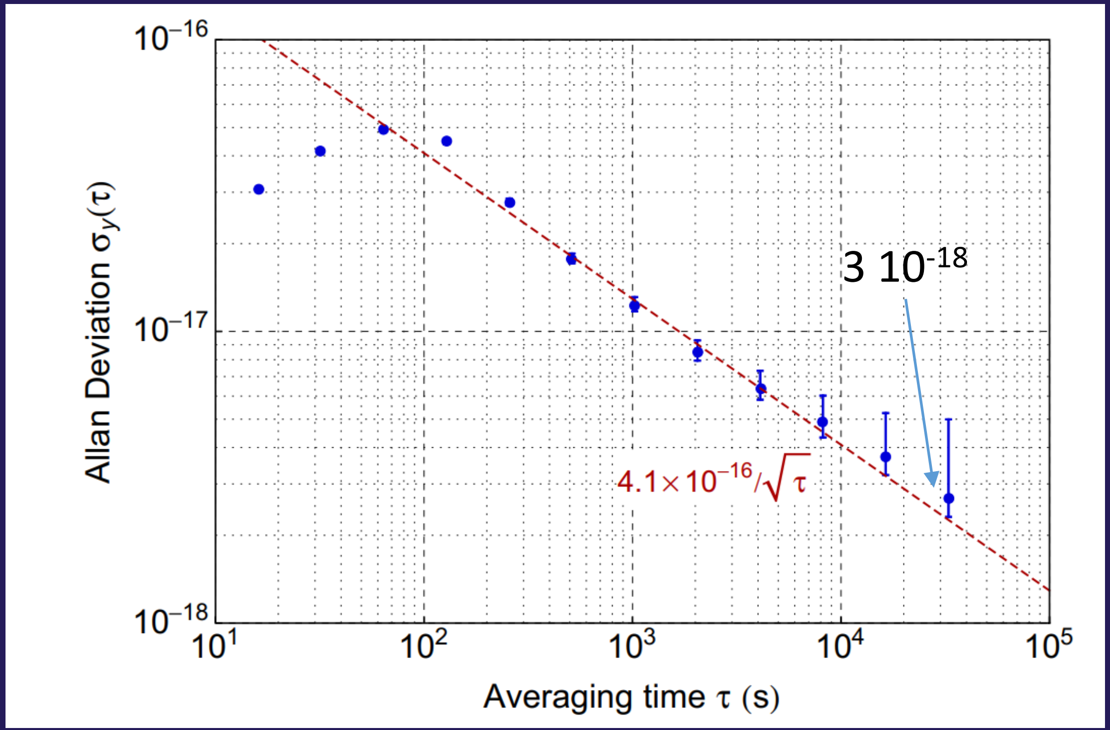
Sr

Optical link phase locking technology
(e.g. LISA-PF)

Technology Roadmap:
De-risking in ground-based
large scale atom interferometers
(10m, 100m, 1km)

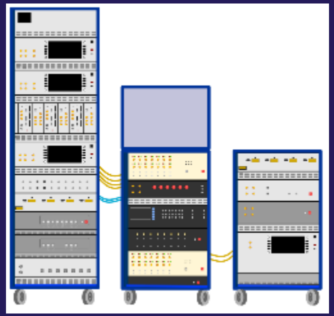
Journal of Cosmology and Astroparticle Physics 05, 011 (2020)

Sr Optical Lattice Clock Developments at Birmingham

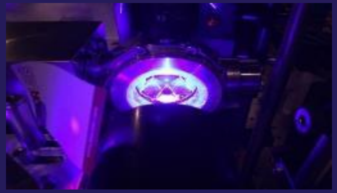


Phys Rev A ***98****, 053443 (2018)*

SOC II, iSOC – led by U Düsseldorf
FACT – led by UoB
Volume ~1000l
3 10^{-18} with PTB clock laser
Phys Rev A ***98****, 053443 (2018)*



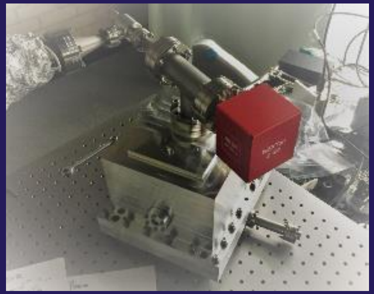
iQclock – led by U Amsterdam
UoB led commercial clock
Volume ~1000l
Aim ~10^{-16}



Miniature optical lattice clock – led by UoB
Volume ~200l
Now: atoms in optical lattice
Adv. Opt. Tech. ***9****, 313 (2020)*
Optics Express ***28****, 15943 (2020)*
US Patent 15/128,731

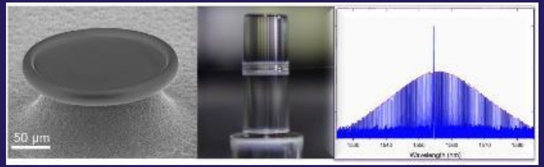
Timing and Phase-Locked Links for Radar

Robust Oscillators



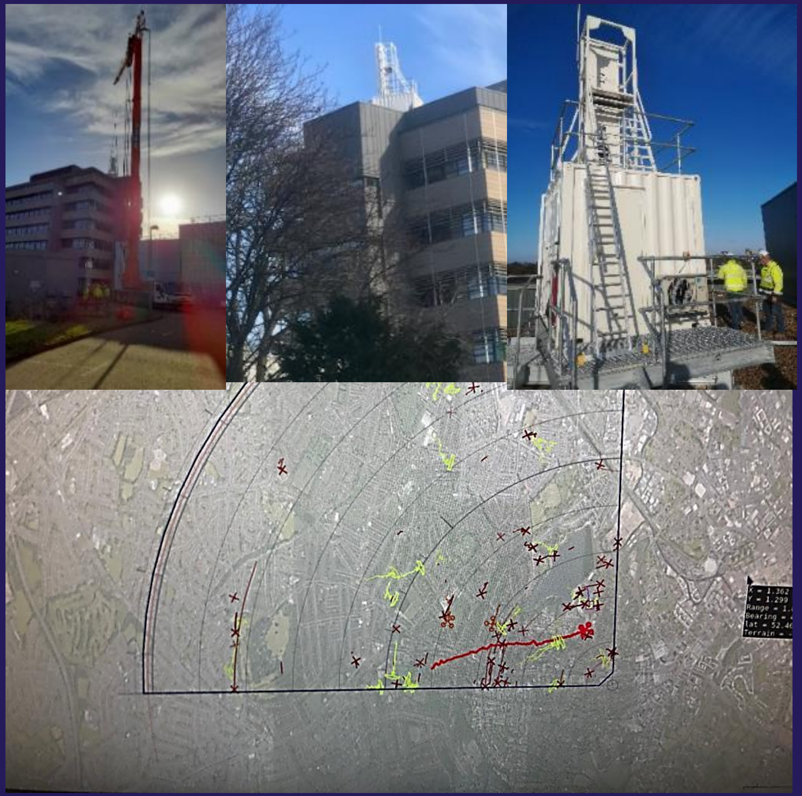
Microcombs

NPL National Physical Laboratory | QMI Quantum Metrology Institute



Sub-mW microresonator comb thresholds
Zhang et al, Optica 2019
NPL femtosec comb capability at 10^{-21} level
Johnson et al, Metrologia 2015

Radar Test Facility



Stakeholder Discussions

Civil Aviation Authority

NATS

West Midlands Police

AVEILLANT A Thales company

BAE SYSTEMS

Collaboration: physics, material science, electrical engineering, social sciences, industry

UK Quantum Technology Hub Sensors and Timing

UK National Quantum Technologies Programme

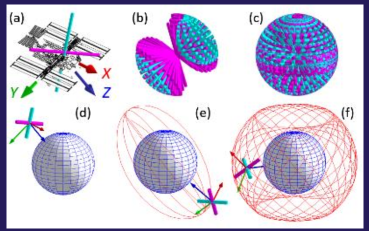
Intermediate Space Missions

Clock Technology

AI Technology

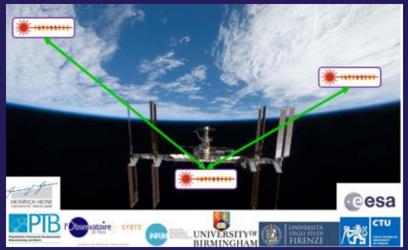
Fundamental Physics

Lorentz Invariance

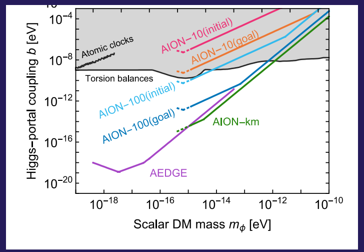


http://www.kerffufler.com/list/

Gravitational Redshift



GW and Dark Matter



Equivalence principle

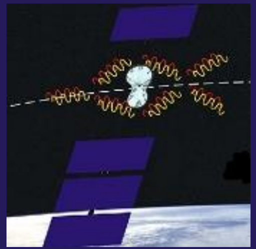


Image: STE-QUEST

Climate

Underground Water

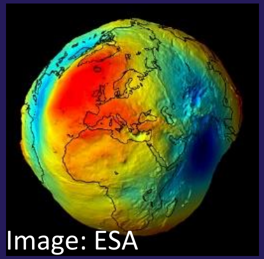


Image: ESA

Atmospheric Drag

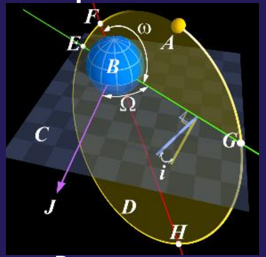


Image: Peo~commonswiki

Economy

Satellite Navigation

Image: NOAA

Communications

To be explored: Brain health in human space flight, satellite radar, radar for space debris detection,…

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Thank you for your attention

Questions?

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