Development of a Retro-Reflection Platform for the MAGIS and AION Experiments Towards Kilometre-scale Atom Interferometry

University of Liverpool

IOP Joint APP and HEPP Annual Conference 2025

Andrew Carroll

on behalf of the AION and MAGIS collaborations

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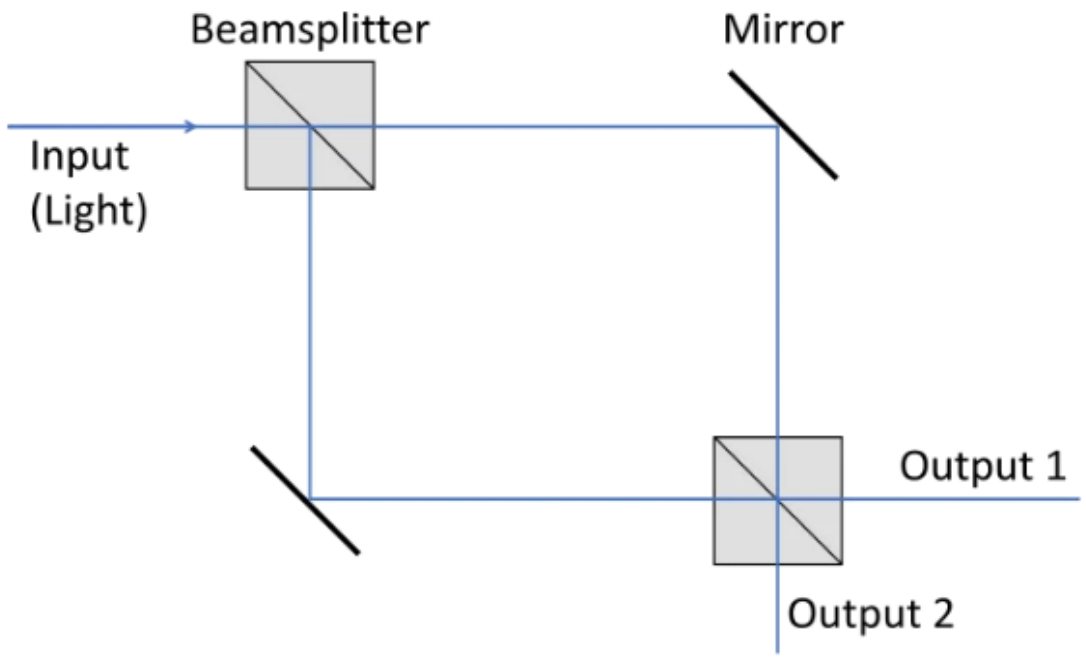
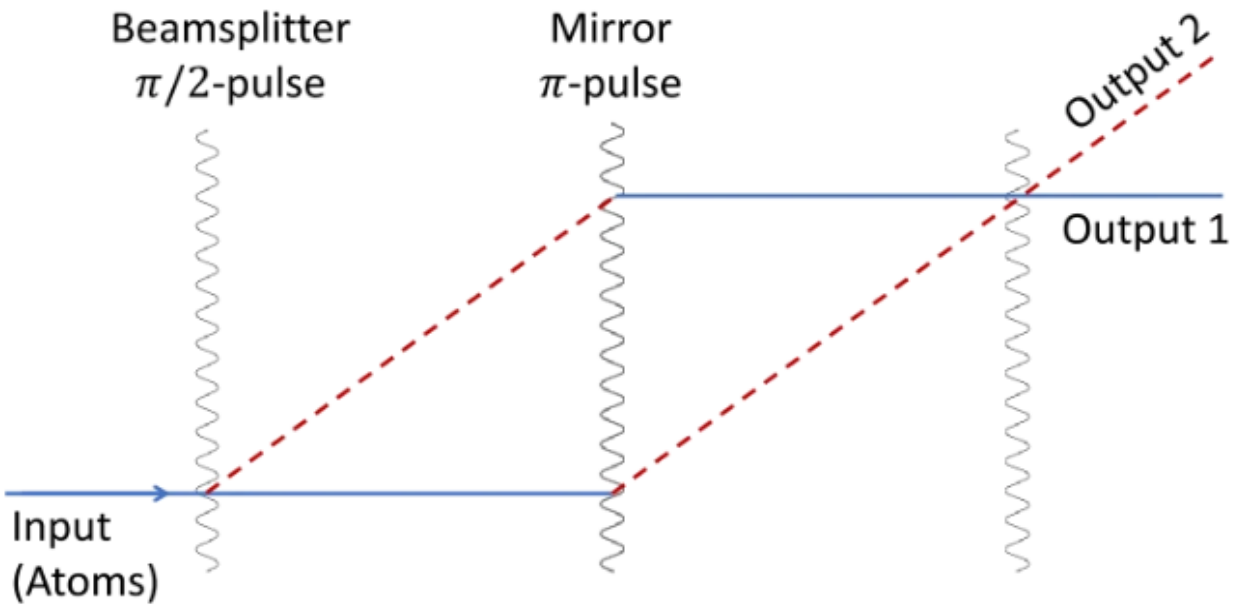
Atom Interferometry

Laser Interferometer



Atom Interferometer



Abdalla, A., *et al.*, *EPJ Quantum Technol.* **12**, 42 (2025)

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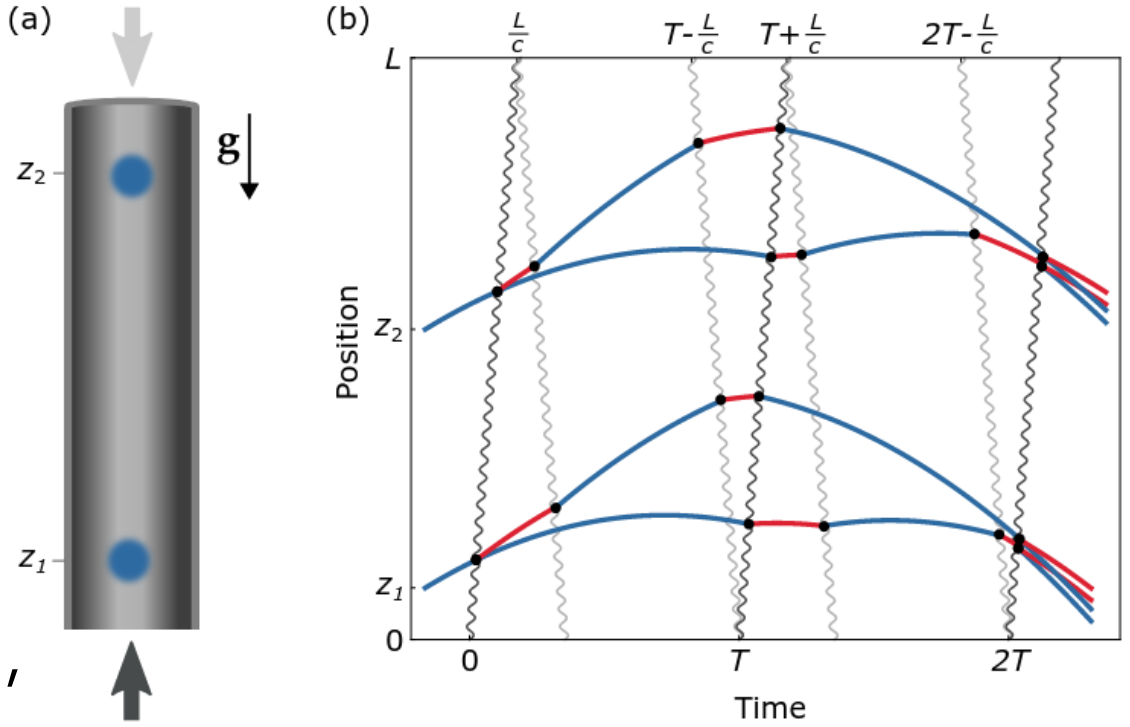
Atom Interferometry

- Sensitivity scales with spacetime area
- Gradiometery supresses common mode noise
- Longer flight times, larger spatial separation
- Larger baselines, launching, multiple laser interactions (LMT)



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

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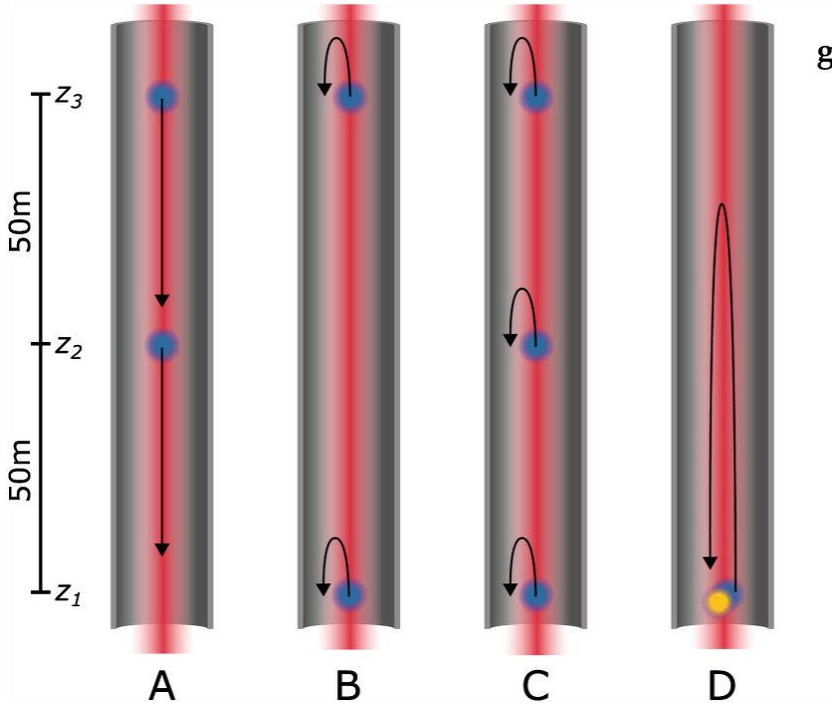
- 100-meter strontium gradiometer located at MINOS shaft in Fermilab
- Multiple atom sources to create gradiometric configuration
- 10-m prototype under construction in Stanford



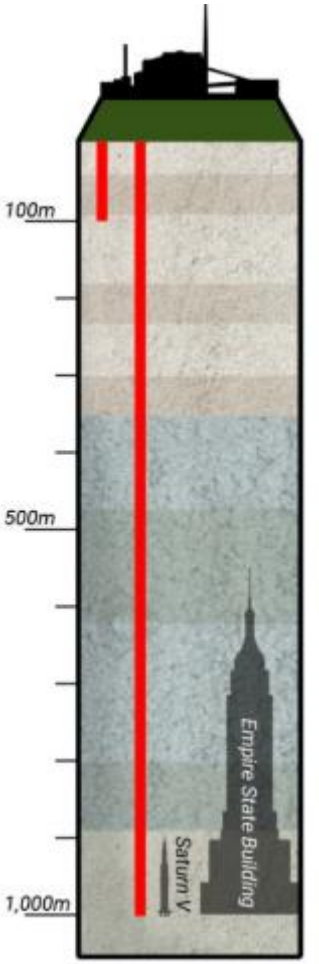


Image courtesy of Ben Gilliland, STFC

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

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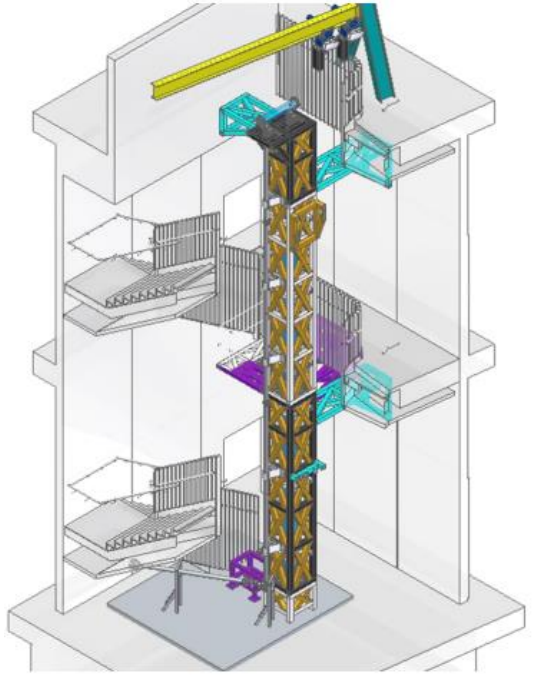
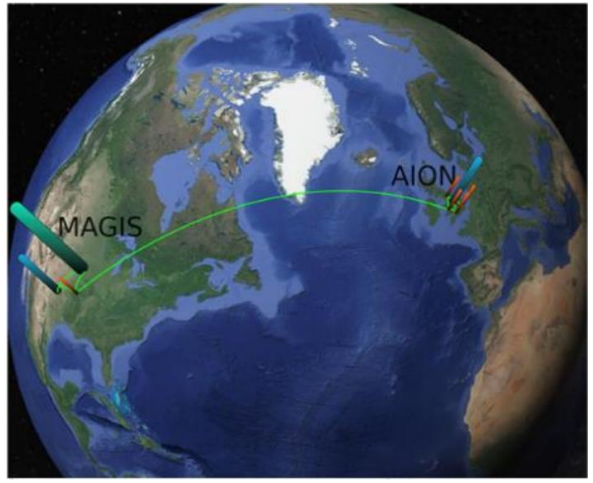
- Multi-institute collaboration
- 10-metre tower located at the Beecroft building in Oxford
- Future stages to include 100-m and 1-km baselines





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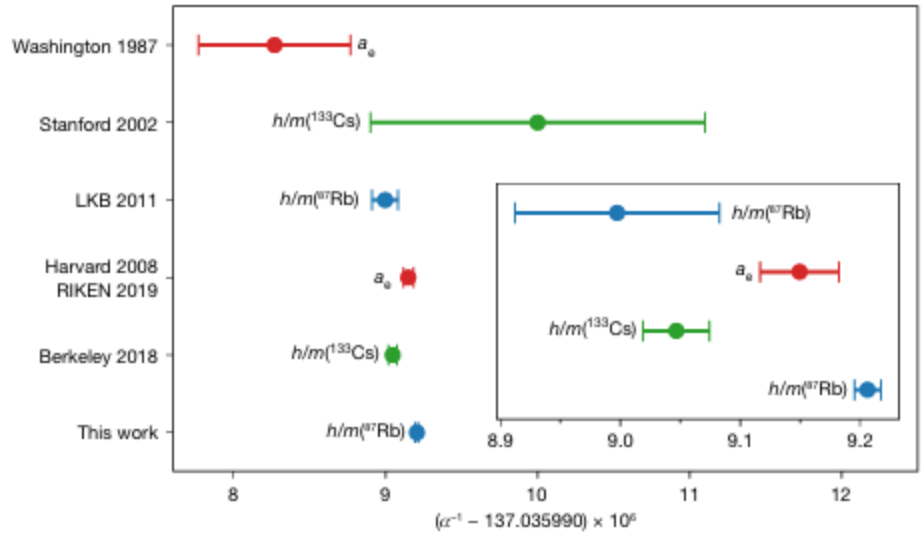
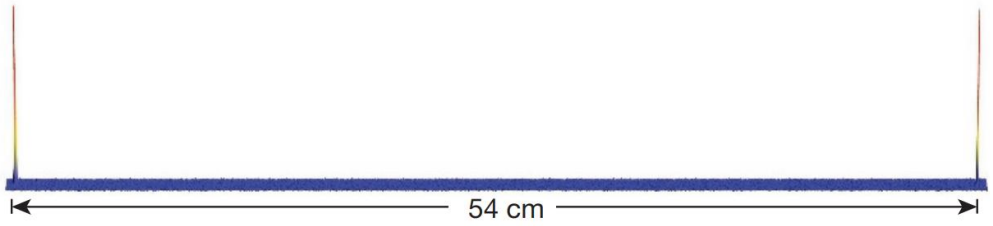
Applications for Fundamental Physics

Fine-Structure Constant



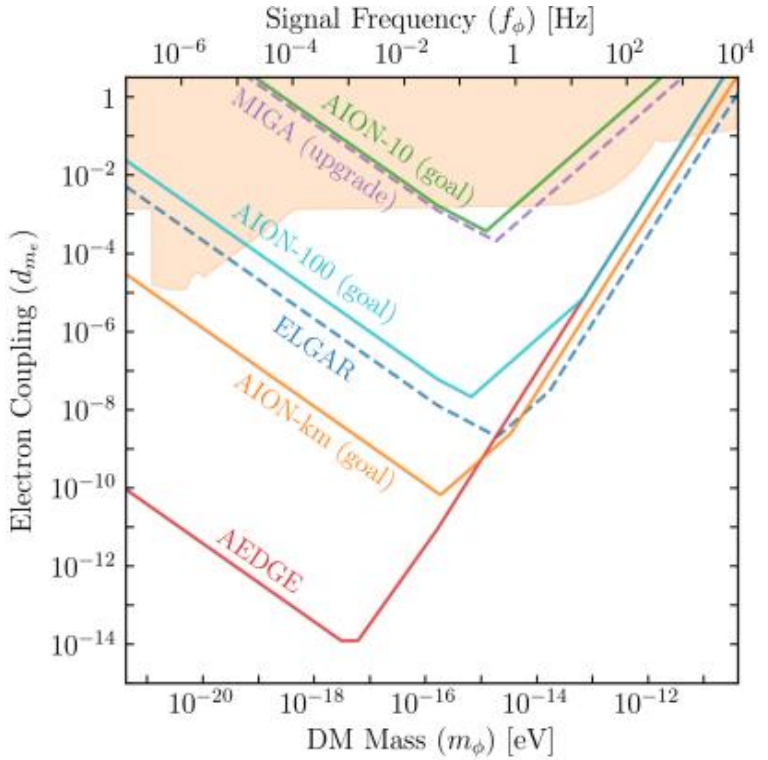
Morel, L., Yao, Z., Cladé, P. *et al*. *Nature* **588**, 61–65 (2020)

Macroscopic Superposition



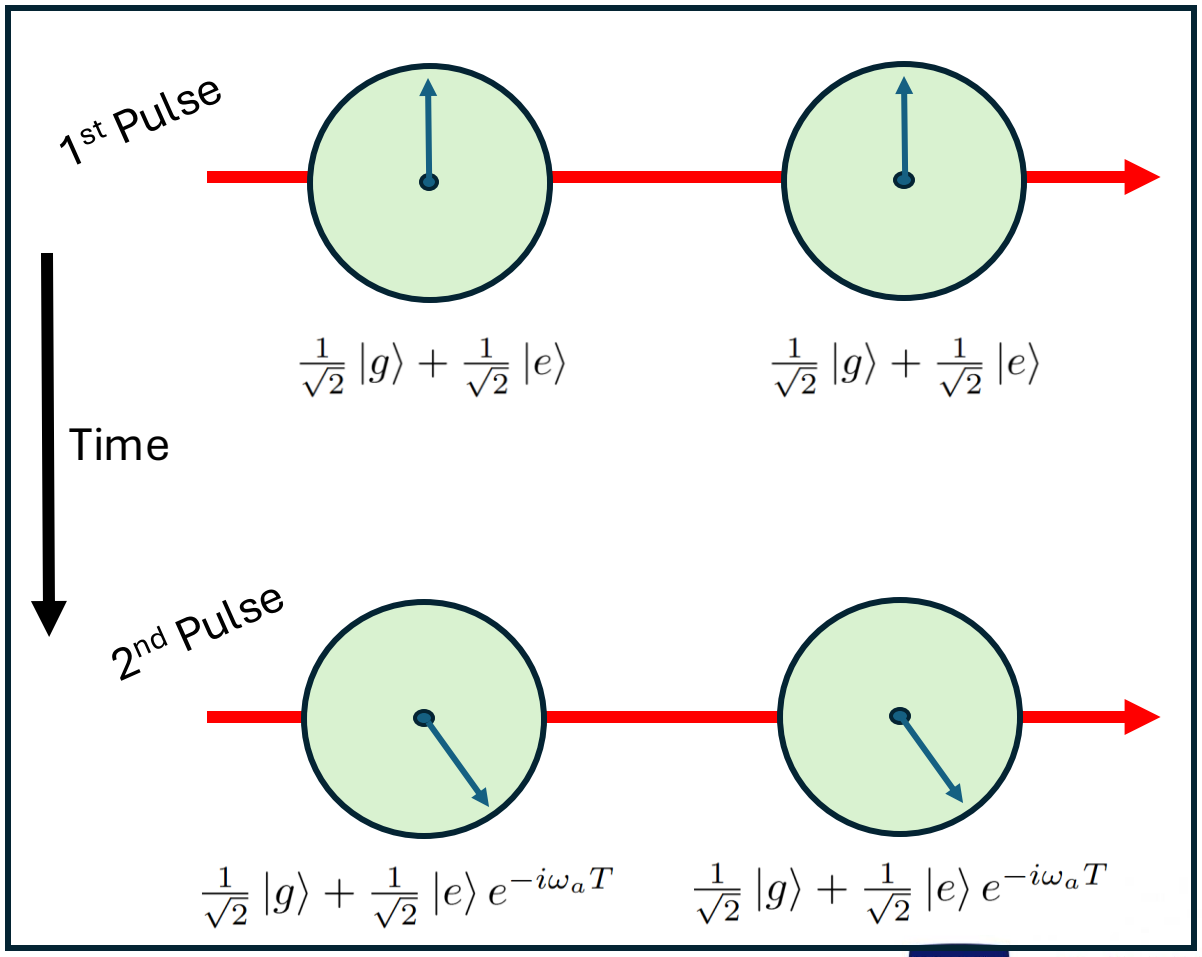
Kovachy et al., *Nature* **528**, 530–533 (2015)

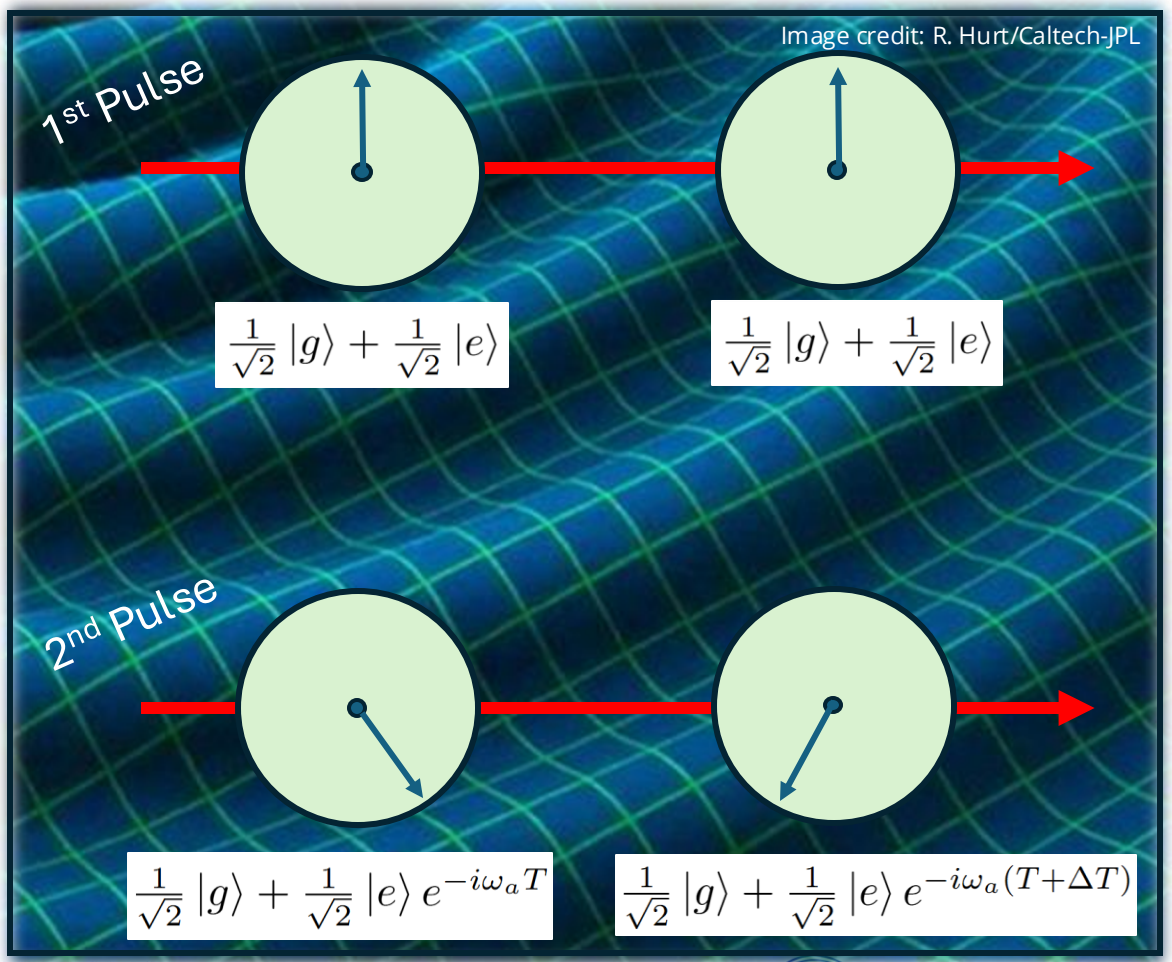
Ultralight Dark Matter Searches



I. Alonso et al., EPJ Quantum Technology 9, 30 (2022)

Gravitational Wave Detection





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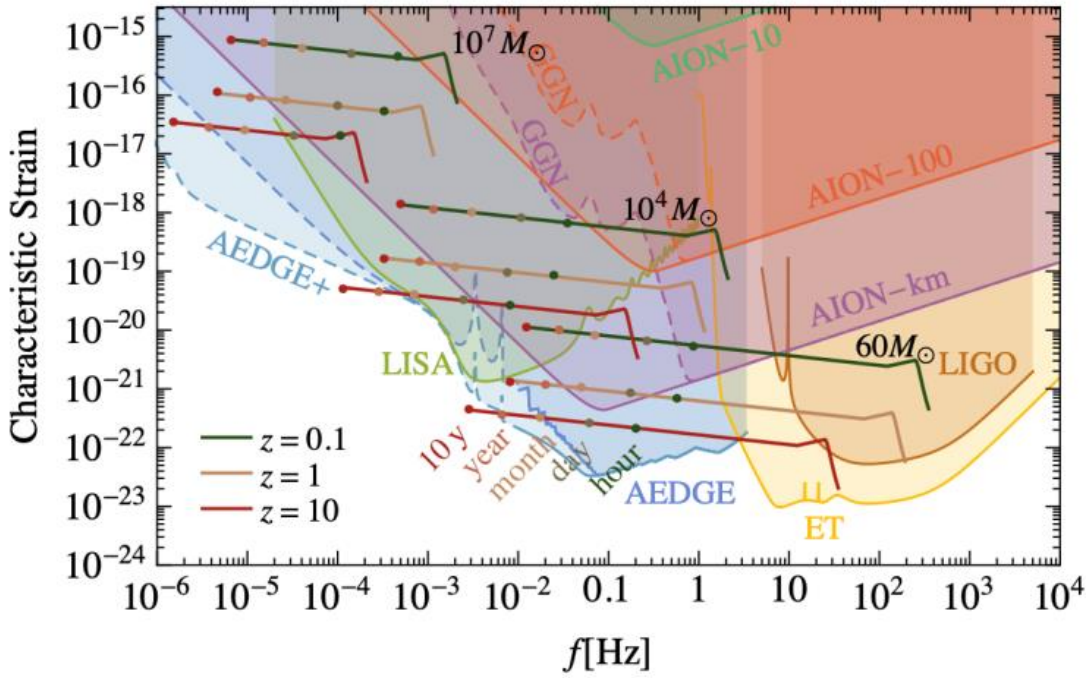
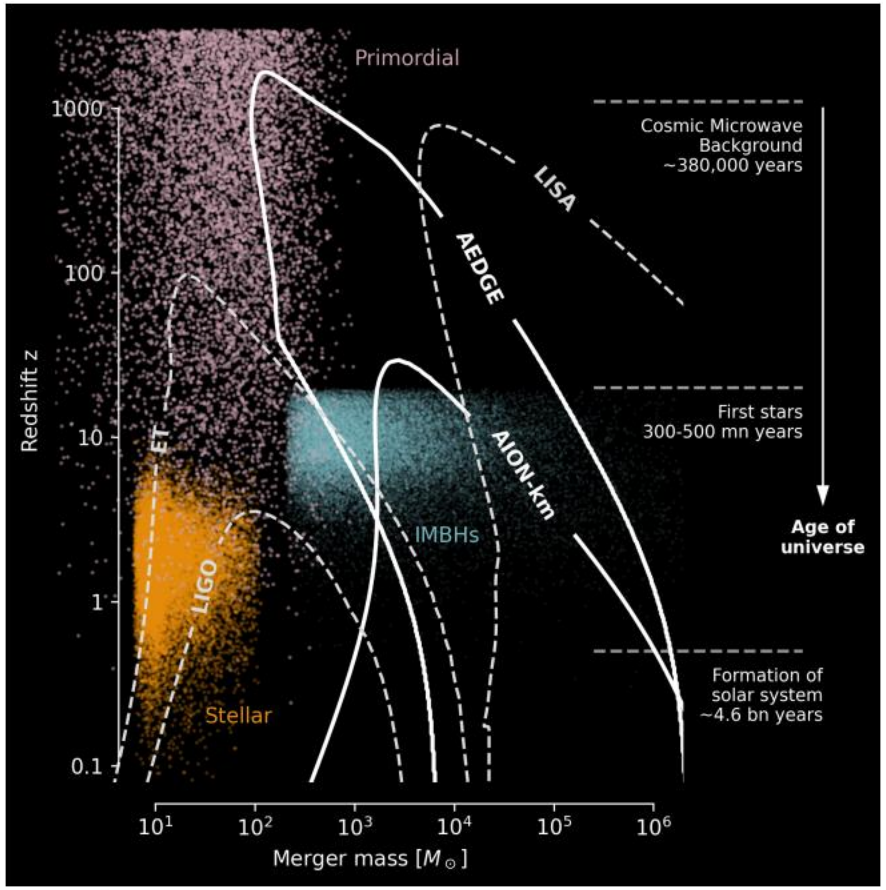
Gravitational Waves Sensitivity

- Mid-band gravitational waves exist between LIGO/VIRGO (10^2) and LISA (10^{-2})
- Allows measurement of intermediate mass black hole mergers



Mid-band Gravitational Waves

- Measuring black hole mergers in this region will provide clues about the formation of SMBHs
- Measurement of lower frequency inspirals allows early sky localisation for multi-messenger detection



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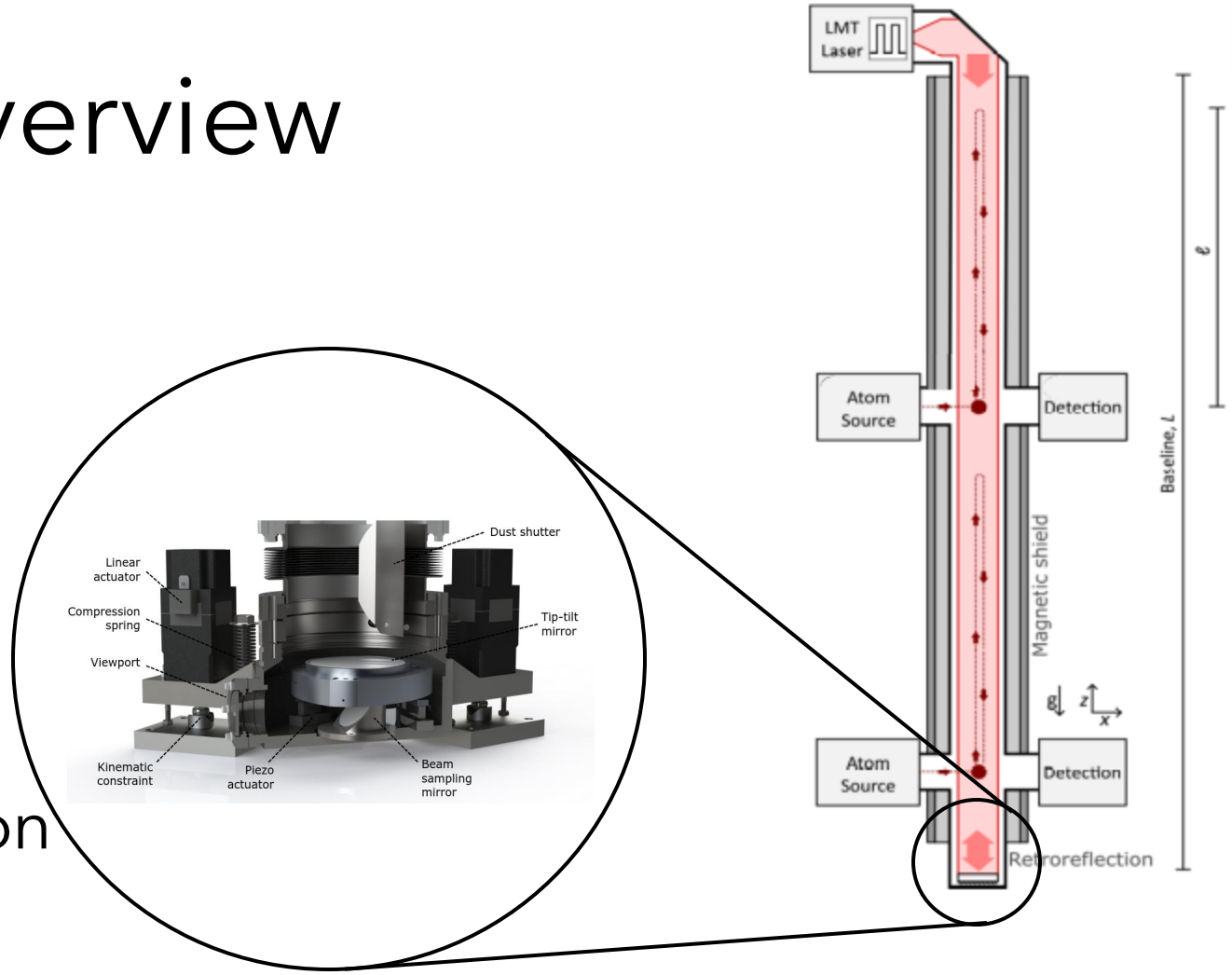
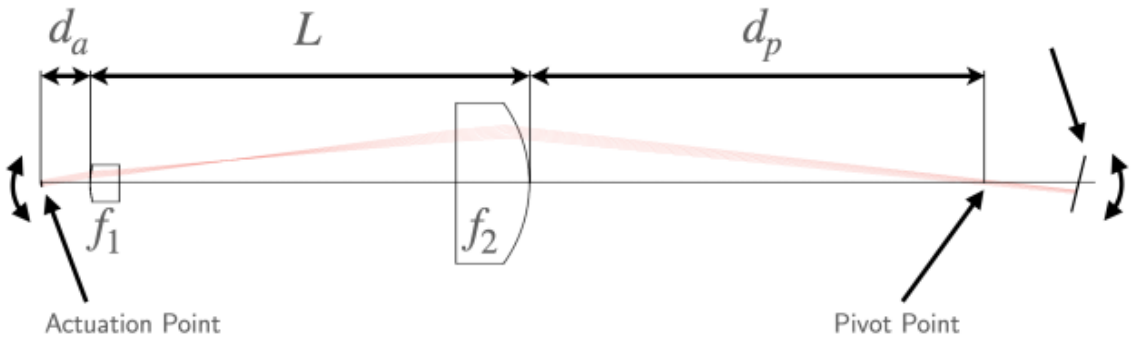
Retro-chamber Overview

- Retro-reflection mirror controlled by three Piezoelectric Transducers
- Angular feedback via strain gauges and optical lever
- Designed to have 50 nrad angular resolution resolution



Coriolis Compensation

- Accurate enough that Coriolis force of earth becomes major systematic
- Scales with baseline length
- For very long baseline experiments, added Coriolis effects cause dephasing and loss of contrast



J. Glick et al., *AVS Quantum Sci.* 6, 014402 (2024)

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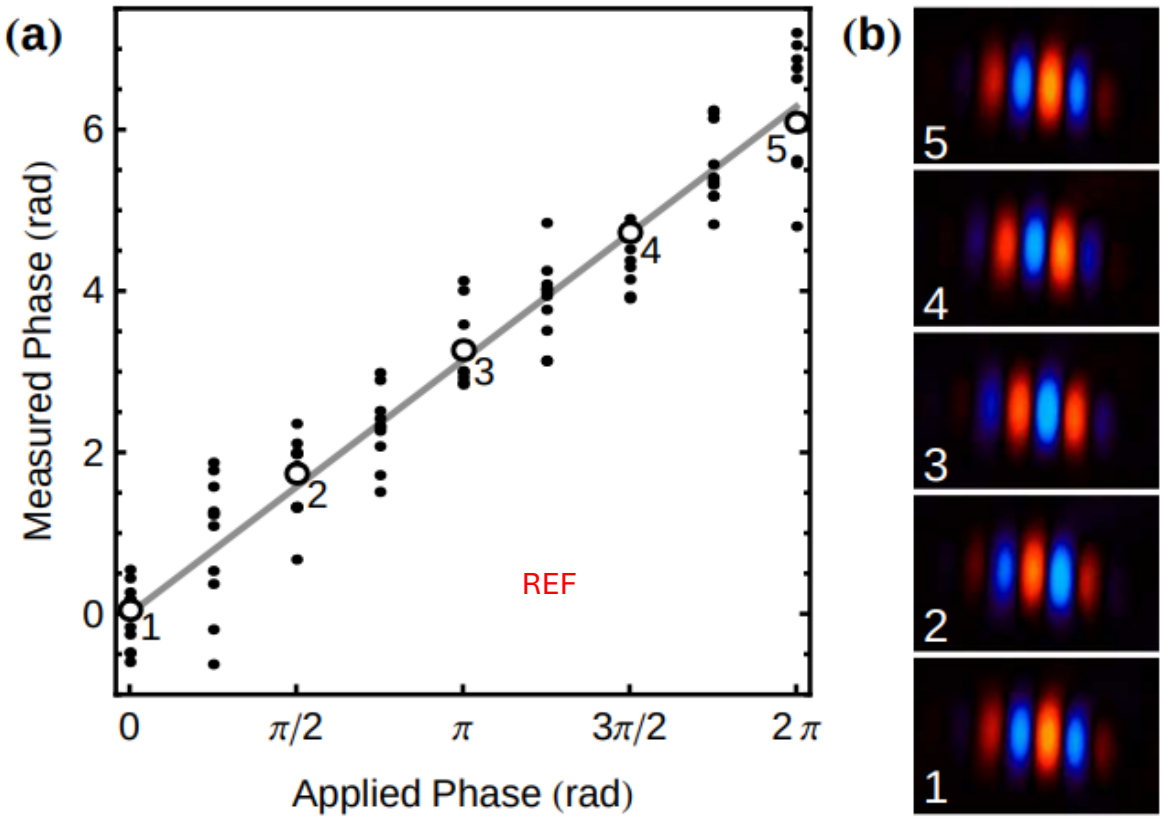
Phase Shear

- Conventional detection methods require multiple shots to infer contrast
- Tilting the retroreflection mirror for the final pulse imprints laser phase on to the atom cloud
- This phase transfers to state population which is then imaged



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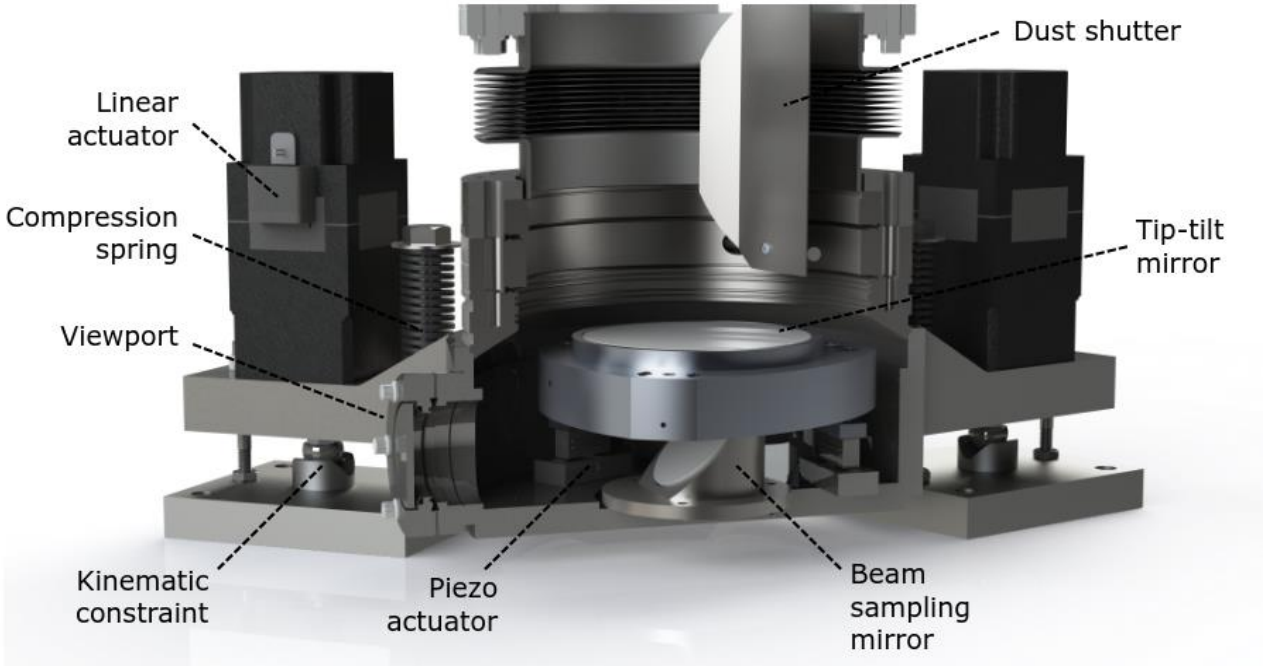

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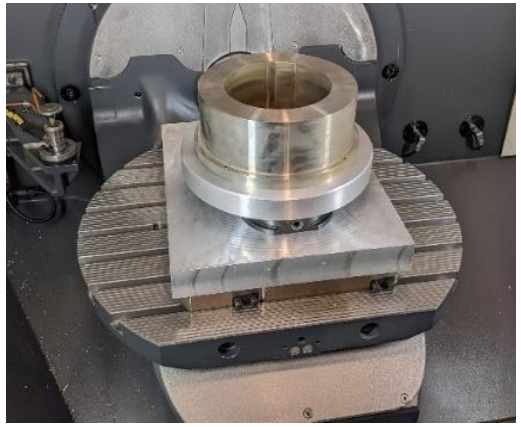
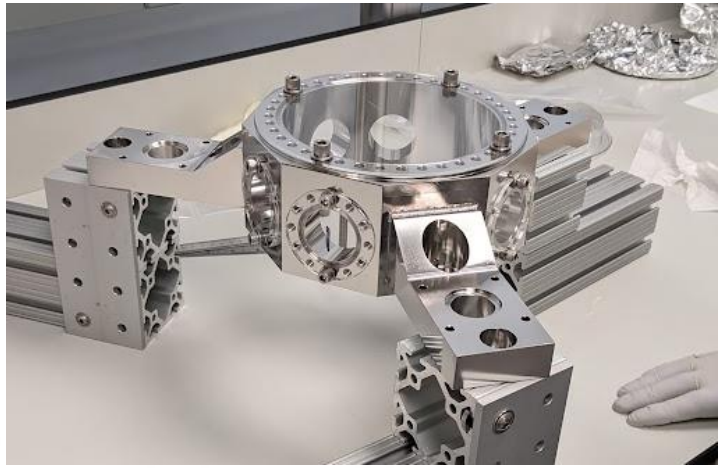
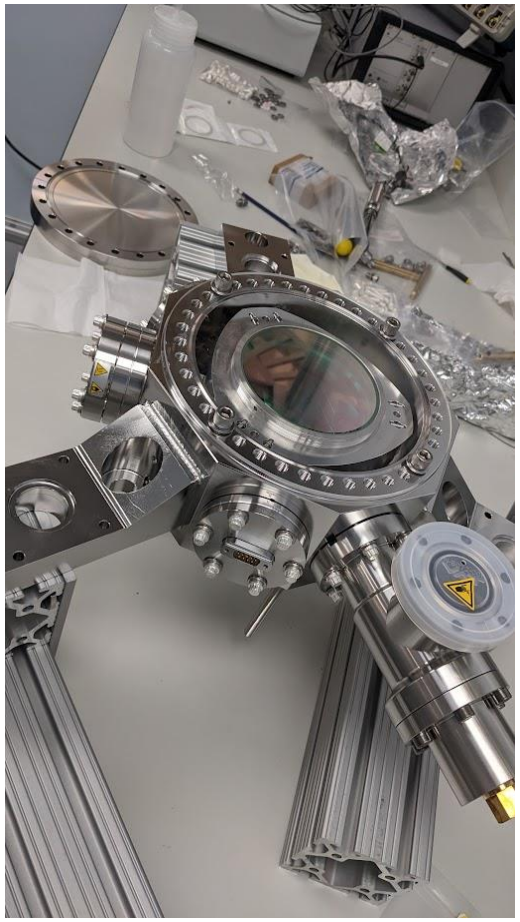
Retro-chamber Design and Installation

- University of Liverpool involved in design, manufacturing, prototyping, assembly and commissioning
- MAGIS prototype commissioned at Stanford
- In process of constructing chamber design with optical lever feedback







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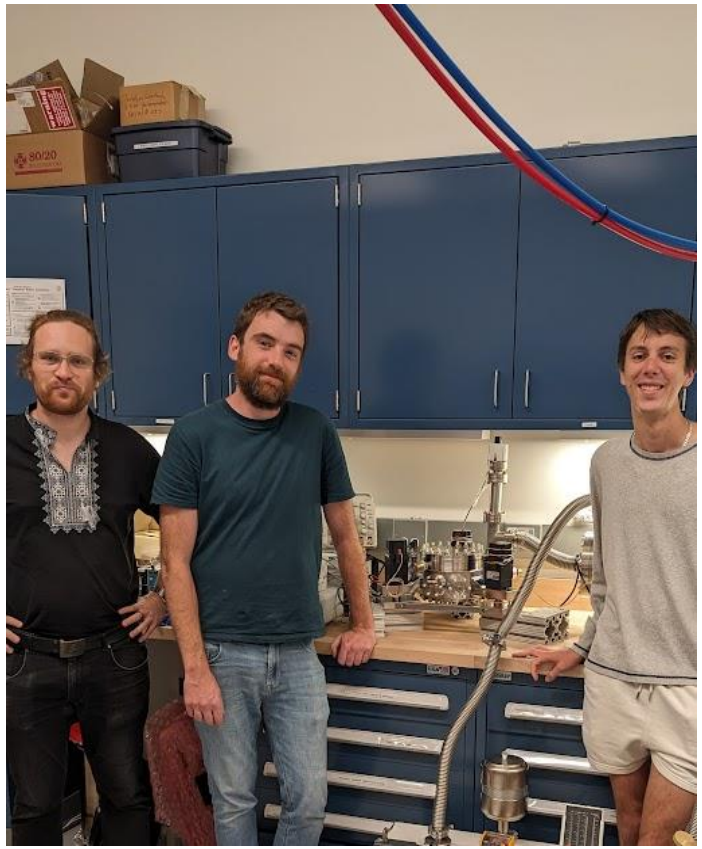

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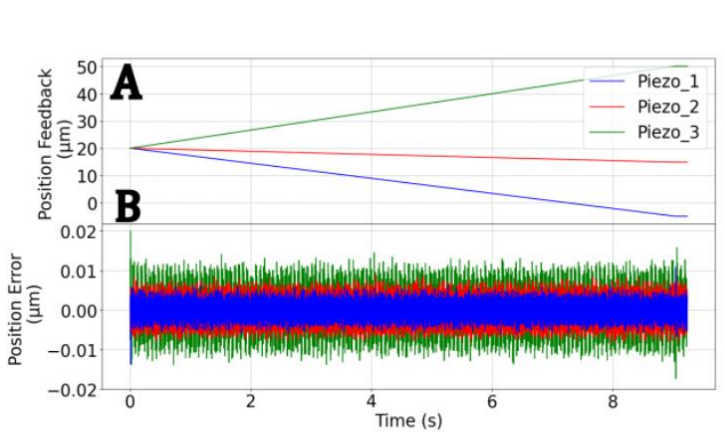
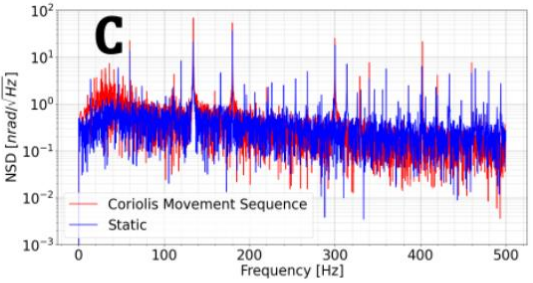
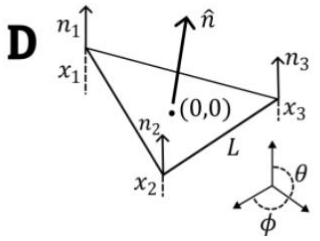
Retro-chamber Results

- Investigated the noise sources inherent in the PZTs, servo-loops
- Characterisation of these and how the imprint on to the mirror angle
- See Henry Throssell's presentation for more details





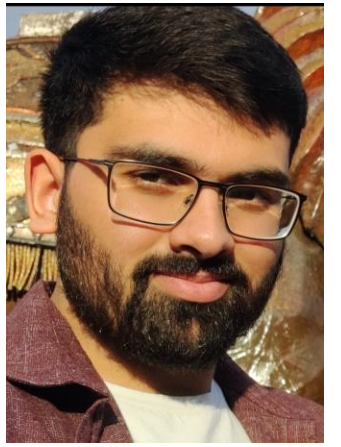


University of Liverpool Team

Kieran Bridges

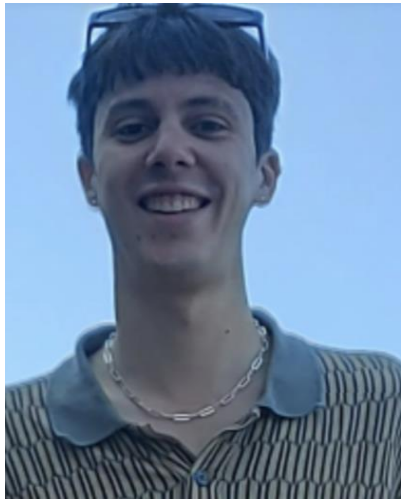
Jonathon Coleman

Gedminas Elertas



Kamran Hussain

Carl Metelko

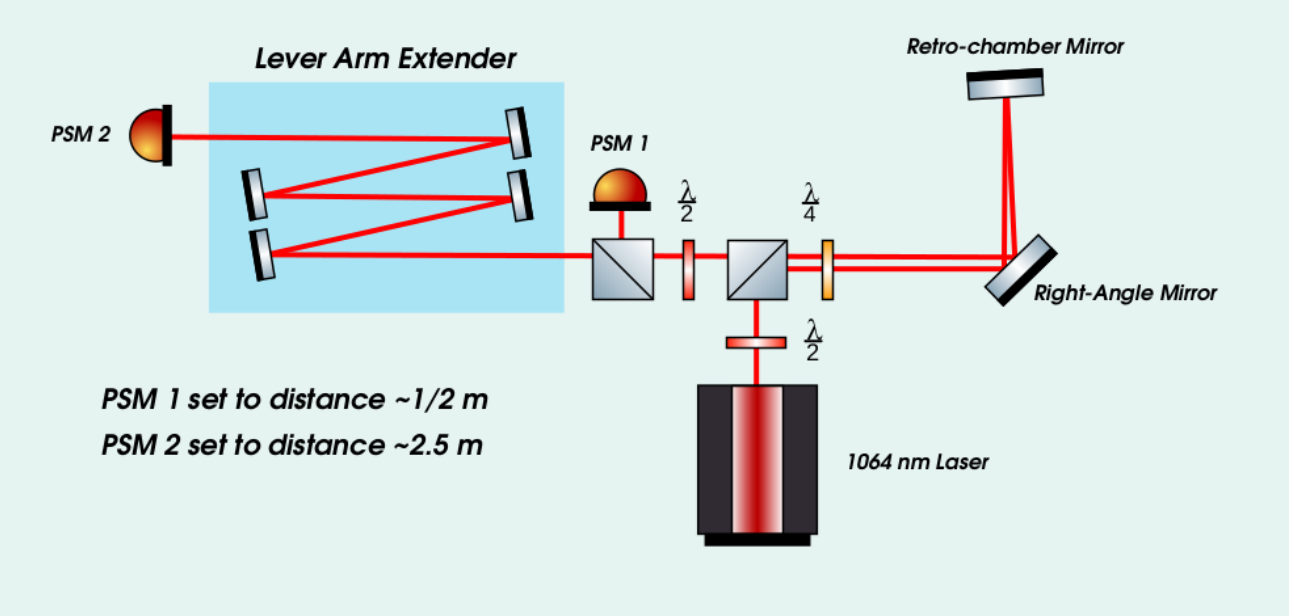


Henry Throssell

Jonathan Tinsley

Optical Lever

- Retro-reflection mirror is coated on both sides to allow reflection of lever laser
- Lever laser is then measured on Position Sensing Module to infer mirror angle
- Lever scales with length, requiring ~1m length to get down to the 50 nrad level
- Setup must be stabilised against air currents, vibrations, thermal expansion
- PSM output can be used for optical feedback of PZTs



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