Atom Interferometry for Fundamental Physics

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UNIVERSITY OF BIRMINGHAM

UK Quantum Technology Hub Sensors and Timing

Outline

I. Basics of atom interferometry

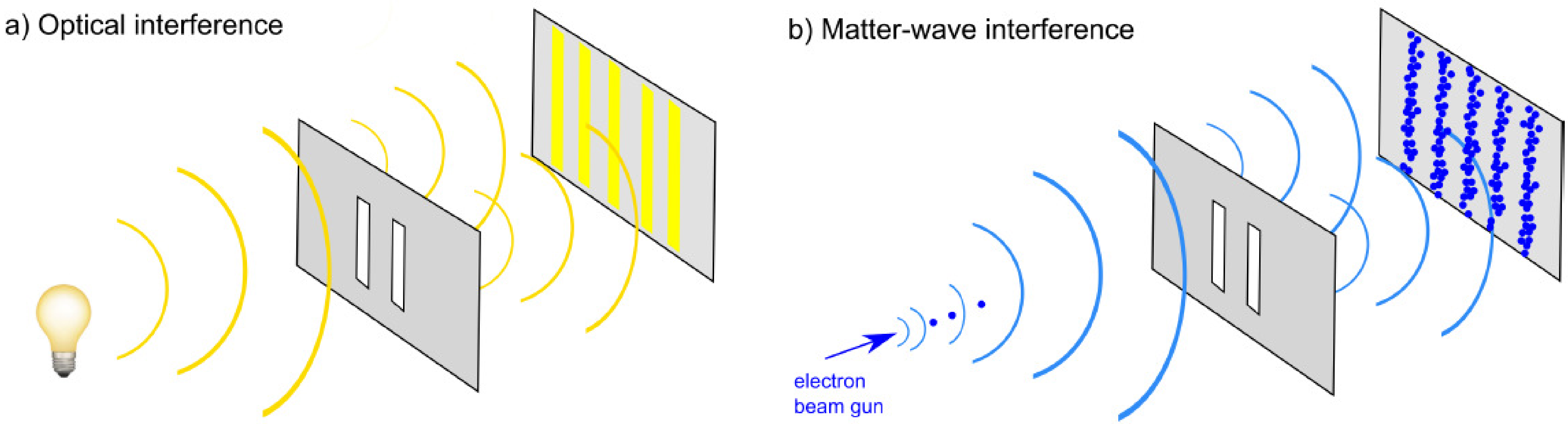
II. Practical applications in quantum sensing

III. Fundamental physics applications: the AION project

PART I.

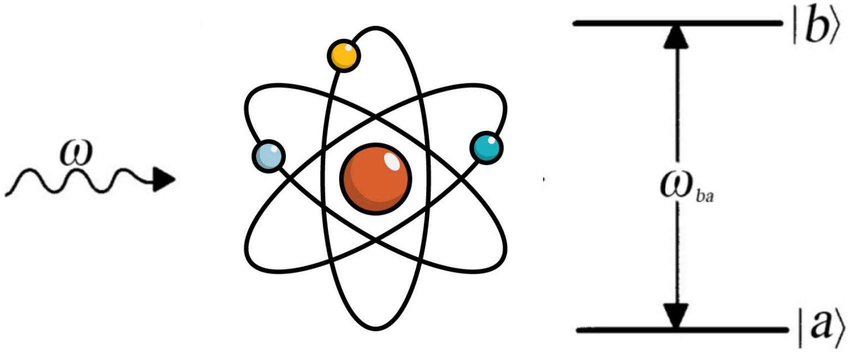
BASICS OF ATOM INTERFEROMETRY

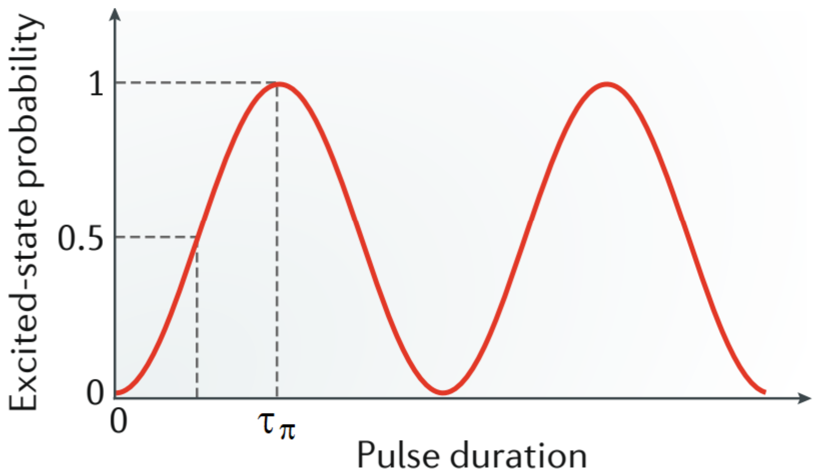
Interference of matter-waves



Manipulating atoms with light pulses

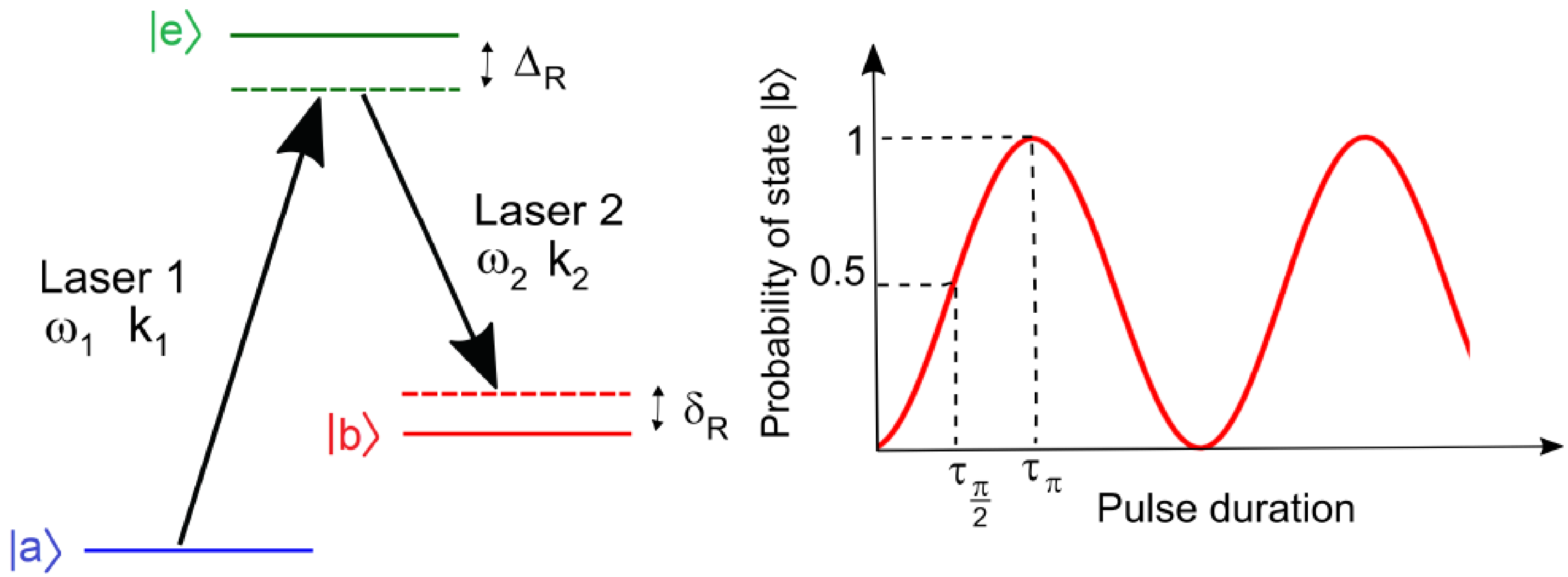
The two-level atom: Rabi oscillations



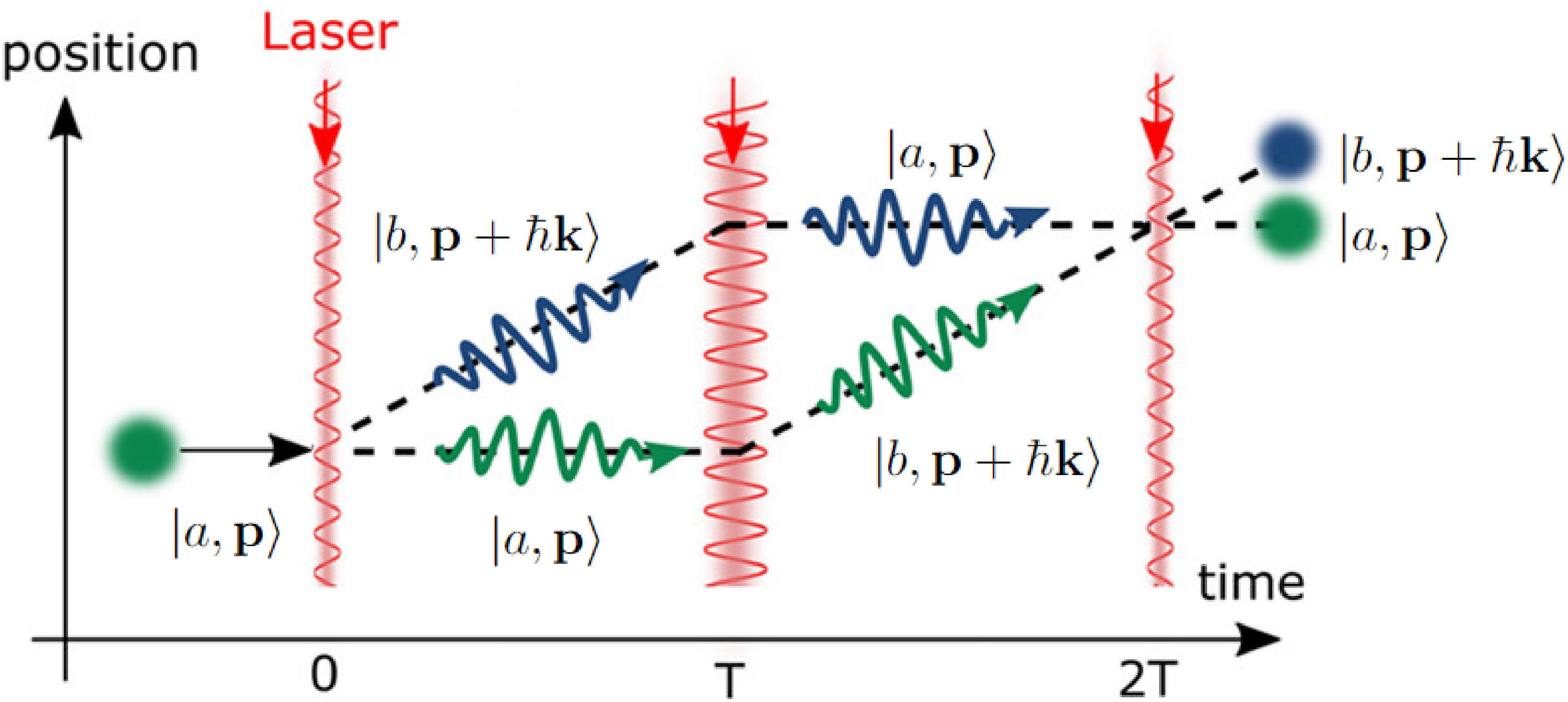


Manipulating atoms with light pulses

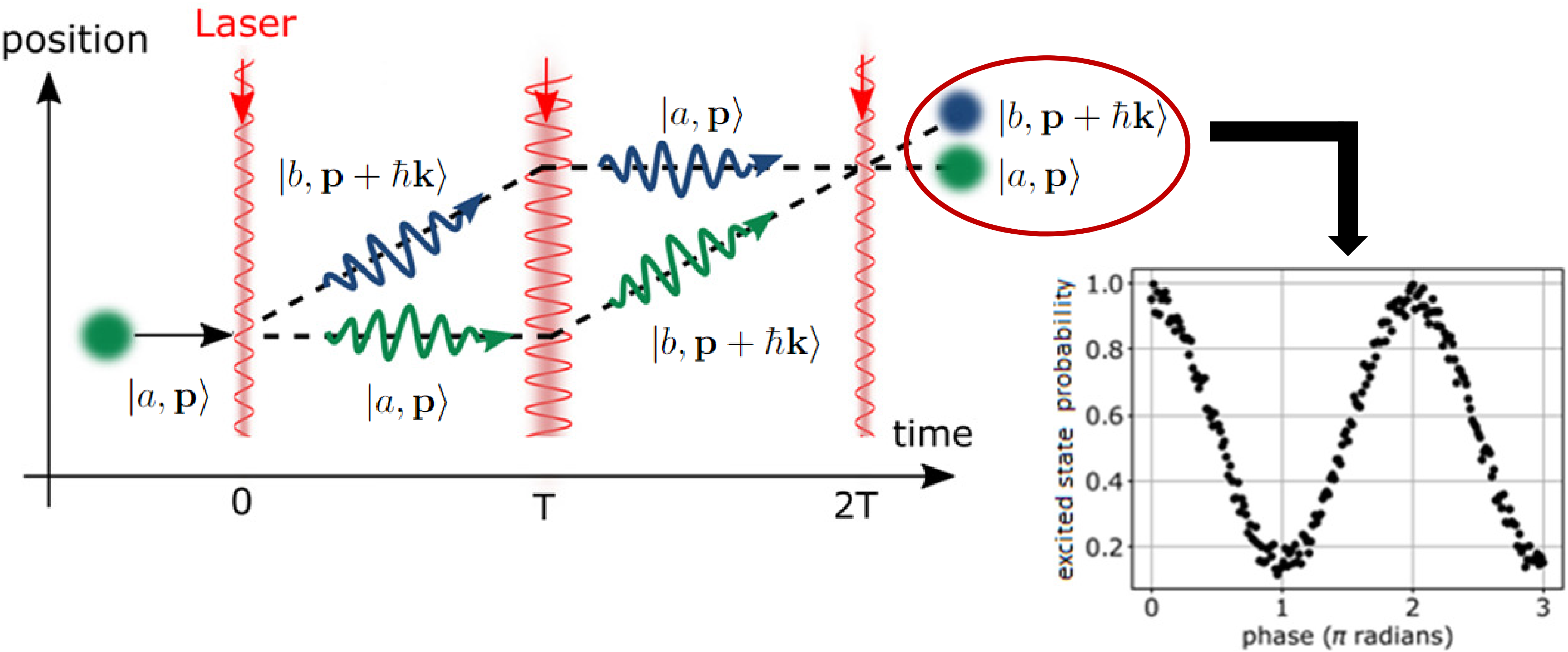
Stimulated Raman transitions



Atom interferometry

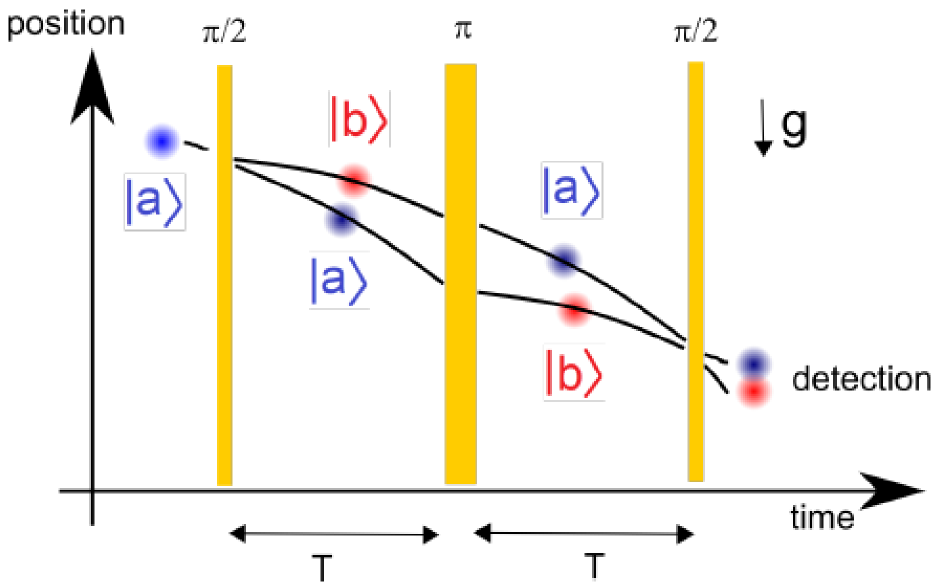


Atom interferometry



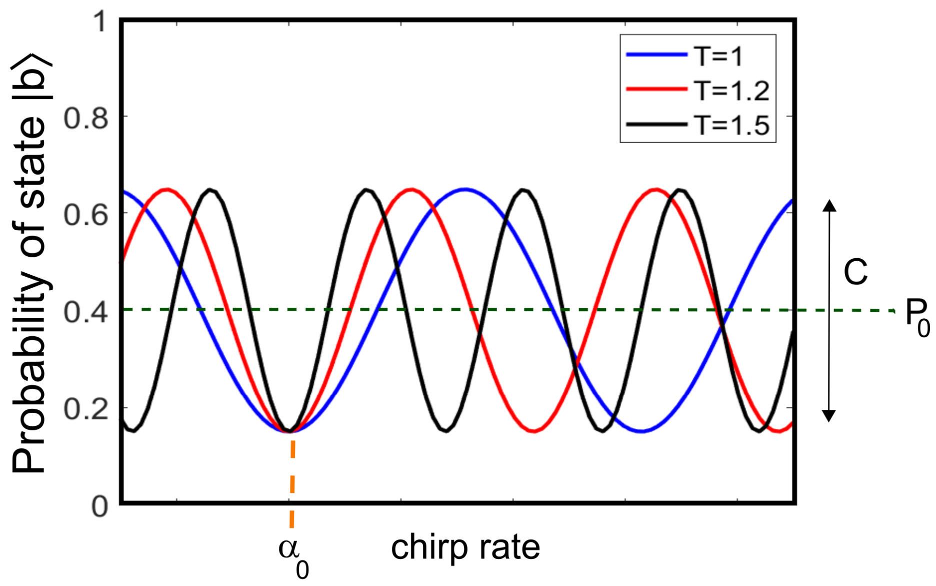
$$P_b = P_0 - C/2\cos(\Delta\Phi)$$

Example: performing a gravity measurement



In free fall under gravity: $\Delta\Phi = \mathbf{k}_{\text{eff}}.\mathbf{g}T^2$

$$P_b = P_0 - C/2\cos(\Delta\Phi)$$



In practice, we chirp the laser frequency linearly with time, $\omega \rightarrow \omega+\alpha t$, and we determine the chirp rate α_0 which cancels out the gravity phase shift for any T: $g=2\pi\alpha_0/k_{eff}$

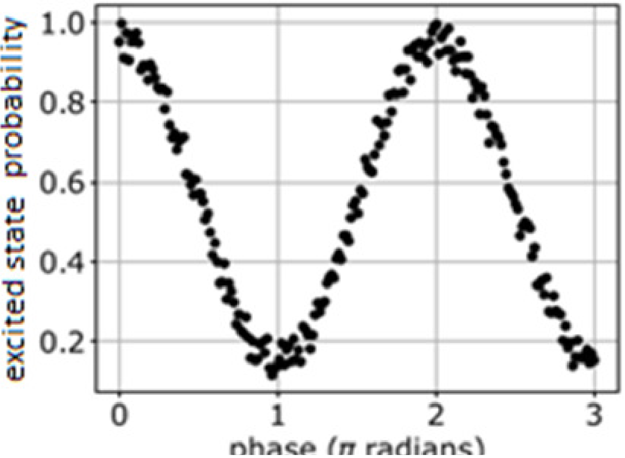
Advantages of atom interferometry

$$\Delta\Phi = \mathbf{k}_{\text{eff}}.\mathbf{g}T^2$$

Accuracy: Arises from the large scale-factor of the interferometer, $k_{eff}T^2$

Long-term stability: The scale factor is immutable and controlled with high precision

Sensitivity: In the absence of any noise source, the sensitivity is limited by the quantum projection noise



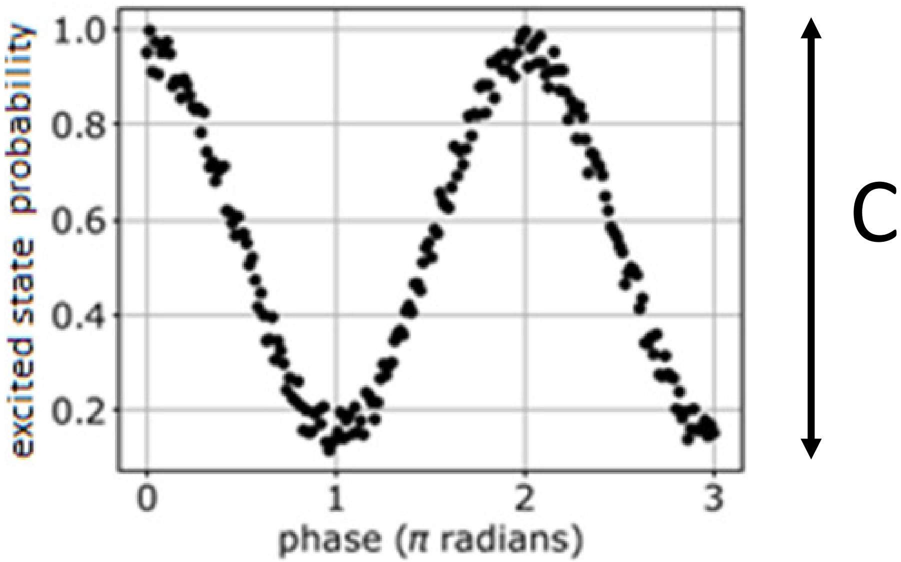
$$\sigma_g = \frac{1}{C\mathbf{k}_{\text{eff}}T^2\sqrt{N}}$$

Enhance contrast

Increase momentum separation

Increase interrogation time

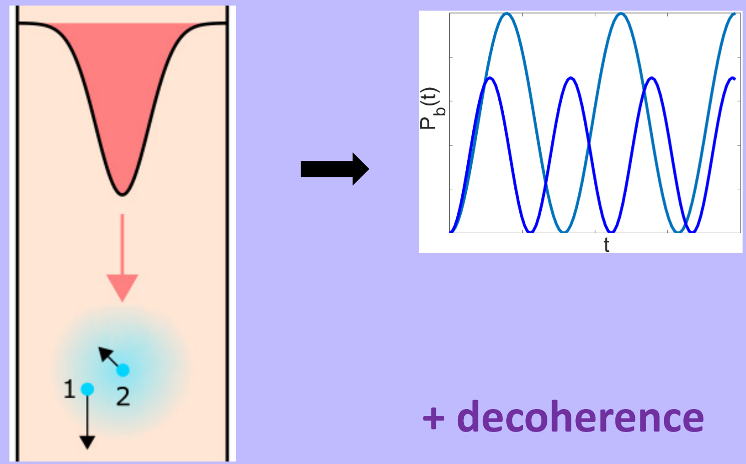
Interferometer contrast



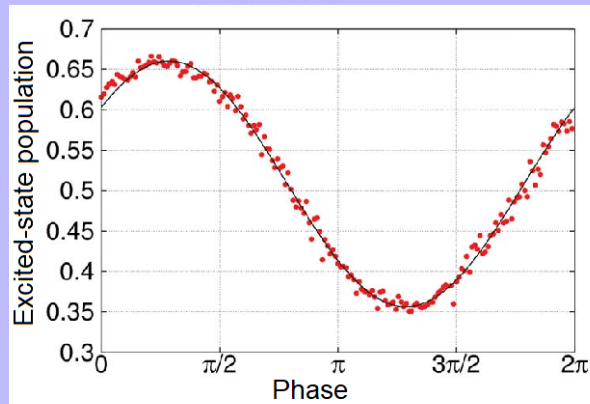
$$P_b = P_0 - C/2\cos(\Delta\Phi)$$

Contrast losses

Cloud inhomogeneities



+ decoherence



PART II.

PRACTICAL APPLICATIONS IN QUANTUM SENSING

Quantum sensing technologies

Gravimetry

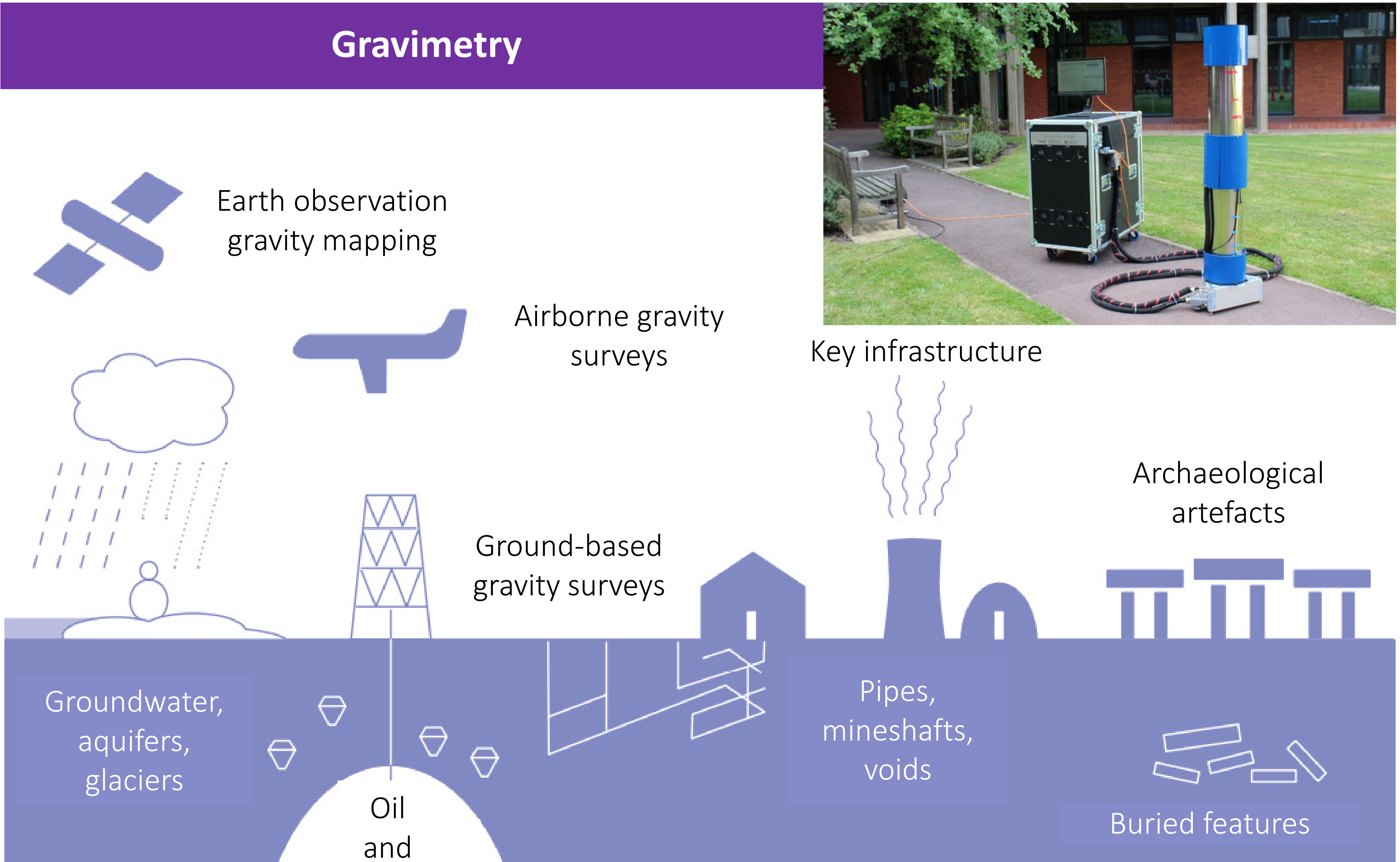
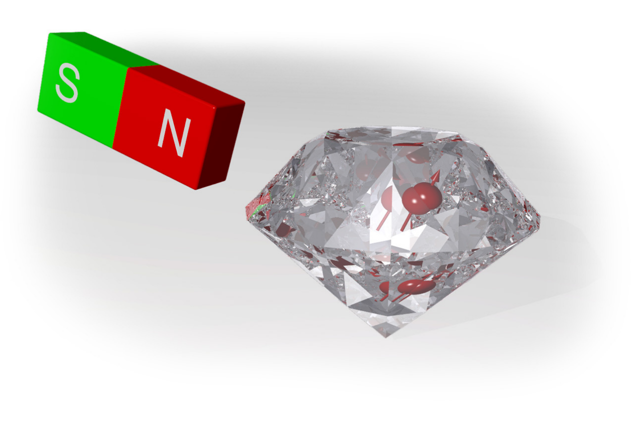
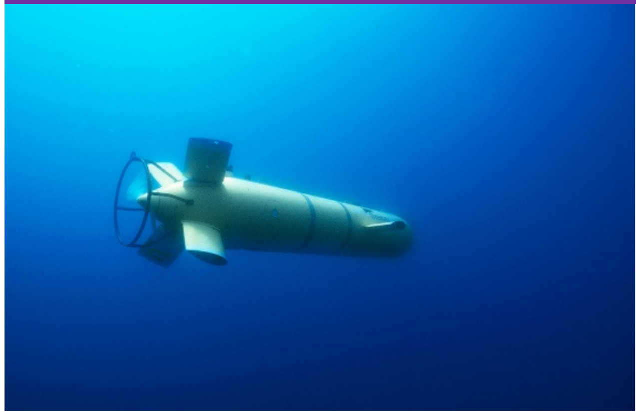


Image from Quantum technologies: Blackett review, 2016

Magnetometry

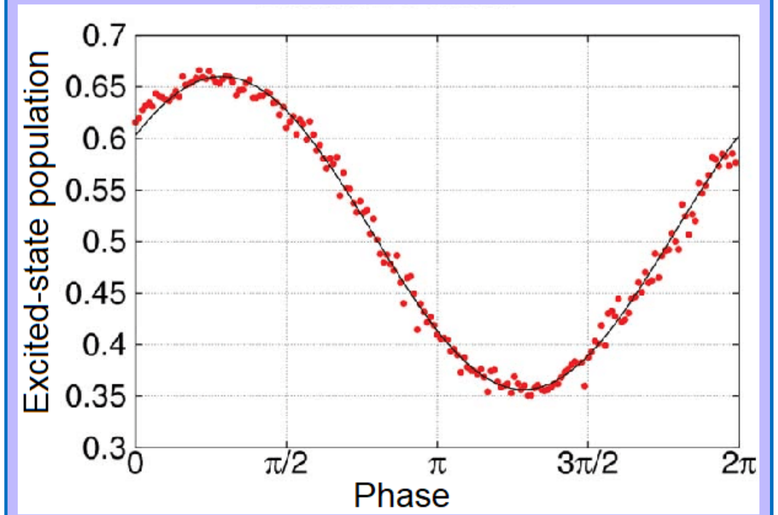


Inertial sensing

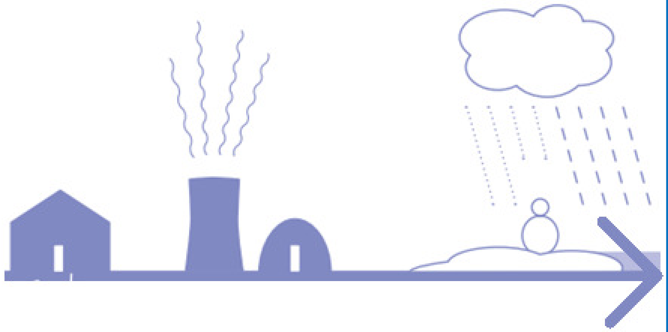


From the lab to the field

In lab conditions

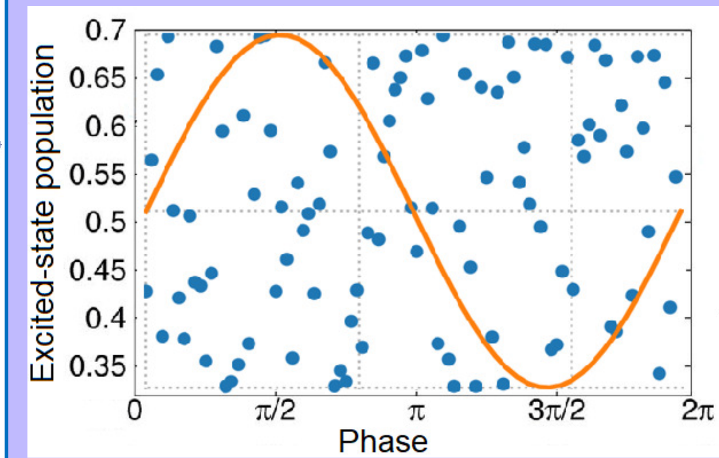


Laser tilts, misalignements
Laser phase noise, intensity noise
Wavefront aberration
Background magnetic fields
…



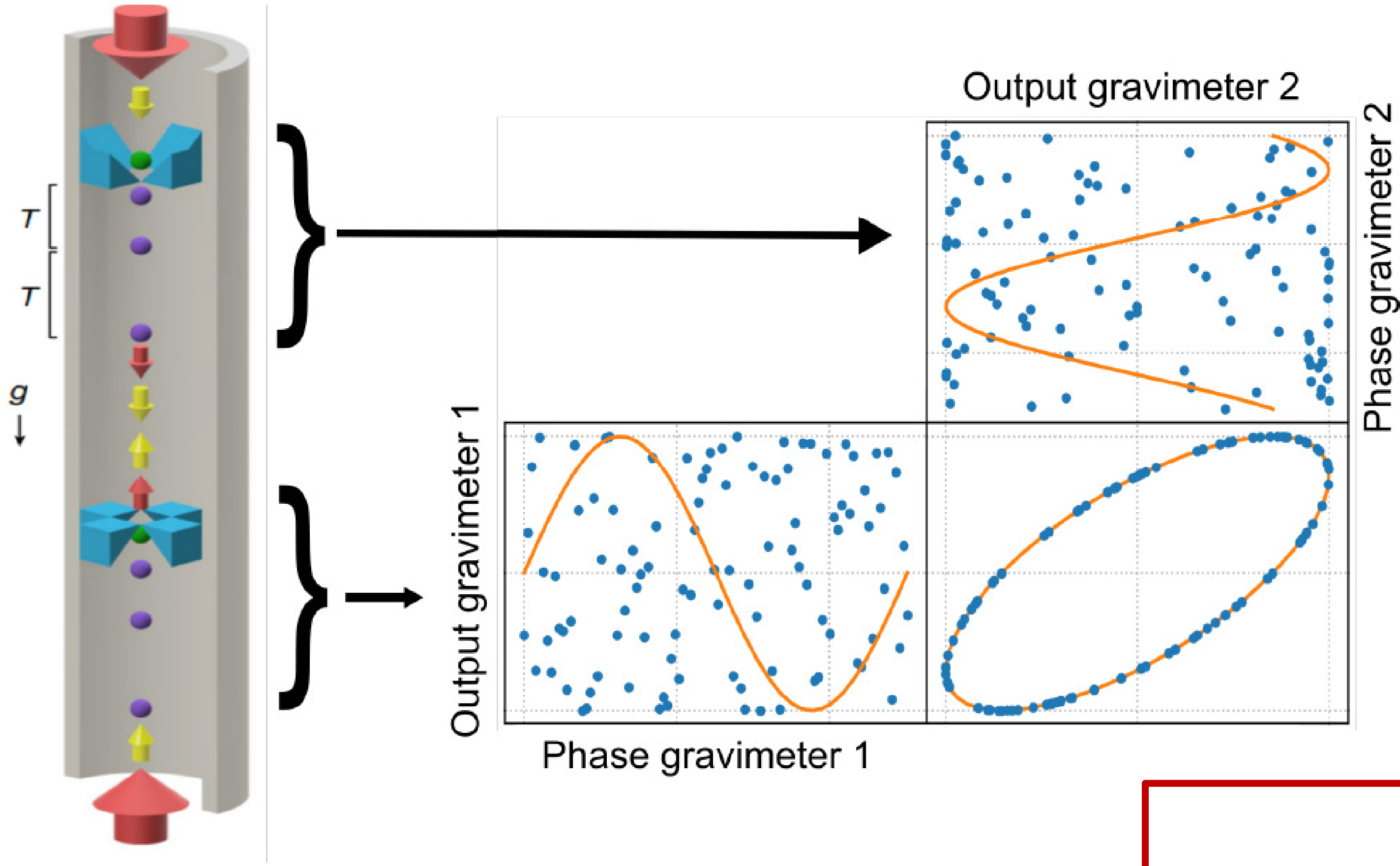
External noise sources

Unwanted additional contributions to the interferometric phase



Vibrations
Platform motion
External field influences
…

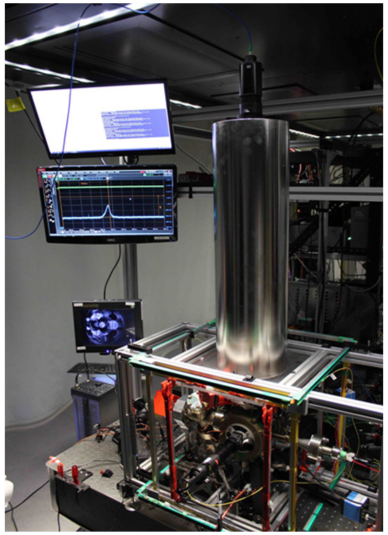
Gravity gradiometry

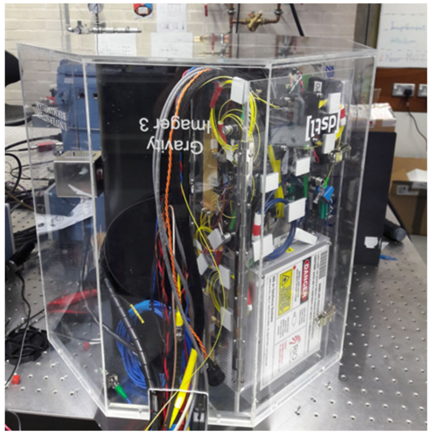


$$\sigma_{\nabla g} = \frac{\sqrt{2}}{2Ck_{\text{eff}}T^2L\sqrt{N}}$$

Increase baseline

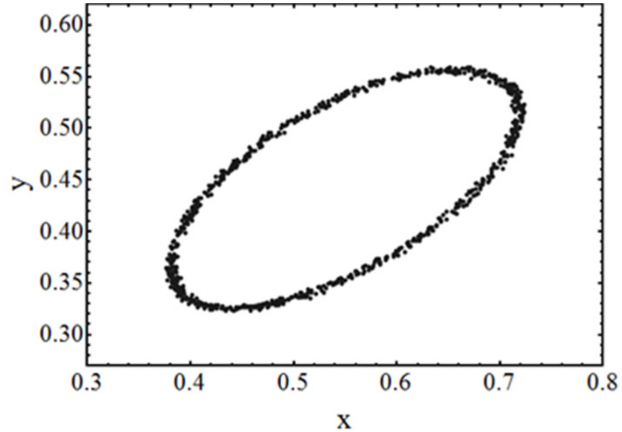
Atom interferometry at UoB





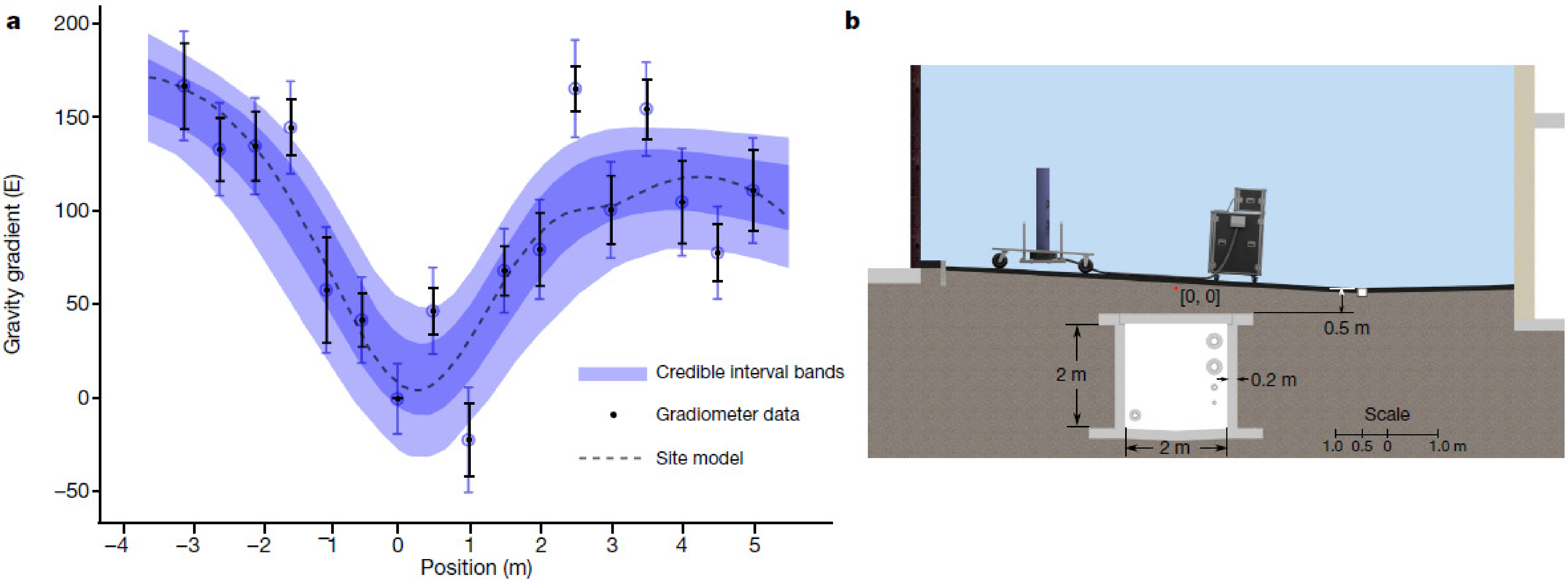
Top left: GGTOP. Top right: iSense project (EC collab.). Bottom: GI3 (DSTL).

Bottom: Field gravity gradiometer (DSTL, IUK, EPSRC). Right: Ellipse (11/2020)



Atom interferometry in the field

Detection of a real-world application feature at UoB



B. Stray et al., *Quantum sensing for gravitational cartography*, Nature 602, 590–594 (2022)

PART III.

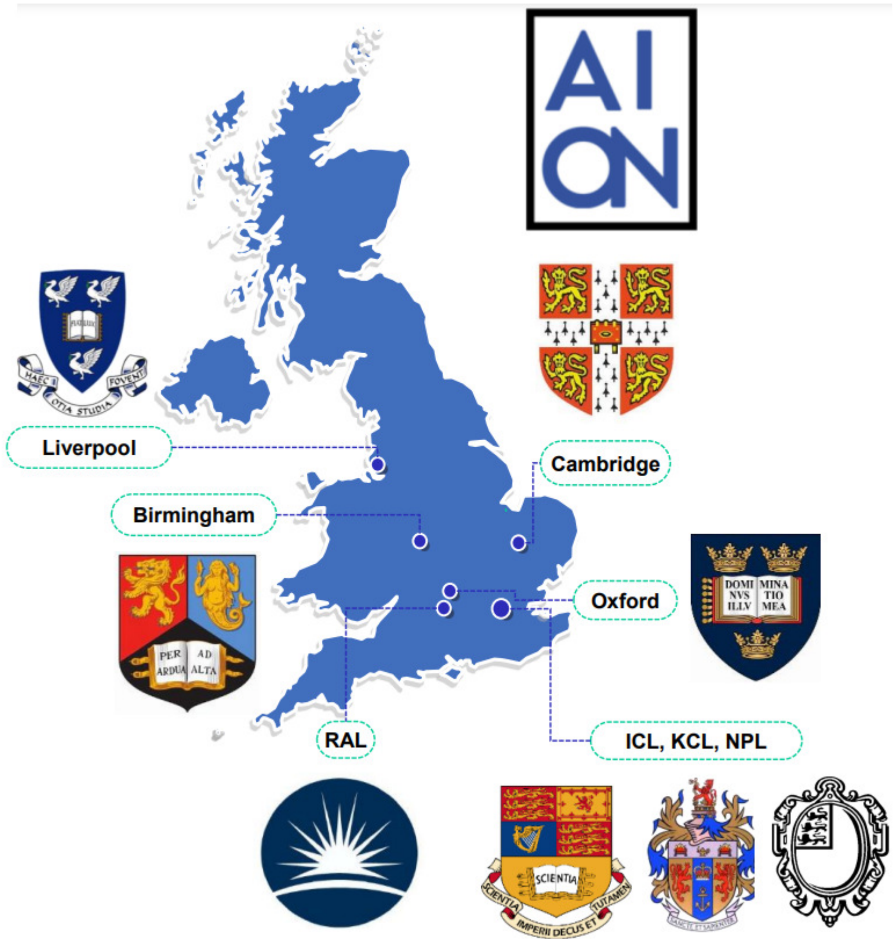
ATOM INTERFEROMETRY FOR FUNDAMENTAL PHYSICS: THE AION PROJECT

An Atom Interferometric Observatory and Network (AION)

Construct and operate an Atom Interferometric Observatory and Network (AION) that will :

- enable the exploration of properties of dark matter and searches for new fundamental interactions.

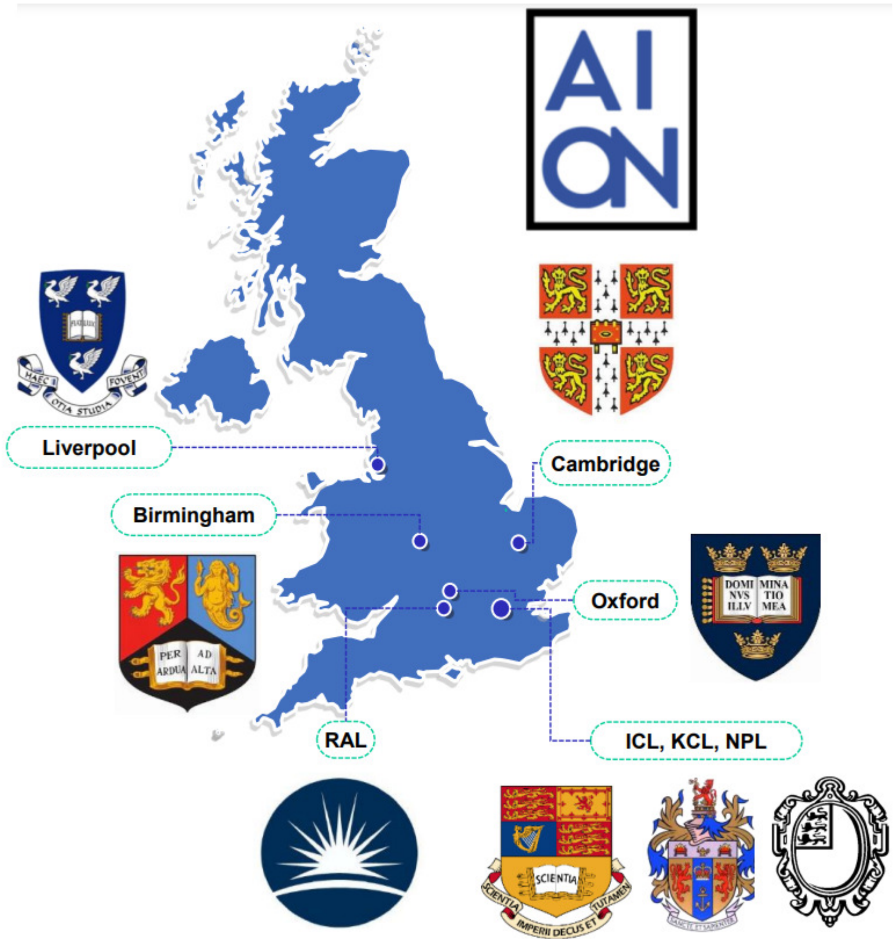
- provide a pathway towards detecting gravitational waves in the mid-frequency band [0:01 Hz - few Hz] where currently operating and planned detectors are relatively insensitive.



An Atom Interferometric Observatory and Network (AION)

Four stages corresponding to increased levels of performance:

- Stage 1: AION-10: 10m detector
- Stage 2: AION-100: 100m detector
- Stage 3: AION-1km: terrestrial 1km detector
- Stage 4: AION-SPACE: space detector



Detecting gravitational waves (GW)

Resonant mass antennas (AURIGA, EXPLORER, ALLEGRO…)

Laser interferometers (LIGO, VIRGO, LISA…)

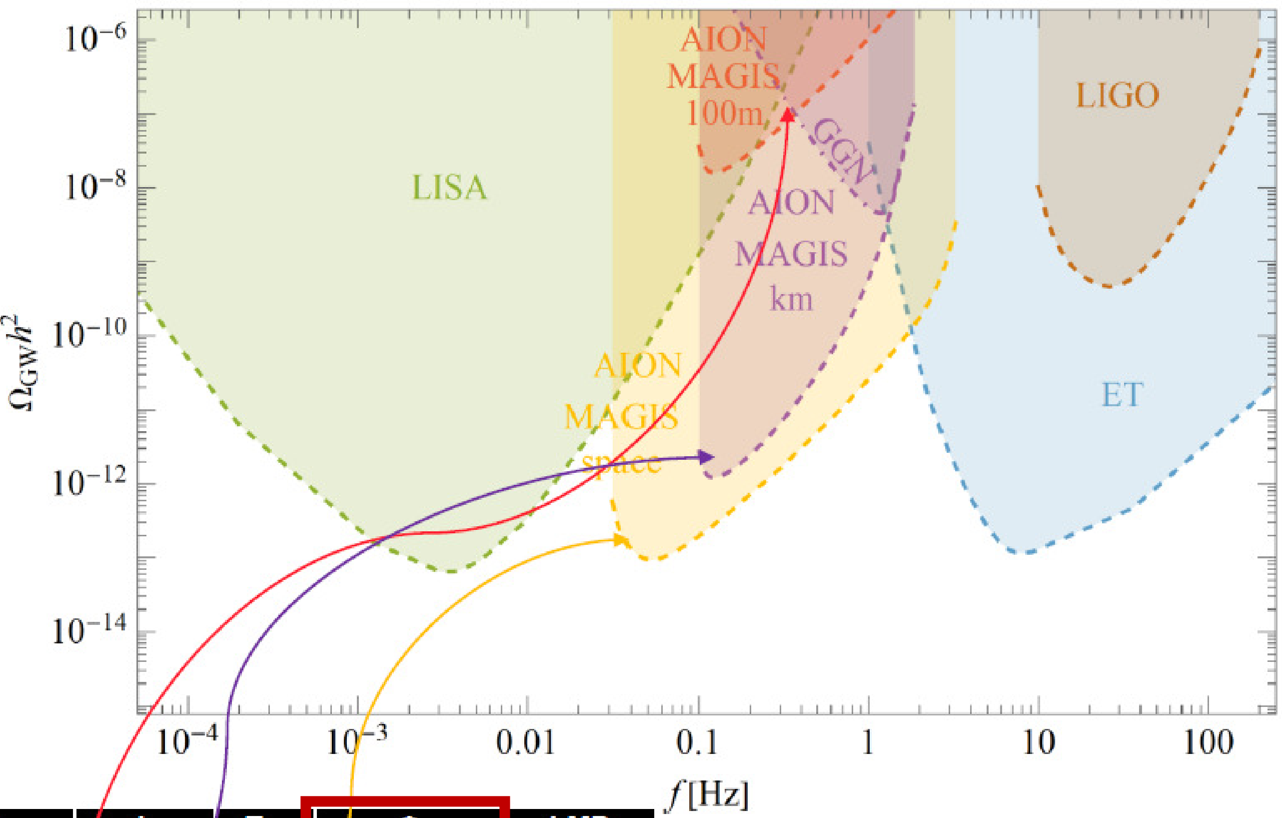
First detection of GW, 2015

Remain limited by low-frequency noise in the mid-frequency band [0.01-10 Hz].

Atom interferometers (MAGIS, AION…)

A passing gravitational wave is detected via the strain it creates in the space between the free-falling atoms.

Detecting mid-band gravitational waves

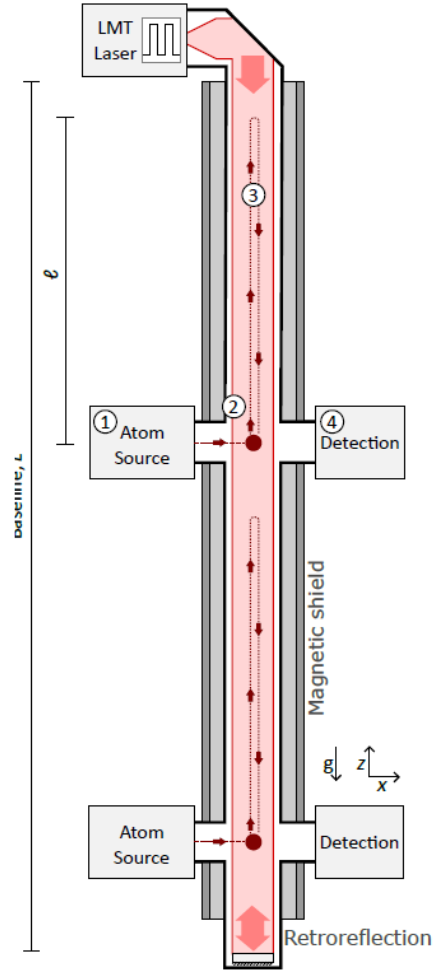


Sensitivity Scenario	L [m]	T_{int} [s]	Φ [1/√Hz]	LMP [#]
AION-100-today	100	1.4	10^{-3}	100
AION-100-ultimate	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000
AION-space	4.4×10^{7}	300	10^{-5}	<1000

Probing ultralight dark-matter (DM)

As of today, theoretical extensions of the standard model provide many candidate particles for DM, yet there has been no positive experimental result.

→ Reveal the nature of DM / blueprint a new method to probe the associated theoretical frameworks

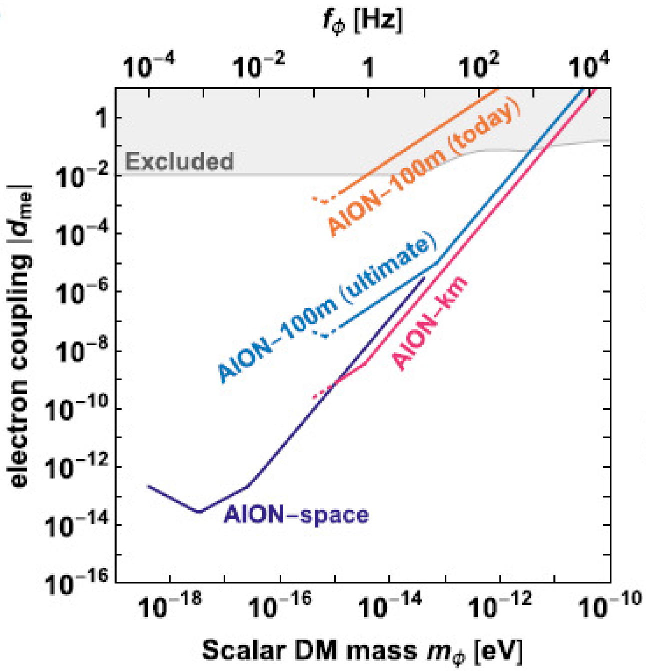


Ultralight dark-matter induces a small time-dependent perturbation to the atomic transition frequencies.

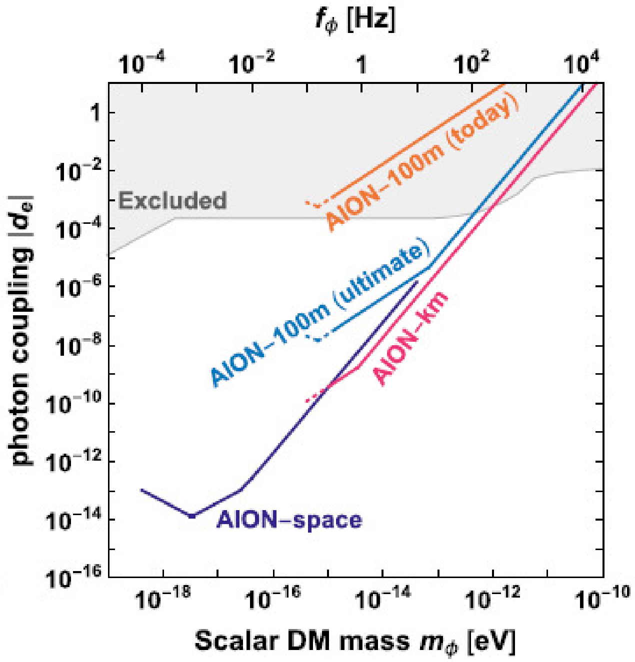
Since the laser interacts with the separate interferometers at different times due to the light propagation delay, this perturbation will be observable as fluctuations in the differential phases accumulated by the separate interferometers.

Probing ultralight dark-matter

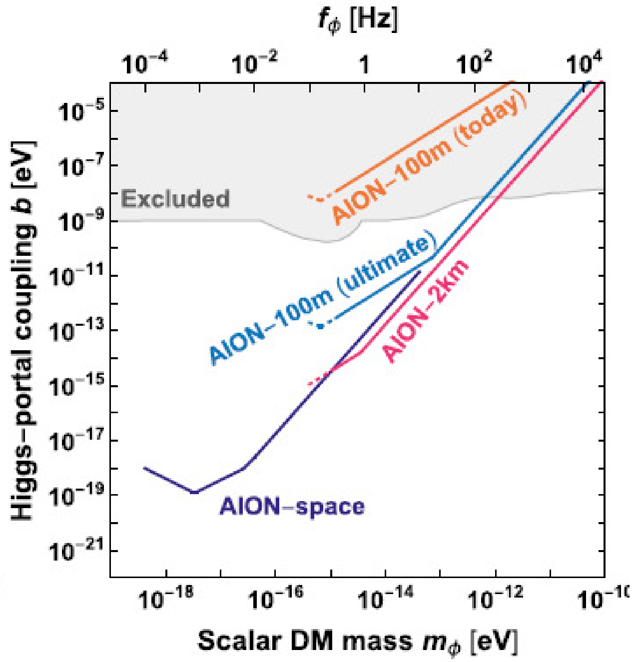
Coupling to e



Coupling to photon



Higgs Portal b coupling



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

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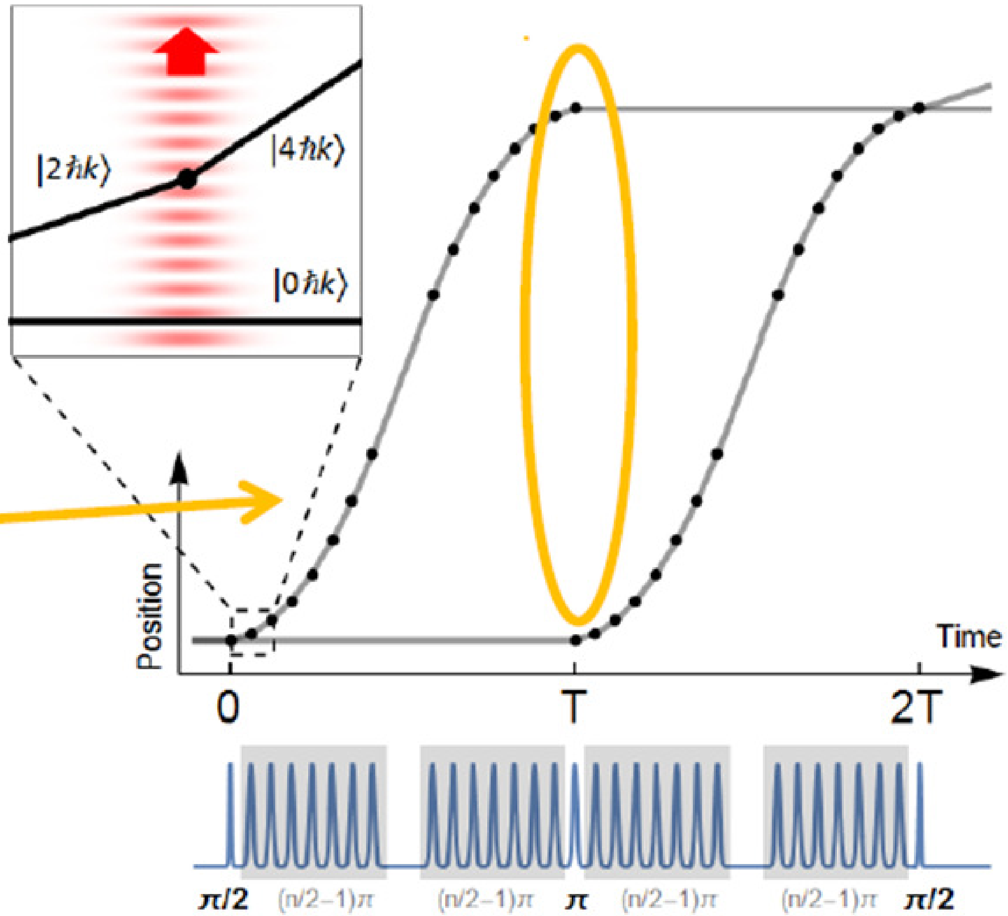
Large-momentum transfer (LMT) interferometry

Increasing the momentum separation by applied successive light pulses

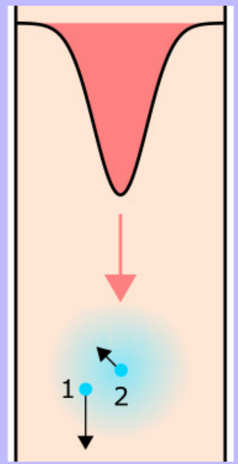
Nhk momentum splitting

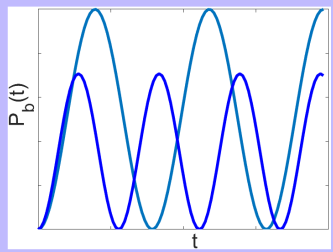


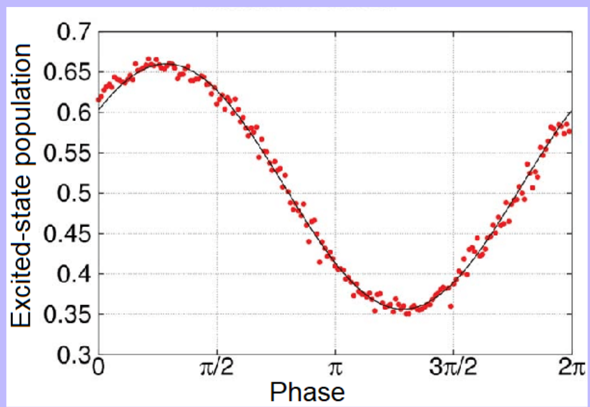
<u>Challenge:</u> each light pulse must have a >99.9% efficiency !

Large-momentum transfer (LMT) interferometry

Contrast losses





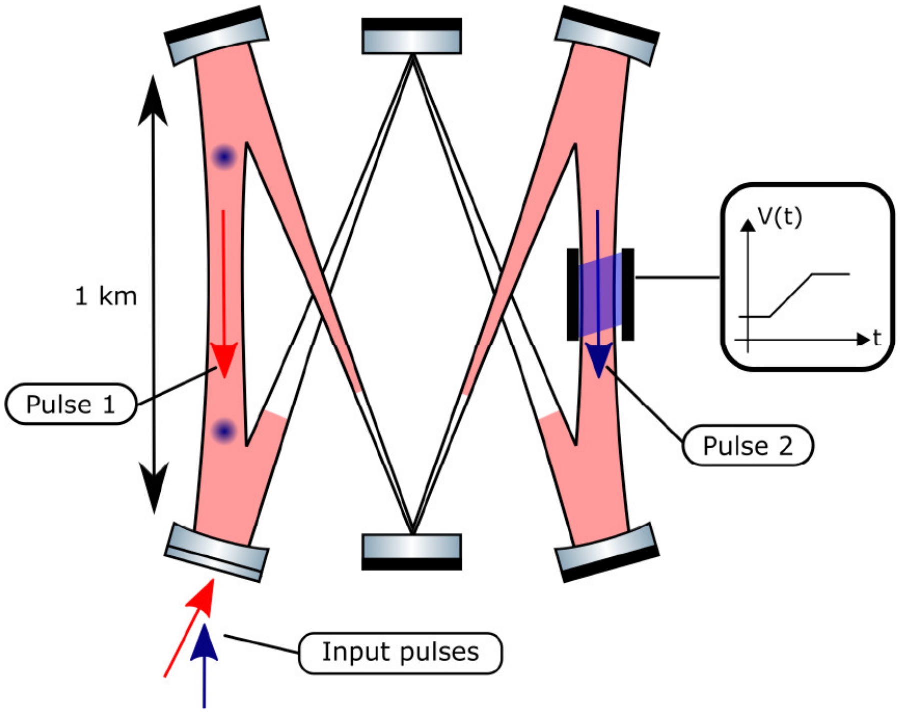


Very large beams/small clouds
Ultracold temperatures
High laser power

	AION 10 (goal)			AION 100 (goal)		
Scheme	689nm	698nm		689nm	698nm	
Beam diameter (mm)	10-20	10		-	50	
Temperature (nK)	0.1 - 1	1	0.1	-	1	0.1
Laser power (W)	> 20	A few 100	A few 1	-	135k	5k

Enhanced atom-optics

Cavity-based interferometry

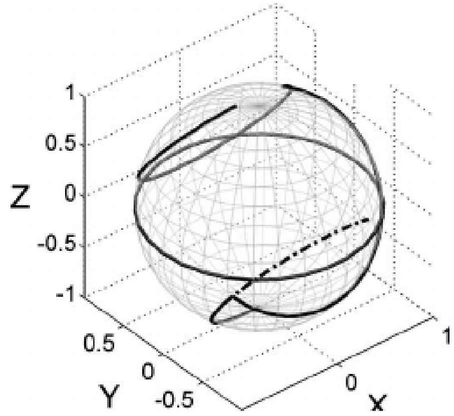


R. Nourshargh, S. Lellouch, S. Hedges, M. Langlois, K. Bongs, M. Holynski, Circulating pulse cavity enhancement as a method for extreme momentum transfer atom interferometry. *Communications Physics* 4, 257 (2021).

Advanced pulse techniques

Composite pulses

Experimental trials at UoB



Floquet atom-optics

Wilkason T, Nantel M, Rudolph J, et al. Atom interferometry with floquet atom optics. Phys Rev Lett. 2022;129:183202.

Shaped pulses

Lellouch et al. *EPJ Quantum Technology* https://doi.org/10.1140/epjqt/s40507-023-00165-2

THANK YOU!