QUANTUM SENSORS

Tutorial

Prof. Kai Bongs
Institutsdirektor QT

DLR-Institut für Quantentechnologien
Wilhelm Runge Straße 10
89081 Ulm

DLR

GERMAN AEROSPACE CENTER (DLR)

Research, technology and knowledge transfer for a sustainable future and to strengthen Germany as a location for science and business

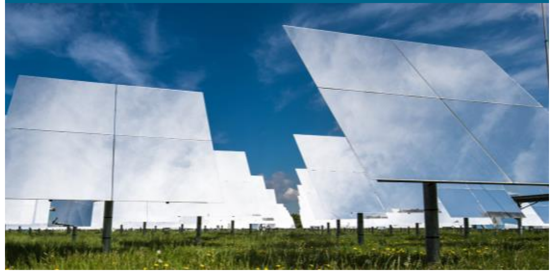
DLR

Research Center + Space Agency + Project Management

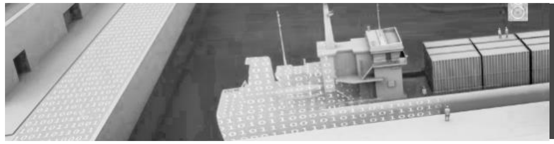
AERONAUTICS

SPACE

ENERGY



TRANSPORT



SECURITY
civil security & defence research

DIGITALISATION, QUANTUM TECHNOLOGY AND SYSTEM MODELLING

- Europe's largest research centre for aeronautics and space
- Close cooperation with academia, research, business and industry
- BMWK is the primary funding ministry, BMVg provides institutional funding, BMI, BMU and others provide project funding

DLR sites

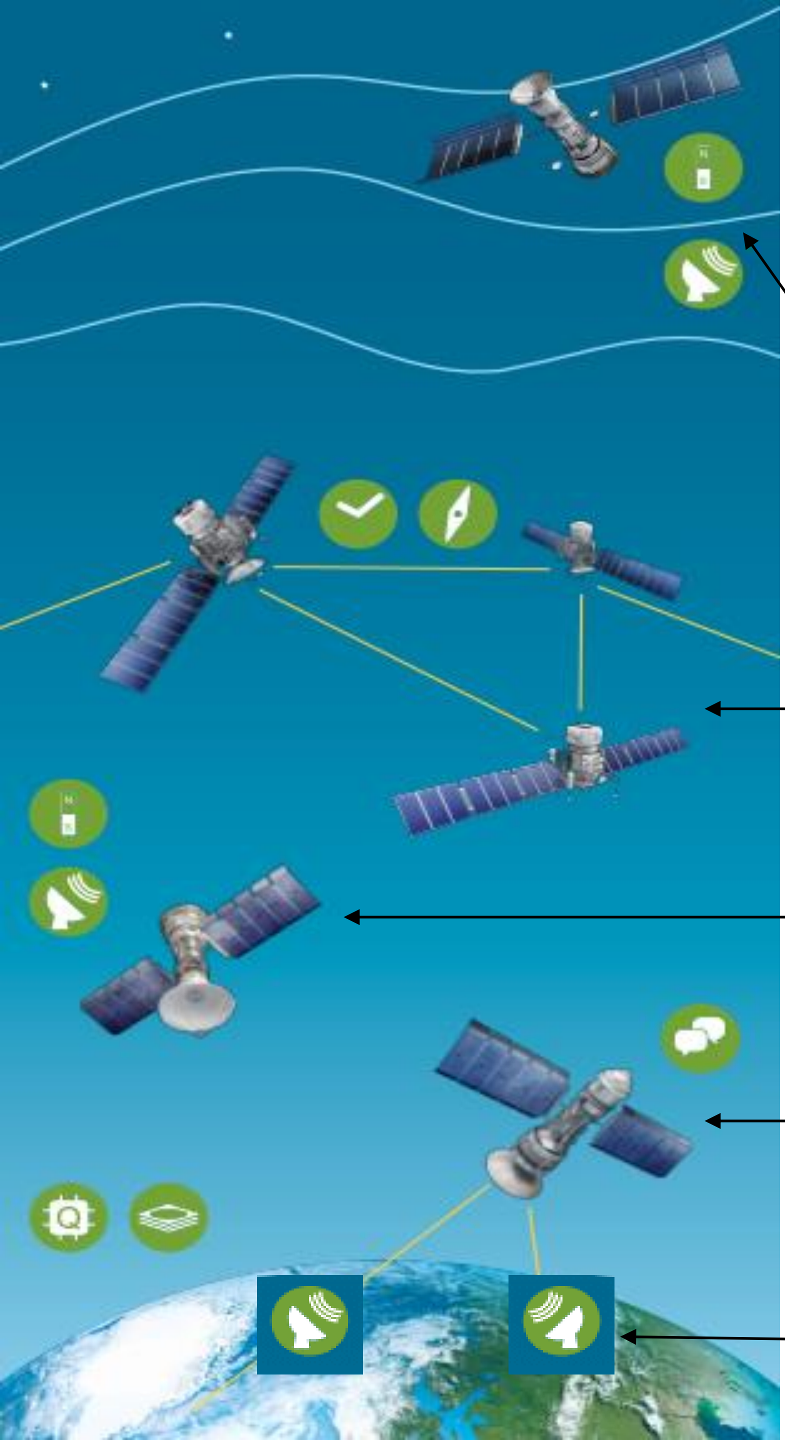
- **54 institutes and facilities across 30 sites**
  - 8 research stations
  - 4 international offices
- **More than 10.000 employees**
  - ~ 5.800 Scientific Staff
- **Budget: ~ 1.100 Mio. €** (2021)
  - ~ 550 Mio. Third-Party Funding

DLR Institute for Satellite Geodesy and Inertial Sensing

DLR Institute for Quantum Technologies

Quantum Technology Institutes
(also: DLR Quantum Computing Initiative)

DLR Institute for Communication and Navigation
Galileo Competence Center



Institute for Quantum Technologies

Quantum technologies for Space

Data for ionosphere-troposphere-models
(quantum magnetometers and accelerometers)

Global Navigation Satellite Systems, resilient time
(quantum clocks)

Earth observation, resilient communication
(quantum RF receivers)

Gobal networks with advanced quantum functionality
(quantum communication, authentication, client computing)

Space traffic management, Space asset monitoring
(Quantum oscillators and clocks for radar)

UN proclaimed 2025 as:

INTERNATIONAL YEAR OF
Quantum Science
and Technology

100 years of quantum is just the beginning...

International Year of Quantum Science and Technology (quantum2025.org)

Quantum Science, how it started

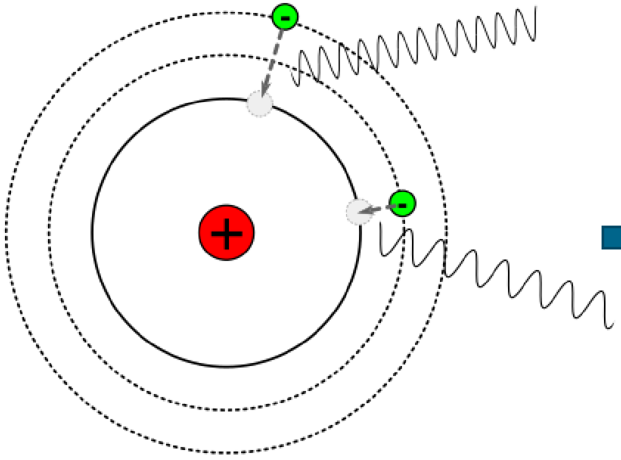
1900: Thermal radiation

Planck postulate: Electromagnetic energy can only be emitted in quantized form

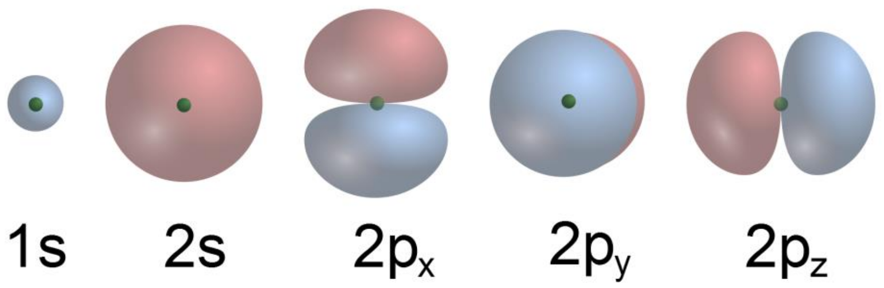
$$E = h\nu$$

Quantum Waves

~1925: Wave-particle duality as central concept in quantum mechanics

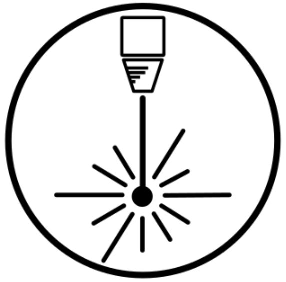


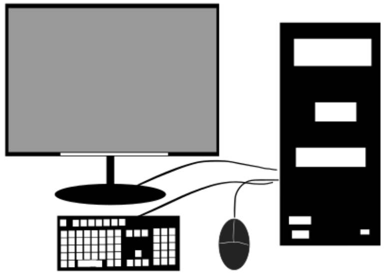
Bohr‘s atom model

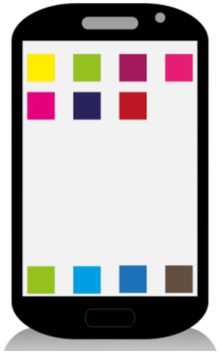


Quantum 1.0

Technology based on quantum mechanical understanding of condensed matter







Massive economic impact!!!
→ High expectations for Quantum 2.0

What are Quantum Technologies?

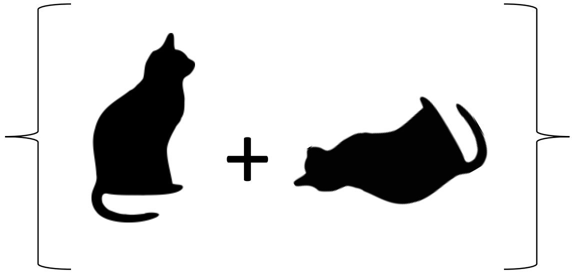
Definition from EU QT Flagship

→ Quantum 2.0: Technologies using quantum superposition and/or quantum entanglement

Quantum 2.0

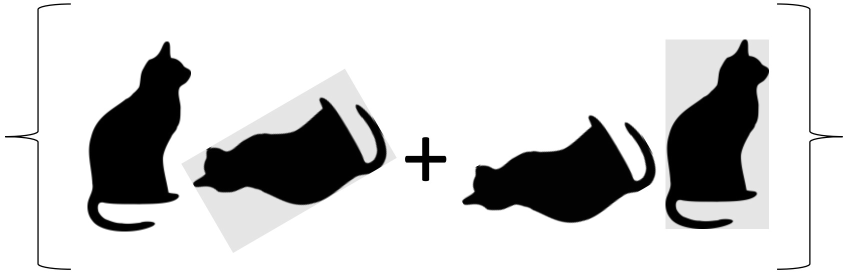
Superposition and Entanglement

Superposition



Particles simultaneously in several states
→ Schrödinger cat

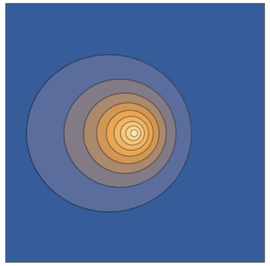
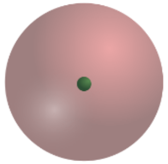
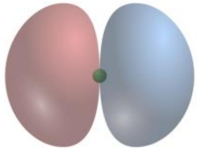
Entanglement



„Superposition involving several particles“

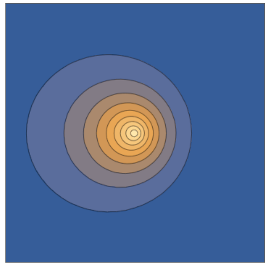
Example: Superposition in an Atom

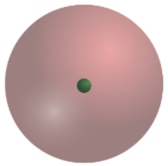
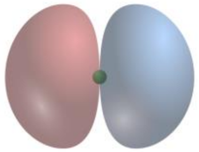
Oscillating Electron Cloud

 $= \frac{1}{\sqrt{2}} \Big\{$  $+$  $e^{-i\frac{\Delta E}{\hbar}t} \Big\}$

Example: Superposition in an Atom

Oscillating Electron Cloud



$= \frac{1}{\sqrt{2}} \Bigg\{$  $+$  $e^{-i\frac{\Delta E}{\hbar}t} \Bigg\}$

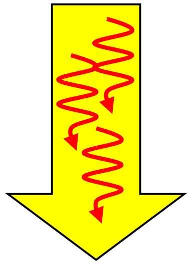
Mapping of Observables onto Frequency outputs

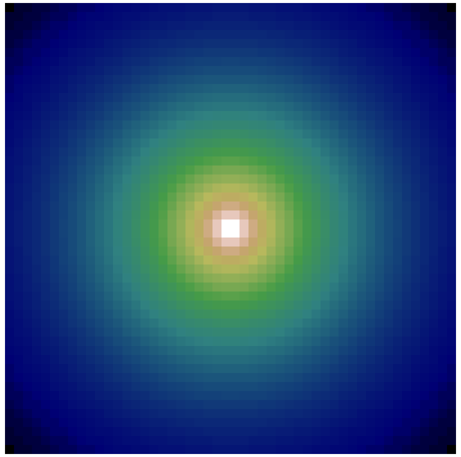
→ Clocks are a natural quantum technology

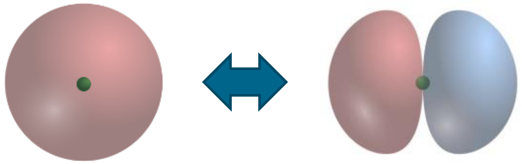
→ Clocks are fundamentally needed for referecing in all measurements (can be internal in differential configurations)

Creation of Superposition

Electromagnetic Wave - Atom Interactions

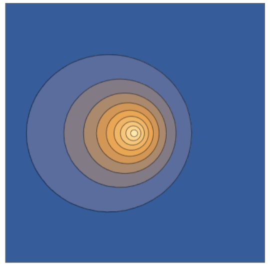






How does a Quantum clock work?

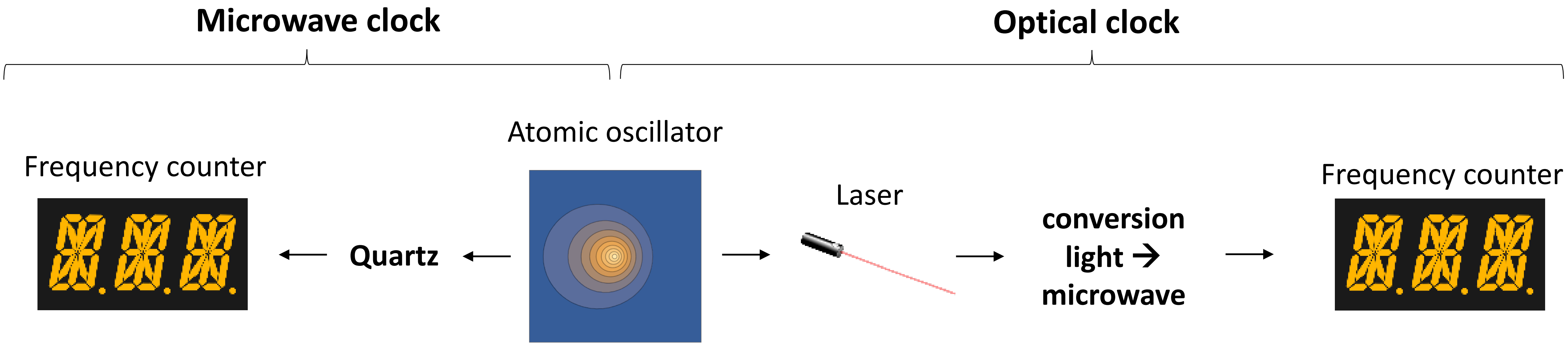
In a quantum clock an atom replaces the oscillator of a classical clock



Reproducible and precise

Microwave clocks (old) and optical clocks (new)

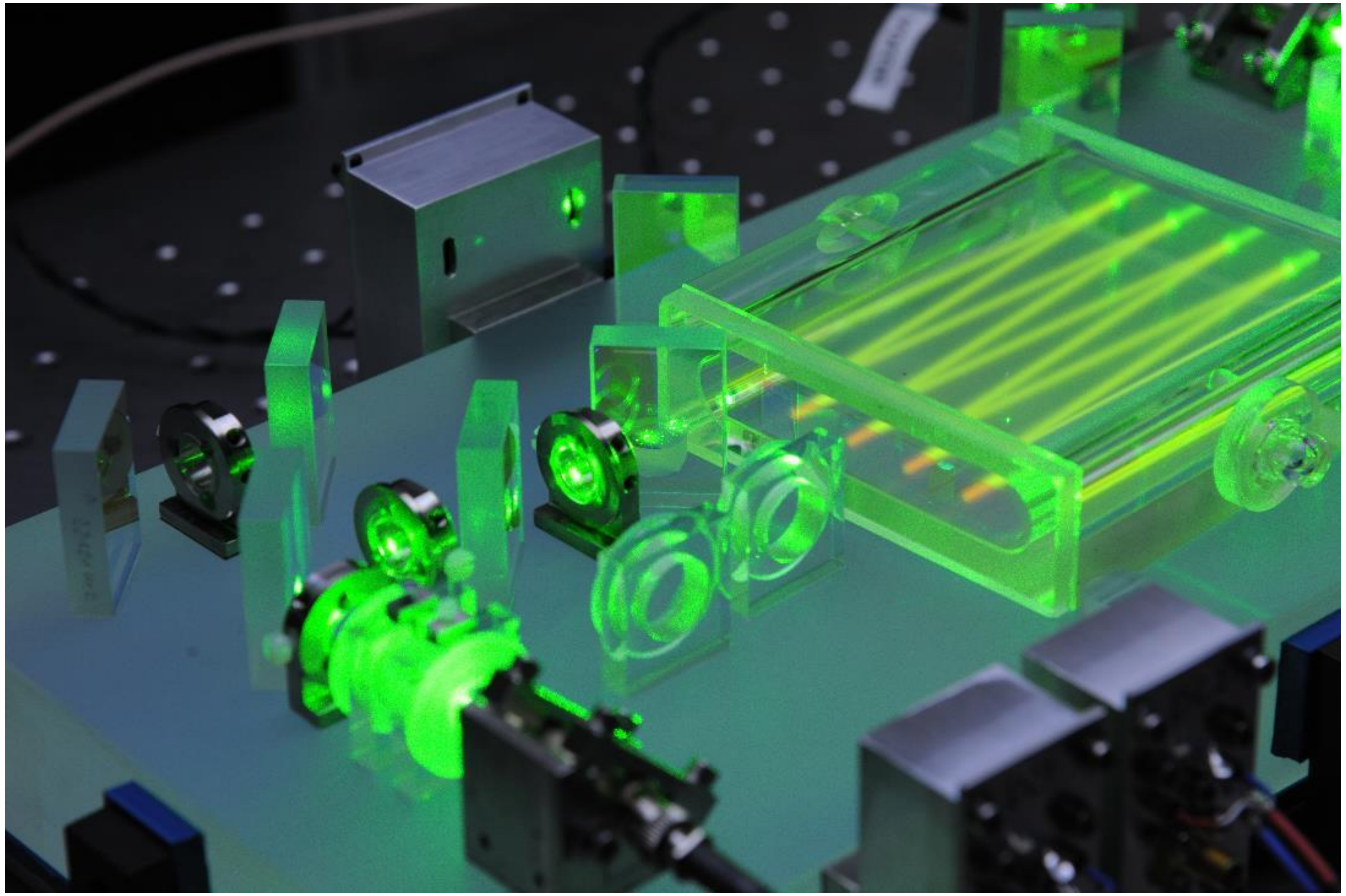
Optical clocks allow higher precision and faster synchronization



Disruptive: 100x better synchronisation as compared to GNSS
Lower phase noise than Quartz-oscillators

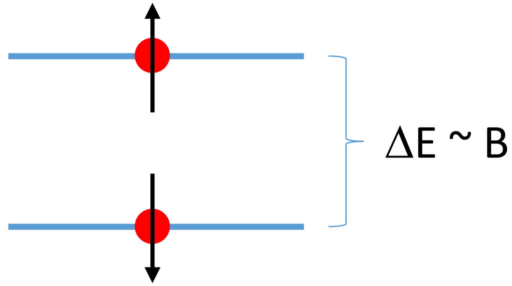
This is how it looks like

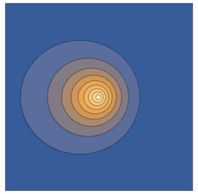
DLR Iodine clock



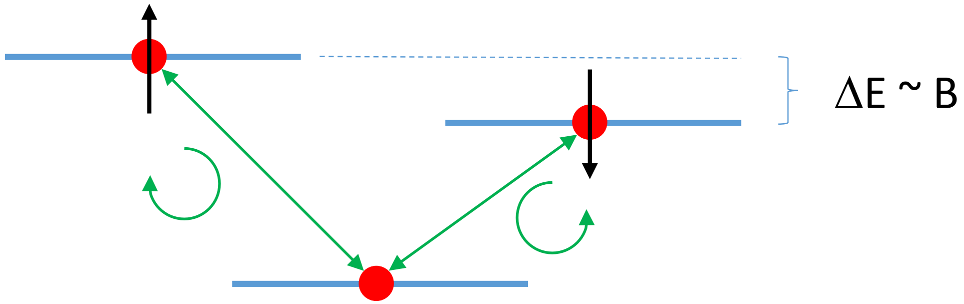
Quantum Magnetometers

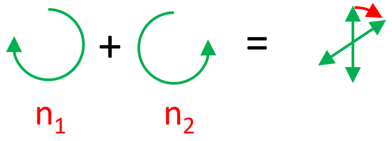
Superposition of energy levels depending on external magnetic field





Oscillation frequency depends on magnetic field

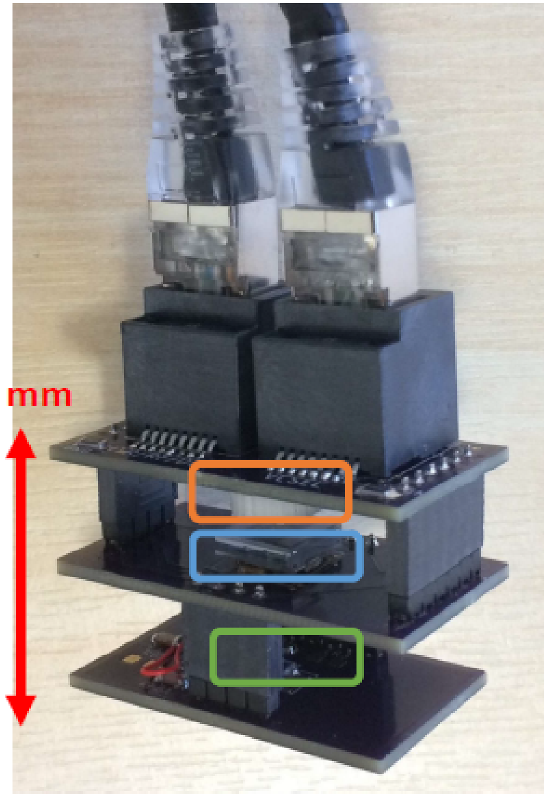




Rotation of polarization

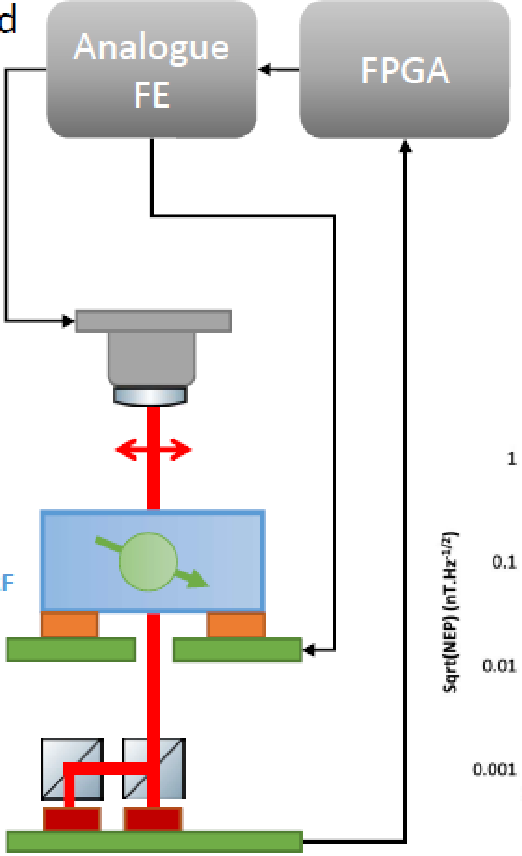
Miniaturisation of atomic magnetometers

University of Strathclyde Science



28 mm

- 75 cm³ sensor head
- 60 g weight
- 5 W power

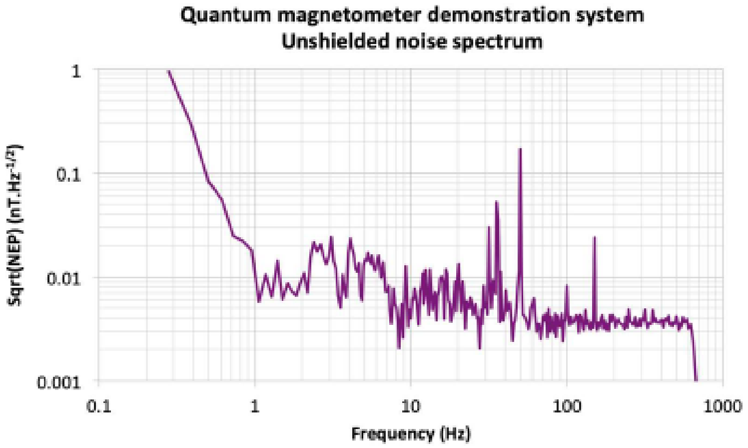


895 nm VCSEL with thermal feedback

^{133}Cs vapour cell & B_{RF} coils

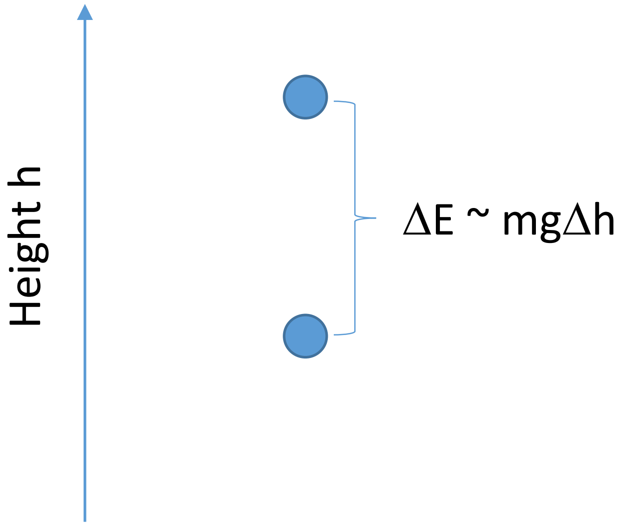
Balanced polarimeter

- High sensitivity
  - ~$pT.Hz^{-1/2}$
  - 0.1 ppm in Earth's field

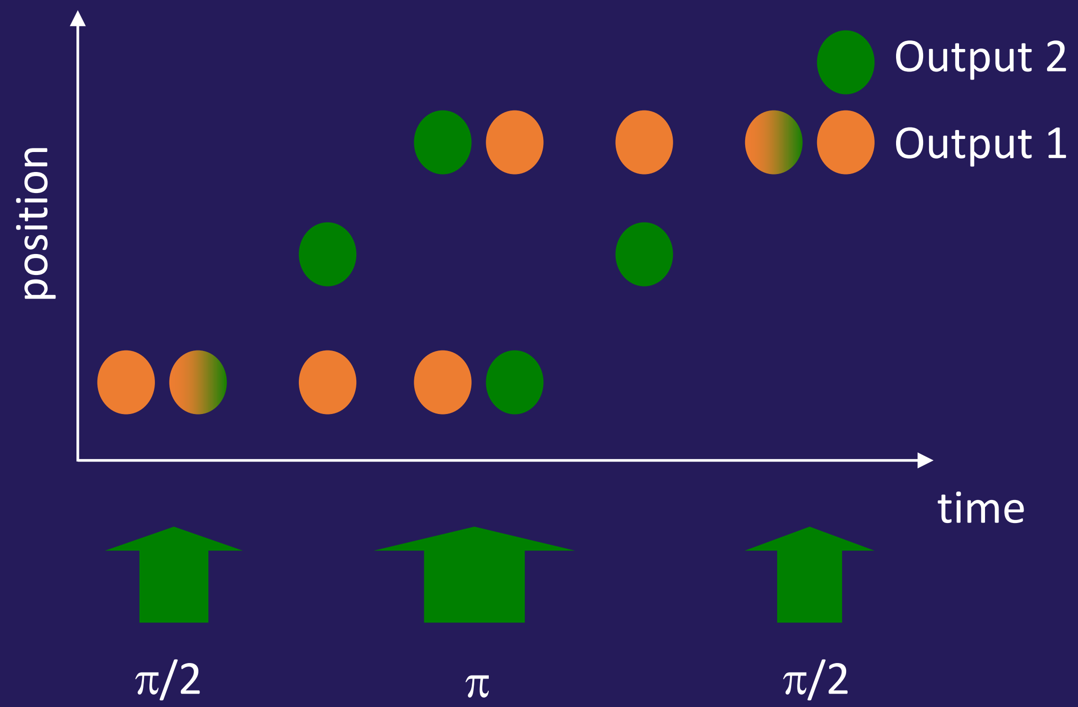


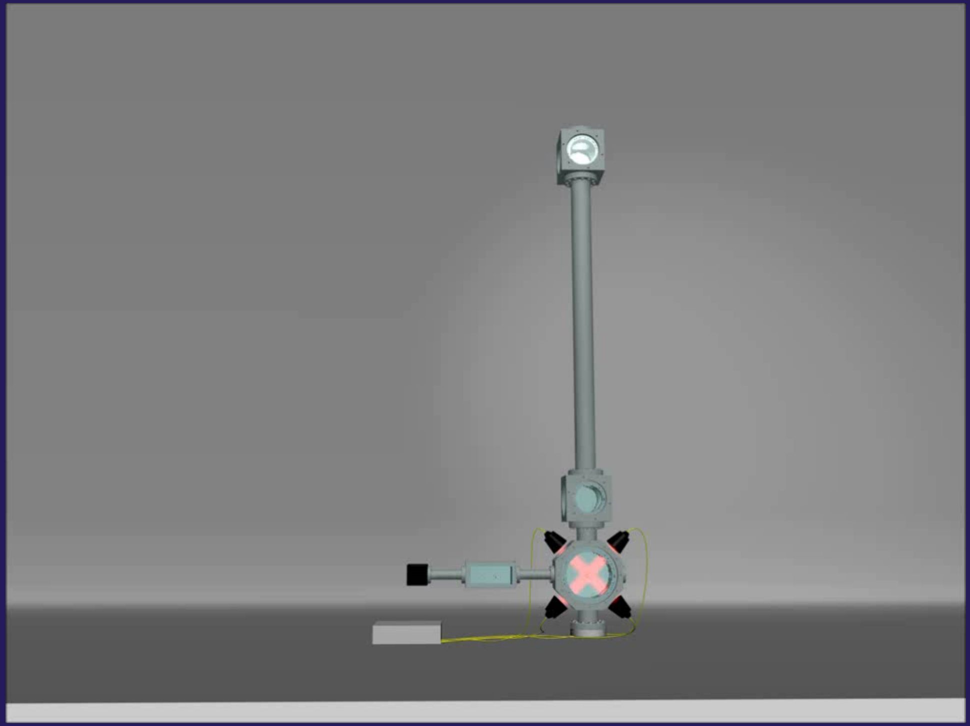
Quantum Gravimeters / Inertial Sensors

Potential difference leads to different phase evolution



Atom Interferometer





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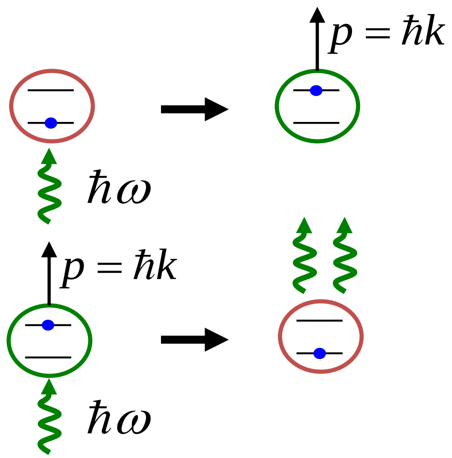
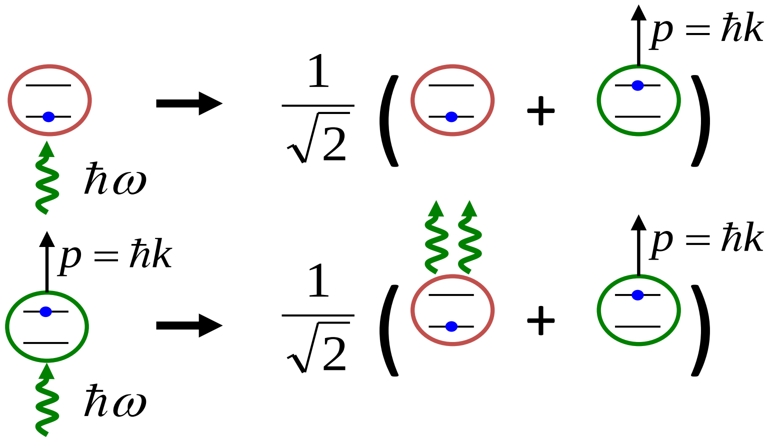
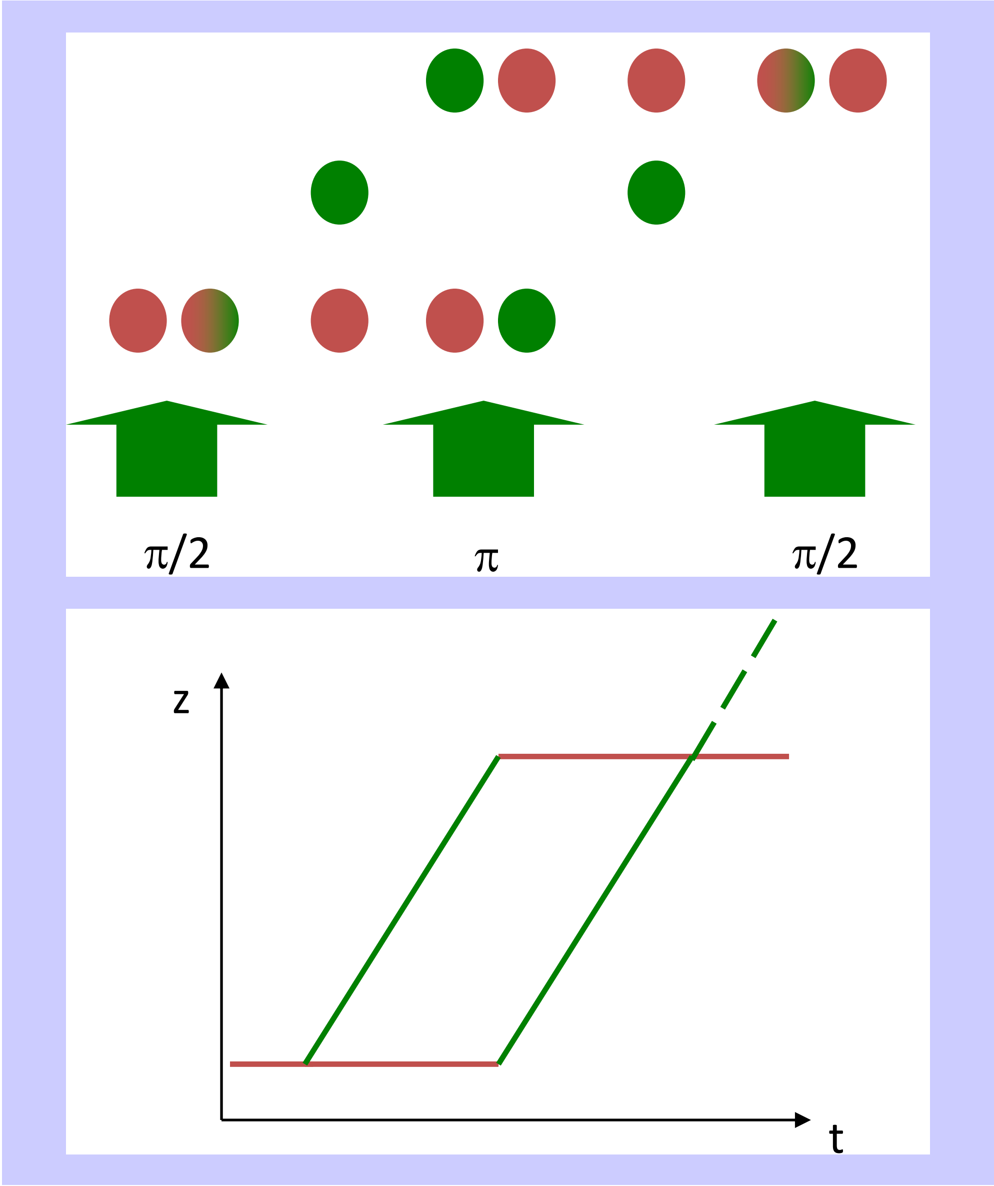
Light pulse atom interferometer

π- pulse -> mirror



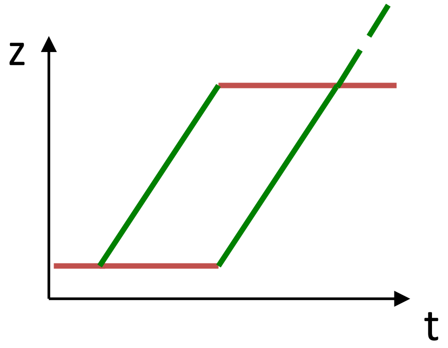
π/2- pulse -> beam splitter



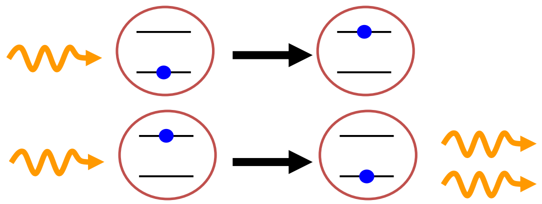


Phase Contributions

$$\Delta\Phi_{total} = \Delta\Phi_{laser} + \Delta\Phi_{prop} + \Delta\Phi_{sep}$$



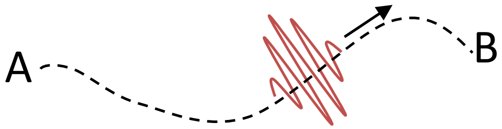
– imprinted laser phase, $\Delta\Phi_{laser}$



$$\Delta\Phi_{laser} = \vec{k} \cdot \vec{r}$$

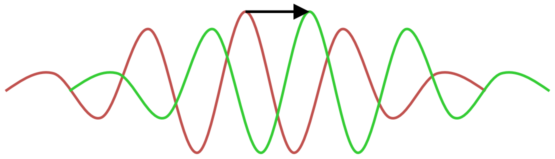
$$\Delta\Phi_{laser} = -\vec{k} \cdot \vec{r}$$

– propagation phase, $\Delta\Phi_{prop}$



$$\Delta\Phi_{prop}(AB) = \tfrac{1}{\hbar} S_{cl,AB} = \tfrac{1}{\hbar} \int_{t(A)}^{t(B)} L[\vec{r}(\tau), \vec{v}(\tau)] d\tau$$

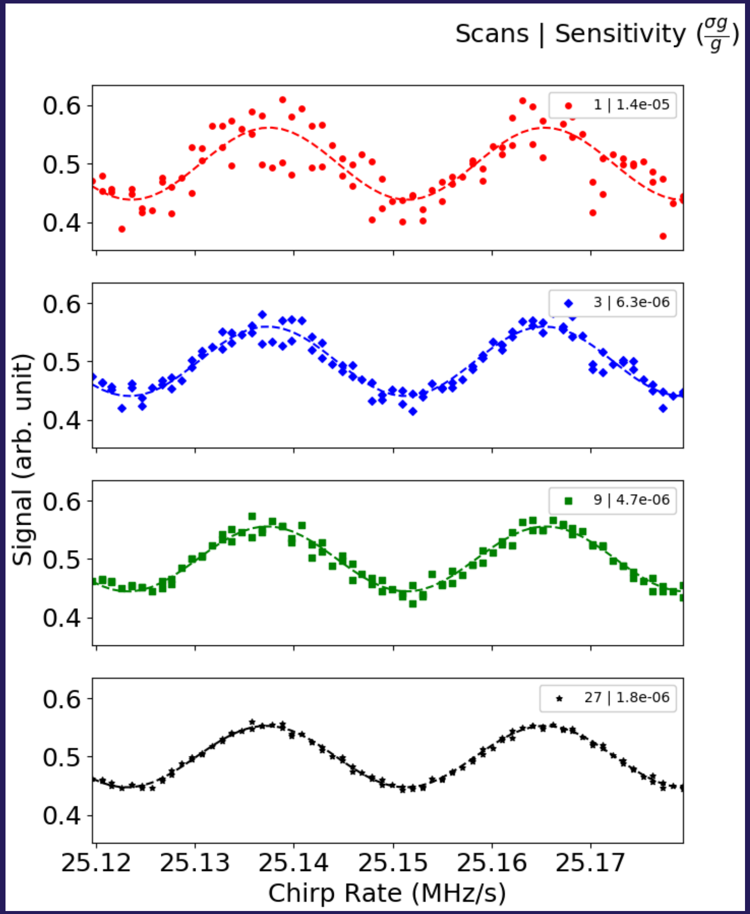
– separation phase, $\Delta\Phi_{sep}$



$$\Delta\Phi_{sep} = \frac{m\vec{v} \cdot \Delta\vec{r}_{sep}}{\hbar}$$

P. Storey and C. Cohen-Tannoudji, Journal de Physique II, T.4, 1999 (1994)
E. J. Heller, J. Chem. Phys. **62**, 1544 (1975)

Atom interferometer output signal



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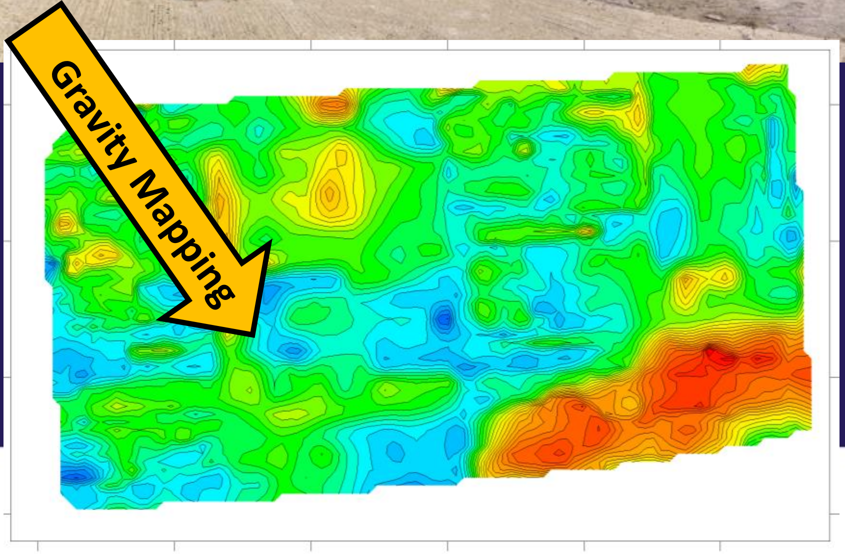
Microgravity Surveys and their Limitations

Example: Brown Field Site Survey



Classical microgravity sensors are sufficiently sensitive to deliver useful information!

BUT:
They take 5-10 min/measurement point

Sensor drift needs to be corrected by periodically returning to a calibration point

In this example: 1 month for 1 ha with 3 sensors and 4 persons

→ Commercial uptake hindered by cost of operation, not the sensitivity of the instrument

RSK

UNIVERSITY OF BIRMINGHAM

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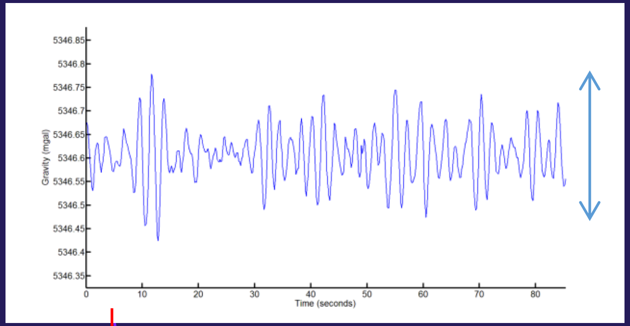
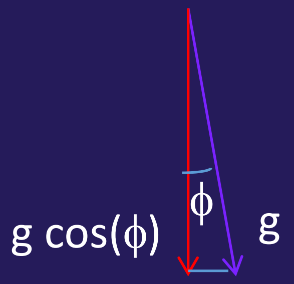
Why do Gravity Measurements take so much Time?

- Acceleration vs gravity



30-100 ng → Minutes / point

- Tilt



→ 0.001° alignment

Requirement to achieve 1 ng

Better gravity sensors only provide calibration benefits, not lower measurement time/point !!!

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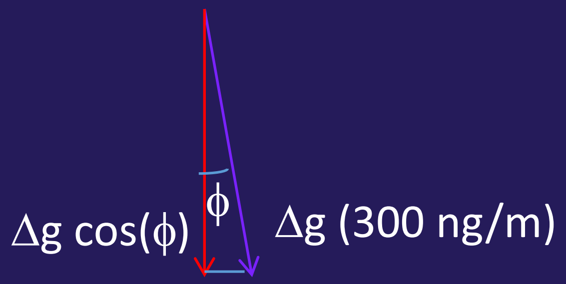
Solution: Gravity Gradiometry

- Suppression of Accelerations
- Reduced Tilt Sensitivity



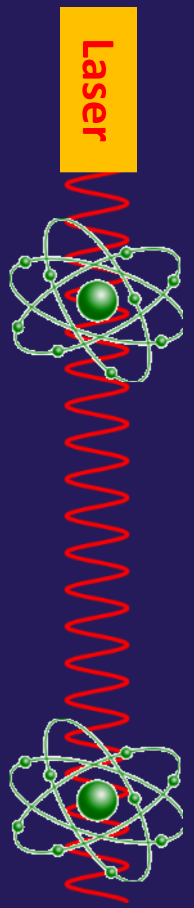
Requirement to achieve 1 ng/m

As fast as your instrument
→1 s / point

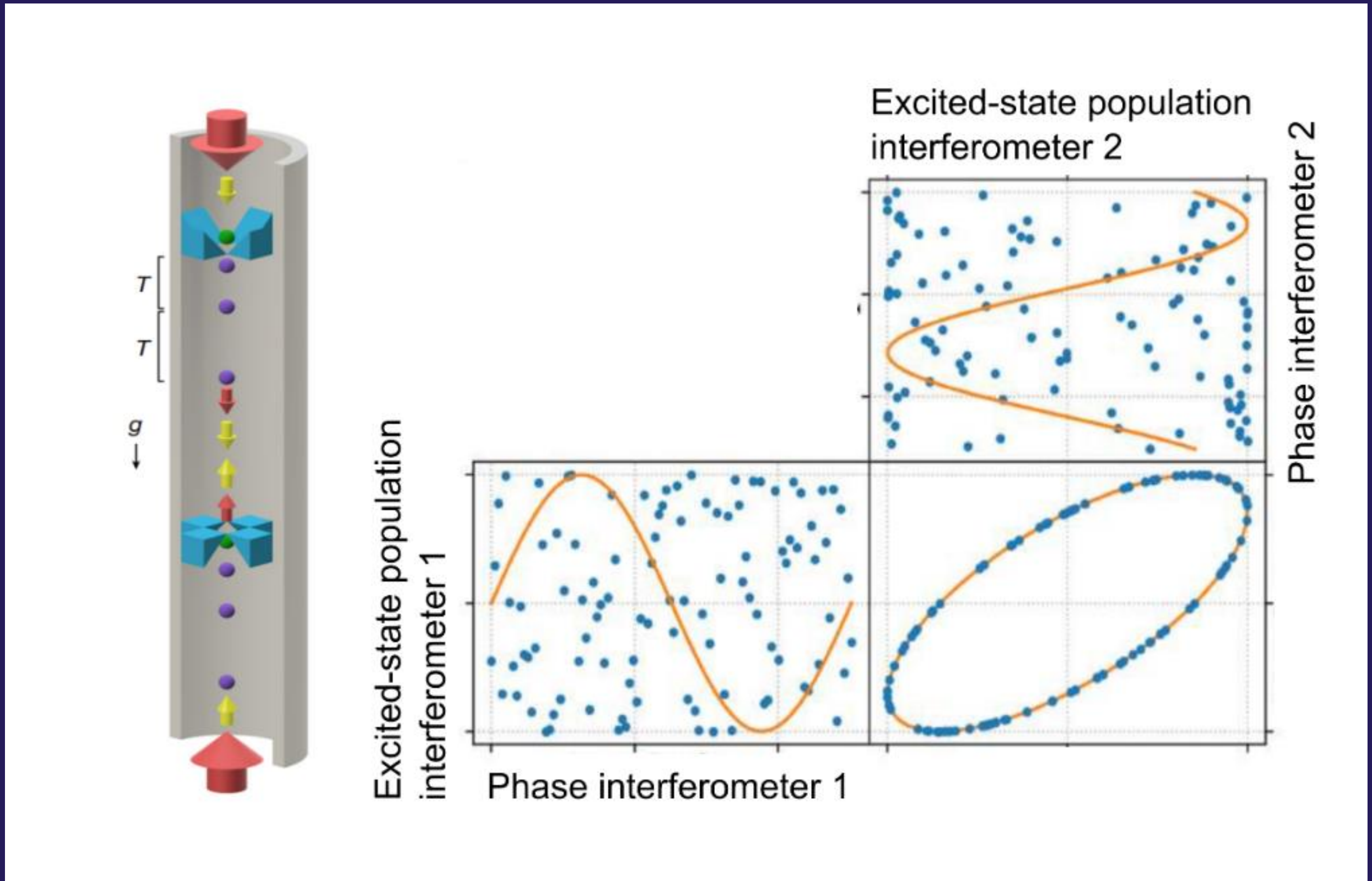
3° alignment

Common laser beam

Near-Perfect acceleration suppression and alignment in Atom Interferometry



Solution: Gravity Gradiometry



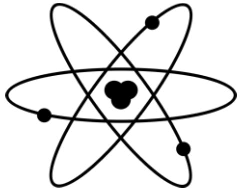
Common laser beam

Near-Perfect acceleration suppression and alignment in Atom Interferometry

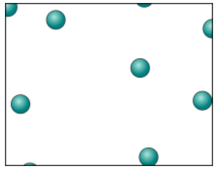
Nature **volume 602**, pages590–594 (2022)

Ingredients for Quantum Technologies

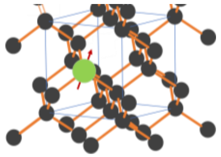
Quantum Particles + Control



Atoms / Ions

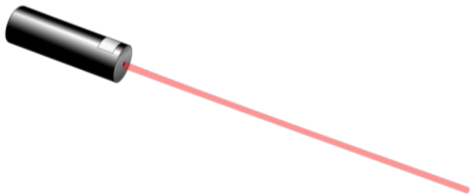


Natural Atoms

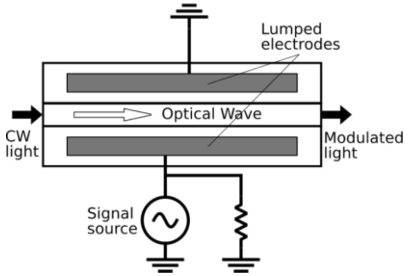


Artificial Atoms

Photons



Laser- or RF Pulses



Nonlinear crystals
Photonics

Electronics
Software
Shielding
Packaging
User interface
...

Techology Considerations

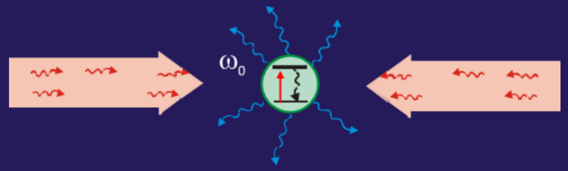
Photons versus radio waves

- Radio waves:
  - Standard electronic integration technologies
  - Cryogenics required to avoid thermal background and excitations

- Photons:
  - Operation at quantum level at room temperature possible
  - Photonic integration technologies required to drive cost down.

Requirements for Laser Systems

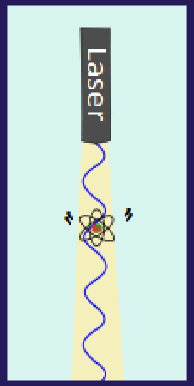
Laser Cooling – need to address atomic transition

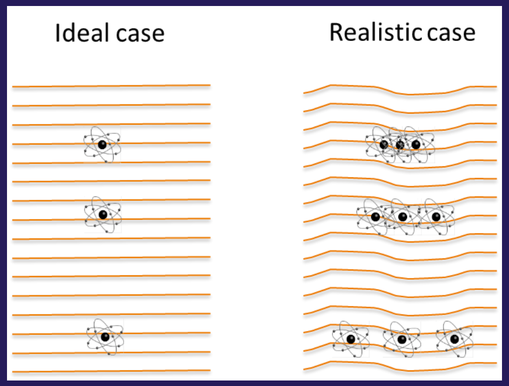


→ Laser linewidth and absolute frequency stability < MHz (<natural linewidth)
→ For red cooling transition in Sr <kHz !

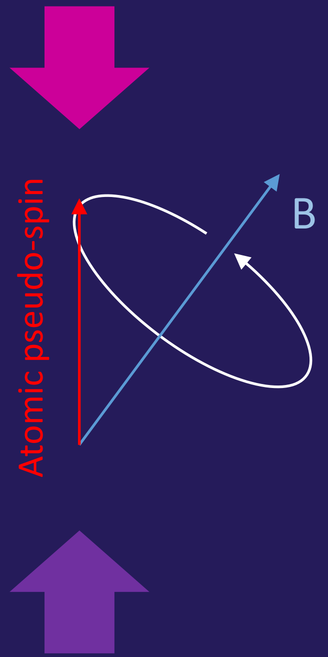
Atomic State Manipulation

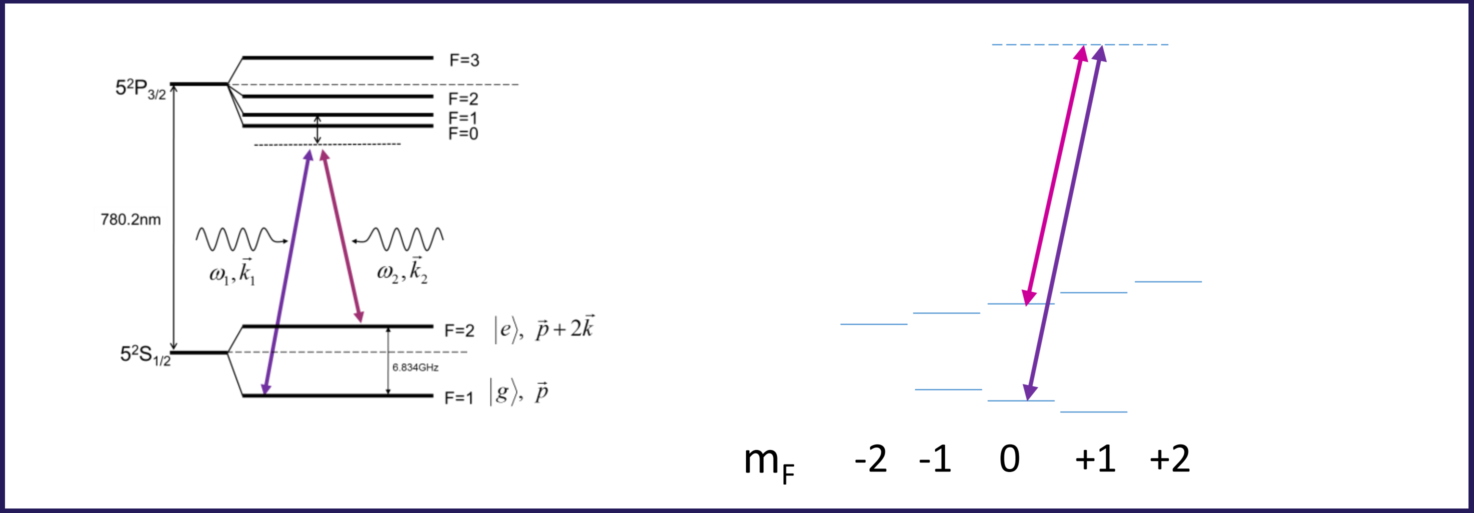
→ Linewidth depends on order of transferred momenta and pulse length
→ Potentially Hz-level required
→ Wavefront flatness to achieve <mrad fluctuations





Quantisation Field Alignment





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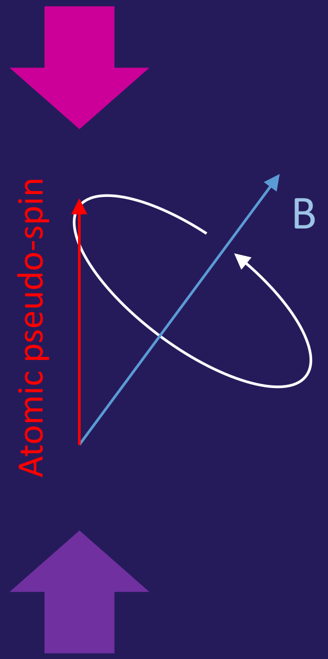
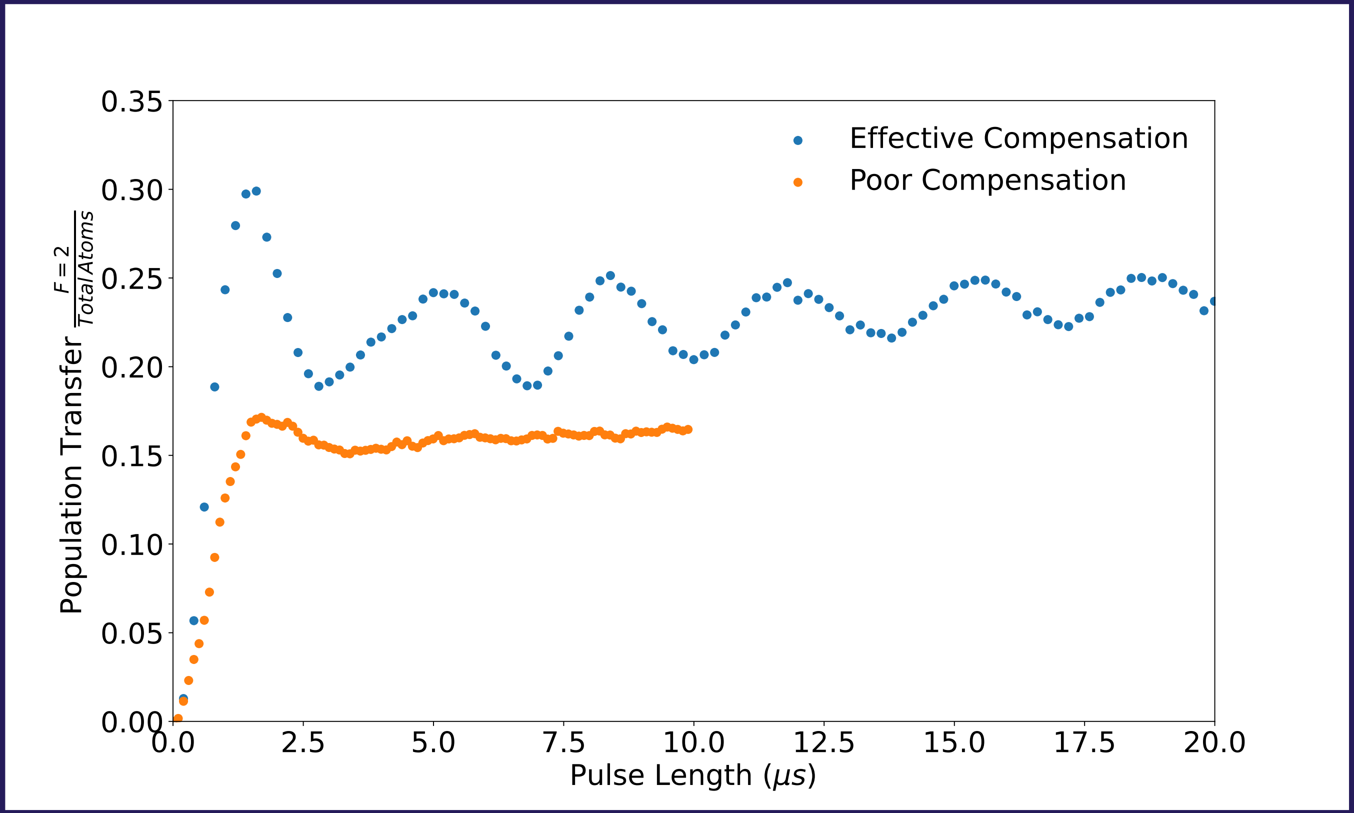
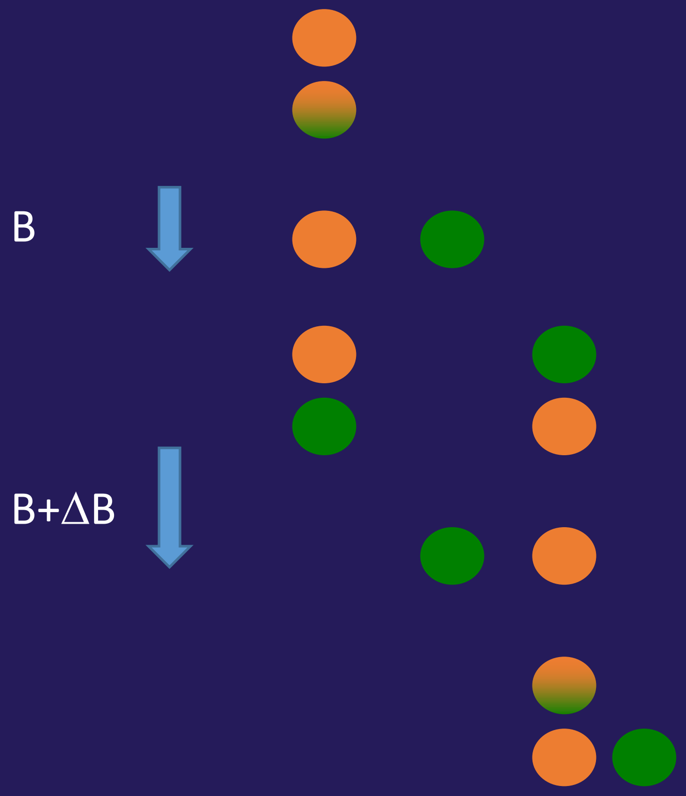
Quantisation Field Alignment - Magnetic Field Compensation





Spatial Magnetic Field Variations



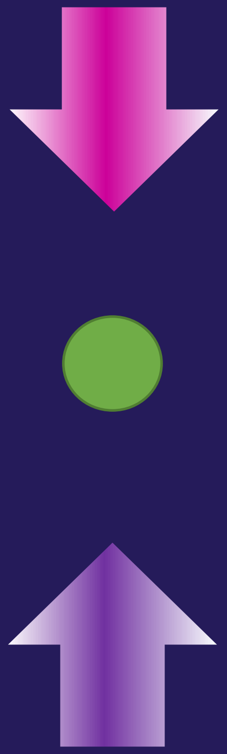
Second-order Zeeman shift

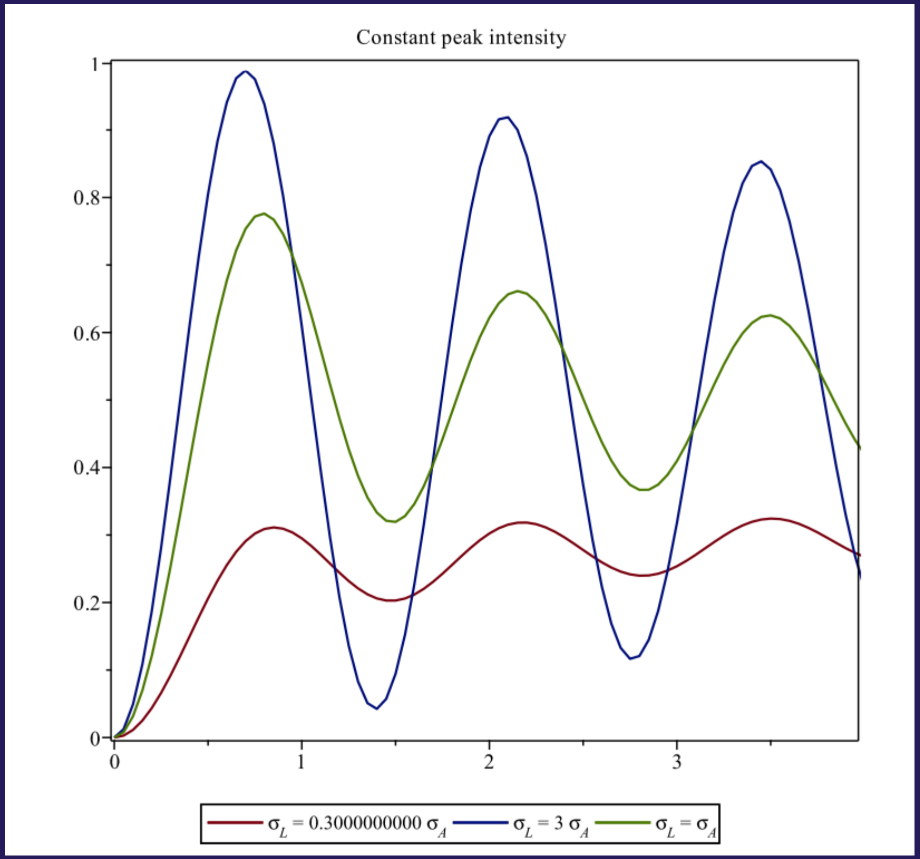
$$\Delta\Phi = \int_{-\infty}^{+\infty} g_S(t) 2\pi K B(t)^2 dt.$$

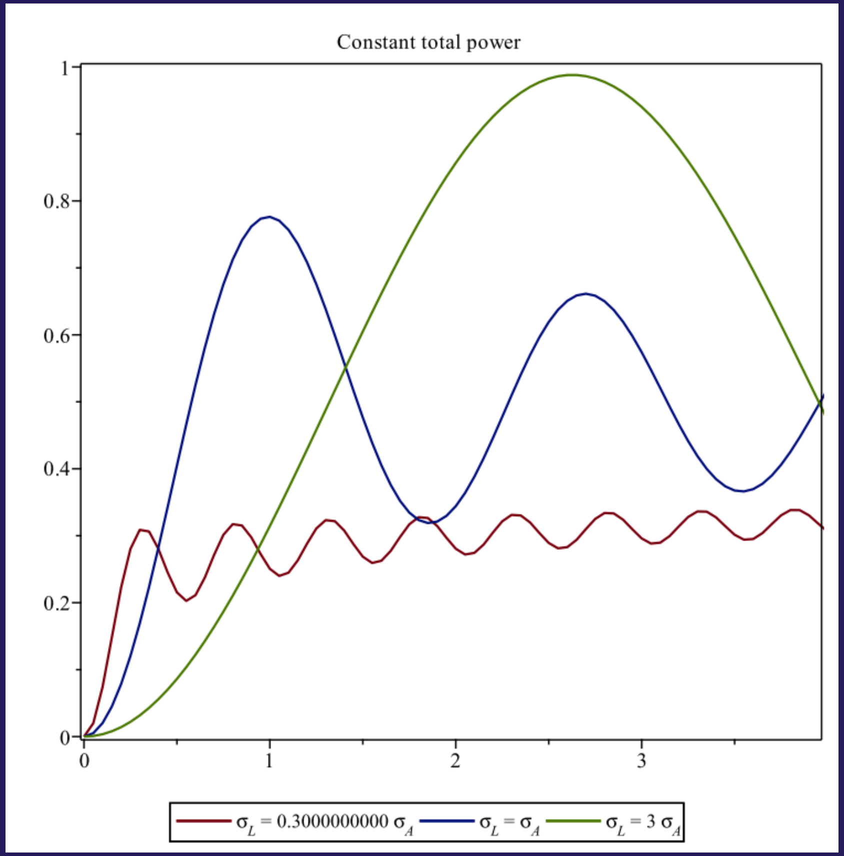
K=575 Hz/G^2

B=1G, T=100 ms, $\Delta\Phi$ < 10 mrad
→ ΔB < 10 μG

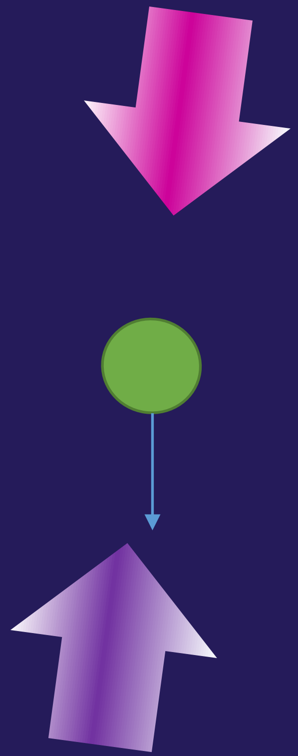
Beam diameter and atom temperature

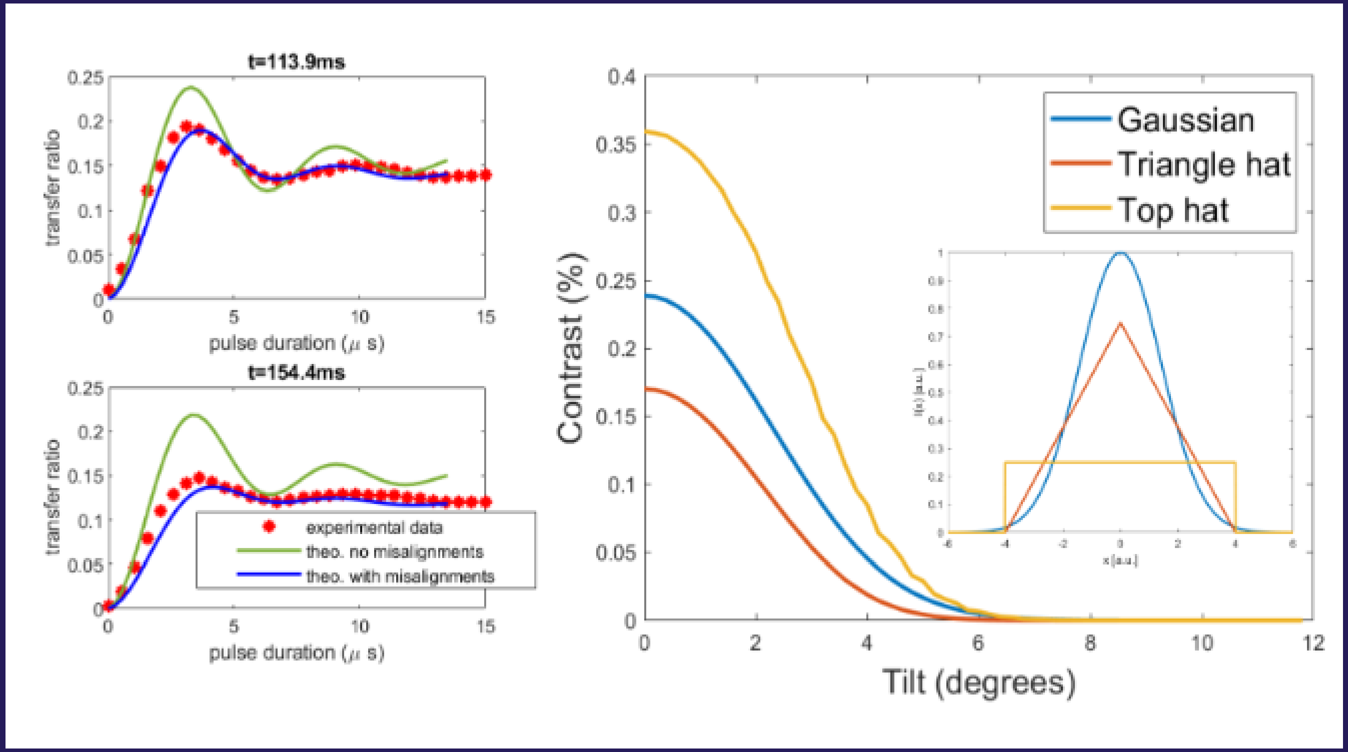




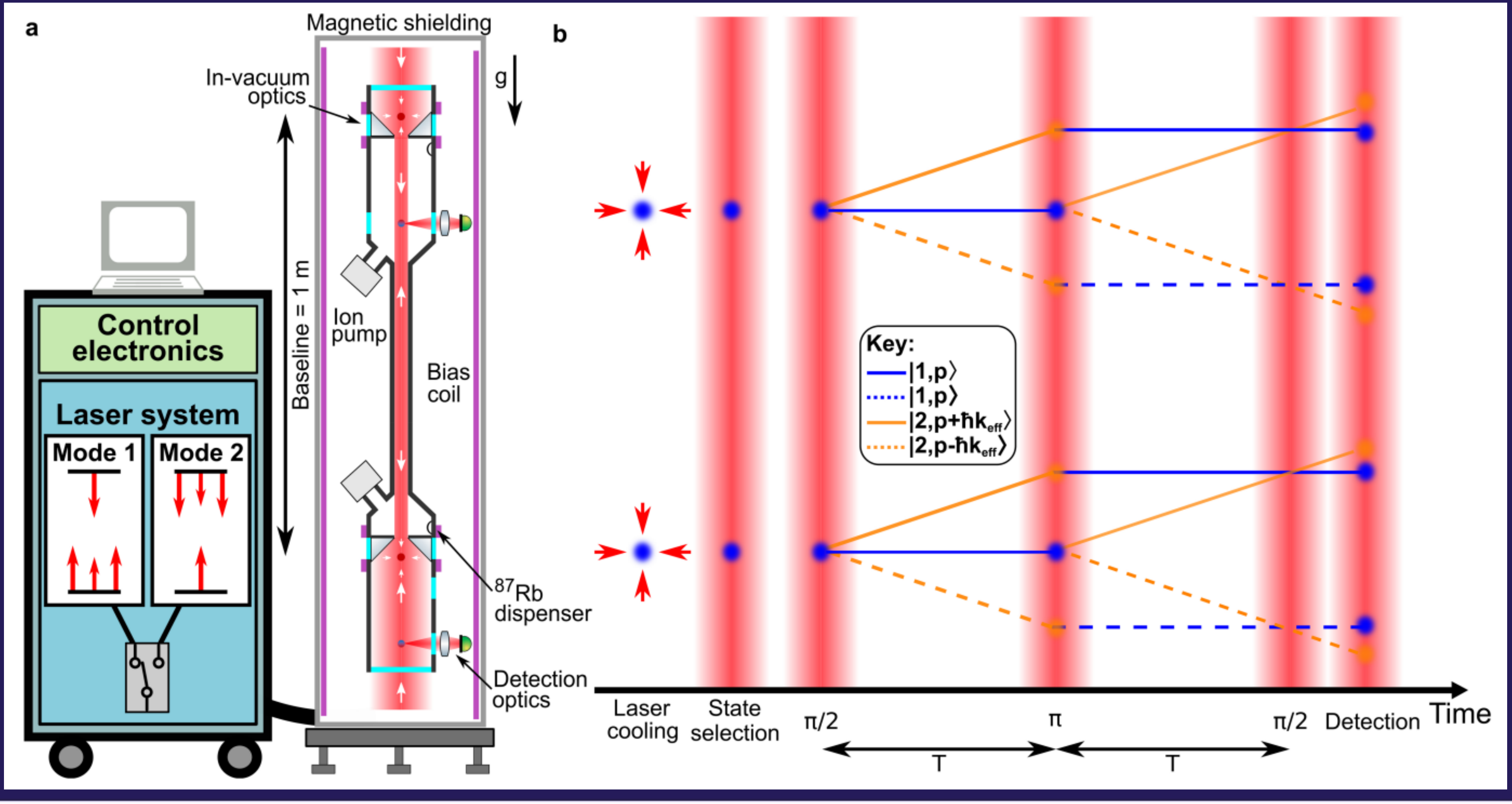


Tilt effects





Magnetic fields and k-reversal



Nature **volume 602**, pages590–594 (2022)

Quantum Sensor Applications and their Impact

How important are sensors?

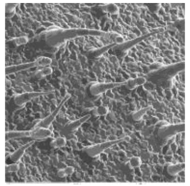
- What sensors did you use today?

Disruptive consequences of new sensors

Sensors and clocks are enabling system capabilities with large economic impact

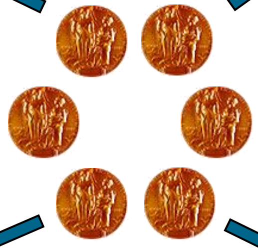
- Historic examples based on sensor-related Nobel Prizes

X-rays



Electron Microscope

MRI



Aperture synthesis in radioastronomy → SAR Radar

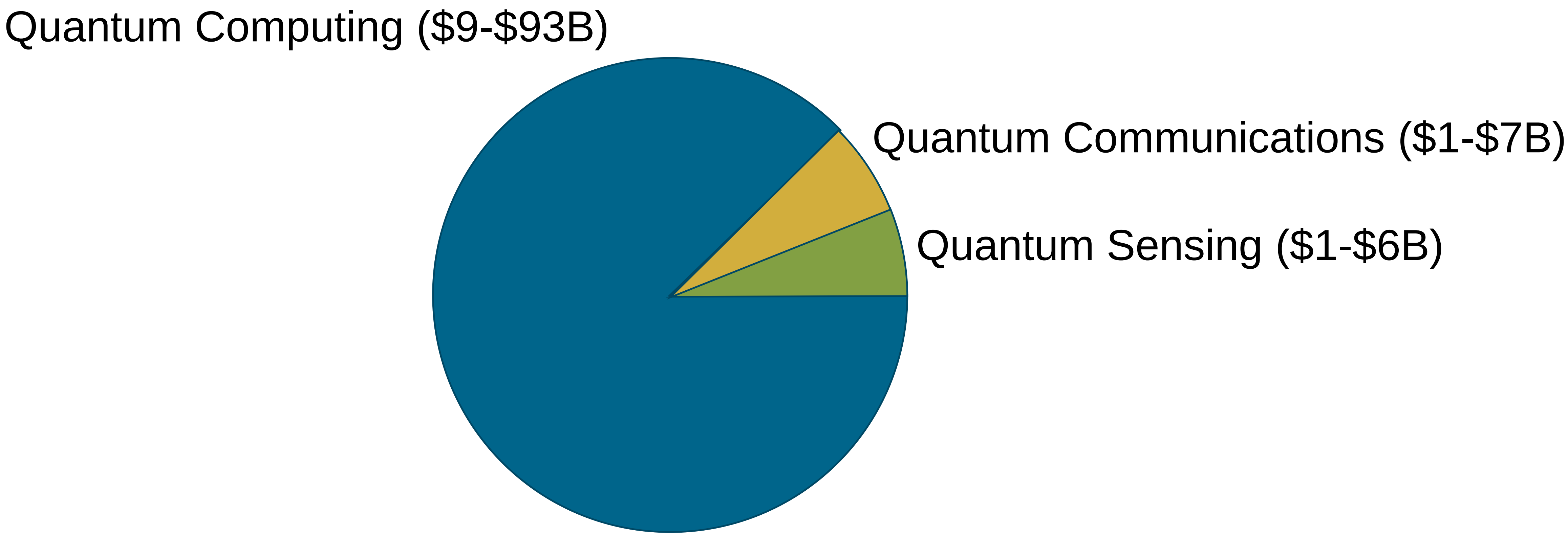
Giant Magnetoresistance → Hard Drives

CCD

Sensor utility needs systems thinking!

Quantum Technology Applications and Markets

Market estimates in 2024 (source: McKinsey Quantum Technology Monitor, 2023)

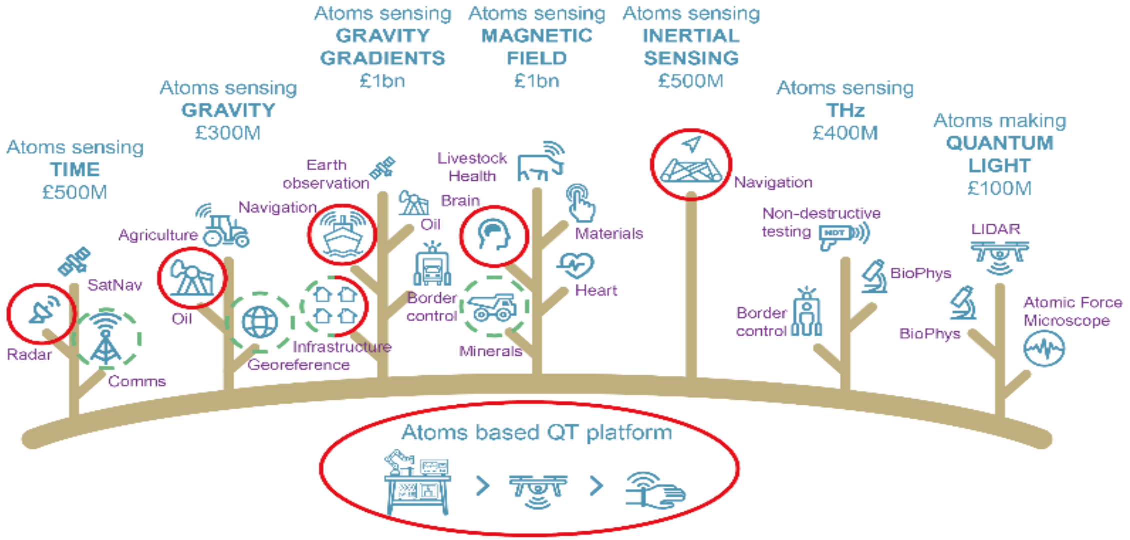


Overall economic impact much larger (e.g. estimate for QC in 2035: $620B-$1270B)

Quantum Sensing and Clocks

Underpinning Technology for Wider Economic Impact

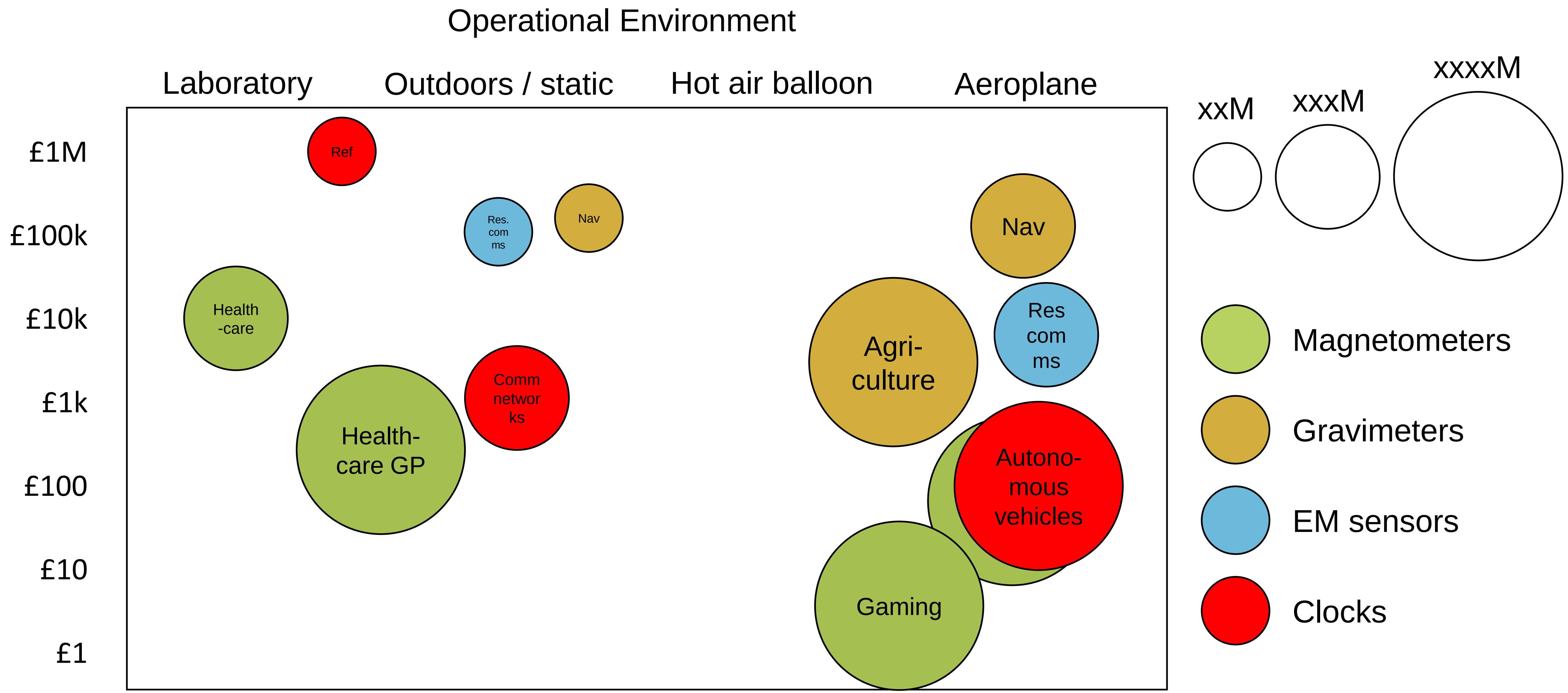
- Boston Consulting Group:
  - Total attainable market for sensors in 2030: $170B-$200B
  - Quantum Sensing Market to reach $3B-$5B by 2030
- QT Hub thinking (GBP 4B):



- Sensors provide huge leverage for overall economic impact

Potentially Accessible Quantum Sensor Markets

Key Drivers: Robustness and Cost



Magnetometers for Healthcare

Epilepsy: 60M people worldwide

Dementia: 1% GDP

Schizophrenia: 1% of population

Trauma: 100.000 / year in UK

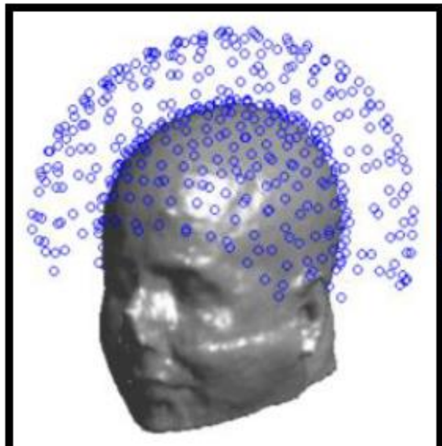
What is “good enough”?

What are the barriers QT could overcome?
→ Adaptation to head size
→ Movement while measurement
→ System cost

Several commercial sensors available:
e.g. QuSpin with <15 $fT/Hz^{-1/2}$, 3-100Hz bandwidth
→ This allows 5-10 times SNR enhancement over SQUID-MEG
→ Good enough

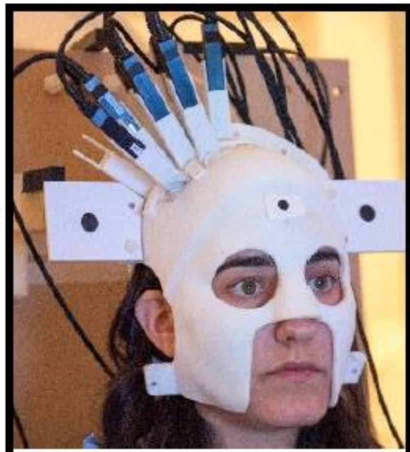
OPM-MEG development – 2015 – 2019 - Adaptation to Head Size

Conventional MEG



On scalp MEG simulations 2016

Single channel recording 2017



First wearable OPM array 2018

First paediatric helmet 2019

First VR-MEG recording 2019

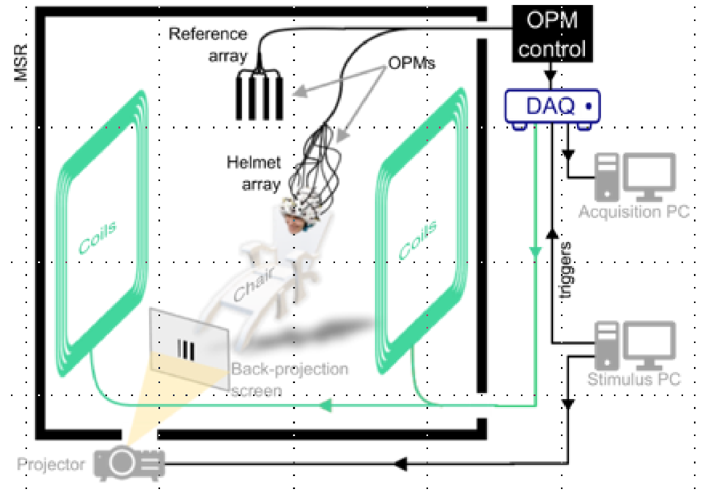
First Gen II OPM recordings 2019

First simultaneous OPM/EEG 2019

50 channel whole head system 2020

A new generation of quantum sensors have enabled 'wearable' brain imaging technology

Its here NOW: Commercial Offering

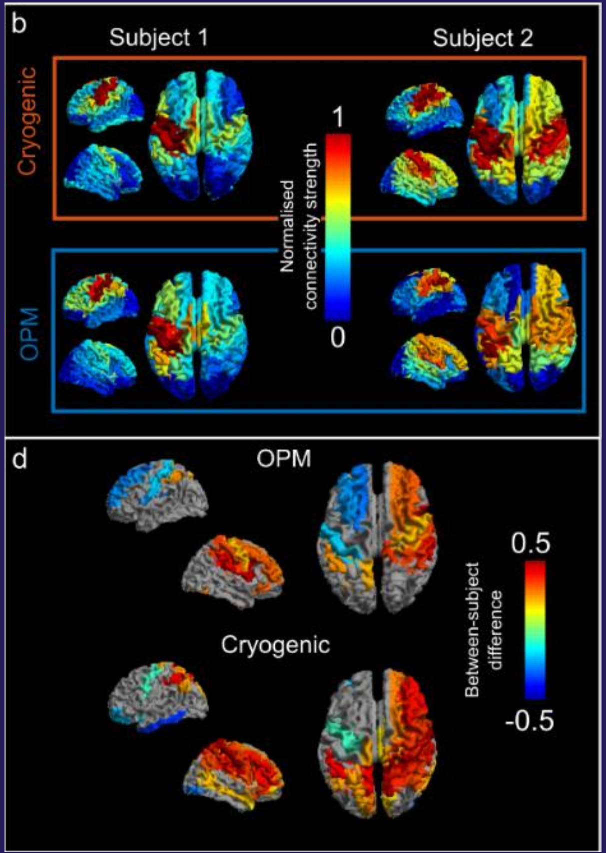


Cerca's market offering:

- Integrate system components into one OPM-MEG system
- Test and validate system
- Single point of contact for customer
- Provide warranty for integrated system

cerca Magnetics Limited

Joint venture between University of Nottingham and Magnetic Shields Ltd.



UK Quantum Technology Hub Sensors and Timing

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Gravity Gradients for Construction

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

Drainage

Voids leading to sinkholes

Badger setts

Leakage from canals and reservoirs

Mineshafts

Density of mine entries in an urban setting, West Midlands. (Topography based on Ordnance Survey mapping © Crown Copyright and Database Right 2011). Ref: *Geoscientist* April 2016.

Collaboration: physics, civil engineering, geophysics, industry

UK Quantum Technology Hub Sensors and Timing

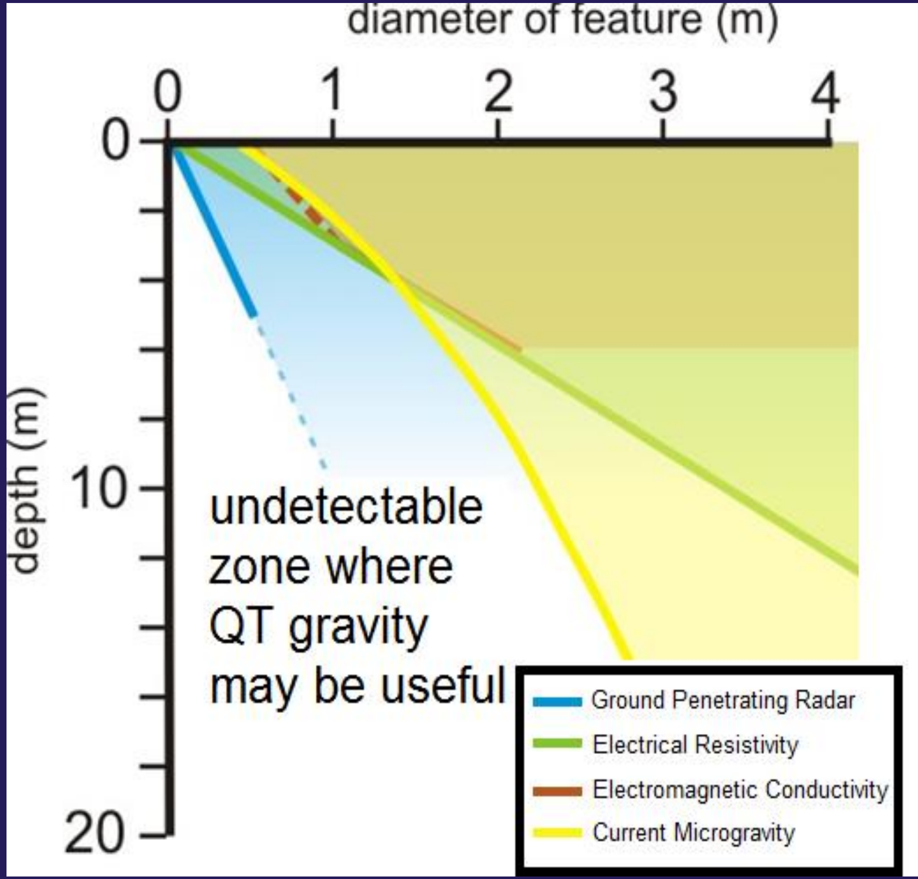
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Civil Engineering Sensors and QT Opportunities

Ground Penetrating Radar

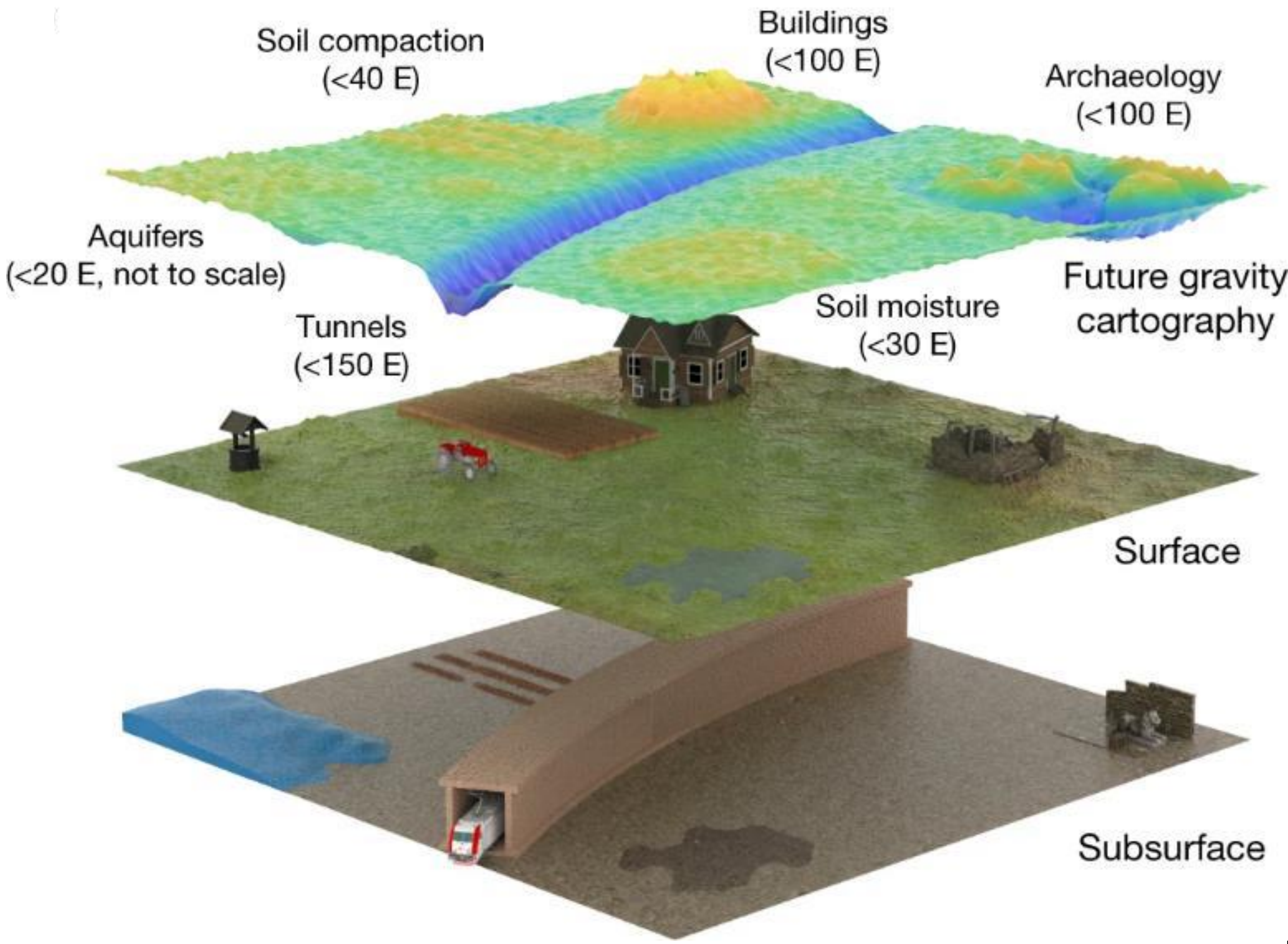
Microgravity - Scintrex CG6

Magnetometer
(www.geomatrix.co.uk)

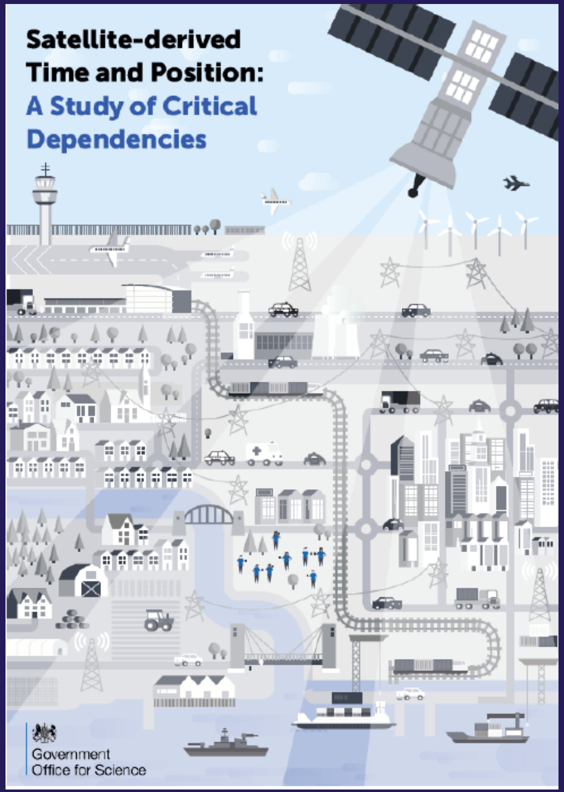


Enabling Gravity Cartography

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



Gravity Sensors for Navigation



~7% GDP

Motivation: GNSS Vulnerabilities

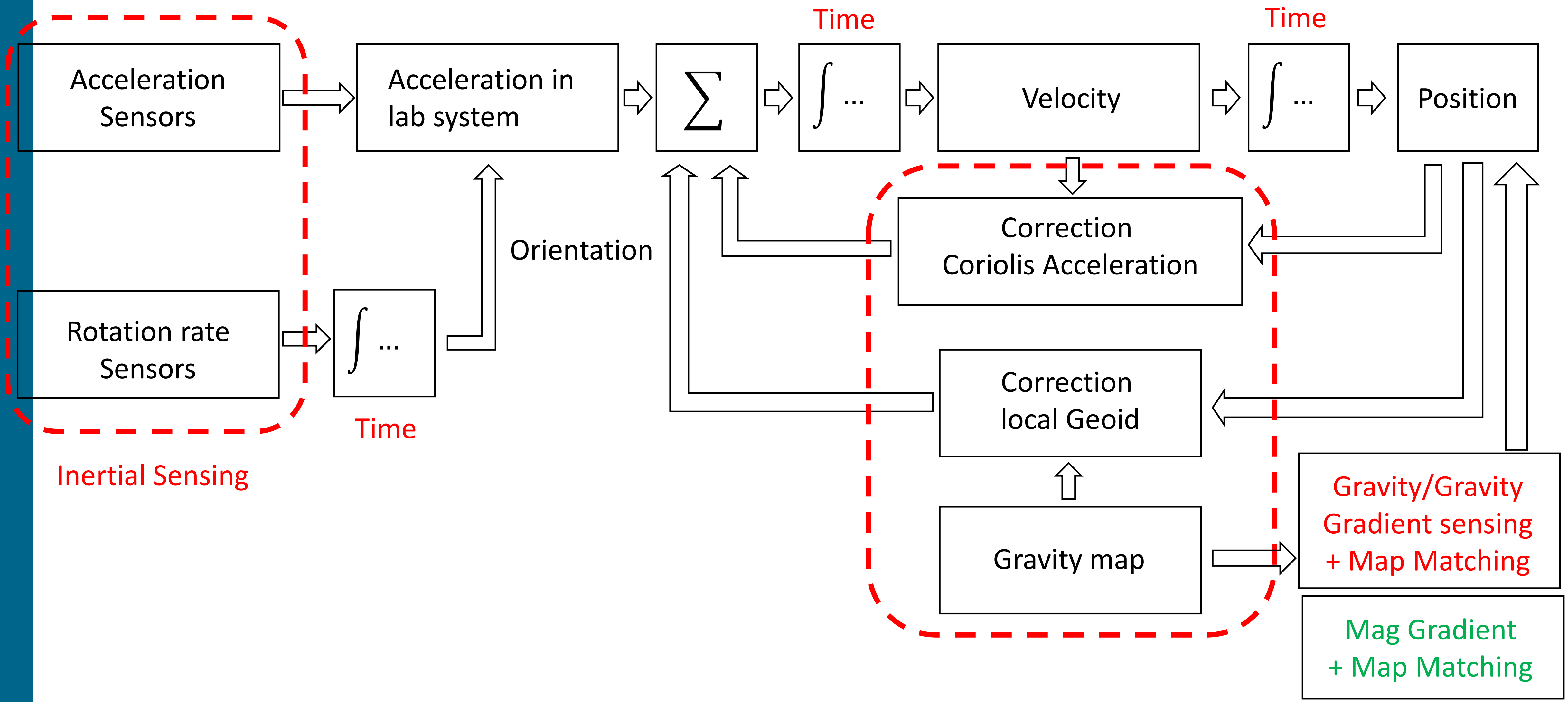
- Reduced precision in cluttered spaces
- Does not work indoors, underwater, or underground
- Can be easily jammed or spoofed

Collaboration: physics, materials science, electrical engineering, industry

UK
Quantum Technology Hub
Sensors and Timing

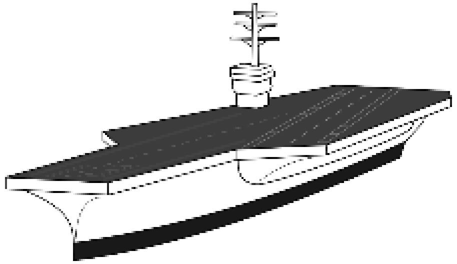
UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

Schematic Setup of a Quantum Navigation System

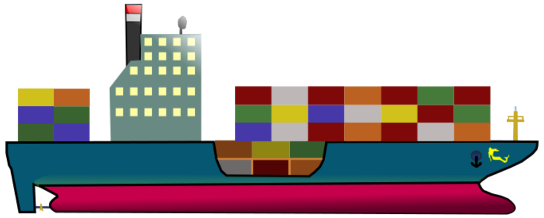


Market Roadmap for Quantum Navigation Systems

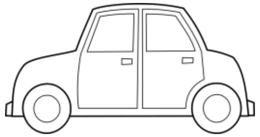
Cost and regulatory requirements as key drivers



Strategic platforms



Autonomous ships and underwater vehicles

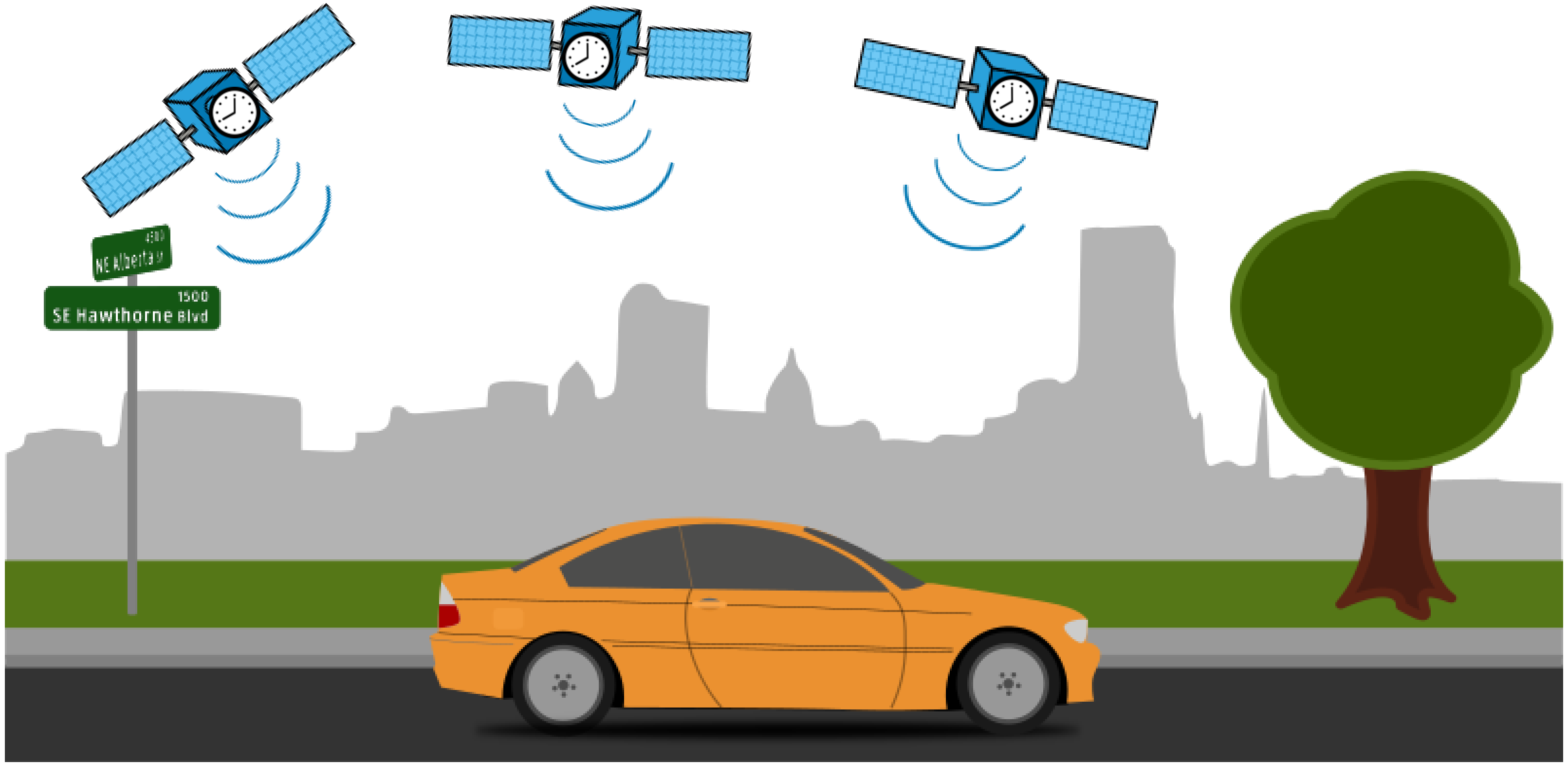


Autonomous vehicles

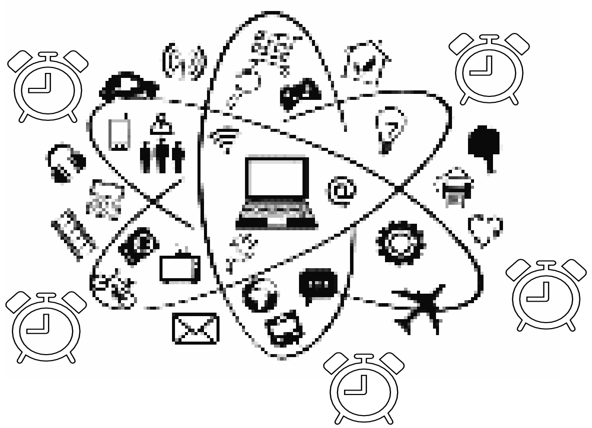
	2030	2040	2050
Unit cost	xM€	xxxk€	xxx€
Market volume	xxM€	xxxM€	xxxxxM€

Quantum 2.0 for Navigation and Time

Quantum clocks are powering current global satellite navigation systems



Navigation

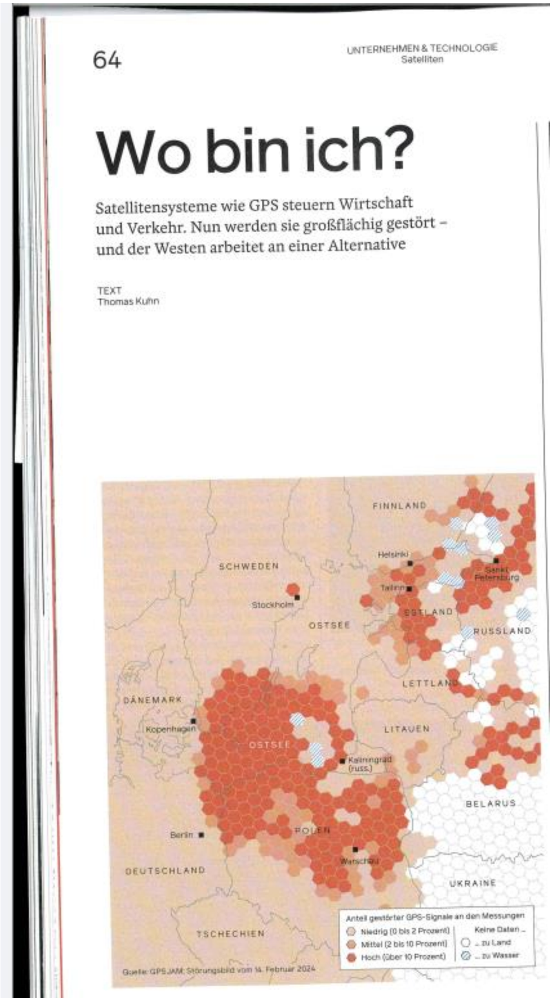


Synchronisation

Impact: 5-10% of GDP

GNSS critical dependencies

Need for independent alternatives


64 UNTERNEHMEN & TECHNOLOGIE Satelliten

Wo bin ich?

Satellitensysteme wie GPS steuern Wirtschaft und Verkehr. Nun werden sie großflächig gestört – und der Westen arbeitet an einer Alternative

TEXT Thomas Kuhn

Wirtschaftswoche 10, 2024


NATIONAL ARCHIVES

FEDERAL REGISTER

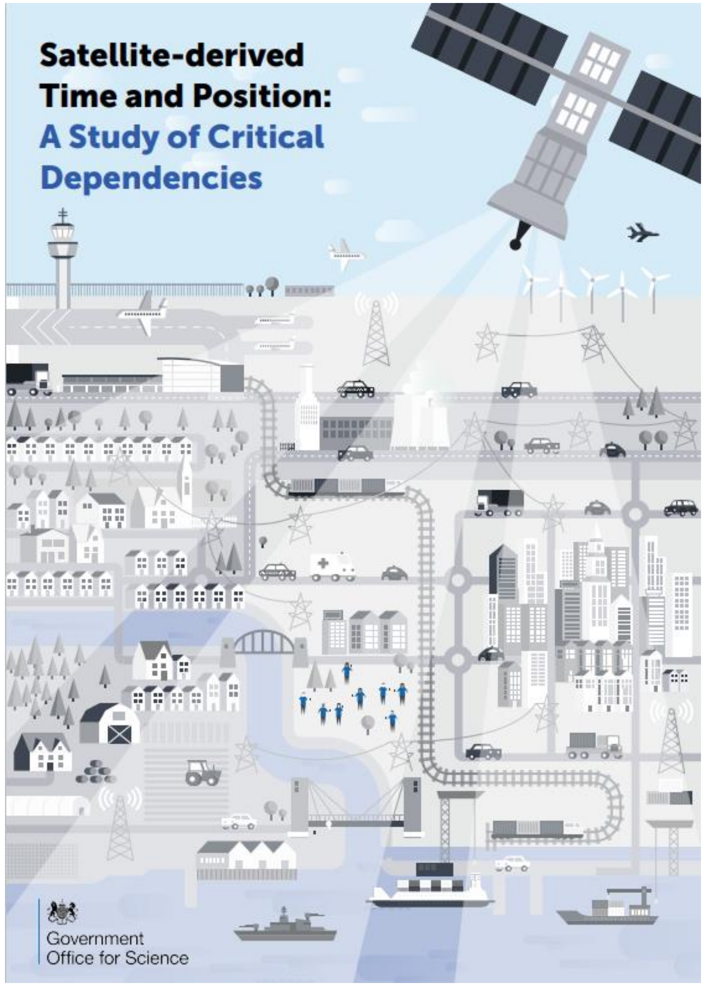
The Daily Journal of the United States Government

Presidential Document

Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services

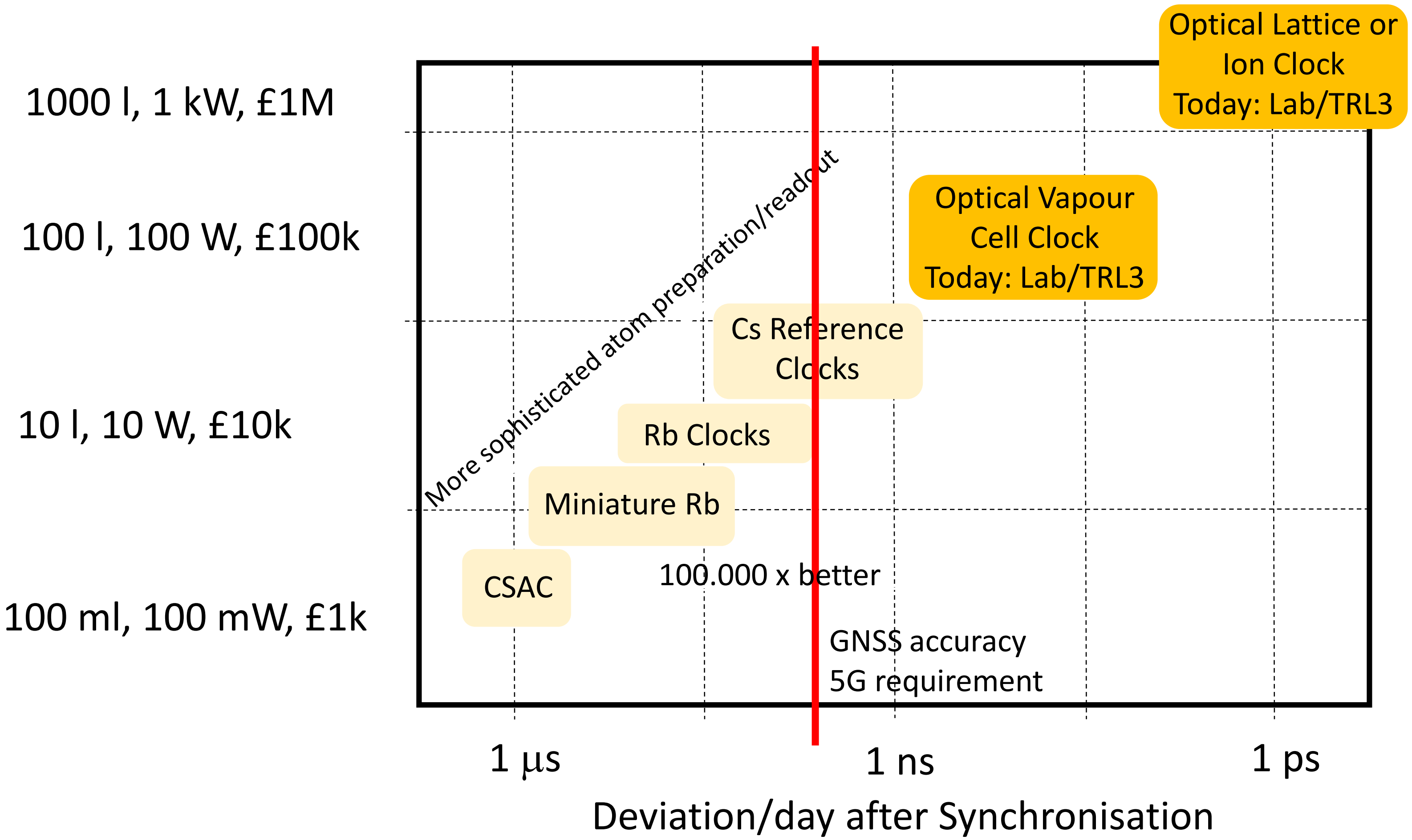
A Presidential Document by the Executive Office of the President on 02/18/2020

UK Blackett Report 2018



Why are Optical Clocks Disruptive?

So far: "linear" relationship between SWAP-C and stability



Why are Optical Clocks Disruptive?

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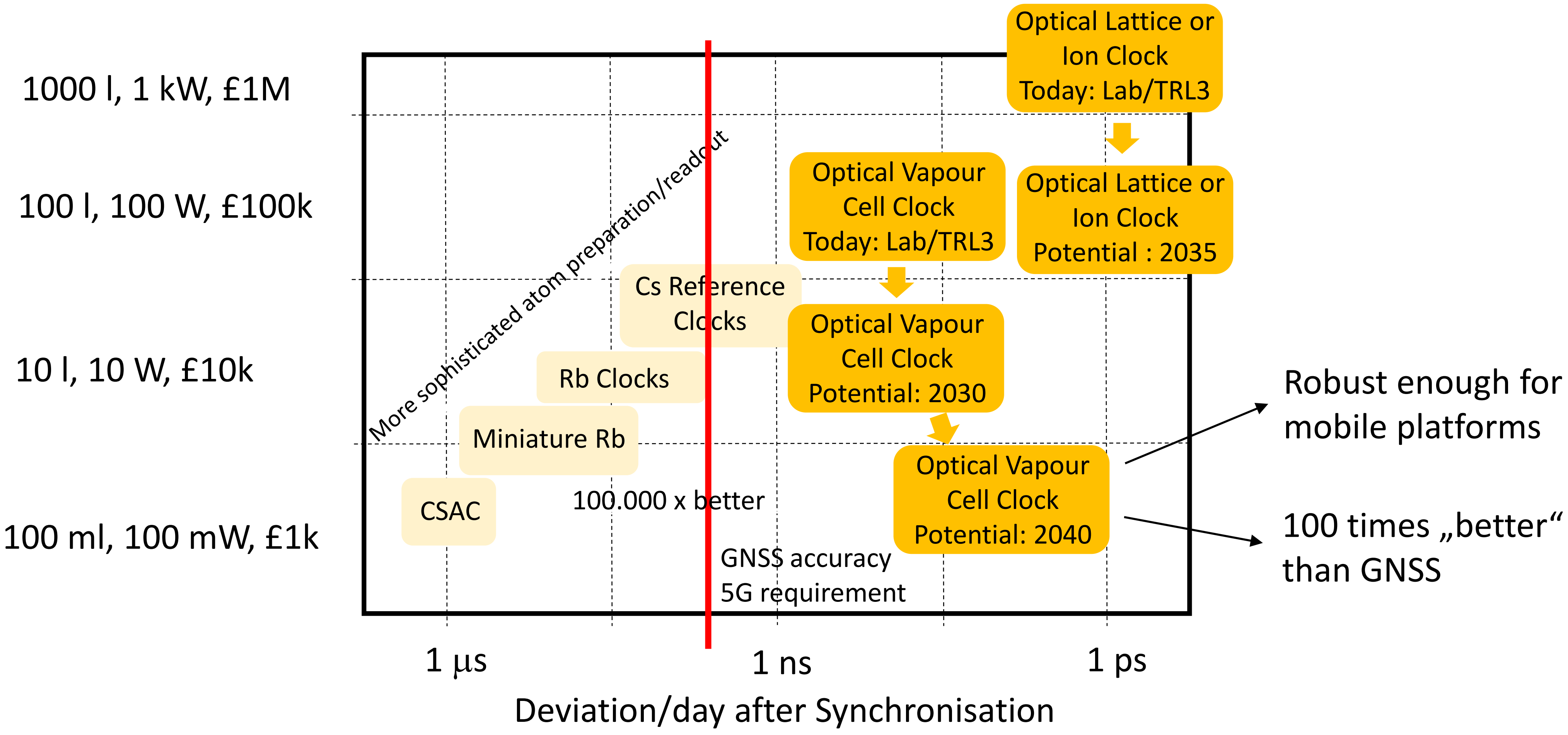


DLR-QT Optical Clock Technology

DLR

Iodine optical vapour cell clock

GPS Solutions (2021) 25:83
https://doi.org/10.1007/s10291-021-01113-2

Table 1 Summary of the key figures of the different optical clock technologies, together with the corresponding figures of the Galileo RAFS and PHM

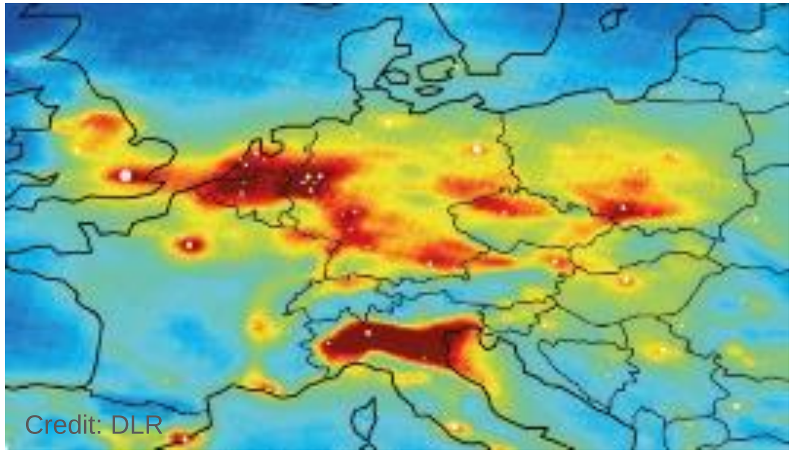
		Galileo RAFS	Galileo PHM	Ca beam	I_2 MTS	Rb MTS	Rb TPT	Sr Lattice clock	Ca single ion clock
	References	Orolia datasheet (2016)	Leonardo datasheet (2017)	Shang et al. (2017)	Schuldt et al. (2017); Döringshoff et al. (2019)	Zhang et al. (2017)	Martin et al. (2018)	Bongs et al. (2015); Origlia et al. (2018)	(Delehay and Lacroute 2018; Cao et al. 2017)
Frequency stability (in RAV @ integration time τ)	1 s	3×10^{-12}	2×10^{-12}	5×10^{-14}	6×10^{-15}	1×10^{-14}[a]	4×10^{-13}	n/s	n/s
	10 s	1×10^{-12}	3×10^{-13}	2×10^{-14}	3×10^{-15}	4×10^{-15}[a]	1×10^{-13}	1×10^{-16}	6×10^{-15}
	10^2 s	3×10^{-13}	7×10^{-14}	5×10^{-15}	2×10^{-15}	3×10^{-15}[a]	4×10^{-14}	4×10^{-17}	2×10^{-15}
	10^3 s	6×10^{-14}	2×10^{-14}	2×10^{-15}	2×10^{-15}	n/s	1×10^{-14}	1×10^{-17}	6×10^{-16}
	10^4 s	3×10^{-14}	7×10^{-15}	n/s	3×10^{-15}	n/s	5×10^{-15}	4×10^{-18}	2×10^{-16}
	10^5 s	Long-term drift $<10^{-10}$ / year	Long-term drift $<10^{-15}$ / day	n/s	$<2\times10^{-14}$	n/s	n/s	n/s	n/s
	10^6 s			n/s	n/s	n/s	n/s	n/s	n/s
	Longest reported (continuous) τ (s)			1600	700,000	600	180,000	30,000	30,000
Clock transition frequency/wavelength		6.8 GHz	1.4 GHz	657 nm	532 nm	420 nm	778 nm	698 nm	729 nm
Clock transition natural linewidth				0.4 kHz	300 kHz	1450 kHz	330 kHz	6 mHz	140 mHz
SWaP Budgets[b,c]	Mass (kg)	3.4	18.2	n/s	21 + 10[b]	10[d] + 10[b]	12[e] + 10[b]	< 250	n/s
	Power (W)	35	60[f]	n/s	44 + 66[b]	20[d] + 66[b]	25[e] + 66[b]	n/s	n/s
	Volume (l)	3.2	26.3	300 + 7[b]	33 + 7[b]	n/s	8[e] + 7[b]	< 1000	540
Complexity	# Lasers	n/a	n/a	2	1	1	1	5	6
	Vacuum chamber			Yes	No	No	No	Yes	Yes
	Cavity pre-stabilization	n/a	n/a	Yes	No	No	No	Yes	Yes
TRL		9	9	4	4-5[g]	4	4	4	4

Commercial Opportunities through Quantum Clocks

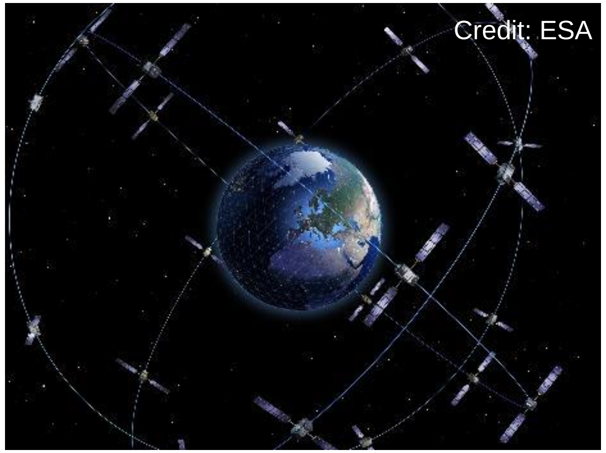
Communication

3D Radar

Urban Flight



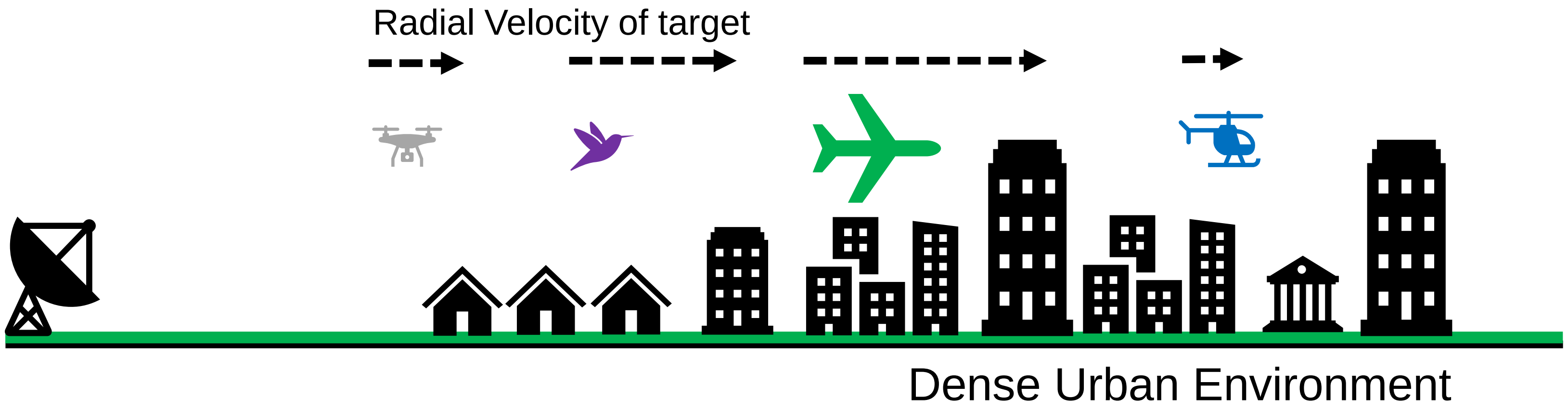
Global Height Reference

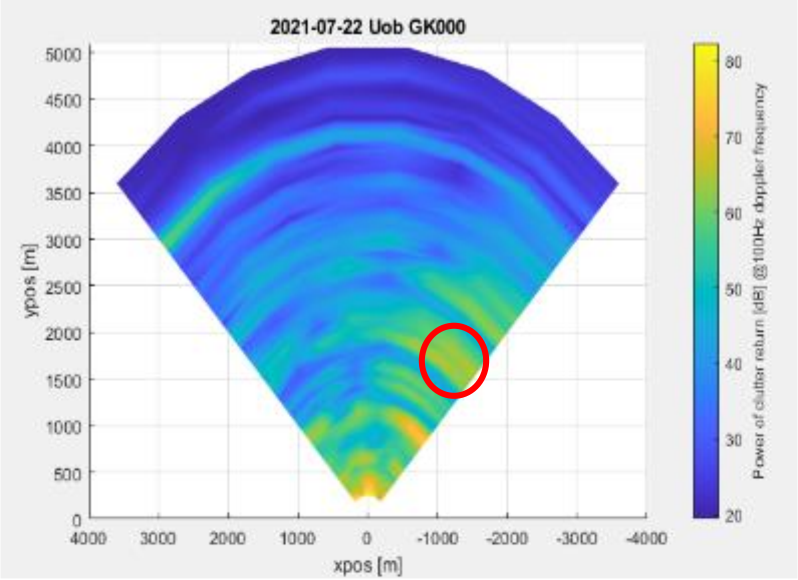


Satellite Navigation

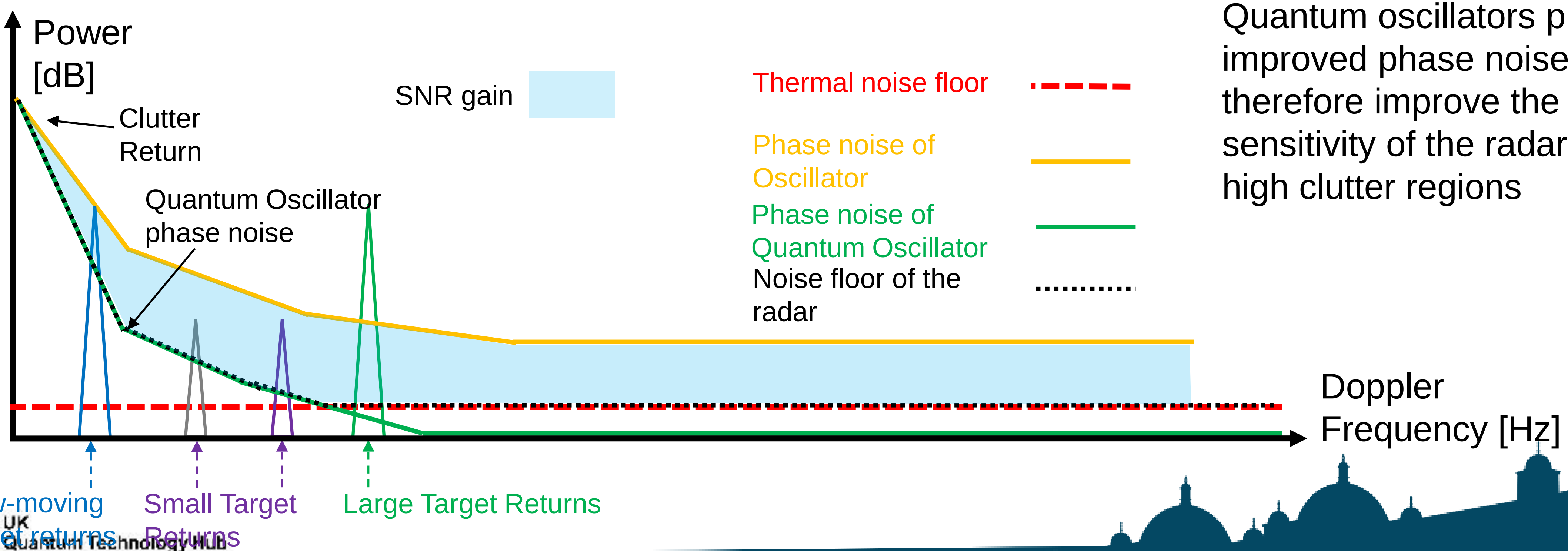
Autonomous Vehicles

Noise limitations in radar

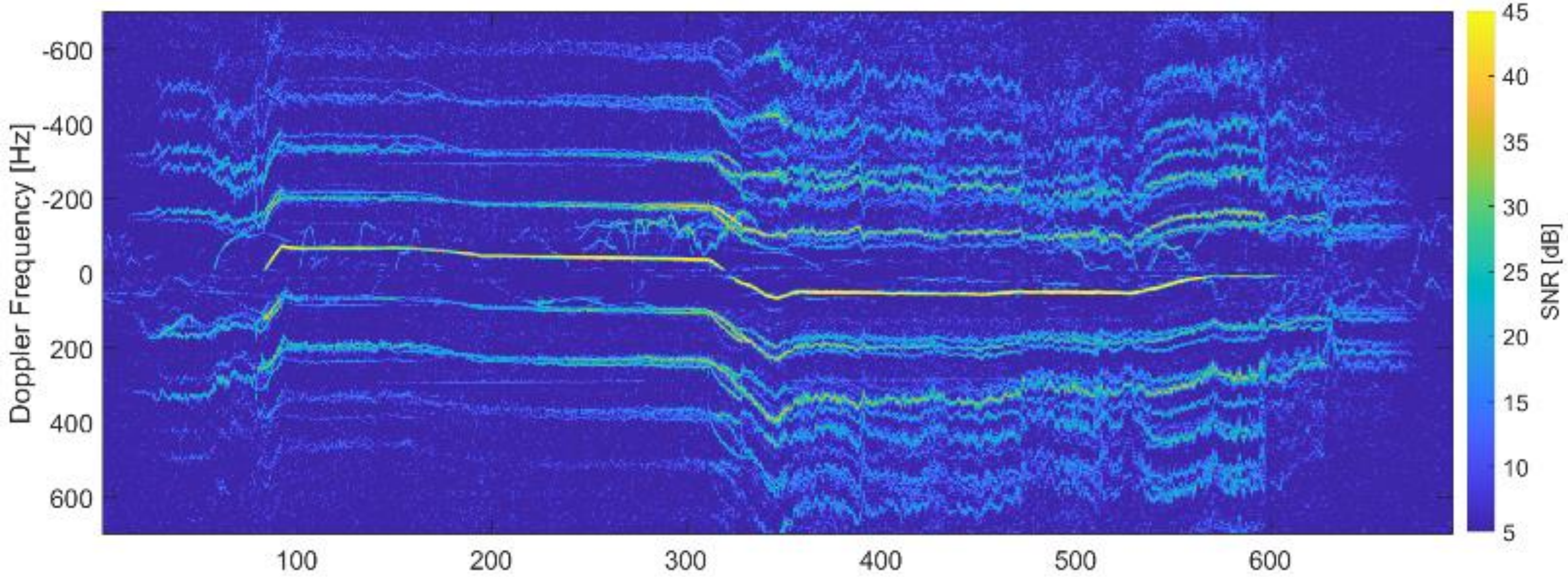




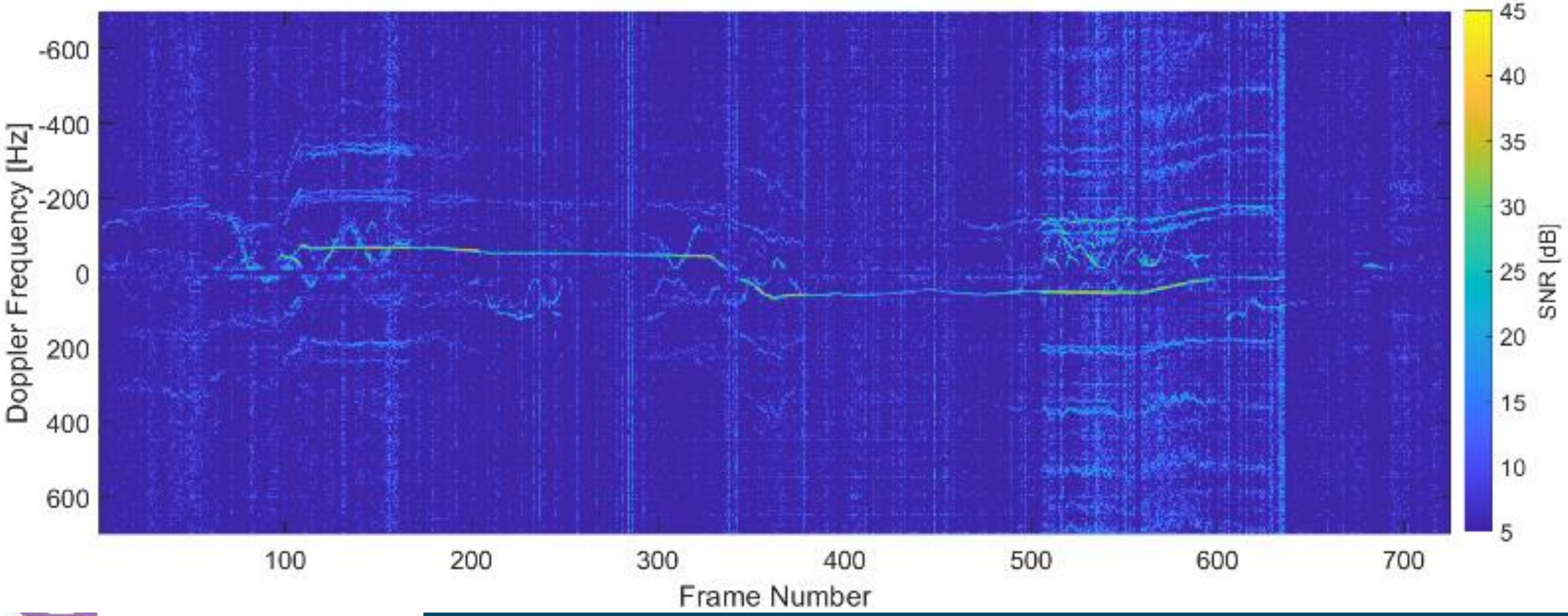
Quantum oscillators provide improved phase noise and therefore improve the sensitivity of the radar in high clutter regions



Better oscillator: more features



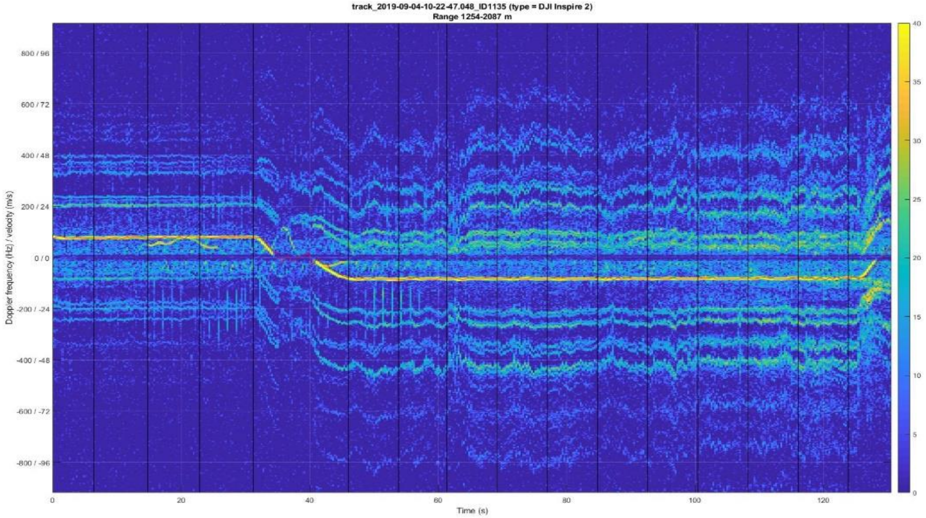
GK007
Monostatic
(Better oscillator)

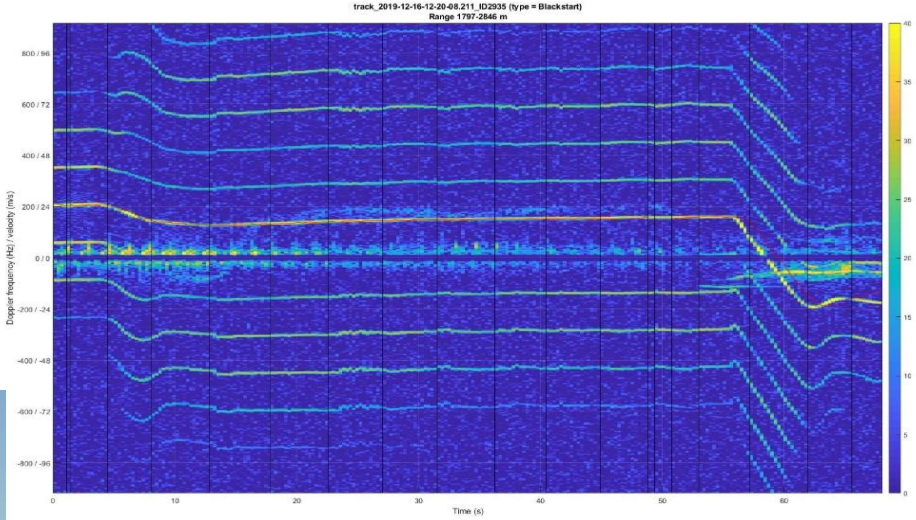


GK000
Monostatic

Discrimination via Micro-Doppler

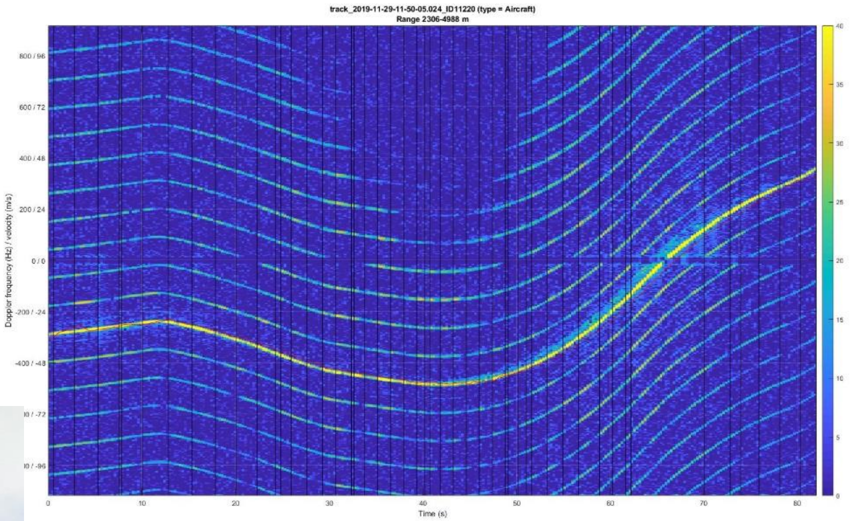
Rotary wing vs Fixed Wing

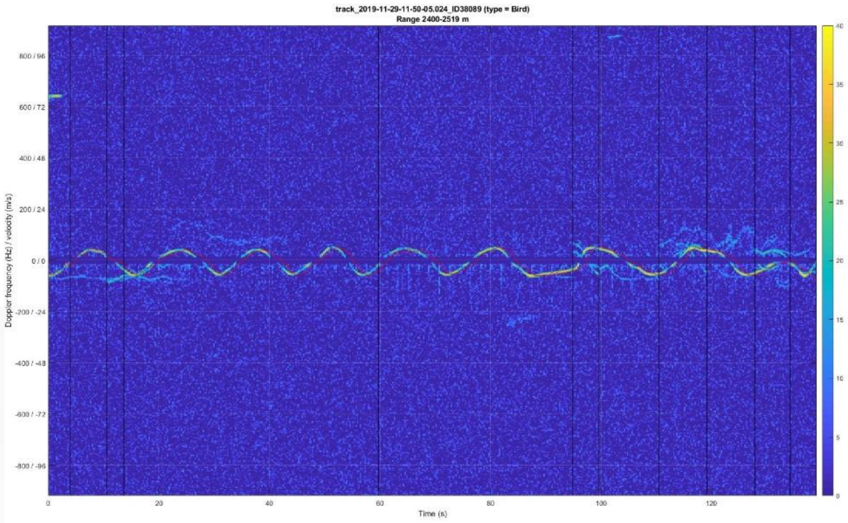




Discrimination via Micro-Doppler

Opportune targets – Light aircraft vs large bird





Radar Improvement with better Oscillator – Drone Tracking

Small Drone Tracked by two radar

Side-by-side comparison: Tracker output

Radar#1
Purple lines

Radar#2
Yellow Line - Better Phase Noise

misl

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Thank you for your attention

Questions?