# DEVELOPMENTS IN QUANTUM SENSORS AND THEIR ECONOMIC OPPORTUNITIES

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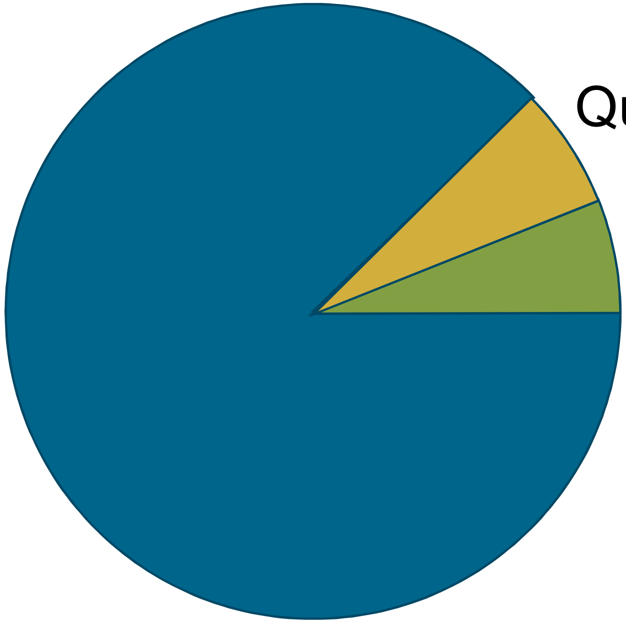
# Quantum Technology Applications and Markets

**Market estimates in 2040 (source: McKinsey Quantum Technology Monitor, 2023)**

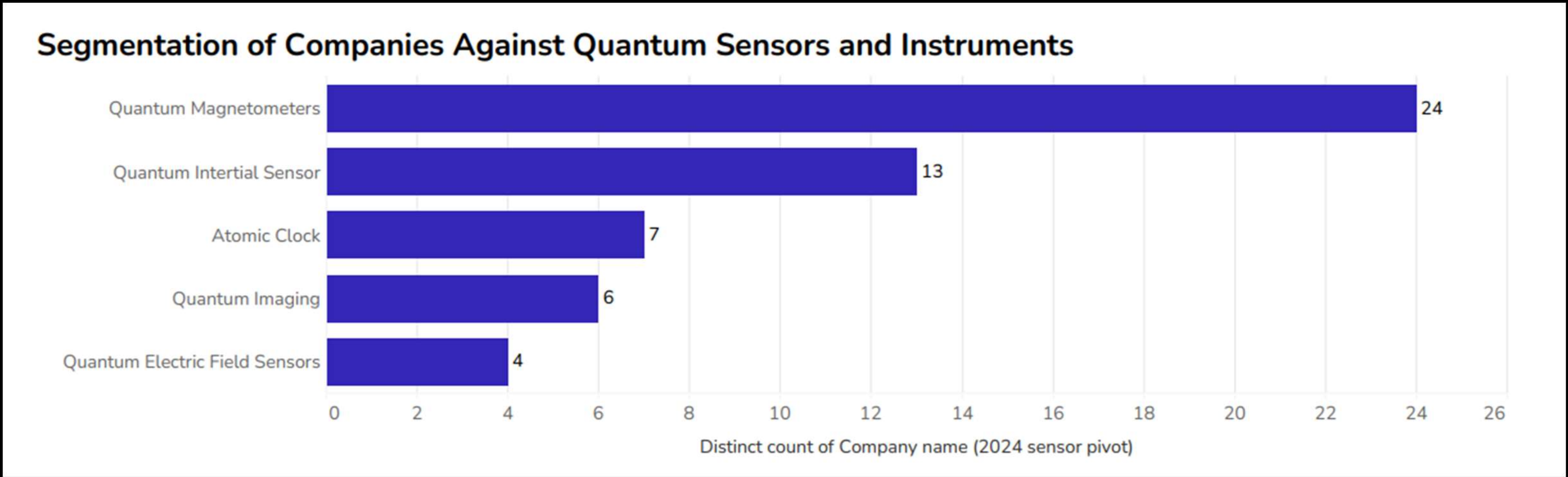



Overall economic impact much larger (e.g. estimate for QC in 2035: $620B-$1270B)

# Quantum^BW

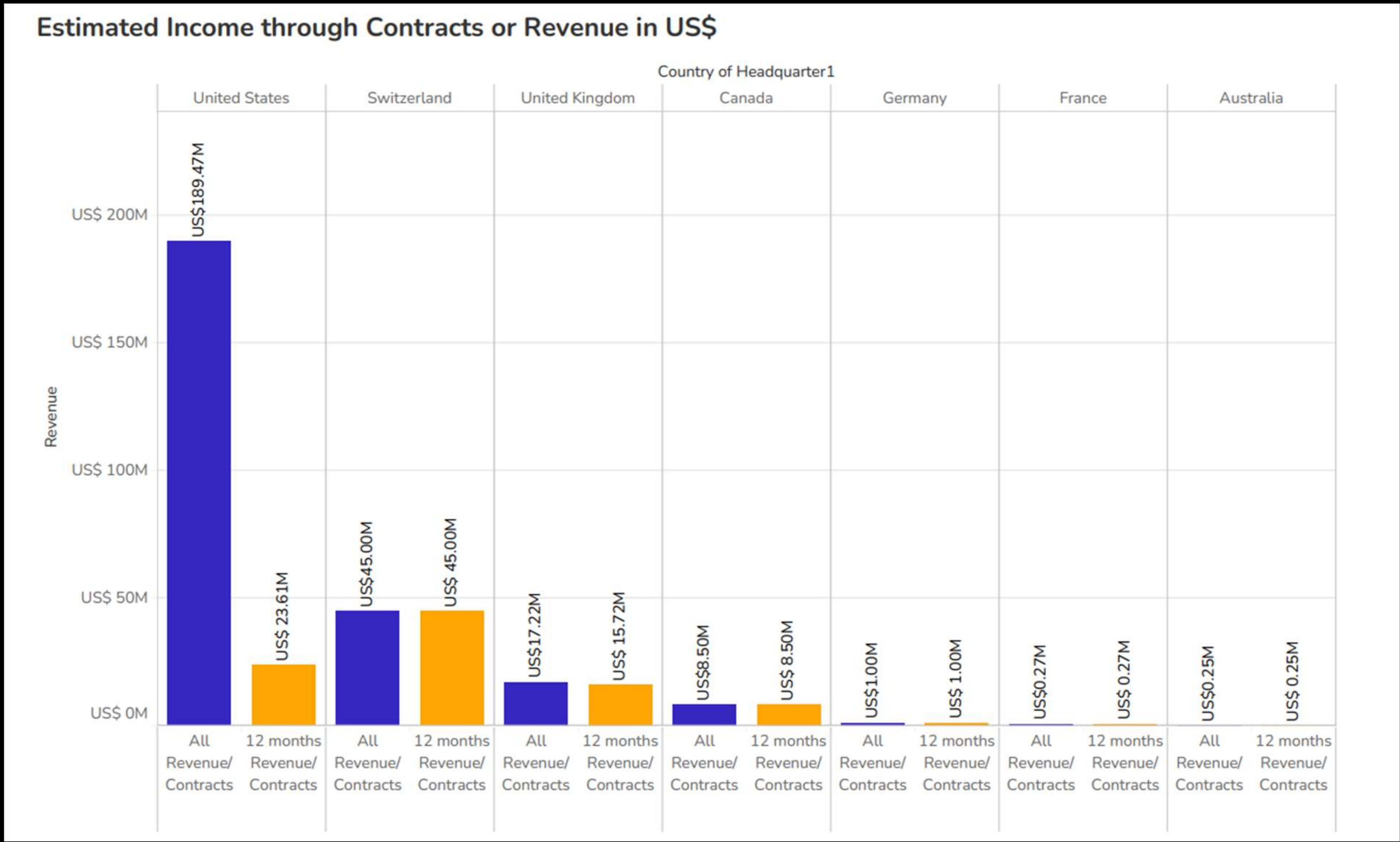
Part of
THE
LÄND

# REPORT BY ANCHOREDIN




Quantum[BW]

# REPORT BY ANCHOREDIN




Quantum[BW]

# REPORT BY ANCHOREDIN

**Table 2: Quantum Platform Technologies Underpinning Sensor Modalities**

| | Vapour Cell | Cold Atoms | NV-diamond | Other | Quantum Photonics |
|---|---|---|---|---|---|
| Quantum Magnetometers | ● | ● | ● | ● | |
| Quantum Electric Field Sensors | ● | | ● | ● | |
| Atomic Clock | ● | ● | | | |
| Quantum Intertial Sensor | ● | ● | | | |
| Quantum Imaging | | | | | ● |

# Quantum Technologies – Beginnings

**1900: Radiation of hot objects**

Planck Postulate: Electromagnetic energy is quantised

$$E=h\nu$$

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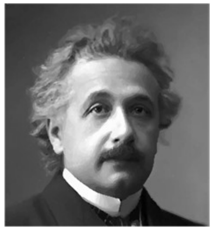
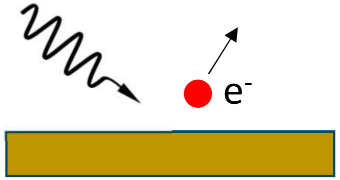


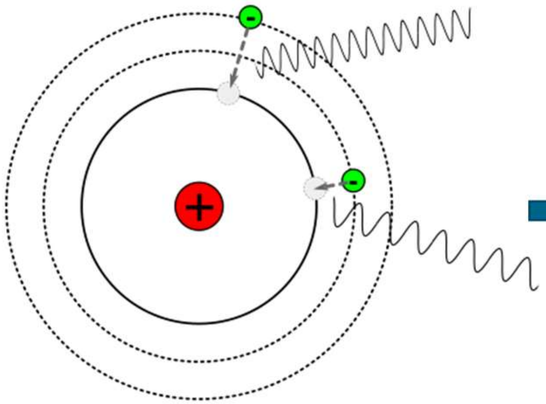
Albert Einstein explains photocelectric effect using light quantum hypothesis



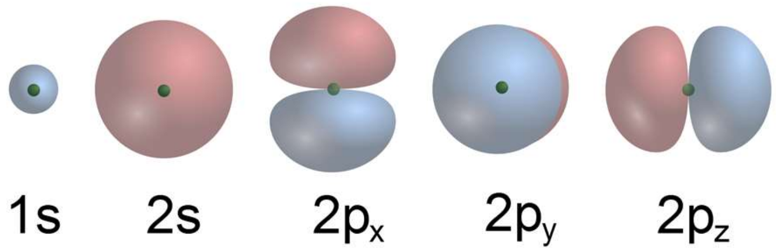

→ Nobel Prize 1921

# Quantenwellen

**1920-30: Wave particle duality**

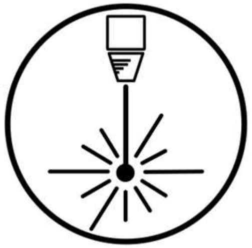


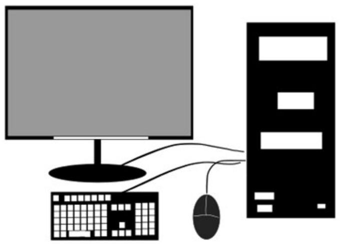
Bohr‘s Atom model

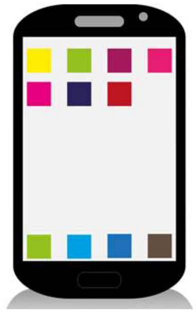


# Quantum 1.0

**Technology based on understanding quantum levels in solids**





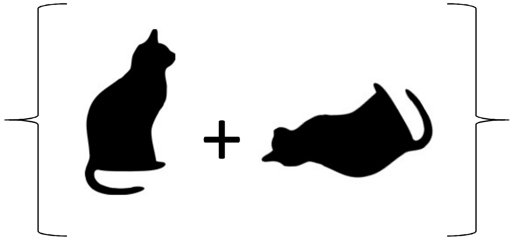


**Large expectations for Quantum 2.0**

# Quantum 2.0

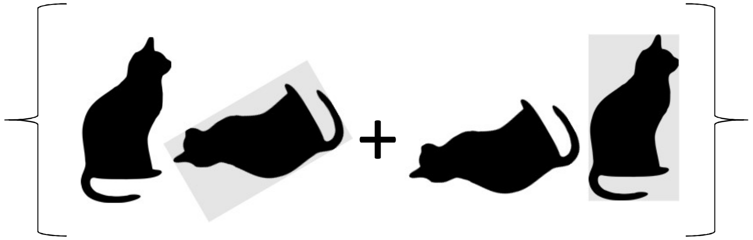
## Superposition and entanglement

**Superposition**



Particle simultaneously in several states
→ Schrödinger‘s cat

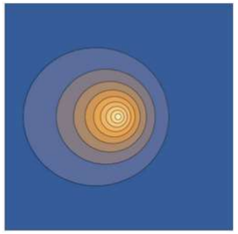
**Entanglement**



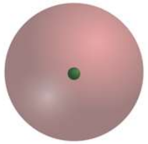
„Superposition across several particles“

# Example: Superposition in an atom

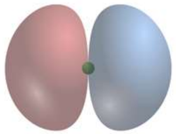
**„Oscillating electron cloud“**



$$= \frac{1}{\sqrt{2}} \Bigg\{$$



$$+$$

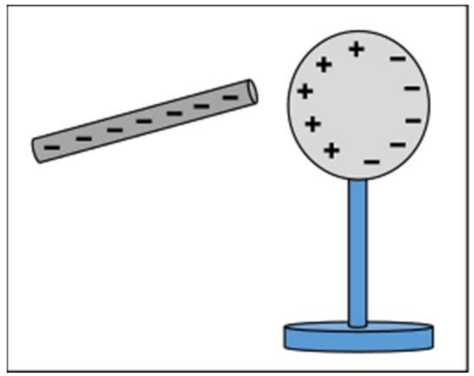


$$e^{-i\frac{\Delta E}{\hbar}t} \Bigg\}$$

# How to make an atom oscillate?

## „Push“ using electric field

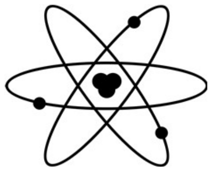
Pushing a classical oscillator



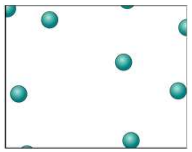
Induced electric dipole

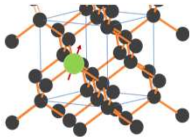
# Ingredients for Quantum Technologies

## Quantum Particles + Control

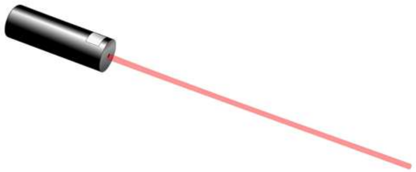


Atoms / Ions

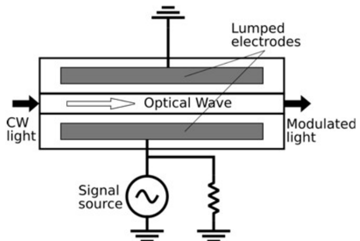




Photons



Laser- or RF Pulses




Nonlinear crystals
photonic systems

Electronics
Software
Shielding
Packaging
User interface
…

# Techology Considerations

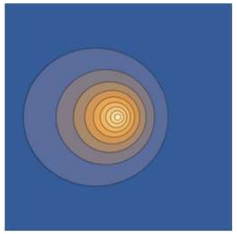
## Photons versus radio waves

- 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 size, weight, power and cost down.

# How do Quantum Clocks work?

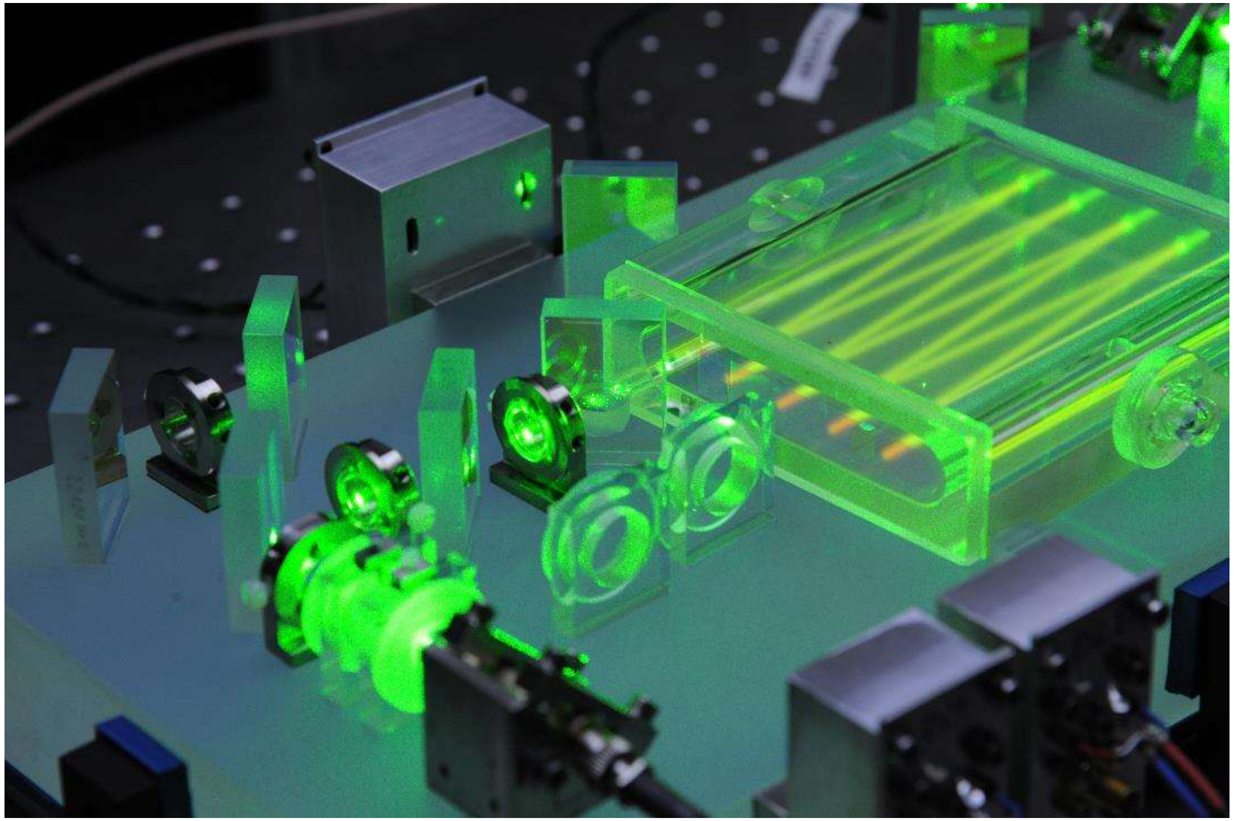
**Replacing the classical oscillator with an atom**



**Reproducible and precise due to laws of nature**

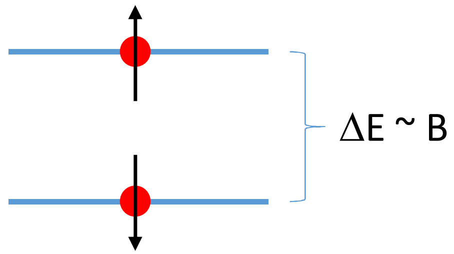
# This is how it looks like

**DLR Iodine clock**

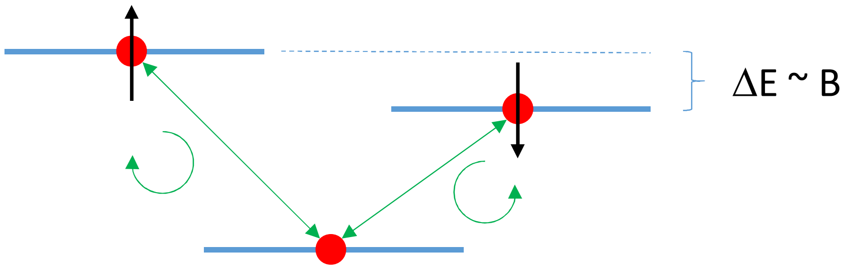


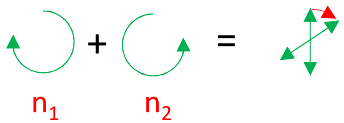
# Quantum Magnetometers

**Superposition of energy levels depending on external magnetic field**




Oscillation frequency depends on magnetic field

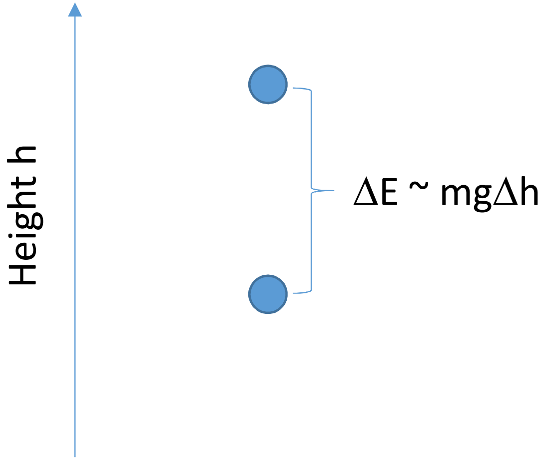



Rotation of polarization

# Quantum Gravimeters / Inertial Sensors

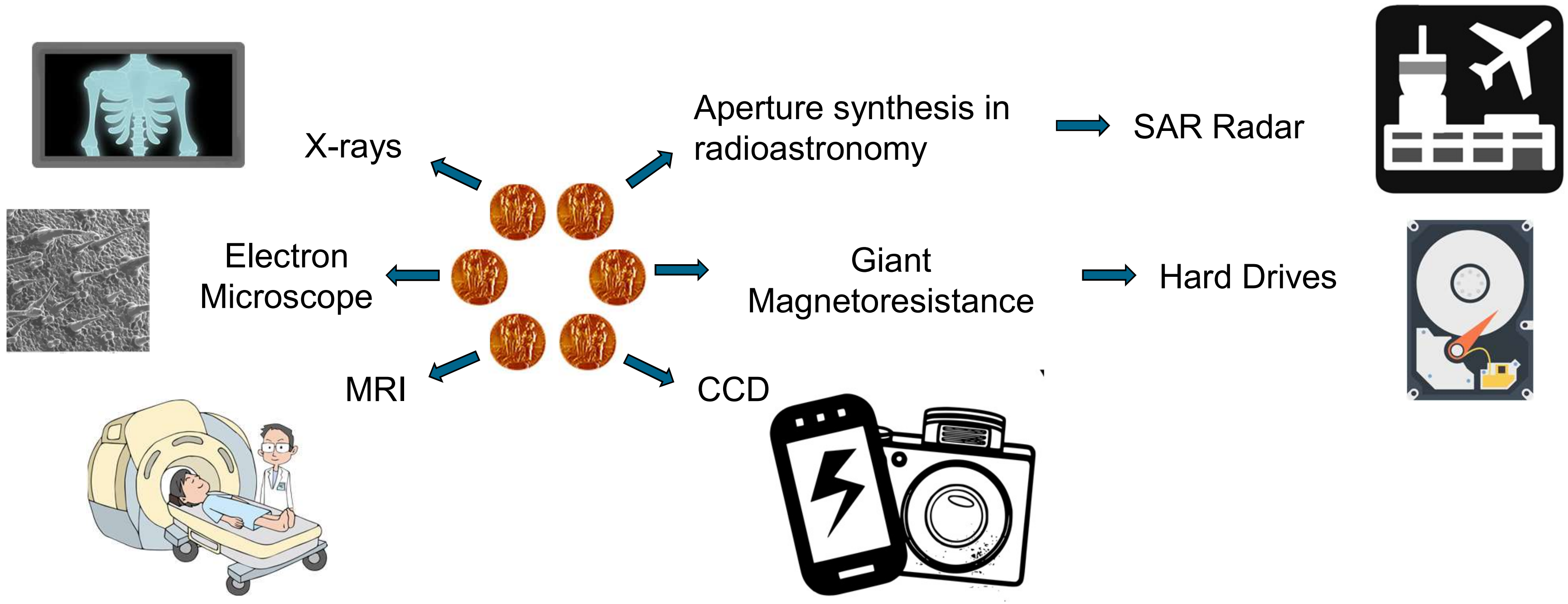
**Potential difference leads to different phase evolution**



# Disruptive consequences of new sensors

**Sensors and clocks are enabling system capabilities with large economic impact**

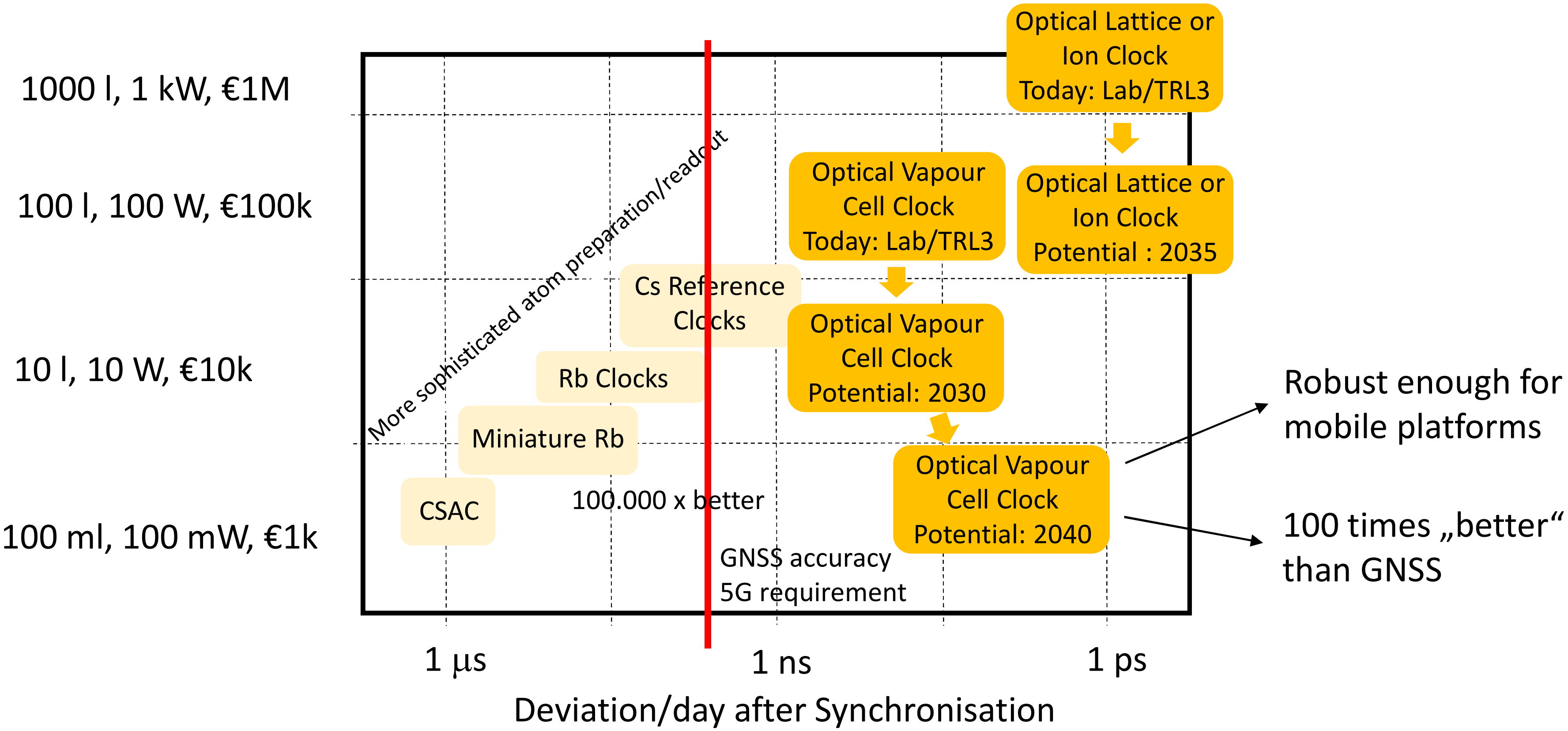
- Historic examples based on sensor-related Nobel Prizes




**Sensor utility needs systems thinking!**

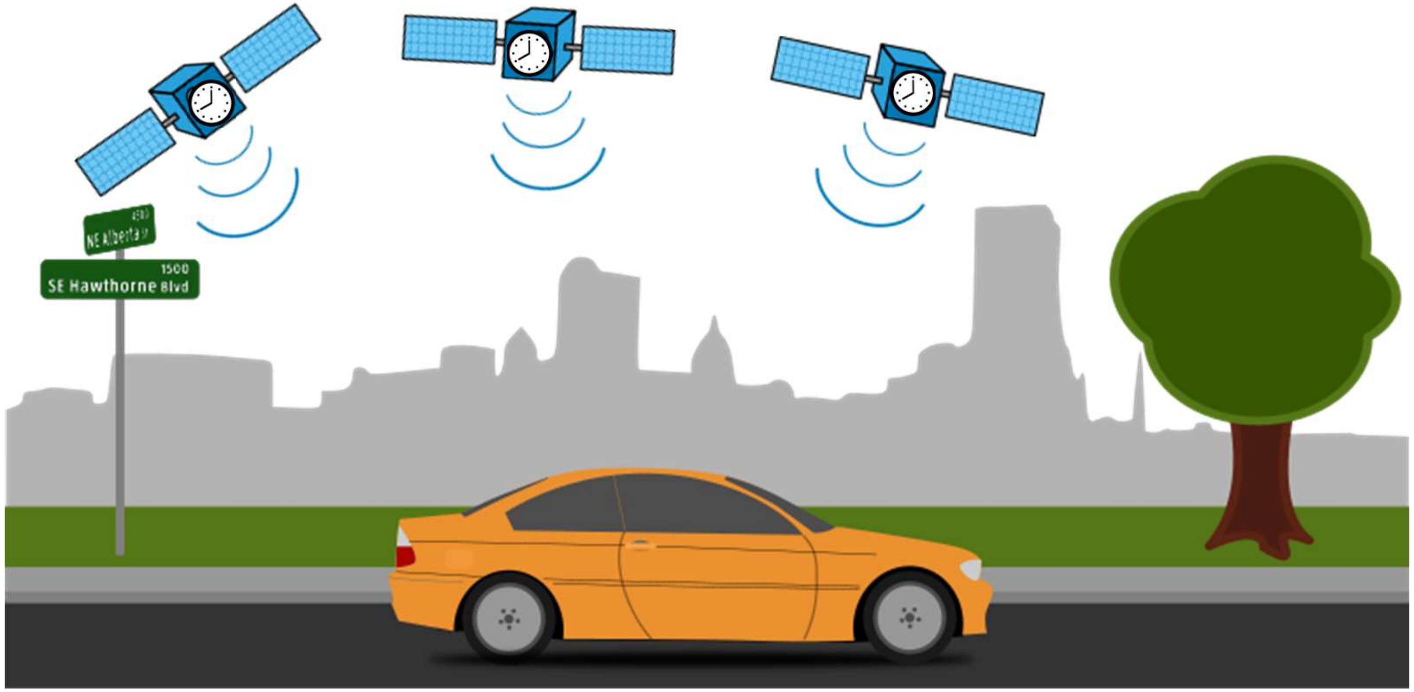
# USPs of Quantum Sensors

**Quantum Clocks: highest accuracy**



# Quantum 2.0 for Navigation and Time

**Quantum clocks are powering current global satellite navigation systems**

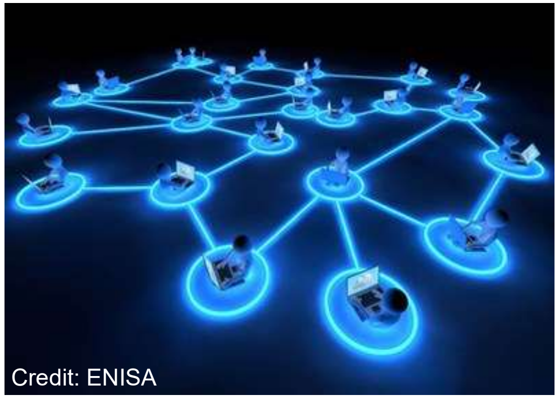



Navigation


Synchronisation

**Impact: 5-10% of GDP**

# Commercial Opportunities through Quantum Clocks


Credit: ENISA

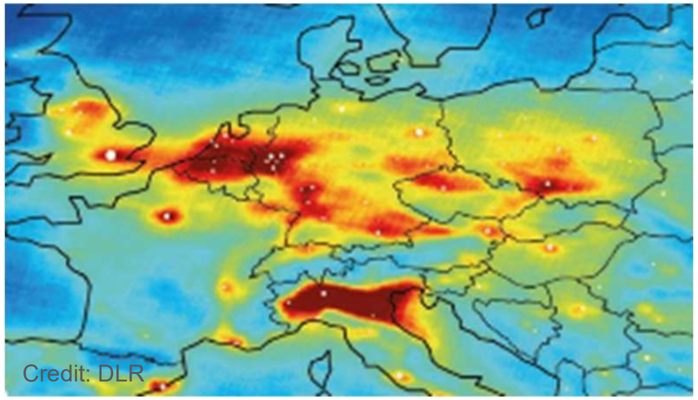
Communication


Credit: DLR

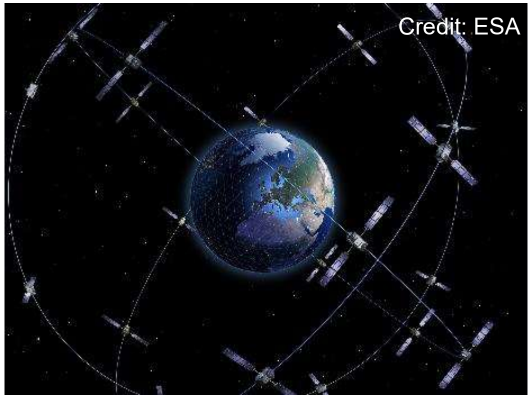
3D Radar


Credit: DLR

Urban Flight


Credit: DLR

Global Height Reference


Credit: ESA

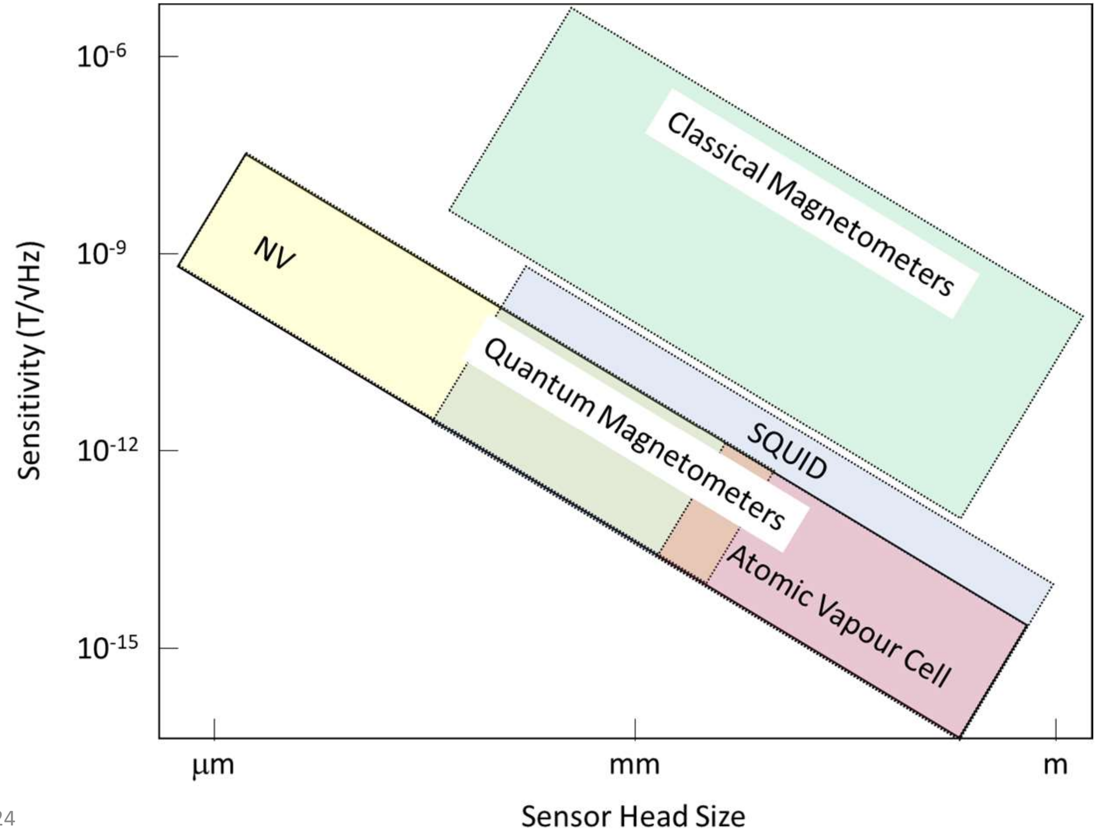
Satellite Navigation

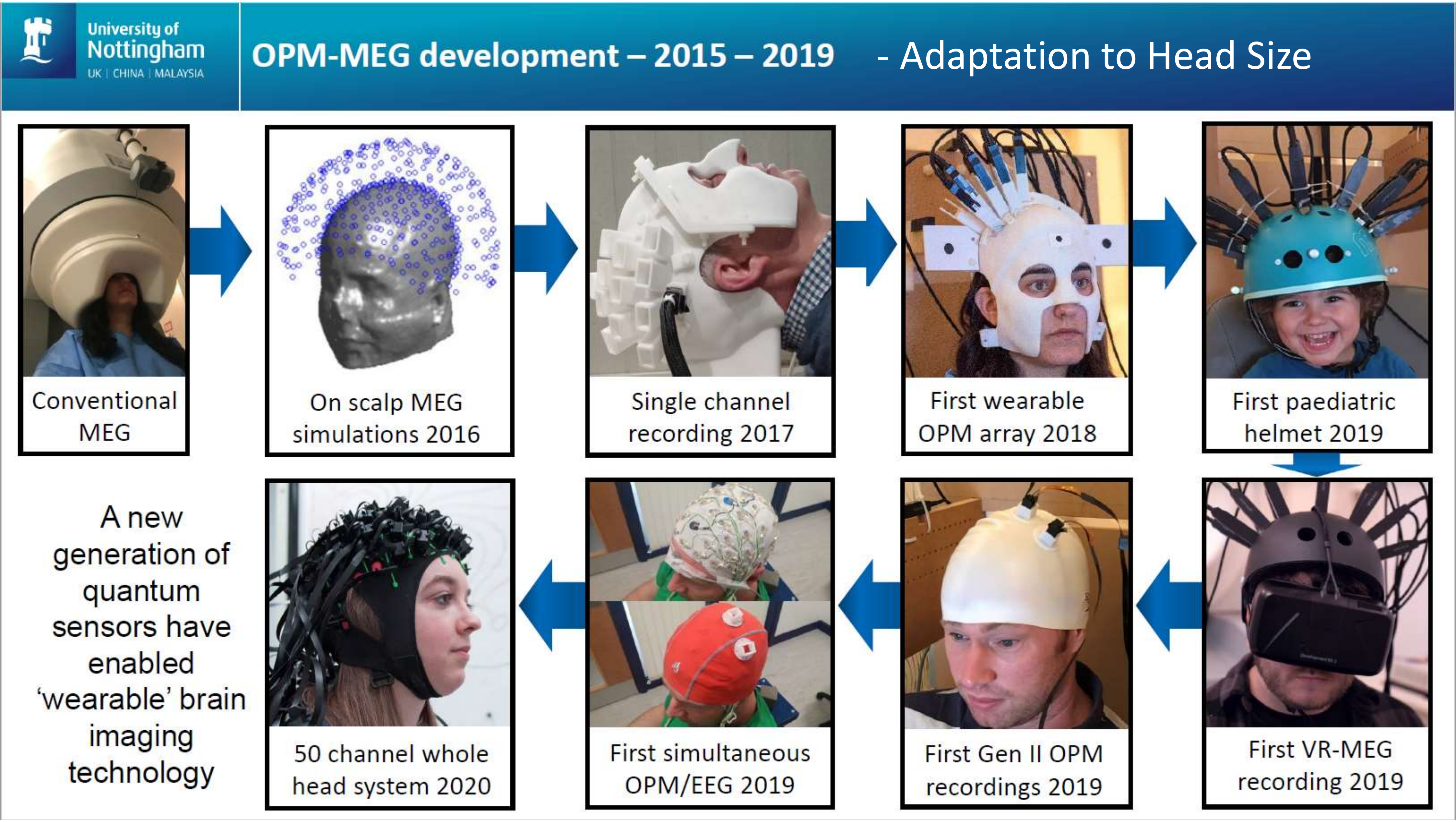

Credit: DLR

Autonomous Vehicles

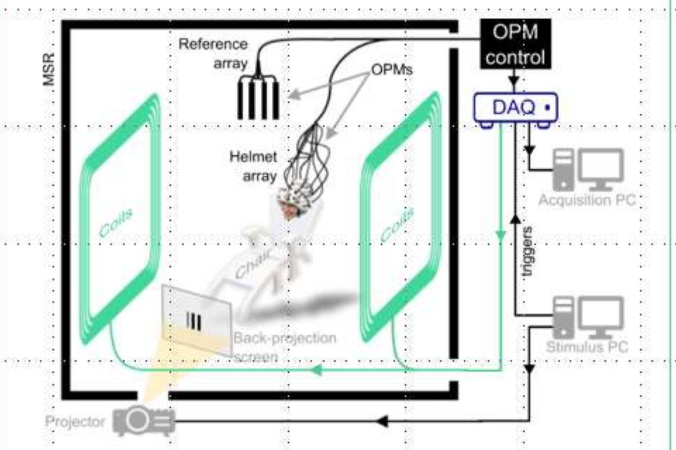
# USPs of Quantum Sensors

**Quantum Magnetometer: highest sensitivity at room temperature**




University of Nottingham
UK | CHINA | MALAYSIA
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

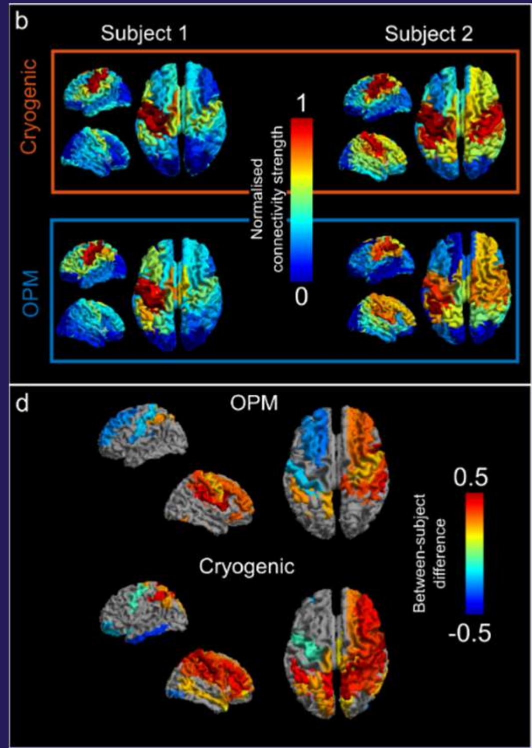



**Cerca's market offering:**

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

cerca
Magnetics Limited

Joint venture between University of Nottingham and Magnetic Shields Ltd.



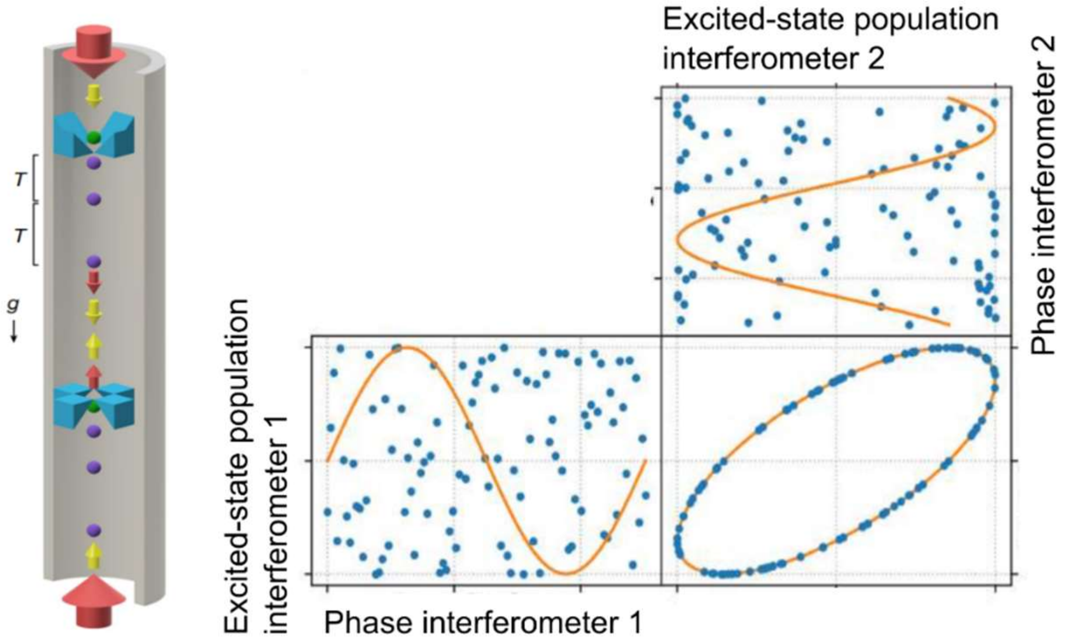

UK
Quantum Technology Hub
Sensors and Timing

UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

# USPs of Quantum Sensors

**Quantum Inertial Sensors (including gravimeters): low bias and high scale factor accuracy**

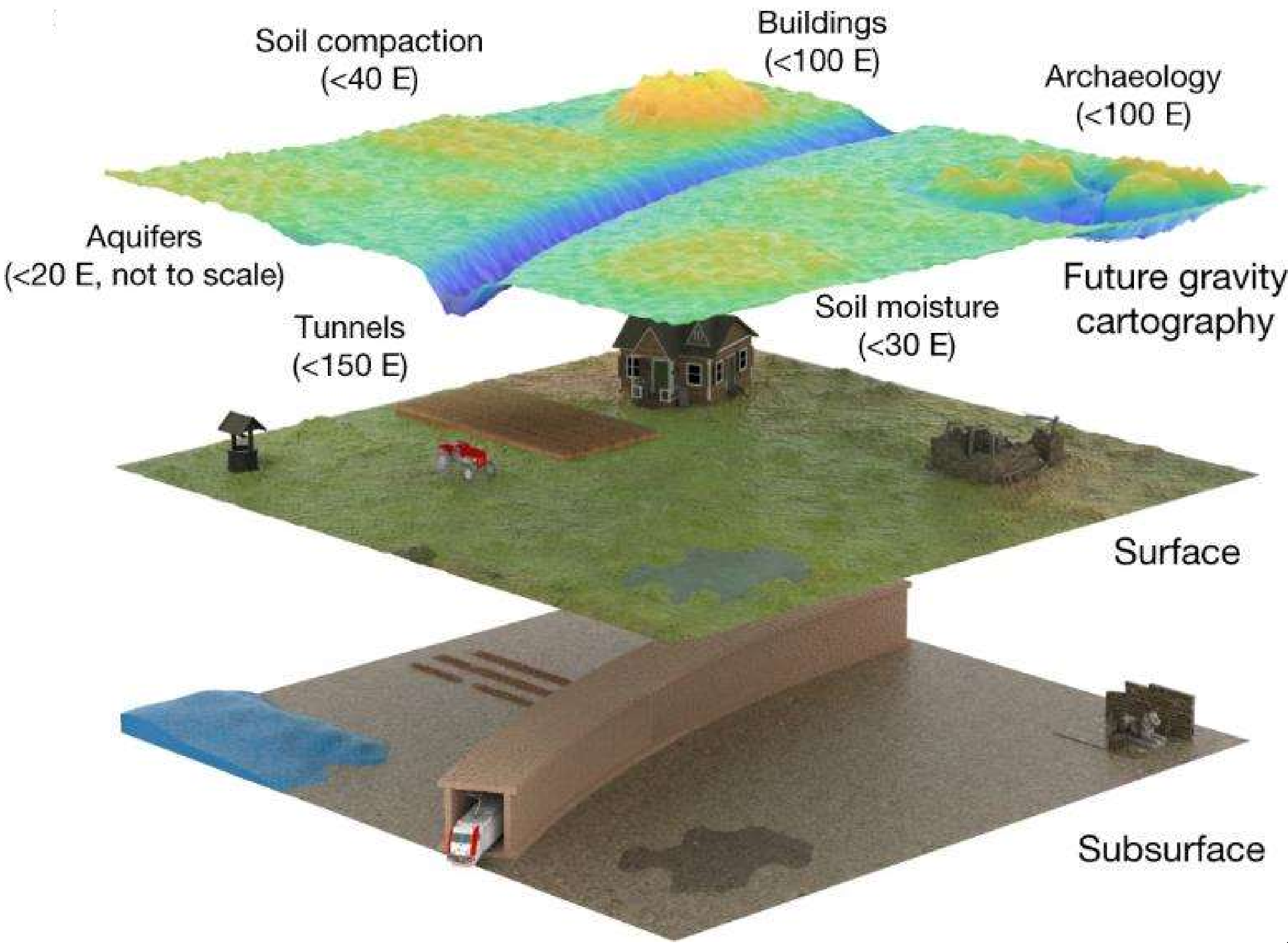
Allows e.g. high common mode suppression in differential measurements



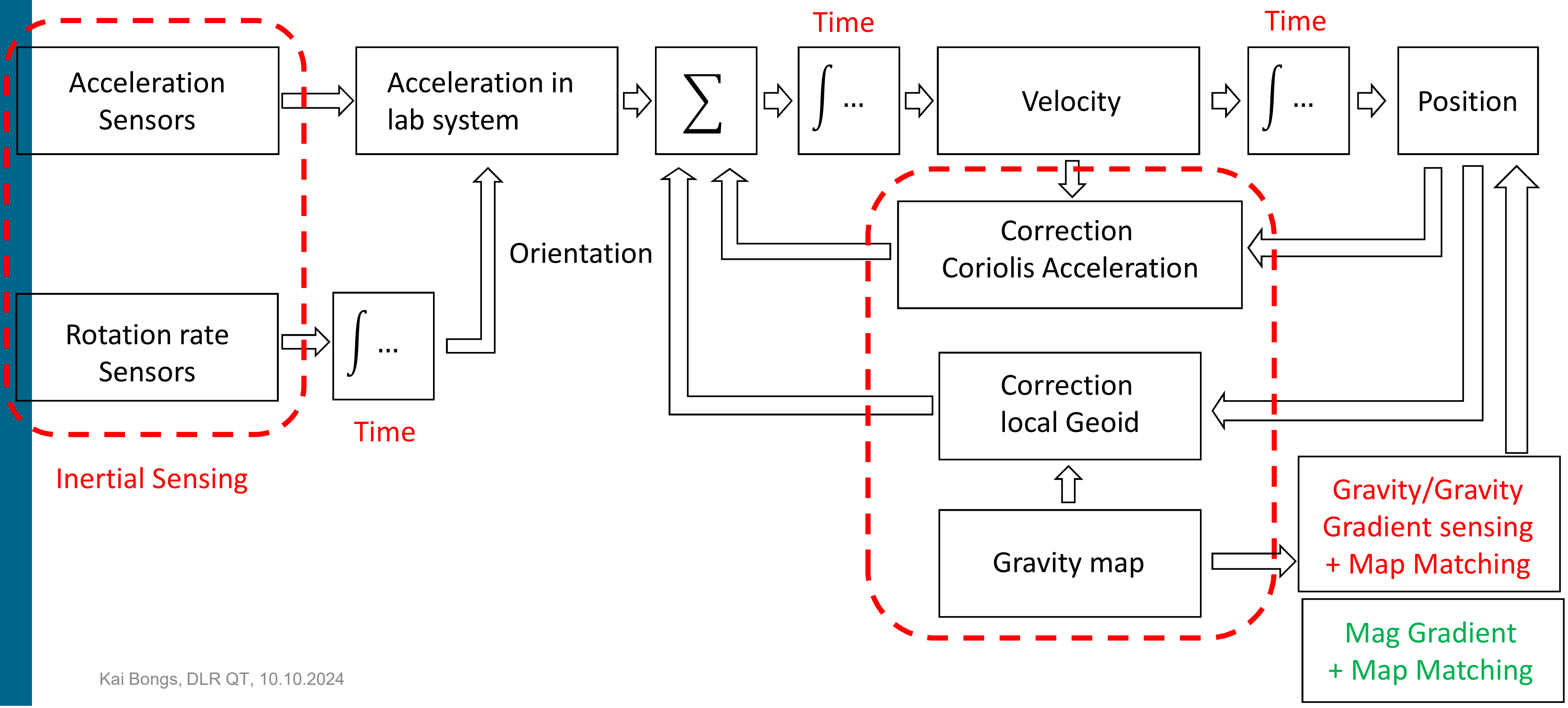

*Nature* **volume 602**, pages590–594 (2022)

# Enabling Gravity Cartography

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

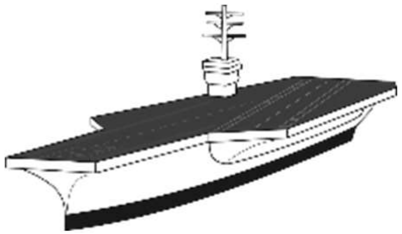


# Schematic Setup of a Quantum Navigation System

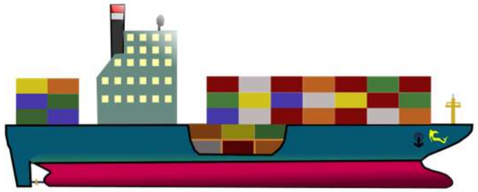


# Market Roadmap for Quantum Navigation Systems

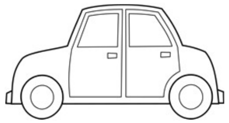
**Cost and regulatory requirements as key drivers**



Strategic platforms



Autonomous ships and underwater vehicles

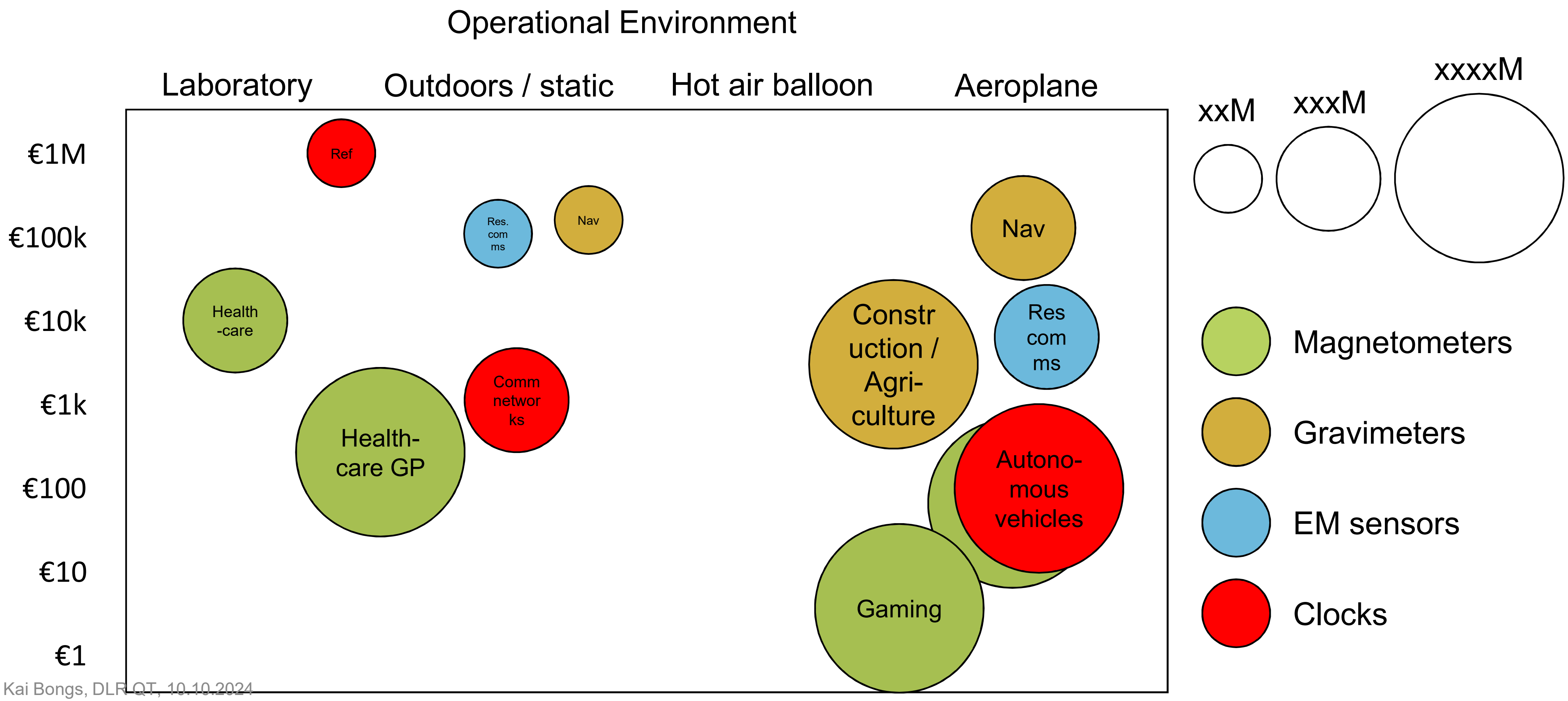


Autonomous vehicles

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

# Potentially Accessible Quantum Sensor Markets

## Key Drivers: Robustness and Cost



# Thank you for listening

**Questions?**

- Key messages:
- Quantum Sensors offer USPs, which could allow significant markets and huge economic impact
- Hybrid electro-optomechanicl integration is a key enabler for market success of quantum sensors