Quantum for Underground Sensing

An Overview in context of Dutch Quantum Ecosystem

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Image: Scope of ANT research – from integrated photonic & quantum tech to life science & forensics

What is Quantum 2.0

***Quantum 2.0** is enabled by modern technologies, allowing precise engineering and control of individual quantum systems.*

Two physical cornerstones of Quantum 2.0

Superposition

Flipping coin analogy

Entanglement

Quantum Anticorrelation

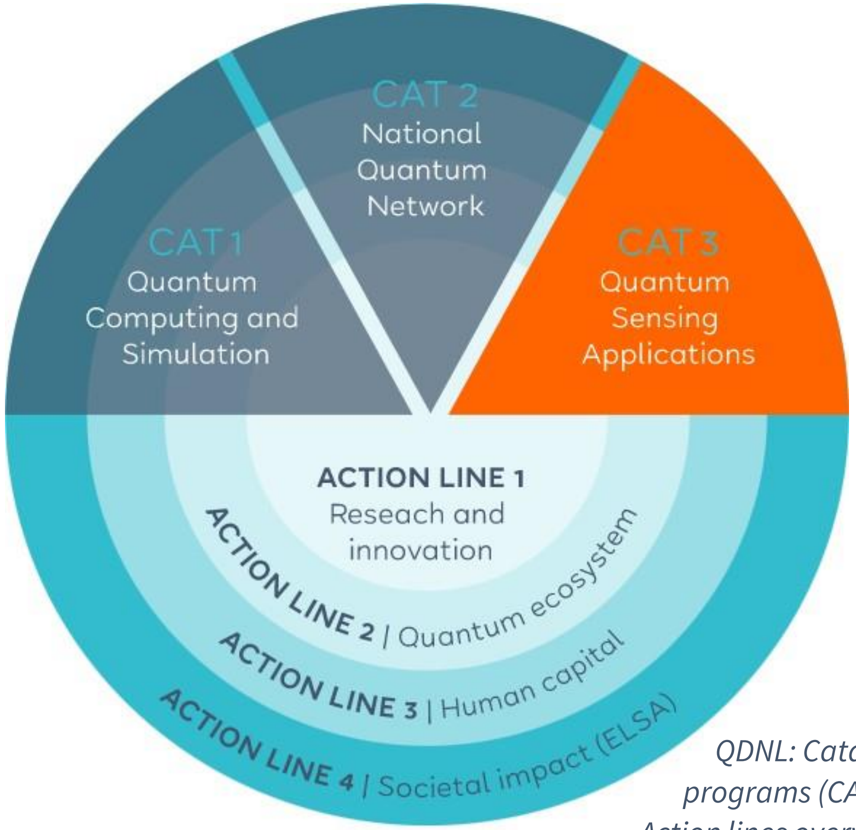
Coin A: |0> |1> |0> |0> …

Coin B: |1> |0> |1> |1> …

National Growth Fund Program

€615 million
2021-2027

QDNL



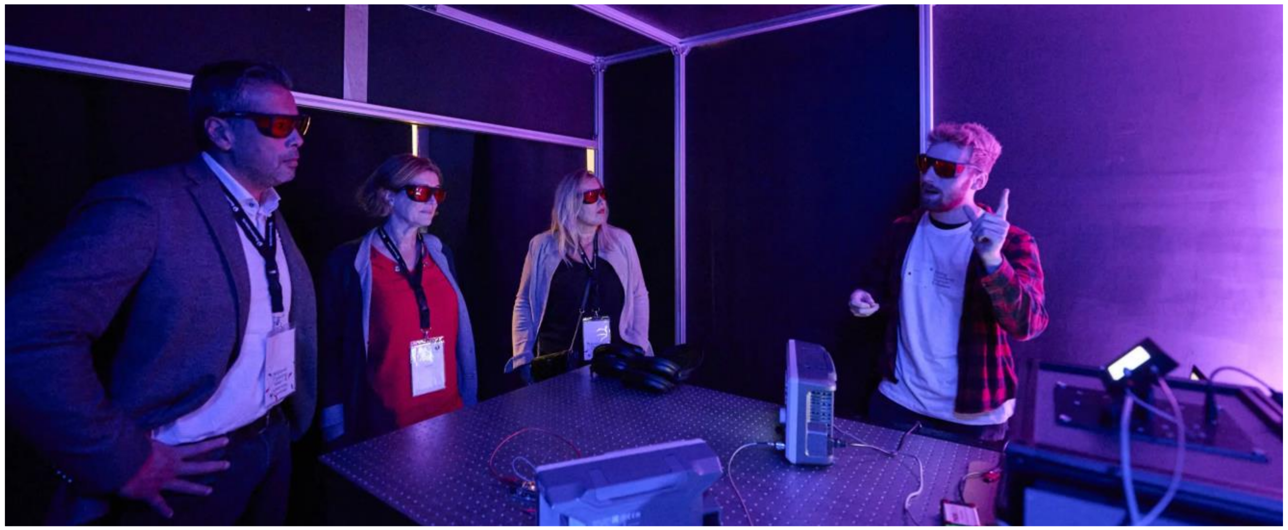
QDNL: Catalyst programs (CAT) & Action lines overview

Opening of Quantum Talent & Learning Center Twente

7 November 2023

QDNL

… and of our *Applied Quantum Photonics Lab*



Hogeschool van Amsterdam

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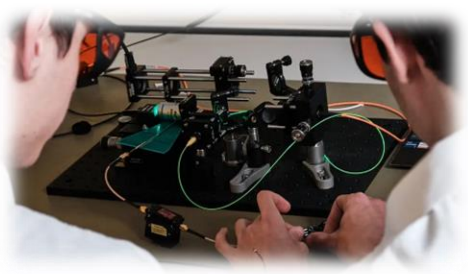
Applied Quantum Photonics Lab, ANT / TLC Twente, Ariensplein 1, Enschede

Applied Quantum Technology @ Saxion

Quantum System Design & Implementation

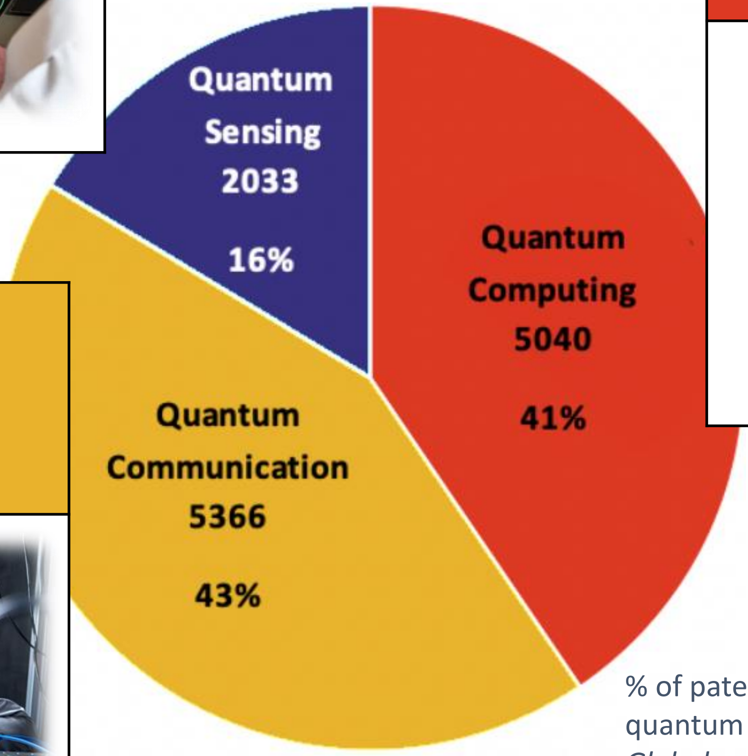
Quantum Sensing

NV-centers in diamond
Quantum sensing with undetected photons



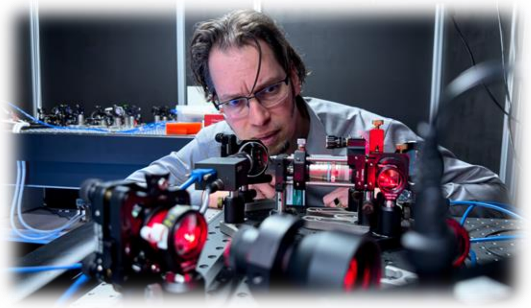
Photonic Quantum Computing

Quantum integrated photonics
Correlated photon-pair sources



% of patents by quantum segment: *Global overview, January 2024*

Quantum Secure Authentication & Communication



Quantum Sensing for Underground Detection

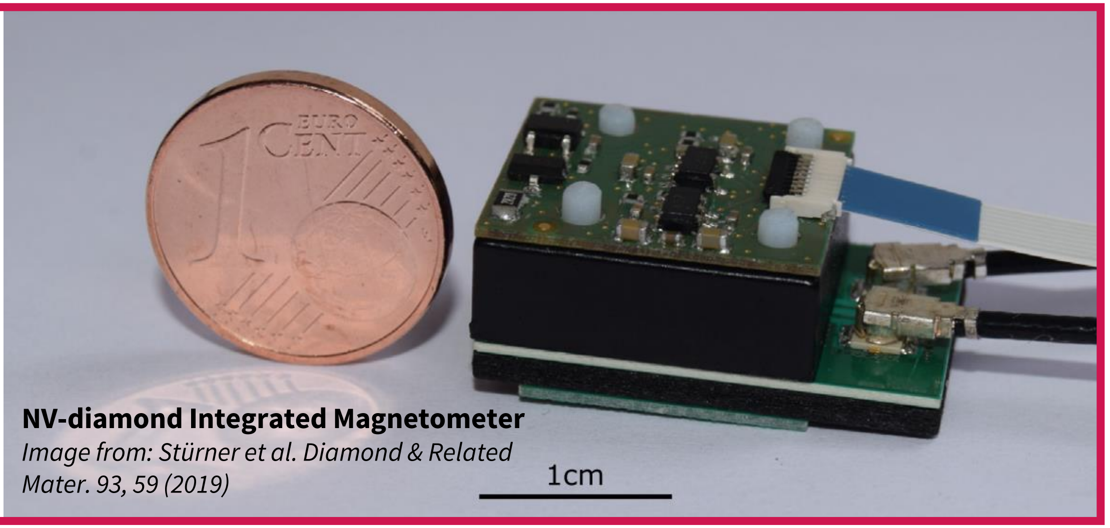
Two Main Modalities: Magnetic & Gravitational Anomalies

Nitrogen-Vacancies (NV) in Diamond Magnetometry

Sensitivity: exceptional sensitivity **(<10 pT/√Hz)** at **room temperature**

Specialty: Miniature, robust, however, not sensitive to non-metallic features.

Applications: From material science and neuroscience to microscopy to navigation and underground sensing



NV-diamond Integrated Magnetometer
Image from: Stürner et al. Diamond & Related Mater. 93, 59 (2019)

EXAIL Gravimeter on Mount Etna

Quantum Gravimetry using Atom Interferometry

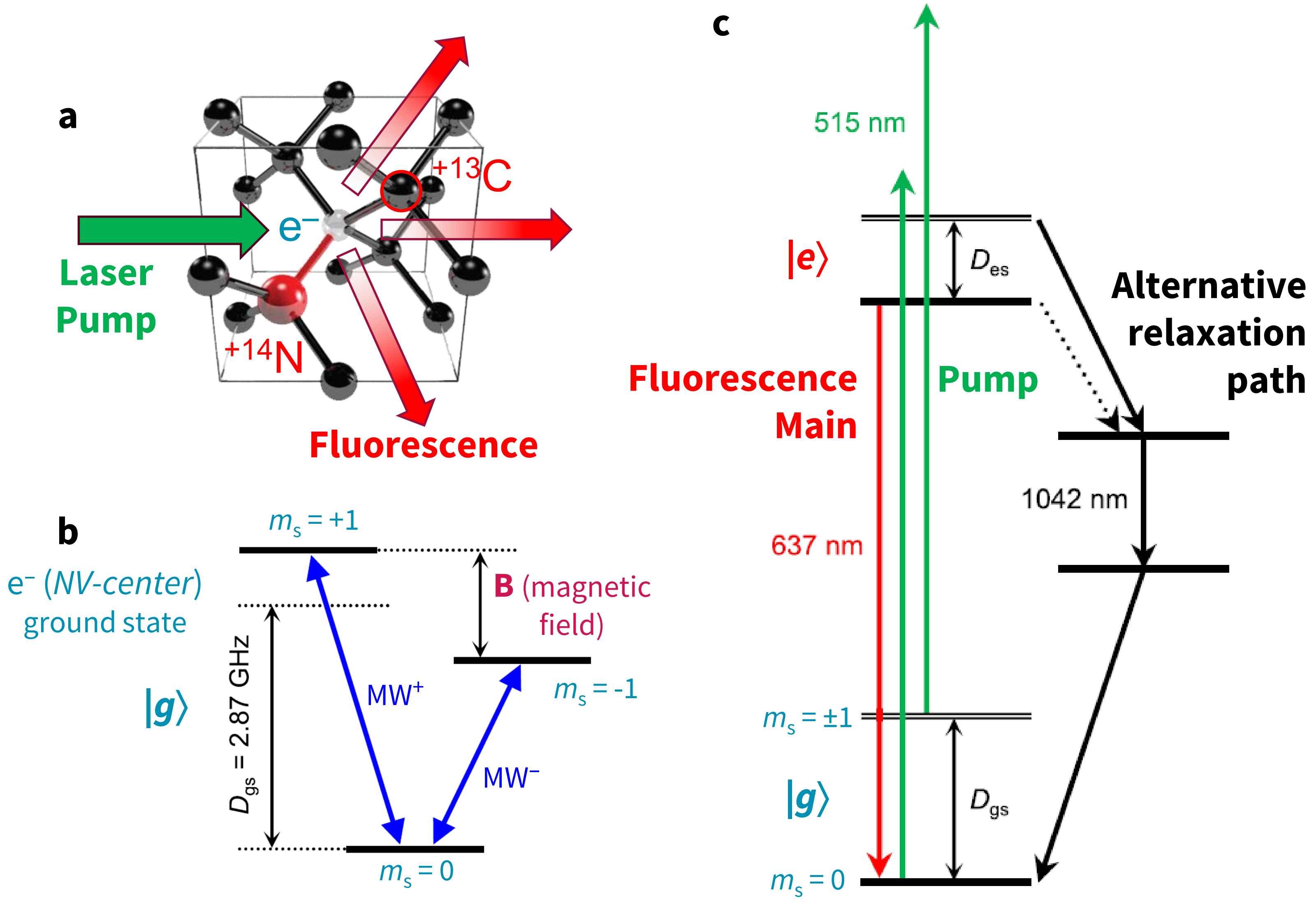
Sensitivity: **microgal (μGal)** acceleration level or **10^{-9} g** weight variation

Specialty: Sensitive to **non-magnetic features** such as voids, water-filled regions, or geological discontinuities

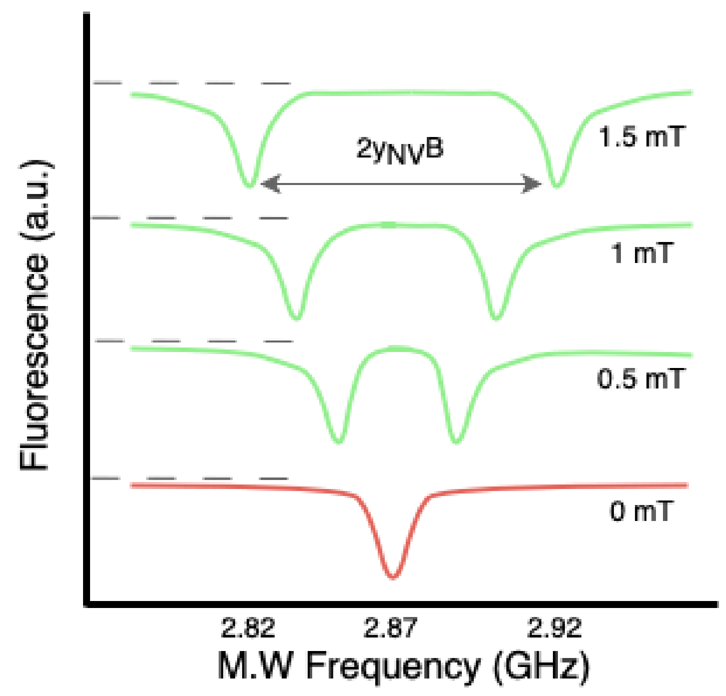
Applications: Geophysics, hydrology, volcanology, and surface imaging

Magnetometry using NV Diamonds

Principle & Measurements



Magnetic field measurements



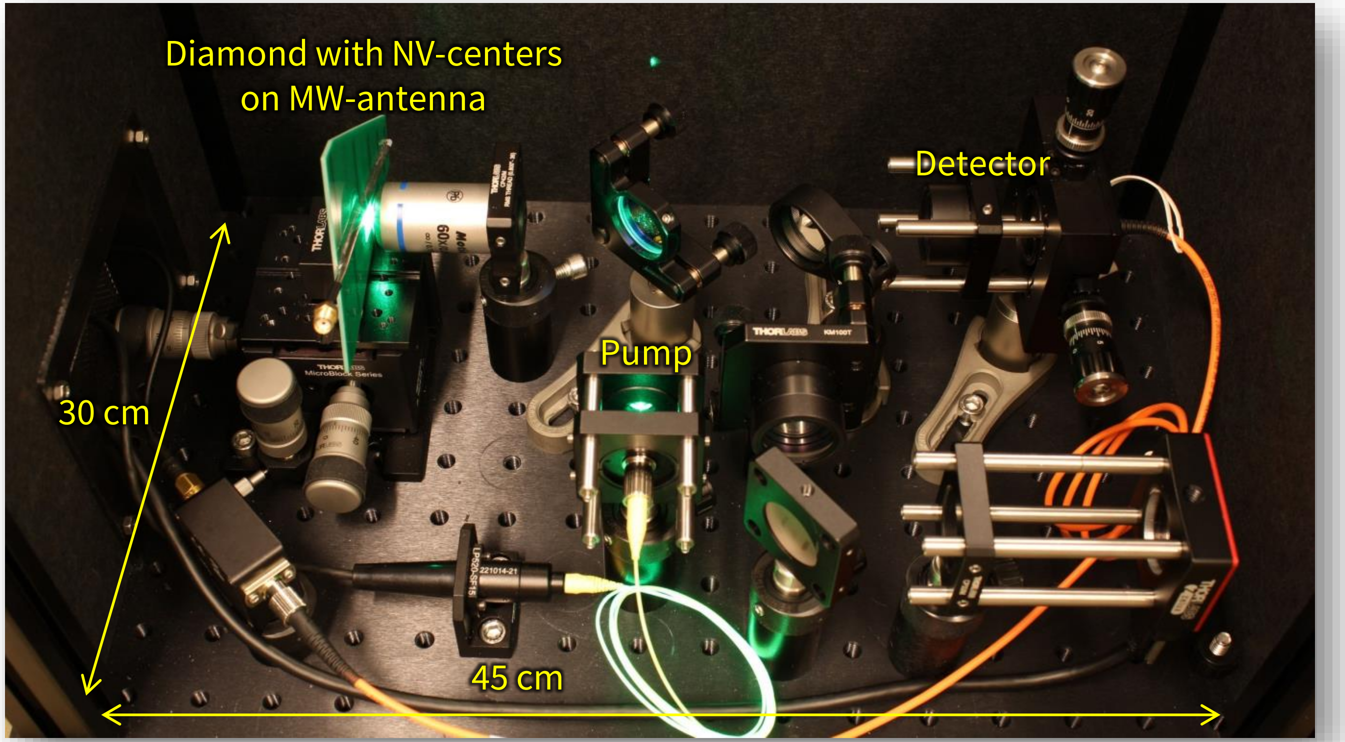
Images adapted from:

*[1] Eisuke Abe, and Kento Sasaki, J. Appl. Phys. **123**, 161101 (2018)*
[2] K. Jensen, P. Kehayias and D. Budker, Magnetometry with Nitrogen-Vacancy Centers in Diamond

Magnetometry using NV Diamonds

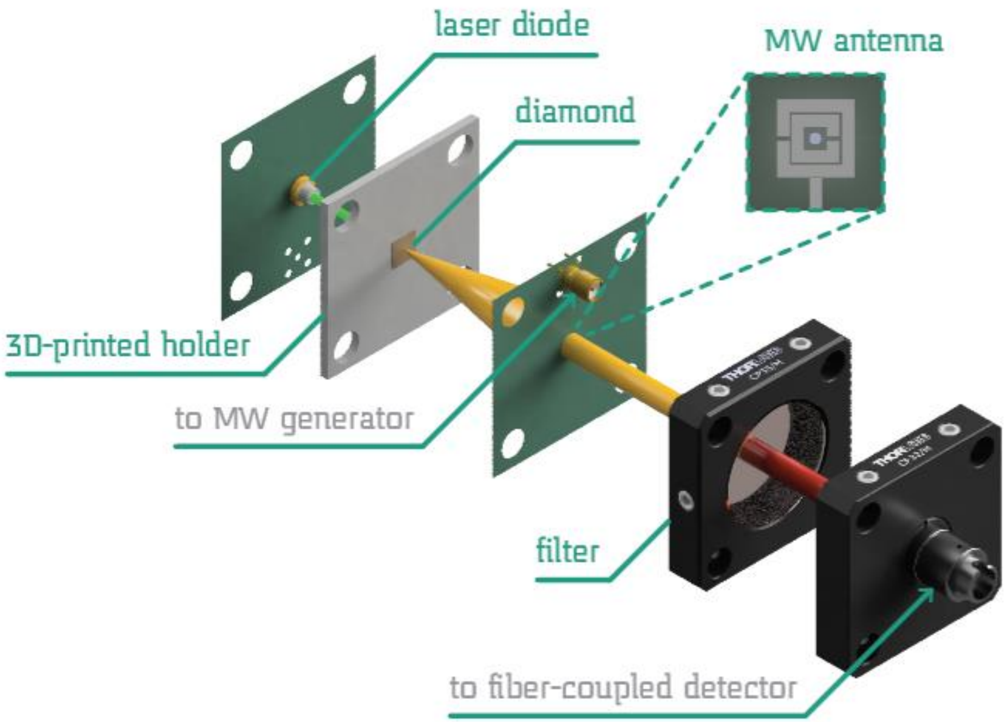
Developments at ANT, Saxion

Prototype 1: NV-center magnetometer for classroom demos



Courtesy of Demetra Sitnic, Ari Ortiz-Moreno, and Tjeerd Bollmann, ANT, Saxion

Prototype 2: Compact & portable NV-center magnetometer for in-field sensing



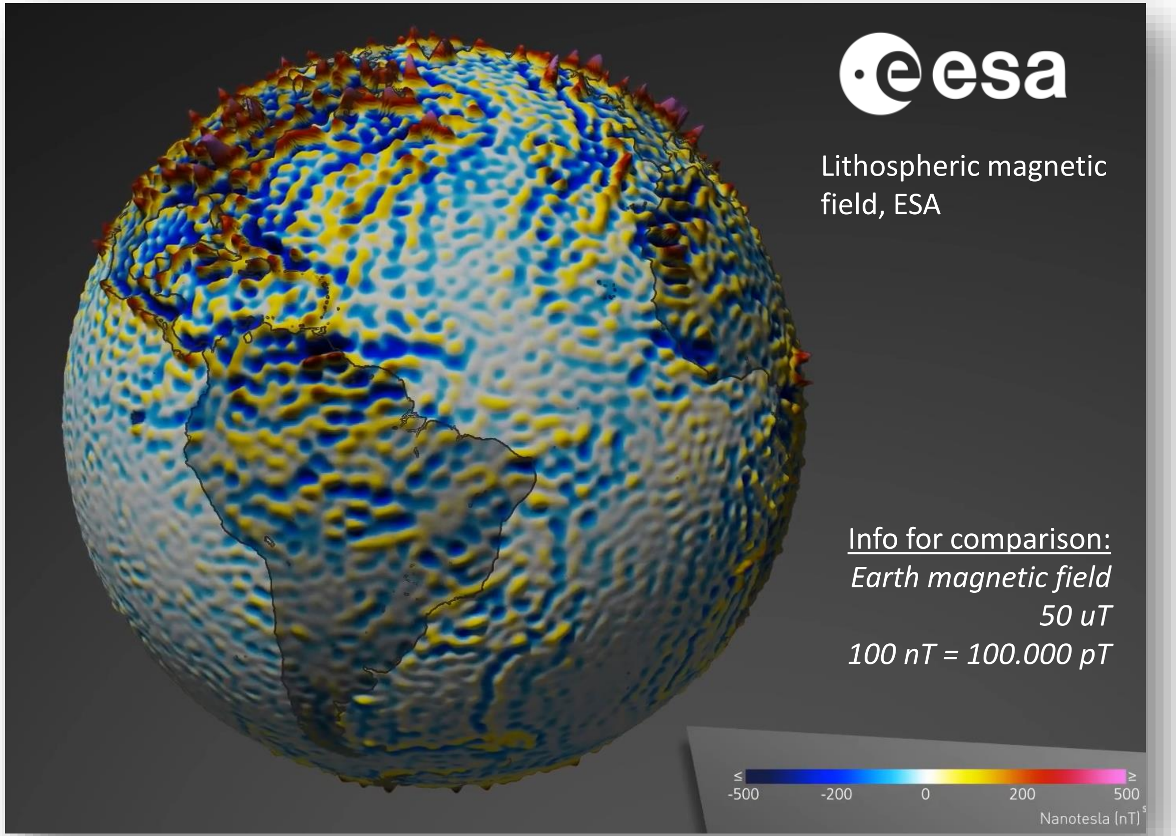
Magnetometry using NV Diamonds

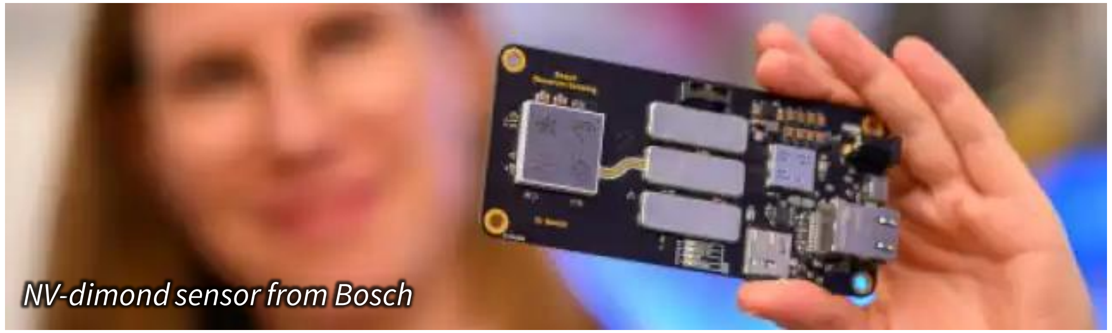
Underground Sensing

Pros & Cons

+ *Sensitivity:* 10-100 pT/√Hz (for typical NV-center assemblies), down to ~1 pT/√Hz
+ *Formfactor:* compact (cup-size) and light (< 1 kg)
+ *Vectorial magnetometry*: measures both the magnitude and direction of the field

– Suitable only for **objects with magnetic features**, like cables, iron-rich rocks, steel-reinforced structures, etc.
– Not suitable for underground voids, water-filled regions, or geological discontinuities




NV-dimond sensor from Bosch

Selected applications

- High-resolution maps of surface magnetic anomalies (e.g. airborne by drones): the meter scale is possible
- Buried structures, cables detection, groundwater flow (?)
- GPS-denied navigation

Magnetometry using NV Diamonds

Quantum Sensing Testbed at TNO

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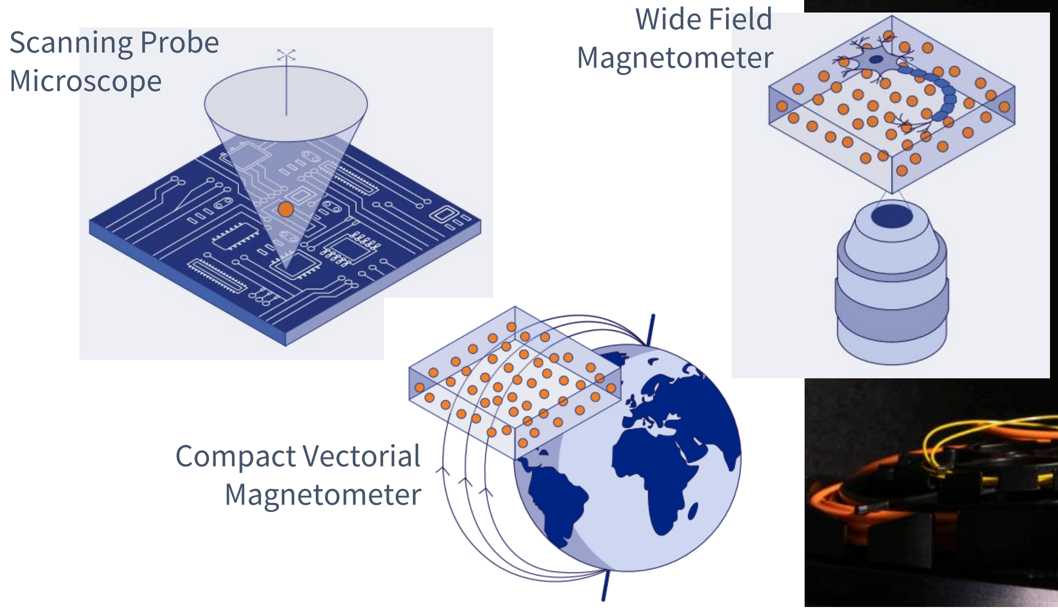
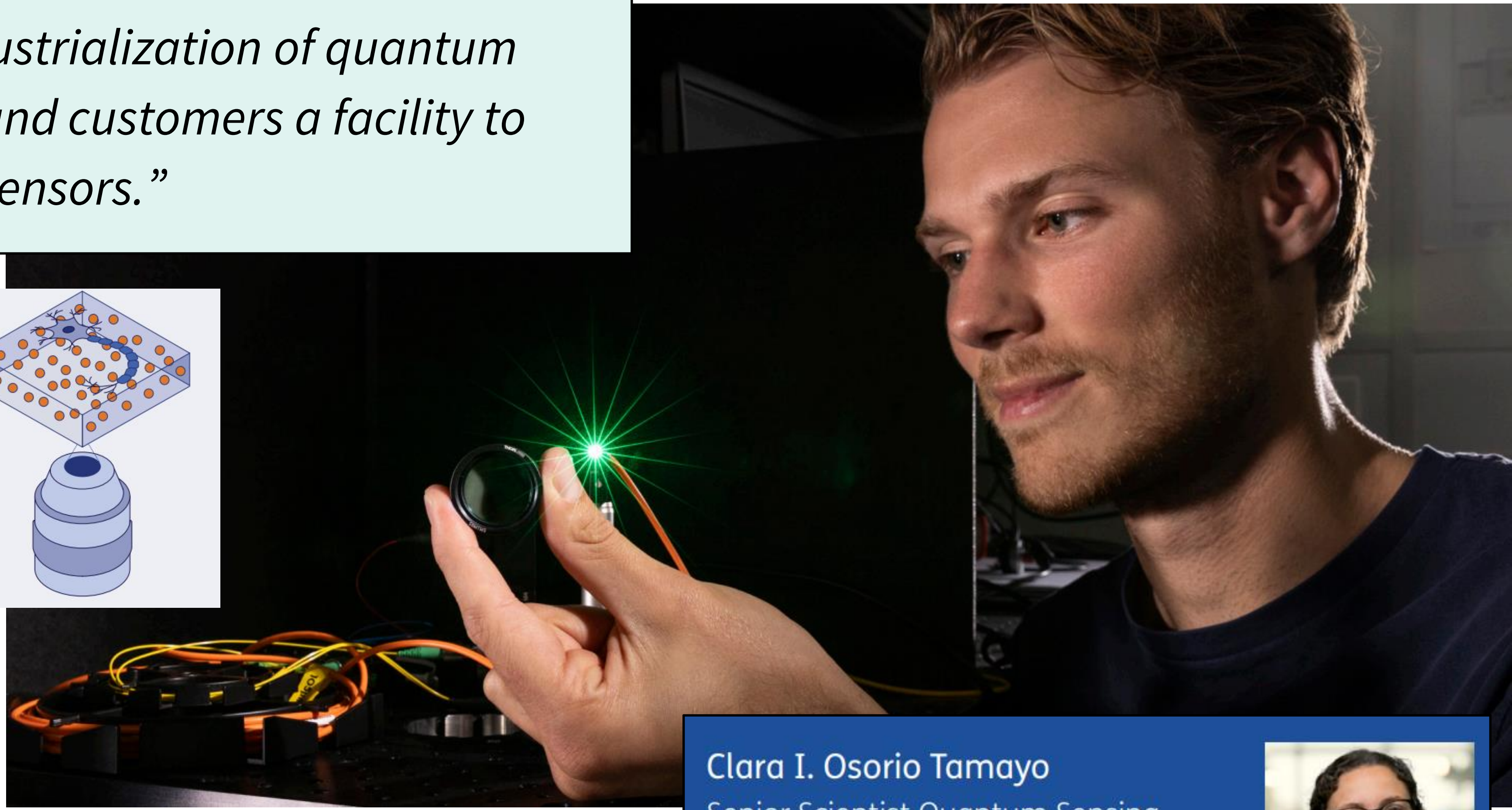
QDNL

Mission: "To accelerate the industrialization of quantum sensors by providing partners and customers a facility to test state-of-the-art quantum sensors."





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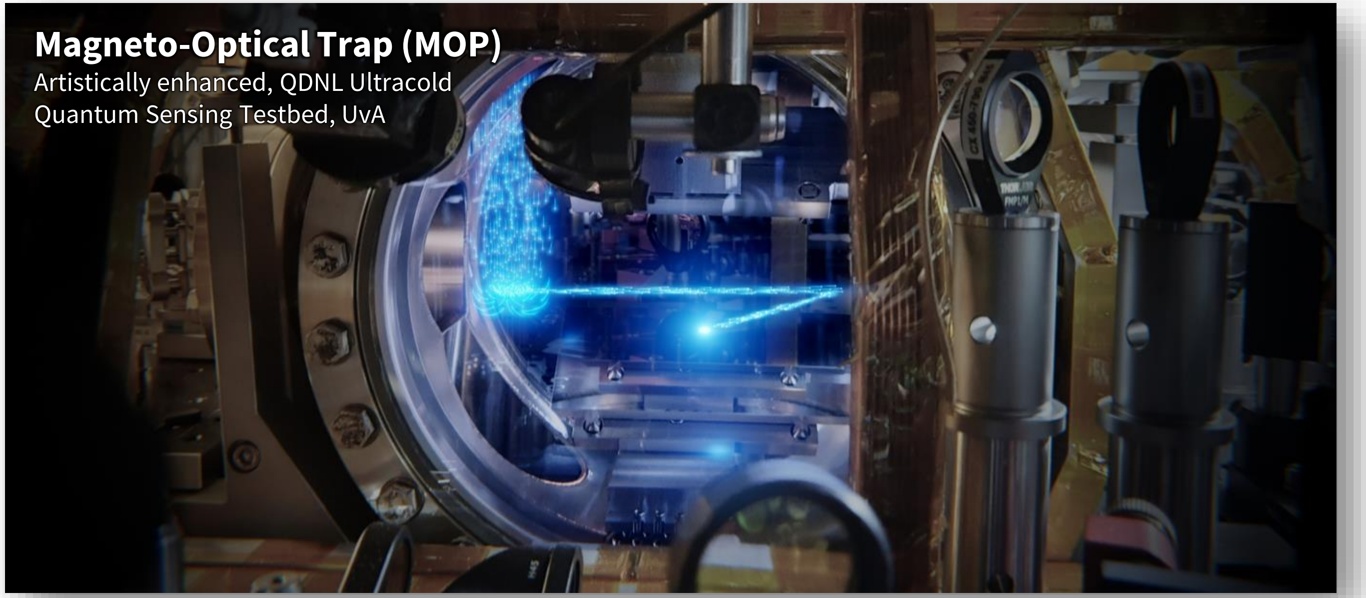
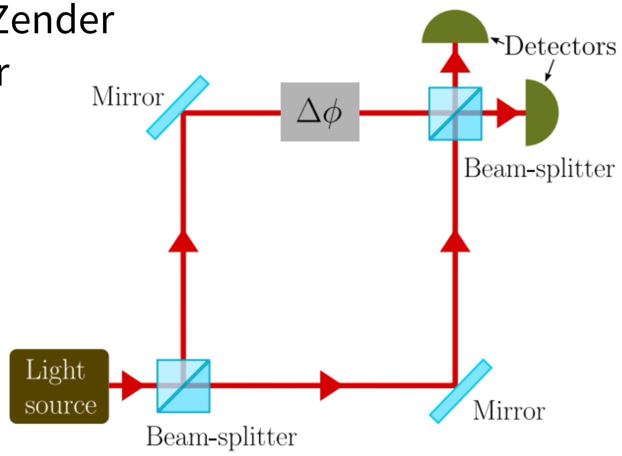
TNO innovation for life

Quantum Gravimeter based on Atom Interferometry

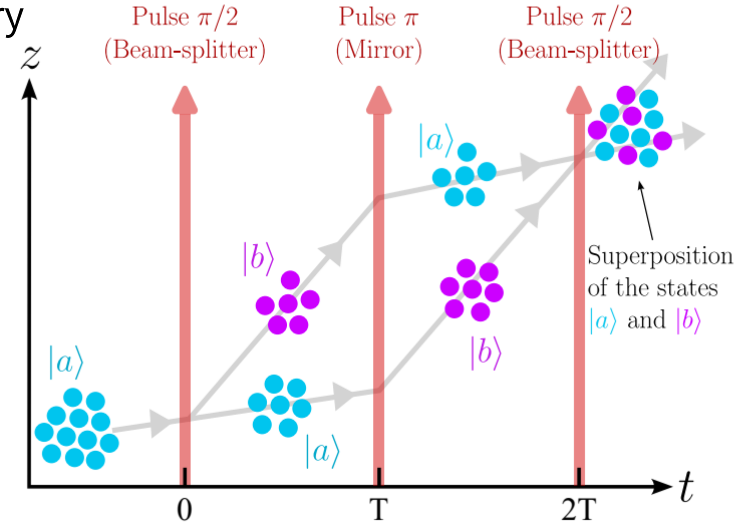
Physical Principle



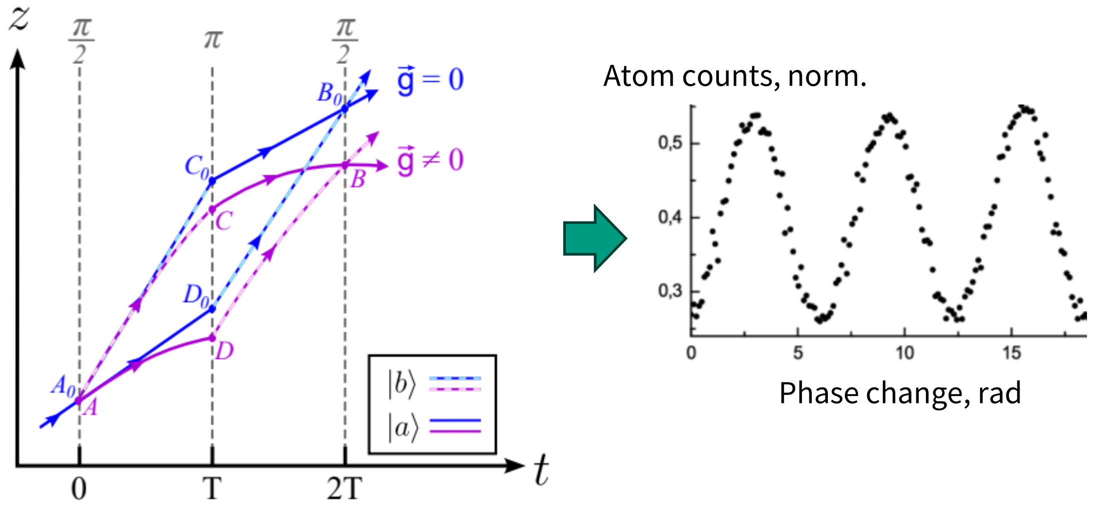
a Optical Mach-Zender Interferometer



b Quantum MZI for atom interferometry



c Gravity effect on atom interference



Graphics source: I.R. de Sauza Jn., Quantum gravimeters for geophysical applications, PhD thesis, 2025

Quantum Gravimeter based on Atom Interferometry

How practical is it?

Pros & Cons

+ *Absolute (not relative) gravimeters!*
+ *Sensitivity:* microgal (μGal) acceleration level or 10^{-9} g weight variation
+ *Longterm stability* without recalibration
+ Sensitive to non-magnetic features such as voids, water-filled regions, or geological discontinuities

– Complex and large systems, though transportable(!), and expensive (up to €1 million or more)

– Sensitivity to vibration: sophisticated vibration compensation is required. Therefore, difficult integration with drones or aircraft.

– Slow measurements, therefore, less suitable for rapid surveys / gravitational mapping

Product example:

Exail AQG-A, France
<100 kg
≈1 m³ form factor

Applications: Groundwater flows, volcanic mass changes, underground cavities / voids, carbon storage monitoring

Engineering challenges: optical systems with reduced size and power consumption, compact and efficient vacuum systems, improved vibration compensation and control.

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Atom Quantum Sensing in the Netherlands

QDNL Ultracold Atom Quantum Sensing Testbed

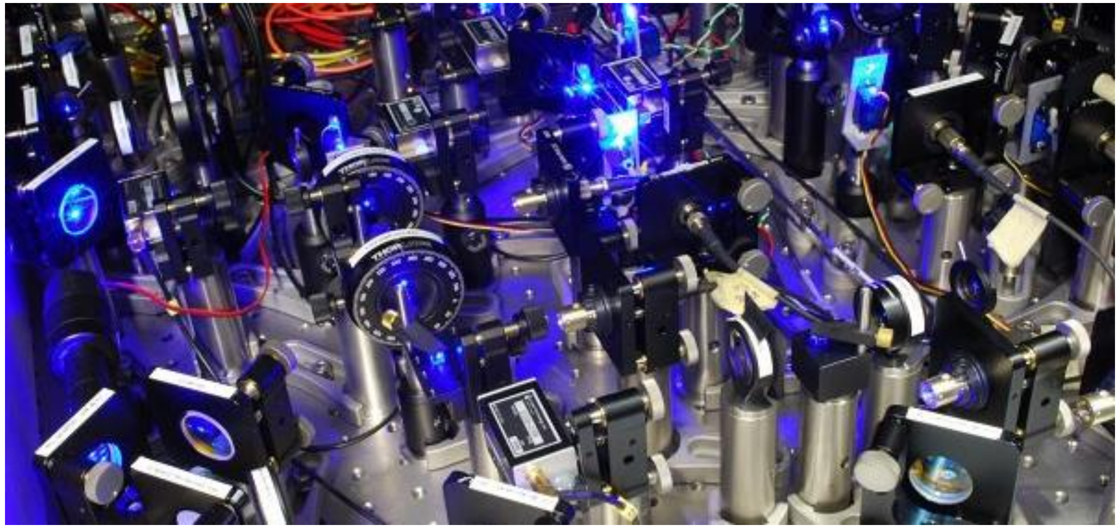
QDNL

Mission: "To explore atom interferometry, atomic clocks and time-frequency distribution together with industry."

UNIVERSITY OF AMSTERDAM

Hyper-accurate clock using a continuous flow of ultracold Sr atoms

Quantum technology for hyper-accurate clock, NWO news article, 2021



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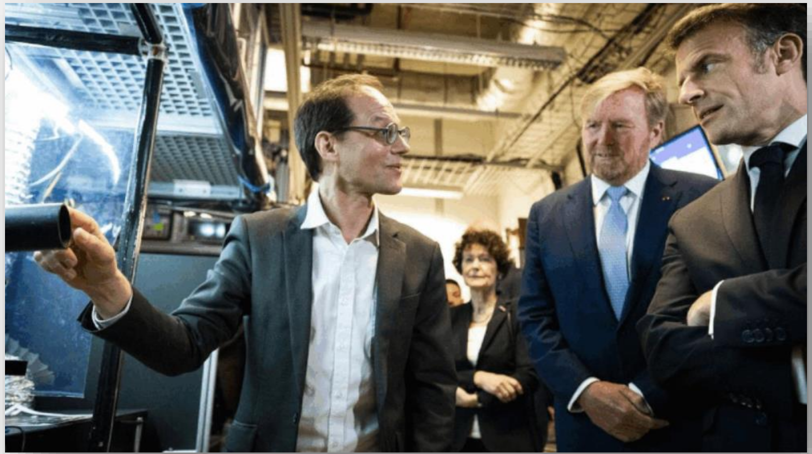
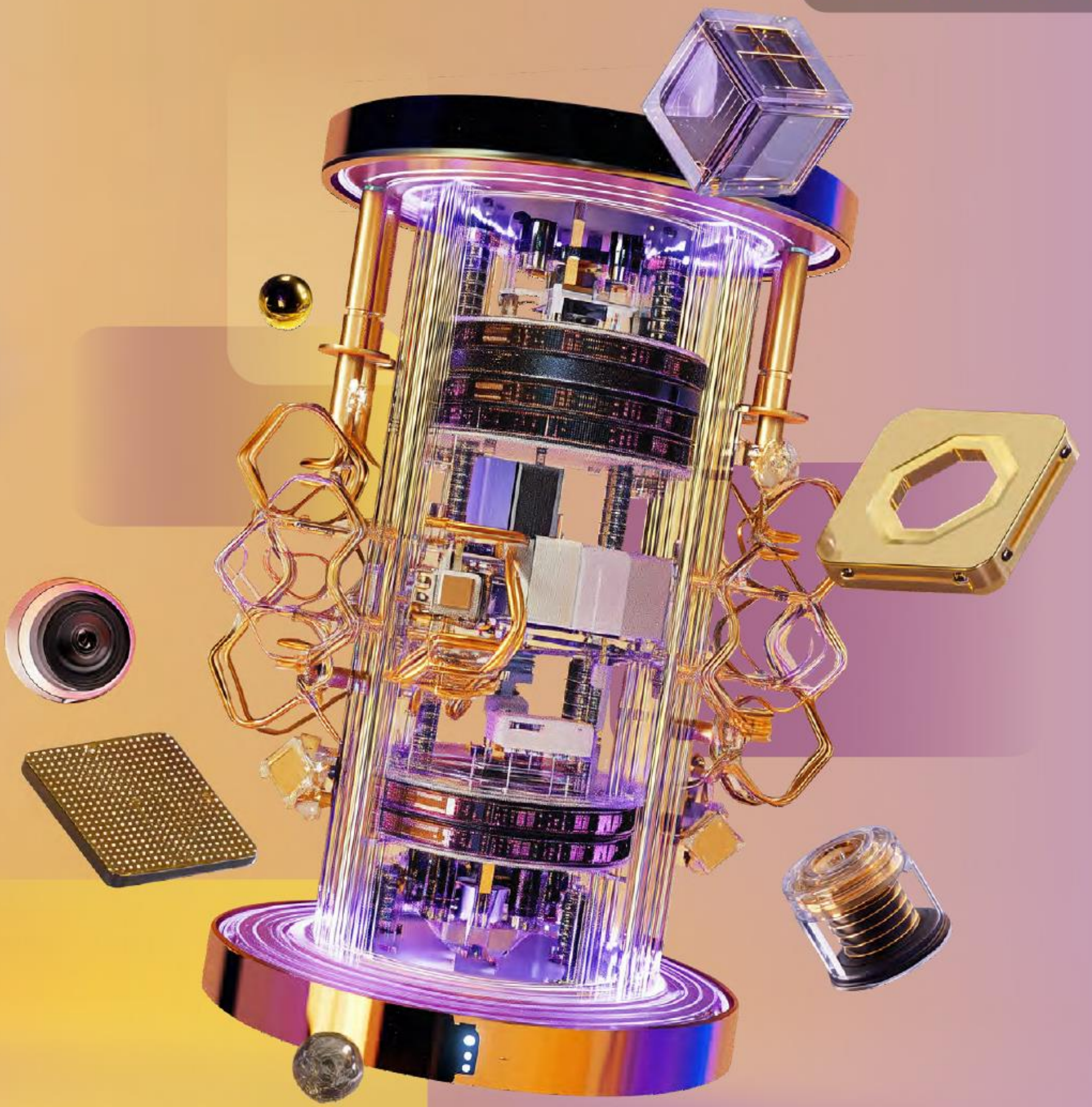


Quantum Technologies



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Thank you!

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