Market Research Study in Nanoscale Quantum Optics

COST Action MP1403 “Nanoscale Quantum Optics (NQO)”, TEMATYS

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Tematys Exploration of photonics markets

Motivation

- Aim of the COST Action NQO has been to support and coordinate research activities in **nanoscale quantum optics**, explore innovative approaches by identifying, establishing and exploiting cross-links between **quantum science & technology, nanoscale optics & photonics and materials science**, and facilitate the early-involvement of end-users

- The Action has recently released a **NQO Research & Innovation Roadmap** disseminated in Europe to various decision makers

- It has commissioned a **Market Research Study (MRS)** to present the innovation potential of the field in terms of application opportunities and markets

Contents

Introduction & Methodology

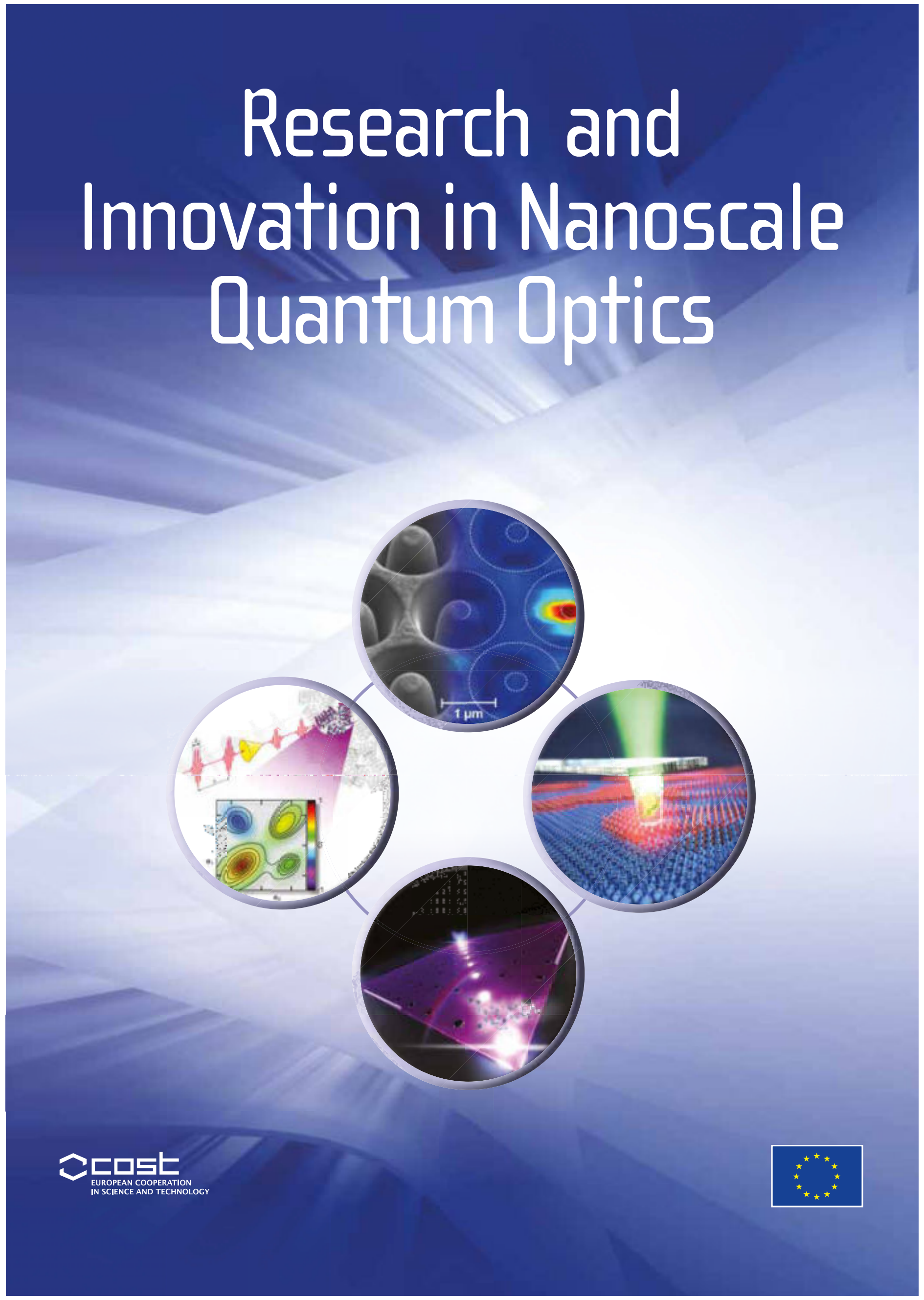
COST Action NQO - Scientific Focus

4 Working Groups
Generation, detection & storage of quantum states of light at the nanoscale
Nonlinearities & ultrafast processes in nanostructured media
Nanoscale quantum coherence
Cooperative effects, correlations and many-body physics tailored by strongly confined optical fields

Applications: ICT, sensing & metrology, energy efficiency

The NQO Roadmap

- Outlines research and innovation in NQO
- Shaped during Action's meetings and other networking events
- Structure of the NQO Roadmap:
    - Executive summary
    - Presentation of the COST Action NQO
    - 4 working-group scientific areas
        - Research topics
    - Technological outlook
- Available for download at: www.cost-nqo.eu/support/documents/



Technological Outlook

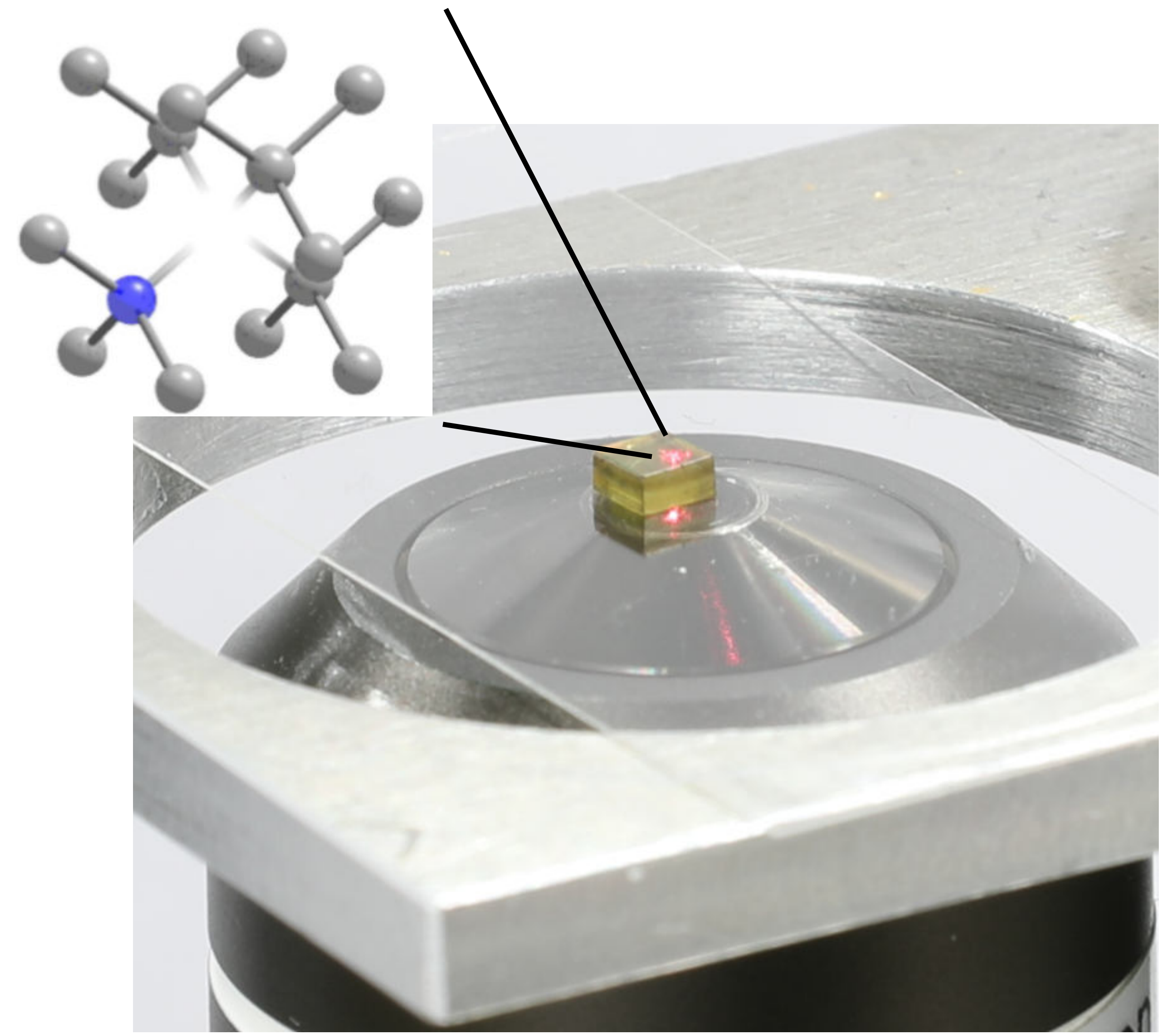
- Several companies have emerged or have expanded their activities in the field of NQO
- Quantum Photonic Devices and Systems:
  - Single-photon sources
  - Single-photon detectors
  - Photonic integration
  - Single-spin sensing
- Enabling technologies:
  - Software
  - Lasers
  - High-speed electronics
  - Cryogenics
- COST Action NQO industry partners at www.cost-nqo.eu/industry

MRS: Approach & Methodology

- May 2018 - Initial market analysis to identify technologies (NQO Roadmap and COST Action)
- June 2018 - Positioning in terms of functions and characteristics that can be of interest for companies, collect information through discussion with players along the value chain (workshop, interviews, …)
- September 2018 - Validation of potential applications and market information (online surveys, interviews, …)
- November 2018 - Final market analysis (acquisition of missing information by follow-up bilateral discussions, interviews and secondary research, …)

Selected Topics

- Quantum Communication
  - Quantum Key Distribution (QKD)
  - Quantum Random Number Generator (QRNG)
- Quantum Sensing
  - Atomic Sensors
  - Sensors based on Nitrogen Vacancy (NV) centres



(courtesy of U Siegen)

Quantum Communication

Quantum Communication

- Communication systems that use quantum effects to securely transmit data
- Near-term technologies: QRNG for secure key or token generation, point-to-point QKD for secure key exchange in crypto systems
- Mid/long-term technologies: quantum key distribution (QKD) networks, quantum repeaters, …
- Expected applications: telecom, fin-tech, online gaming, security and defense, commercial transactions, user authentication, ATM withdrawals, …

Quantum Random Number Generators (QRNG)

- Most applications (e.g. computer simulations) for random numbers use pseudo-random numbers, i.e. series with an extremely long period.
- However the fundamentals of quantum mechanics - state superposition and quantum measurement - allow for generation of true random numbers in a relatively simple way.
- Competing technology (True RNG) exploits physical unclonable functions (PUF) in complex physical systems
- Example: two integrated circuits even with the same layouts cannot be identical

QRNG - Key Results

- First expectation is on higher generation rate and device size in this application segment (power comes next)
- Supplementary value for QRNG is not clear against former True RNG, whereas extra-cost is clearly perceived
    - “True RNG” from electronic manufacturers (phase noise, electronic noise) are sold as ASICs and FPGA chips at 1-2 $ for 1000 units
    - Other quantum solutions (radioactive decay) allows Gbps RNG data-rate for few tens $
    - 60% don’t envisage optics-based RNG in future products
    - Internet of Things will require QRNG for few cents, automotive sensors for no more than 1 $. About target market for QRNG, end-price should be less than 20$ for markets around 10k to 100k units (answers from telecom companies)
- There is potentially an opportunity for QRNG in QKD systems as a complement manufacturer’s portfolio in the whole system
- Same issue as atomic-clock on chip: Technical feasibility to integrate a RNG function on-chip, but what about the market linked to this level of performance?

Superior randomness of QRNG versus PUF?

- METAS has awarded the QRNG devices a certification based on applying the Diehard tests over 10 data sets of 100 MB for each tested device. Other TrueRNG devices, *urandom* and *Chaos Key* both pass these tests under similar conditions and are significantly less costly.

- The difference between the biases in each QRNG module sample suggests that the issue is not reproducible in any single form, but instead, a unique set of biases is generated in each sample. This shows that there is a degree of randomness provided by these devices, likely sufficient to appear random when tested under traditionally accepted suites such as FIPS 140-2, NIST STS, and Diehard. However, a byte-level analysis shows that there is a consistent degree of failure and associated levels of bias, despite the changing form, in which said bias presents itself between samples from a single device.

- It is advisable to test innovative random number generators with as many available tests as possible, with as large a sample as technically possible.

References QRNG

- *Quantum random number generation*, X. Ma, *et al.*, npj Quantum Information 2, 16021 (2016)

- *Quantum random number generators*, M. Herrero-Collantes, J.C. Garcia-Escartin, Review Modern Physics 89, 015004 (2017)

- *Quam Bene Non Quantum: Bias in a Family of Quantum Random Number Generators*, D. Hurley-Smith, J. Hernandez-Castro, Cryptology ePrint Archive: Report 2017/842 (2017)

Quantum Key Distribution (QKD)

- Quantum key distribution (QKD) is a secure communication method, which implements a cryptographic protocol involving quantum mechanics.

- It enables two parties to produce a shared random secret key, which can then be used to encrypt and decrypt messages

- An important and unique property of QKD is the ability to detect the presence of any third party trying to gain knowledge of the key

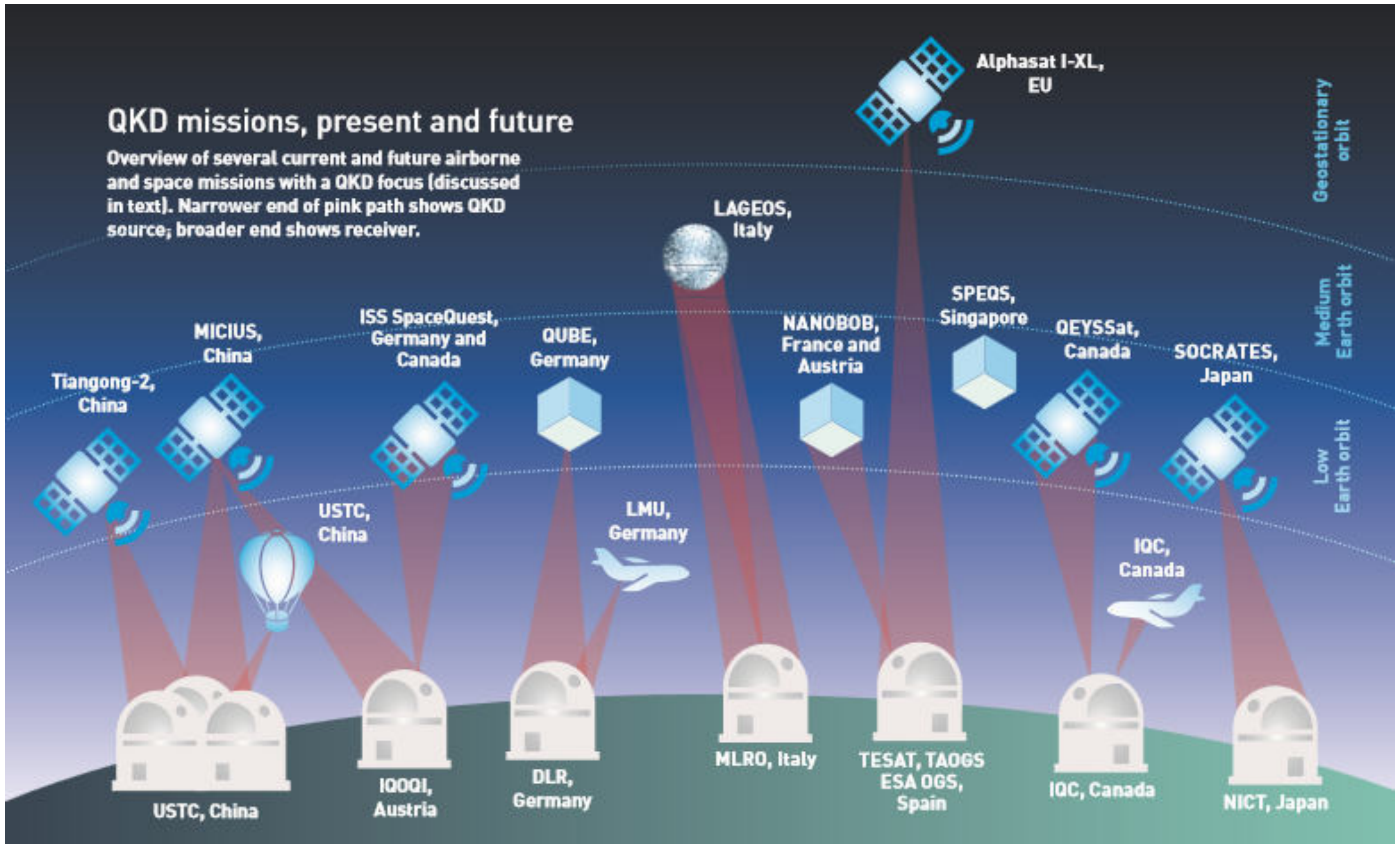
QKD in Space - Key Advantages

- Fibre optics QKD is limited by losses that scale exponentially with distance (about 0.2dB/km) allowing maximum link distances of few hundreds of km.

- Losses for free-space links scale with the square of the distance. This enables intercontinental links as well as links with satellites in high orbits, such as Global Navigation Satellite Systems (GNSS) at 20000 km.

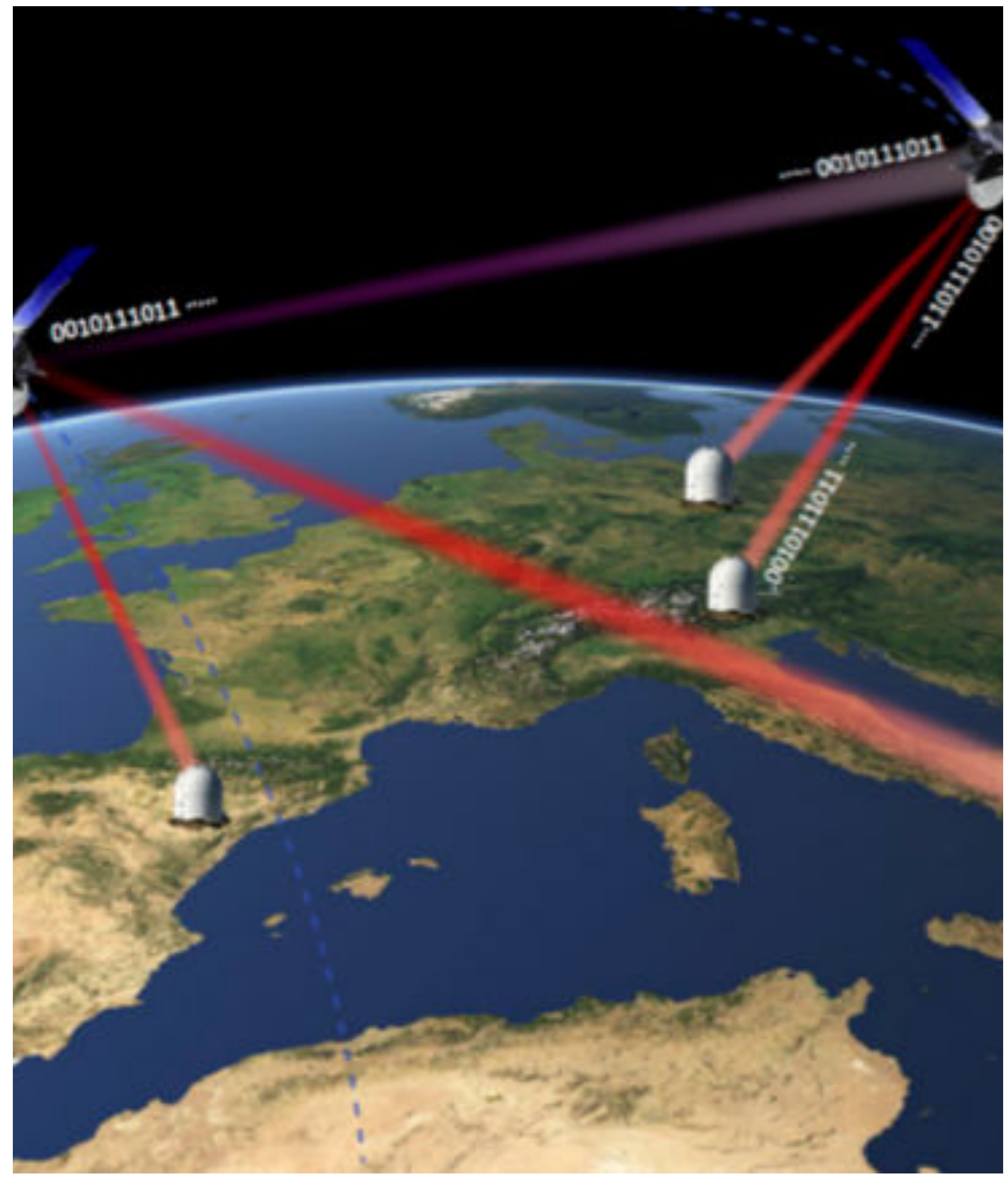
QKD in Space - Current Technology

- The Micius satellite, launched by China in 2016, is equipped with an optical system delivering 10 µrad of divergence and has demonstrated QKD rates of tens of kHz with ground stations with telescopes of 1m aperture
- A dedicated transmitter with the optical characteristics of Micius in global navigation satellite system (GNSS) orbit could allow for few kHz QKD rates with the Matera Laser Ranging Observatory (1.5 m aperture)
- See perspective from ESA (ongoing study)



QKD in Space - Applications

- Satellites provide strategic services for both civil and military operations (e.g. GNSS)
- QKD could offer an unprecedented level of security for future GNSS generations, allowing unconditional security for satellite-to-ground communications as well as for intra-satellite communications
- A QKD can also be used to protect ground-based strategic infrastructures, such as the synchronous power grid of continental Europe
- Space-based QKD would allow secure communication between remote locations even if central nodes are compromised
- An interconnected network of ground stations and a QKD satellite constellation could guarantee a secure network with high availability, independent of the atmospheric conditions.



References QKD in Space

- *Quantum cryptography*, N. Gisin, G. Ribordy, W. Tittel, H. Zbinden, Review Modern Physics 74, 145 (2002)
- *The security of practical quantum key distribution*, V. Scarani, H. Bechmann-Pasquinucci, N. J. Cerf, M. Dušek, N. Lütkenhaus, M. Peev, Review Modern Physics 81, 1301 (2009)
- *Satellite-relayed intercontinental quantum network*, S.-K. Liao, *et al.*, Physical Review Letters 120, 030501 (2018)
- *Space photons bring a new dimension to cryptography*, http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Space_photons_bring_a_new_dimension_to_cryptography

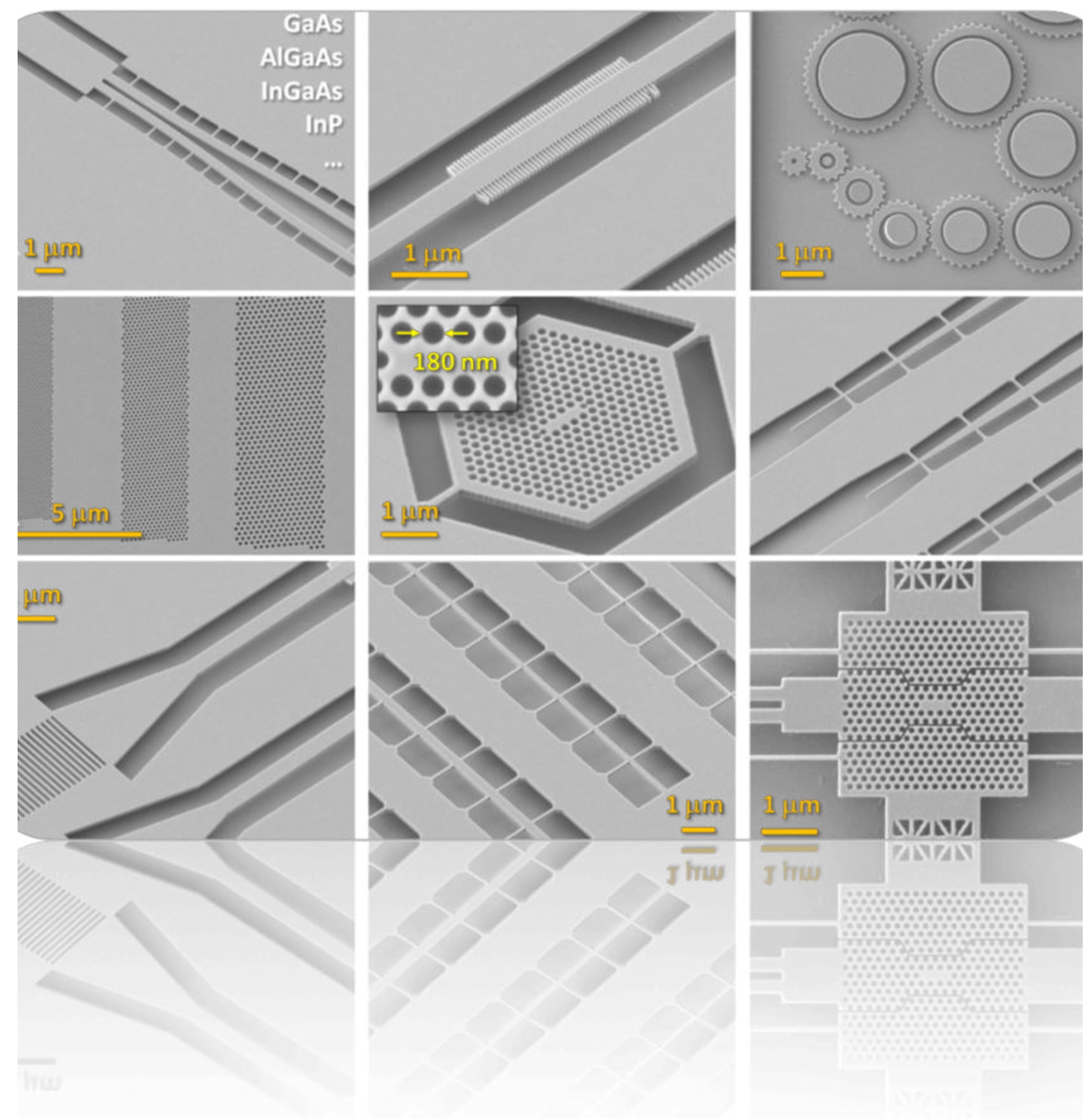
QKD Systems

- Quantum Key Distribution (QKD) systems deliver digital keys for cryptographic applications on fibre-optic based networks
- They allow key distribution over standard telecom fibre links over a distance sufficiently long for metropolitan coverage
- QKD systems can be used for a variety of cryptographic applications, e.g., encryption or authentication of sensitive documents, messages or transactions.

(source Toshiba Cambridge Research Laboratory)

Integrated QKD Systems

- Available scalable manufacturing processes and dedicated foundry services
- Desirable co-integration of integrated components
- Encodings of information: discrete/ continuous, path, time-bins, polarization, quadrature/phase of the field
- Compatibility with optical communication infrastructures and multiplexing protocols. In particular, use of the telecommunication wavelength range (1.3/1.55 μm)



(courtesy of Nanophab)

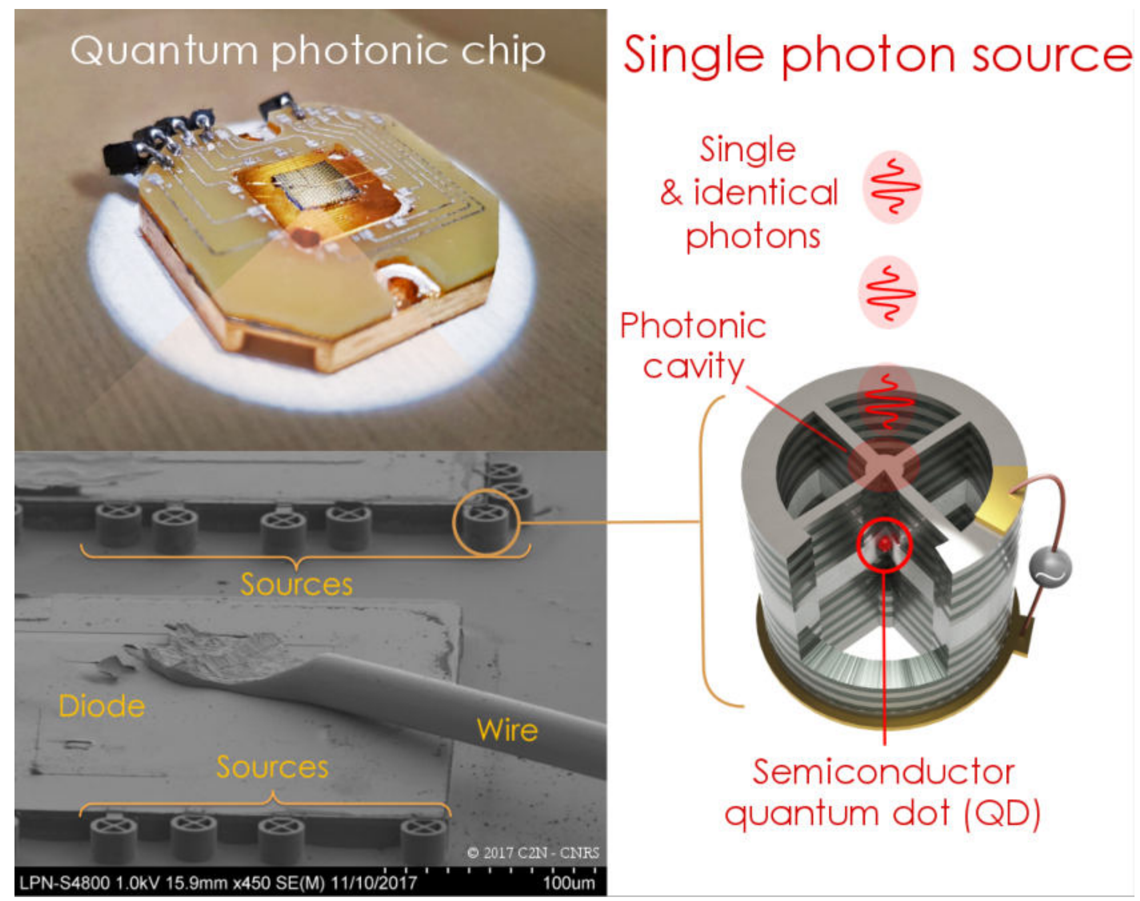
Individual Components

- Single-photon sources and/or weak coherent laser sources
- Single-photon detectors such as avalanche photodiodes (SPAD) or superconducting nanowire single-photon detector (SSPDs); SSPDs offer higher quantum efficiency, less dark counts, compatibility with several material platforms, but must be operated at cryogenic temperatures
- Low-loss waveguides
- Interferometers featuring nonlinear and electro-optic effects for phase-shifters
- Spectral filters
- Quantum repeaters (not yet developed)
- Encoding converters
- Integration with fast (>10 GHz) electronics for synchronization

Single-Photon Sources

From an online survey (2016) about 60% of researchers in optical quantum information processing considered laser-based single-photon sources as the main bottleneck for the development of optical quantum technologies

- Single-photon sources based on quantum emitters:
  - Color centers in diamond, e.g. nitrogen-vacancy, silicon-vacancy, …
  - Quantum dots, …
- Nanophotonics:
  - Photonic structures to enhance photon collection efficiency from high-index material, e.g. solid-immersion lens, waveguides, antennas, …
- Key performances:
  - Typical count rates (cw excitation): 100 kHz to few GHz
  - Typical count rates (pulsed excitation) : > 25 MHz
  - Single photon purity : > 98%
  - Photon Indistinguishability : > 90%
- Applications: QKD, optical quantum computing, imaging, quantum metrology (quantum candela, detector calibration), quantum lidar



QD-based single-photon source (courtesy of Quandela)

Single-Photon Detectors

- Single-photon avalanche photodiodes (SPAD)
  - Sensitive from UV to NIR (Si, InGaAs)
  - Highest efficiency at 550 nm
  - Dead time: < 80 ns
  - Time jitter < 50 ps
  - Low noise: dark counts < 1 Hz
- Superconducting Single-Photon Detector (SSPD)
  - Sensitive from UV to MIR
  - Highest efficiency for NIR
  - Short dead time: < 5 ns
  - Time jitter < 50 ps
  - Low noise: dark counts < 20 Hz
- Applications: security & defense, information technology, space observation, research

SSPD (courtesy of Single Quantum)

Silicon-based Platforms: Si, SiN, SiC

- Advantages:
  - Pre-existing CMOS and Si facilities with available MPW runs (IMEC, LETI, TSMC, VTT,…)
  - Low-cost
  - Very high refractive index and high mode confinement: compact circuit and nonlinear effects
  - Available heralded single-photon sources based on Spontaneous Four-wave Mixing (SFWM)
  - High quality notch filters for laser emission suppression
  - Up to 50 GHz modulation BW possible, up to 50 GHz detection possible with Ge detectors (high responsivity and low dark current), Ge on Si SPADs are not available yet, but under development.
- Disadvantages:
  - Poor mode-matching with optical fibers, although gratings with 0.6 dB coupling loss have been demonstrated, and VTT platform has 0.5 dB loss with tapered fibers
  - High propagation loss (not always true: VTT platform has 0.1 dB/cm los)
  - Absence of laser sources, slow thermo-optics effects
  - MZI modulators are the most promising, but have high losses, high driving voltages and large footprint

III-V-based Platforms: InP, GaAs, GaN, AlGaAs

- Advantages:
  - Direct bandgap: integration of laser emission
  - Available Deterministic single-photon sources such as semiconductor quantum dots
  - Available Heralded single-photon sources based Spontaneous Parametric Down-Conversion (SPDC)
  - Efficient detection at telecom via InGaAs detectors
  - High refractive index: compact circuits, strong second-order nonlinearities (frequency conversion), high and fast electro-optics effect
- Disadvantages:
  - Foundry services less developed than Si facilities, but widely developed for the telecom market (Oclaro, Smart Photonics, nanoPHAB, Fraunhofer HHI, poet,…).
  - High cost, poor mode-matching with optical fibers, high propagation loss

Submicron Lithium Niobate Waveguides

- Advantages
  - Record high second-order and non-linear effects with PPLN waveguides
  - Available Heralded single-photon sources based Spontaneous Parametric Down-Conversion (SPDC).
  - Very low propagation losses (3 dB/m)
  - High and fast electro-optic effects compatible with CMOS voltages
- Disadvantages
  - Foundry services missing to date
  - High cost
  - Poor mode-matching with optical fibers
  - No light sources

Other Material Platforms

- Diffused waveguides in nonlinear dielectric materials (LiNbO$_3$, KTP)
  - Advantages: strong second-order and non-linear effects, available heralded single-photon sources based on Spontaneous Parametric Down-Conversion (SPDC), efficient coupling with fibers
  - Disadvantages: less developed foundry processes, weak mode confinement-> large circuits
- Glass waveguides (i.e. silica-on-silicon or femtosecond laser writing)
  - Advantages: Excellent mode matching with fibers, very fast prototyping, suitable to implement large interferometers with many beam splitters, 3D integration of waveguides, polarization control, cost-effective
  - Disadvantages: less developed foundry processes for large-scale production, weak mode confinement: large circuits, absence of sources and non-linear effects

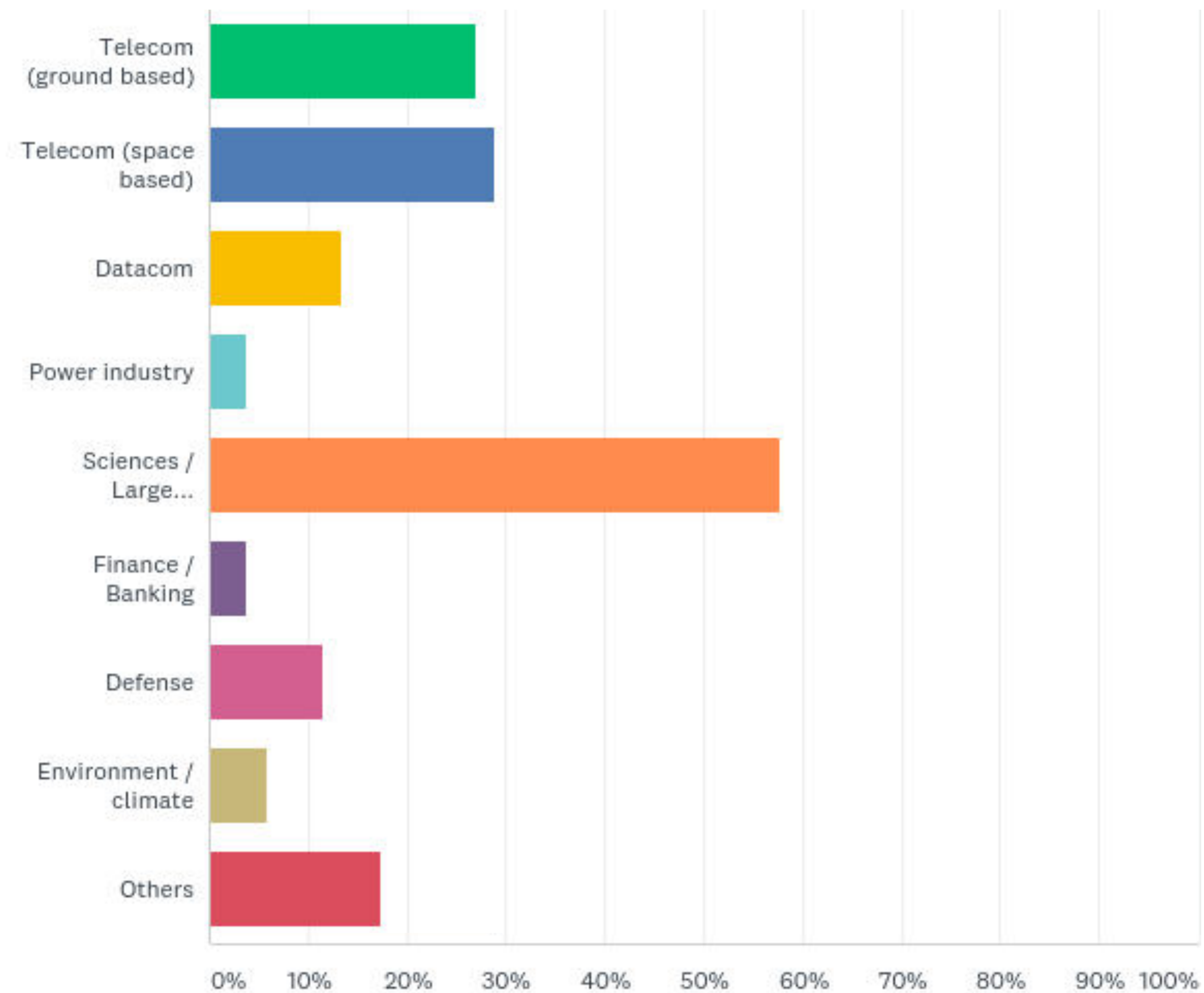
References Integrated QKD Systems

- *Photonic integrated circuits for quantum technologies*, M. Heck, M. Kues, Pics4All Application Note (2019)
- *Chip-based quantum key distribution*, P. Sibson, *et al.*, Nature Communications 8, 13984 (2017)
- *Providing the ultimate, long-term data protection in a post-quantum world,* https://www.idquantique.com/quantum-safe-security/products/
- *ID Quantique, SK Telecom & Nokia Secure Optical Transport System Using Quantum Key Distribution (QKD)*, https://www.idquantique.com/idq-sk-telecom-nokia-secure-optical-transport-system-using-qkd/
- *Integrating quantum key distribution with classical communications in backbone fiber network*, Y. Mao, et al., Optics Express 26, 6010 (2018)

QKD Survey - Companies & Markets

- 52 participants
- 50% private and government organisations
- 50% non-profit public organisations
- Good feed-back from large organisations (50% > 250 employees)
- Answers mainly from EU countries
- More than 50% of private and government organisations are working on QKD devices implementation, leading to product deployment in the near-term (33% are on field tests)
- Development phase leading to a weak interest for on-going external R&D

Company sectors (% of respondents)



QKD Survey - Performances and Costs

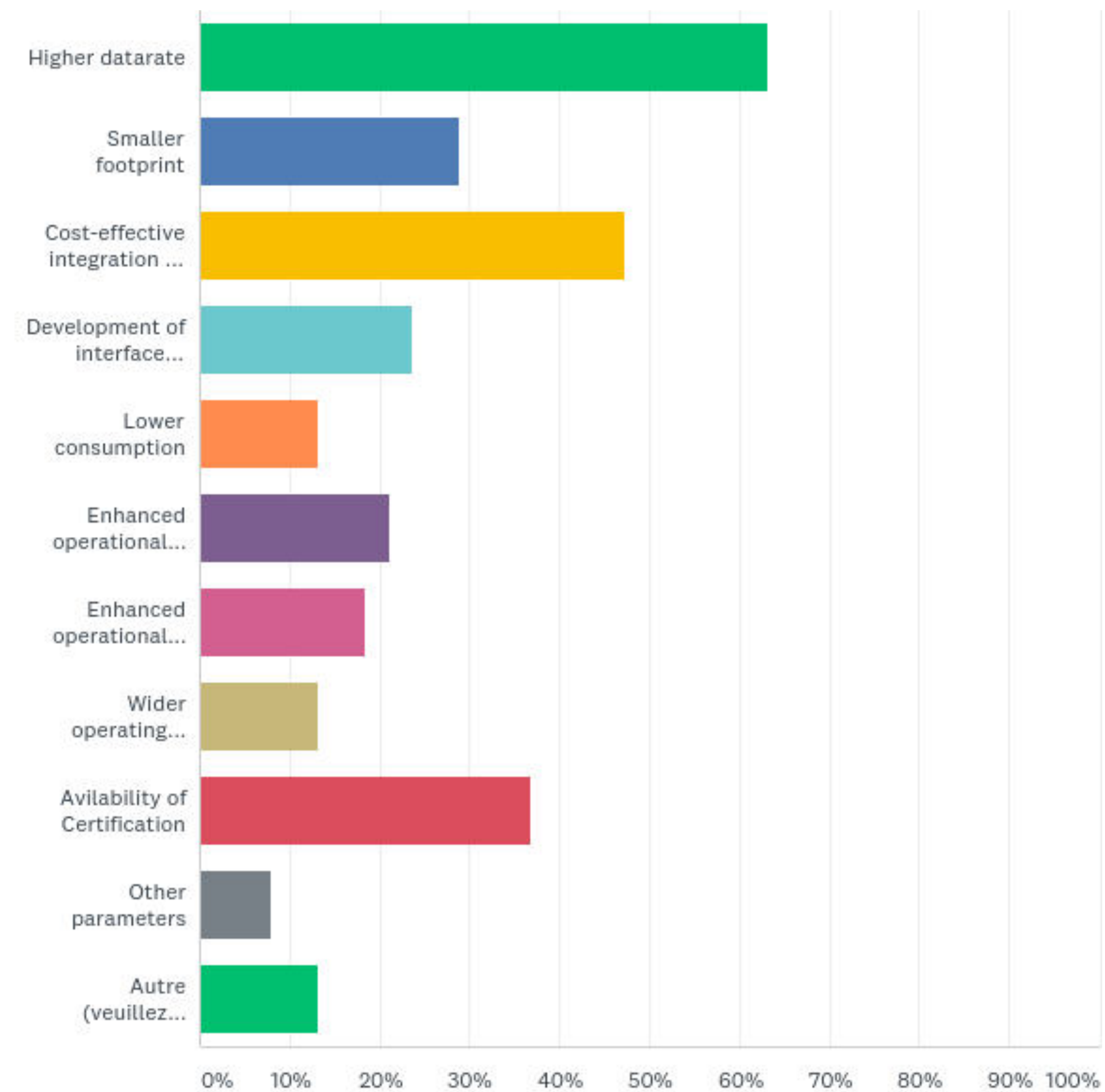
- 3 key parameters to improve before QKD field deployment: higher data rate, certification, cost-effective integration

- Willingness to pay for high security link is about 15-50%

- From a unit price of about +50k$ today to 8-10k$ in market widespread

- Market is expected to reach maturity at few thousands units per year

Desired performances (% of respondents)



Quantum Sensing

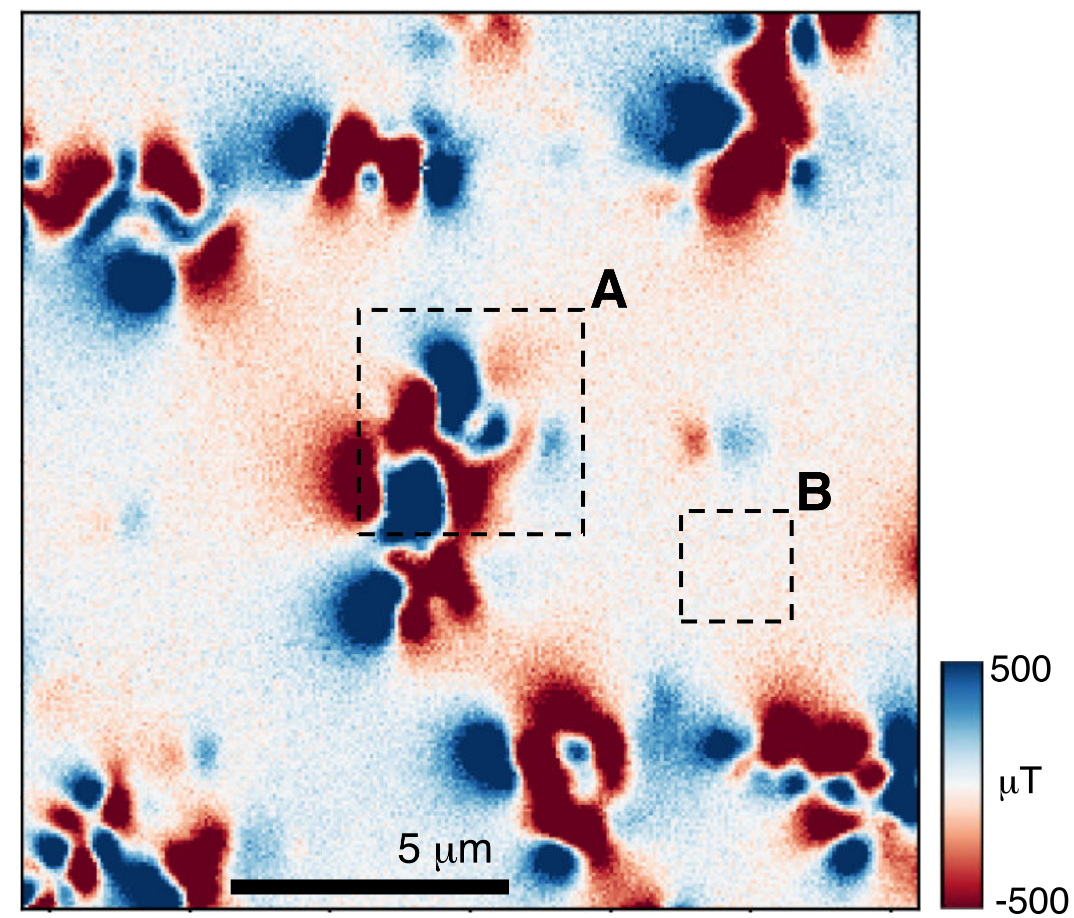
Quantum Sensing

- Quantum sensing describes the use of a quantum system, quantum properties or quantum phenomena to perform a measurement of a physical quantity

- Historical examples of quantum sensors include magnetometers based on superconducting quantum interference devices (SQUID), atomic vapors magnetometers, or atomic clocks.

- More recently, quantum sensing is expected to provide new opportunities especially with regard to high sensitivity and precision in applied physics and other areas of science

- Quantum sensors capitalize on the central weakness of quantum systems: their strong sensitivity to external disturbances



Investigation of magnetic domains for novel magnetic memories (courtesy of ETH Zurich/QZABRE)

Atomic Sensors

- Optical Atomic Clocks (OAC)
  - Based on narrow optical transitions in laser-cooled atoms or ions
  - Frequencies ~10^5 times higher than microwave frequencies
  - Q-factor ~10^{15} (or even higher)
  - Better time resolution (clock “ticks” faster)
  - Better stabilities than microwave clocks
- Matter-Wave Interferometers (MWI)
  - Laser-cooled atoms exhibit strong quantum properties and behave like matter-waves
  - MWI offer unique properties for high performance inertial measurements as gravity sensors, accelerometers, gyroscopes
  - Sensitivity ~ 10^{-13} g.

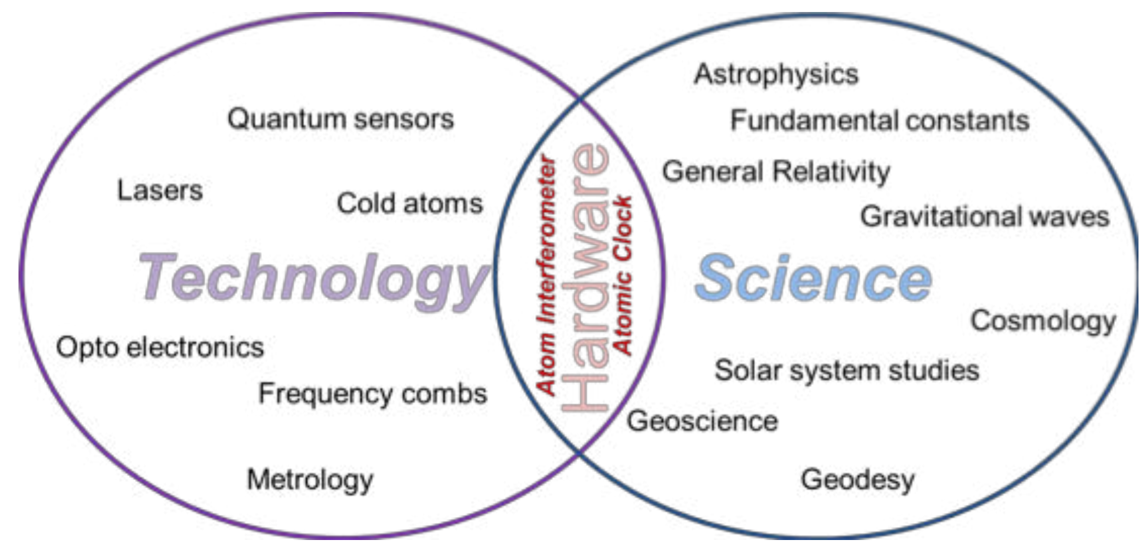
Cold Atoms Lab (source NASA-JPL)

OAC - Performances

- Continuous improvement in clock stability/precision in 8 years. In 2018:
  - Fractional stability: 5×10^{-19} after 1 hour of averaging time
  - Relative precision: 2.5×10^{-19}, Sr lattice clock at JILA, USA
- Opens new doors into new science and key applications
  - Ultra-stable frequency performance (generation and distribution) requires systems based on optical frequencies

OAC - Applications

- Fundamental Physics
  - Searches for violation of the Einstein Equivalence Principle
  - Search for gravitational variation in fundamental physical constants (unification of gravity and quantum mechanics, vastly improved gravitational redshift measurements, Shapiro time-delay measurements)
- Earth Observation
  - Direct measurement and mapping of Geoid at few cm level for civil engineering, oil & gas exploration, ordinance survey, ice sheet mass, and ocean dynamics
- Global navigation (GNSS)
  - Improved satellite clock prediction accuracy (greater integrity and longer autonomy of space segment, master clock in space for optically enhanced frequency distribution)
- Satellite Telecommunications
  - High bandwidth optical satellite-satellite secure communications



(courtesy of European Space Agency)

OAC - Developments

- The highest performance has been demonstrated in a terrestrial laboratory environment
- The environment of space would remove the limiting aspect of an earth based system
    - Clean gravity environment
    - Long interaction times due to the absence of gravity
- System complexity must be reduced for space
    - The past and current approach is based on bulk optics, electro optics, lasers, …
    - Future must closely examine CMOS manufacturing processes
    - The future must embrace integrated photonics
- Technologically disruptive concepts must be evaluated by
    - Examining non-conventional system approaches
    - Reduce reliance on physically limiting techniques

MWI - Ground Applications

- Sustainable management of underground resources
  - Geothermics & Hydrology
  - Oil & Gas
  - Mining Industry
- Environmental Security
  - Volcanology
  - Seismology
- Subsurface imaging
  - Civil engineering
  - Void, tunnel and cavity detection

First generation absolute quantum gravimeter (courtesy of Muquans)

MWI - Space Applications

- Basic science based on interactions with external electric fields and gravity
- Enhanced and new observations at short and long time scales:
  - Gravity anomalies
  - …
- State-of-the-Art:
  - In-Orbit Laser cooled 87-Rb Atomic Clock (Chinese Academy of Sciences, 2016)
  - MAIUS (DLR / Hannover, 2017): Sounding Rockets: First BEC in space
  - Cold Atom Lab (NASA-JPL, 2018): Aboard the ISS

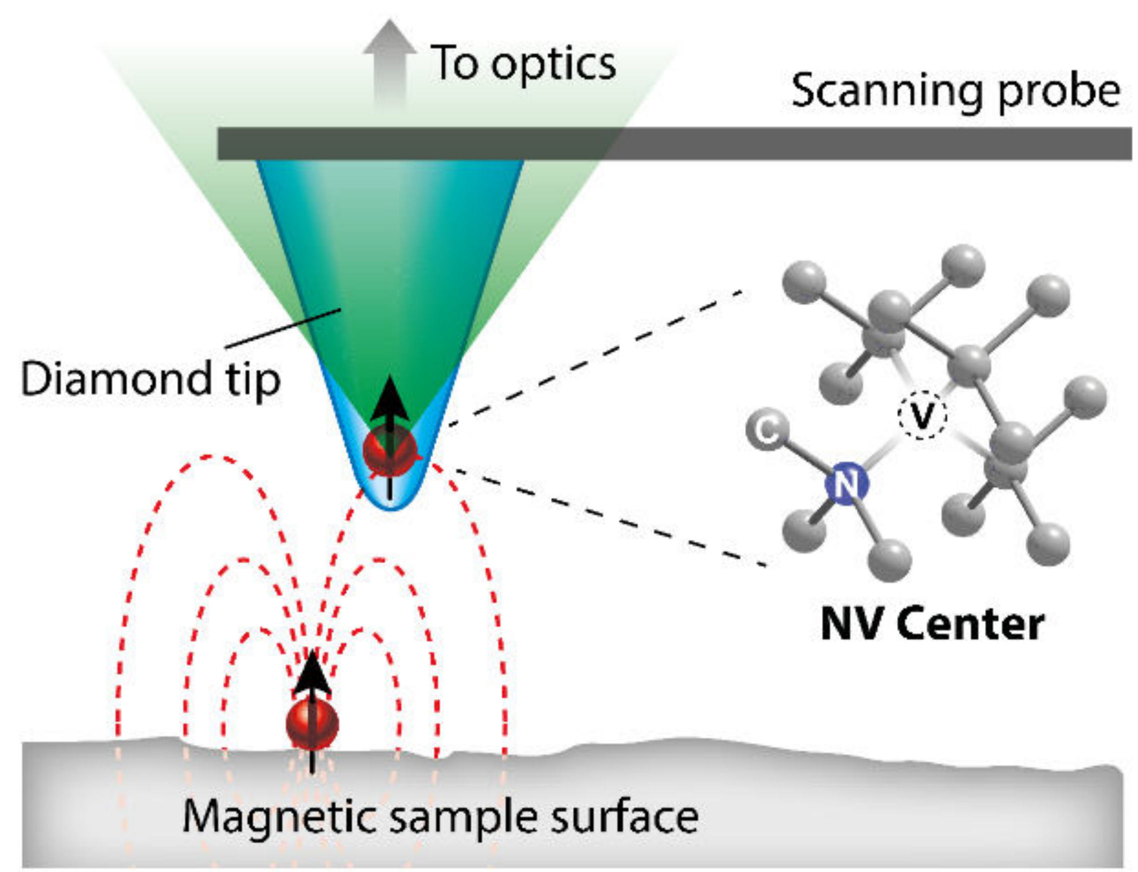
(courtesy of European Space Agency)

References Atomic Sensors

- *Atomic Sensors – A Review*, J. Kitching, S. Knappe, E. A. Donley, IEEE Sensors Journal 11, 1749 (2011)
- http://www.atomsensors.com/index.php/en/
- https://www.ralspace.stfc.ac.uk/Pages/Cold-Atoms-and-Quantum-Sensors.aspx
- *Single molecule and single atom sensors for atomic resolution imaging of chemically complex surfaces*, G. Kichin, *et al*., Journal American Chemical Society 133, 16847 (2011)
- *Toward the optical second*, E. Cartlidge, Optics & Photonics News, Feb. 2019

NV Centres as Quantum Sensors

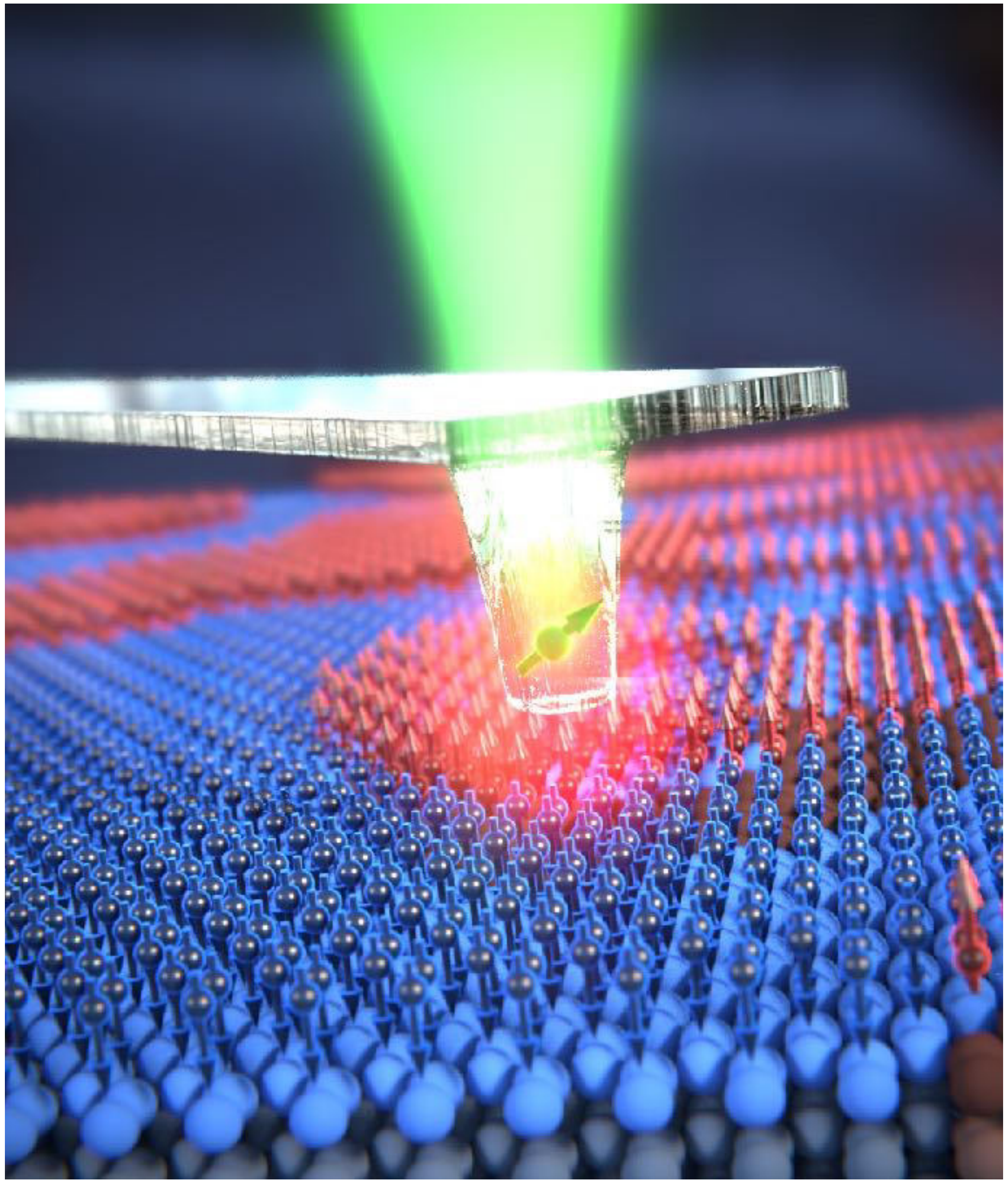
- Basic Features
  - Electron spin readout by fluorescence
  - Spin initialization
  - Nanoscale spatial resolution/proximity
  - Coherence improves sensitivity
  - High sensitivity to magnetic fields, temperature, …
  - Biocompatible
- Performances
  - Single electron spin detection (~20 nT/Hz$^{1/2}$)
  - Single proton spin detection
  - Spatial resolution (~ 1-20 nm)



NV scanning microscopy
(courtesy of QZABRE)

NV Centres - Applications

- Solid-state physics
  - Domain-walls in ferromagnets
  - Ferromagnetic resonances
  - Hard drive read-head field imaging
- Life sciences
  - Magnetic cell-labelling
  - Single proton spin detection
  - Nanoscale MRI



Single-spin scanning magnetometry
(courtesy of U Basel)

NV Centres - Technology

- All-diamond scanning probes
  - Micron scale platforms with nanopillars
  - Harness atomic size of color centres in diamond
  - Nanoscale, multifunctional sensing feasible
- Integration into atomic-force microscopes
  - Mounting to tuning fork
  - Stable feedback to follow sample topography
  - Controlled approach to sample surface

All-diamond scanning probe
(courtesy of QNAMI)

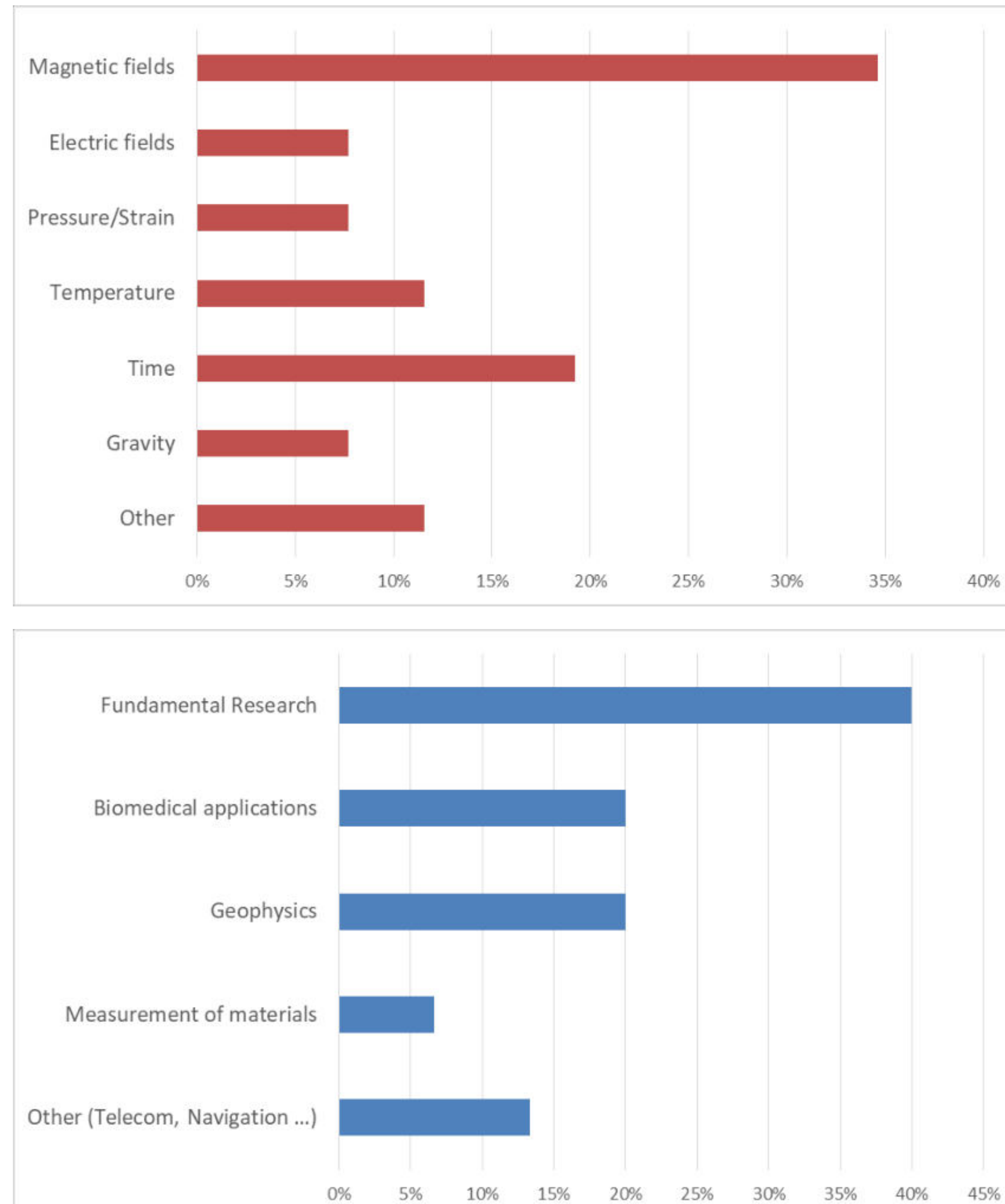
References NV Centres

- *Quantum sensing*, C.L. Degen, F. Reinhard, and P. Cappellaro, Review Modern Physics 89, 035002 (2017)
- *A robust scanning diamond sensor for nanoscale imaging with single nitrogen-vacancy centres,* P. Maletinsky *et al.*, Nature Nanotechnology 7, 320 (2012)
- *Single-cell magnetic imaging using a quantum diamond microscope*, D.R. Glenn, *et al.*, Nature Methods 12, 736 (2015)
- *The nature of domain walls in ultrathin ferromagnets revealed by scanning nanomagnetometry*, J.-P. Tetienne *et al.*, Nature Communications 6, 6733 (2015)

Quantum Sensing Survey - Companies & Markets

- 30 participants
- 30% manufacturers
- 30% users or potential users
- Mix of startups, SMEs and large companies
- Answers mainly from EU countries
- The types of measurement using quantum sensors are mostly time and magnetic fields

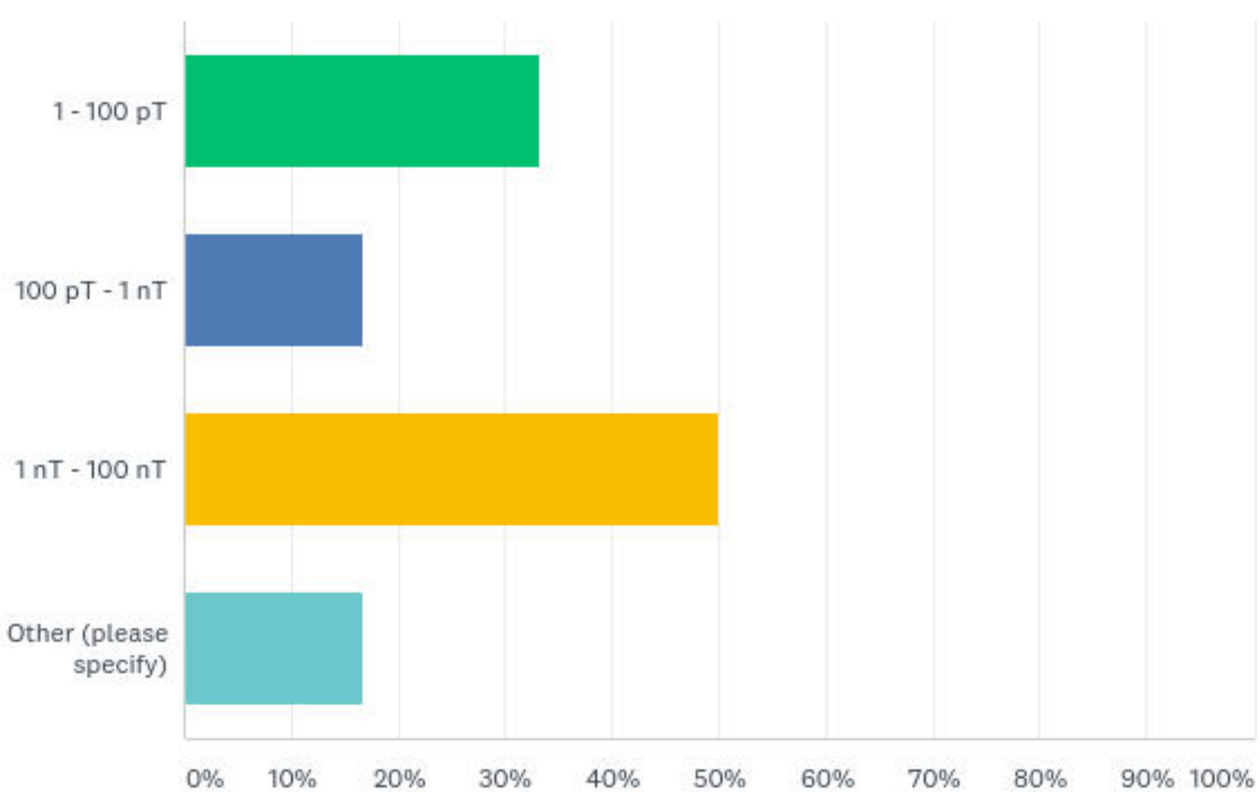
Measured quantity and applications (% of respondents)



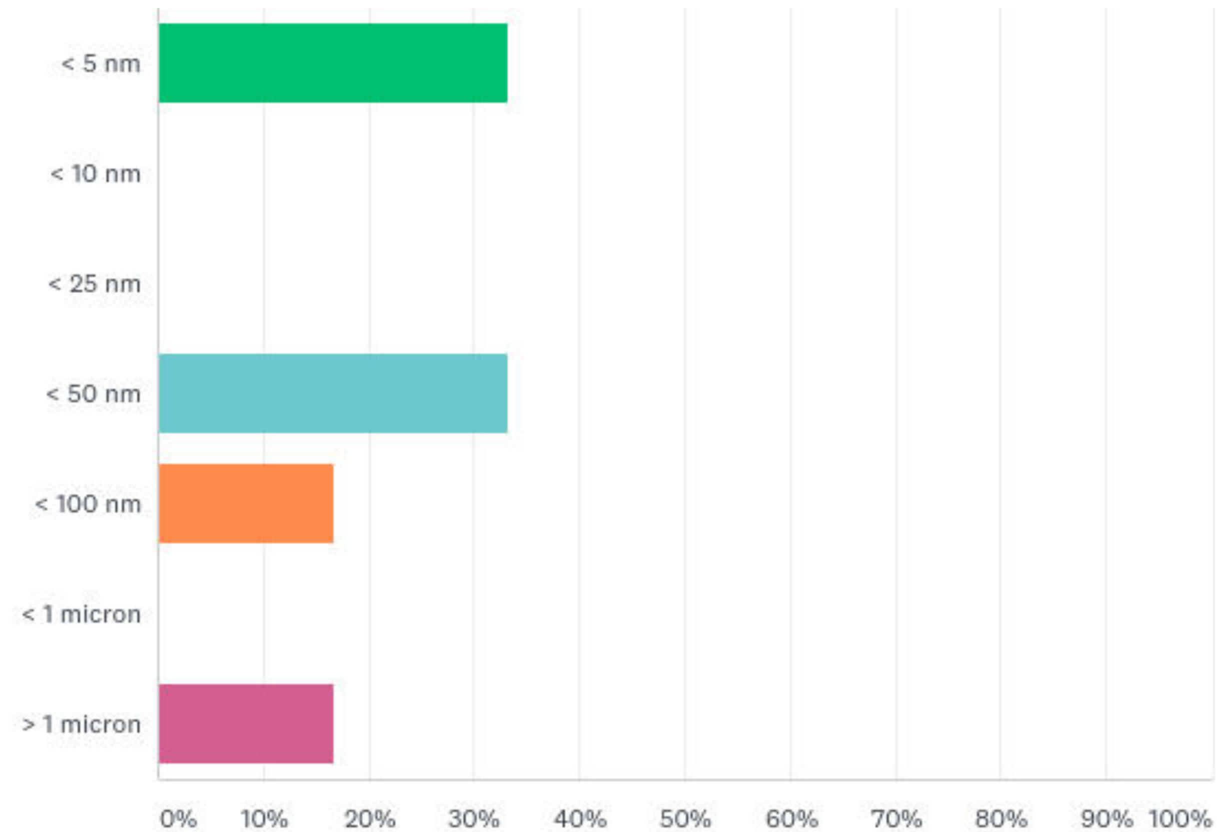
Quantum Sensing Survey - Magnetic Field Sensing

- Needs in term of sensitivity for detection or measurement of magnetic fields are varied
- Needs in term of frequency/repetition rate for detection or measurement of magnetic fields are also varied
- Needs in term of spatial resolution for magnetic fields are mainly nanoscale measurements

Desired sensitivity (% of respondents)



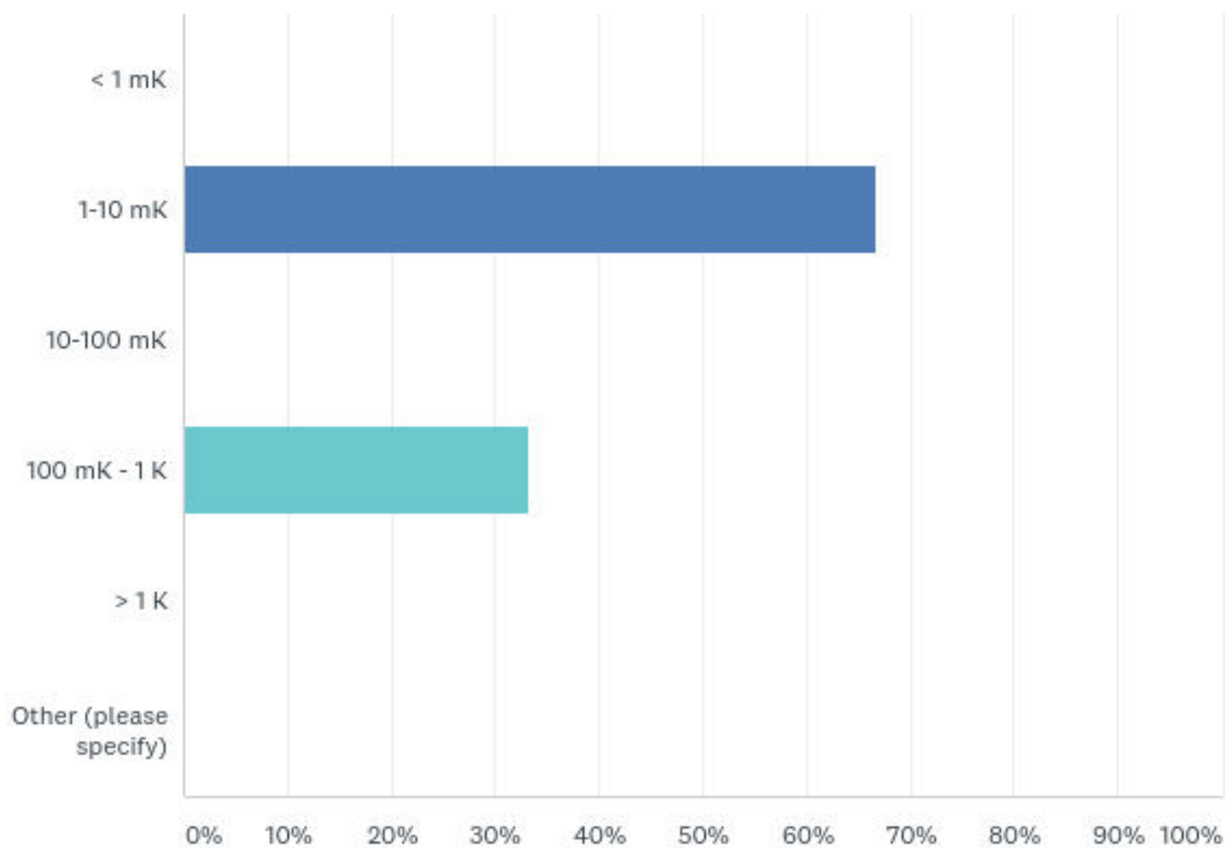
Desired spatial resolution (% of respondents)



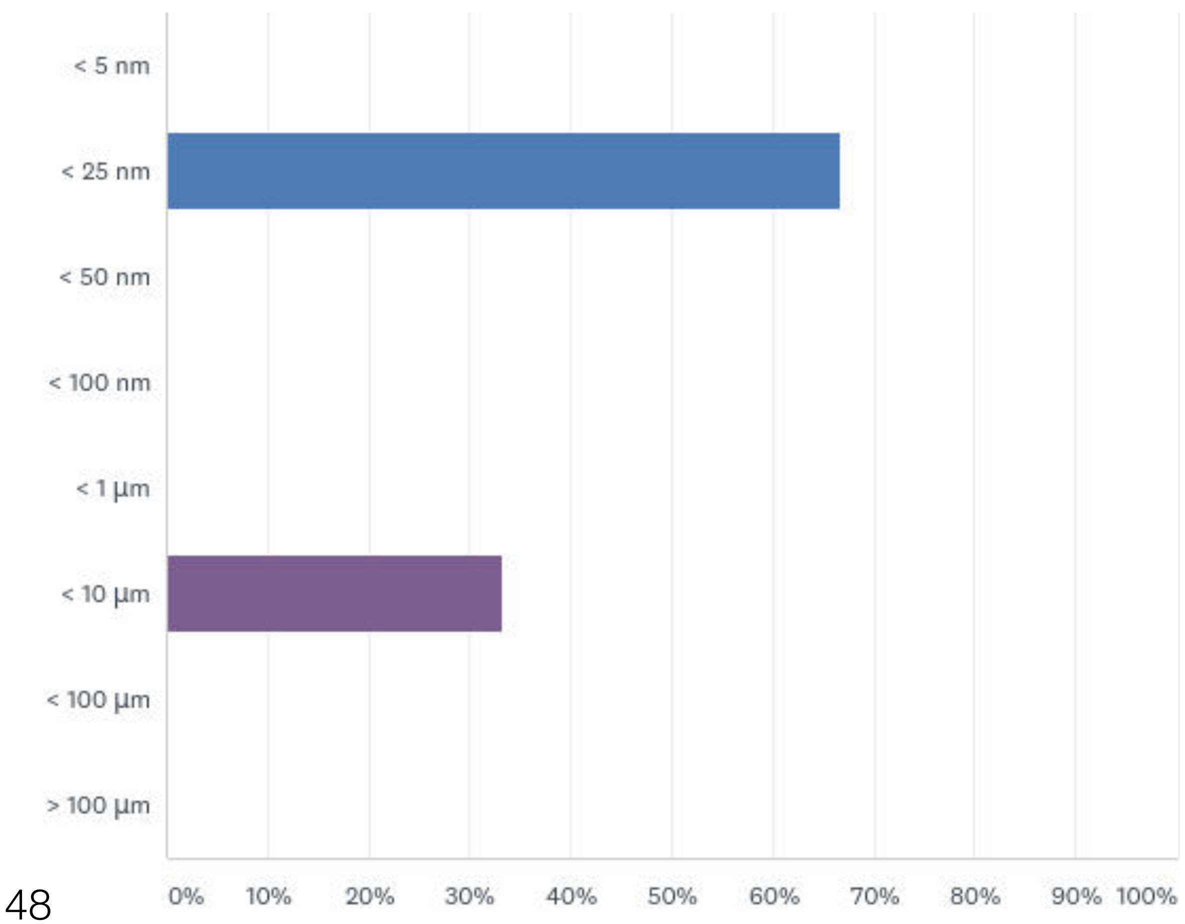
Quantum Sensing Survey - Temperature Sensing

- Needs in term of sensitivity for temperature measurement are primarily ~ 1-10 mK
- Needs in term of spatial resolution for temperature are mainly nanoscale measurements

Desired sensitivity (% of respondents)

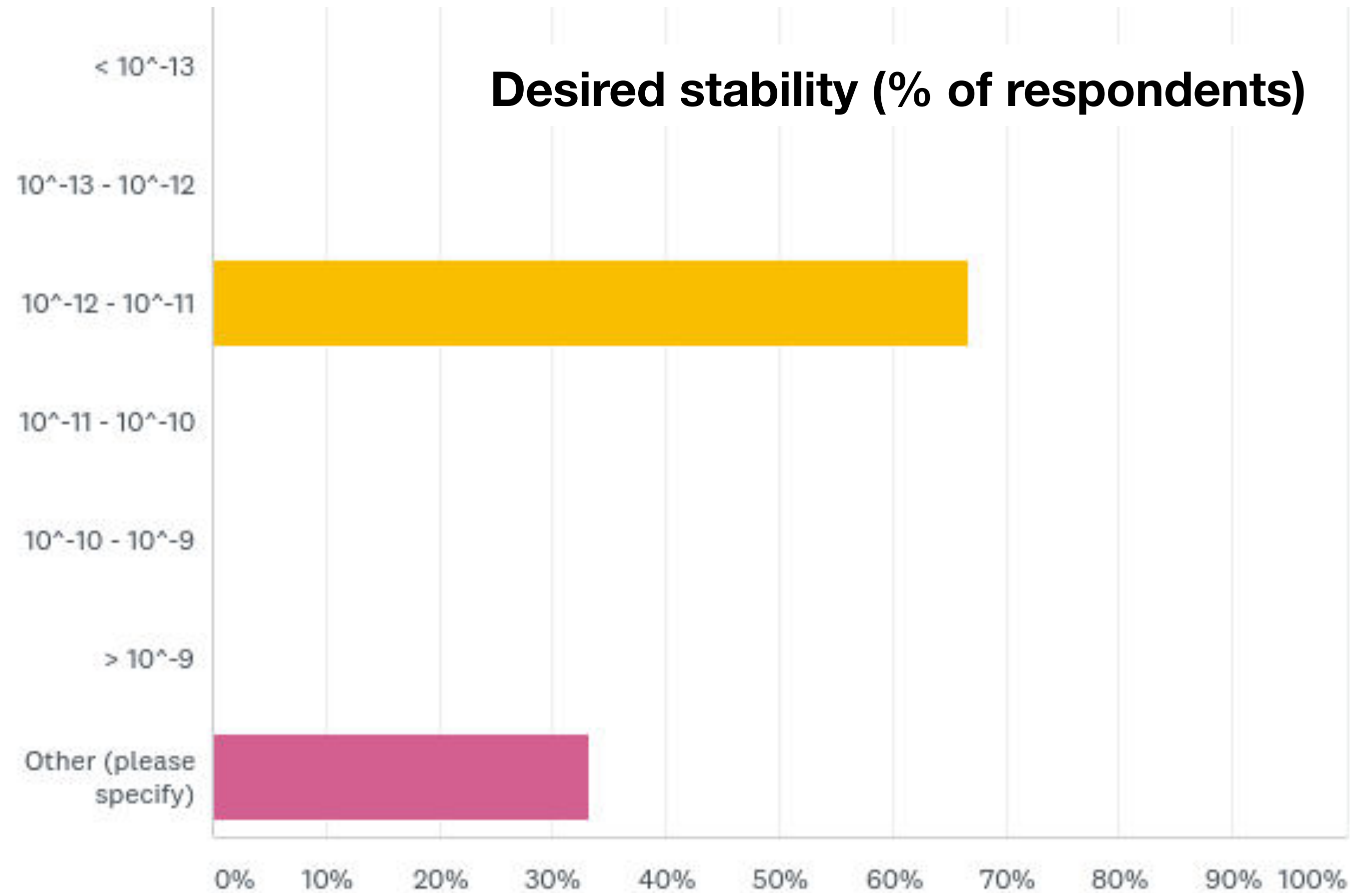


Desired spatial resolution (% of respondents)



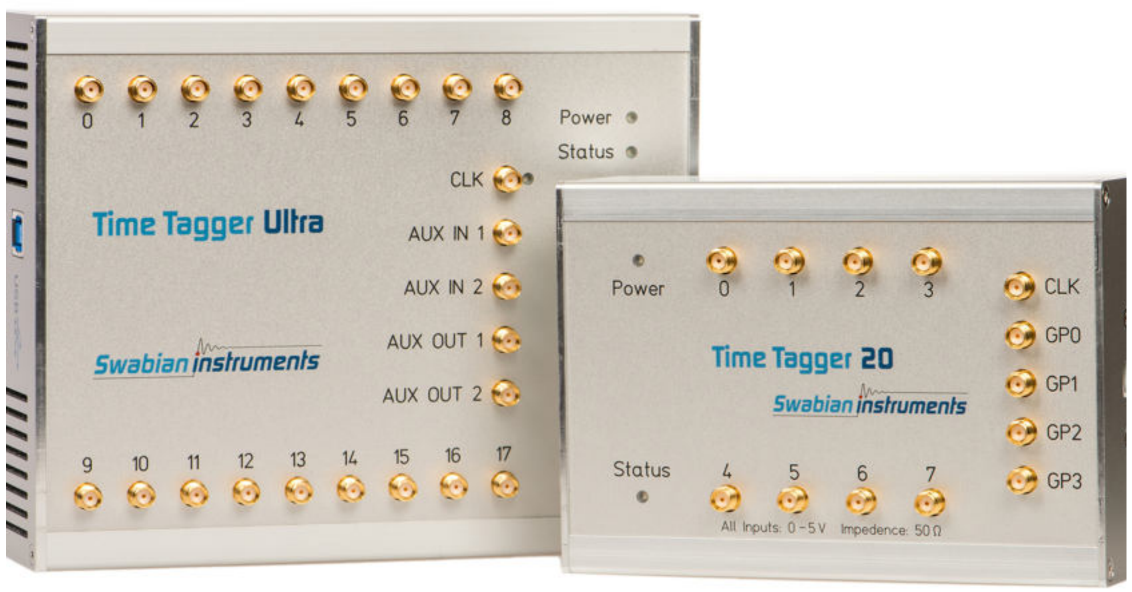
Quantum Sensing Survey - Time Sensing

- Needs in term of stability for measurement of time: < 1 µs/day (note 10^{-11} <=> µs/day)
- Main application: Telecoms



Enabling Technologies

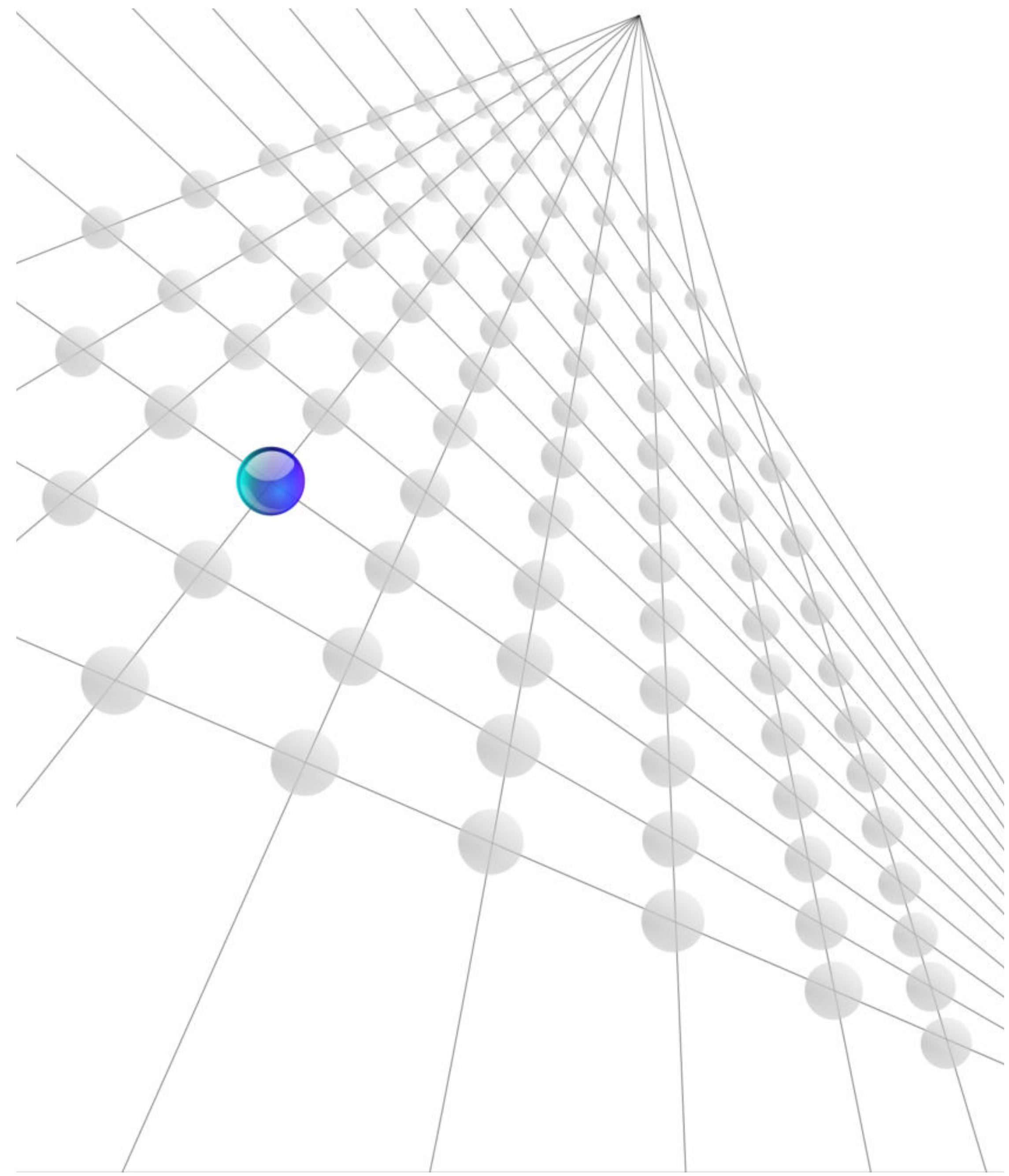
- Software
- Electronics
- Lasers
- Photonics
- Nano-lithography



Time tagging electronics
(source Swabian Instruments)

Software

- Unmet demand for design software for quantum nanophotonic devices
- Novel theoretical and computational methods are required for designing and modelling the building blocks of quantum nanophotonic devices that exploit *Quantum 2.0* phenomena: entanglement and superposition
- Targeting both academic research and companies in the quantum computing sector, whose revenue is projected to exceed $5 billion by 2020
- Broad range of applications encompassing quantum computing, telecommunications, metrology and sensing



(courtesy of Quantopticon)

Market Analysis

Potential Applications for QKD

Sectors	Applications
Public administration	Government departments, justice administration, ministries
Financial services	Banks, insurance companies
Chemical industry	Production, transport, storage, and processing of chemicals
Energy	Power supply, oil & gas supply
Waste disposal	Waste water, industrial and domestic waste
Public health	Medical care and hospitals, medicine laboratories
Information and communication technologies	Telecommunications, information systems and networks, internet
Water and food	Food supply and food security, potable water supply
Public safety, emergency and defense	Emergency organizations (police, fire service emergency, …), civil protection, armed forces
Transport	Road, rail, air transport, postal services and logistics

Industry Players in QRNG

- ComScire
- Crypta Labs
- EYL Partners
- KETS-Quantum
- IDQ-QTEC
- ID Quantique
- InfiniQuant
- Quantum Base
- Quantum Numbers Corp
- Quintessence Labs
- QUSIDE
- Qrypt
- SK Telecom
- ...

Industry Players in QKD

- ADVA Optical (end user)
- Applied Communication Science (end user)
- KPN Netherlands (end user)
- ID Quantique
- IDQ-QTEC
- InfiniQuant
- MagiQ
- Nokia (end user)
- NTT Japan (end user)
- Nucrypt
- QuantumCTek
- Qasky
- Qubittekk
- Quintescence Labs
- Senetas
- SK Telekom
- Whitewood Encryption Systems
- Toshiba CRL
- ...

Market Progression in QKD

- **Market growth:**
  - First plateau in ~ 5 years (space and airborne deployment)
  - Second plateau in ~ 7 years (ground telecom professional segment)
  - Third plateau in ~ 10 years (ground telecom network)

- **Market size:**
  - Space and airborne: ~ 1000 units/year @ 50000 €, i.e. 50 M€
  - Ground telecom (professional segment): ~ 10000 units/year @ 15000 €, i.e. 150 M€
  - Ground telecom (network): ~ 30000 units @ 10000 €, i.e. 300 M€

Conclusion on QKD Market

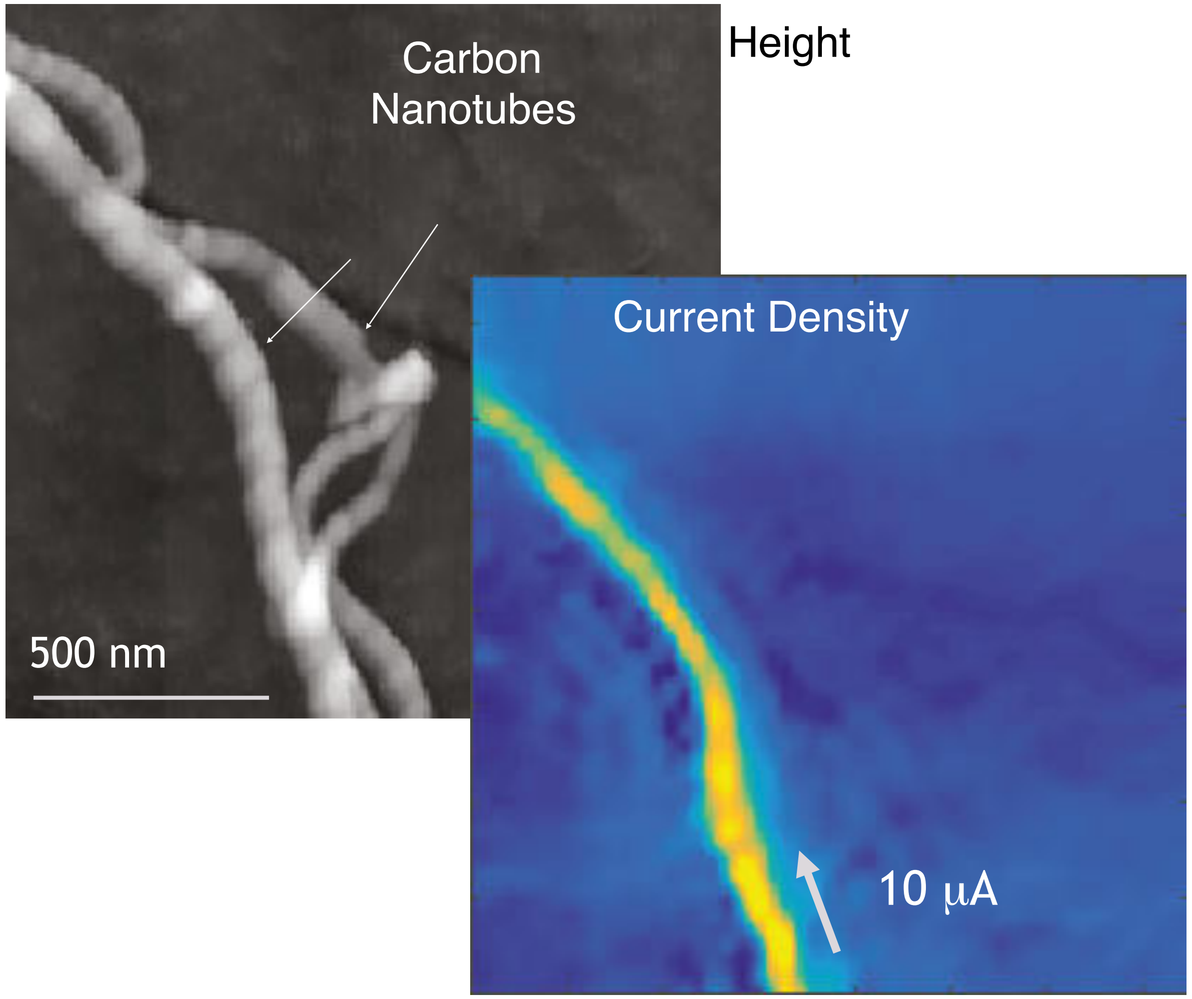
- Key parameters to improve before QKD field deployment
  - Higher data-rate: strong adherence to 1 Gbps
  - Cost-effective integration
  - Establishment of standards and procedures for certification
  - Availability of QKD complement rather than replace conventional cryptography
- Willingness to pay for QKD link : around +15% to +50%
- From a unit price of about 50-100 k€ today to 8-10 k€ for a market reaching few 10's thousands units per year

Sensing & Metrology

- Use quantum effects to precisely measure properties like time, electromagnetic fields, temperature …
- Near-term technologies: atomic clocks, quantum gravity sensors, magnetic sensors
- Mid/Long-term technologies: quantum magnetometers, quantum electrometers, integrated compact sensors for chemical and materials analysis, labelling, trace element detection …
- Expected applications: time certification (commercial and financial transactions), natural resources exploitation and monitoring, sensors for healthcare (such as brain imaging and magneto encephalography (MEG)), security and defence, time stamping applications, synchronization, infrastructure monitoring, precise positioning, …

Imaging

- Use quantum effects to offer improved technical or fundamental noise and sensitivity limitations over classical imaging devices or techniques
- Near/Mid-term technologies: NMR imaging, scanning tunneling microscope single pixel imaging
- Mid/long-term technologies: in-vivo cellular and neural imaging, single photon imaging
- Expected applications: healthcare, biotechnology, infrastructure monitoring, security and defense.



Imaging currents in carbon nanotubes (courtesy of ETH Zurich/QZABRE)

Quantum Sensing - Technologies

Technology	Quantity to measure	With what / applications	Term
Atom chips	Time	Atomic clocks	Now
Atom chips	Gravity (& acceleration)	Quantum gyrometers, quantum accelerometers	> 5 years
Atom chips	Rotation	Quantum gravimeters	Now
NV centers	Magnetic fields	Nanoscale characterization of magnetic fields Microwaves (analyze in real time the spectrum) Measure currents in IC or PCB Molecular analysis (NMR in vitro) Magnetic memories	~ 5 years
NV centers	Electric fields	Measurement of IC and semiconductors Measurement of neuron signal	~ 5 years
NV centers	Pressure	Constraints (esp. for high pressure applications)	~ 5 years
NV centers	Temperature	Nanoscale temperature measurement	~ 5 years

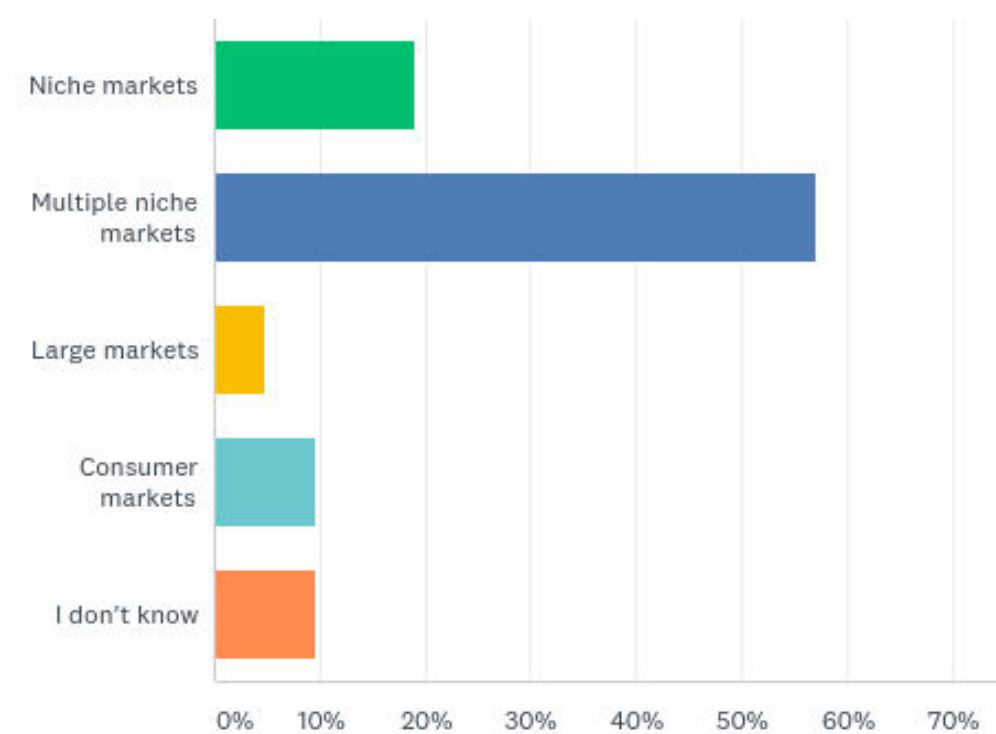
Market Progression in Quantum Sensing

- Improvements expected by NV centers are better performance and integration (seen as market barriers)
- Market growth:
  - NV centers - high/rocket growth expected by all manufacturers
  - Atom-chip sensors - steady growth expected by manufacturers
- Market size in 5 years:
  - Quantum sensing devices will reach multiple niche markets
  - NV centers sensors : ~ 1000-3000 units/year @ 5000 - 20000 €, i.e. 5 M€ to 60 M€
  - Atom-chip sensors : ~ 200-500 units/year @10000 - 30000 €, i.e. 2 M€ to 15 M€
- Note that the market for systems using these sensors will be much bigger: for example the market for MEG (Magnetoencephalography) is around 100 M€ while the SQUIDs used in these systems account for about 10 M€

Commercialization barriers (% of respondents)

Cost	66,67%
Size	16,67%
Weight	8,33%
Integration (in systems, production lines ...)	58,33%
Implementation complexity	50,00%
I don't know	0,00%
Other (please specify)	29,17%

Markets (% of respondents)



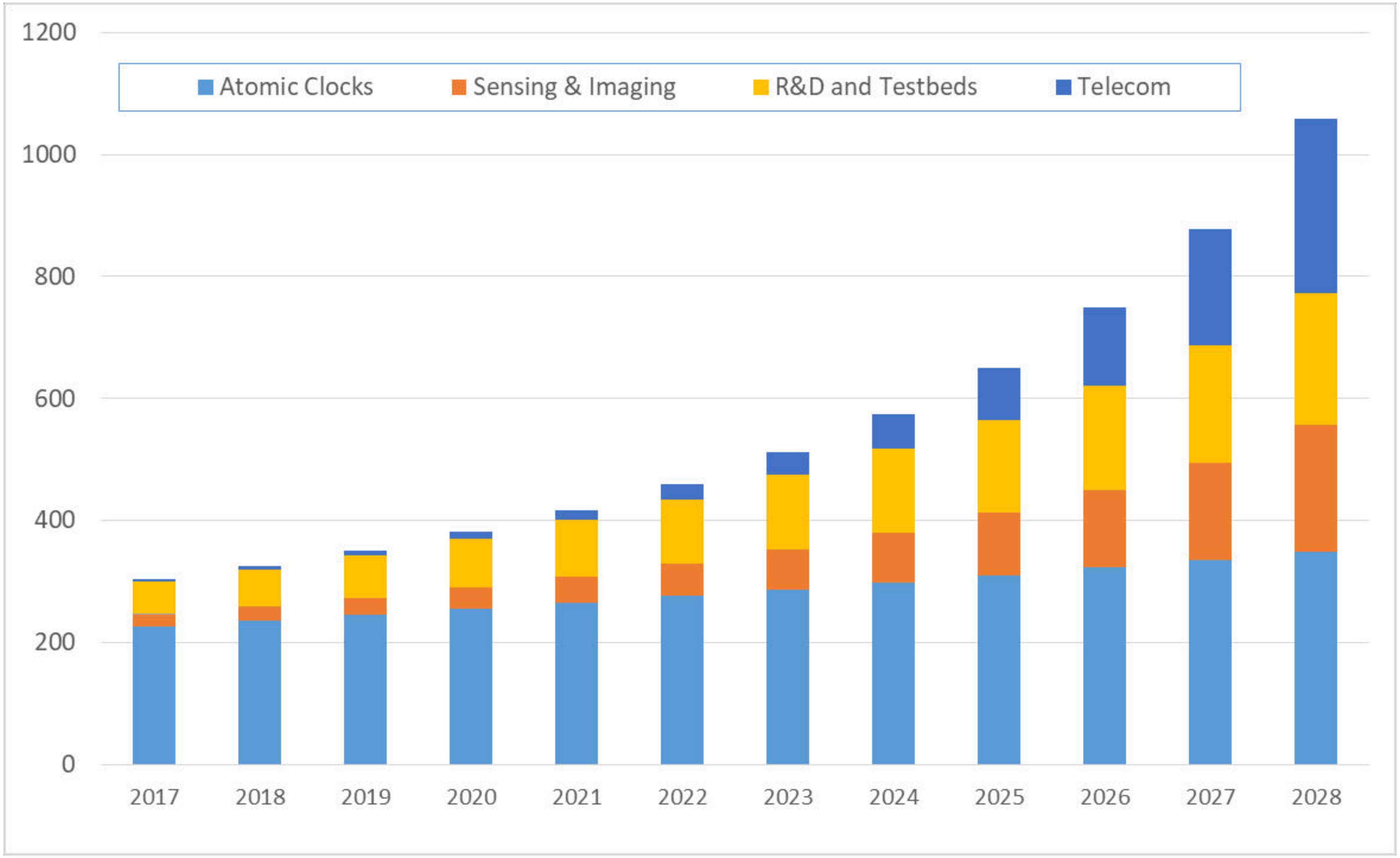
Summary of Technologies and Applications

Quantity to measure	Applications	Term
Time	Atomic clocks for time measurement & certification Synchronization for networks, GPS …	Now
Rotation & acceleration	Quantum gyrometers Quantum accelerometers	> 5 years
Gravity	Natural resources exploitation and monitoring	Now
Magnetic fields	Current Measurement in IC, batteries … Molecular analysis (NMR in vitro) NMR imaging Magnetoencephalography (MEG)	< 5 years
Electric fields	Measurement of IC and semiconductors Measurement of neuron signal (EEG)	< 5 years
Pressure	Constraints in materials (esp. for high pressure)	~ 5 years
Temperature	Nanoscale temperature measurement	~ 5 years

Industry Players in Quantum Sensing

- Adamas Nanotechnologies (diamond material)
- AOSense (atomic sensors)
- ColdQuanta (atomic sensors)
- Diamond Quantum Technologies (NV sensors)
- Dust Identity (NV sensors)
- Element 6 (diamond material)
- Frequency Electronics (end user)
- Geometrics (end user)
- Microsemiconductors (sensing)
- Muquans (atomic sensors)
- NVision (NV sensors)
- Qnami (NV sensors)
- Quspin (atomic sensors)
- Qzabre (NV sensors)
- Robert Bosch (sensing)
- Southwest Sciences (sensing))
- Squtec (NV sensors)
- Thales (sensing)
- Twinleaf (atomic sensors)
- ...

Total Market for Quantum Communication and Sensing (M€)



Conclusions on Market for Quantum Communication and Sensing

- **Market in 5 years (2023) :**
  - Atomic clocks will still represent the biggest market share.
  - Sensing and imaging will account for about 60 M€ with the most part coming from Nanoscale Quantum Optics (NV centers and atom chips).
  - Telecom market will be < 50 M€.
- **Market in 10 years (2028) :**
  - Sensing and imaging will account for around 200 M€ with the most part for magnetometers.
  - Telecom market will be around 300 M€.
- **Total Market** will account for about 7 B€ for the next 10 years. The associated systems and services will represent around 10 times this amount.

Contributions to Technology Modules

- QRNG (I. Artundo)
- QKD in space (P. Villoresi)
- Integrated QKD systems (M. Cherchi, M. Petruzzella)
- Single-photon sources (C. Becher, V. Giesz, N. Somaschi)
- Single-photon detectors (S. Dorenbos)
- Optical atomic clocks (O. Carraz, E. Murphy)
- Matter-wave interferometers (B. Desruelle, E. Murphy)
- NV centres (P. Maletinsky, E. Neu, C. Degen, G. Puebla-Hellmann)
- Software (G. Slavcheva)

Contributions to MRS Workshops

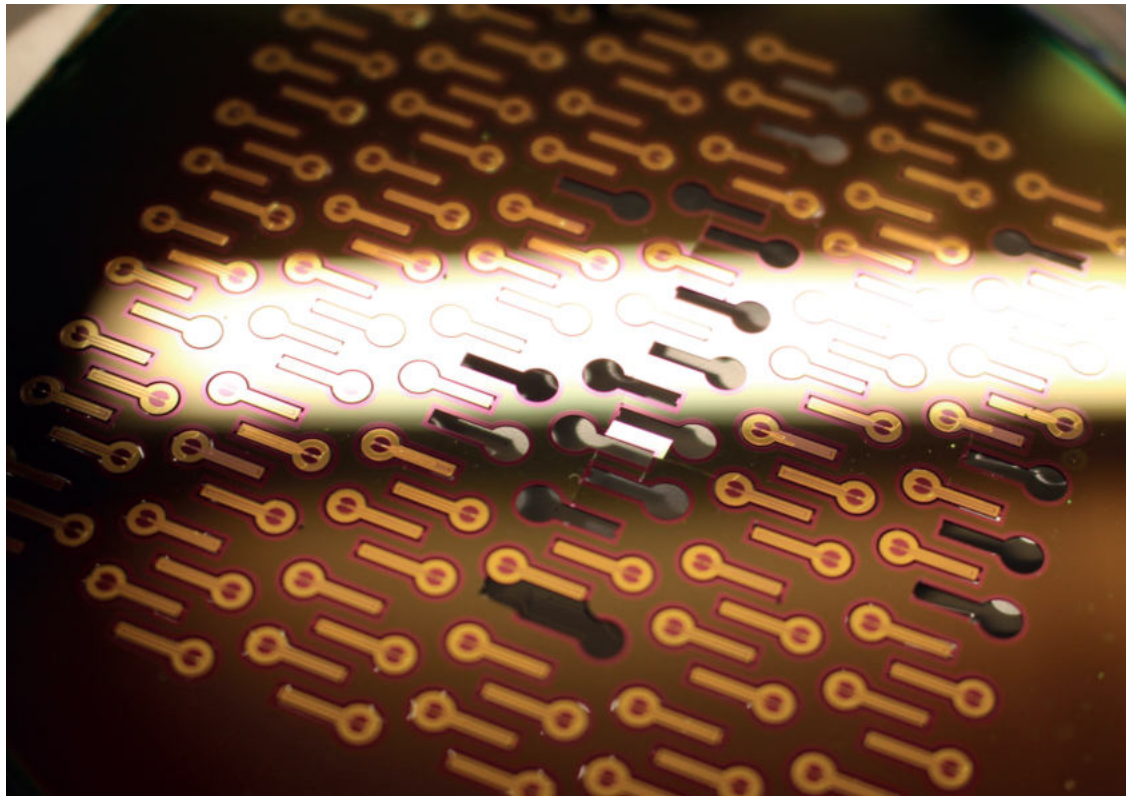
- Mario Agio, Germany
- Vikas Anant, USA
- Sella Brosh, USA
- Philippe Bouyer, France
- Matteo Cherchi, Finland
- Jacques Cochard, France
- Thierry Debuisschert, France
- Bruno Desruelles, France
- Sander Dorenbos, The Netherlands
- Valerian Giesz, France
- Jan Huwer, UK
- Nicola Massari, Italy
- Mathieu Munsch, Switzerland
- Maurangelo Petruzzella, The Netherlands
- Andreas Poppe, Austria
- Thierry Robin, France
- Ralph Stübner, Belgium
- Paolo Villoresi, Italy

Contact Information

- MRS on Quantum Communication
  - Jacques Cochard - jcochard@tematys.com
- MRS on Quantum Sensing
  - Thierry Robin - trobin@tematys.com
- COST NQO & MRS Dissemination
  - Mario Agio - mario.agio@uni-siegen.de
  - Irene D'Amico - irene.damico@york.ac.uk
  - Félix Bussières - felix.bussieres@idquantique.com
  - Valerian Giesz - valerian.giesz@quandela.com
  - COST Action - cost-nqo@uni-siegen.de
- COST Association
  - Ralph Stübner - ralph.stuebner@cost.eu

List of Abbreviations

- BW - Bandwidth
- CMOS - Complementary Metal Oxide Semiconductor
- GNSS - Global Navigation Satellite System
- MIR - Mid Infrared
- MRI - Magnetic Resonance Imaging
- MZI - Mach-Zehnder Interferometer
- MWI - Matter-Wave Interferometer
- NIR - Near Infrared
- NQO - Nanoscale Quantum Optics
- NV - Nitrogen Vacancy
- OAC - Optical Atomic Clock
- PPLN - Periodically-Poled Lithium Niobate
- PUF - Physical Unclonable Functions
- QKD - Quantum Key Distribution
- QRNG - Quantum Random Number Generator
- RNG - Random Number Generator
- SPAD - Single-Photon Avalanche Diode
- SPS - Single-Photon Source
- SSPD - Superconducting Single-Photon Detector
- SV - Silicon Vacancy
- UV - Ultraviolet



(courtesy of U Geneva, U Siegen)