From quantum science to quantum technologies

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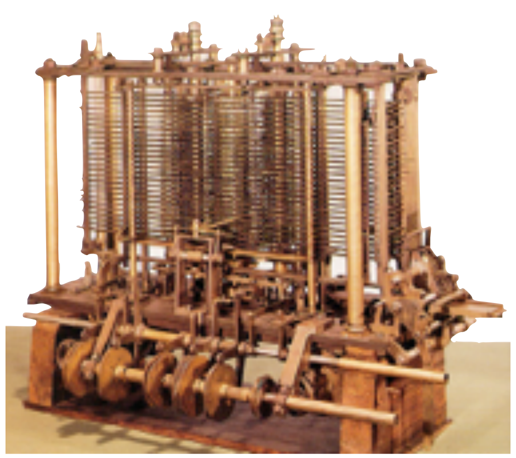
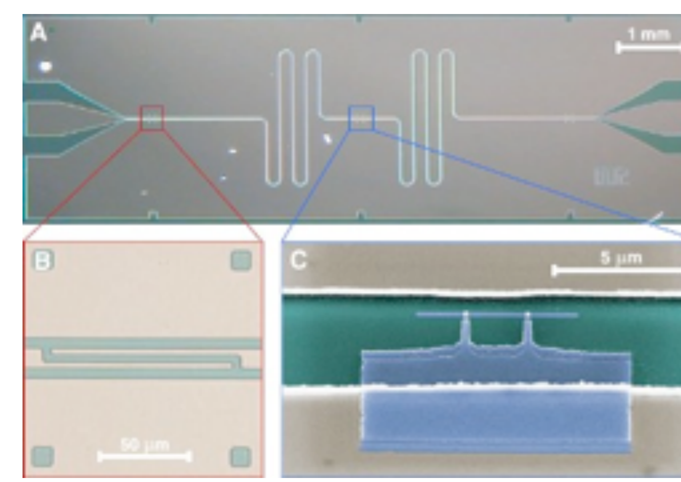
the future
IS quantum

- Basic science is motivated by the quest to understand the world
- It is a long-term undertaking, but...
- ...it results in **transformative** (as opposed to incremental) changes in technology, and...
- ...it's exactly these changes that define the modern society





"quantum information is a radical departure in information technology, more fundamentally different from current technology than the digital computer is from the abacus".

W. D. Phillips, 1997 Nobel laureate
member of the EU Integrating Project AQUTE

second quantum revolution

- Information, its acquisition, storage, transmission and processing is fundamentally physics
- Ultimate elements of processors will be of quantal size
- Tremendous "speed-up" may be possible using quantum mechanical systems
- Quantum techniques will have wide applications in science and technology

"But it could be that the most profound and mysterious feature of quantum mechanics, known as 'quantum entanglement' has not been exploited yet. Quantum entanglement opens the way to radically new ways of transmitting and processing information. . ."

Th. W. Hänsch, 2005 Nobel laureate
member of the EU Integrating Project AQUTE

Europe is leading

- Roughly **half of the world's publications** in the field comes from **EU based groups**, funded through **FET**
- **EU roadmap** already in place; constant progress, milestones reached, gaps and challenges identified
- Many countries (**Australia, China, Japan, Singapore, Russia, US**) are developing their **own research programs** in the field

- Overall, many branches of quantum technology have gone past the proof-of-principle phase
- Further profess can only be achieved through the leap in resources and the long-term commitment coming with it.

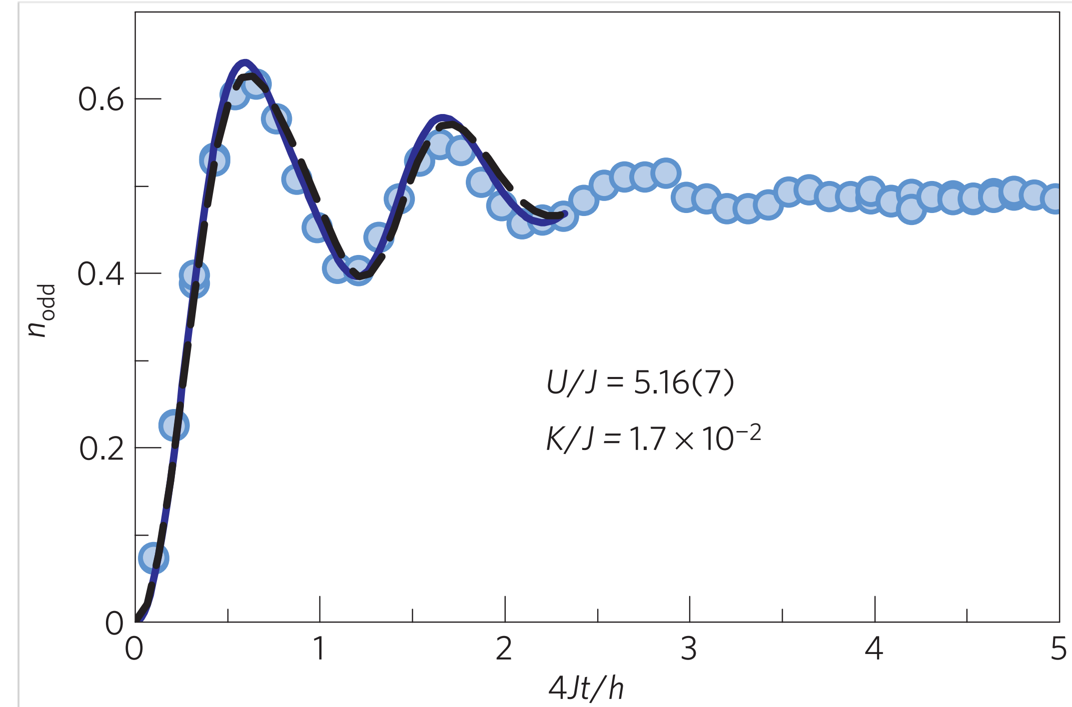
"FET research on quantum technologies opened a new path to 100% secure communications, taken up by companies such as Siemens, Thales and the high tech SME idQuantique SA, a leader in this technology."

Commission Communication

Moving the ICT frontiers, a strategy for research on future and emerging technologies in Europe, COM(2009) 184

quantum computers/simulators

- Next thing on the horizon (3-5 years)
- ***Impact***: Provide **answers** to problems that are fundamentally **beyond classical computing capabilities**



First hints of a quantum simulator outperforming a classical supercomputer

- ***Example***: The development of **high-temperature superconductors** via a quantum simulator would enable **lossless electric transmission lines**

"...trying to find a computer simulation of physics, seems to me to be an excellent program to follow out...and I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

R. P. Feynman, 1965 Nobel laureate
Simulating physics with computers, Int. J. Theor. Phys. 21, 467 (1982)

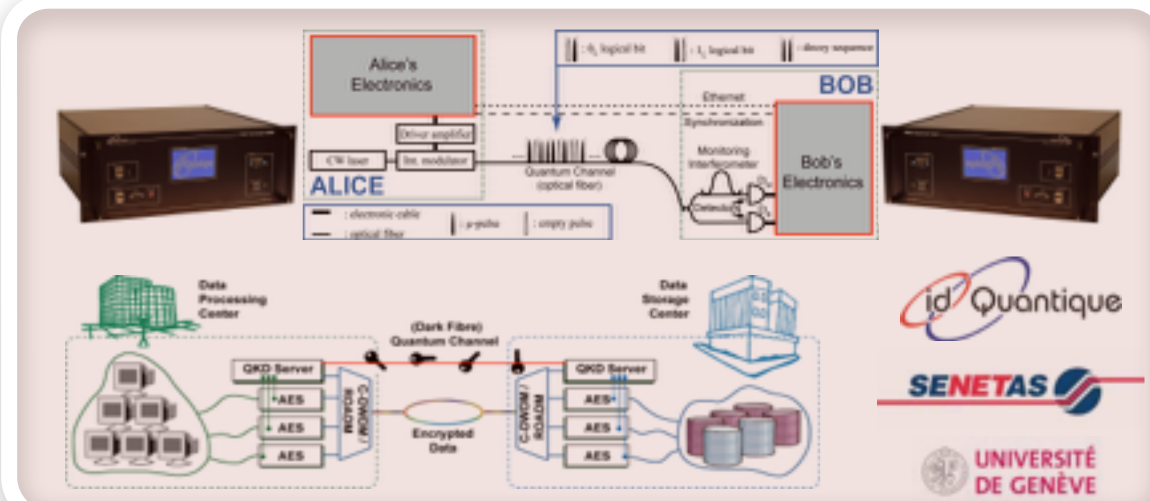
quantum
communication

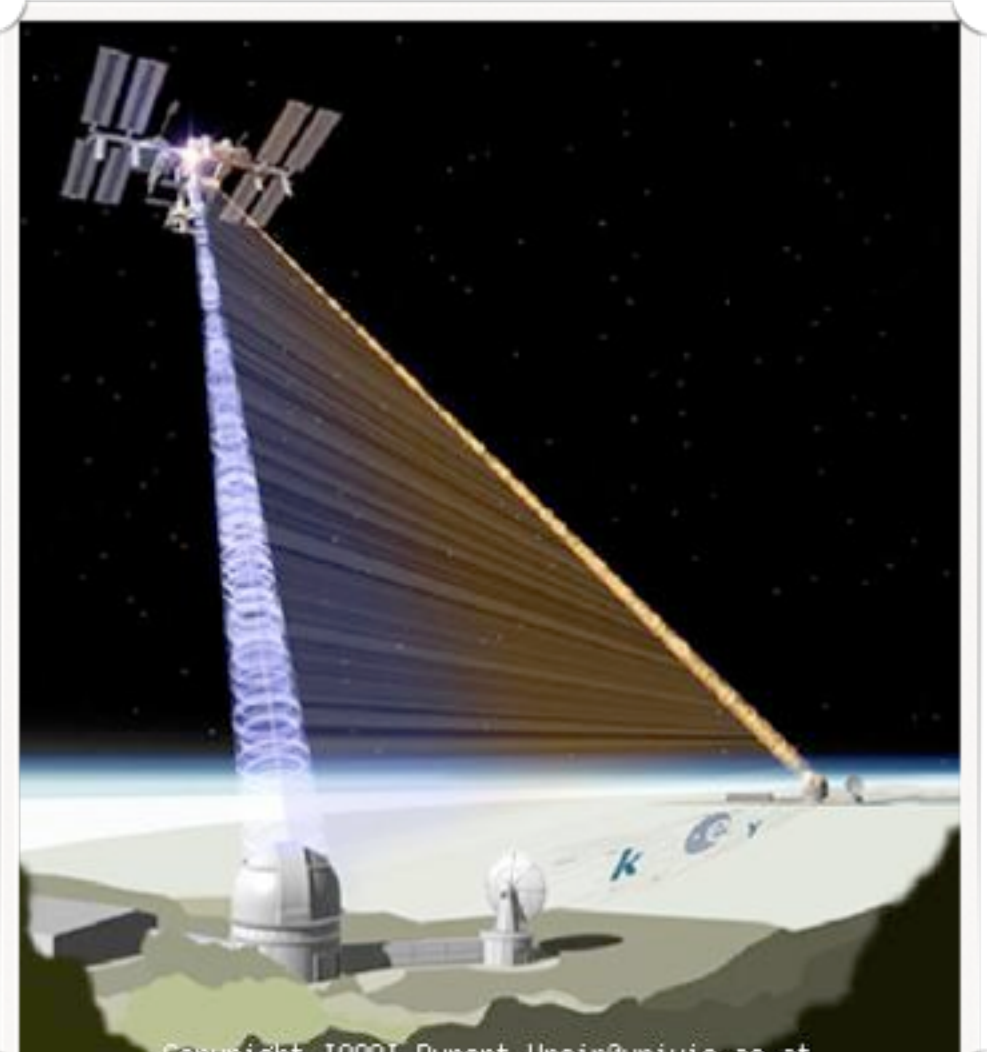
- Already a real-world technology

> "Beyond approximately 10 years into the future, the general feeling among ECRYPT partners is that recommendations made today should be assigned a rather small confidence level, perhaps in particular for asymmetric primitives (ie public key)."

2008 ECRYPT NoE report (conventional cryptography community)

- Vision: **Consumer quantum cryptography** (quantum bank card/ATM, quantum door/car key...)
- Security (**e-commerce; smart grids...**)



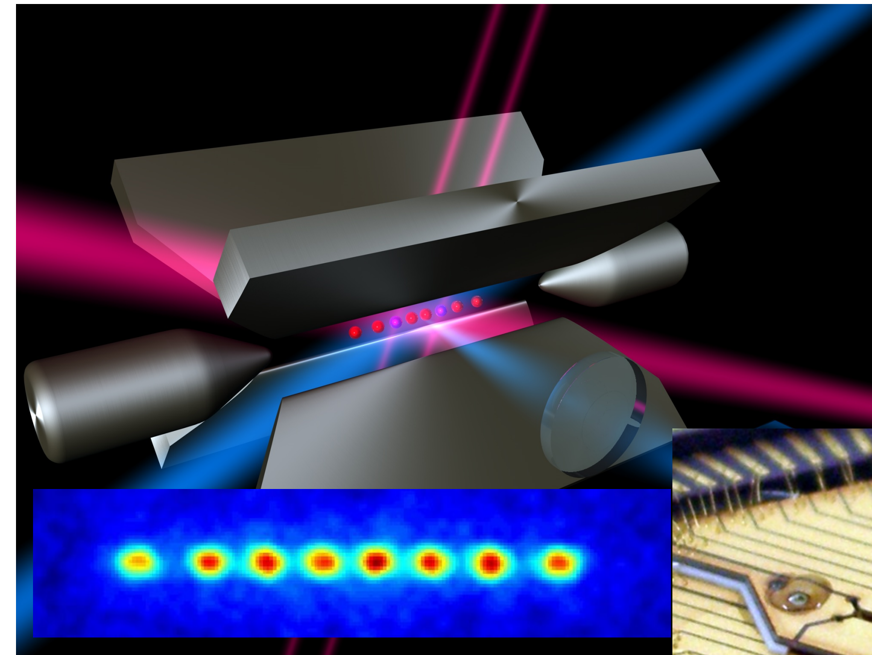


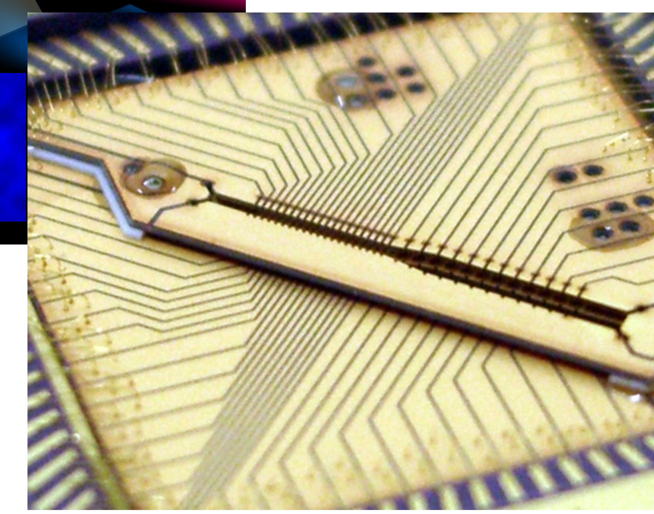
- Challenges: **Continental-scale** quantum communication (***quantum repeaters***)
- European scientific community/SMEs leading at world level

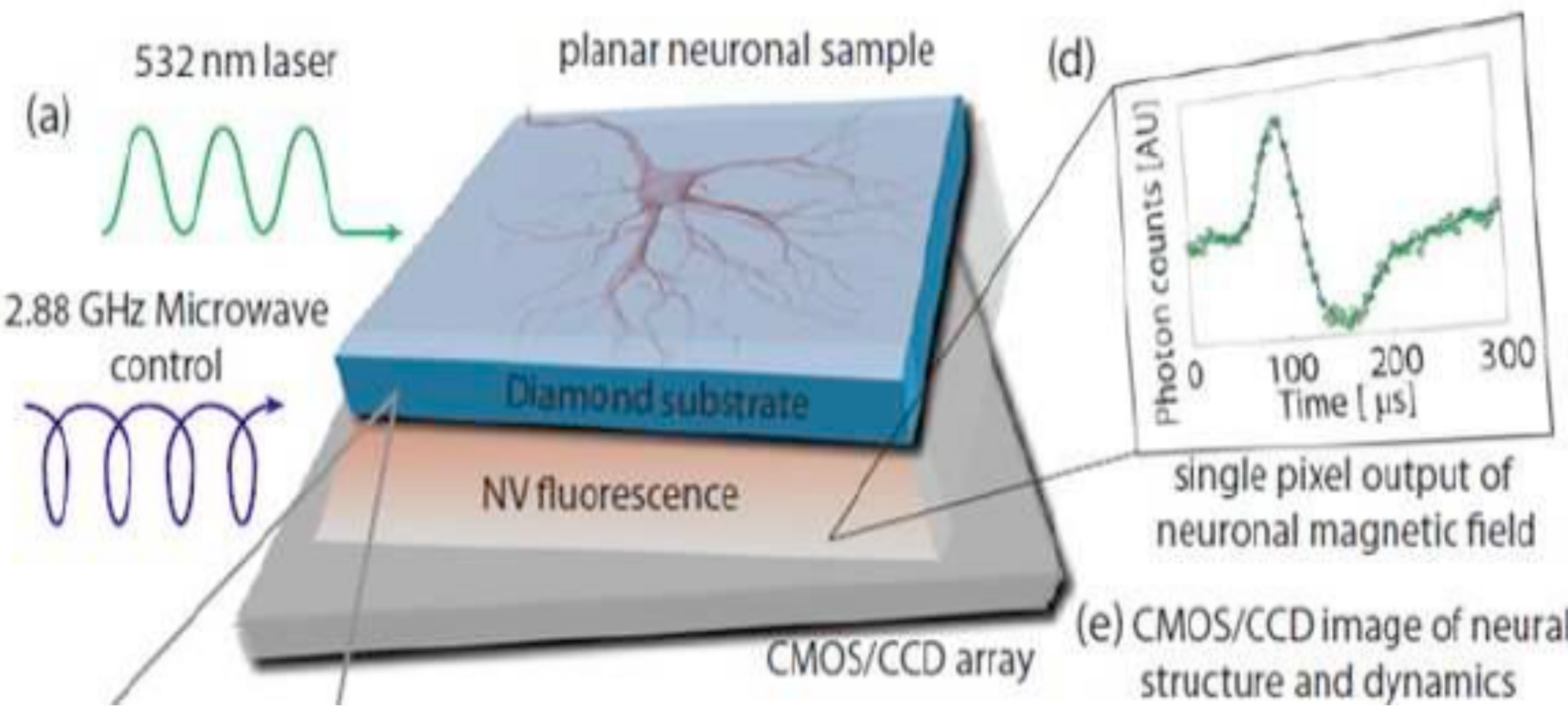
Security

quantum
metrology and sensing

- Potential in many areas
- Quantum-logic based metrology: ultra-precise **atomic clocks** for **navigation** (building on e.g. ESA Galileo satellites)
- Sensing: sub-micron **imaging of tissues** for early detection and **diagnosis** of health problems



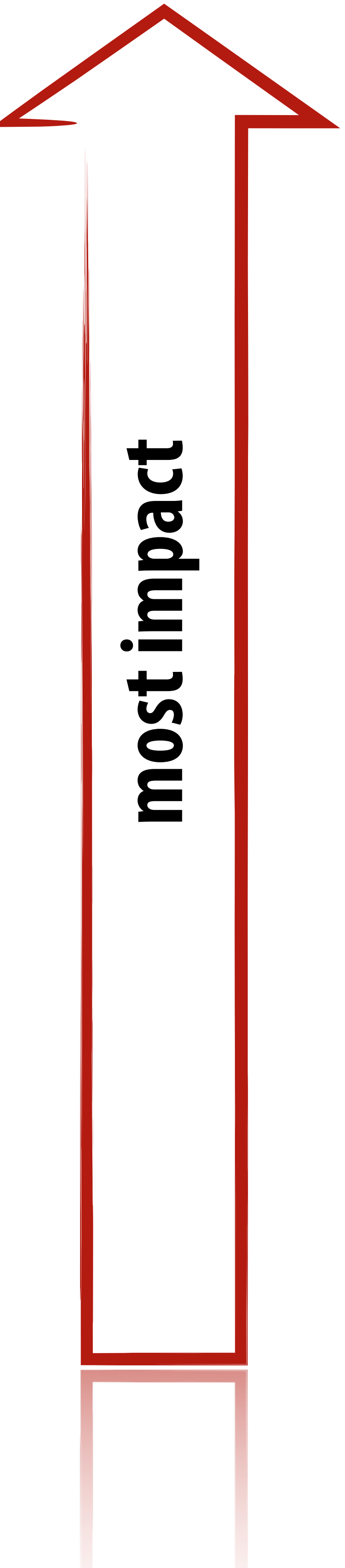




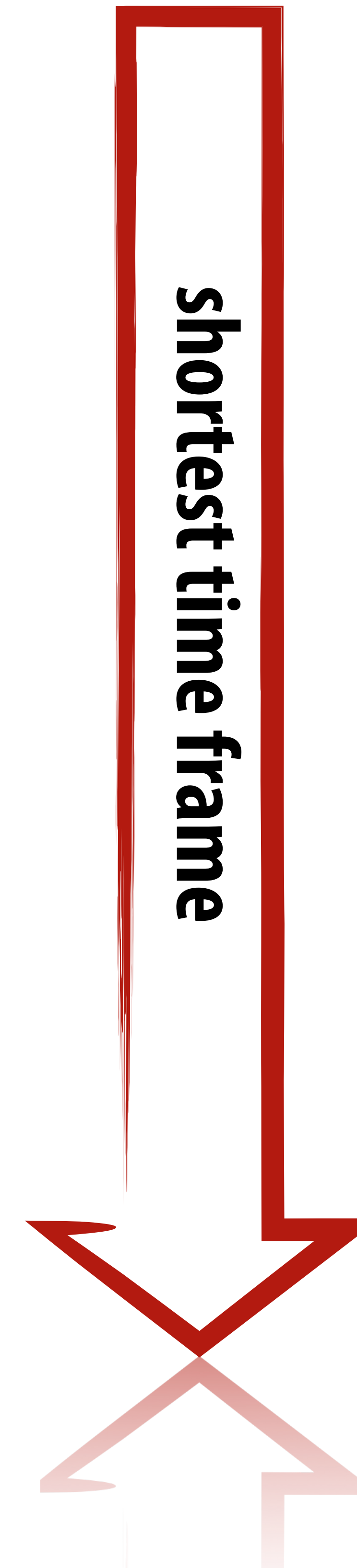
Health

second quantum revolution

potential outcomes



- Ultrafast, “smart” computers
- Quantum internet (absolute security)
- Custom-designed quantum materials
- Quantum sensors
- Atomic clocks



DK Matai
Chairman at Quantum Diamond, Quantum Innovation Labs (QiLabs.net), Tri Gold Swan, AT…

What's Quantum Diamond Spintronic International Watches and Clocks?

TRL Quantum Communication

1. *Basic Science*
2. *Proof of concept (in lab)*
3. *Component and protocol development*
4. *Proof of feasibility (in real world)*
5. *Integration for applications*

Technology/Platform/Implementation	TRL	H2020 area
Quantum Memories	1,2	FET
Quantum Repeaters	1,2	FET
Source (SPCD Integrated/Compact)	2,3	FET→GAP
Source (Single Photon)	1,2,3	FET→GAP
Detection (Superconducting)	3	GAP
Detection (Solid State – InGaAs + Si)	3	GAP
Beyond QKD (protocol development)	2,3	GAP
Trusted-Node QKD[a]	4,5	KET

[a] *Single Photon Sources: there is still a large amount of fundamental work to find new approaches to them (TRL=1), some approaches are more mature but still need to demonstrate basic functionality (TRL=2), others are perhaps more advanced and would profit from having a dedicated development programme (TRL=3).*

[b] *In the case of Trusted-Node QKD, the KET part could consist of short distance point-to-point networks (TRL=5) whereas using trusted node QKD in more complex (passive or reconfigurable) networks as well as new use models (securing information within a hospital for example) could be seen as closer to TRL=4*

TRL Quantum
Computation

1. *Basic Science*
2. *Proof of concept (in lab)*
3. *Component and protocol development*
4. *Proof of feasibility (in real world)*
5. *Integration for applications*

Technology/Platform/Implementation	TRL	H2020 area
Trapped ions	2	FET
Neutral atoms, molecules and cavity QED	2	FET
Superconducting circuits	2	FET
Semiconductor Quantum Dots	2	FET
Linear Optics	3	GAP
Impurity spins in solids and single molecular clusters	2	FET

TRL Quantum

Enabled Applications

1. *Basic Science*
2. *Proof of concept (in lab)*
3. *Component and protocol development*
4. *Proof of feasibility (in real world)*
5. *Integration for applications*

Technology/Platform/Implementation	TRL	H2020 area
Quantum Random Number Generators[a]	4,5	KET
Quantum Metrology and Sensing[b]	1,2,3,4	FET
Quantum Imaging[c]	1,2	FET
Quantum clocks	3	GAP

[a] For Quantum Random Number Generators, we remark that new concepts, such as device independent or certified random number generation falls under TRL=1,2.

[b] Quantum Sensing (single-parameter estimation) has a small element in TRL=3,4 - that is, it is understood how to deal with e.g. losses, and known what sorts of systems are optimal, but they have not yet been put into practice, in part because of the lack of components (e.g. sources and detectors) with the right performance.

[c] The TRL of Quantum Imaging is 1,2, since currently there are no robust protocols for multiparameter estimation or for assessing enhancements in realistic systems.