Towards a quantum internet

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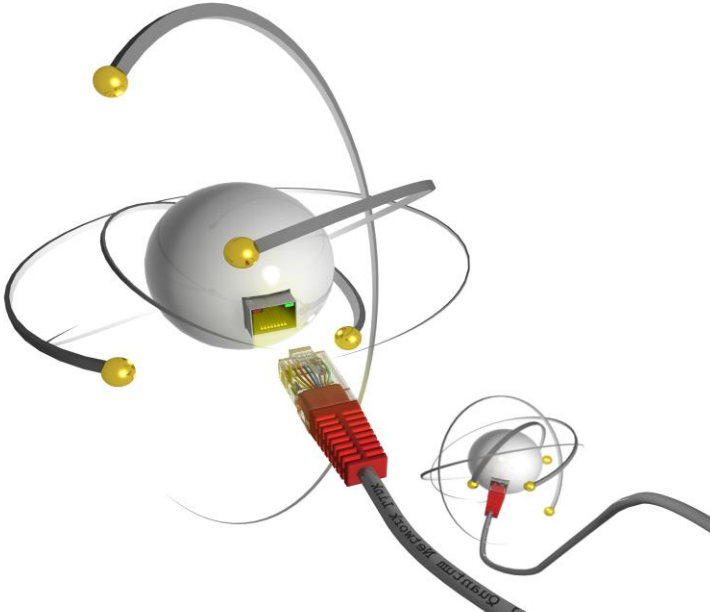
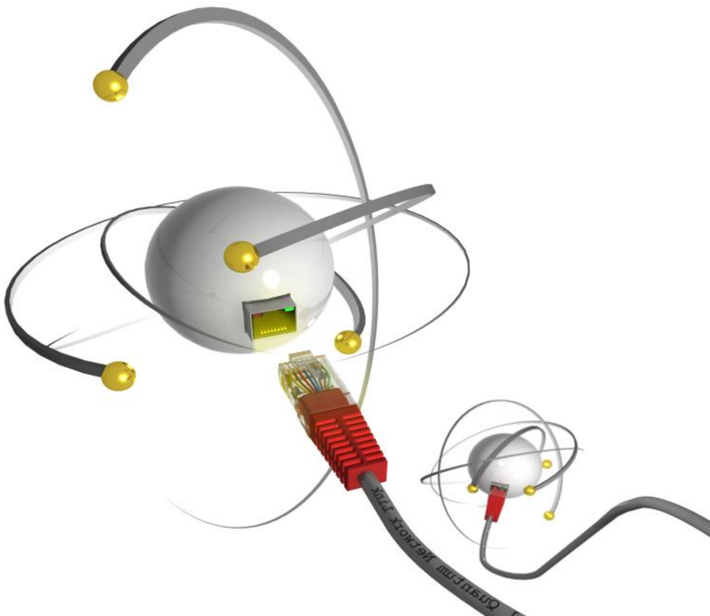


Why? How? When?

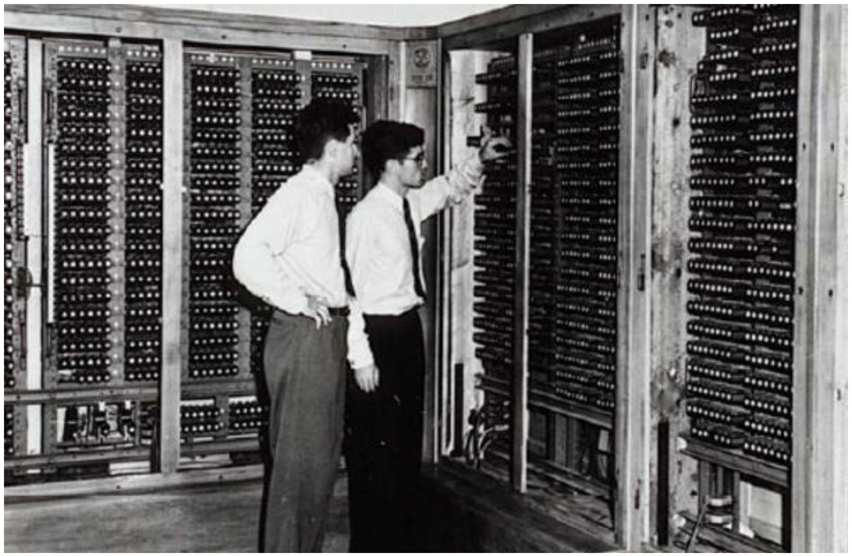
What are the unique applications that are enabled by quantum networks?

What do we need to build a quantum internet?

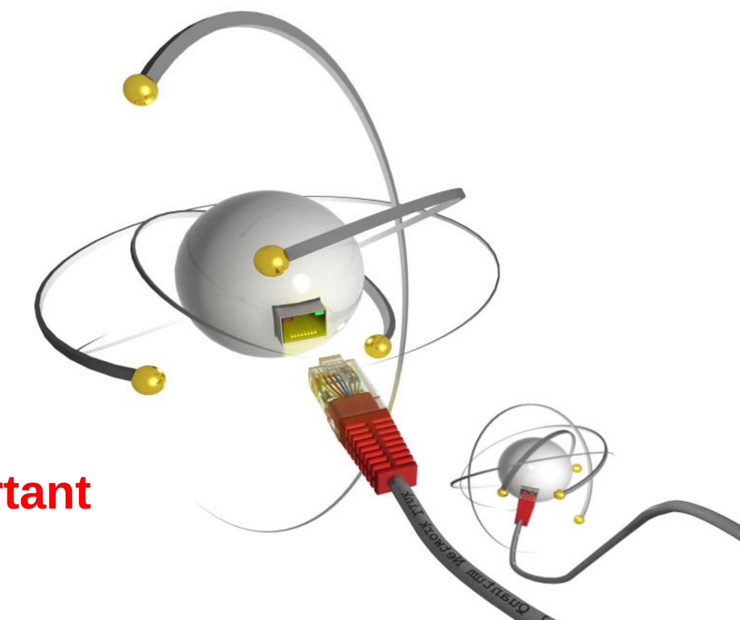
How long will it take?



Quantum information processing



Zuse Z4,
first commercial computer
(2200 relays)



Next decade:
Exponential growth of classical information processing capacity will break down:

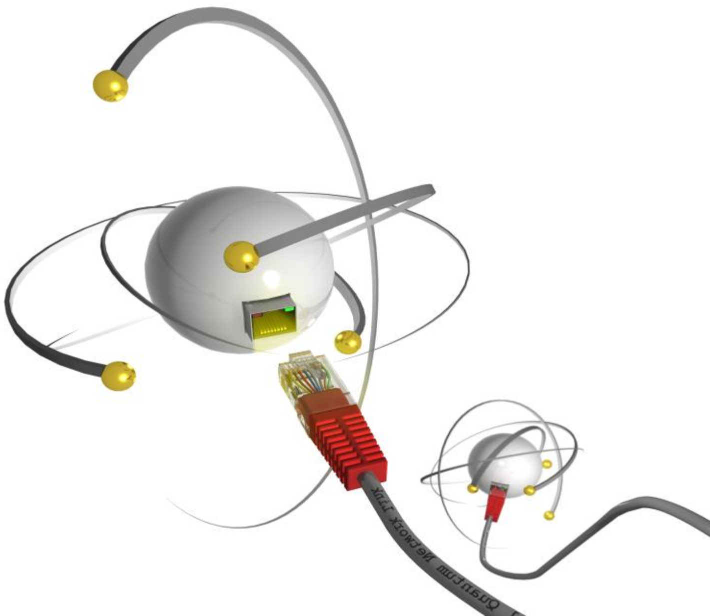
Transistors approach the size of single atoms

New computing paradigms will become important

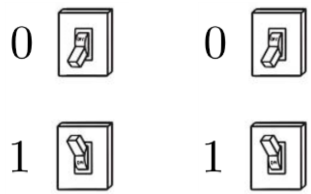
What is the quantum advantage?

"Hilbert space is a big place." (Carlton Caves)

What does not exist cannot be copied.

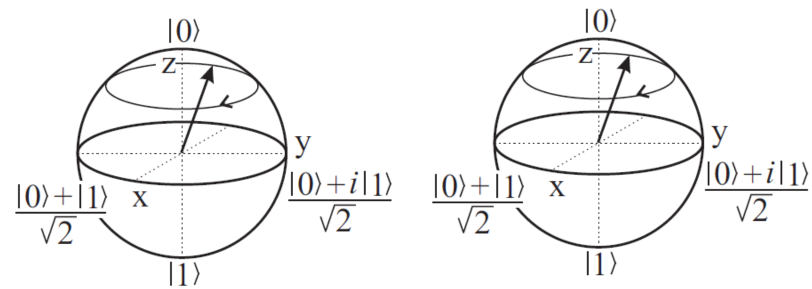


From classical bits to quantum bits



Two bits: 00 or 01 or 10 or 11
n bits: in one out of 2^n states

qubit example: magnetic moment of single atoms

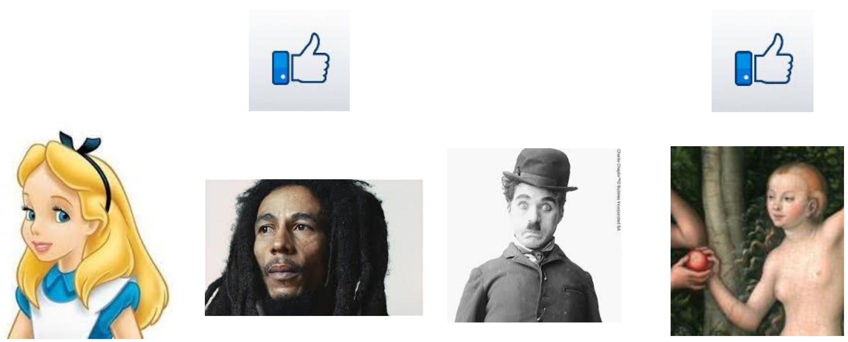


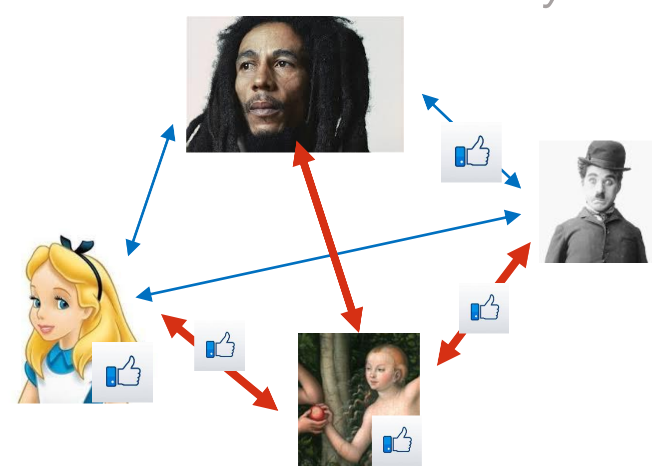
n qubits: Hilbert space with 2^n states

$$a_{00}|00\rangle + a_{01}|01\rangle + a_{10}|10\rangle + a_{11}|11\rangle$$

When *digitized*, n qubits can hold 2^n bits

i.e. the a's can only be 0 or 1





Many qubits

170 qubits can then hold $2^{170} = 10^{51}$ bits
That's more than the number of atoms on earth.
"Hilbert space is a big place." (Carlton Caves)

- Quantum computers and quantum simulators can have unique power.
- Quantum information cannot be sent via a classical network. We need quantum networks.

Still, when measuring an n-qubit state, you only get n bits of classical information

Richard Feynman

- Quantum states don't facilitate increased classical data rates
- Accessing the power of quantum states requires quantum algorithms

What is the quantum advantage?

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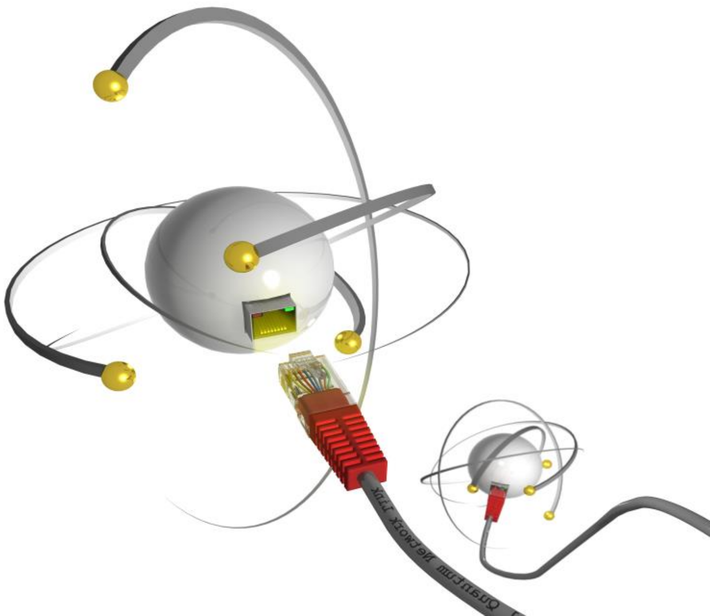
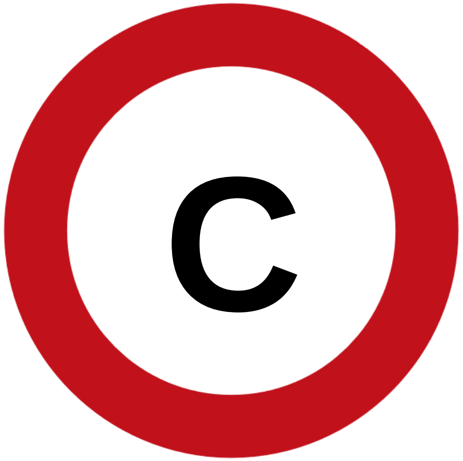
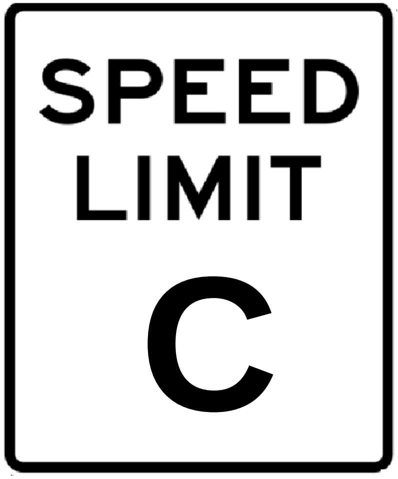


Assumptions of classical physics

Locality: No signal can travel faster than the speed of light. *(Einstein)*

Realism: Physical objects are defined independent of measurement
„I like to think the moon is there even if I am not looking at it.“ (Einstein)





Non-local correlations as a resource

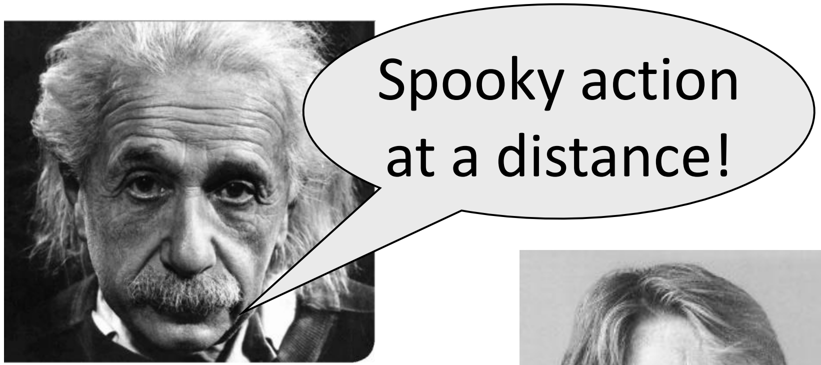
THE NEW YORK TIMES, SATURDAY, MAY 4, 1935.

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.



John Bell invented an experimental test of locality & realism (1964)

Numerous tests. First ones without "loopholes":
*Hensen, AR et al, Nature **526** (2015), Shalm et al., Giustina et al.: PRL 2015*

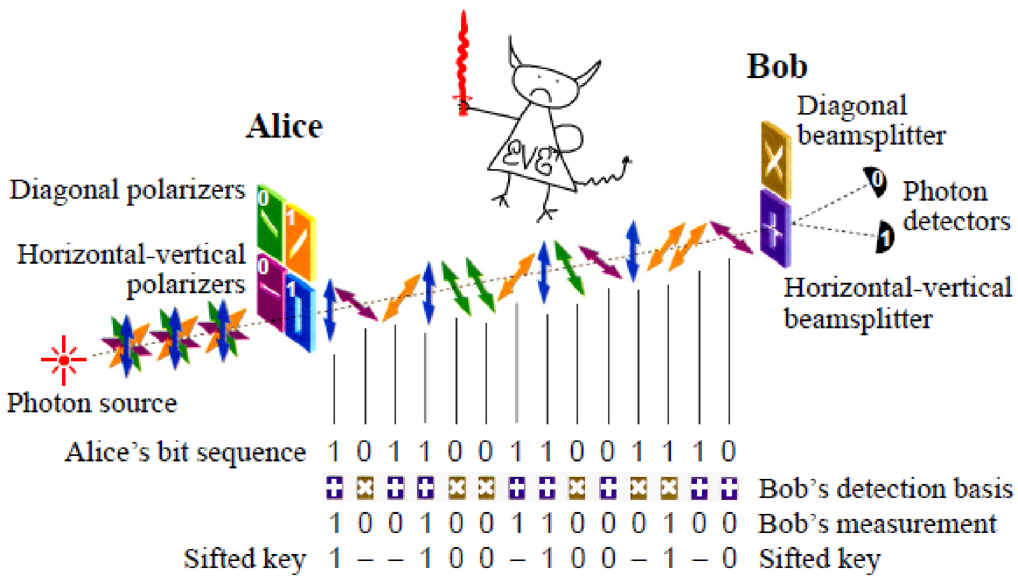
Entangled quantum states **violate the assumptions of classical physics**:
results are random but correlated, even for distant entangled particles

Non-local correlations as a resource

Results of measurements performed on quantum systems only come into existence when the measurement is performed.

What does not exist cannot be copied (or eavesdropped)!

If two parties send information encoded in quantum states, they can proof that no eavesdropper is present!



*Ekert and Renner: "The Ultimate Physical Limits of Privacy," Nature **507**, 443 (2014)*

Tittel, Ribordy, Gisin: "Quantum cryptography" Physics World (1998)

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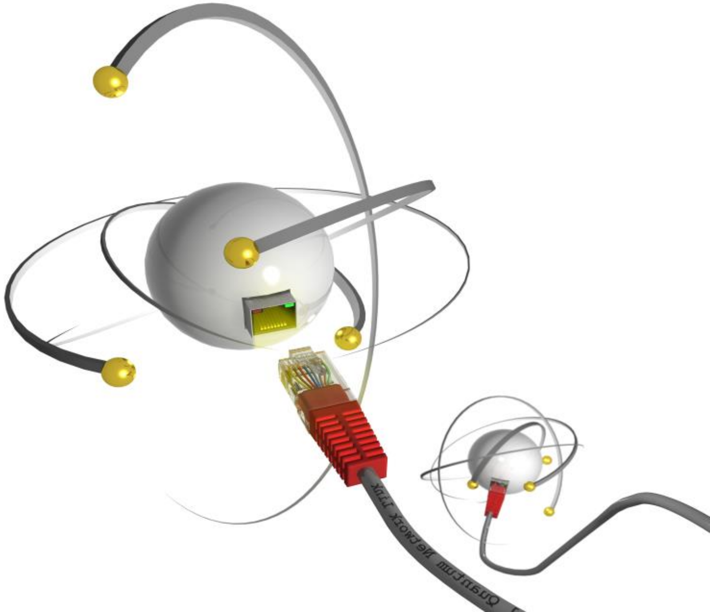
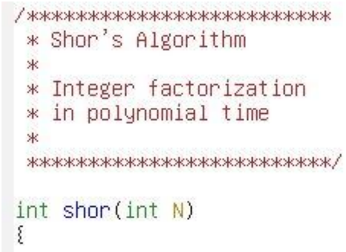


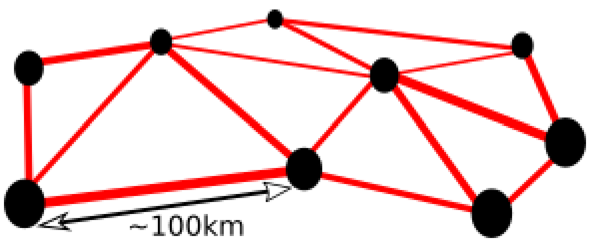
Quantum network applications

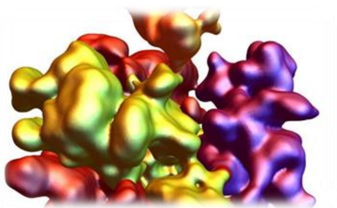
Provably secure communication
(also: voting, quantum money…)

Distributed and blind
quantum computing



Quantum networks:
A cornerstone in the
„second quantum revolution“





Simulation of complex
quantum systems

Many unforeseeable applications
once large-scale quantum
networks become available!

Precision sensing
(e.g. world clock,
gravity, starlight)

Reduce the latency and increase
the resilience of classical networks

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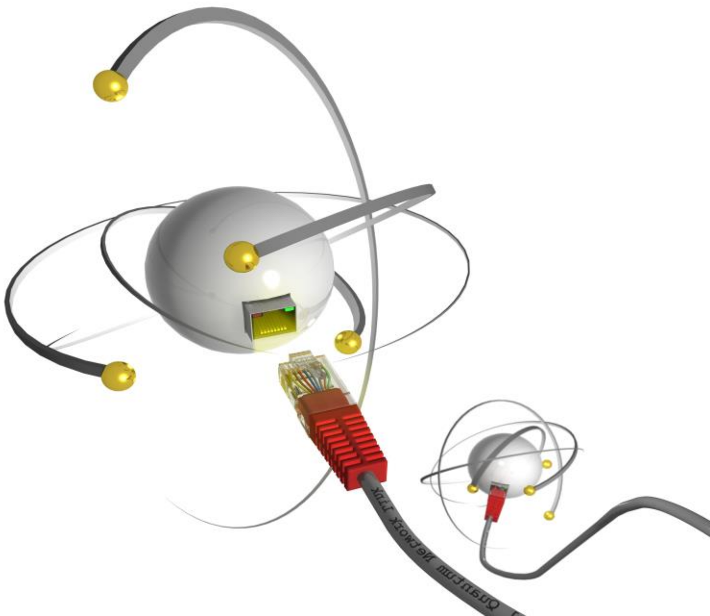
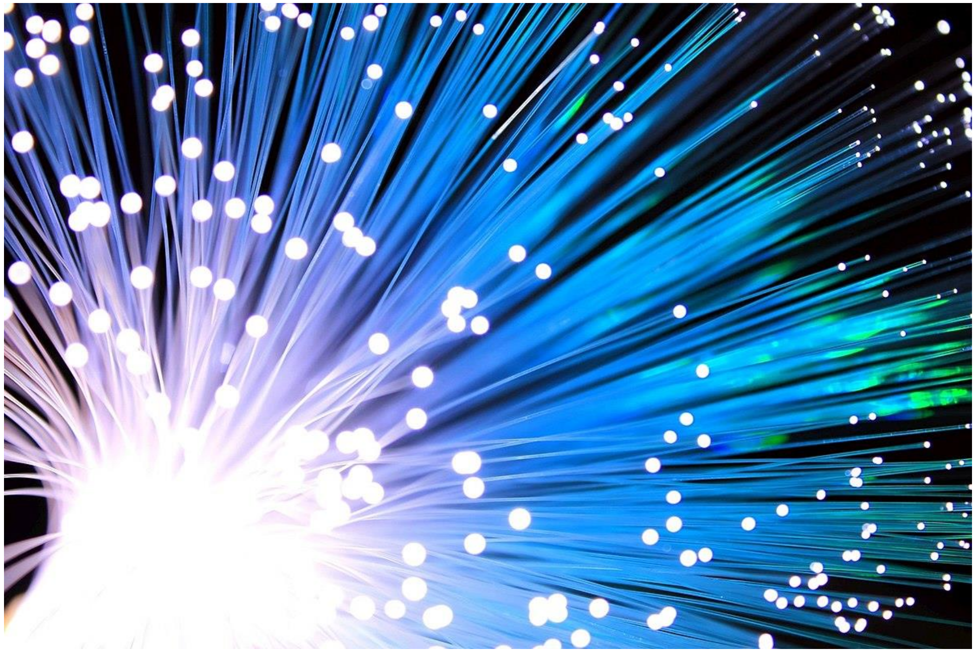


What does it take?

Electromagnetic fields are ideal for distributing information
Energy of the field $E = hf$ needs to be much larger than temperature kT
$\rightarrow$ at room Temperature, you need high frequency

Light in optical fibers allows for quantum state transmission.



- *technically "easy"*
- known since the 90's
- has severe limitations

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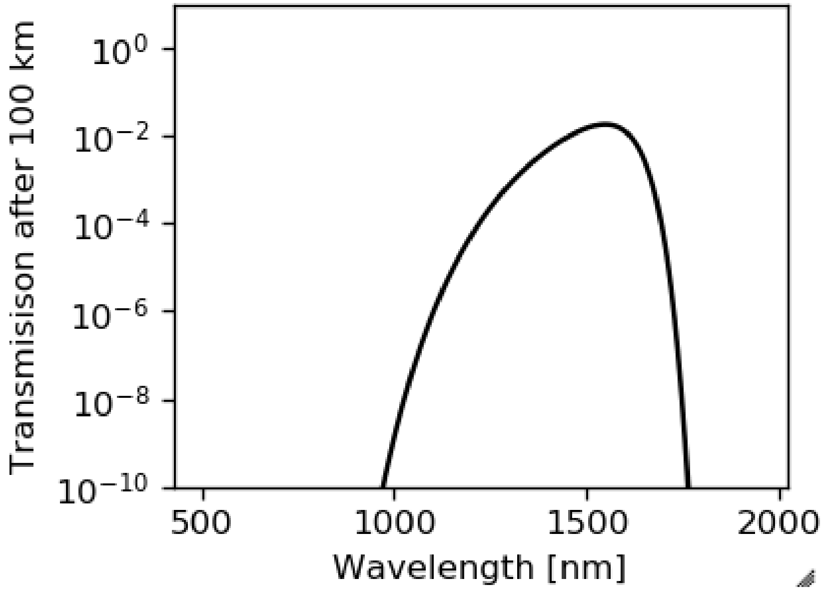


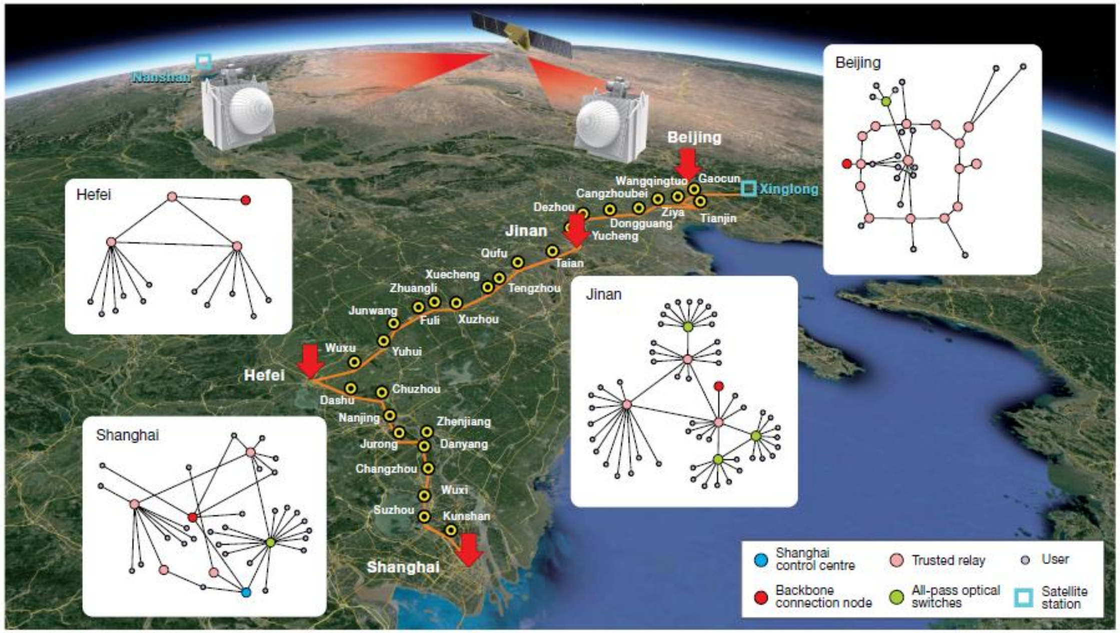
- *technically "easy"*
- known since the 90's
- has severe limitations

Efficient (>1%) fiber optical channels only for < 100 km distance

No improvement expected in terms of fiber transmission.

Lines: "The Search for Very Low Loss Fiber-Optic Materials," Science 226, 663 (1984)

Photonic networks: State-of-the-art



*Yin et al., Science **356**, 1140 (2017)*

*Chen et al., Nature **589**, 214 (2021)*

- Secure communication: ~ 100 km via fiber, ~ 1200 km via satellite
- Similar efforts in US & EU. Practical implementations (soon) available

Slow (~1 MB/s) but secure over global distances if you trust the provider

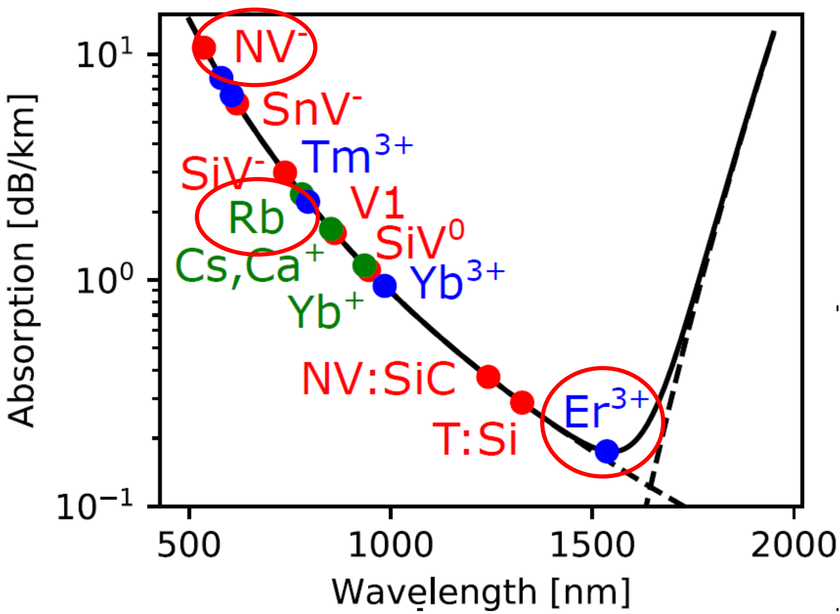
- "Quantum" security only up to ~100 km (~~non-local correlations~~)
- Does not allow to connect quantum computers (~~large Hilbert space~~)

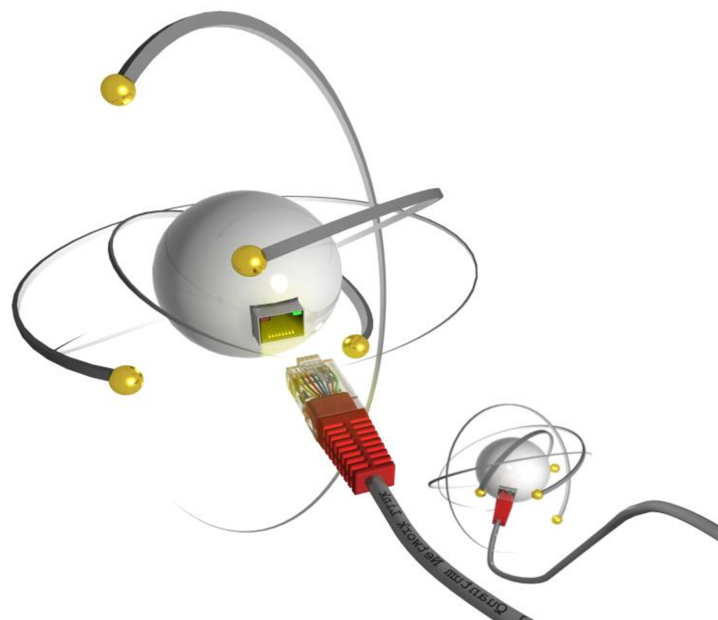
What does it take?

Increasing the distance and qubit number requires efficient connections to matter qubits.

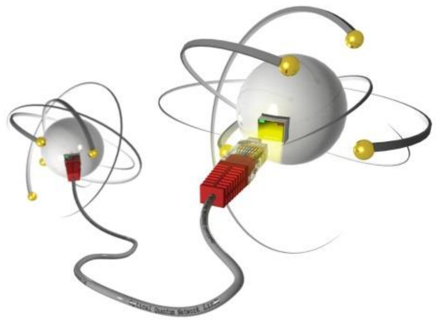
New capacities:

Long-term memory and processing of quantum states





Quantum Networks with matter qubits



Atoms in vacuum

Distance: 21 m

Success probability: 2 %

Fidelity: 98 %

S. Ritter, AR et al., Nature ***484*** *(2012)*

AR & G. Rempe Rev., Mod. Phys. ***87*** *(2015)*

Spins in diamond

Distance: 1.3 km

Success probability 10^{-8}

Fidelity > 83 %

B. Hensen, AR et al., Nature ***526*** *(2015)*

Four qubits in three nodes

Pompili et al, Science ***372****, 259 (2021).*

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Other experiments with trapped ions, atomic ensembles, quantum dots, superconducting circuits, molecules…

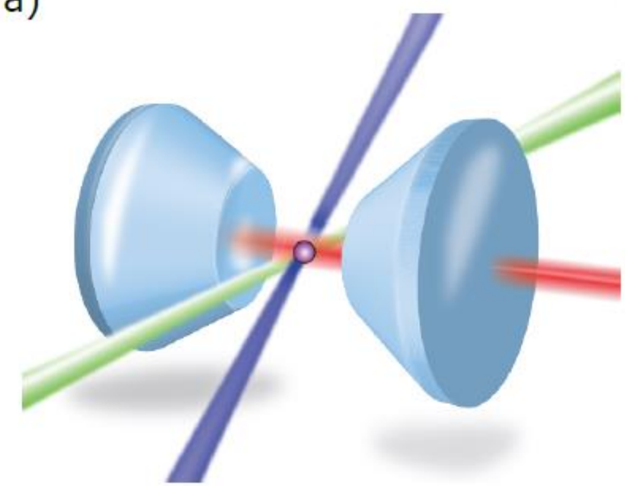
QUTech

MPQ

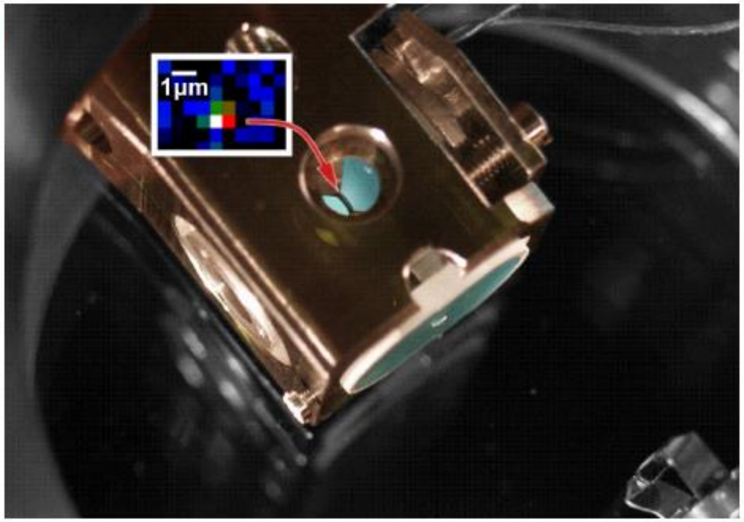
Deterministic spin-photon interaction

- Low interaction probability between stationary qubits and single photons
- Can be enhanced by trapping both in a small volume, i.e. an optical resonator

a)



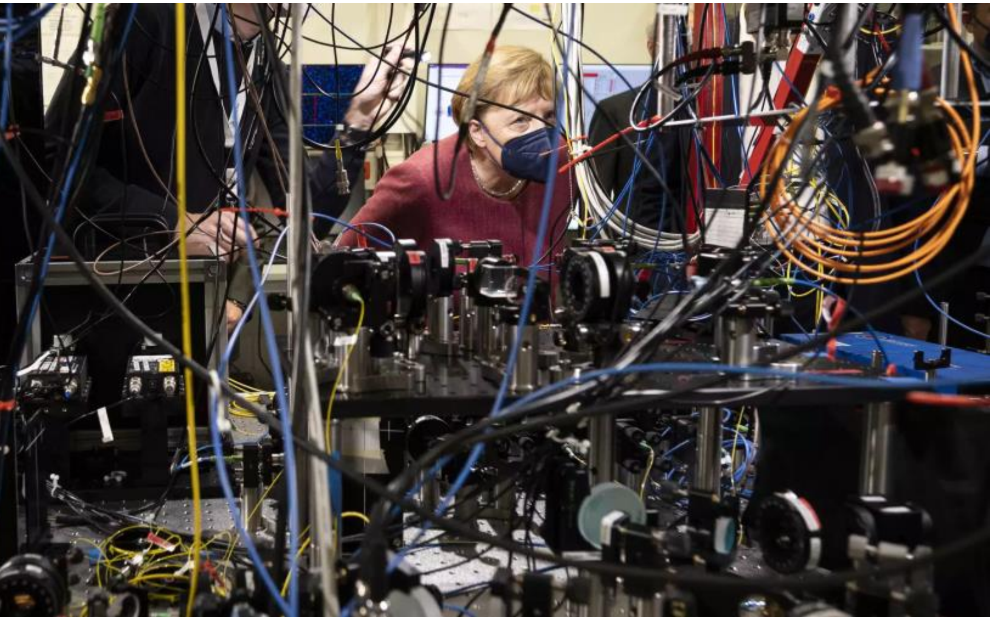
b)



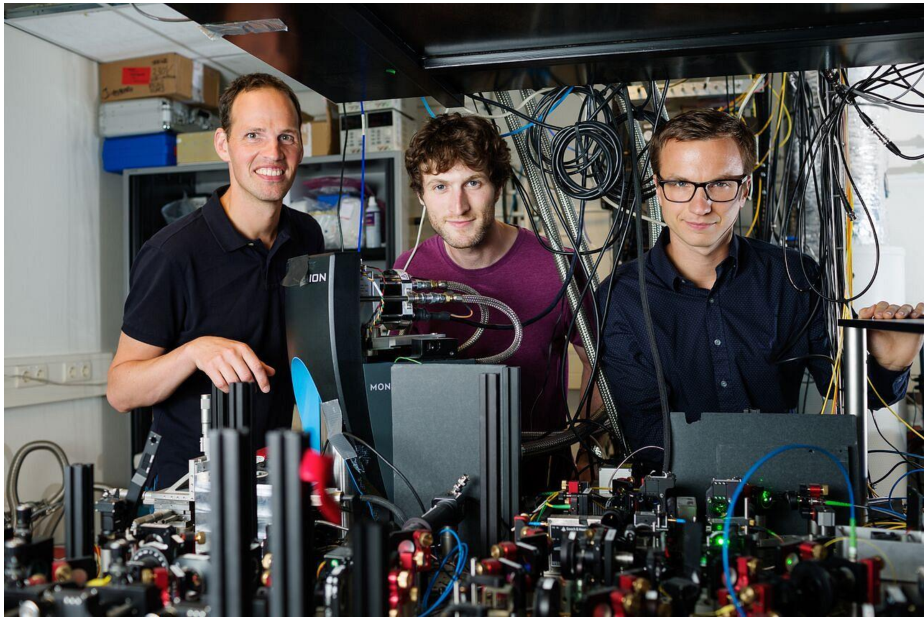
Experimental requirements

- precise high-power lasers
- free-space optical components in a temperature- and vibration-stabilized lab
- ultra-high vacuum or ultra-low temperatures
- high-power electronic control signals
- PhD students
- public funding

Rempe lab @ MPQ Garching



Hanson lab @ Qutech Delft



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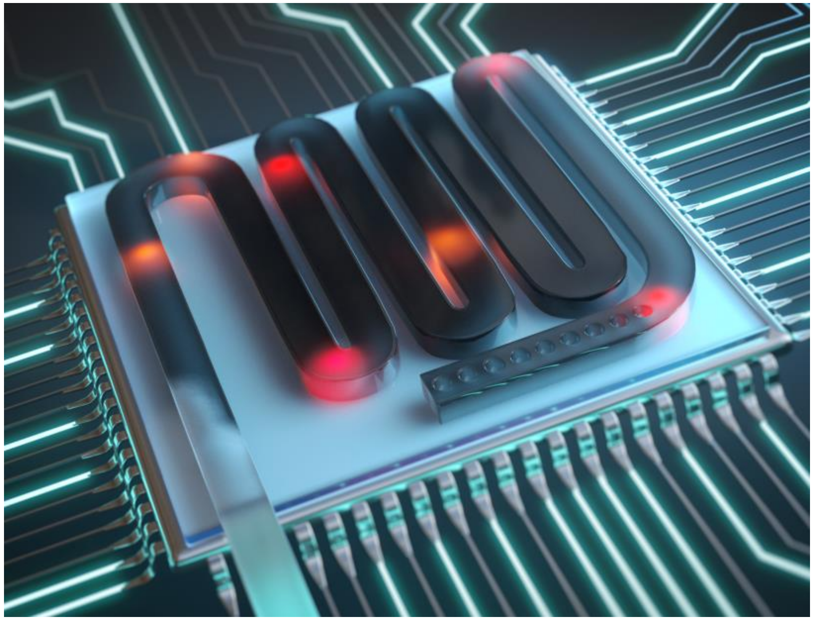
Bundesministerium
für Bildung
und Forschung

project TransQnode:

Entanglement at kHz rate between rack-integrated, transportable quantum network nodes over 100 km of optical fiber (until 2024)



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Weiss, Gritsch*, Merkel, Reiserer; Optica* ***8****(1) 40 (2021)*
Gritsch et al. arXiv:2108.05120 (2021); Patent pending*

MPQ

Outlook

“I don’t make any predictions,
and in particular not about the future.”
– Karl Valentin

Quantum network applications

100 erbium qubits in a single resonator: *Ulanowski, Merkel, Reiserer: Spectral Multiplexing of Telecom Emitters with Stable Transition Frequency. arXiv:2110.09409 (2021)*

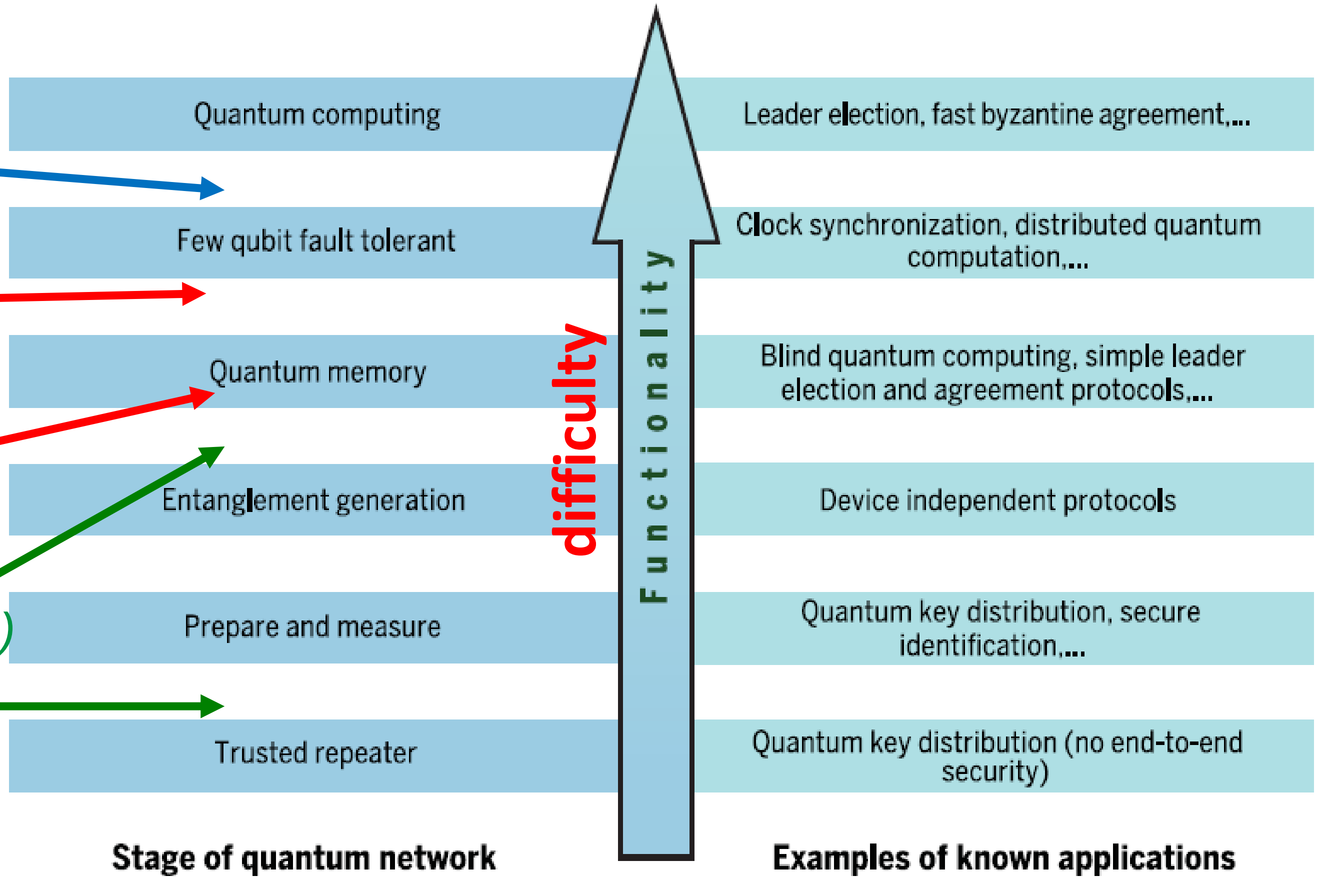
Getting here needs disruptive technology

state-of-the-art in 7 years: 10 qubits, 500 km

practical devices in 3 years (2 qubits)

State-of-the-art (2 qubits 1.3 km, <1 eb/h)

Practical devices



*Wehner, et al: "Quantum Internet: A Vision for the Road Ahead," Science **362** (2018)*

Thank you!

Fabry-Perot resonators: A. Ulanowski, F. Salamon, F. Wintersberger
Silicon nanophotonics: L. Weiß, A. Gritsch, F. Burger, S. Rinner, J. Früh, J. Ebel

Collaborators: T. Boeck (LKZ Berlin), EU Quantum Flagship Project: Quantum Internet Alliance

erc

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