QuTech

Quantum Internet: Applications, Challenges and Opportunities

ARIAN STOLK – QT4HEP 2025

QuTech is a collaboration between TU Delft TNO

Great history of the Web at CERN

1994: Year of the Web! (W3C)

© CERN

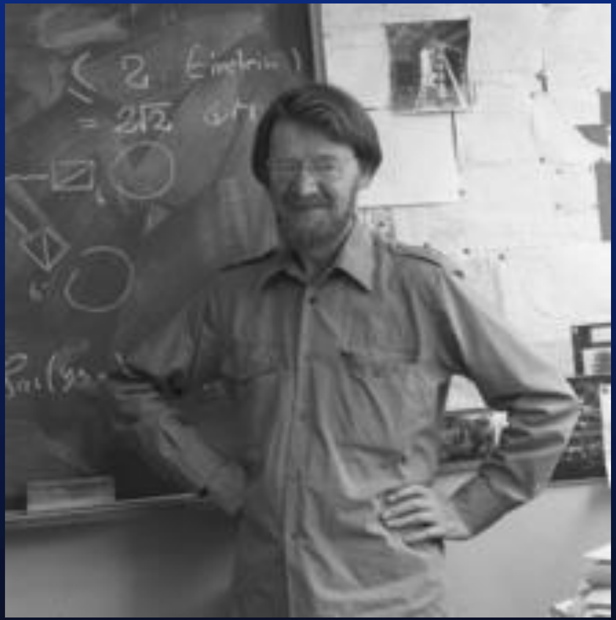
2025: Year of Quantum Science and Technology

INTERNATIONAL YEAR OF
Quantum Science
and Technology

Where was Quantum by 1994?

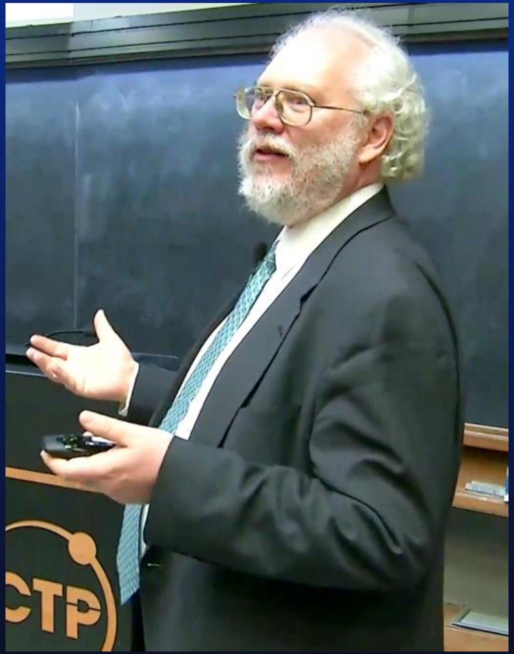
1964: Bell’s Inequality

Quantum States can allow for ***stronger correlations*** than **any** Classical System!



1994: Shor’s Algorithm

Quantum Algorithms can have an ***exponential advantage*** over existing Classical Algorithms!



Information in the Quantum world

$|0\rangle$

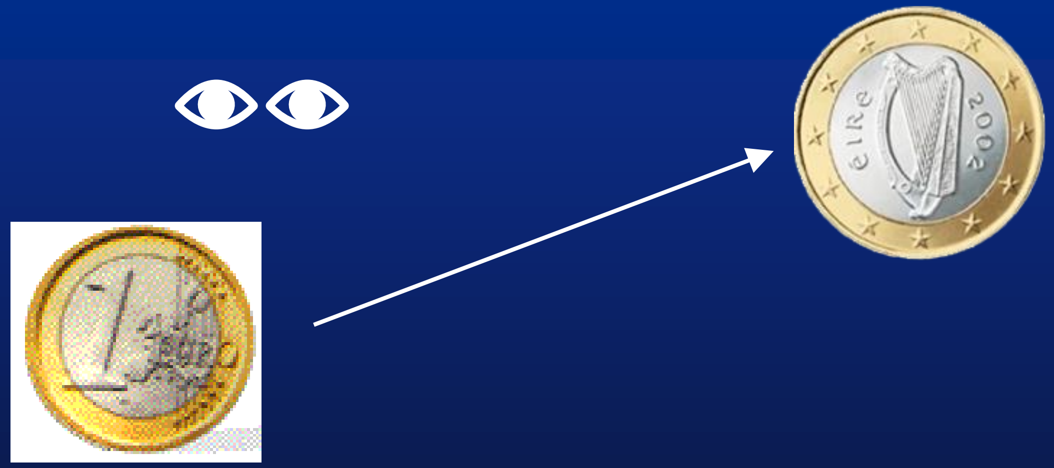
$|1\rangle$

Information in the Quantum world

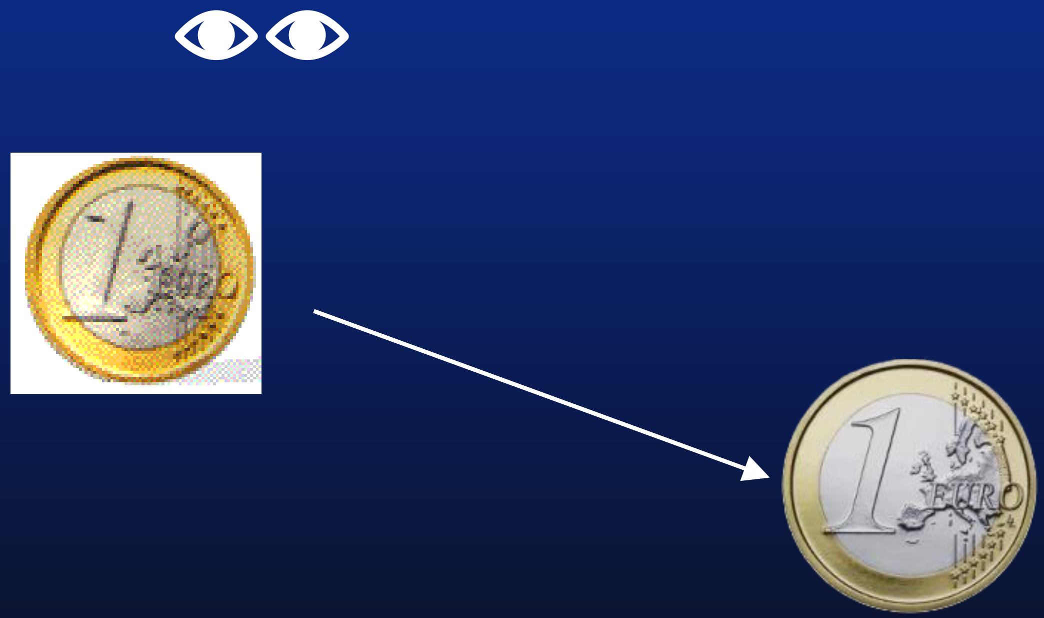
Superposition of both $|0\rangle$ and $|1\rangle$

Information in the Quantum world

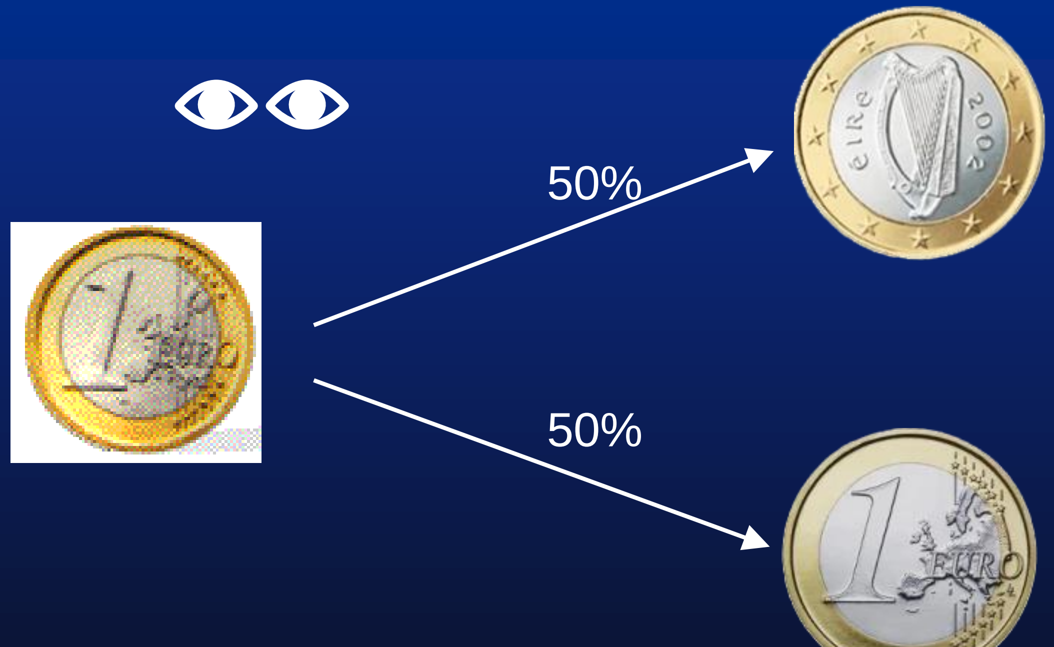
Information in the Quantum world



Information in the Quantum world



Information in the Quantum world

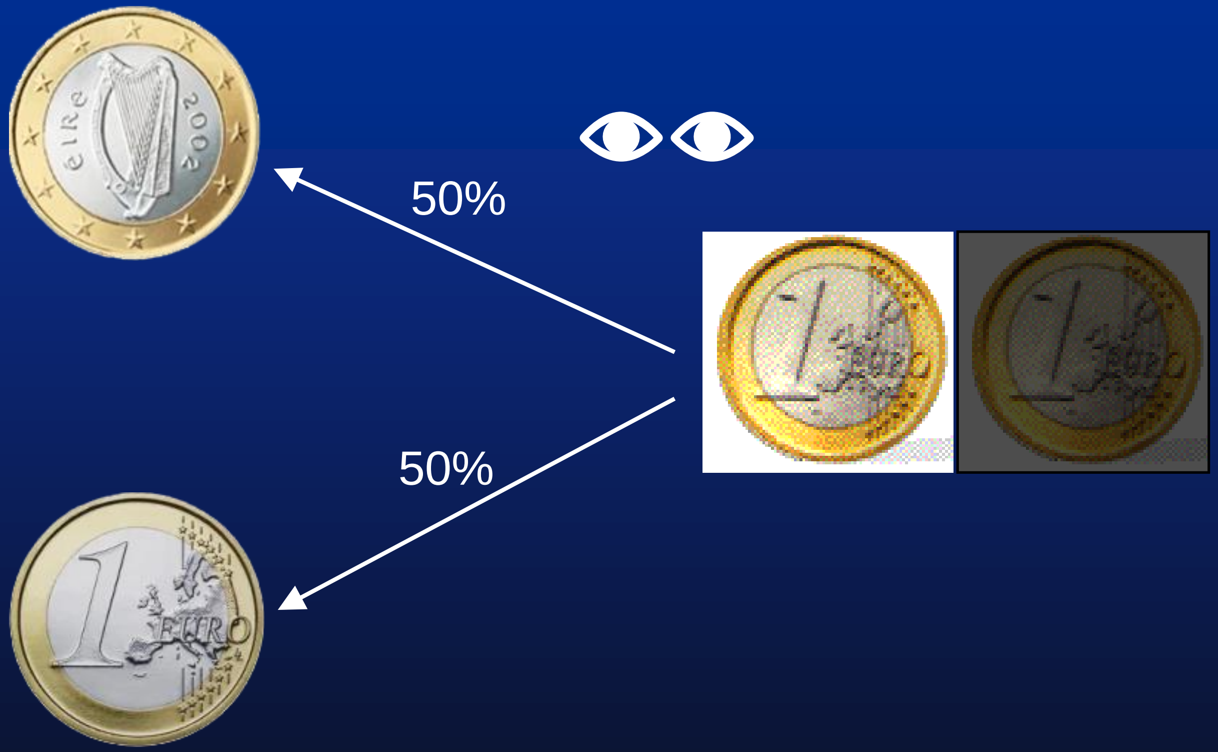


Random

Core of Quantum: Entanglement

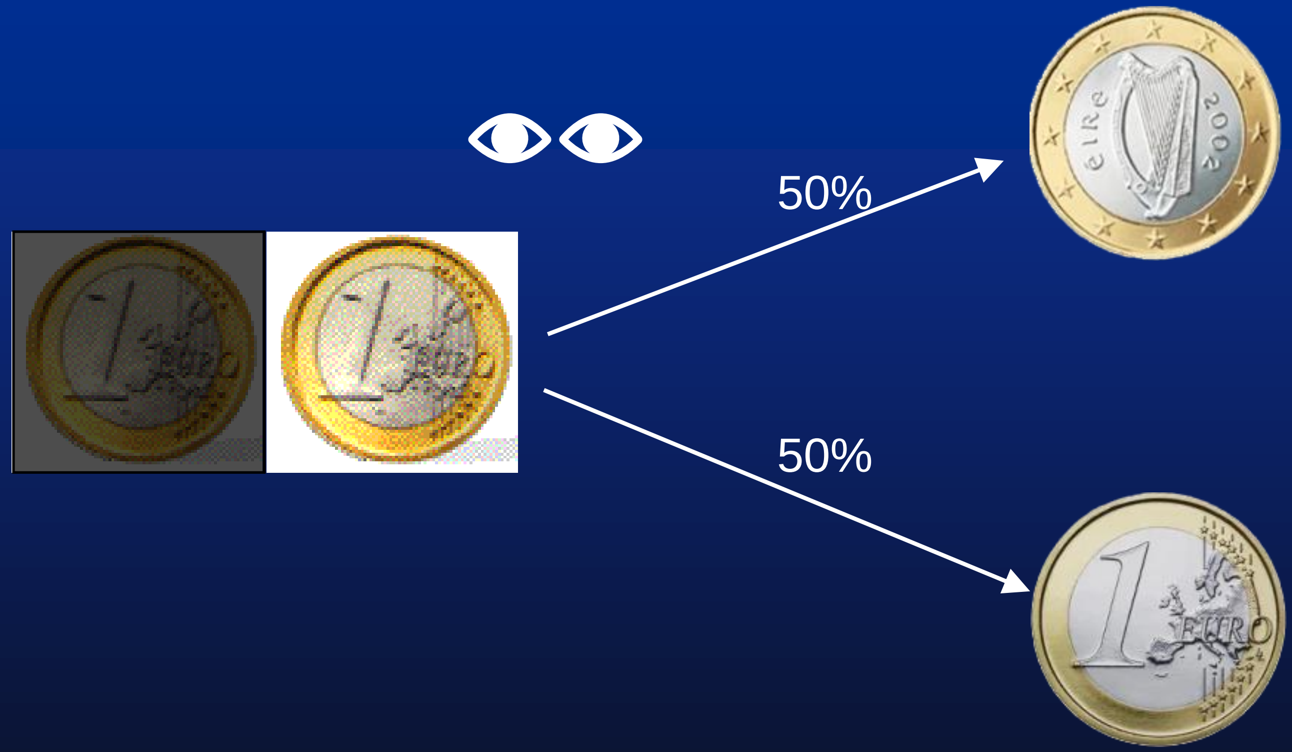
Two qubits in a shared superposition

Core of Quantum: Entanglement



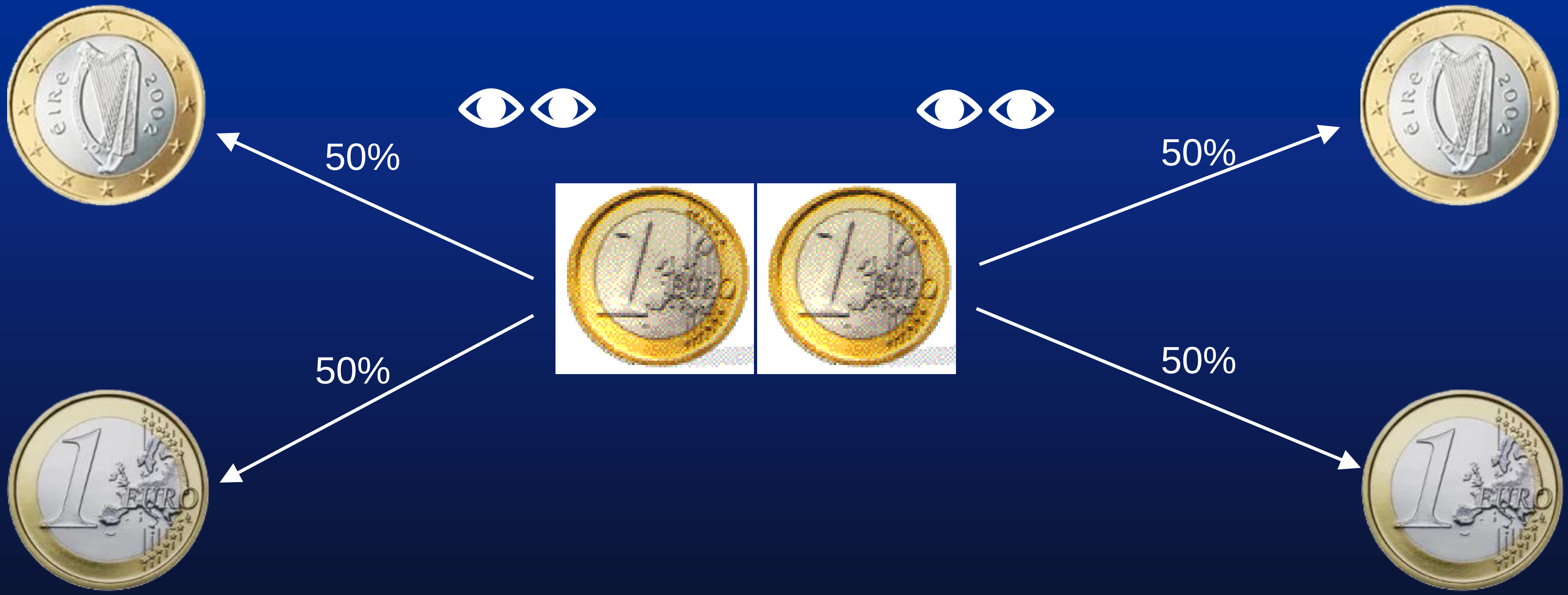
The outcomes of the left qubit are random

Core of Quantum: Entanglement



... And also for the right qubit

Core of Quantum: Entanglement



…but when you compare the outcomes side by side

Core of Quantum: Entanglement

50%

50%

are always the same, even when far apart: non-local!

What is the Quantum Internet?

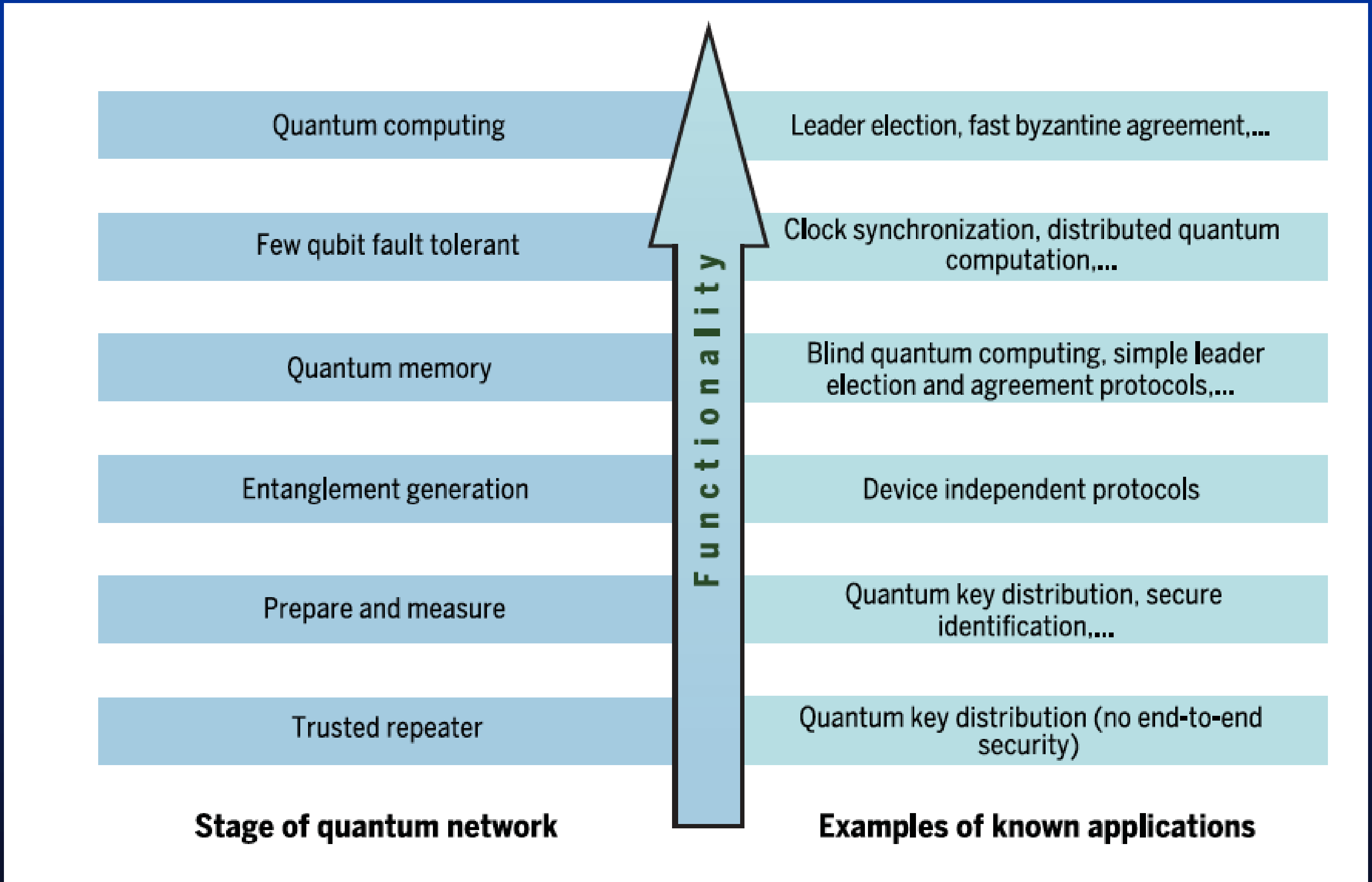
Many *quantum* nodes…

…connected over large distances…

…reliably exchanging
quantum information and **entanglement**!

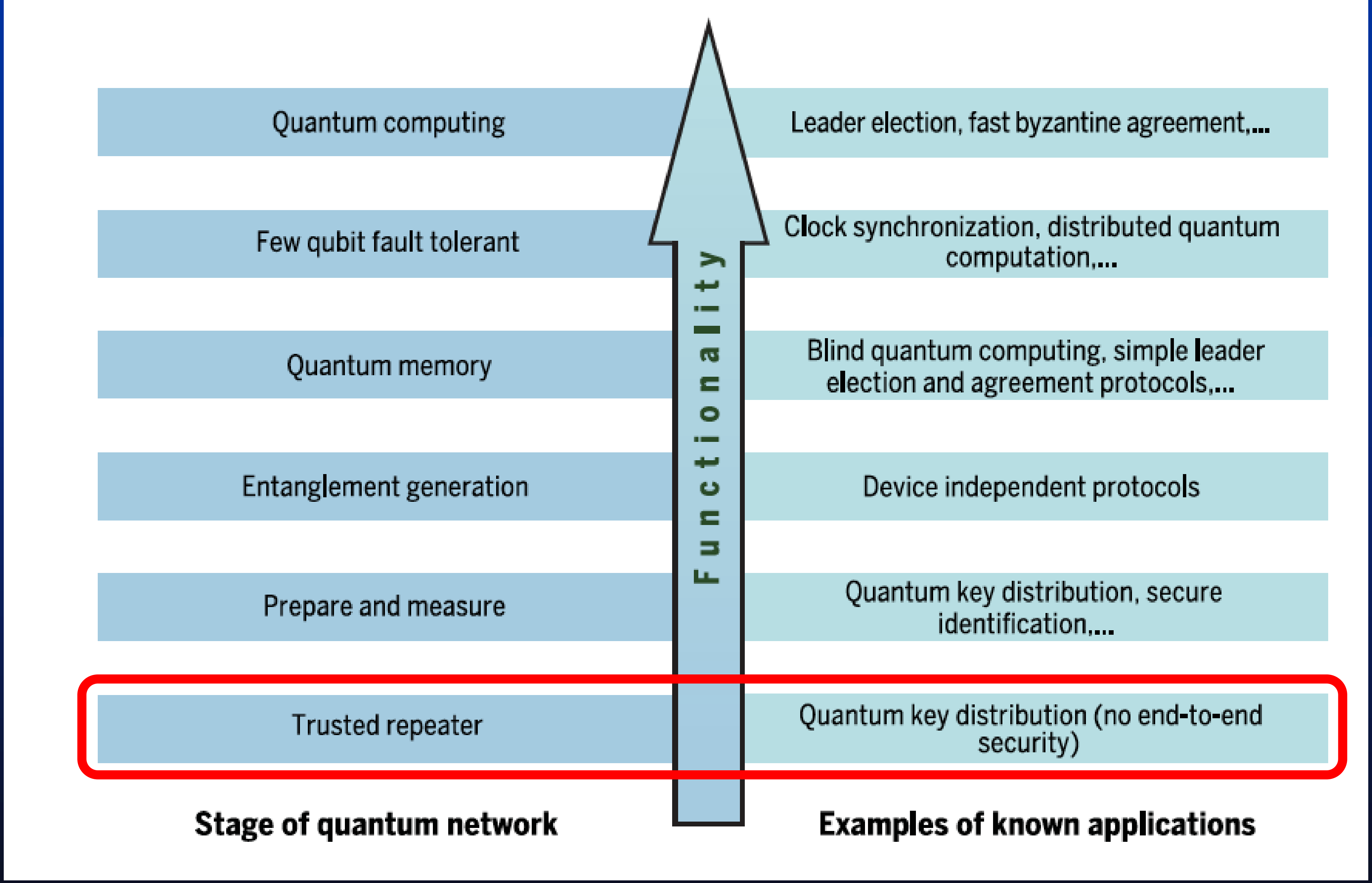
Go through the stages of the Quantum Internet:

-What is already achieved?
-What are the challenges?
-What are the opportunities?



Stephanie Wehner, David Elkouss, Ronald Hanson, Science 2018

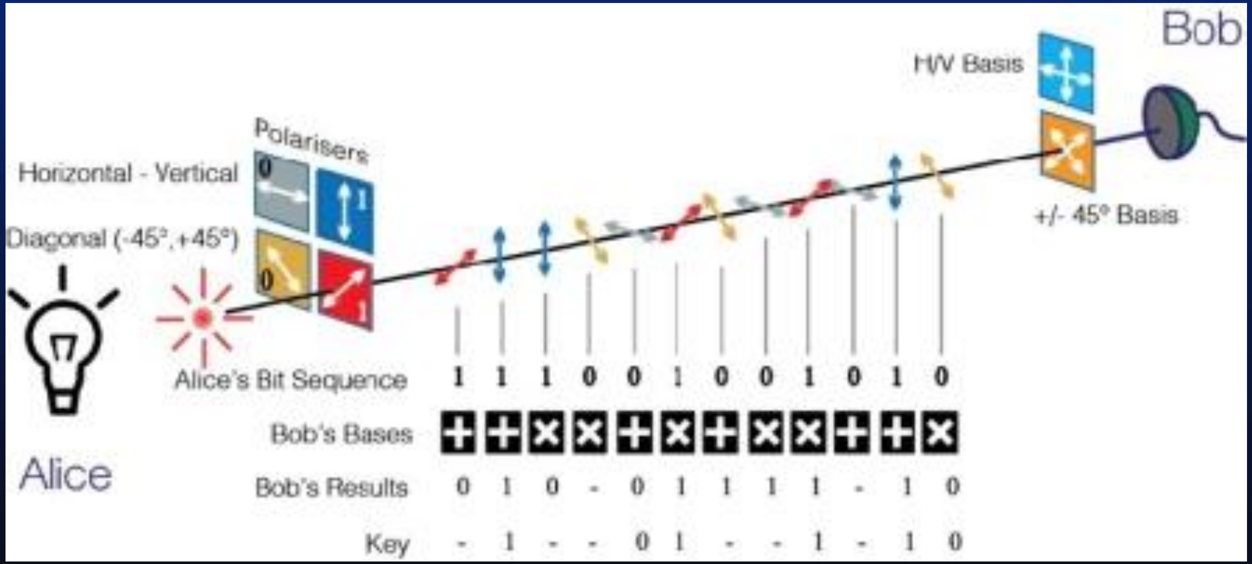
Stages of the Quantum Internet



Stephanie Wehner, David Elkouss, Ronald Hanson, Science 2018

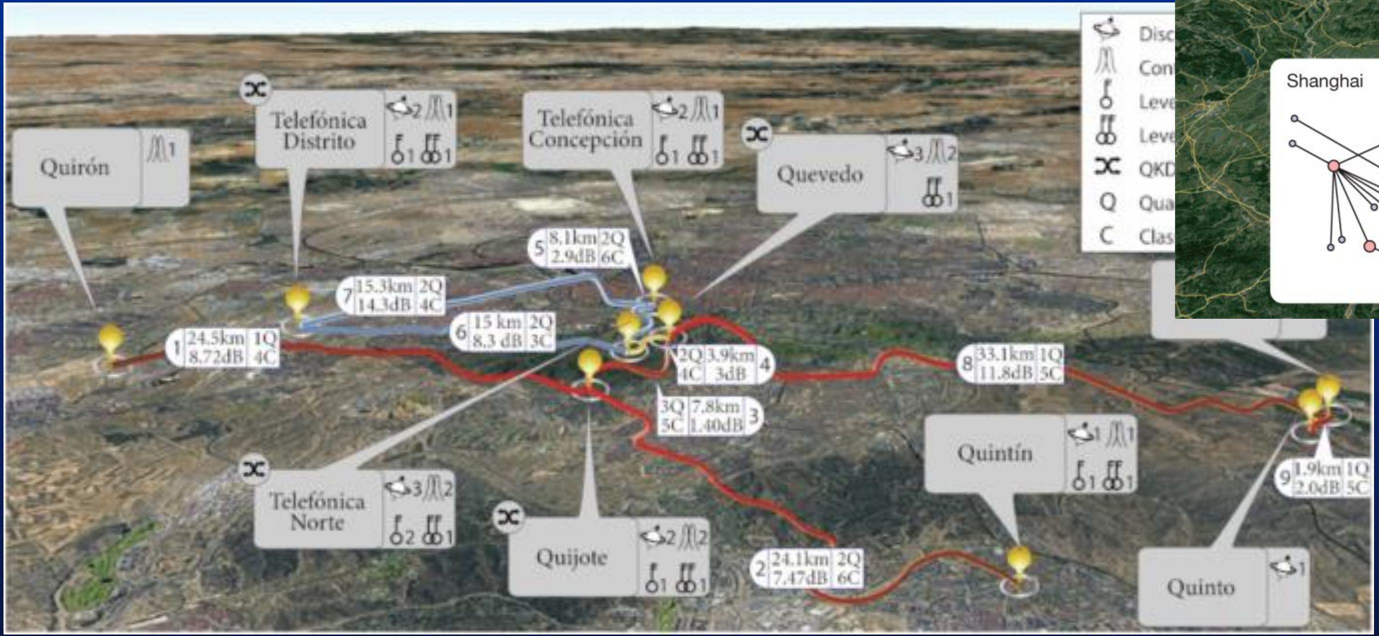
QKD systems

Various hardware vendors: Toshiba, Q*Bird, IDQuantique….

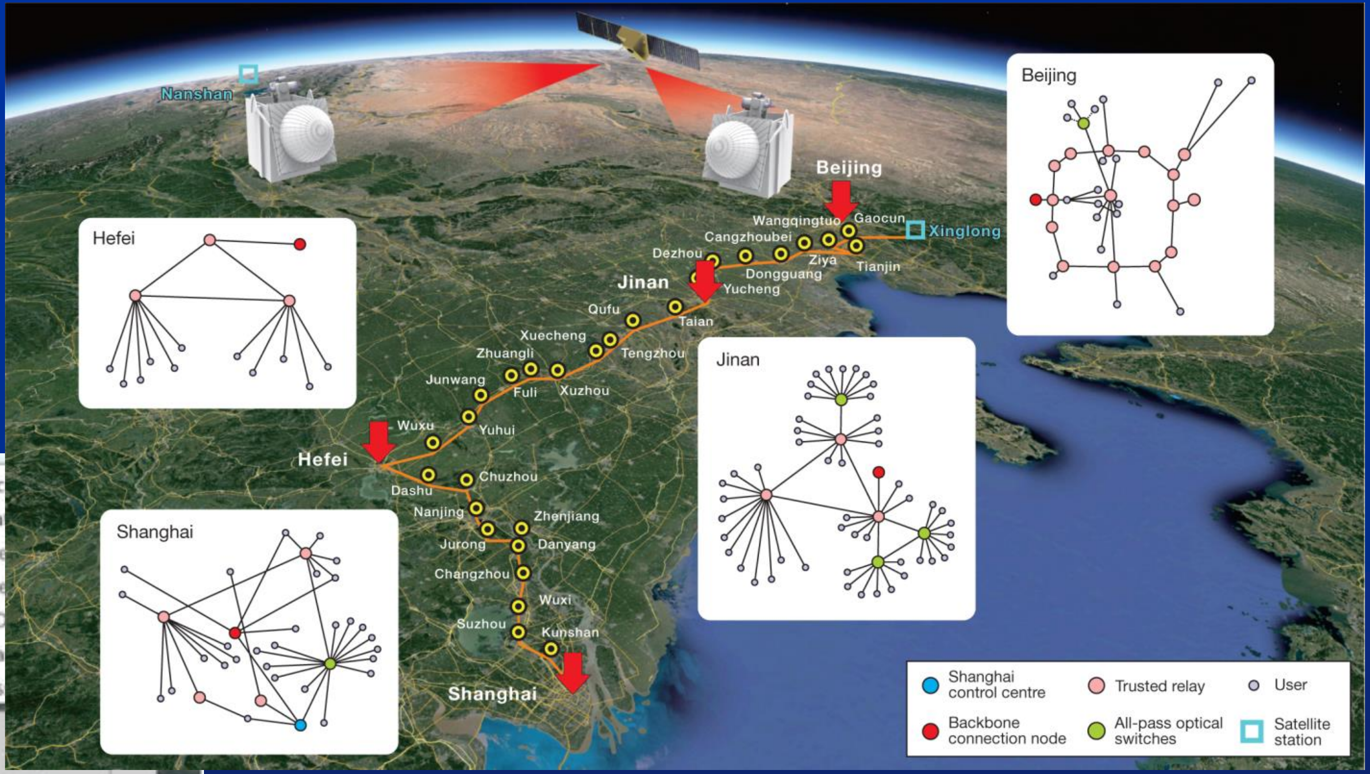


Trusted Repeater

MADQCI: QKD network in Madrid metropolitan area



Martin, V., Brito, J.P., Ortíz, L. *et al.* *npj Quantum Inf* **10**, 80 (2024)

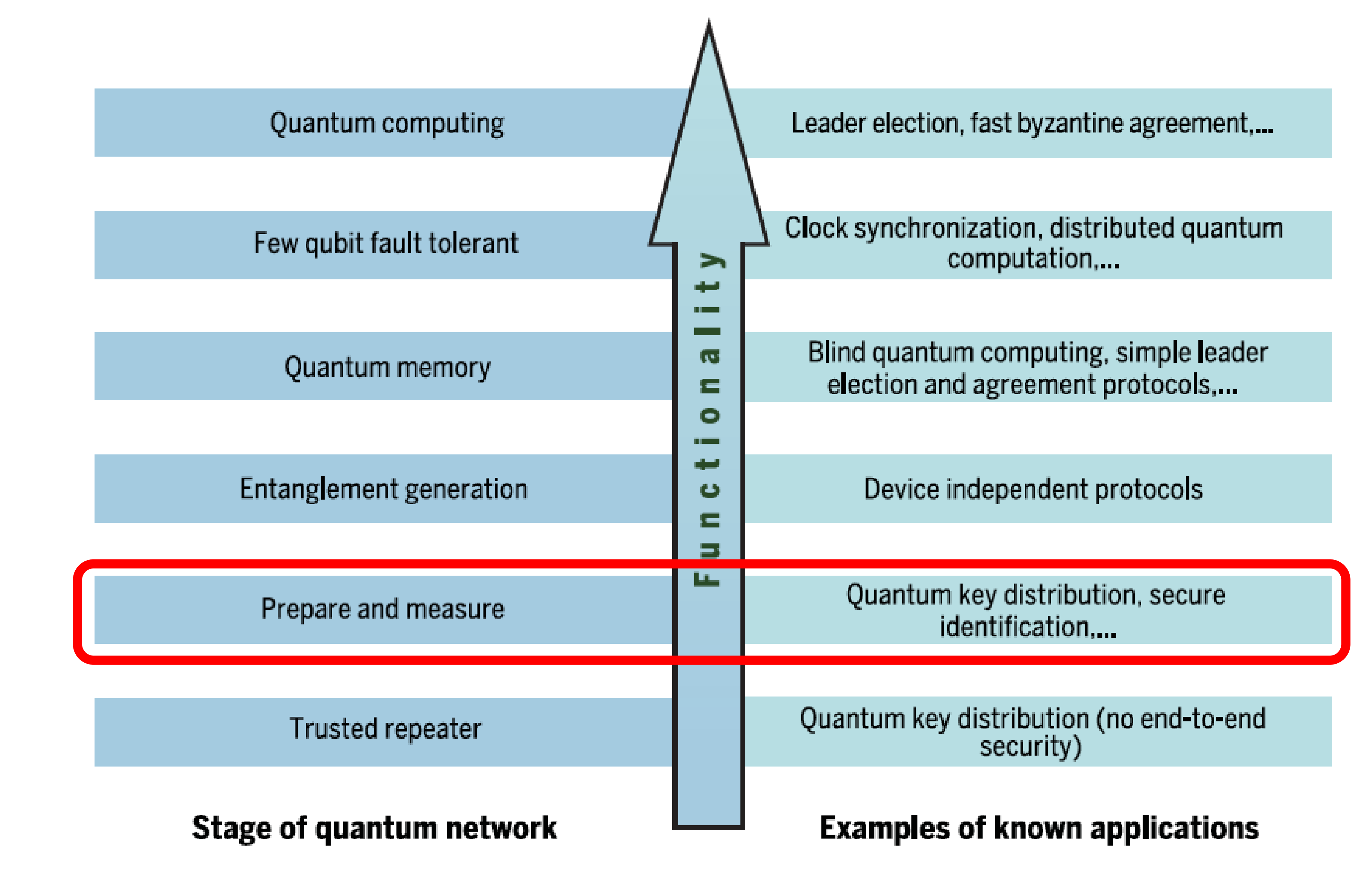


Chen, YA., Zhang, Q., Chen, TY. et al. Nature 589, 214–219 (2021).

4 Metropolitan networks linked by backbone

Generate random bits between remote parties, useful for encryption!

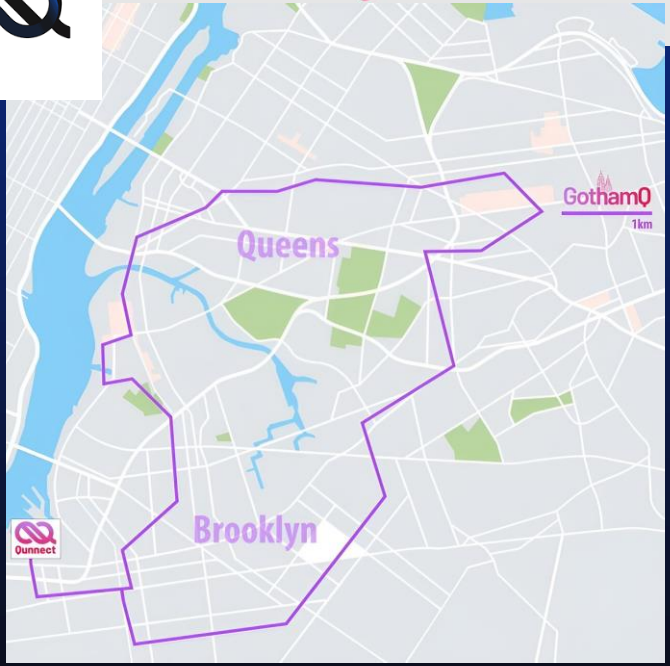
Prepare and measure



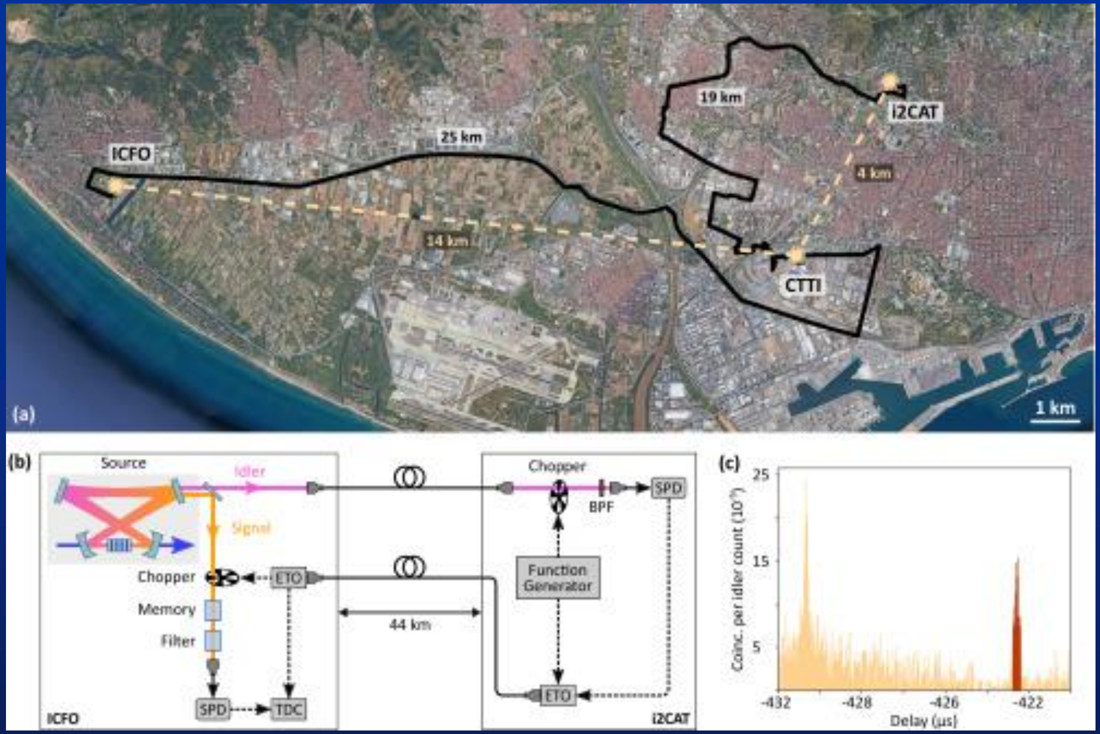
Stephanie Wehner, David Elkouss, Ronald Hanson, Science 2018

Entanglement distribution with photons

Photon pair generation compatible with telecom fiber propagation (Rb gas, SPDC sources, etc…)



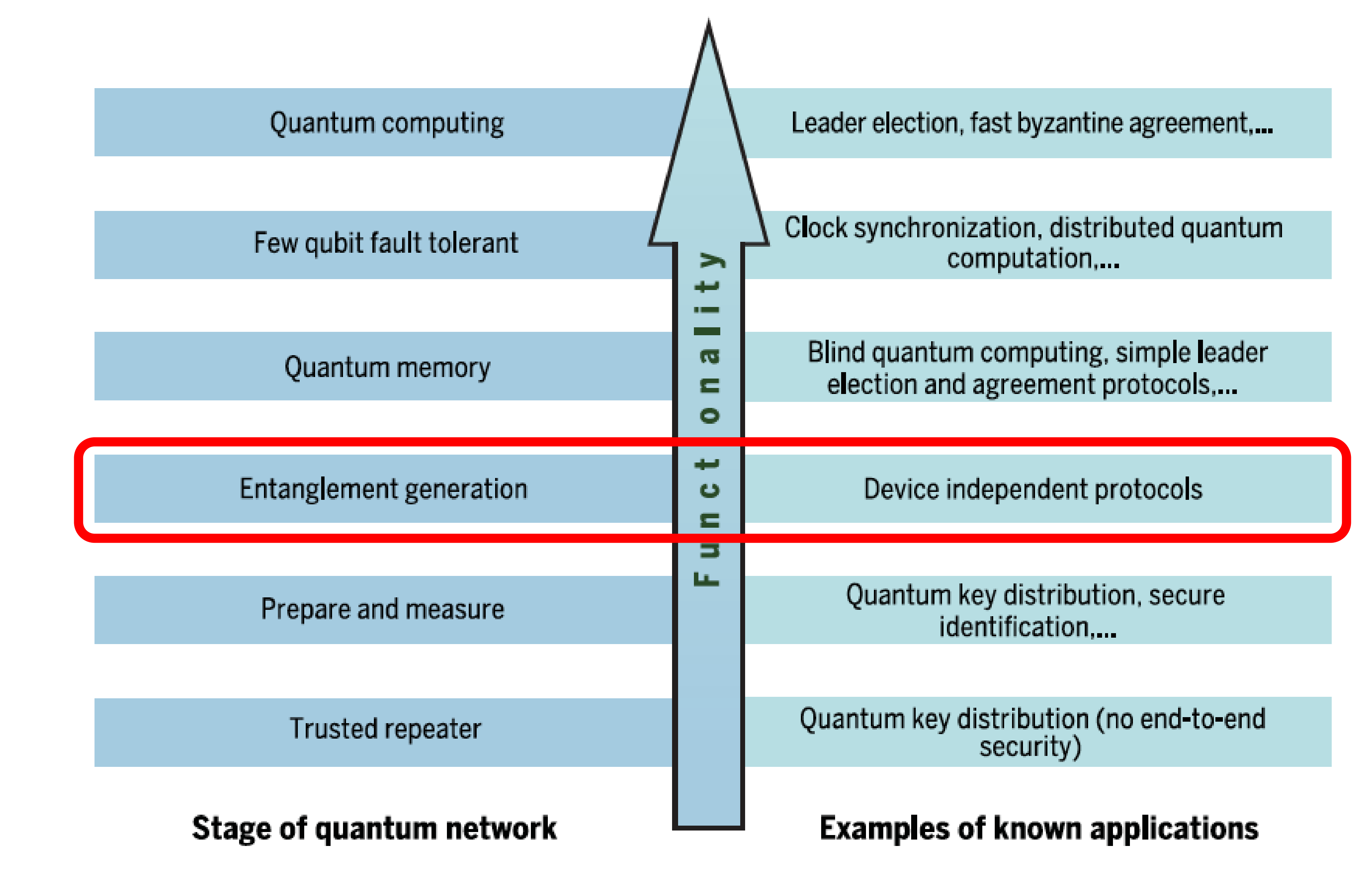
Alexander N. Craddock et al.
PRX Quantum **5**, 030330 **(2024)**



Jelena V. Rakonjac et al, Optica Quantum 1 (2023)

Photons can be stored/retrieved (on demand) from memories *probabilistically* and lack computing capabilities

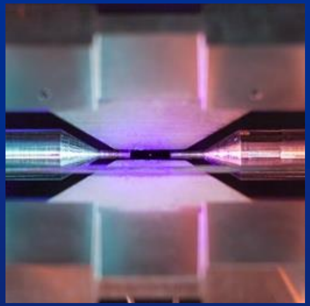
Entanglement generation



Stephanie Wehner, David Elkouss, Ronald Hanson, Science 2018

Entangled processing nodes, lots of activity!

Trapped ions

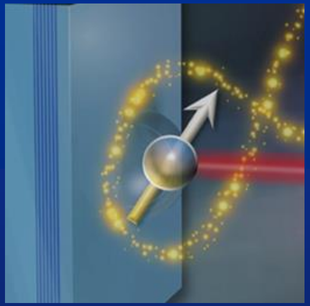


[David Nadlinger]

Moehring et al. "Entanglement of single-atom quantum bits at a distance."
Nature 449, 68 (2007)

Stephenson et al. "High-rate, high-fidelity entanglement of qubits across an elementary quantum network."
PRL 124, 110501 (2020)

Quantum dots

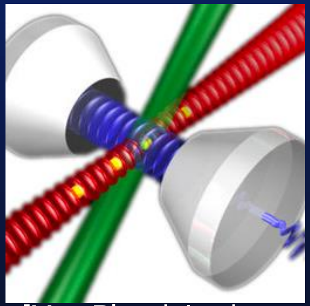


[Aymeric Delteil]

Delteil et al. "Generation of heralded entanglement between distant hole spins."
Nature Physics 12, 218 (2016)

Stockill, Robert, et al. "Phase-tuned entangled state generation between distant spin qubits."
PRL119, 010503 (2017)

Neutral atoms

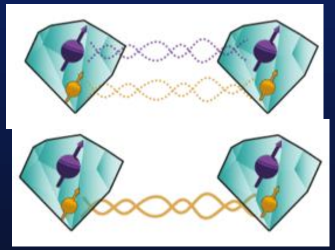


[Max Planck Institute for Quantum Optics]

Hofmann et al. "Heralded entanglement between widely separated atoms."
Science 337, 72 (2012)

Daiss et al. "A quantum-logic gate between distant quantum-network modules."
Science 371, 614 (2021)

Color centers in diamond



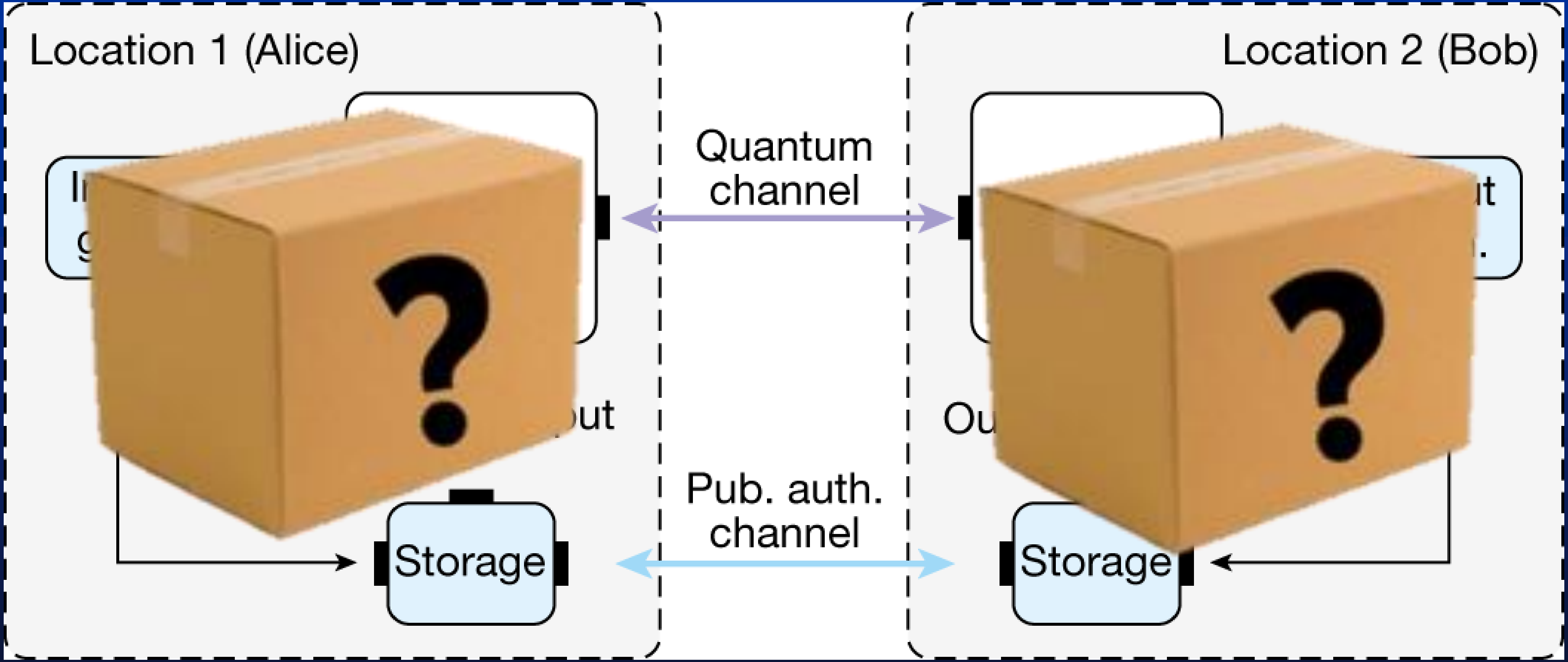
[Kalb et al., Science 2017]

Bernien et al. "Heralded entanglement between solid-state qubits separated by three metres."
Nature 497, 86 (2013)

Humphreys et al. "Deterministic delivery of remote entanglement on a quantum network."
Nature 558, 268 (2018)

Pompili, Hermans, Baier et al., Science 372, 259 (2021)

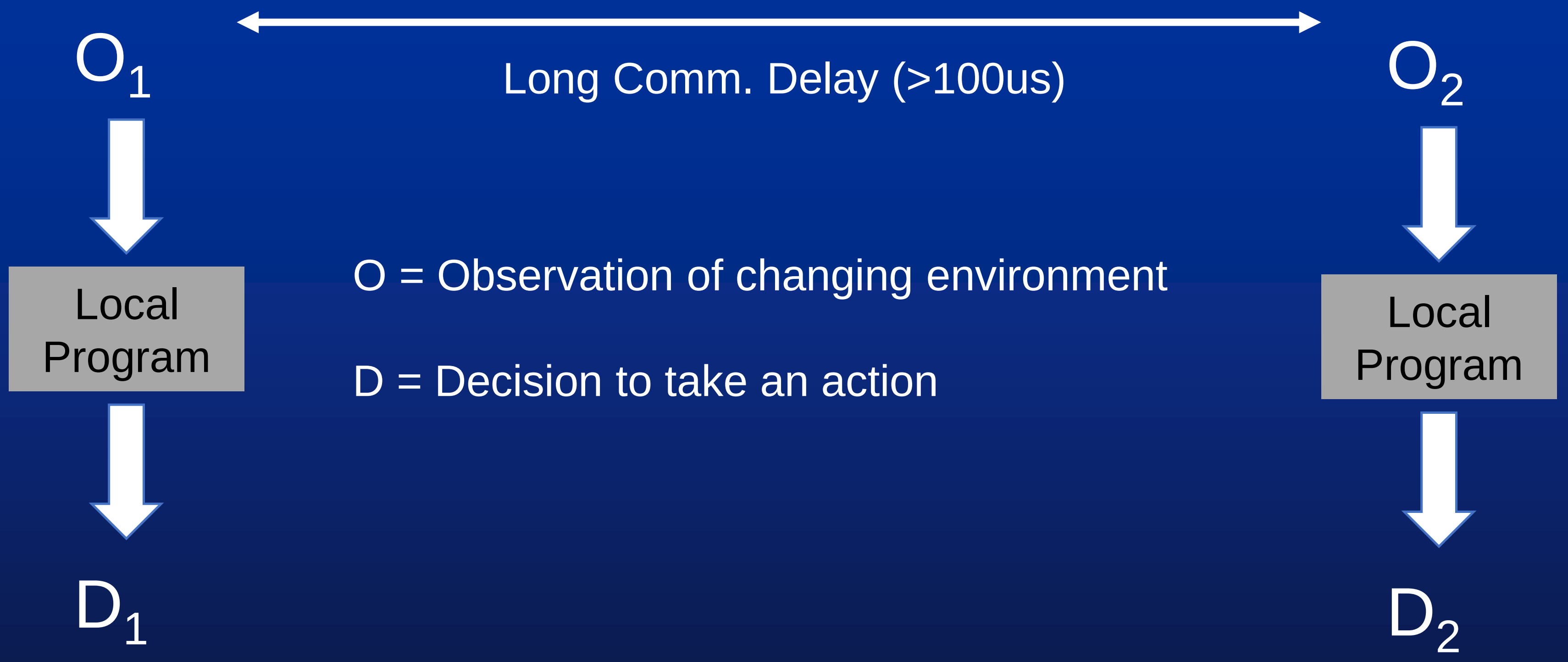

Device Independence via entanglement



Zhang, W., van Leent, T., Redeker, K. *et al.* *Nature* **607**, (2022)

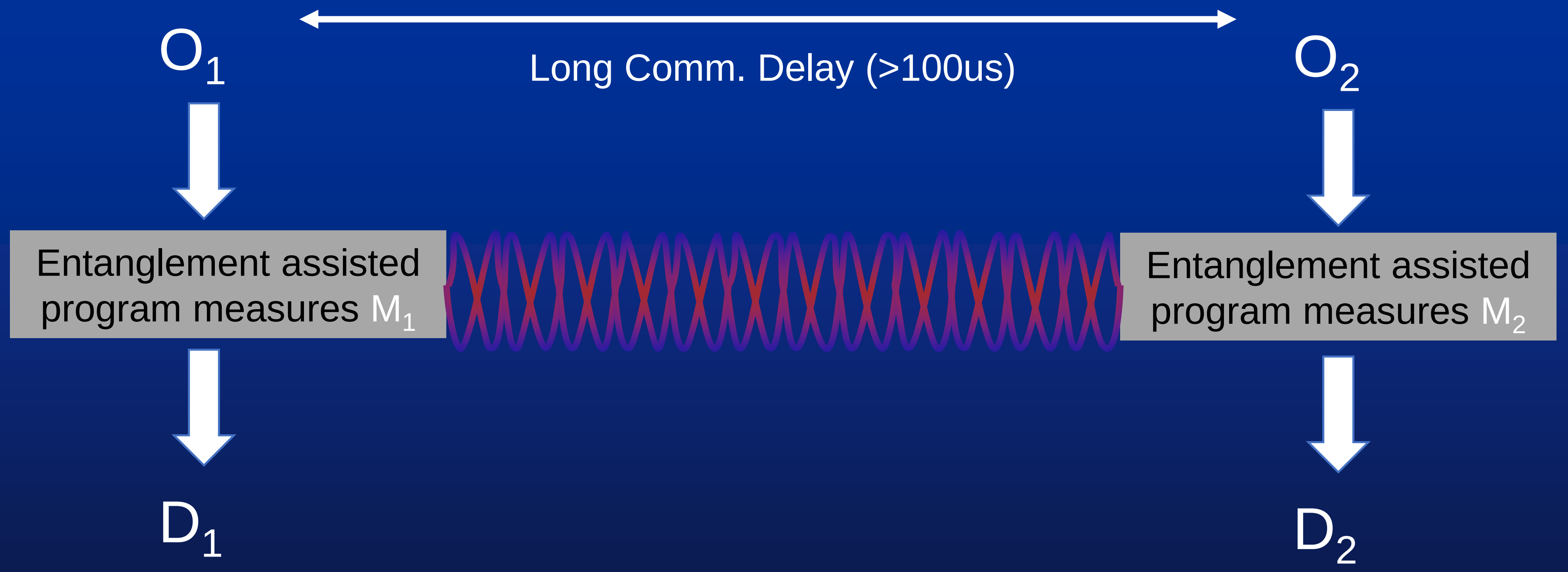
Fundamental security based on the laws of quantum mechanics

Non-local applications: Coordination between non-communicating parties



Distributed systems (HPC, Content providers), Energy grids, Financial Markets etc…

Non-local applications: Coordination between non-communicating parties

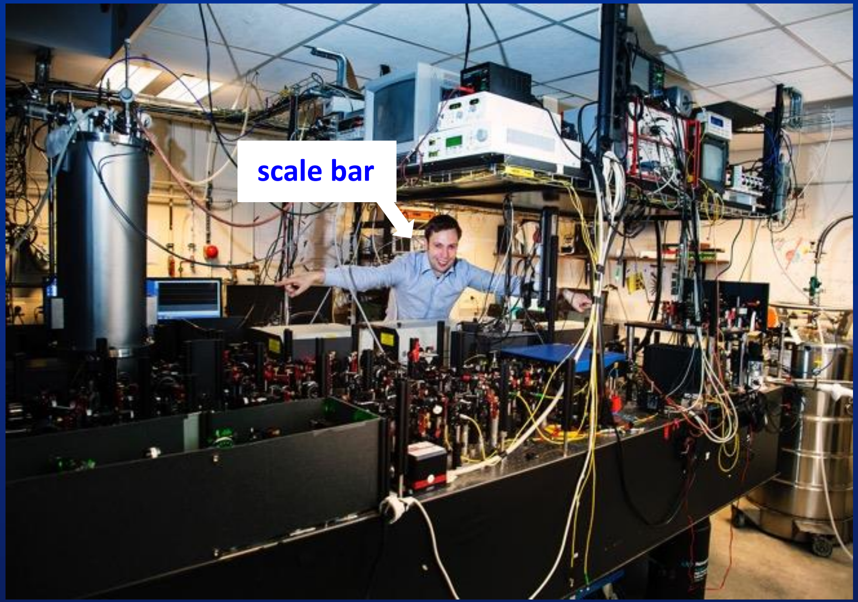


Observations inform measurement basis, measurement outcome informs decision

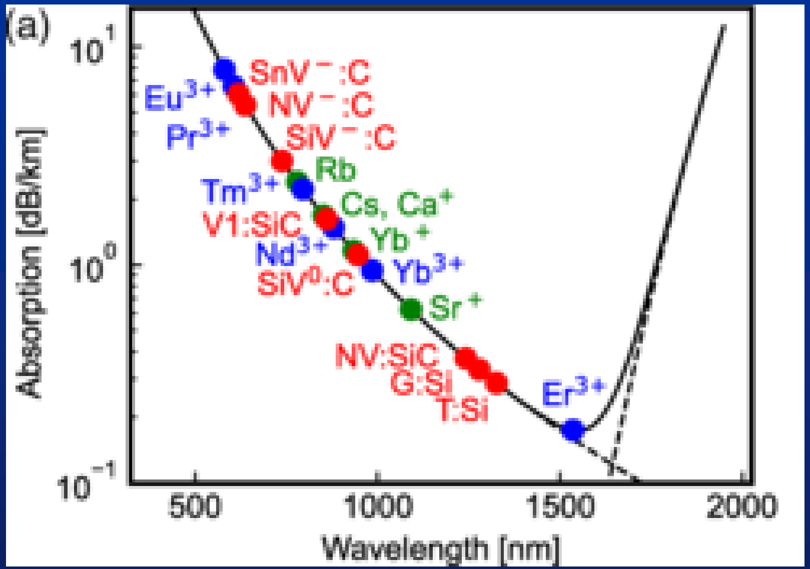
Non-local correlations -> Quantum strategies can beat classical!

For more: Dawei Ding and Liang Jiang, Coordinating Decisions via Quantum Telepathy, arXiv:2407.21723v1

Going to large separation between nodes



Nature 497, 86 (2013)



A. Reiserer, Rev. Mod. Phys. **94**, 041003 **(2022)**

Stationary qubit needs to survive the message of the heralding signal:

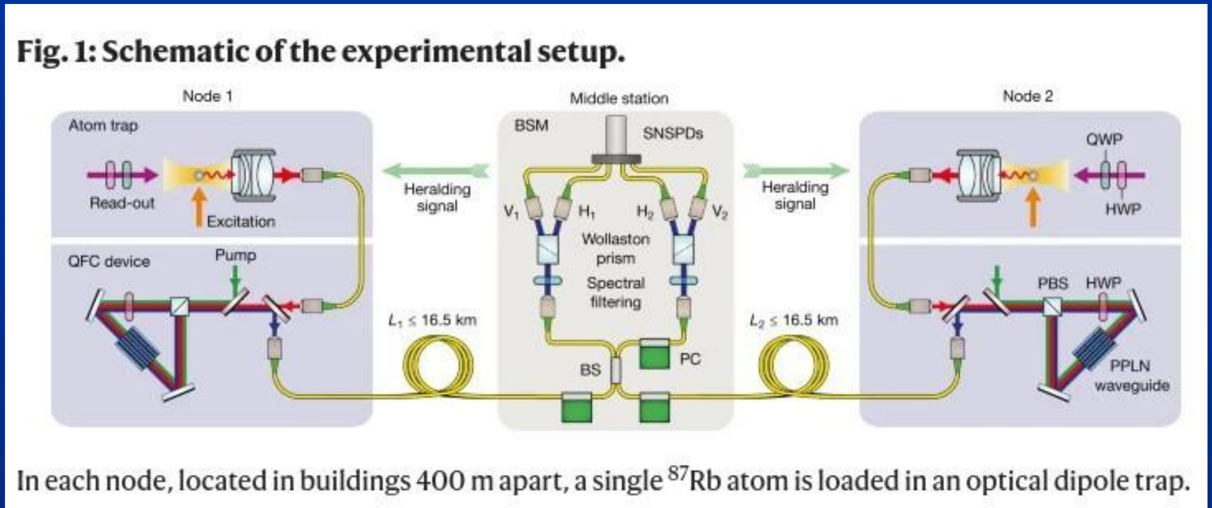
5us per km!

1. Independent

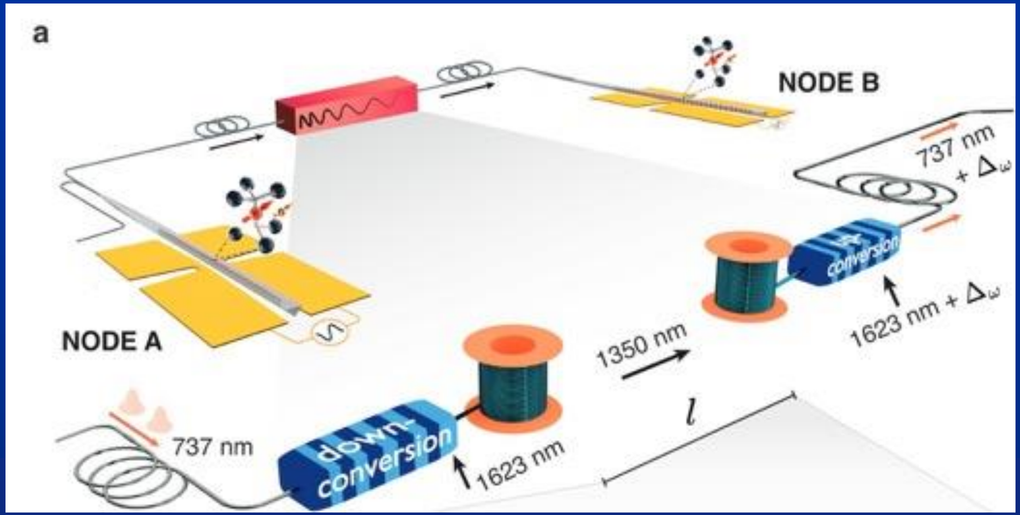
2. Photon Loss

3. Coherence

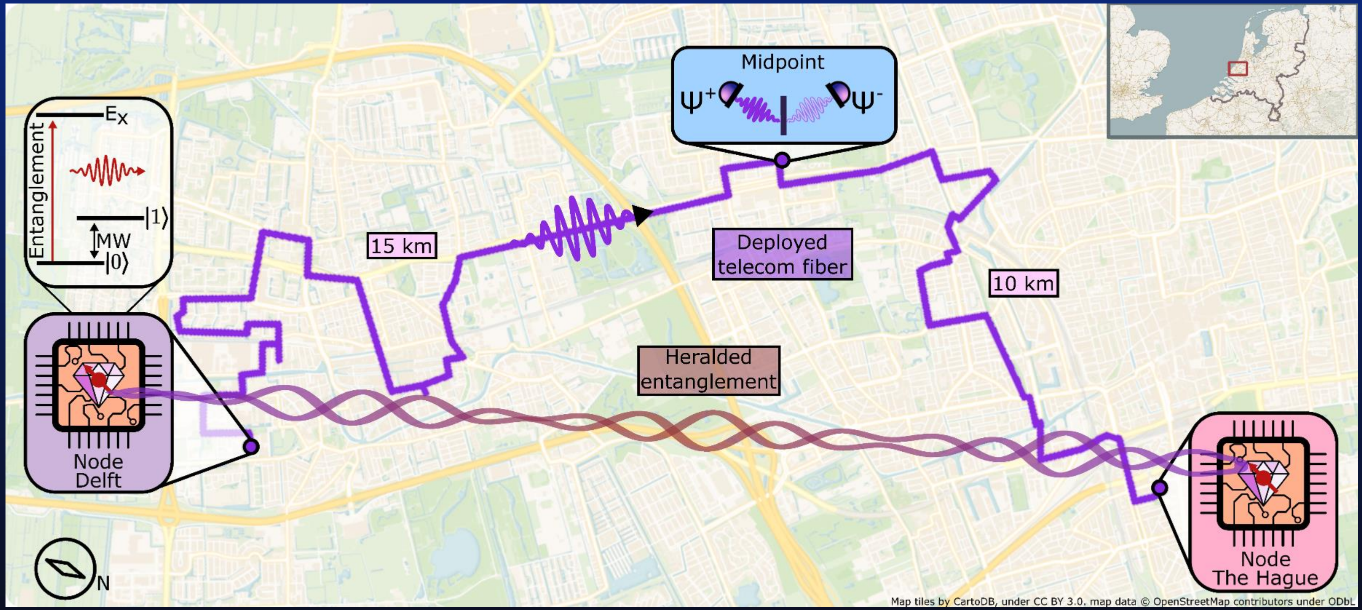
Recent work (towards) metropolitan scale



Leent et al. Nature (2022)



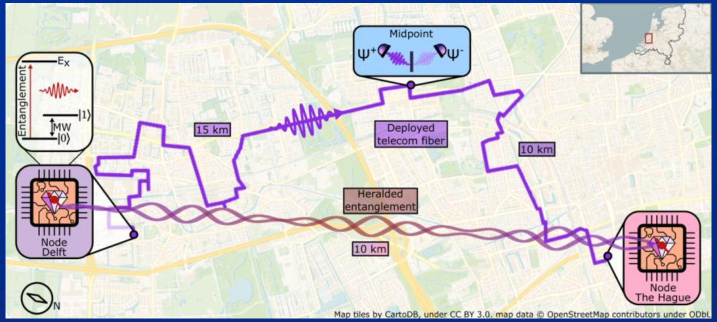
Knaut, C.M., Suleymanzade, A., Wei, YC. *et al. Nature* **629**, (2024).



A.J. Stolk, K.L. van der Enden et al. Sci.Adv. (2024)

Heralded entanglement of NV centers with 10km separation between end nodes

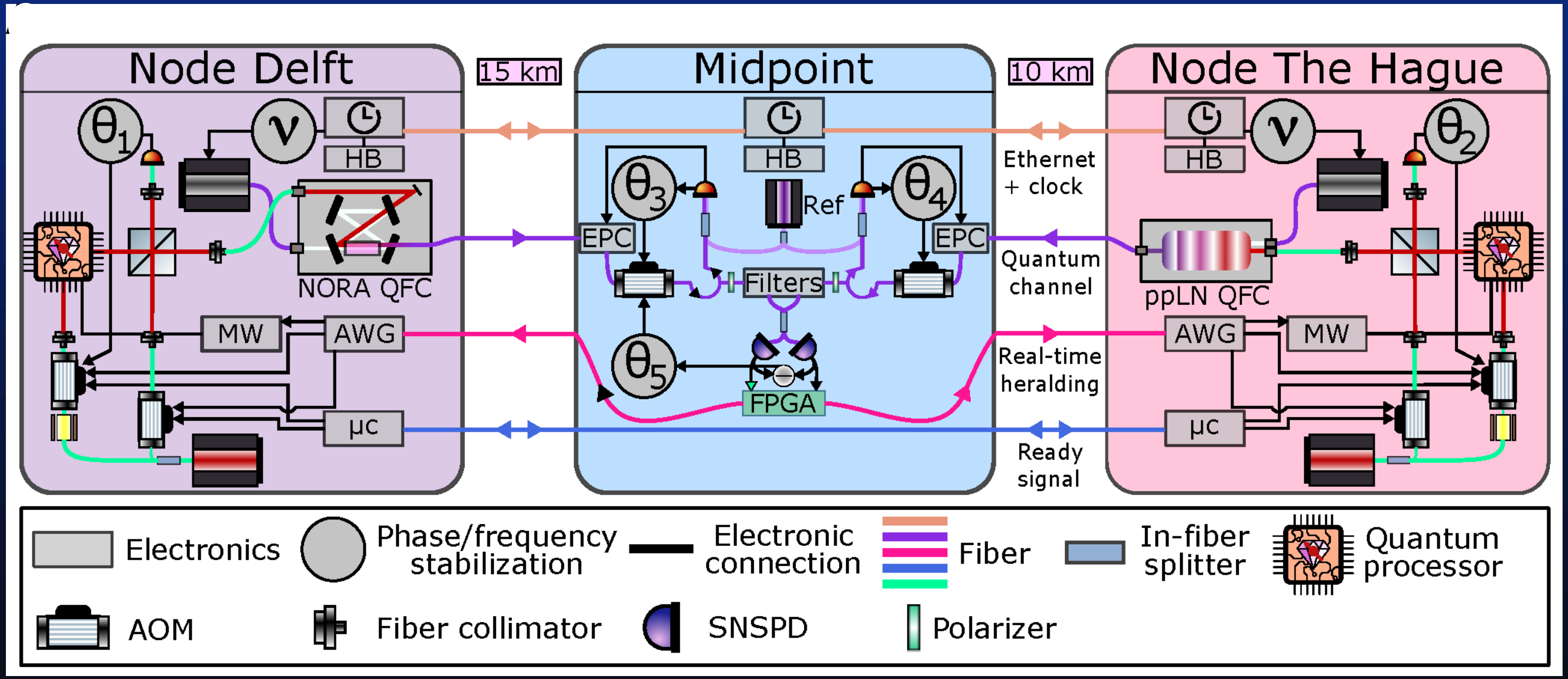
Metropolitan-scale quantum link of solid-state entanglement



1) Independent nodes => boundary condition to the design

2) Overcome photon loss => QFC and single-photon protocol

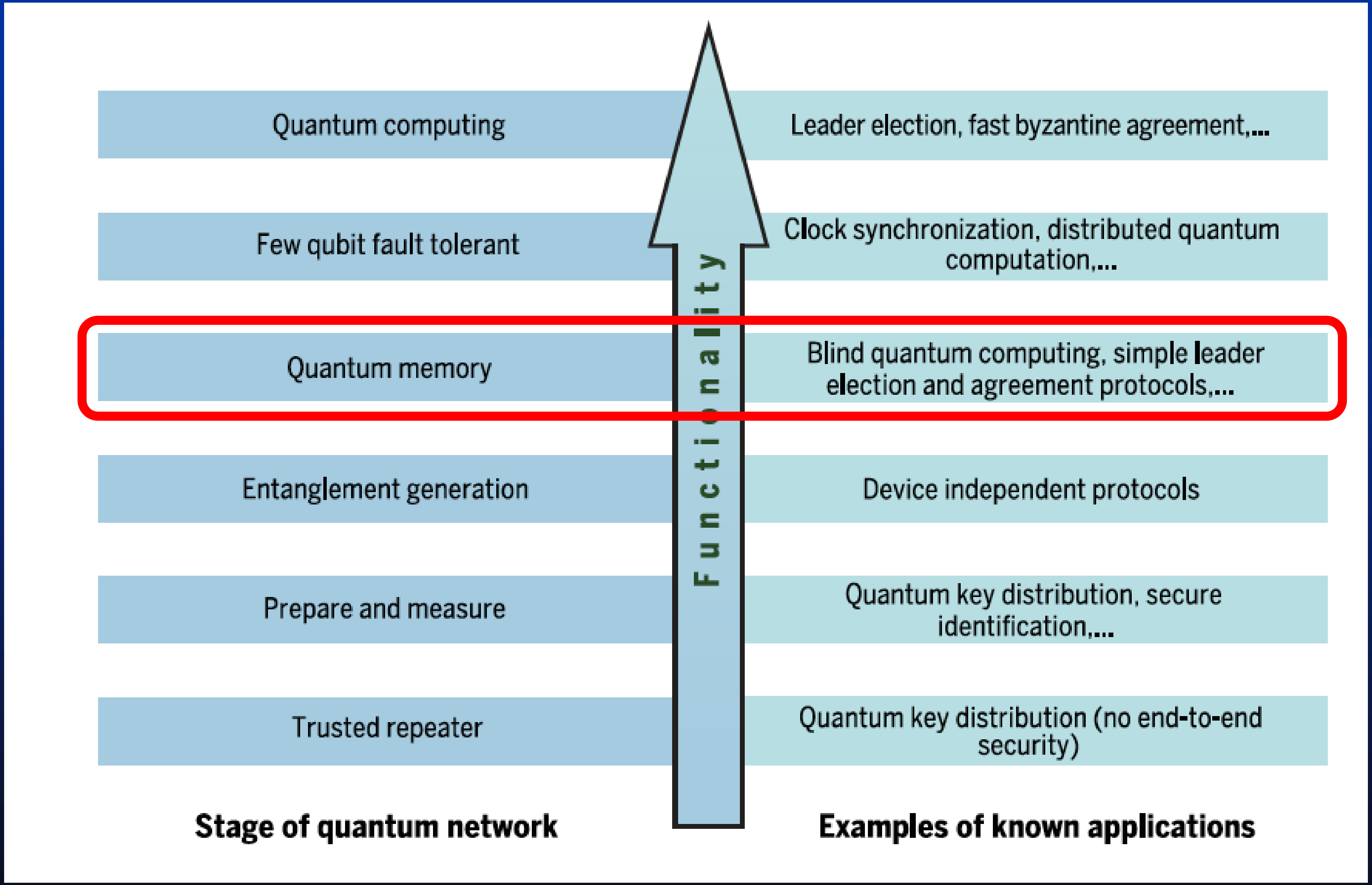
3) Herald within coherence => Real-time heralding and decoupling of qubit



- Optical phase stabilization using 5 interferometers
- Tracking and compensation of polarization and time-of-arrival drift
- Distributed clock (White Rabbit) enables remote sub-nanosecond syncing

Tech paper: A.J. Stolk et al. arXiv:2408.12464 (soon in PRApplied)

Quantum Memory

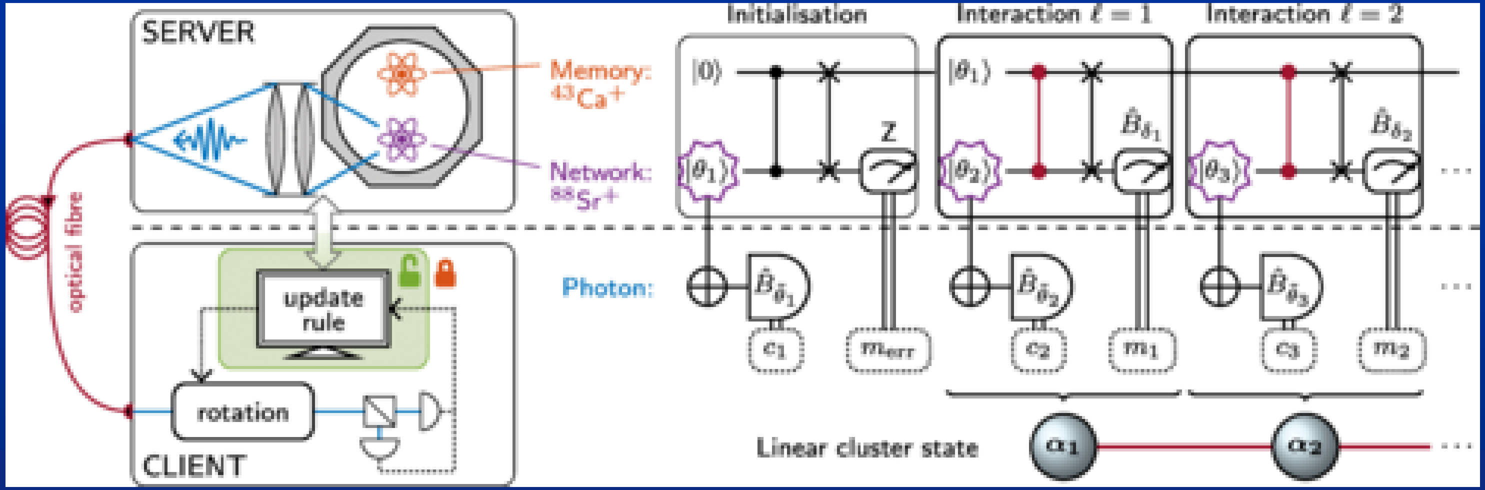


Stephanie Wehner, David Elkouss, Ronald Hanson, Science 2018

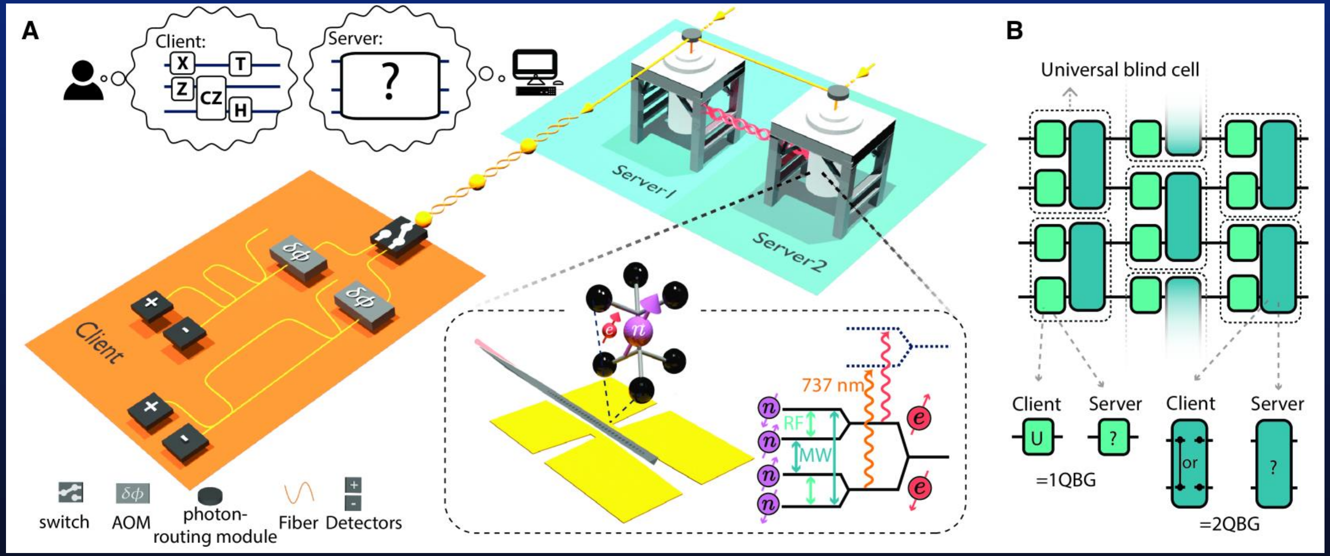
2024: Blind Quantum Computing

Client can perform computations on a remote quantum server.

Server does not know what the computation is. Client gets the correct answer.

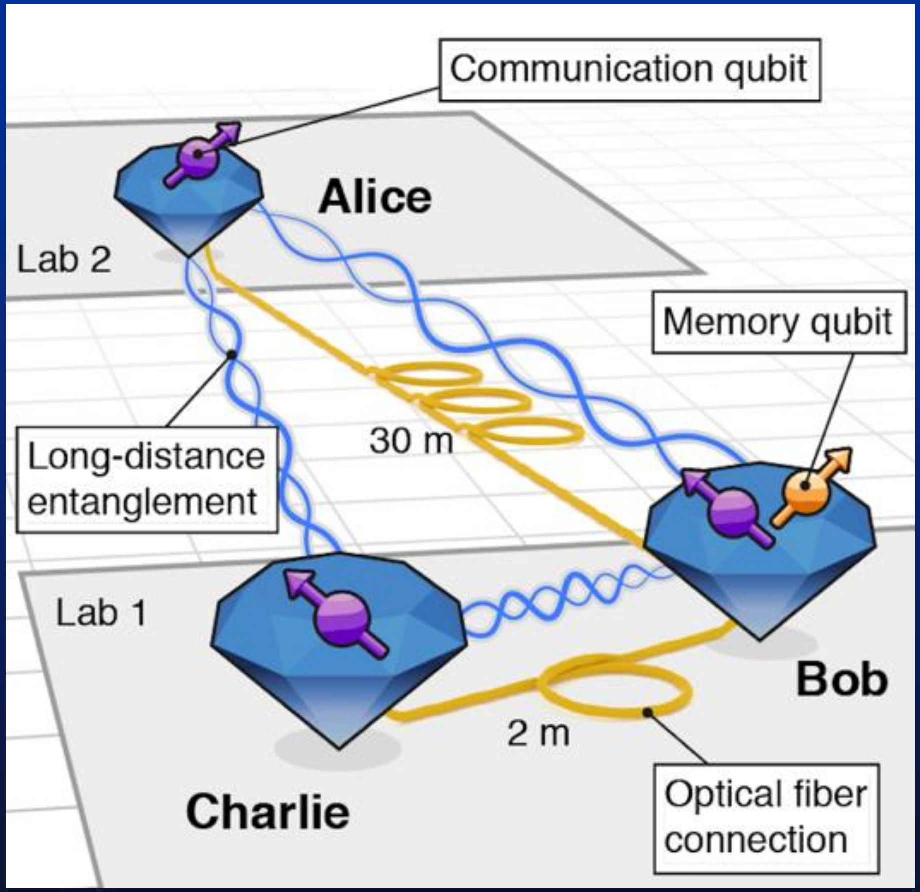


P. Drmota et al, Phys. Rev. Lett. **132**, 150604 – (**2024**)



Y.-C. Wei, P.-J. Stas, A. Suleymanzade, G. Baranes ,arXiv:2412.03020v1 (2024)

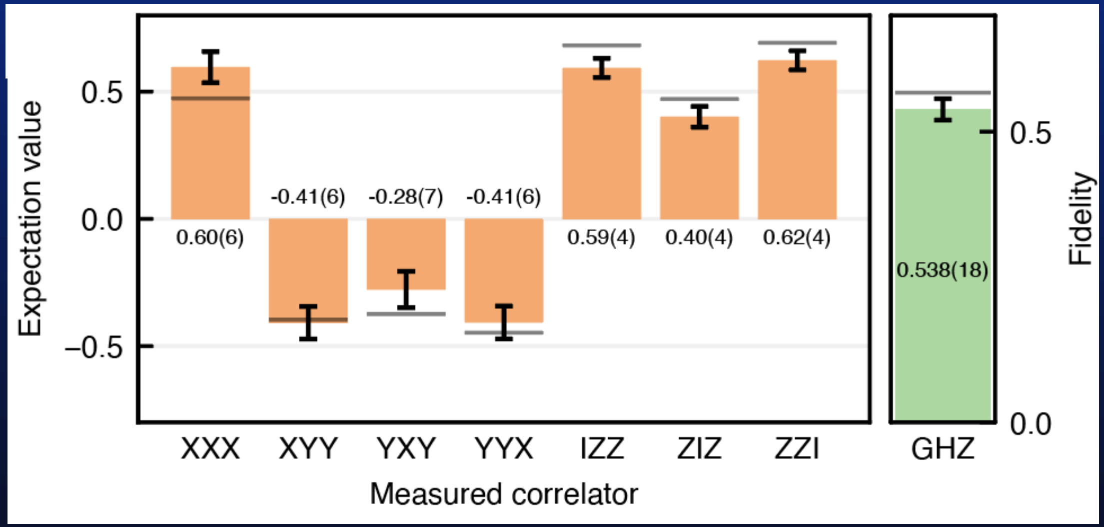
2021: First multi-node network in the lab



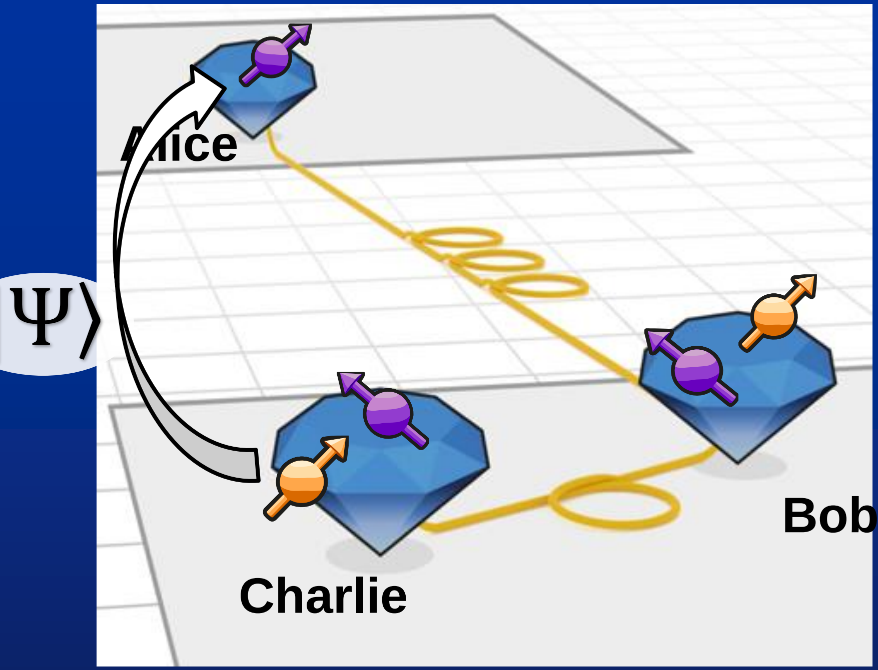
Pompili, Hermans, Baier et al., Science 372, 259 (2021)

Heralded multipartite entanglement distribution

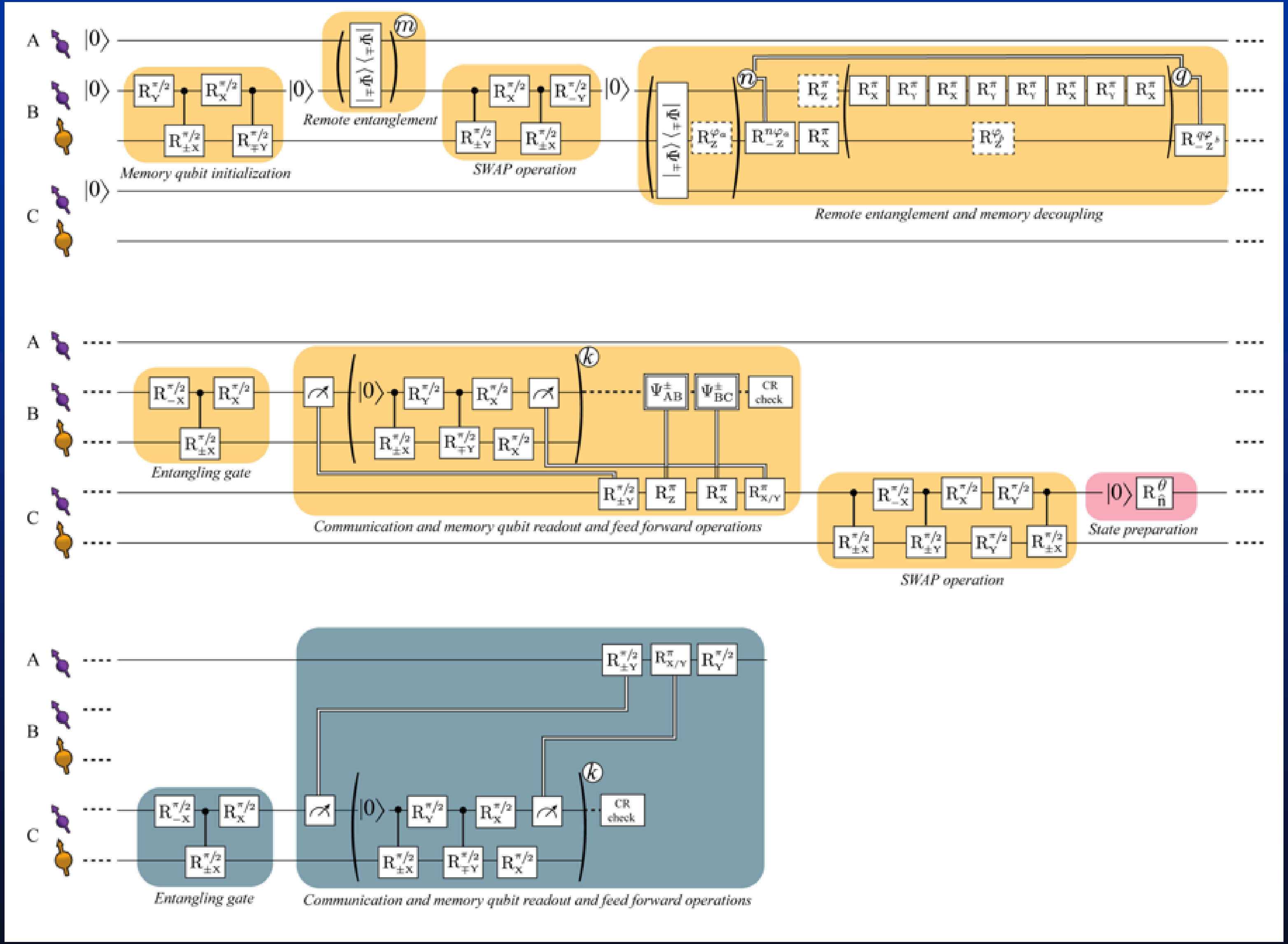
$$|\mathrm{GHZ}\rangle = \left(|000\rangle + |111\rangle\right)/\sqrt{2}$$



2022: Teleportation beyond nearest neighbors



Hermans, Pompili et al., Nature 605, 663 (2022)



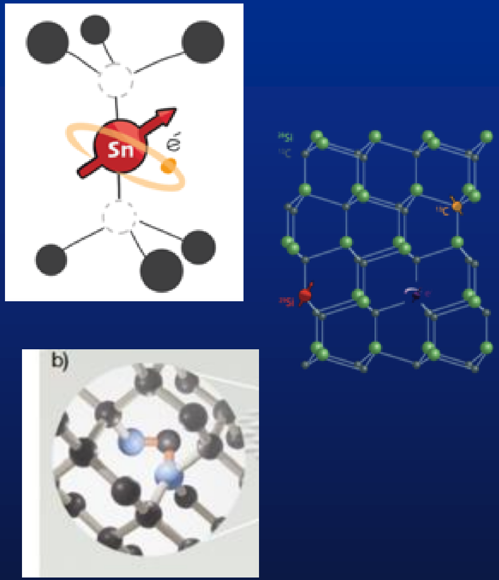
Rates limited by probabilistic entanglement generation and qubit decoherence

Challenges beyond proof-of-principle

	Multi-node Network	**Non-nearest neighbour**	**Metropolitan link**
Avg. time for success	90 seconds	119 seconds	50 seconds
Fidelity with ideal state	0.538	0.702	0.534
Footprint	2 optical labs	2 optical labs	1 server room, 1 lab, 2 19” racks
Probability of Bell pair per attempt	$\sim 7 * 10^{-4}$	$\sim 7 * 10^{-4}$	$7.2 * 10^{-6}$

A hardware vision towards large-scale quantum networks

Stable spin qubits with very long quantum lifetimes



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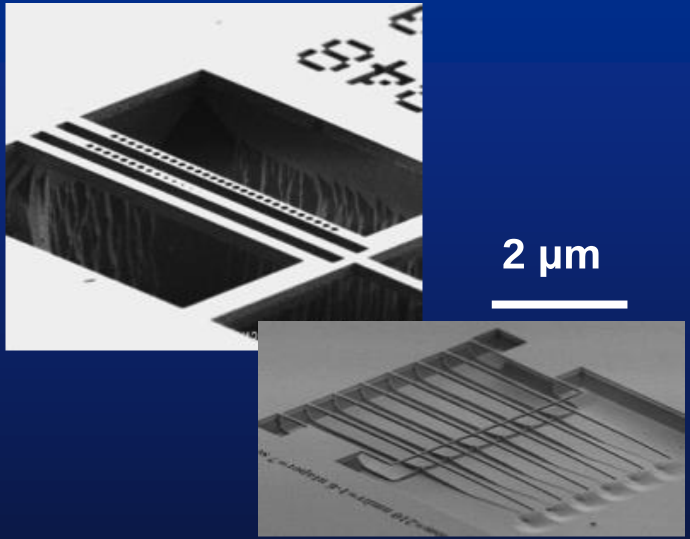
Efficient on-chip quantum optical interfaces



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Photonic integration

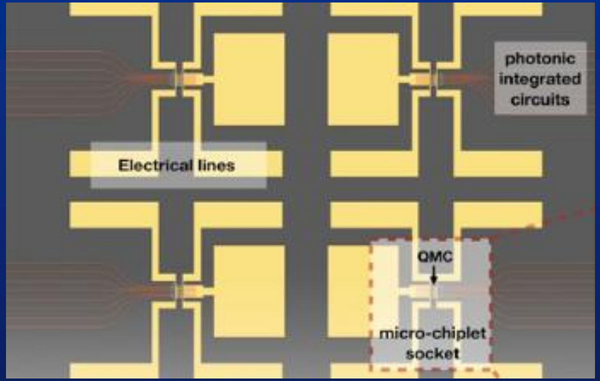


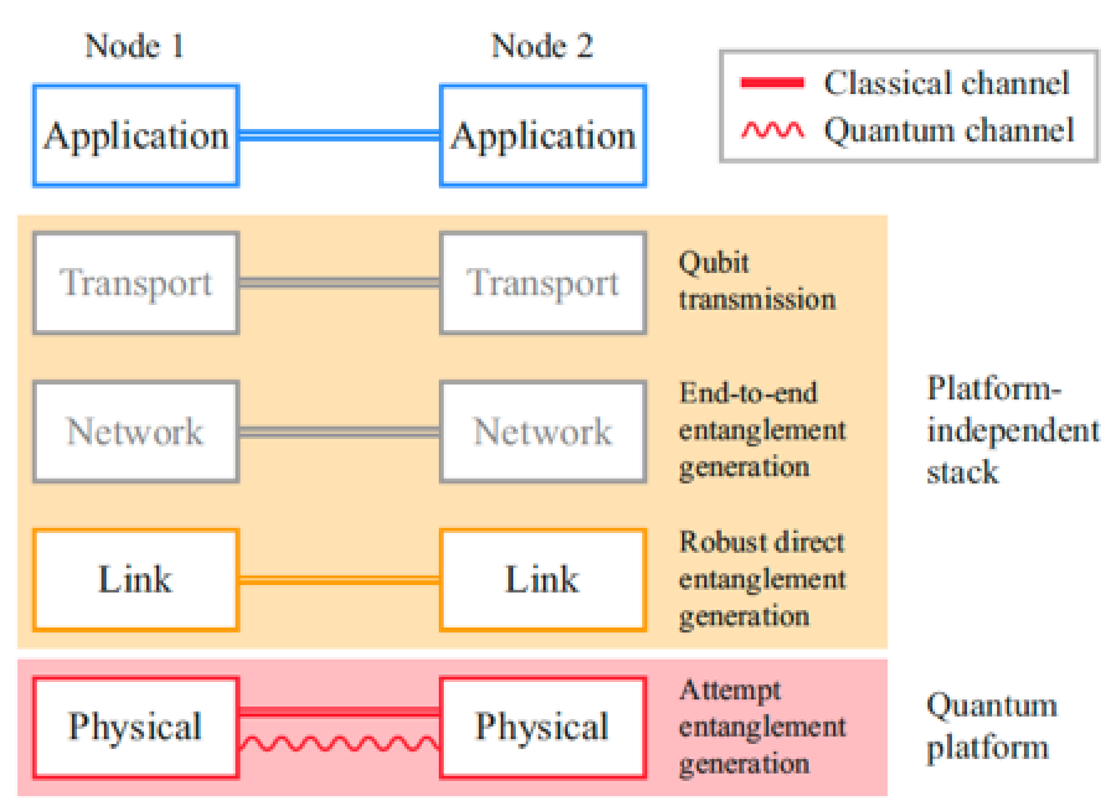
Image: Nature 583, 226 (2020)

Journal of Appl. Phys. 130, 070901 (2021)

- On-chip integration: small form factor and better performance
- Scalable to small quantum computing units for error correction, routing, …
- Large-scale multiplexing (on-chip) for increased rates

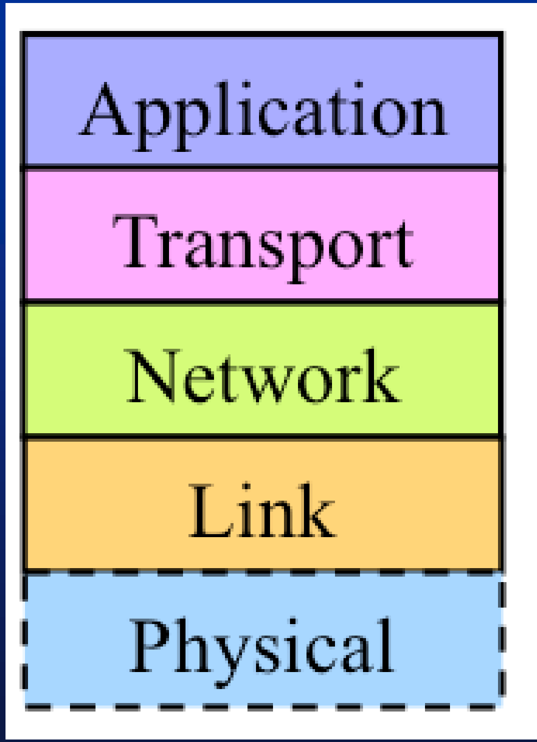
Software for the Quantum Internet

Quantum Network Stack



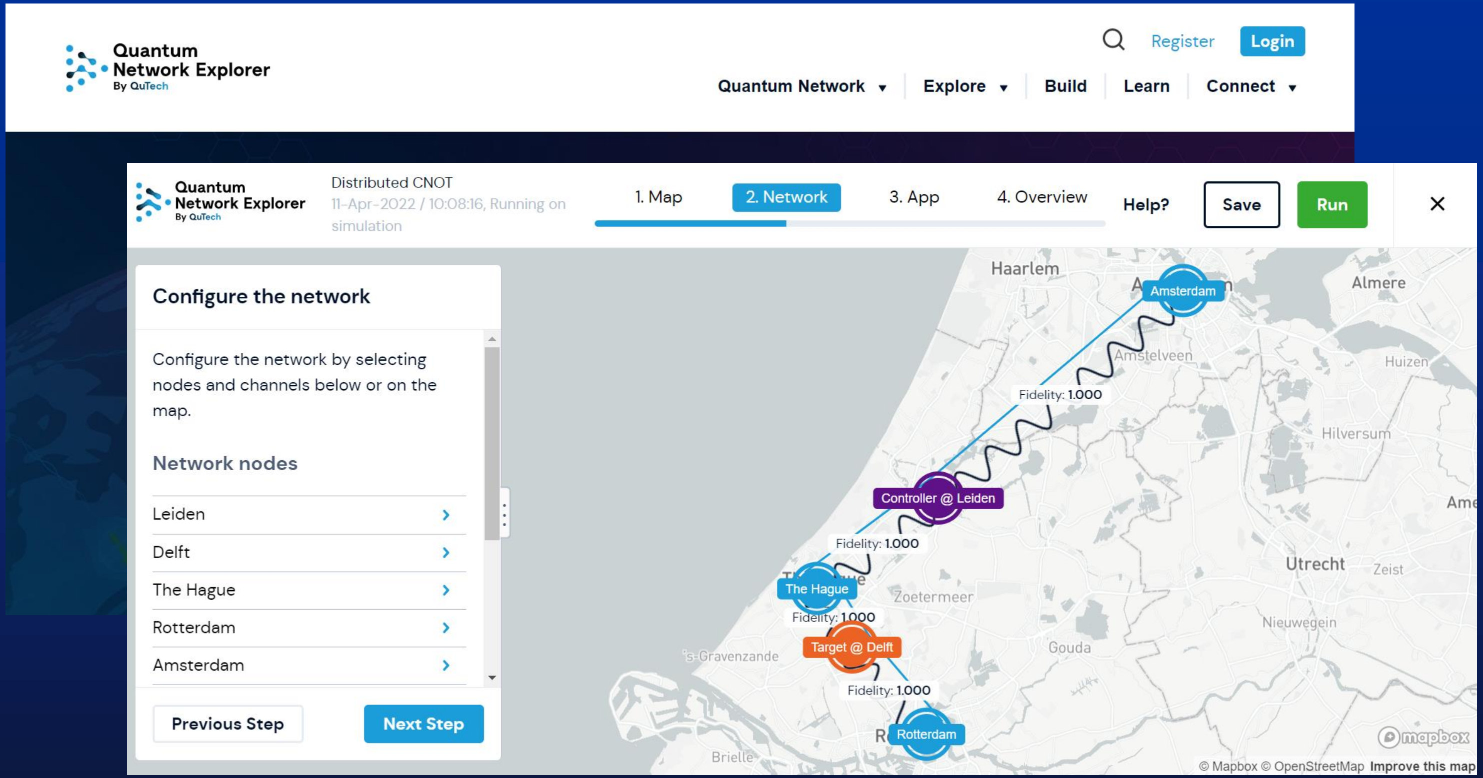
Link layer: NPJ Quantum 8, 121 (2022)

Internet Protocol Stack



Quantum Network Explorer
By QuTech

www.quantum-network.com



Explore
Configure and run applications

Learn
Explainers, Knowledge base, LLM Chatbots

Build
Build new applications using high-level ADK

Connect
Social media channels and forums

Thanks to:

Hansonlab team
QuTech electronics team
TNO engineering team

Fraunhofer ILT, OPNT, KPN,
Holland High-Tech, SURF ,
Element6, Toptica

QUANTUM INTERNET ALLIANCE

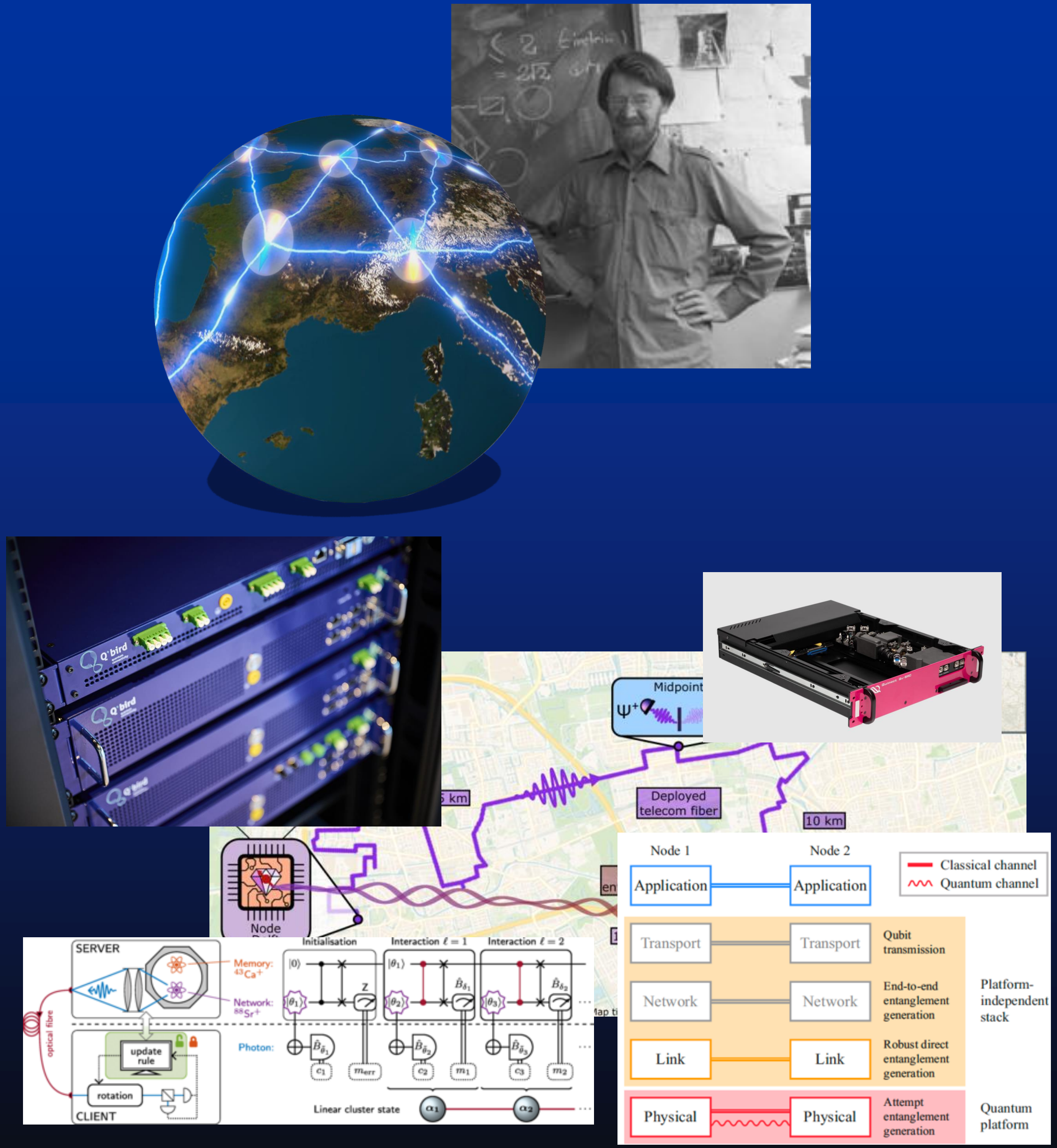
QUANTUM FLAGSHIP

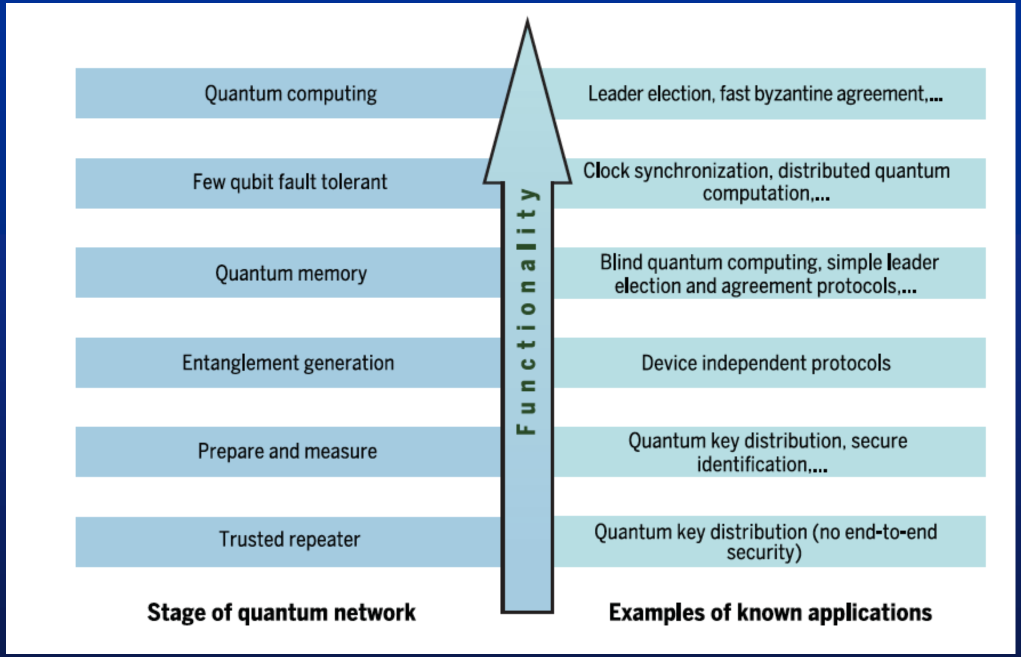
Quantum Delta NL

NWO

Reach out if you want to connect/chat! Arian@qiraffe.nl

The Quantum Internet: Applications, Challenges and Opportunities

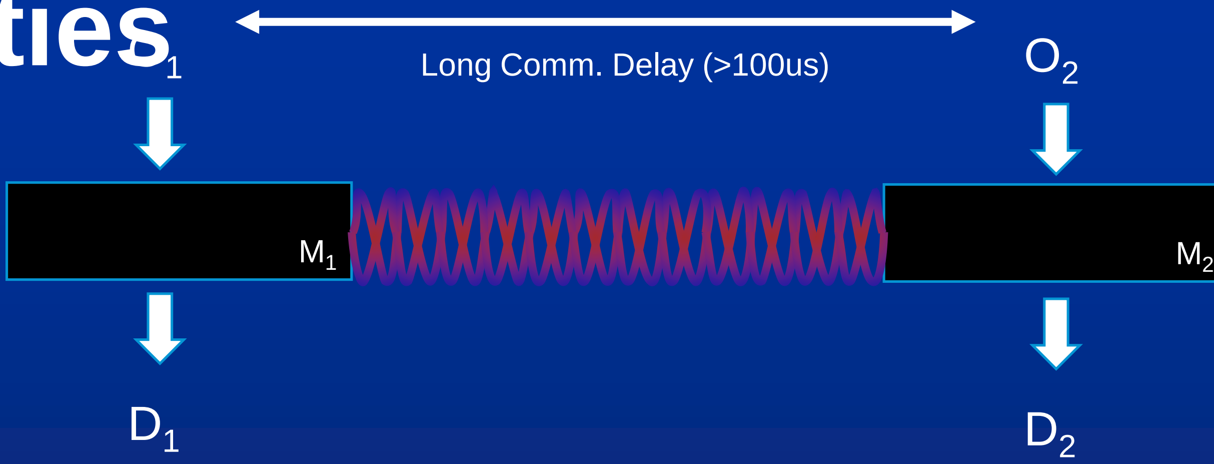




Reach out if you want to connect/chat!
Arian@qiraffe.nl

Backup slides

Non-local applications: Coordination between non-communicating parties



1. High fidelity entanglement -> Higher advantage over Classical strategies
2. High entanglement generation rate -> Many decisions per second
3. Guarantee correlations via heralding

For more: Dawei Ding and Liang Jiang, Coordinating Decisions via Quantum Telepathy, arXiv:2407.21723v1