universität innsbruck

Quantum interfaces based on ions and photons

Tracy Northup, Department of Experimental Physics, University of Innsbruck

QUANTUM iNTERFACES GROUP

stationary and flying qubits

entanglement and how we measure it

how to generate single photons with atoms

decoherence

Hong-Ou-Mandel effect

photon- and atom-based quantum processors

DiVincenzo criteria

DiVincenzo's criteria

D. P. DiVincenzo, "The Physical Implementation of Quantum Computation," *Fortschritte der Physik* **48**, 771 (2000)

"[T]he advantages of quantum information processing are not manifest solely, or perhaps even principally, for straightforward computation only…

The tasks we have in mind here all involve not only computation but also communication. The list of these tasks that have been considered in the light of quantum capabilities, and for which some advantage has been found in using quantum tools, is fairly long and diverse: it includes secret key distribution, multiparty function evaluation as in appointment scheduling, secret sharing, and game playing."

DiVincenzo's (5 + 2) criteria

D. P. DiVincenzo, "The Physical Implementation of Quantum Computation," *Fortschritte der Physik* **48**, 771 (2000)

6. The ability to interconvert stationary and flying qubits
7. The ability faithfully to transmit flying qubits between specified locations

DiVincenzo's (5 + 2) criteria

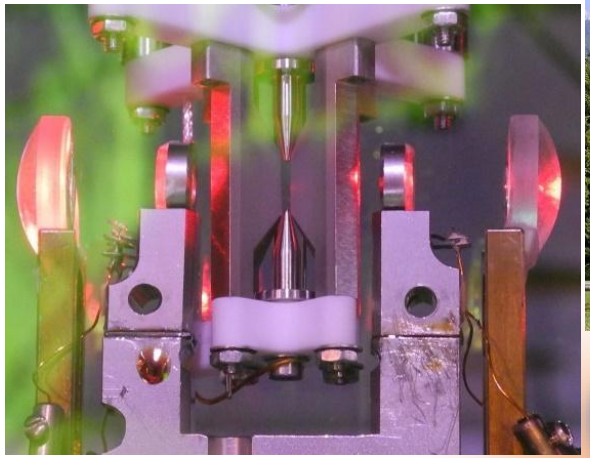
D. P. DiVincenzo, "The Physical Implementation of Quantum Computation," *Fortschritte der Physik* **48**, 771 (2000)

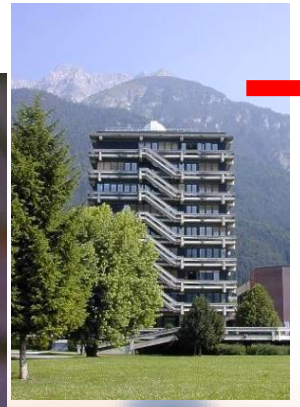
"Requirement 6 is the really hard one; to date the only theoretical proposal sufficiently concrete that experiments addressing it have been planned is the scheme produced by Kimble and coworkers [46] for unloading a cavity photon into a traveling mode via atomic spectroscopy, and loading it by the time-reversed process."

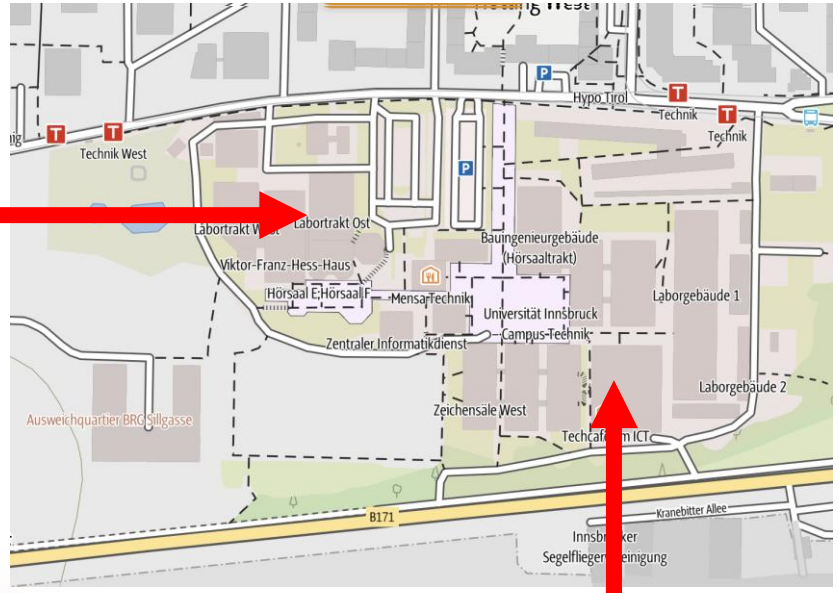
26 years later: we have made a lot of progress, but quantum interfaces are still challenging!

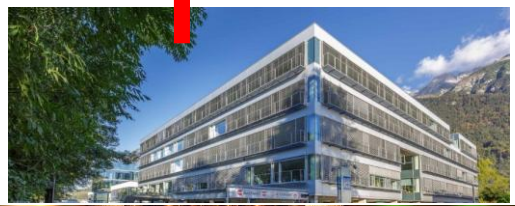
This seminar: one example of a quantum interface

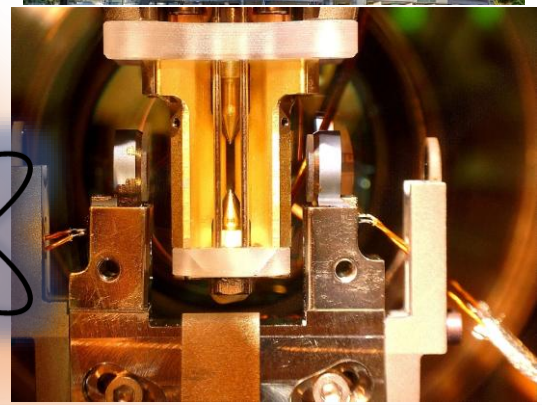
This seminar











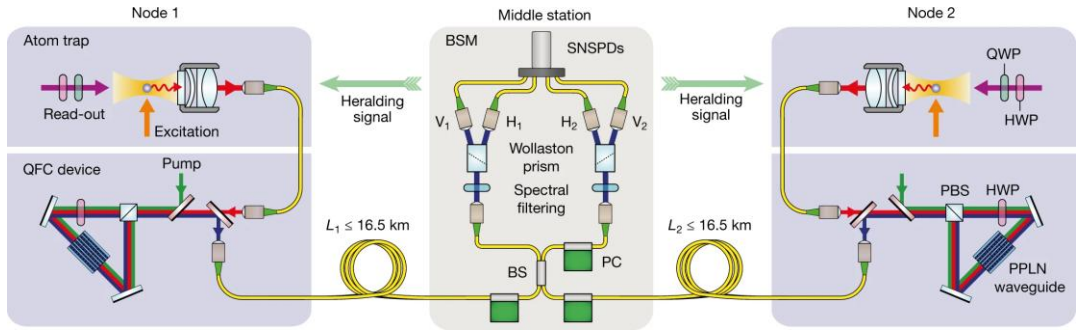
entangled!

Enabling steps:

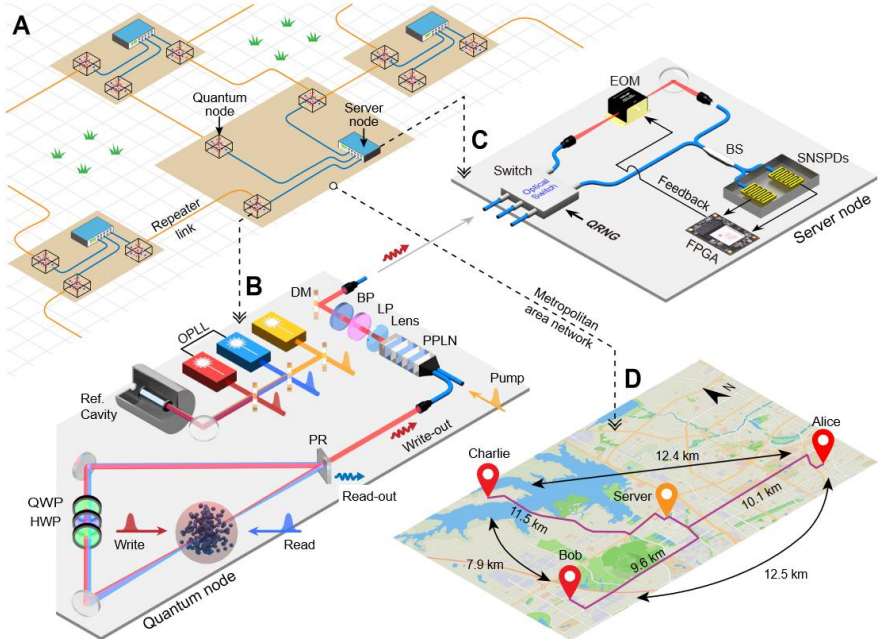
- *matter*: trapped atomic ions,
- *light*: single photons,
- *quantum interfaces* based on optical cavities.

…in the context of quantum network efforts worldwide

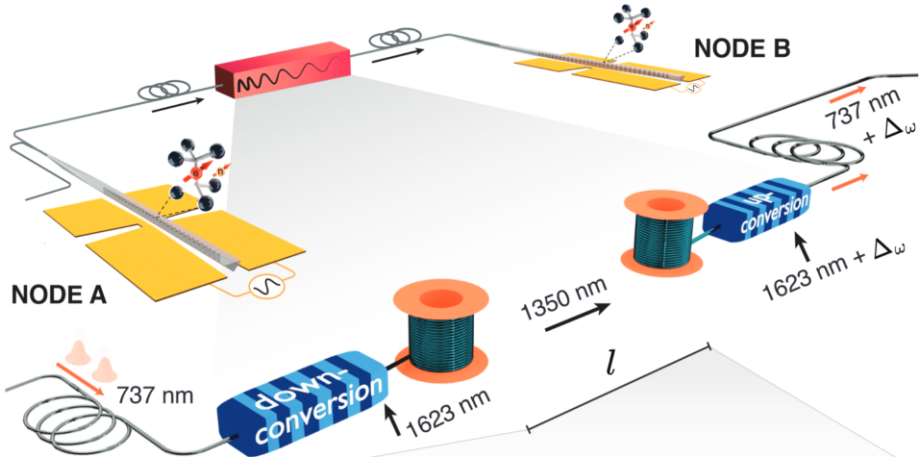
Single atoms entangled over 33 km fiber (400 m distance) in Munich, Germany
T. Van Leent et al., *Nature* **607**, 69 (2022)

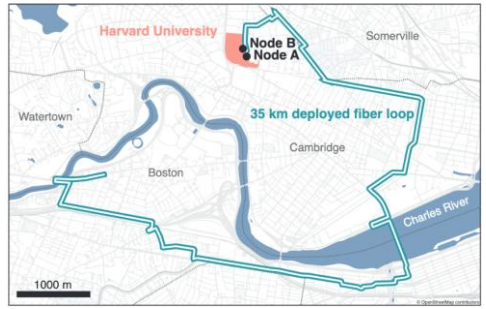


Entanglement across deployed atomic quantum-memory network in Hefei, China (12.4 km)
J. L. Liu et al., *Nature* **629**, 579 (2024)



Entanglement across deployed solid-state quantum-memory network in Cambridge/Boston, USA (35 km)
C. M. Knaut et al., *Nature* **629**, 573 (2024)

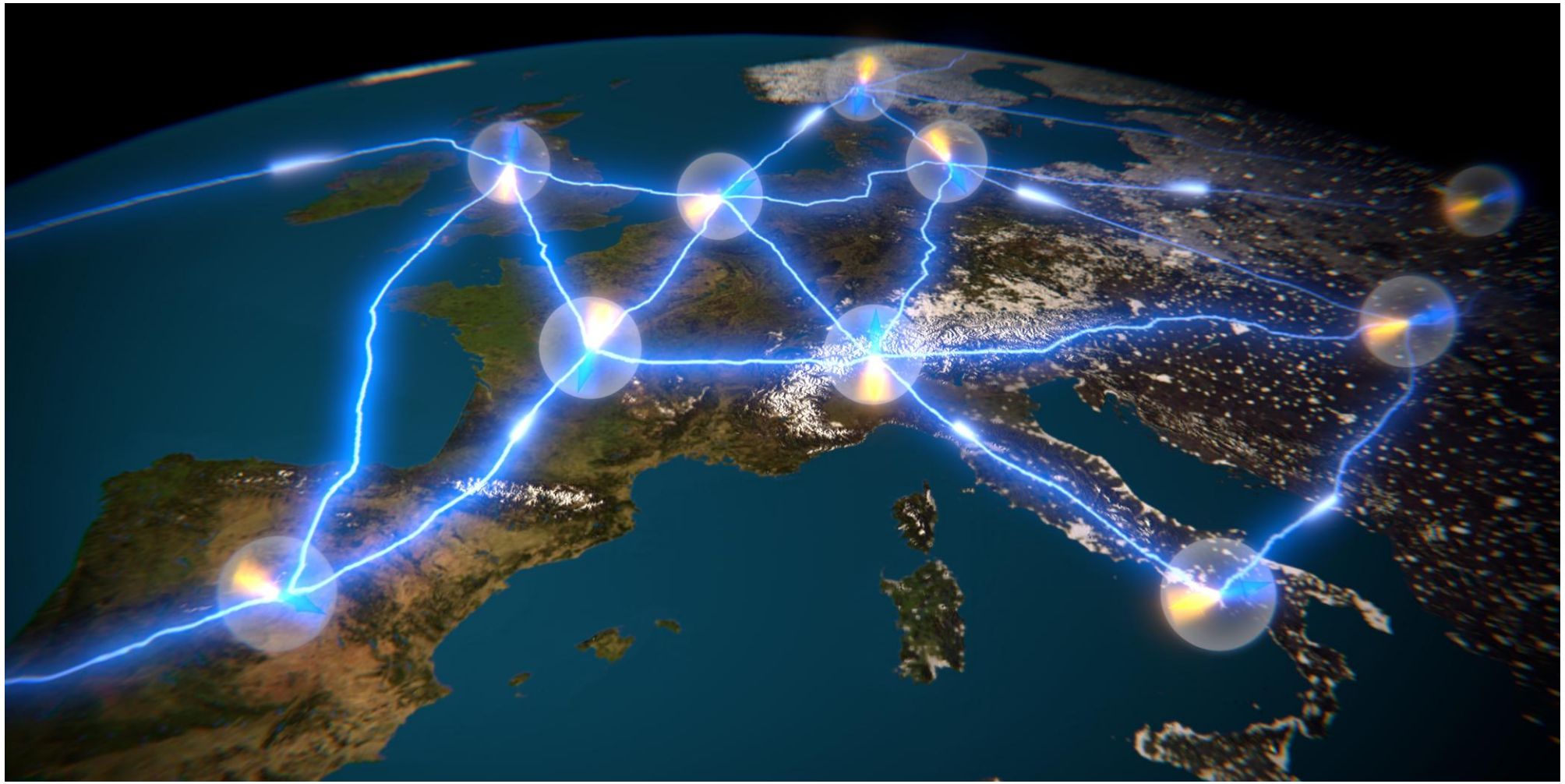




Quantum interfaces based on ions and photons

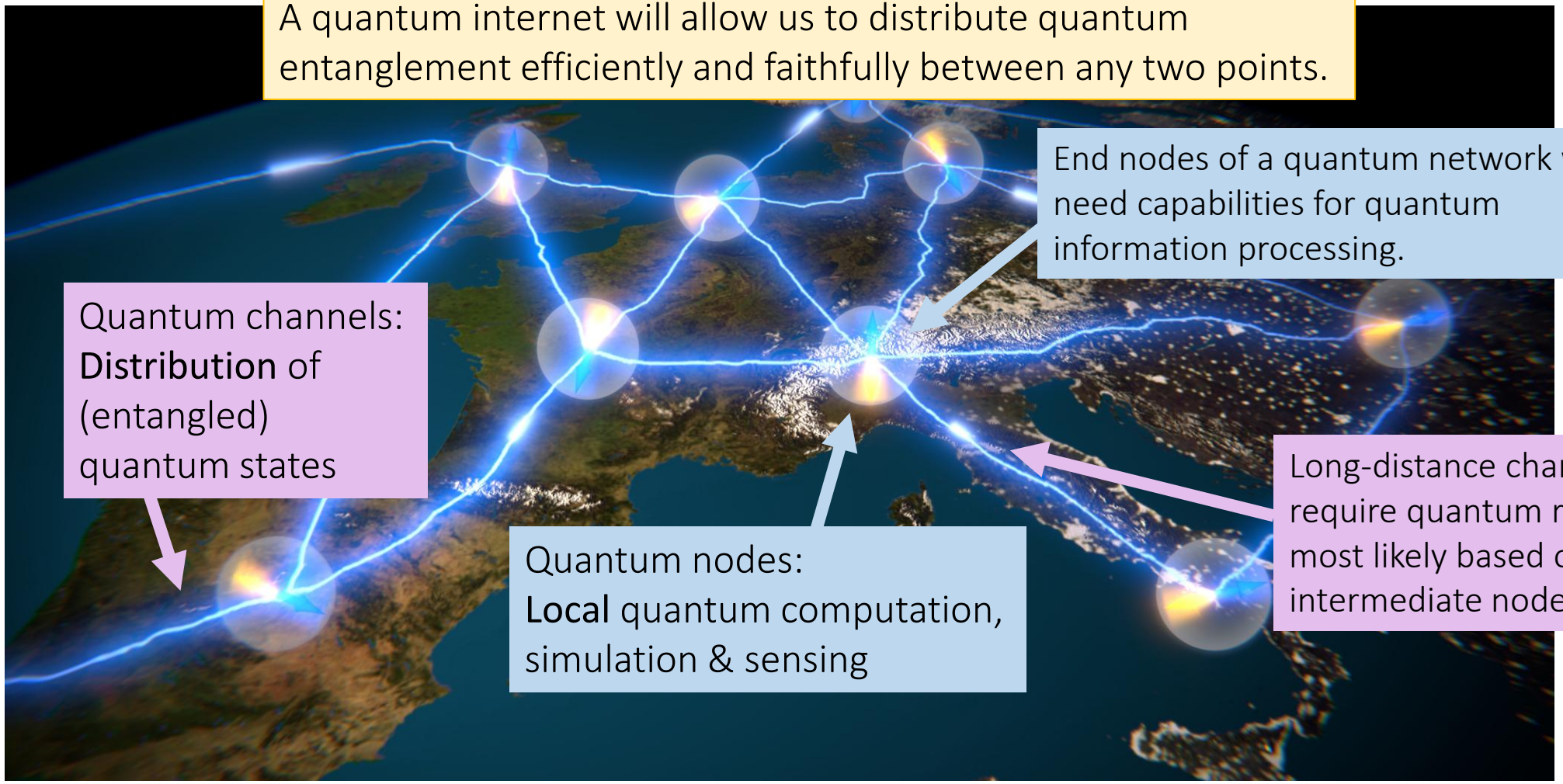
- What is a quantum internet, and why do we want one?
- Trapped ions for a future quantum internet
- Entanglement across the University of Innsbruck campus
- Prospects for scaling up

What is a quantum internet?



What is a quantum internet?

A quantum internet will allow us to distribute quantum entanglement efficiently and faithfully between any two points.



End nodes of a quantum network will need capabilities for quantum information processing.

Quantum channels: **Distribution** of (entangled) quantum states

Quantum nodes: **Local** quantum computation, simulation & sensing

Long-distance channels will require quantum repeaters, most likely based on intermediate nodes.

Why do we want a quantum internet?

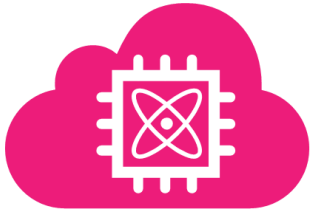
Secure Communication

Current encryption methods for communication could be broken with sufficiently powerful computers. (They are based on problems that are too hard for current computers to solve.)

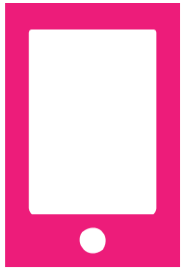
Quantum key distribution offers information-theoretic security — security that is robust even given unlimited computing resources and time.

Why do we want a quantum internet?

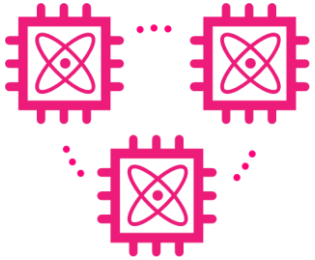
Secure Communication



Secure Quantum Computing in the Cloud



Clock Synchronization
Password Identification
Position Verification
....



Quantum Computing Clusters

Quantum interfaces based on ions and photons

- What is a quantum internet, and why do we want one?
- Trapped ions for a future quantum internet
- Entanglement across the University of Innsbruck campus
- Prospects for scaling up

Trapped ions have many advantages for local quantum computing

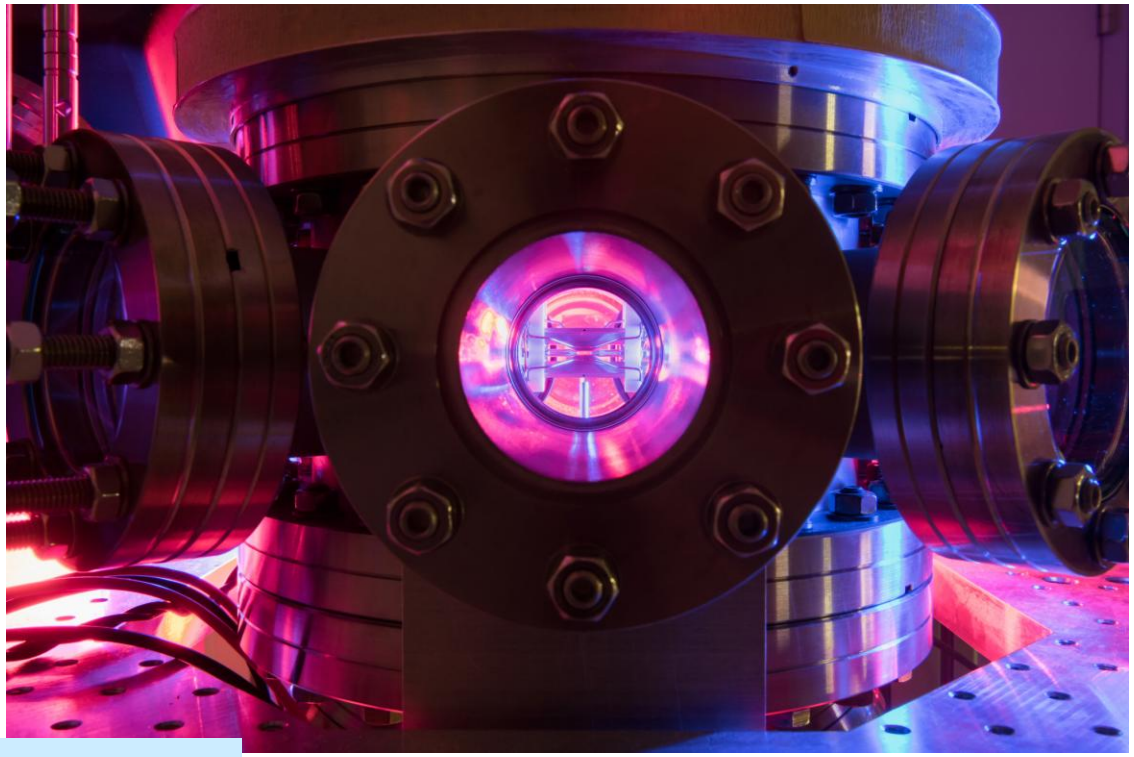
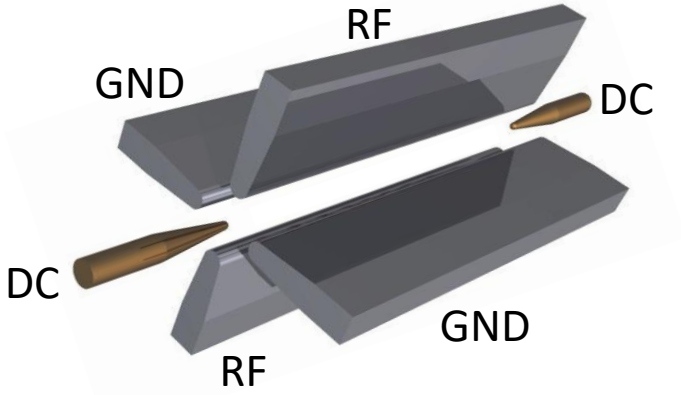


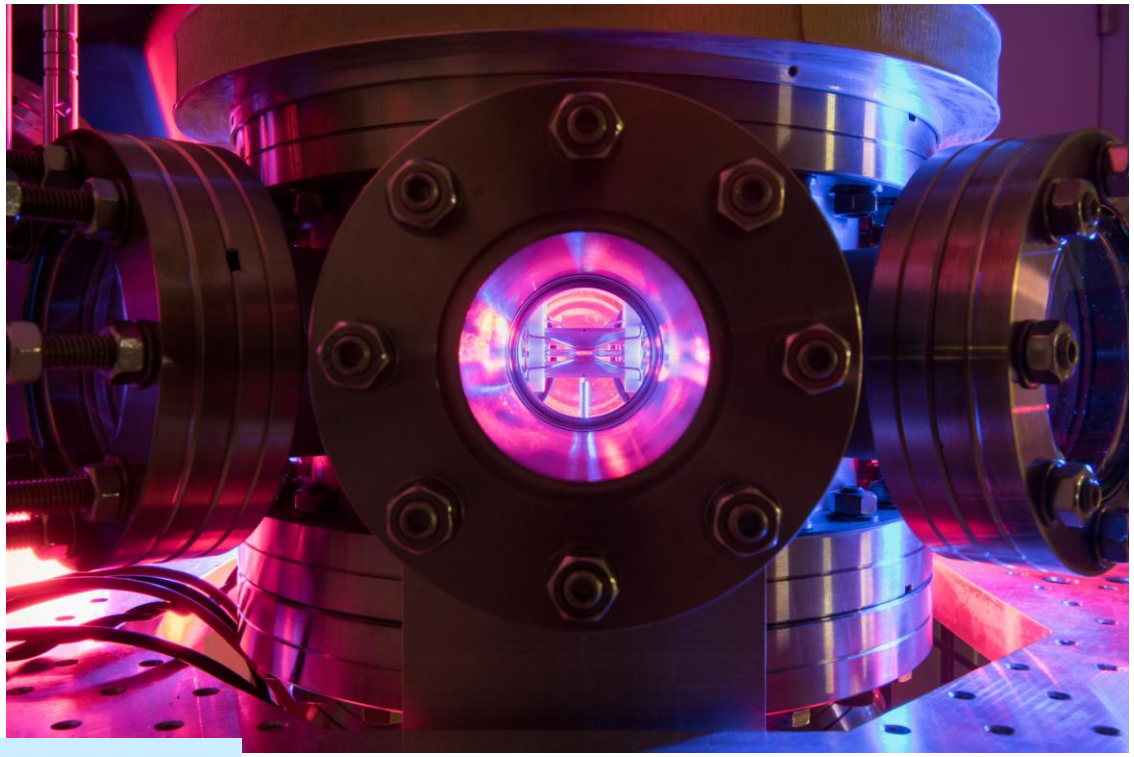
Photo: R. Shone



Linear Paul trap:

- ions are confined in an RF (pseudo)potential in ultra-high vacuum
- coherent manipulation of electronic and motional degrees of freedom with lasers or microwaves

Trapped ions have many advantages for local quantum computing



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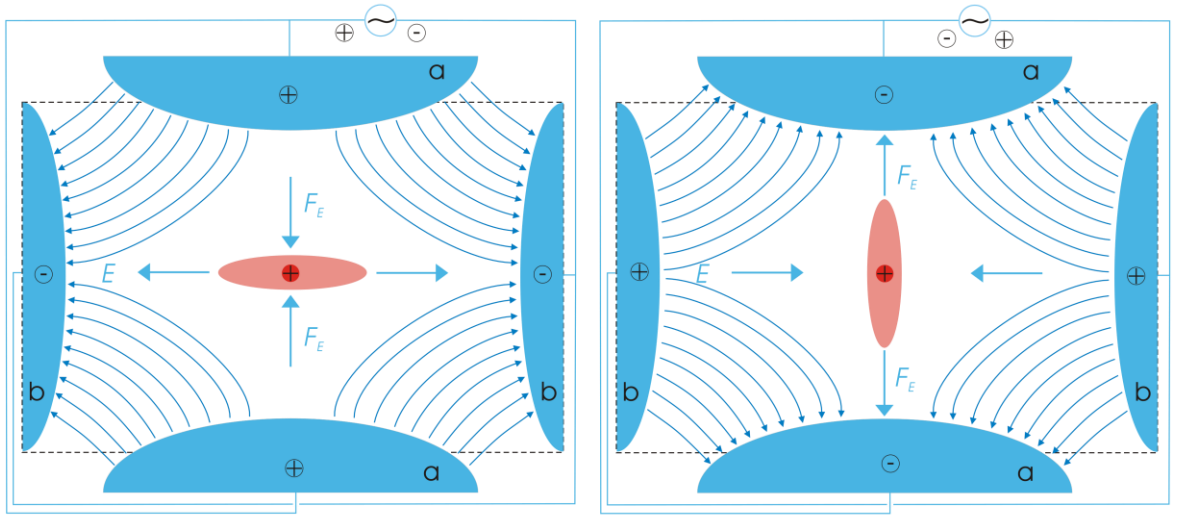

Source: Arian Kriesch, Wikipedia
https://de.wikipedia.org/wiki/Paul-Falle#/media/Datei:Paul-Trap.svg

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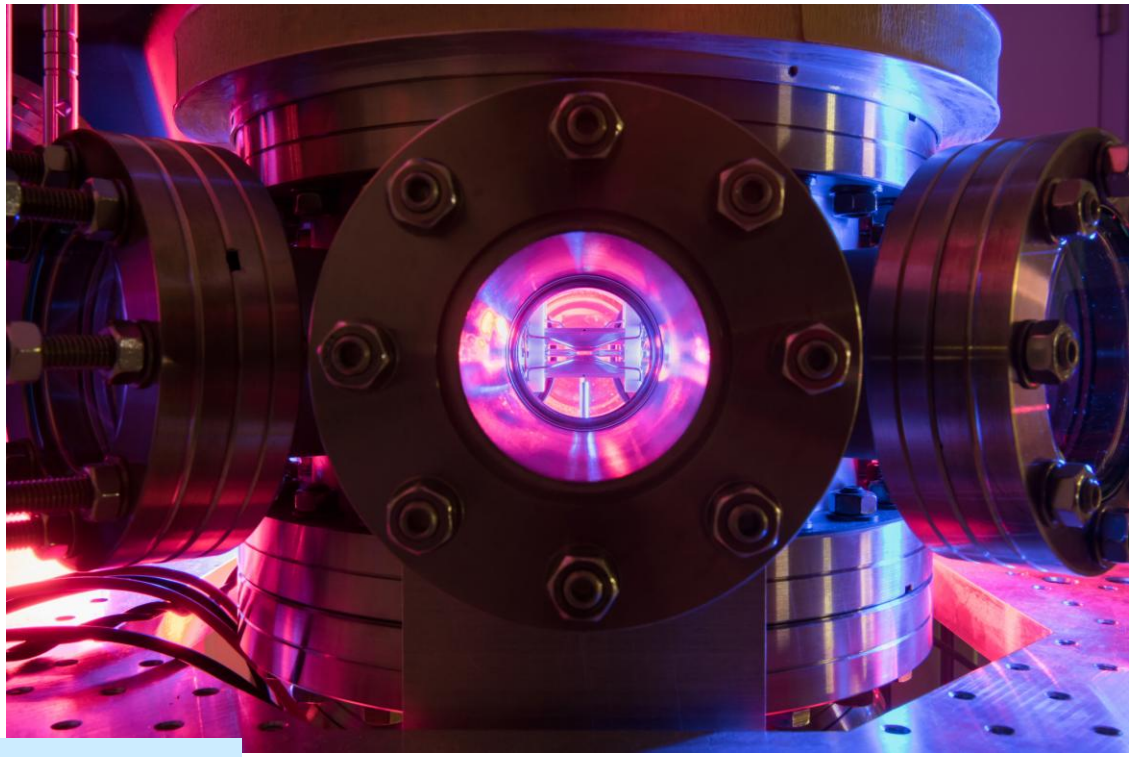

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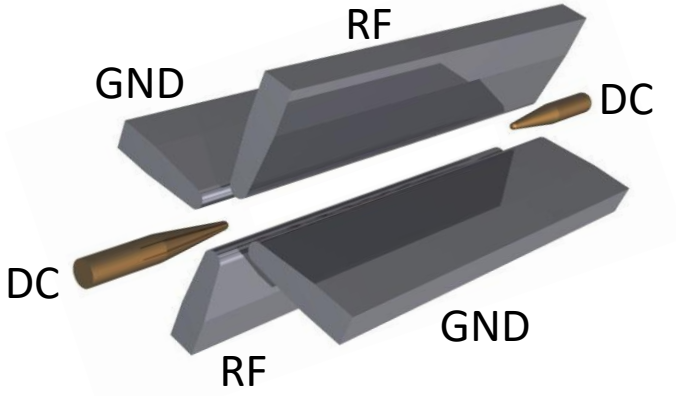

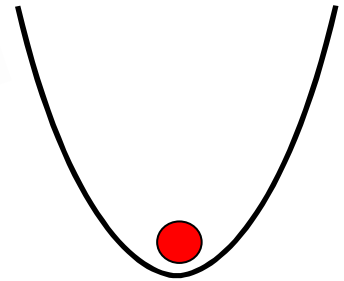

~10 eV deep
~MHz trap frequencies

Linear Paul trap:

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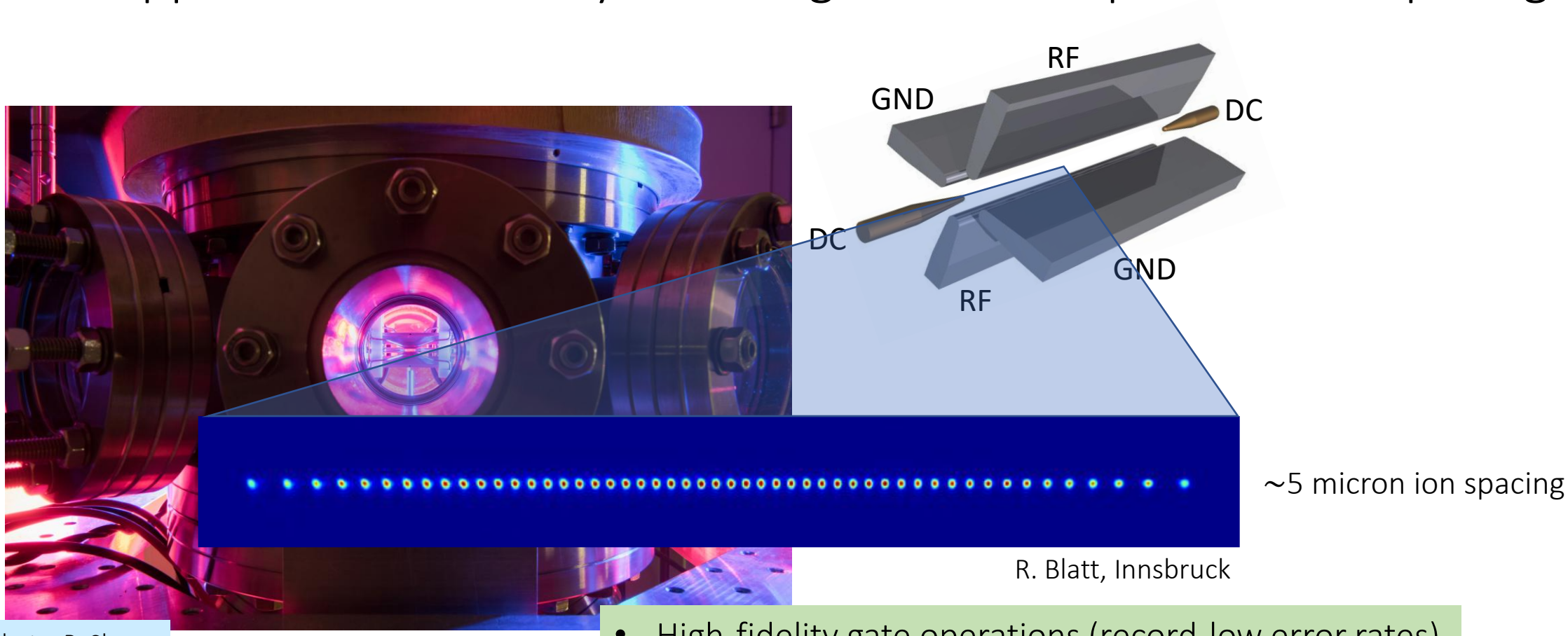


~5 micron ion spacing

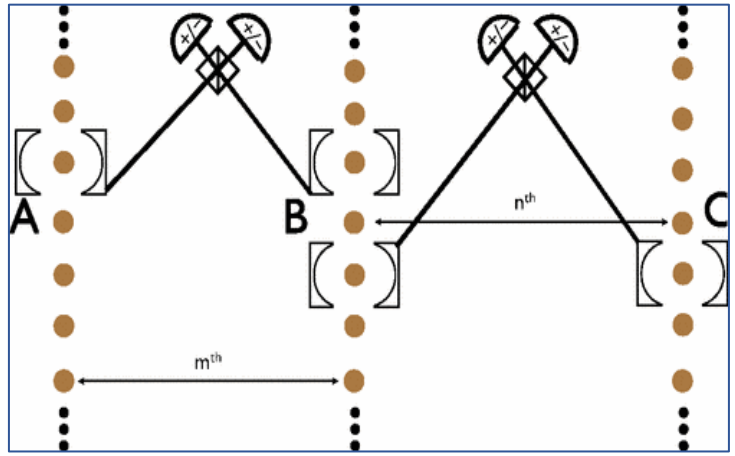
R. Blatt, Innsbruck

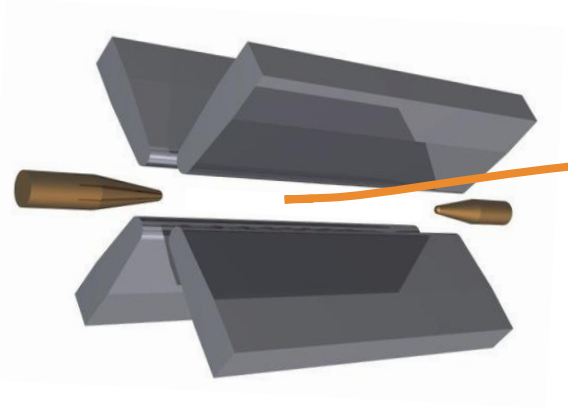
Photo: R. Shone

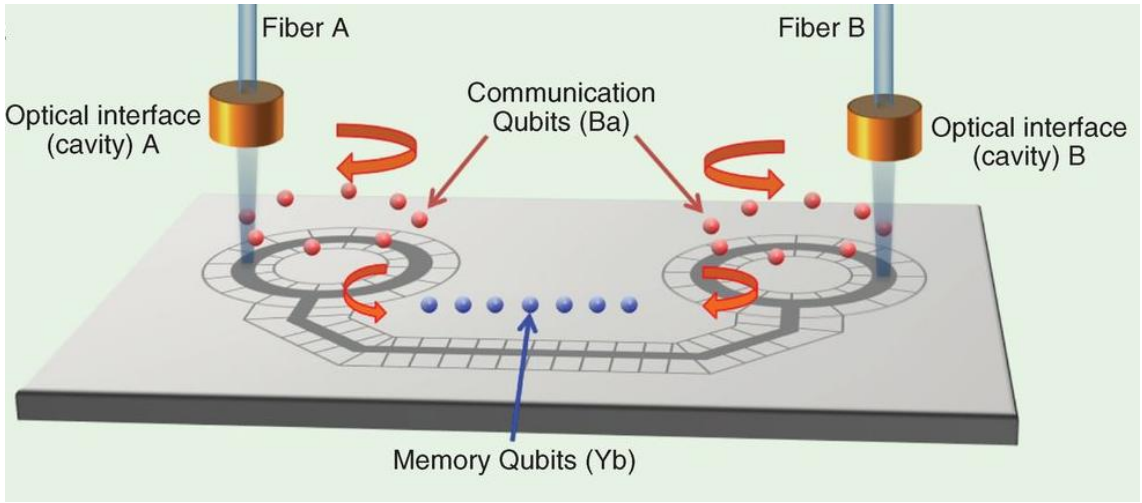
- High-fidelity gate operations (record-low error rates)
- Long coherence times
- Scalability via quantum CCD architecture

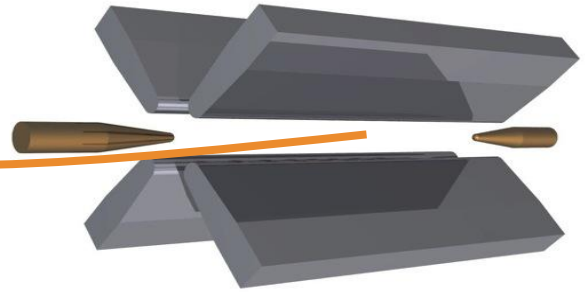
How can we build links between ions in distant traps?

N. Sangouard, R. Dubessy, C. Simon,
Phys. Rev. A **79**, 042340 (2009)









C. Monroe and J. Kim, *Science* **339**, 1164 (2013)

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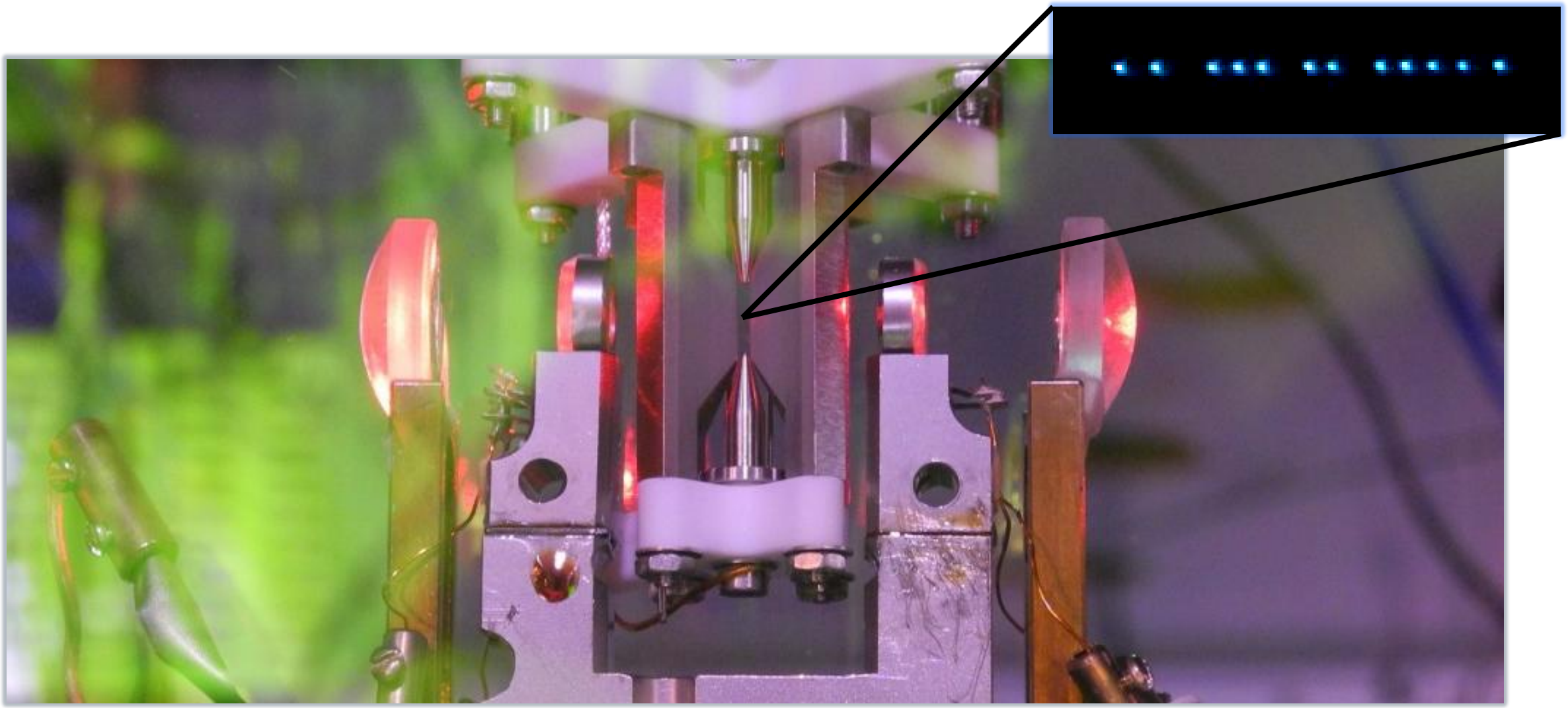
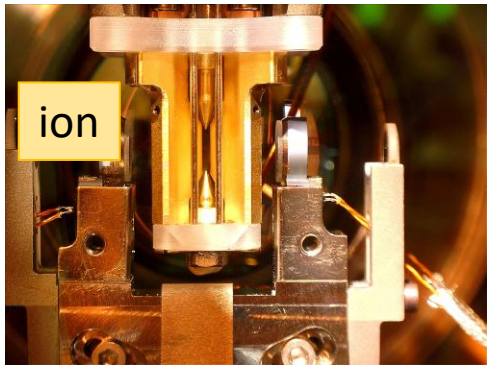


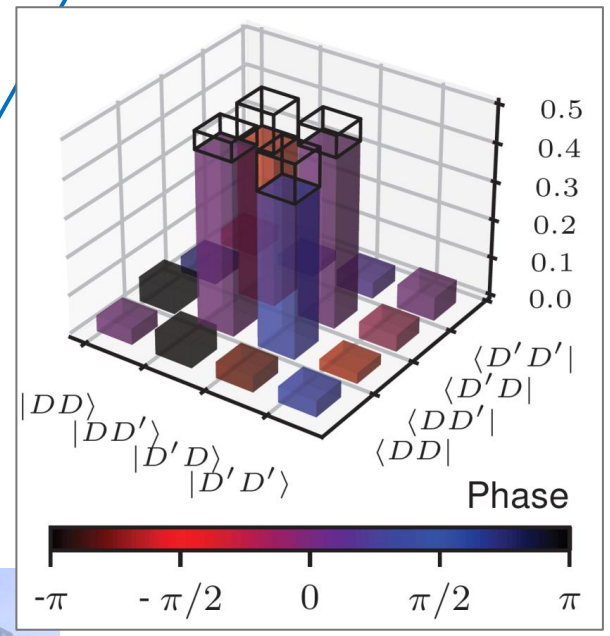
Entanglement of remote trapped ions

- In each laboratory, we generate entanglement between a single ion and a single photon (854 nm).
- The polarization of the photon is entangled with the electronic state of the ion.
- One of the two photons is sent over single-mode optical fiber to the other laboratory.
- There, both photons are sent to a beam splitter, which erases information about which photon came from which laboratory.
- When we measure two photons with orthogonal polarizations, we prepare the two ions in an entangled state.



520 m

photon



$\alpha 01 + \beta 10$

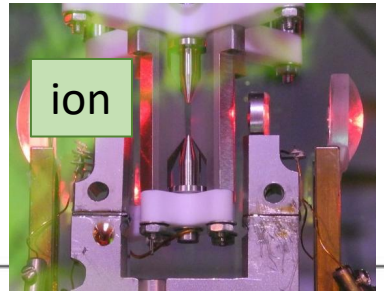
ion

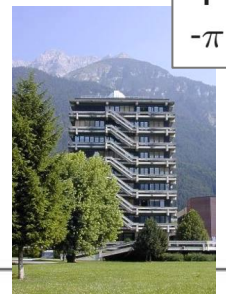
photon

$\alpha 01 + \beta 10$

ion

ion

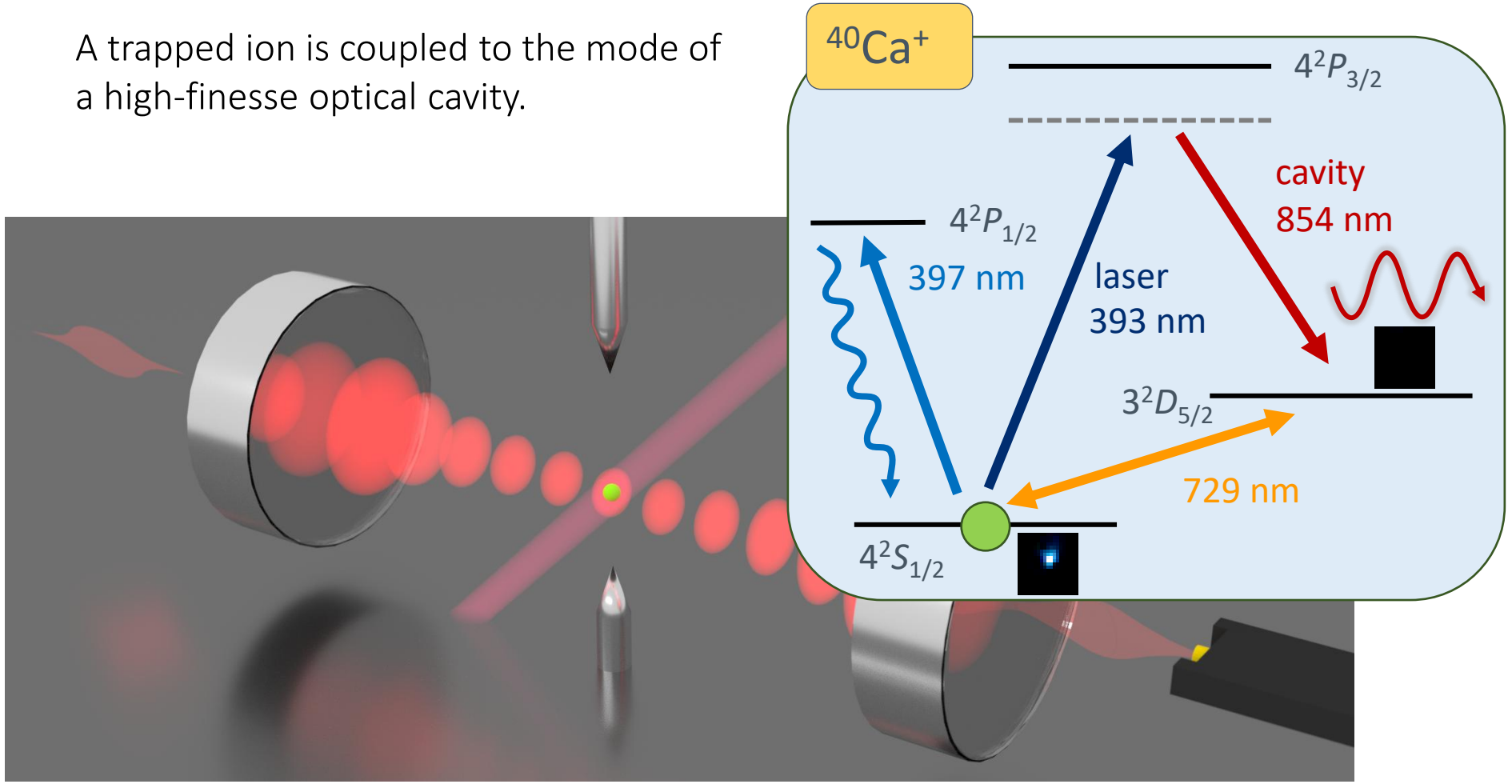




V. Krutyanskiy, M. Galli et al.,
Phys. Rev. Lett. **130**, 050803 (2023)

With an optical cavity, we generate single photons from an ion

A trapped ion is coupled to the mode of a high-finesse optical cavity.



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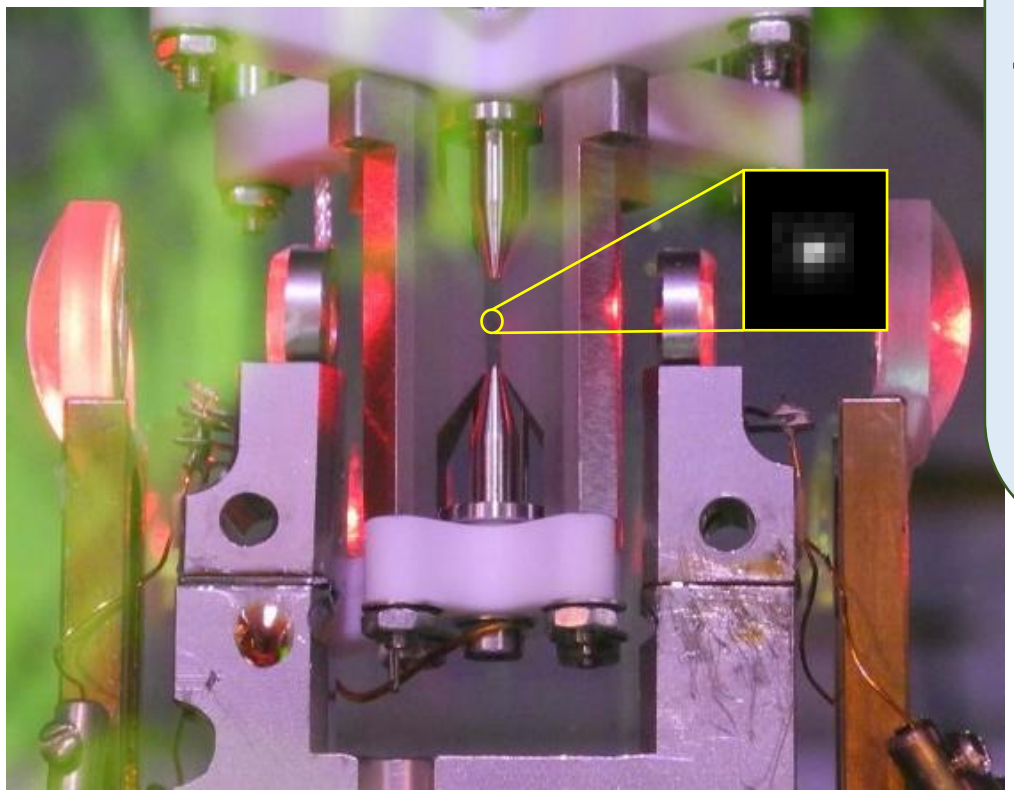
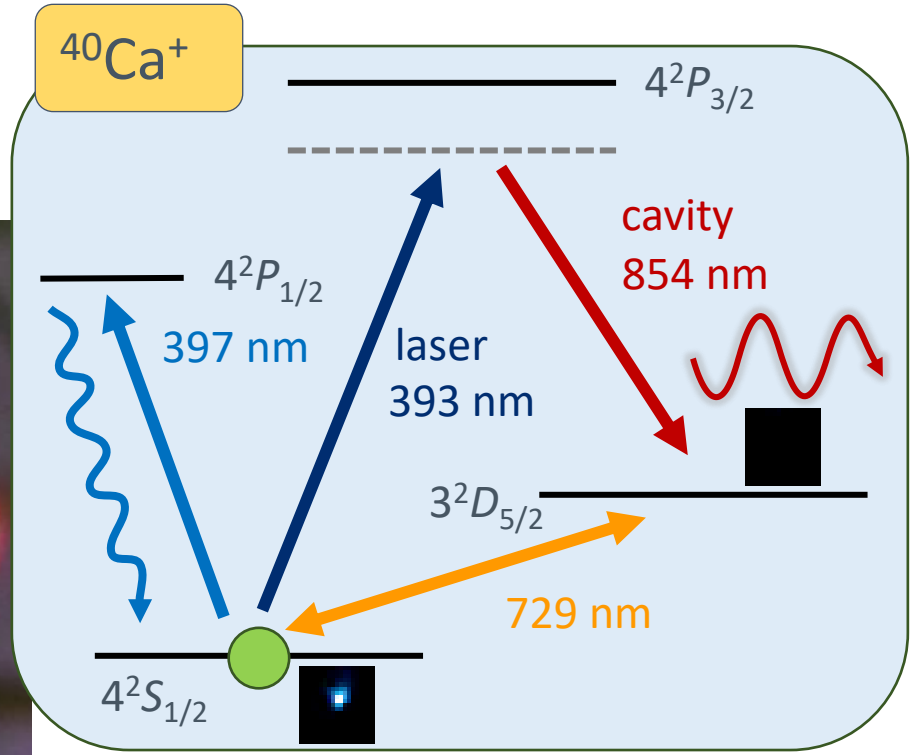
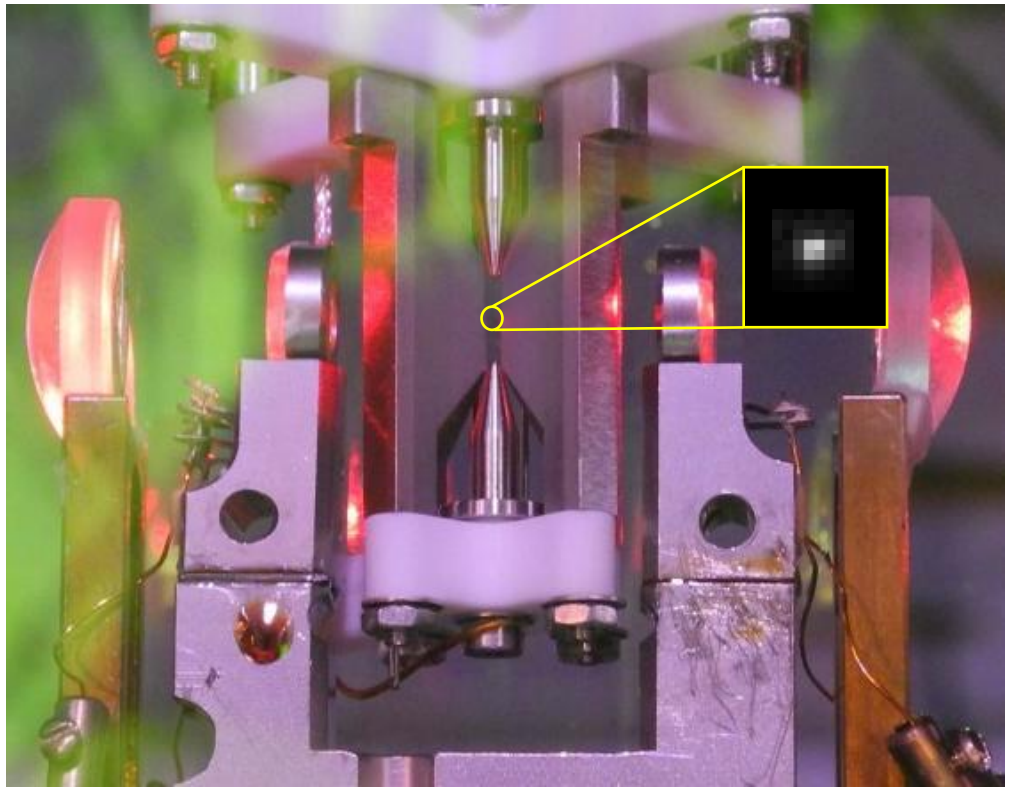
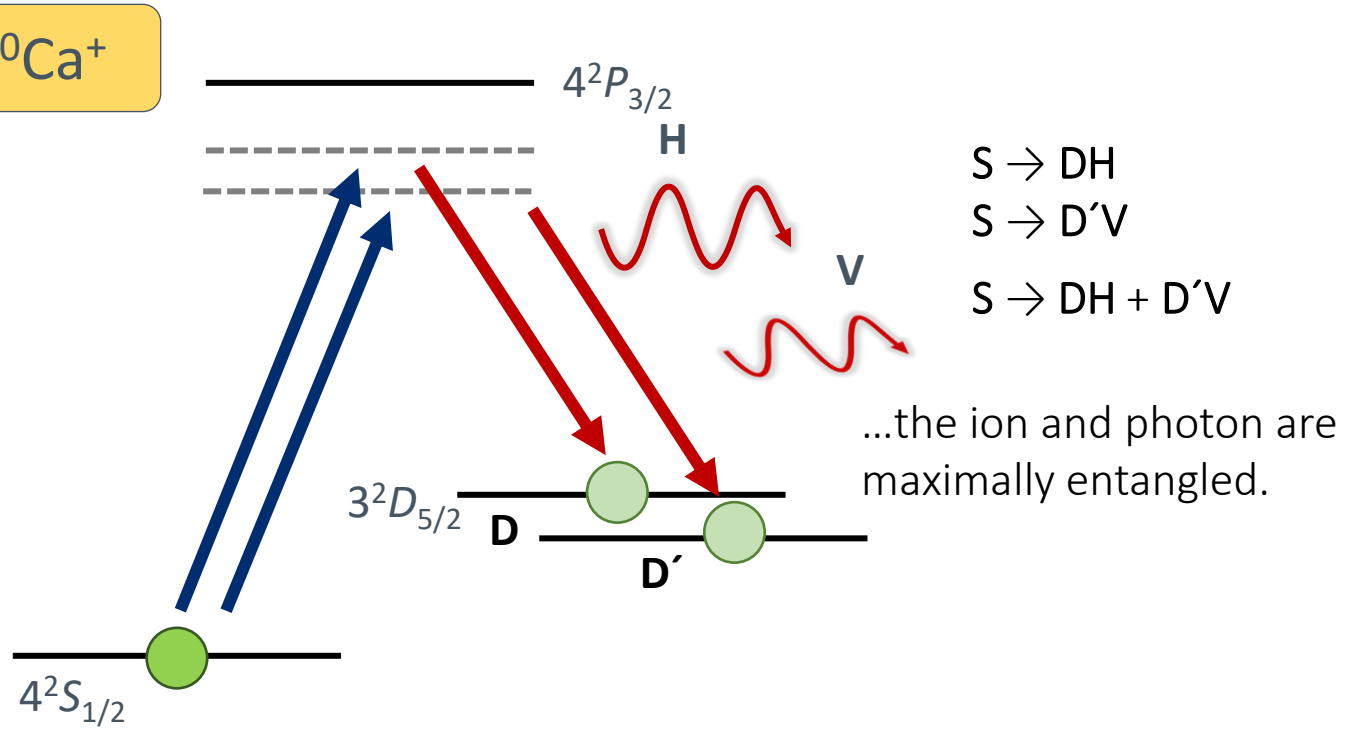




Two (coherent) ways to make a photon: entanglement!

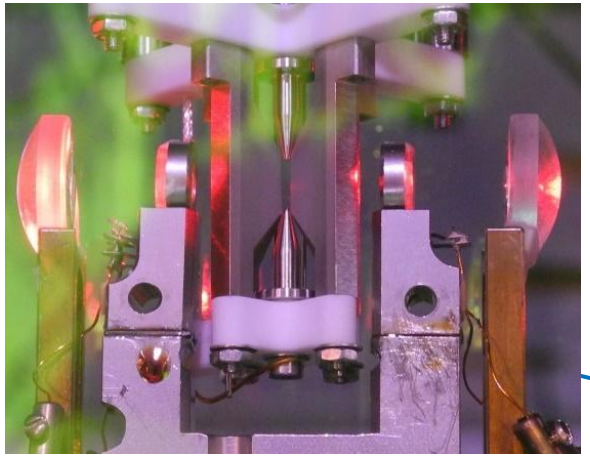
A trapped ion is coupled to the mode of a high-finesse optical cavity.



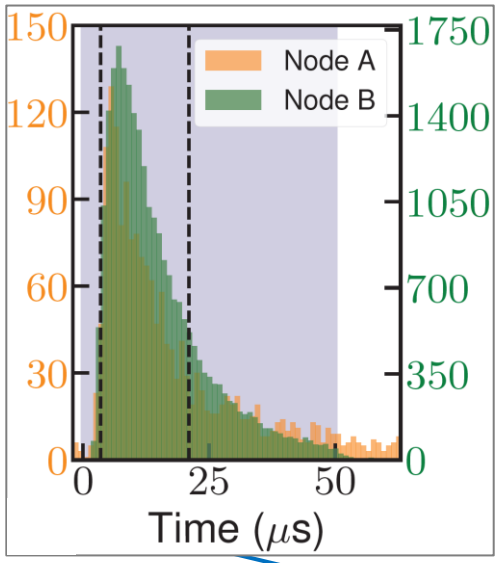


A. Stute et al., Nature 485, 482 (2012)

Entanglement of trapped-ion qubits separated by 230 m



Photon detection events per 1 µs time bin

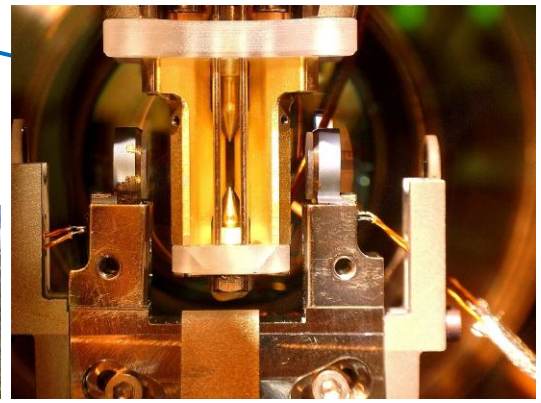


520 m

University of Innsbruck (Northup)

universität innsbruck

IQOQI, Innsbruck (Lanyon)



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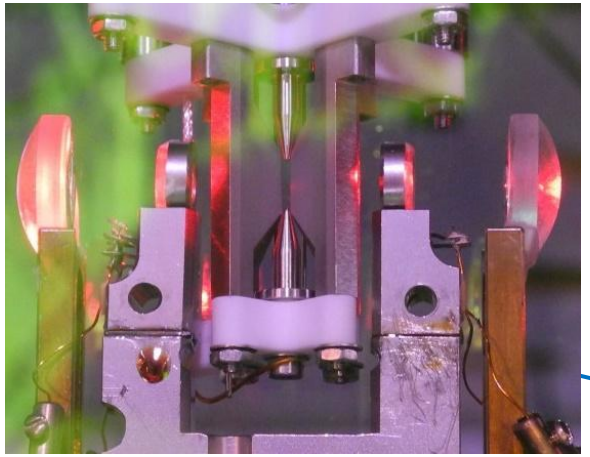

University of Innsbruck (Northup)

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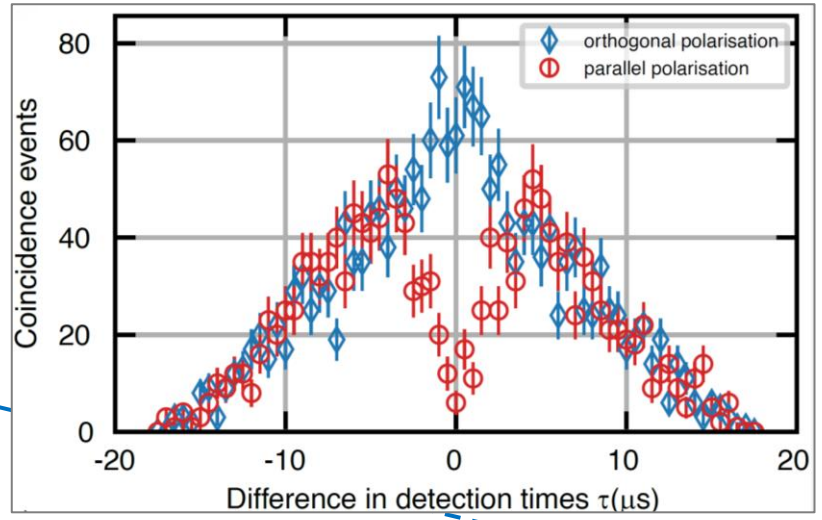

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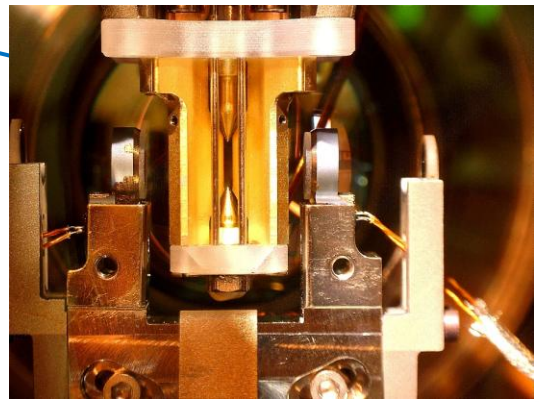

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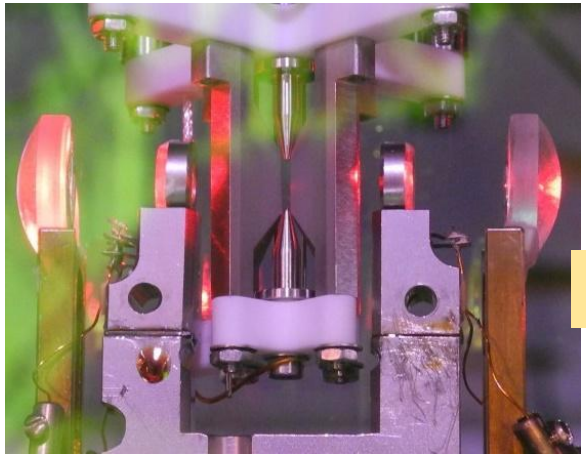
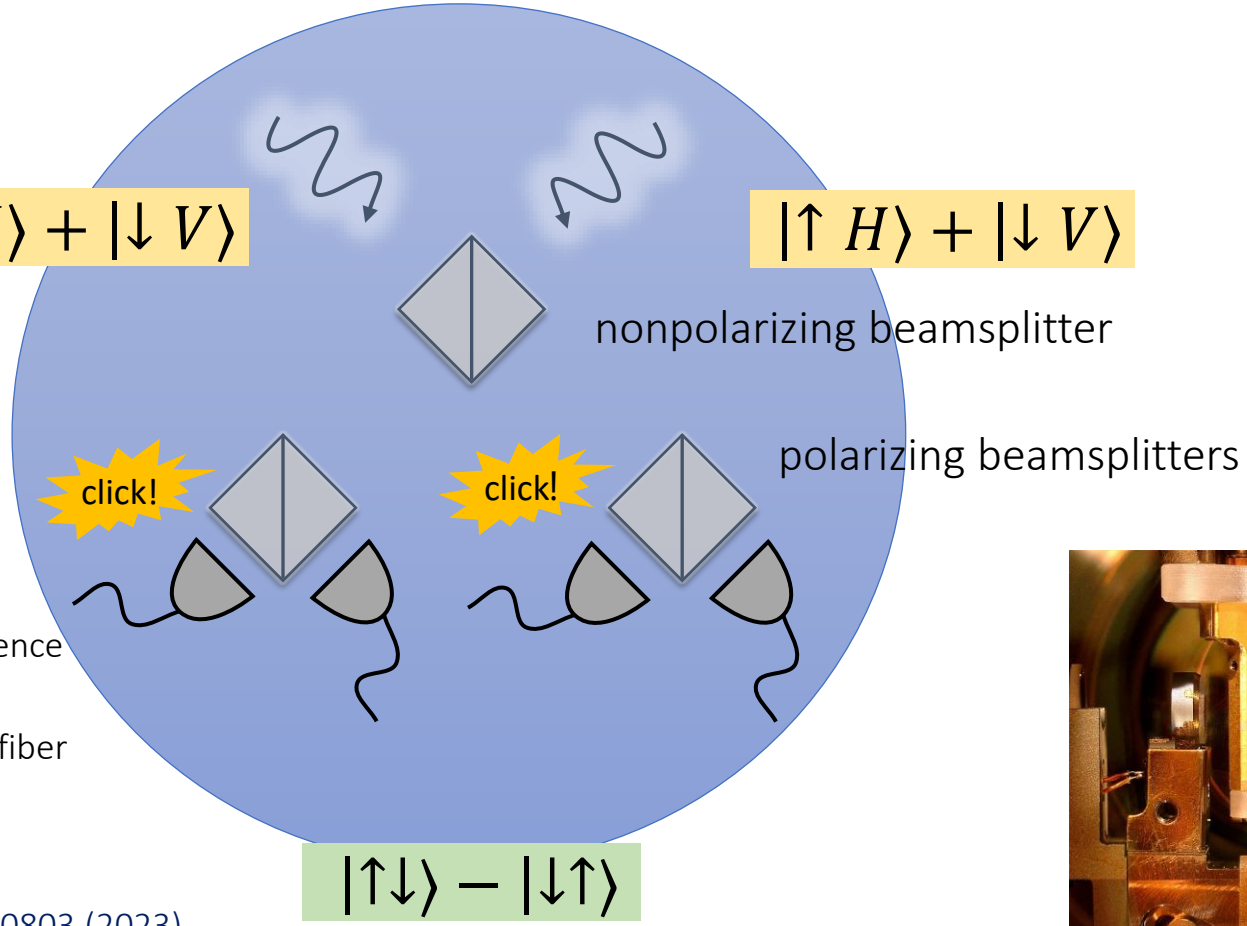
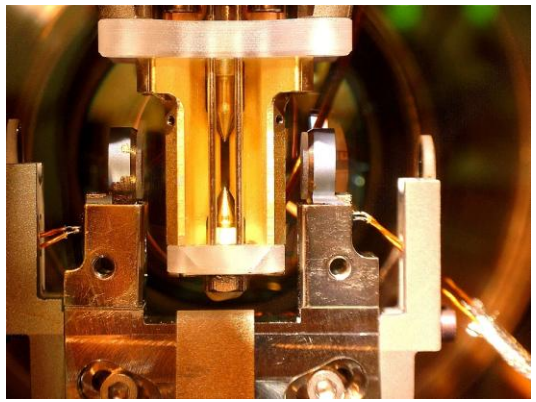




Between the two labs:

- Timing synchronization
  GPS clock signal, trigger for experimental sequence
- Frequency synchronization
  comparison of classical light fields over optical fiber
- Polarization stabilization of fiber link
  periodic correction for polarization rotation

V. Krutyanskiy, M. Galli et al., *Phys. Rev. Lett.* **130**, 050803 (2023)



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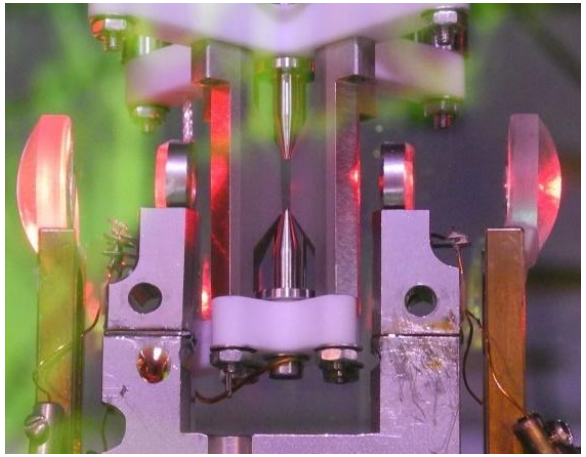
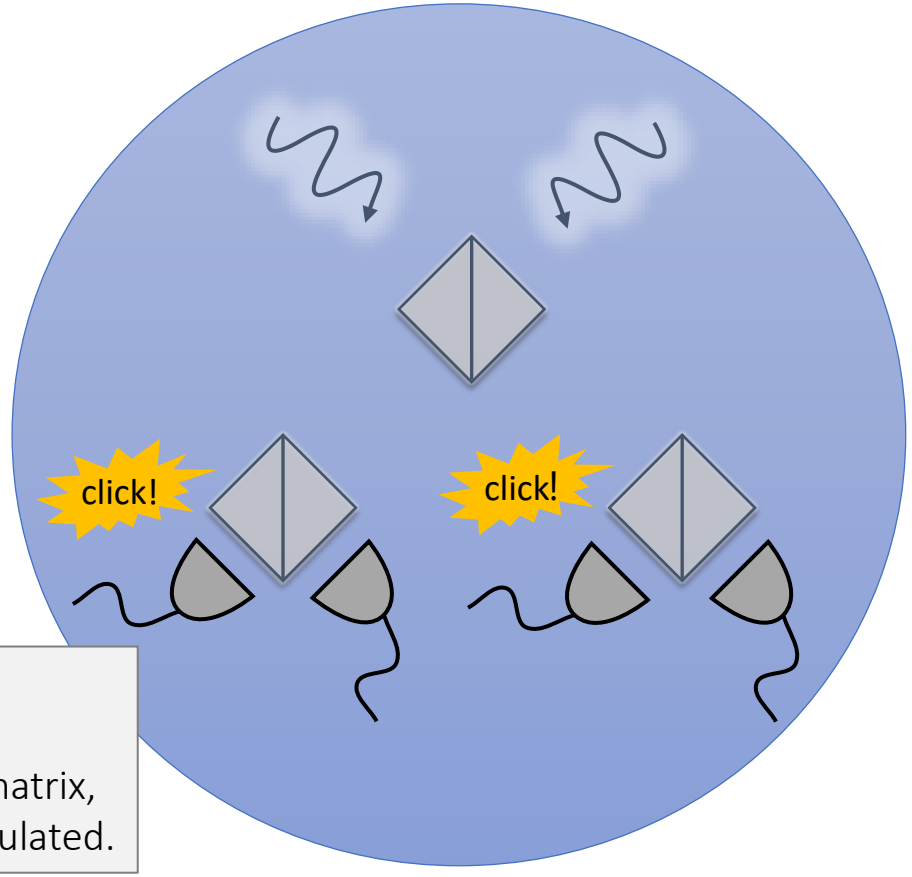
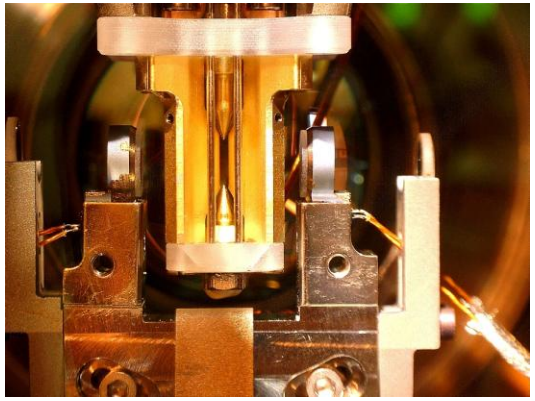




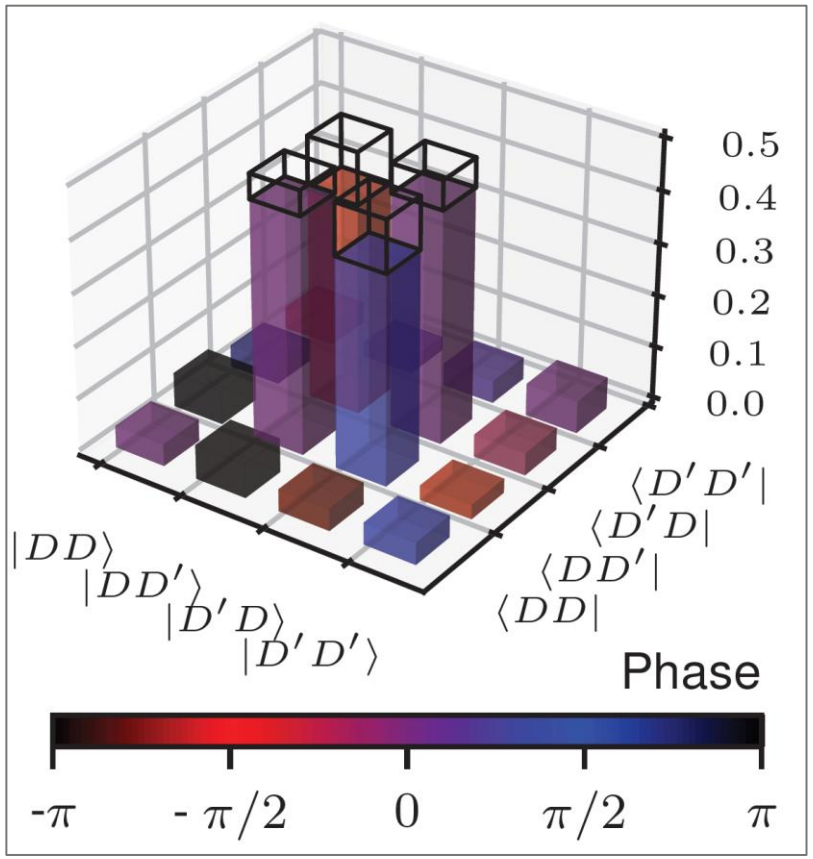
Measurement = bright or dark?

Quantum state tomography:
the two ions are measured in 3 x 3 bases,
which allows us to extract the joint density matrix,
from which entanglement measures are calculated.



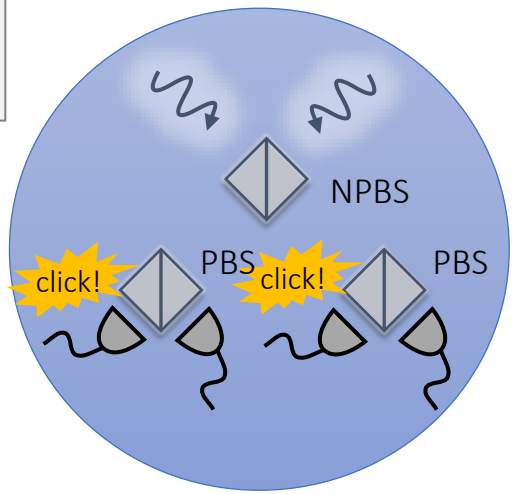
V. Krutyanskiy, M. Galli et al., *Phys. Rev. Lett.* **130**, 050803 (2023)

Entanglement of trapped-ion qubits separated by 230 m



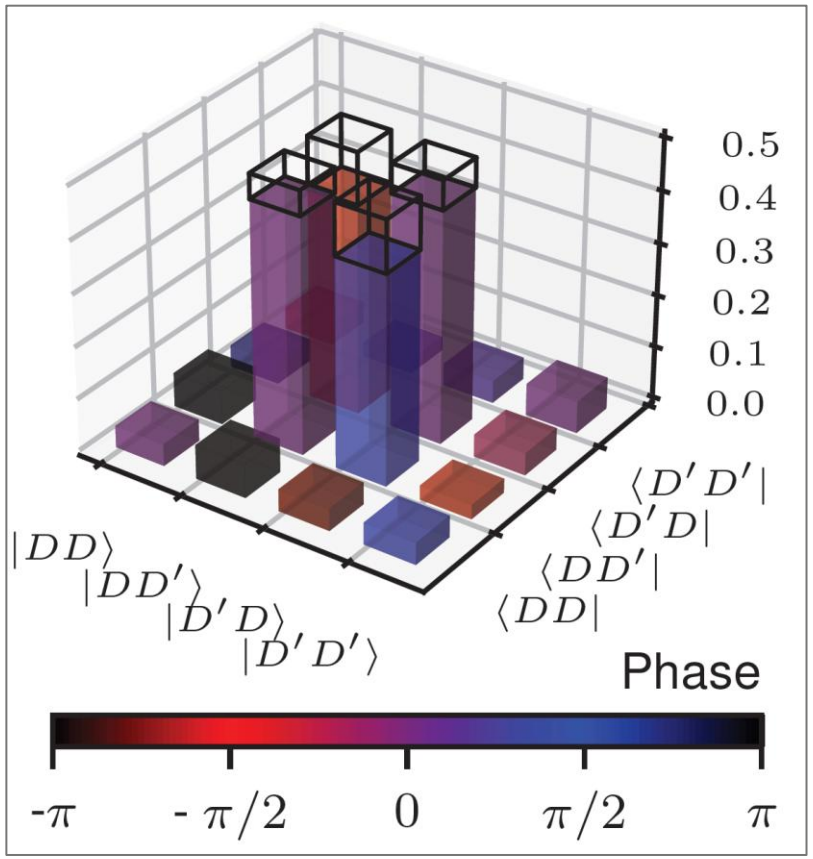
target state:
$|\psi^-\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$
fidelity with respect to target state:
$\langle\psi^-|\rho|\psi^-\rangle = 0.83 + 0.03 - 0.06$
classical bound: 0.5

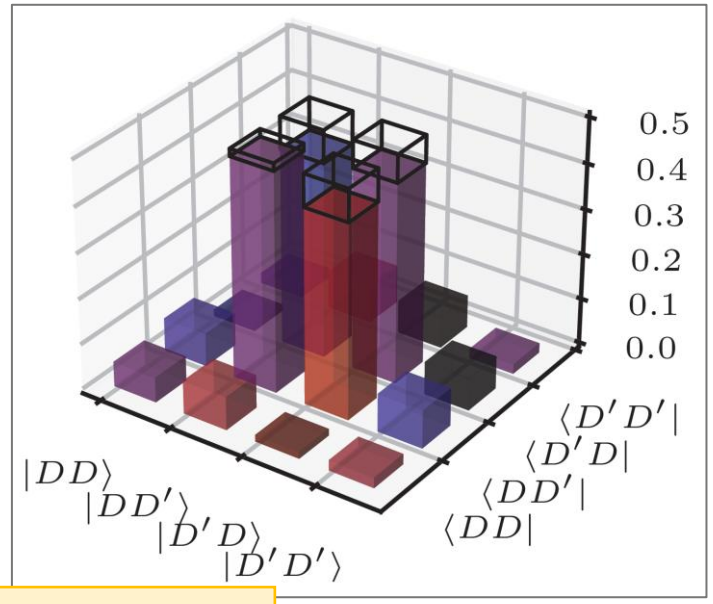
Quantum state tomography:
the two ions are measured in 3 x 3 bases,
which allows us to extract the joint density matrix,
from which entanglement measures are calculated.



V. Krutyanskiy, M. Galli et al., *Phys. Rev. Lett.* **130**, 050803 (2023)

Entanglement of trapped-ion qubits separated by 230 m



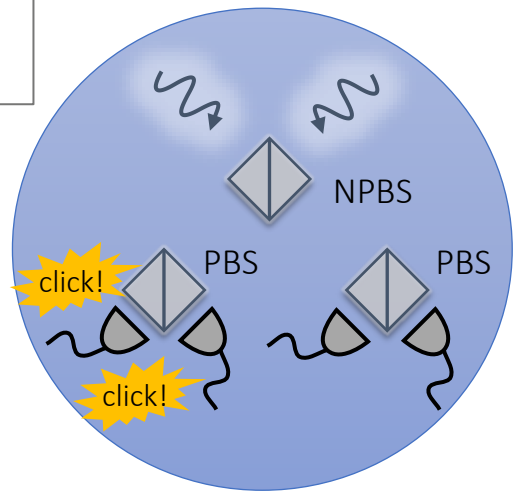


target state:

$|\psi^+\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

$\langle\psi^+|\rho|\psi^+\rangle =$

$0.88 + 0.02 - 0.05$

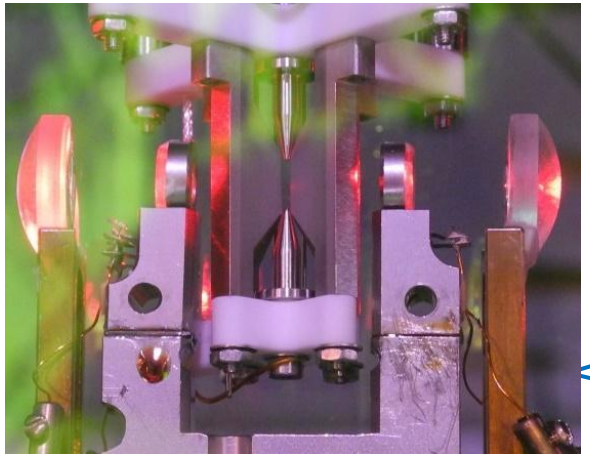


V. Krutyanskiy, M. Galli et al., *Phys. Rev. Lett.* **130**, 050803 (2023)

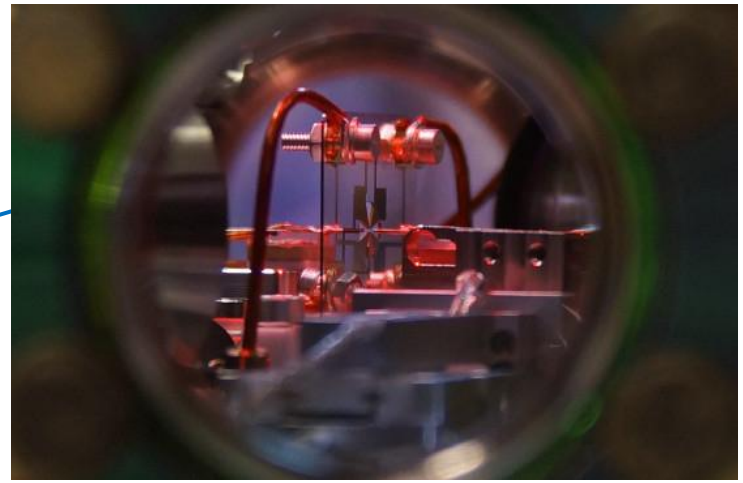
Quantum interfaces based on ions and photons

- What is a quantum internet, and why do we want one?
- Trapped ions for a future quantum internet
- Entanglement across the University of Innsbruck campus
- Prospects for scaling up

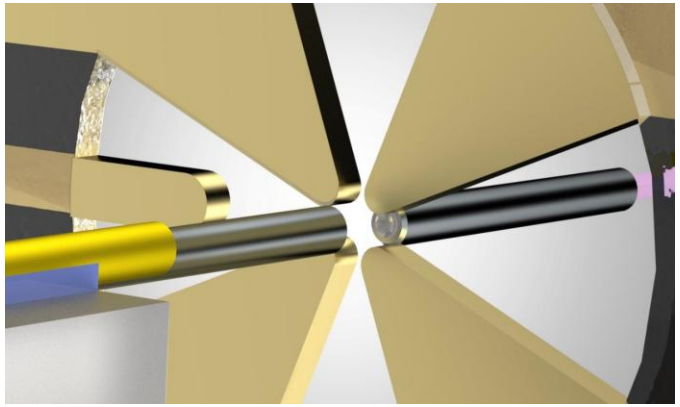
Towards a three-node network



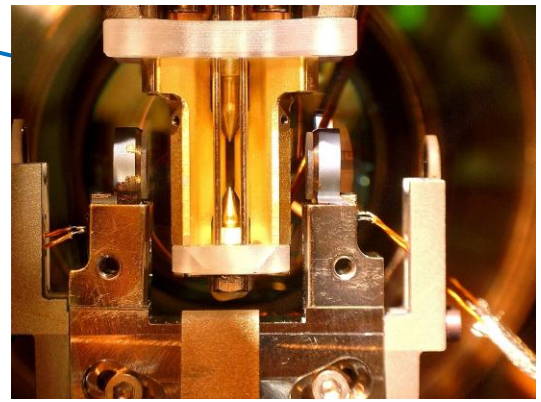
10 m



fiber-based ion-cavity system

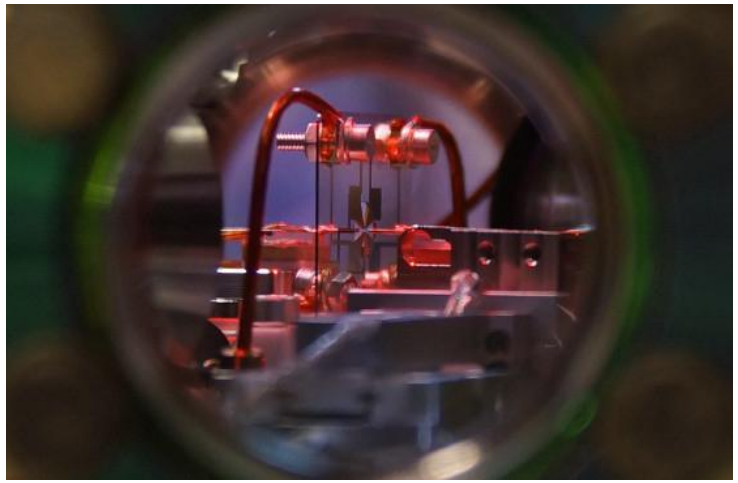


520 m

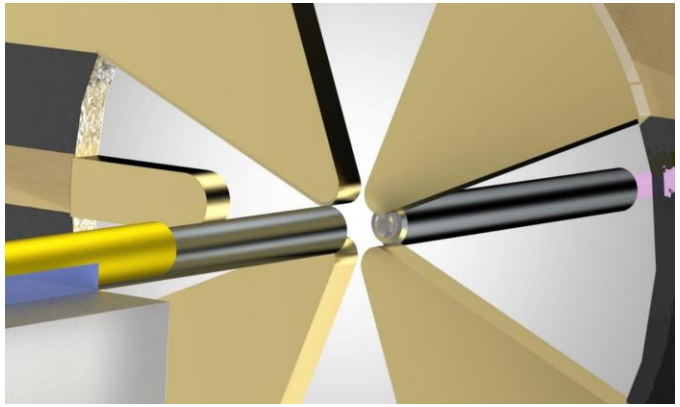


M. Teller et al., *Phys. Rev. Lett.* **126**, 230505 (2021)
M. Teller et al., *AVS Quantum Sci.* **5**, 012001 (2023)

Towards a three-node network

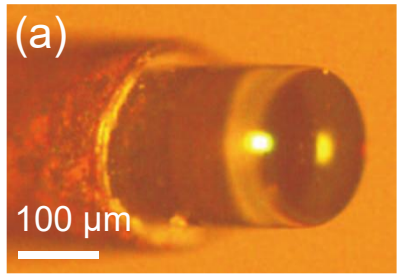


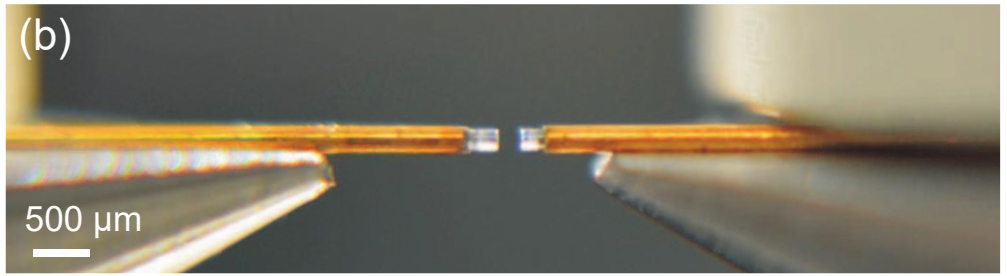
fiber-based ion-cavity system



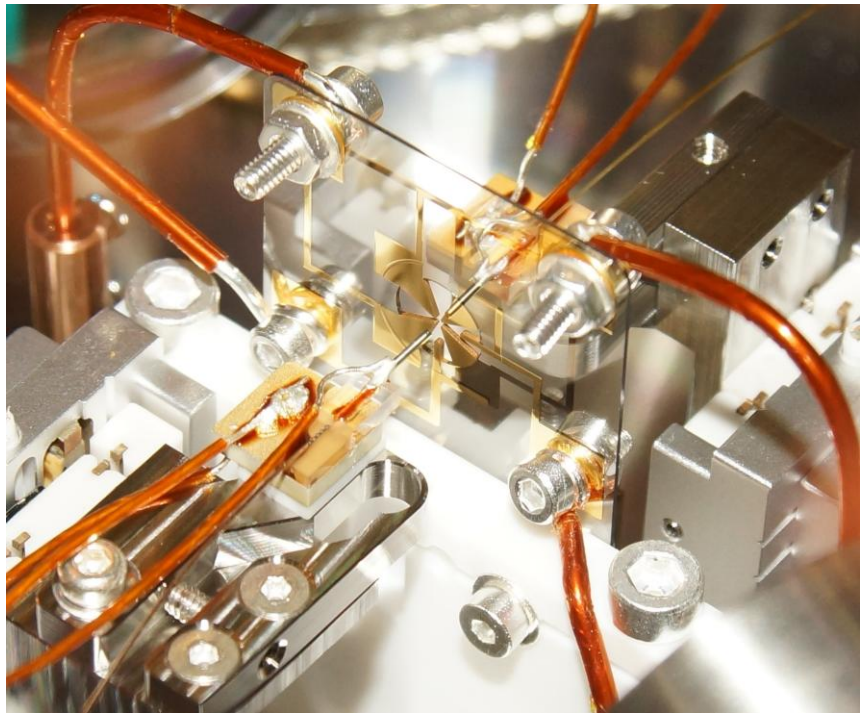
M. Teller et al., *Phys. Rev. Lett.* **126**, 230505 (2021)
M. Teller et al., *AVS Quantum Sci.* **5**, 012001 (2023)

Towards a three-node network

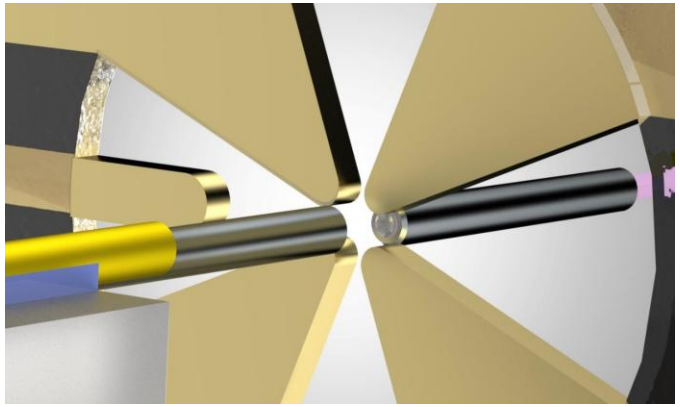




B. Brandstätter et al., *Rev. Sci. Inst.* **84**, 123104 (2013)



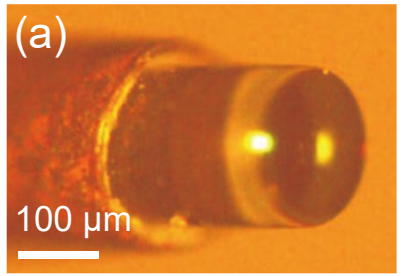
fiber-based ion-cavity system

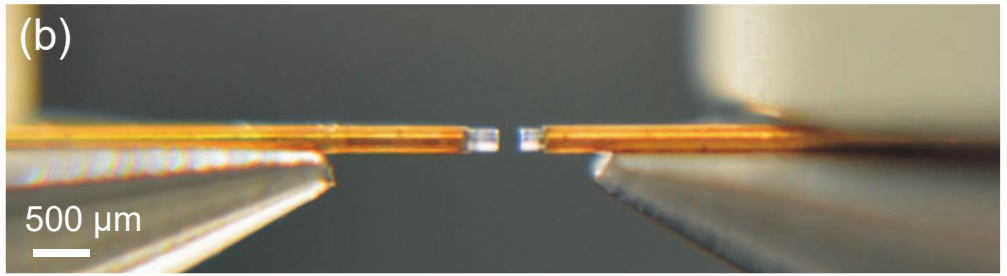


M. Teller et al., *Phys. Rev. Lett.* **126**, 230505 (2021)
M. Teller et al., *AVS Quantum Sci.* **5**, 012001 (2023)

- design based on NIST wheel trap
  J. S. Chen et al., *Phys Rev. Lett.* **118**, 053002 (2017)
- fiber mirrors inside endcap electrodes, fabricated in collaboration with Jakob Reichel's group (ENS, Paris)

Towards a three-node network

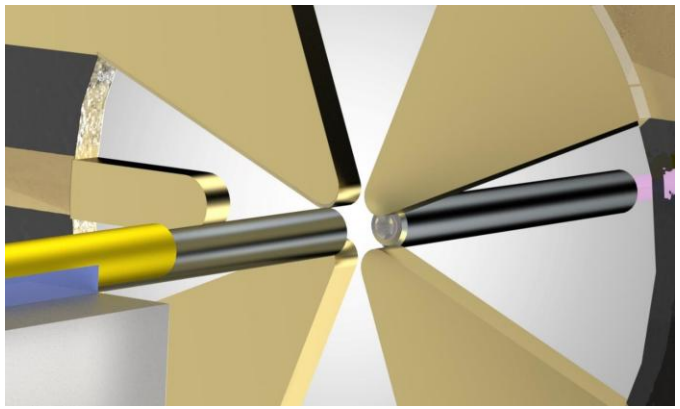




B. Brandstätter et al., *Rev. Sci. Inst.* **84**, 123104 (2013)

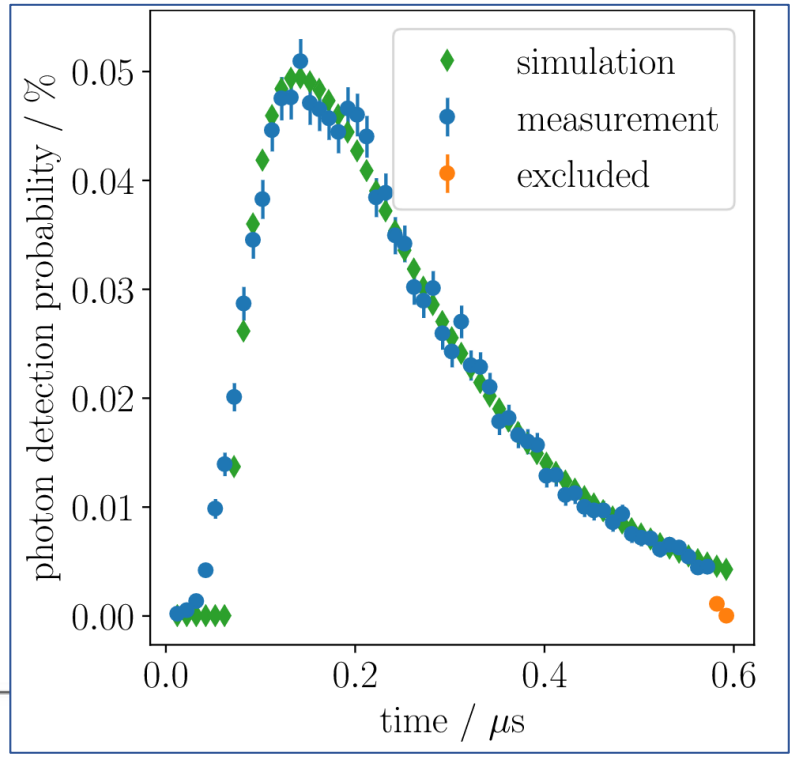
much shorter photons!

fiber-based ion-cavity system

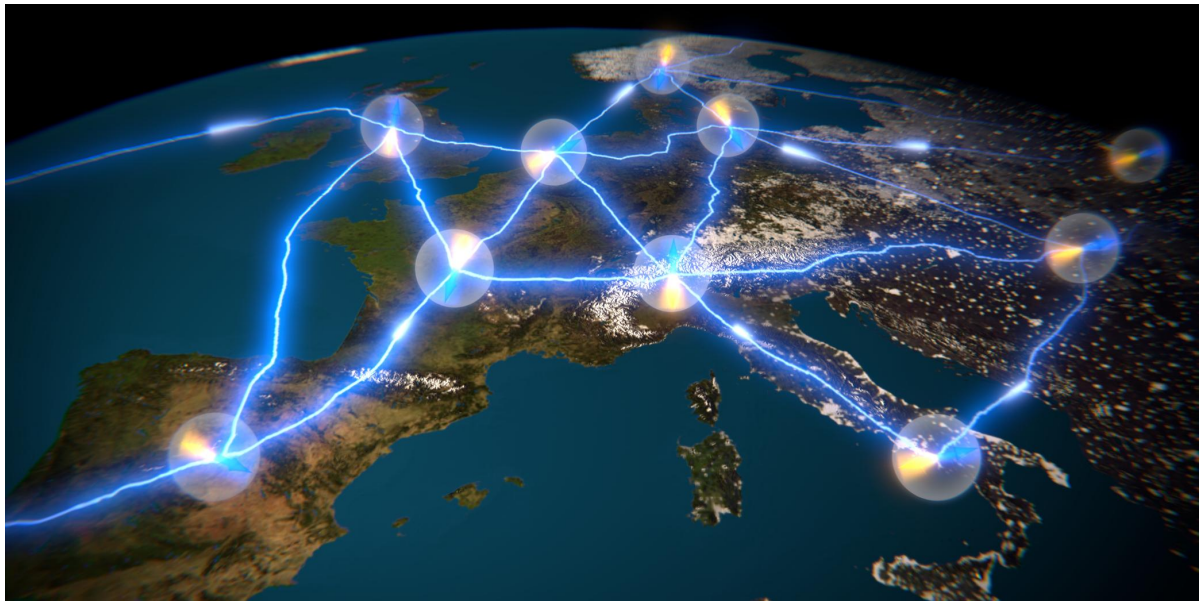


V. Messerer, PhD thesis, University of Innsbruck (2024)

M. Teller et al., *Phys. Rev. Lett.* **126**, 230505 (2021)
M. Teller et al., *AVS Quantum Sci.* **5**, 012001 (2023)



Towards a three-node network

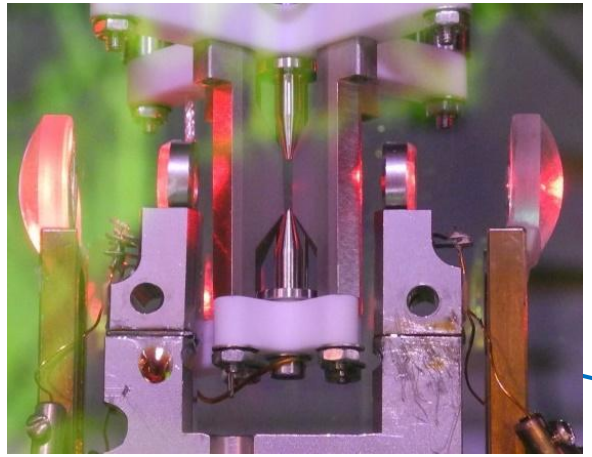


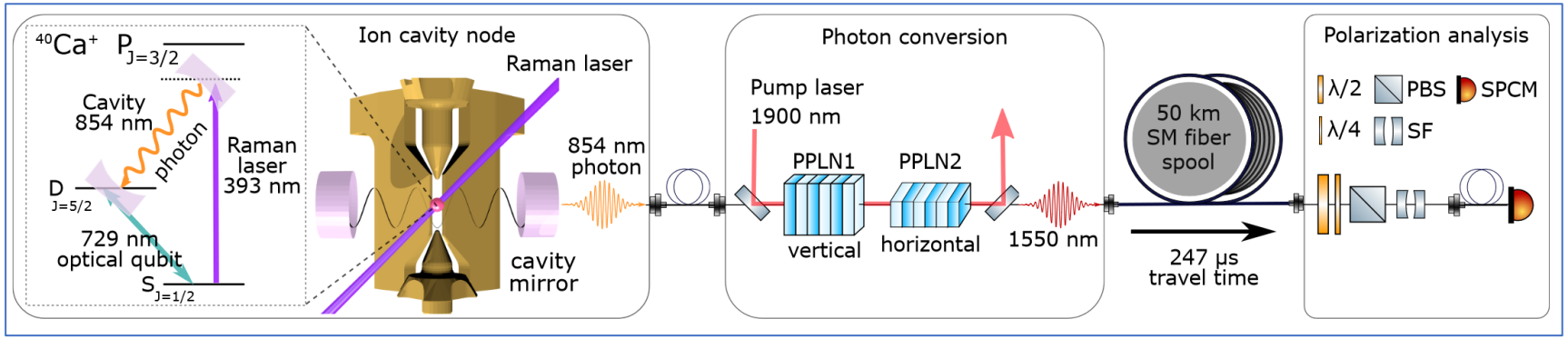
Does it make sense to keep adding nodes?

Only three experiments so far have demonstrated remote entanglement *faster than decoherence at each node.*

In order to build useful quantum networks, we need not only to increase the *number* of nodes but also *entanglement rates* and *coherence times.*

Quantum frequency conversion for long-distance networks



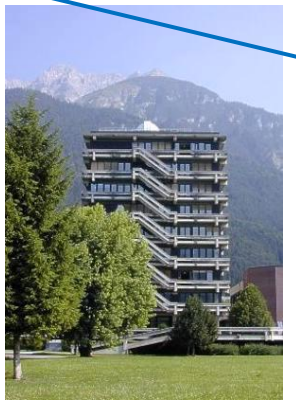


V. Krutyanskiy et al., *npj Quantum Inf.* **5**, 72 (2019)
V. Krutyanskiy et al., *Phys. Rev. Lett.* **130**, 213601 (2023)

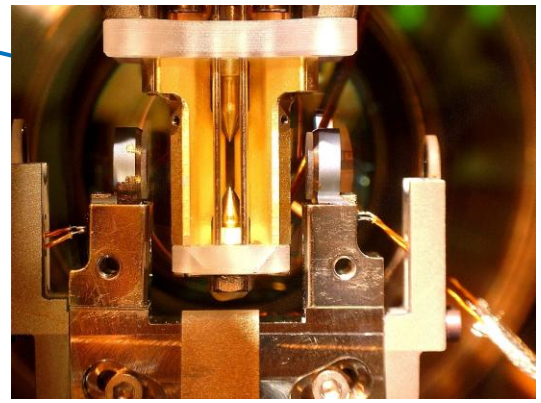
University of Innsbruck (Northup)

universität innsbruck

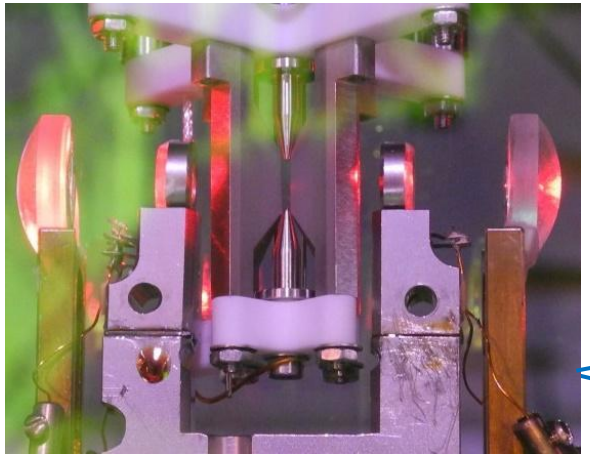
50 km,
using fiber spools



University of Innsbruck (Lanyon)



Quantum frequency conversion: a route to hybrid networks



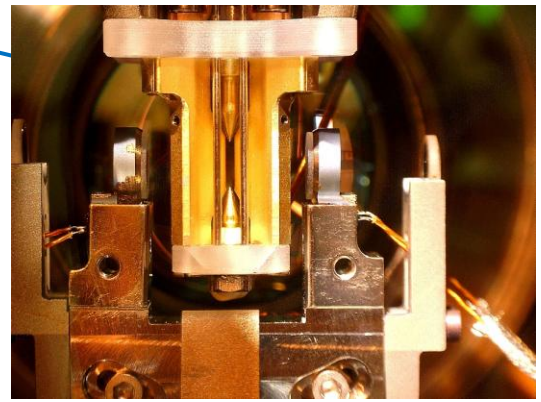
your favorite network node

University of Innsbruck
(Northup)

universität innsbruck

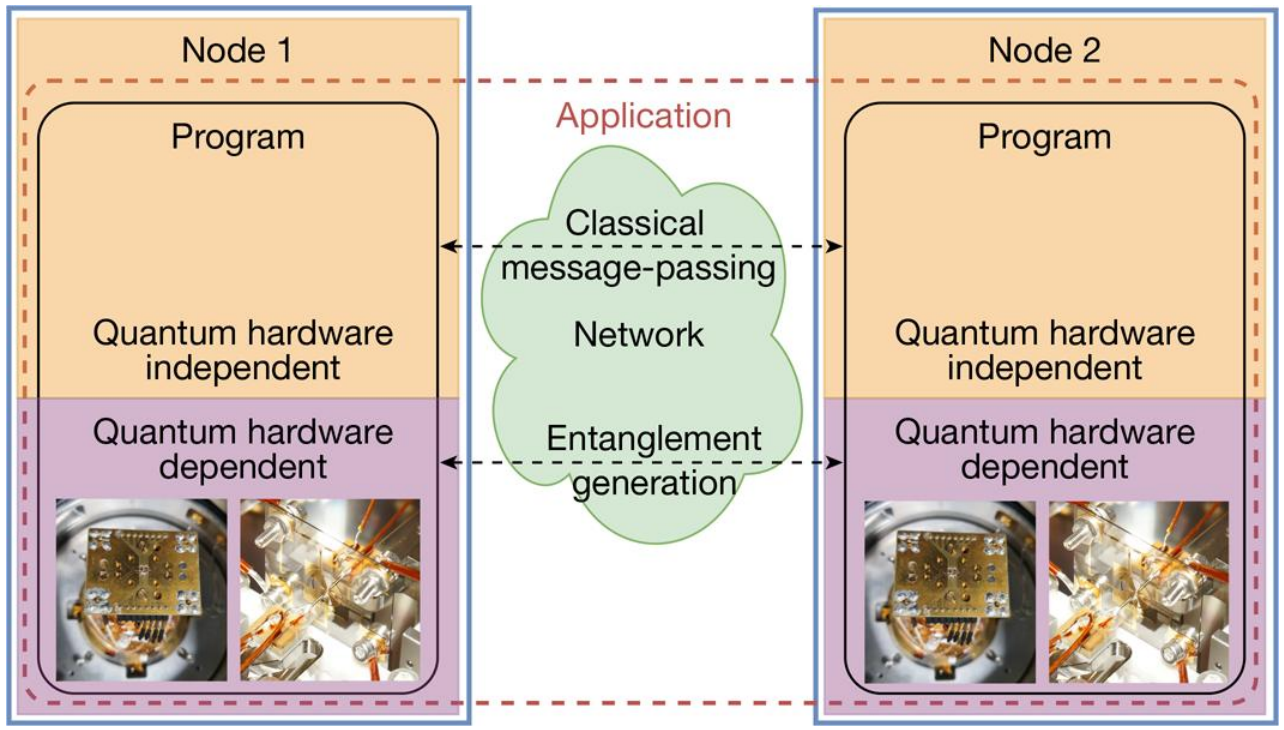
50 km,
using fiber spools

University of Innsbruck
(Lanyon)



Quantum networks: a full-stack approach, not only the hardware!

C. Delle Donne et al., *Nature* **639**, 321 (2025)

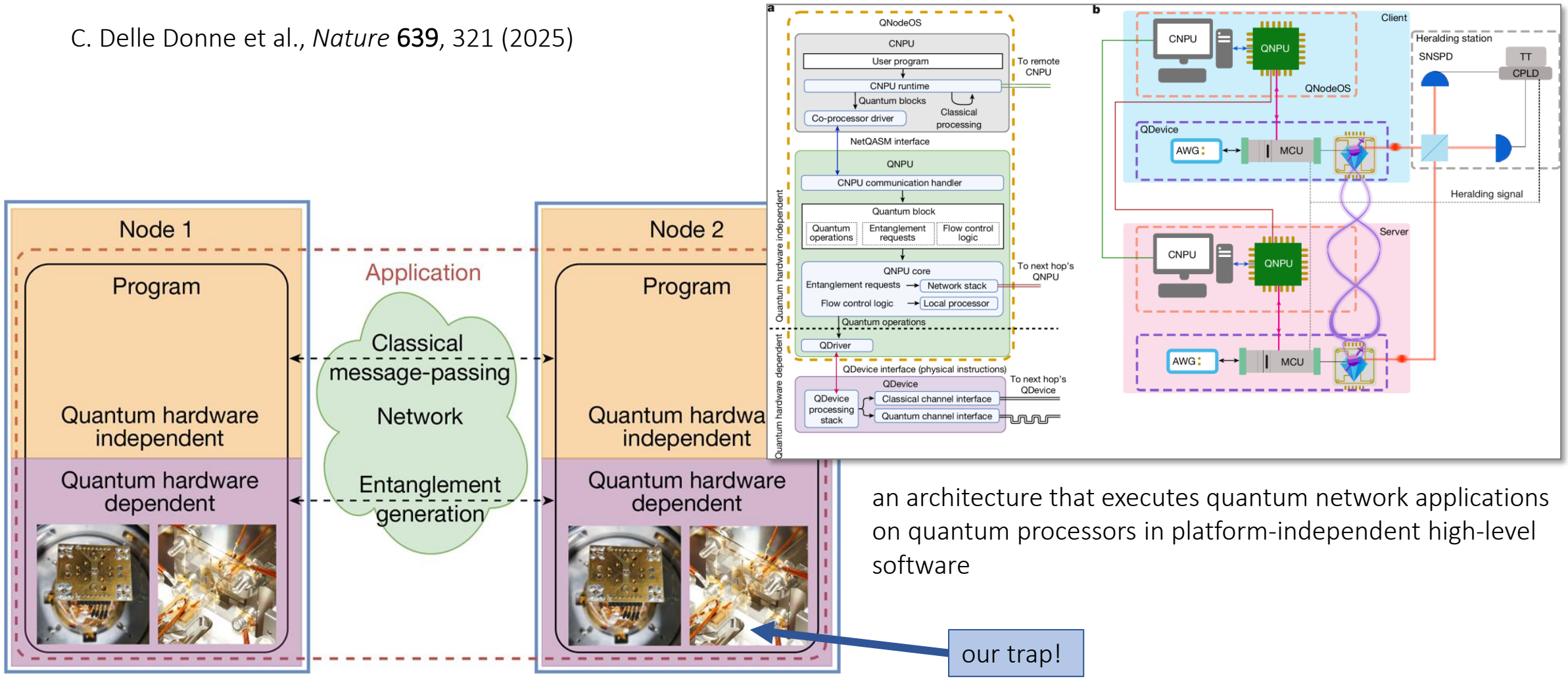


TU Delft: Stephanie Wehner, Mariagrazia Iuliano, Carlo Delle Donne and Bart van der Vecht

…along with collaborators from UIBK, INRIA, CNRS, and QuTech

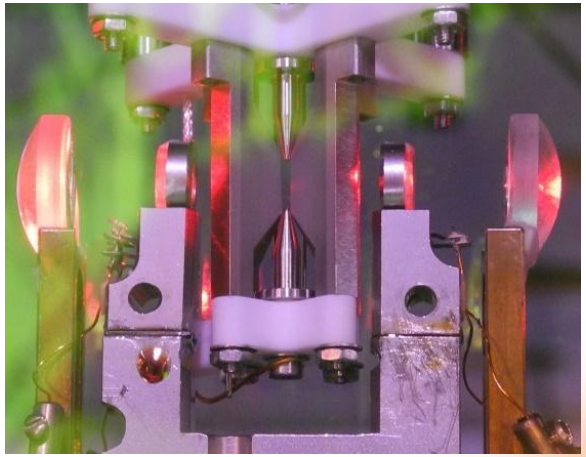
The first operating system for quantum networks

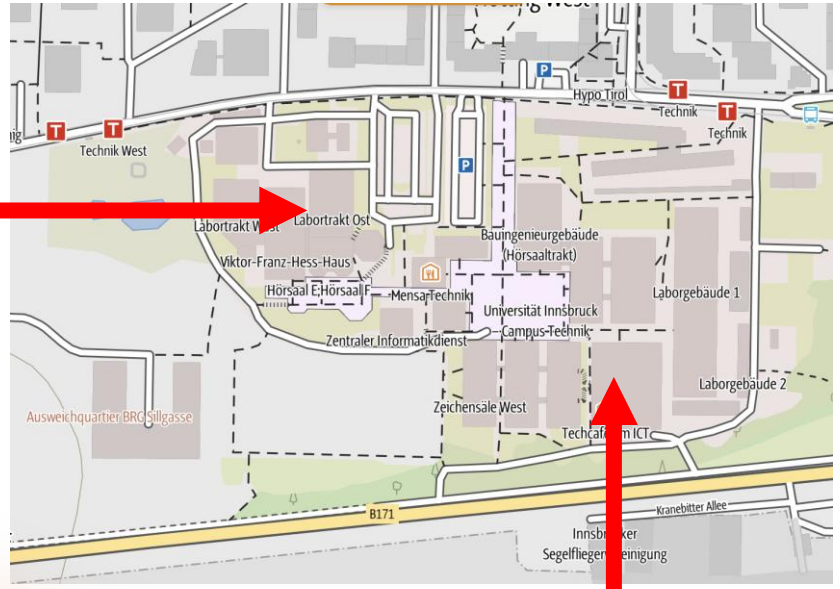
C. Delle Donne et al., *Nature* **639**, 321 (2025)

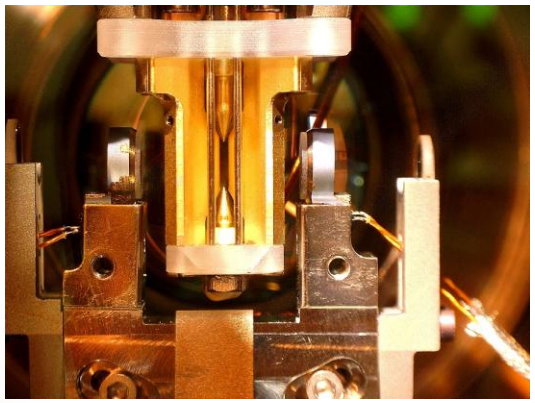


an architecture that executes quantum network applications on quantum processors in platform-independent high-level software

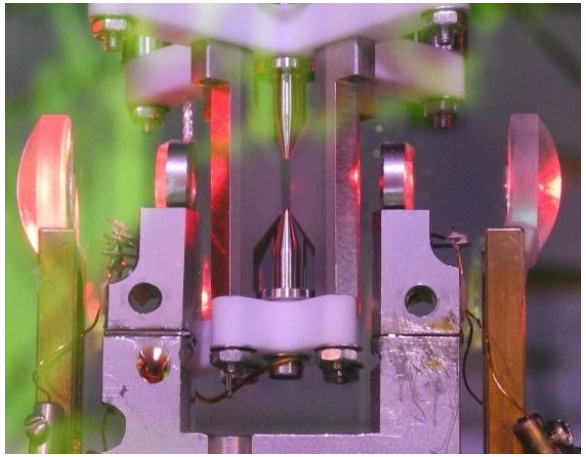
our trap!



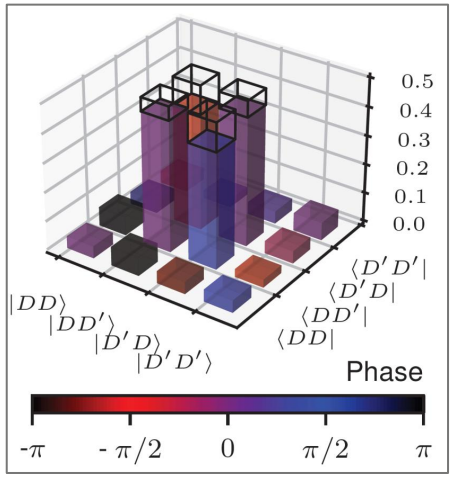

Technik West
Hypo Tirol
Technik
Technik
Laborgebäude 1
Laborgebäude 2
B171



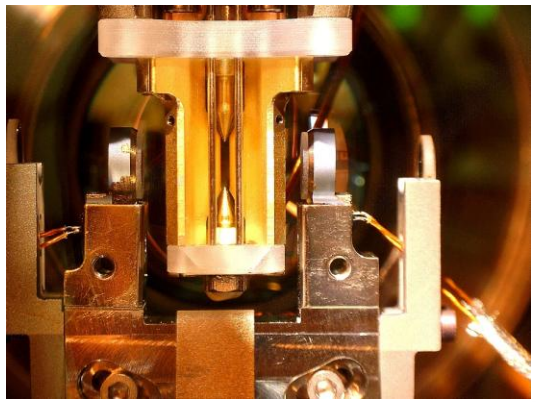
entangled!



- Ion-photon entanglement is a building block for entangling ions over long distances.
- Cavities offer us efficient collection and control over coherent dynamics in quantum interfaces.
- Detection of two photons heralds remote ion-ion entanglement, characterized via state tomography.



- A future quantum internet will require faster entanglement, longer coherence times, and more complex network structures.



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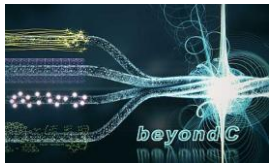
Pavel Sekatski

U.S. DEPARTMENT OF ENERGY | Office of Science

FFG Forschung wirkt.

FWF Der Wissenschaftsfonds.

QIA QUANTUM INTERNET ALLIANCE



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CAESAREO