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Optical cavities and trapped ions: building blocks for quantum networks

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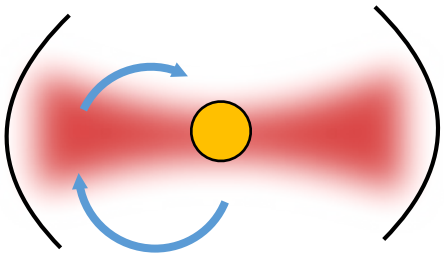
Zeiss Symposium 2018: Optics in the Quantum World

What roles does optics play in quantum technology?

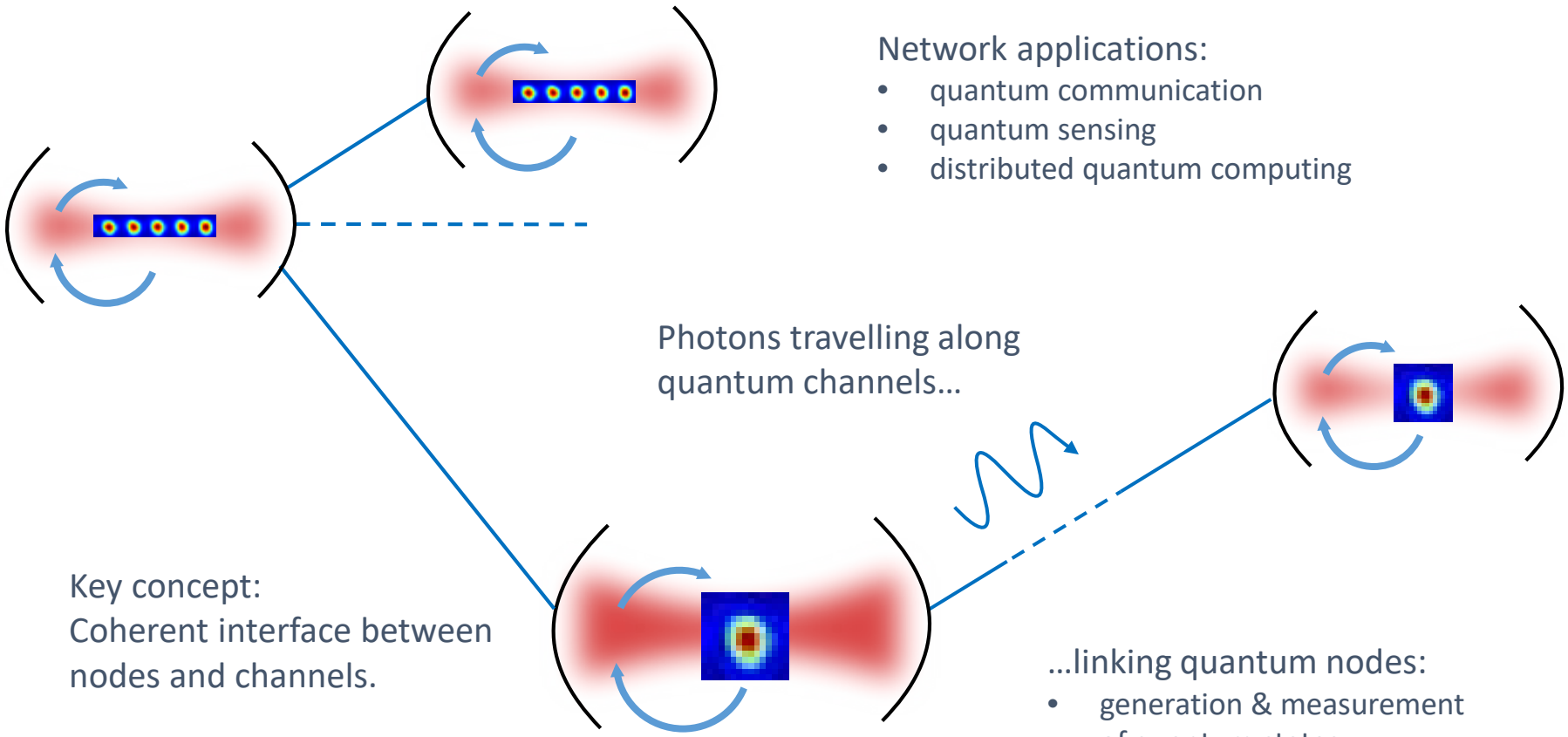
- Quantum light fields for computing, communication & simulation
- Classical light fields for manipulation & measurement of matter-based qubits

Here, optical cavities as an interface between quantum light and quantum matter.



Ingredients for a quantum network

H. J. Kimble, Nature 453, 1023 (2008)



Network applications:

- quantum communication
- quantum sensing
- distributed quantum computing

Key concept:
Coherent interface between nodes and channels.

…linking quantum nodes:

- generation & measurement of quantum states
- quantum memories
- quantum computers

» Trapped-ion qubits for quantum information science

» Optical cavities as building blocks for quantum networks

Entangling ions and photons

Transferring quantum states between ions and photons

» Outlook: applications for ion-based networks

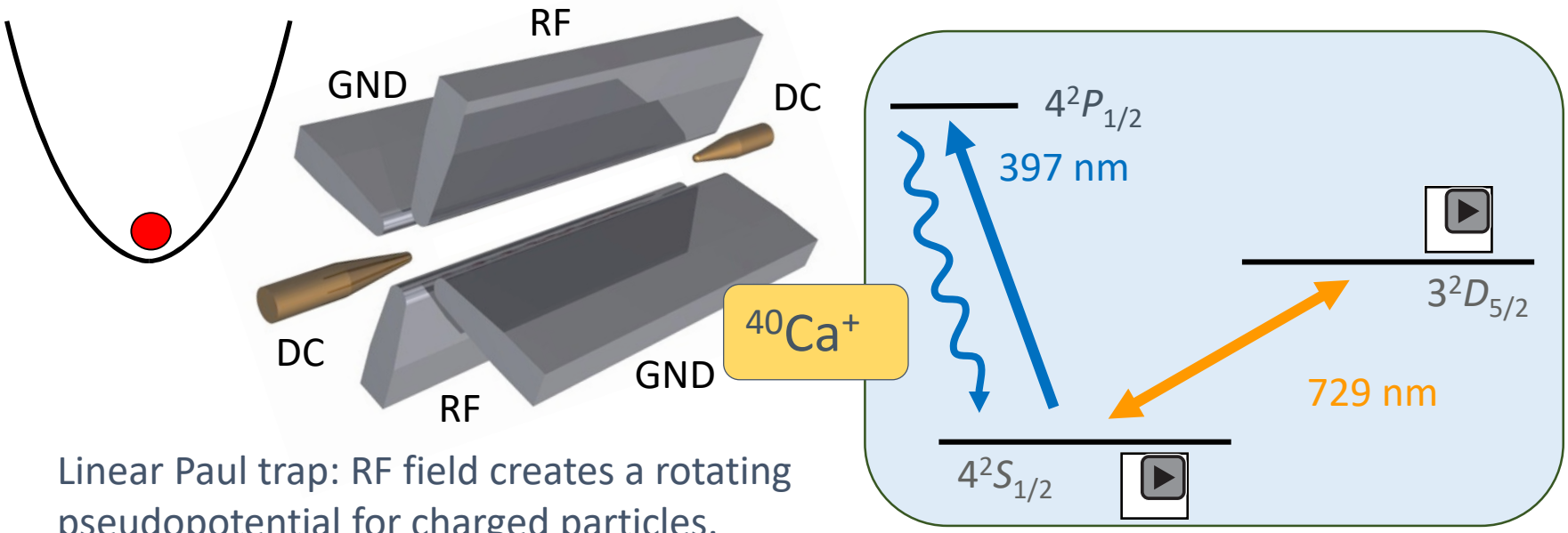
Trapped ions as quantum bits

Ions: a highly controllable two-level system.

» Coherence can be preserved for long times in hyperfine and optical qubits

» Deterministic, high-fidelity, coherent manipulation of both individual qubits and gate operations between qubits

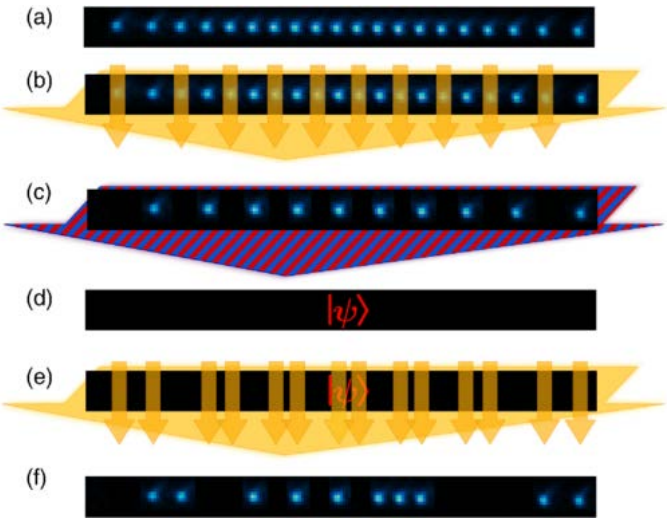
» High-fidelity state readout via electron shelving



Linear Paul trap: RF field creates a rotating pseudopotential for charged particles.

A platform for quantum computing and metrology

Two examples of the state of the art:



1. Multi-partite entanglement in a register of 20 qubits

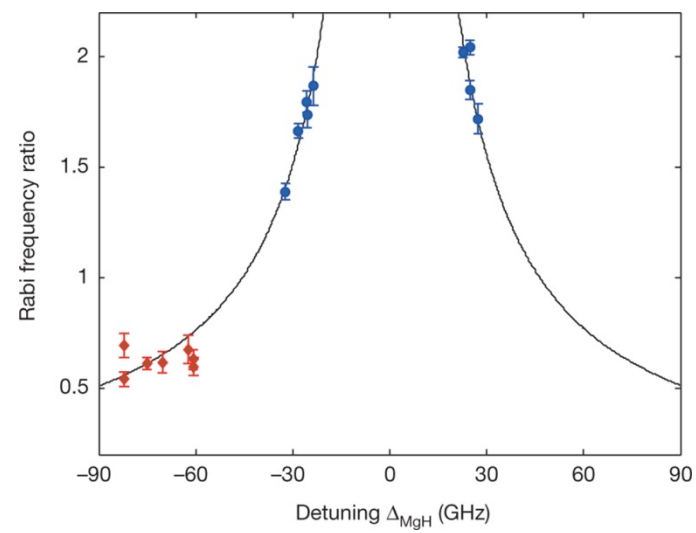
N. Friis, O. Marty, C. Maier, C. Hempel, M. Holzäpfel, P. Jurcevic, M. B. Plenio, M. Huber, C. Roos, R. Blatt, and B. Lanyon, Phys. Rev. X **8**, 021012 (2018)

- Entanglement characterized for neighboring groups of qubits
- Each qubit individually controlled & qubit-qubit interactions turned on and off

2. Spectroscopy of molecular ions via quantum logic

F. Wolf, Y. Wan, J. C. Heip, F. Gebert, C. Shi, P. O. Schmidt, Nature **530**, 457 (2016)

- Quantum state of molecular ion measured via its coupling to an atomic ion



ions as sensors: talk today by J. Hecker Denschlag

» Trapped-ion qubits for quantum information science

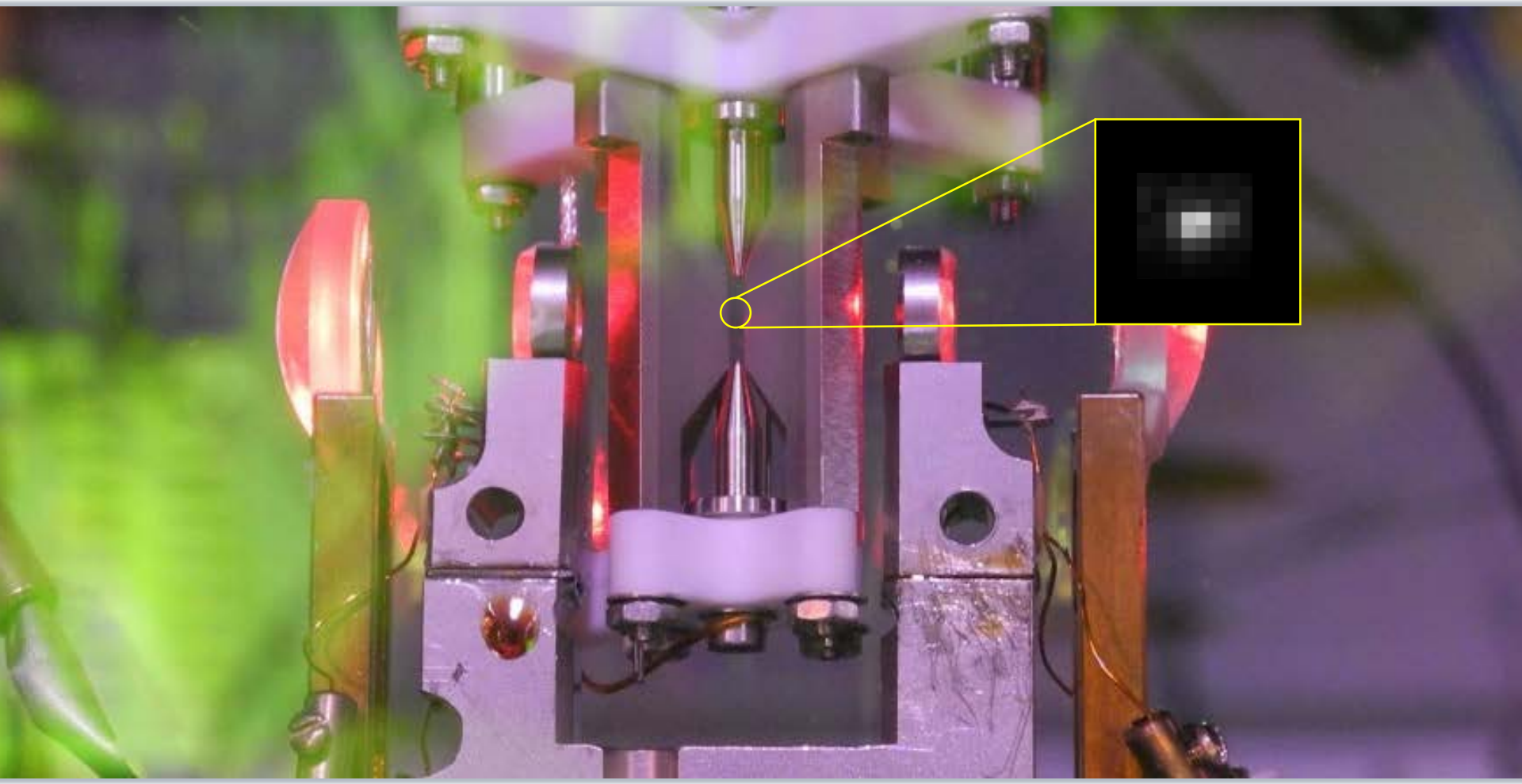
» Optical cavities as building blocks for quantum networks

Entangling ions and photons

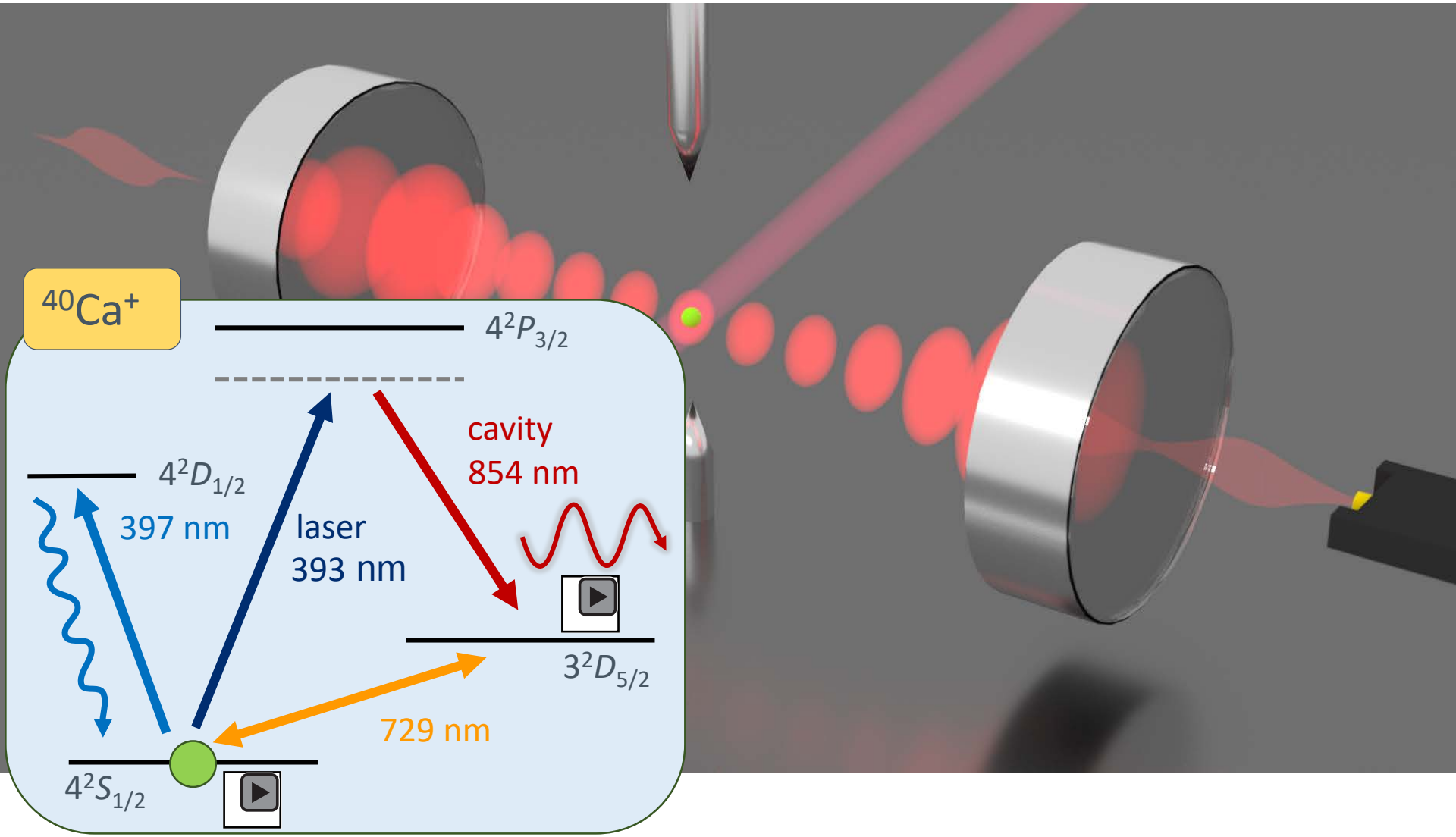
Transferring quantum states between ions and photons

» Outlook: applications for ion-based networks

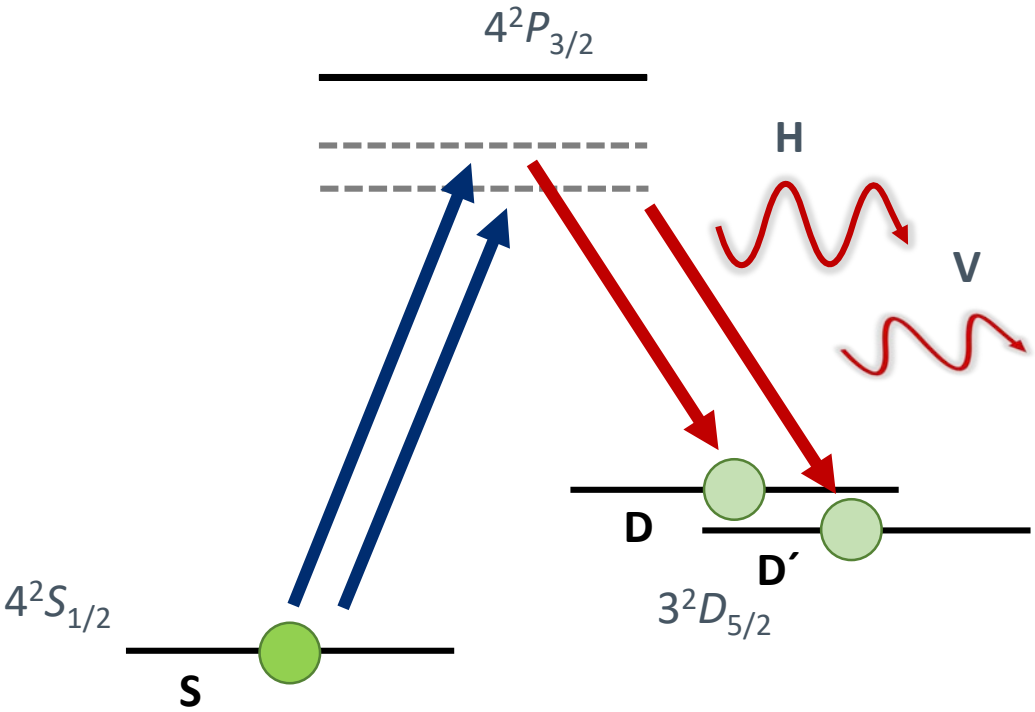
An ion trap integrated with an optical cavity



A Raman process generates single cavity photons



Entangled ions and photons: a network resource



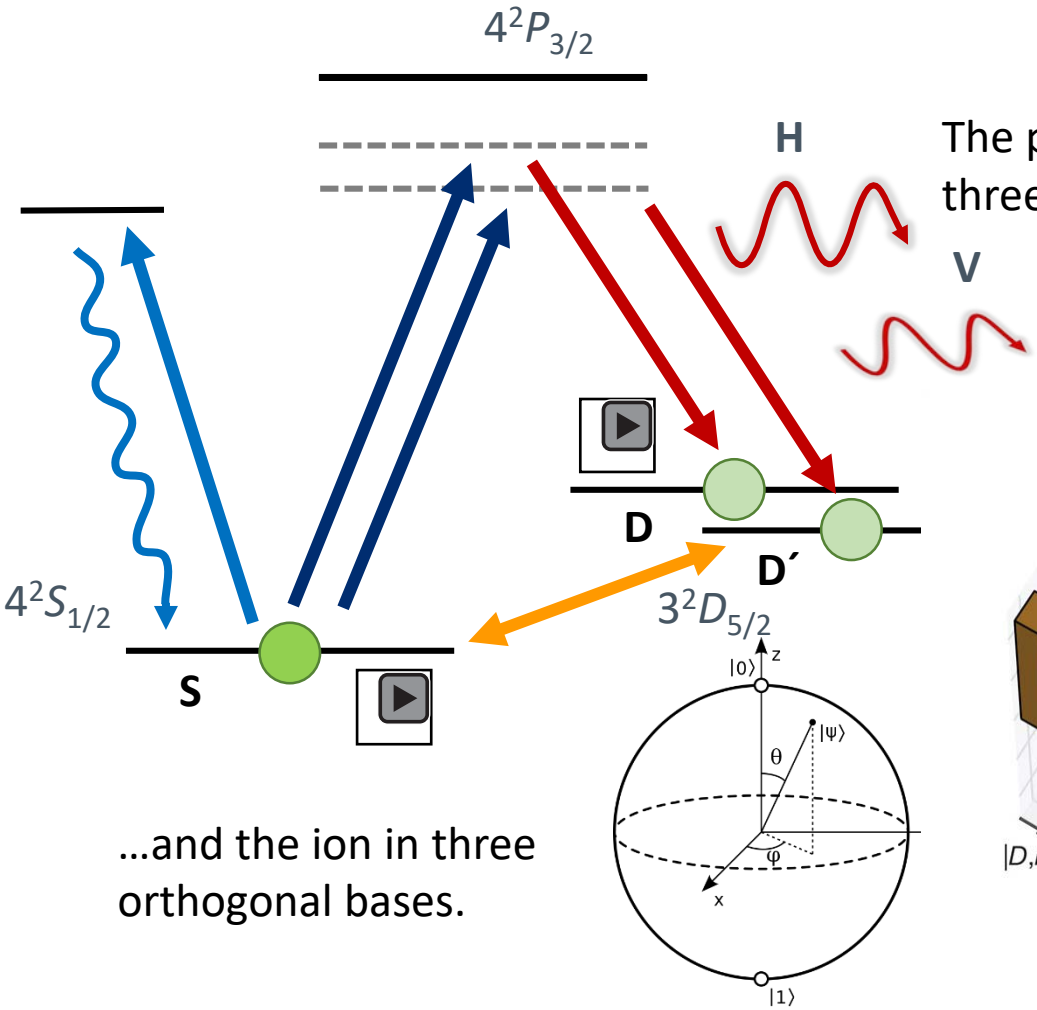
A **bichromatic** Raman field generates entanglement.

S → DH
S → D´V

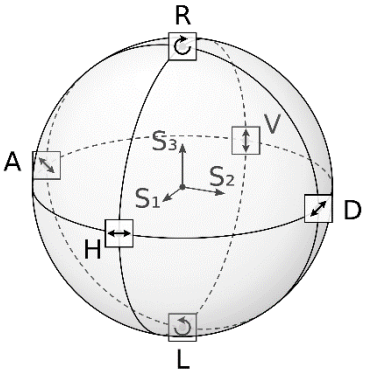
S → DH + D´V

…the ion and photon are maximally entangled.

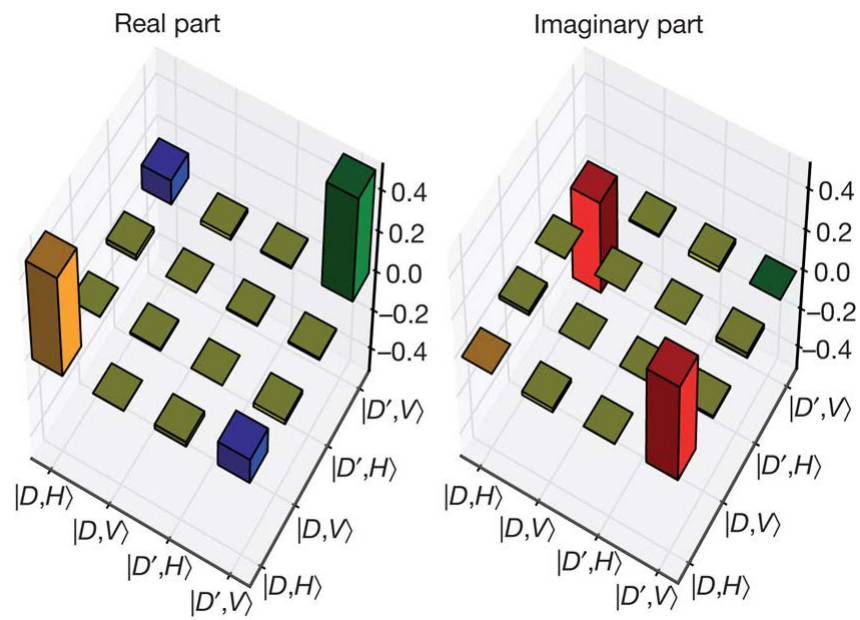
Entangled ions and photons: a network resource



The photon is measured in three orthogonal bases…



…and the ion in three orthogonal bases.



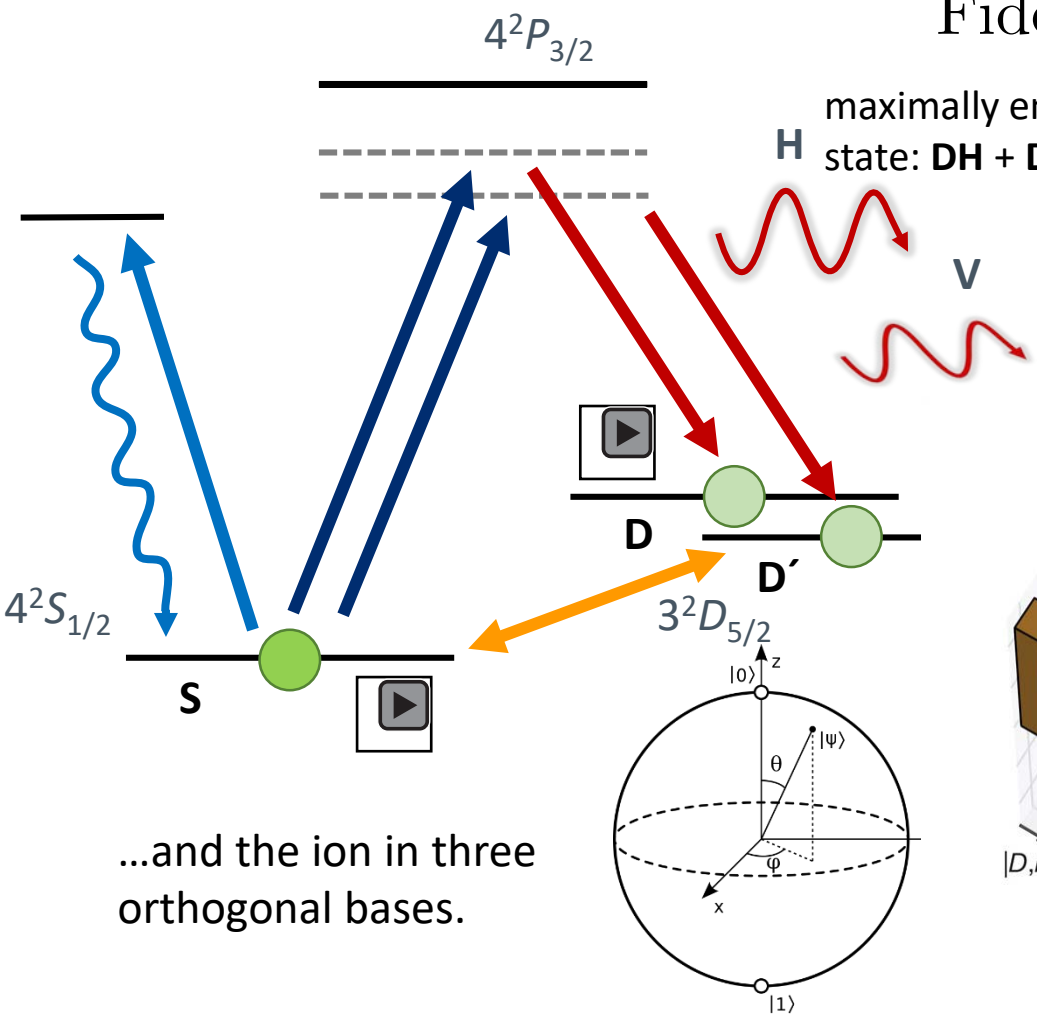
A. Stute et al., Nature 485, 482 (2012)

Entangled ions and photons: a network resource

$$\text{Fidelity} \equiv \langle\psi|\rho|\psi\rangle = 97.4(2)\%$$

classical bound: 50%

maximally entangled state: **DH + D´V**



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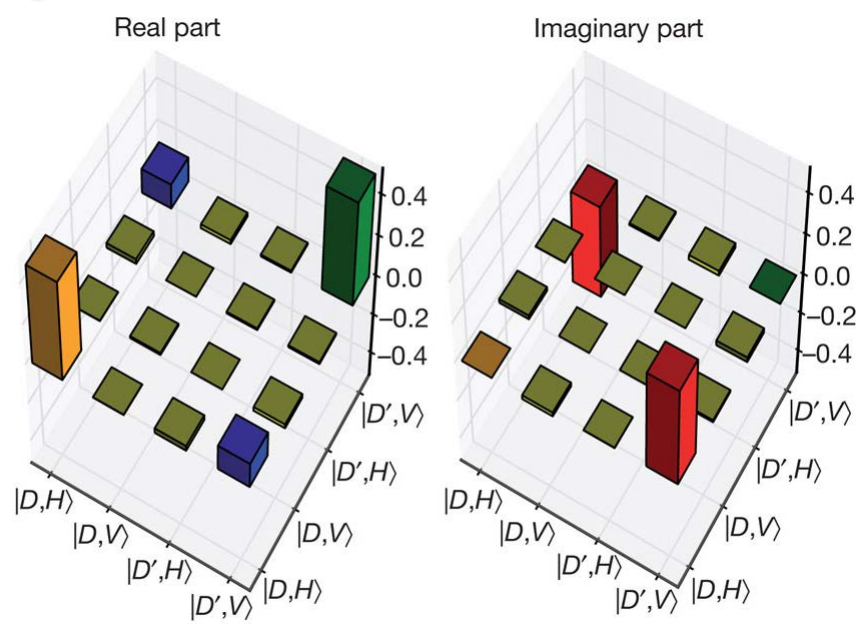
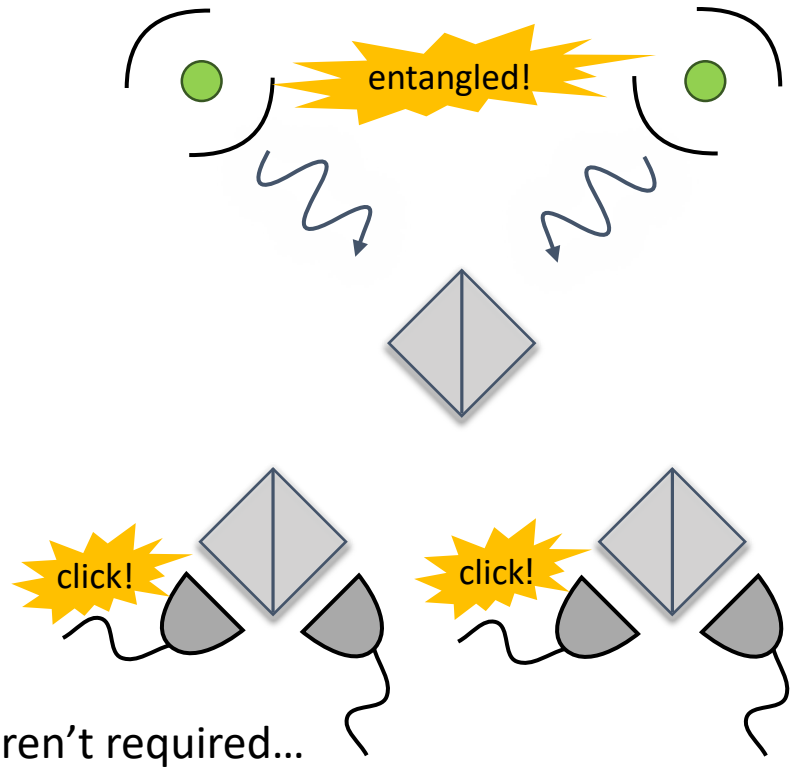


A. Stute et al., Nature 485, 482 (2012)

Ion-photon entanglement enables remote entanglement



Cavities aren't required…

- ions in separate traps
  D. L. Moehring et al., Nature 449, 68 (2007)
- atomic ensembles, neutral atoms, NV centers, quantum dots, ...

...but they are a **means to achieve efficient collection**.

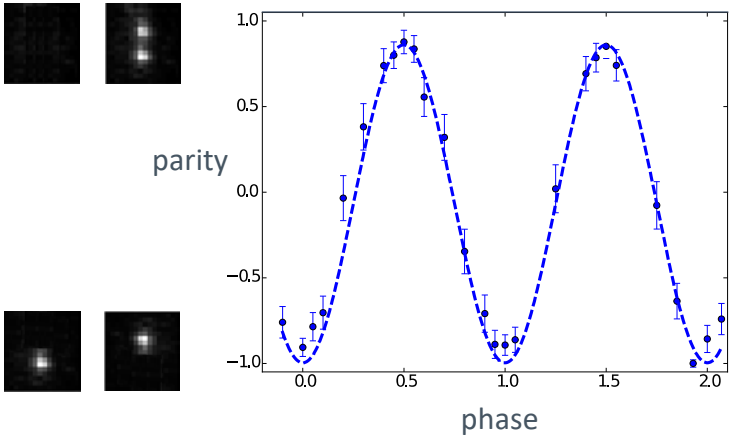
A similar protocol entangles ions in the same cavity

L.-M. Duan, H. J. Kimble, Phys. Rev. Lett. 90, 253601 (2003)

ion 1: **DH** + **D´V**
ion 2: **DH** + **D´V**

→ detect **H** & **V**

→ **DD´** + **D´D**



We prepare ion–ion entanglement with fidelity **≥ (91.9 ± 2.5)%** with respect to a maximally entangled state.

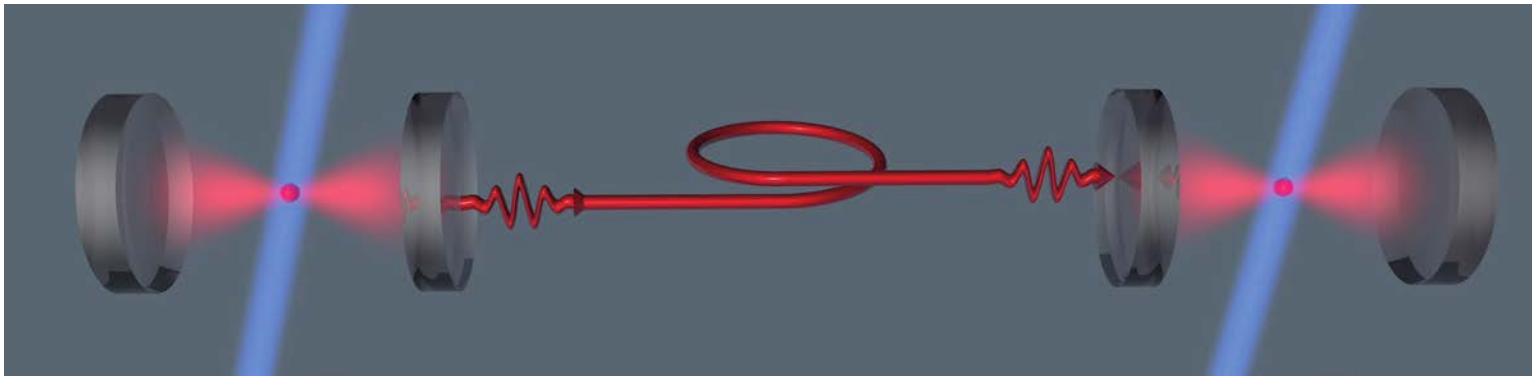
Outlook: cavity-based methods as a route to efficient remote entanglement & teleportation-based networks.

B. Casabone et al., Phys. Rev. Lett. 111, 100505 (2013)

An alternative to teleporation: quantum state transfer

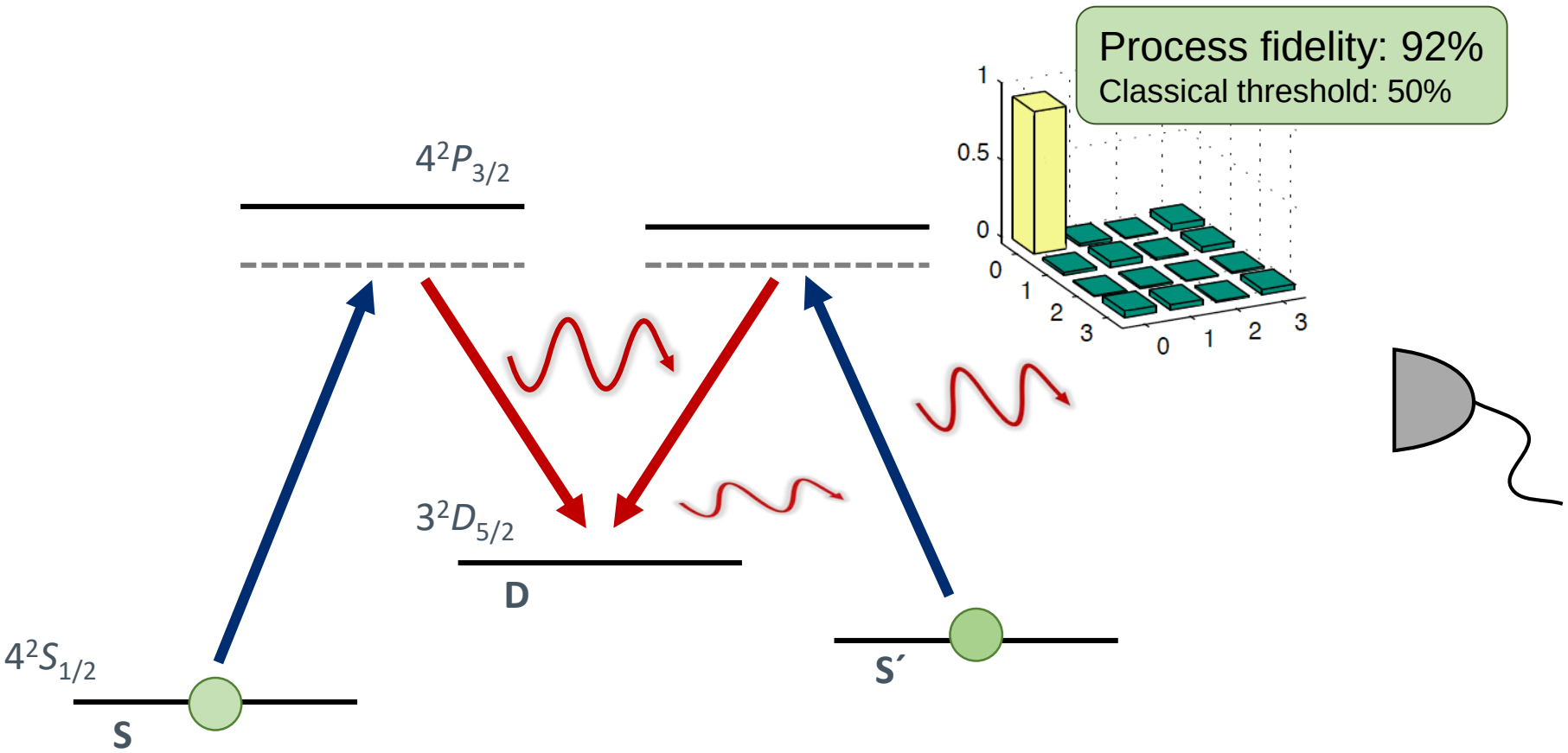
J. I. Cirac, P. Zoller, H. J. Kimble, H. Mabuchi, Phys. Rev. Lett. 78, 3221 (1997)

neutral atoms:
S. Ritter et al., Nature 484, 195 (2012)



TN & R. Blatt, Nature Photon. 8, 256 (2014)

A bichromatic Raman process maps the quantum state

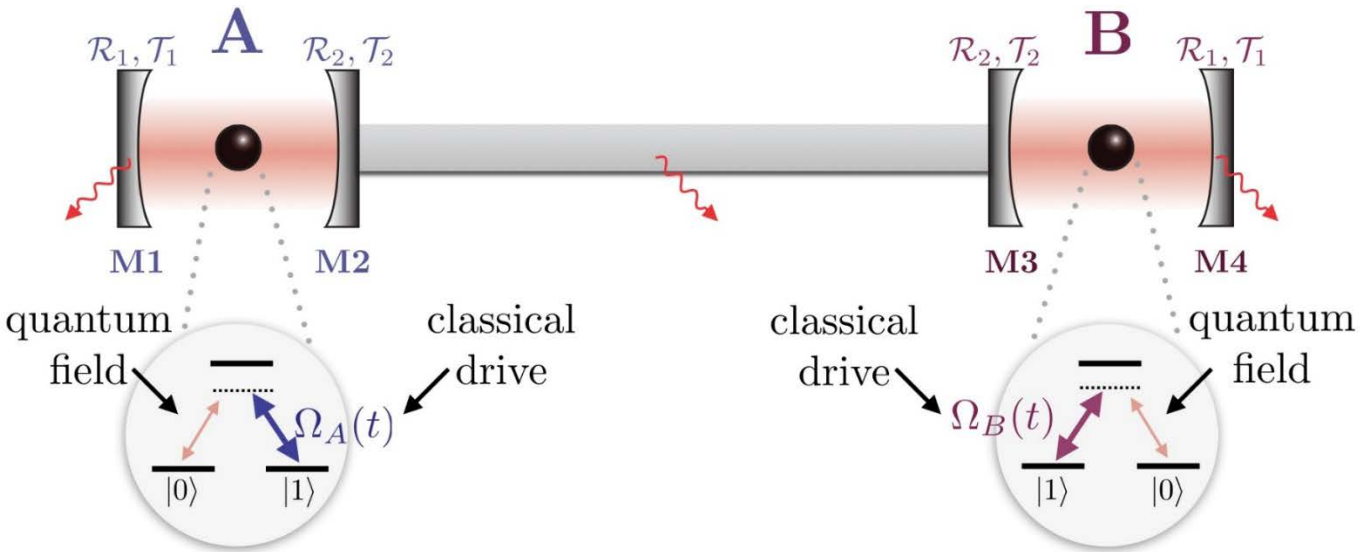


S → horizontally polarized photon
S´ → vertically polarized photon
a**S** + b**S´** → a**H** + b**V**

A. Stute et al., Nat. Photon. 7, 219 (2013)

Addressing decoherence in state-transfer networks

Can we build networks based on direct state transfer along photonic channels?



A significant loss mechanism for current experiments:
scattering and absorption losses in the cavity.

We compare two methods for state transfer;
one method allows us to suppress these losses.

B. Vogell et al., Quantum Sci. Technol. 2, 045003 (2017)

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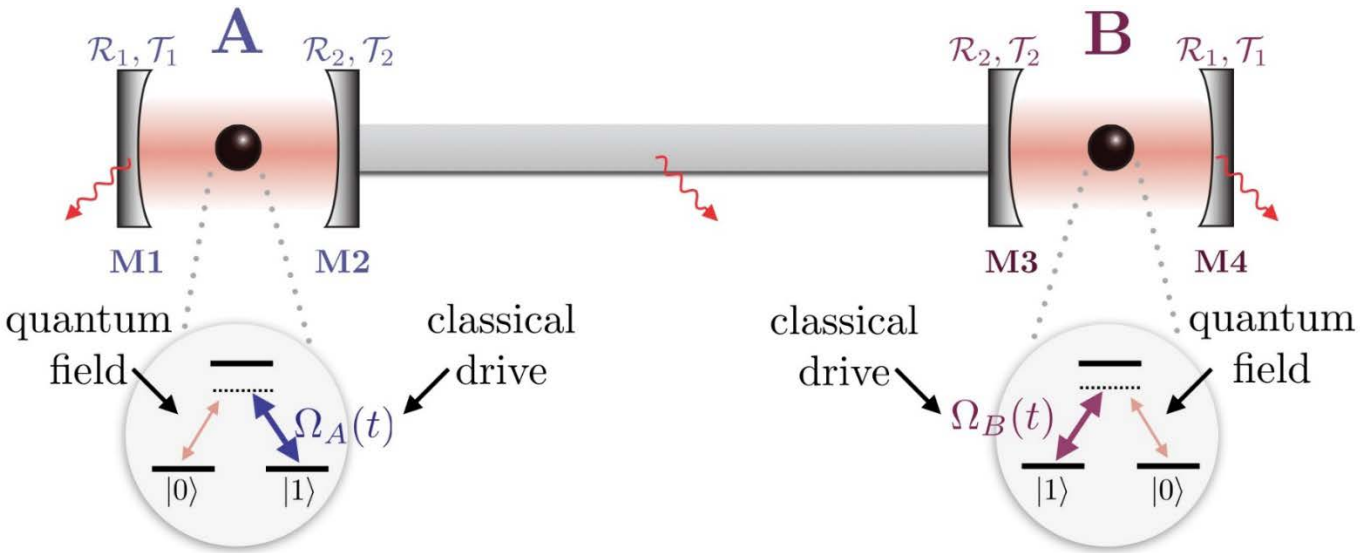
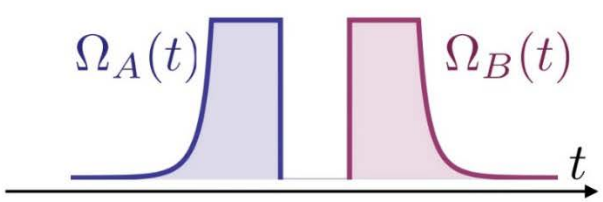


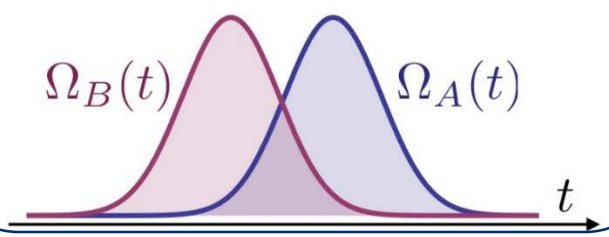
#1 J. I. Cirac, P. Zoller, H. J. Kimble, H. Mabuchi, Phys. Rev. Lett. 78, (1997)

classical drive for wave packet shaping



#2 T. Pellizzari, Phys. Rev. Lett. 79, 5242 (1997)

classical drive for adiabatic passage



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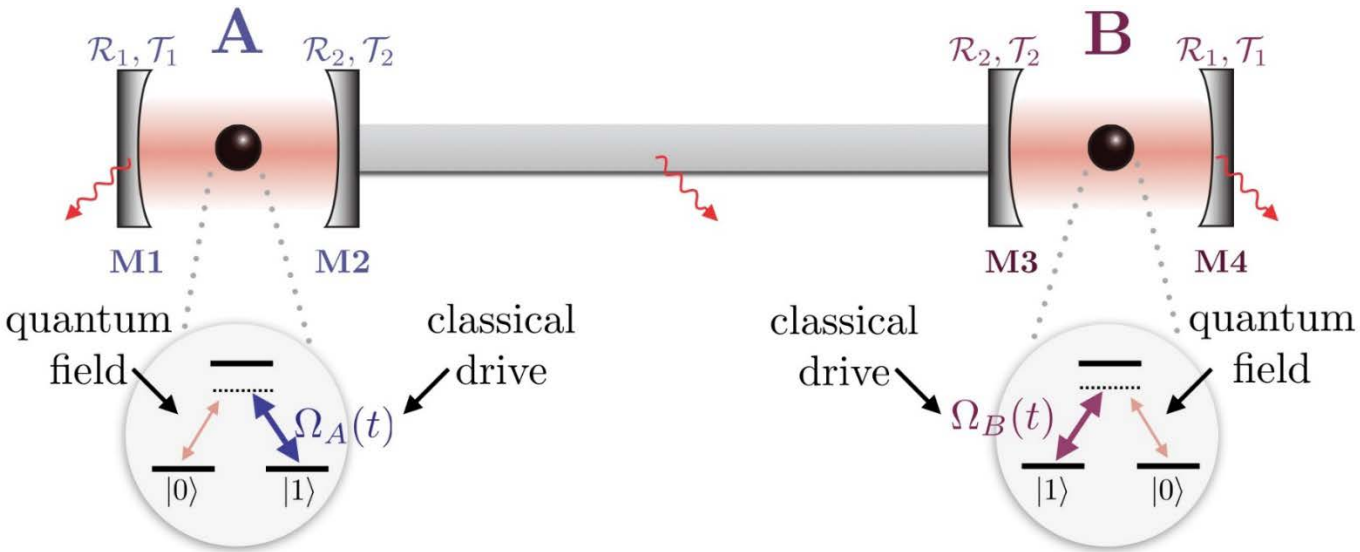

The key idea:
Cavity losses are analogous to spontaneous emission in STIRAP and can be suppressed.

(Channel losses, on the other hand, can't be suppressed.)

B. Vogell et al., Quantum Sci. Technol. 2, 045003 (2017)

» Trapped-ion qubits for quantum information science

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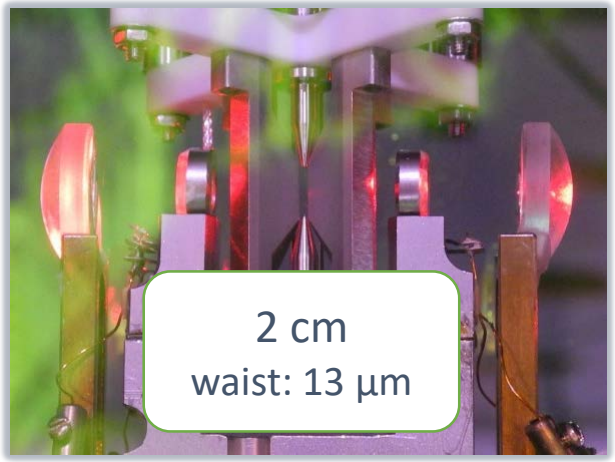
» Outlook: applications for ion-based networks

Scaling up cavity-based interfaces

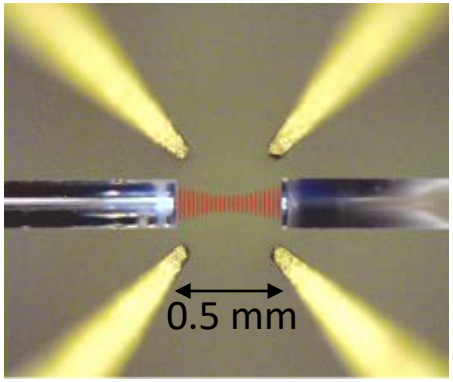
» Smaller cavities → faster interface with higher fidelities



high-finesse mirrors on optical fiber tips, ablated with a CO_2 laser

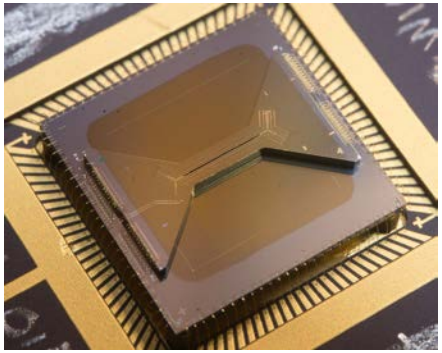
D. Hunger et al., *New. J. Phys.* **12**, 065038 (2010)

K. Ott et al., *Opt. Express* **24**, 9839 (2916)



see also: ions + fiber cavities in Bonn (Köhl), Sussex (Keller), Mainz (Schmidt-Kaler)…

» Scaling up ion traps: ongoing research efforts worldwide



… integrating optics is an important & challenging task.

see: work in Chiaverini group at Lincoln Labs on integrated waveguides for ion addressing

HOA2 trap,
Sandia National Laboratories

Towards a quantum internet

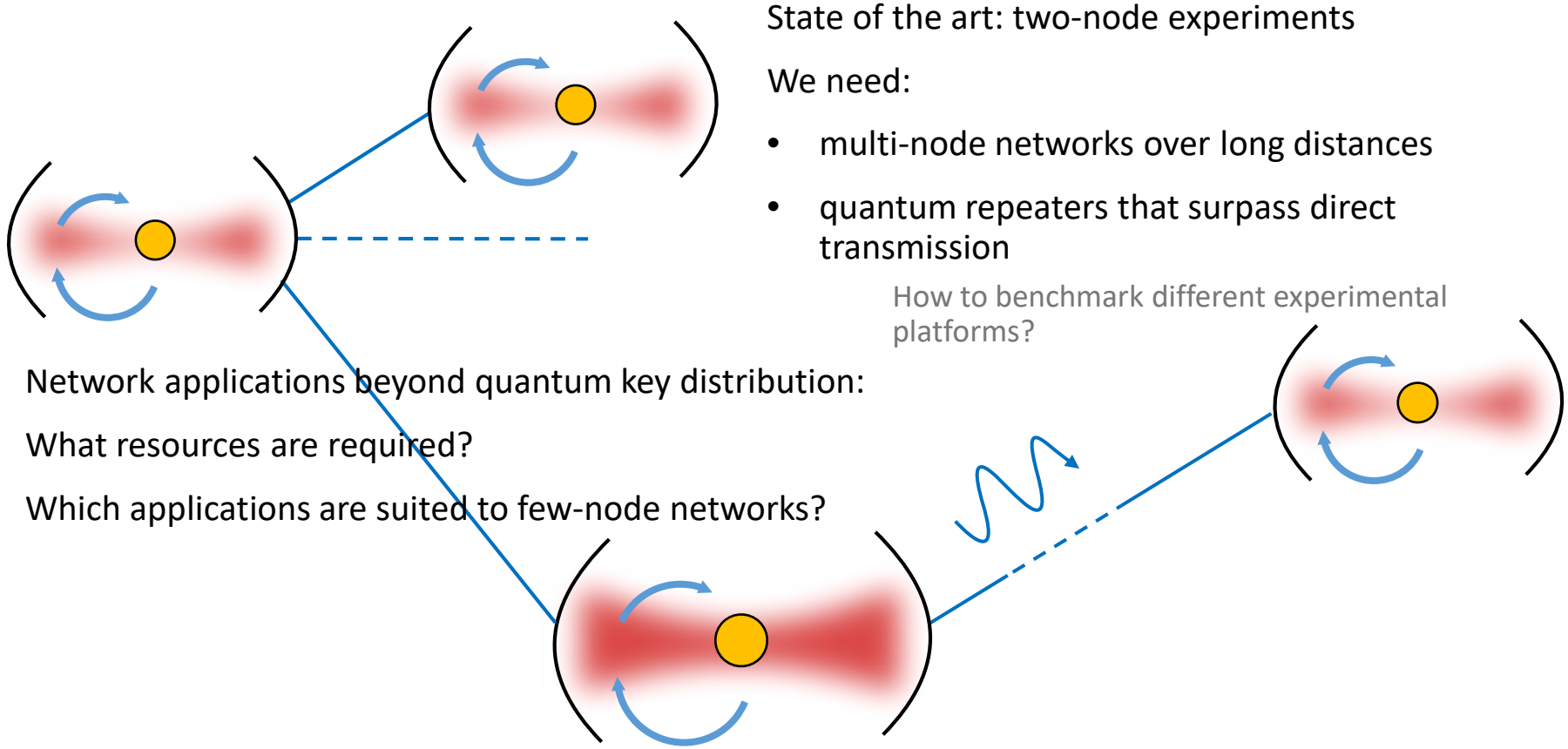
This talk: **ion-photon interactions at one node**

State of the art: two-node experiments

We need:

- multi-node networks over long distances
- quantum repeaters that surpass direct transmission

How to benchmark different experimental platforms?



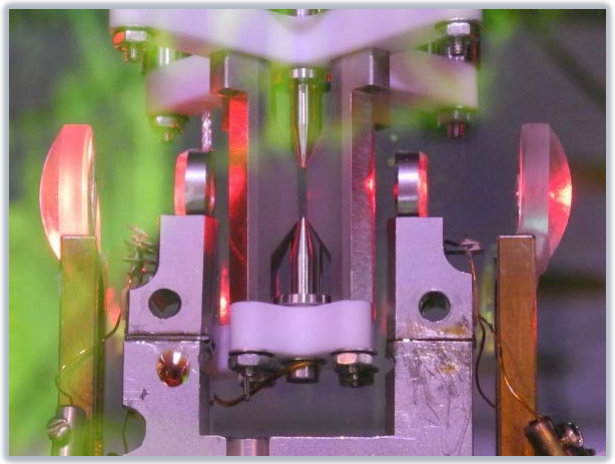
Network applications beyond quantum key distribution:

What resources are required?

Which applications are suited to few-node networks?

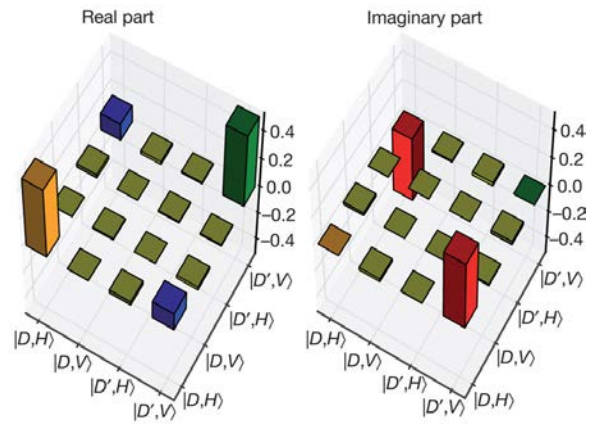
Quantum Internet Alliance
http://quantum-internet.team

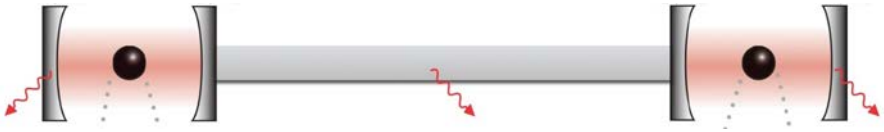
Optical cavities provide an interface between ions and photons, enabling building blocks for quantum networks: **entanglement** and **quantum state transfer**.



Trapped ions are a promising platform for quantum simulation, computation & sensing. Network connectivity enables distributed applications & quantum communication.

Scaling up from experiments with one and two nodes will require us to address decoherence in quantum nodes and channels.





Quantum Light-Matter Interfaces Group

FWF Der Wissenschaftsfonds.

SFB FoQuS Foundations and Applications of Quantum Science

ARL


Matthias Knoll


Dmitry Bykov

Quantum Optics and Spectroscopy Group

Collaborations

Adiabatic passage: B. Vogell, B. Vermersch, B. Lanyon, C. Muschik @ Innsbruck

Fiber cavities: K. Ott, S. Garcia, J. Reichel @ ENS, Paris