universität innsbruck

Cavities as a high-fidelity quantum interface between ions and photons

Birgit Brandstätter

Research group of Prof. Rainer Blatt at the University of Innsbruck

Palacký University, Olomouc

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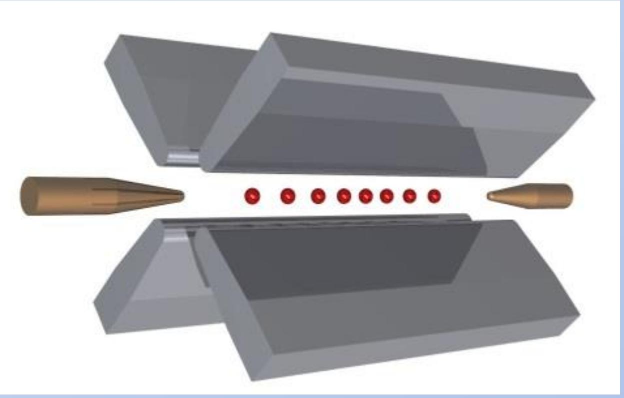
How can we build a quantum interface as the basis for a quantum network?

Trapped ions are versatile tools



stored in electro-magnetic traps

ions are well controlled quantum systems

various applications

precision spectroscopy

clocks, tests of fundamental interactions

sensitive measurement tools

...

used for quantum information processing

Cirac, Zoller, PRL **74**, 20 (1995).

and quantum simulations

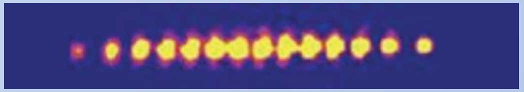
Ions are exemplary quantum processors

DiVincenzo criteria:

well characterized qubits, universal set of gates
reliable initialization, manipulation, and readout

results:

entanglement up to 14 qubits
Monz et al., PRL **106**, 103506 (2011).



repetitive quantum error correction
Schindler et al., Science **332**, 1095 (2011).

long coherence times, high-fidelity gate operations, ...

Can we scale up ion-quantum computers, and if so, how?

Quantum computers linked in a network

link different zones on ion chips

segmented traps

connect processors in network

Cirac et al., PRL **78**, 16 (1997).

DiVincenzo network criteria:

transmission of flying qubits between specified locations

interconvert stationary and flying qubits

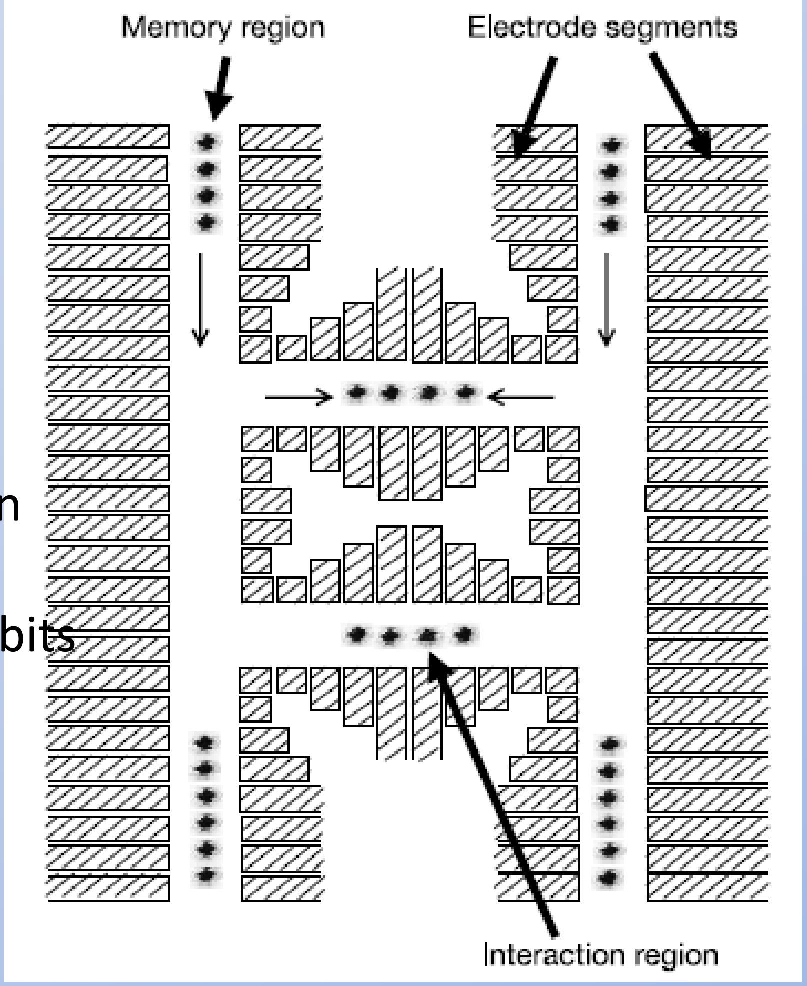
↳ need to be linked via an interface

high NA lens

image charges in electrode

evanescent field of nanofiber

Fabry-Perot resonators



Kielpinski et al., Nature **417**, 709 (2001).

Outline

- A cavity as an ion-photon interface
- Quantum network protocols
  - Ion-photon entanglement
  - Cavity-mediated ion-ion entanglement
  - Ion-photon state mapping
- A new setup for strong ion-cavity coupling

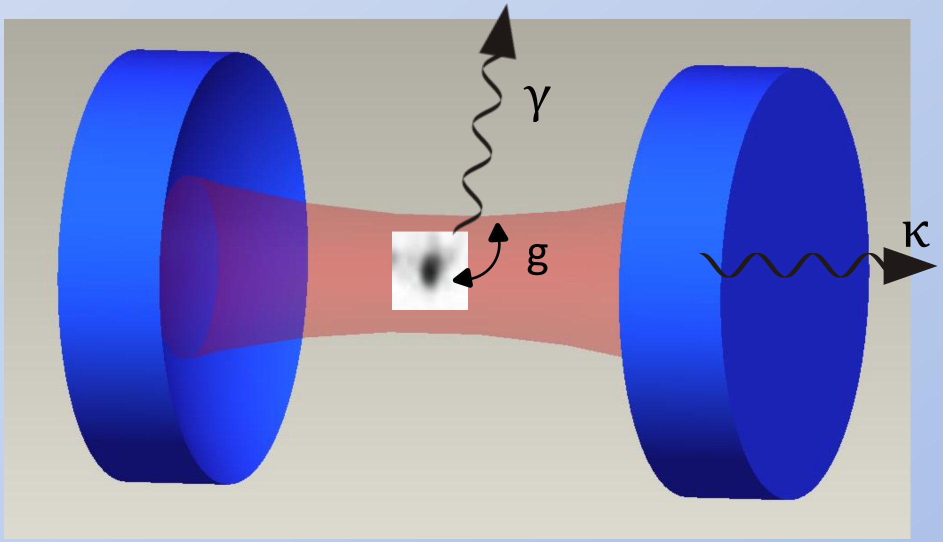
Cavity constitutes an ion-photon interface

ions

information storing and processing

photons

long-distance transport



cavity

interaction

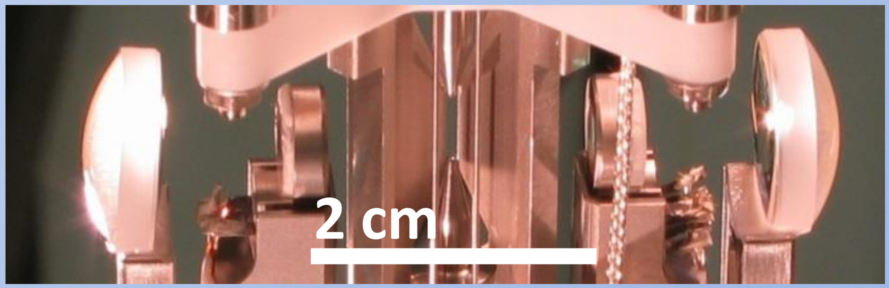
$$\hat{H}_{int} = \hbar g\left(\hat{a}\hat{\sigma}^{+} + \hat{a}^{\dagger}\hat{\sigma}^{-}\right)$$

coherent coupling $g \propto \frac{1}{\sqrt{V}}$

decoherent losses

cavity decay κ

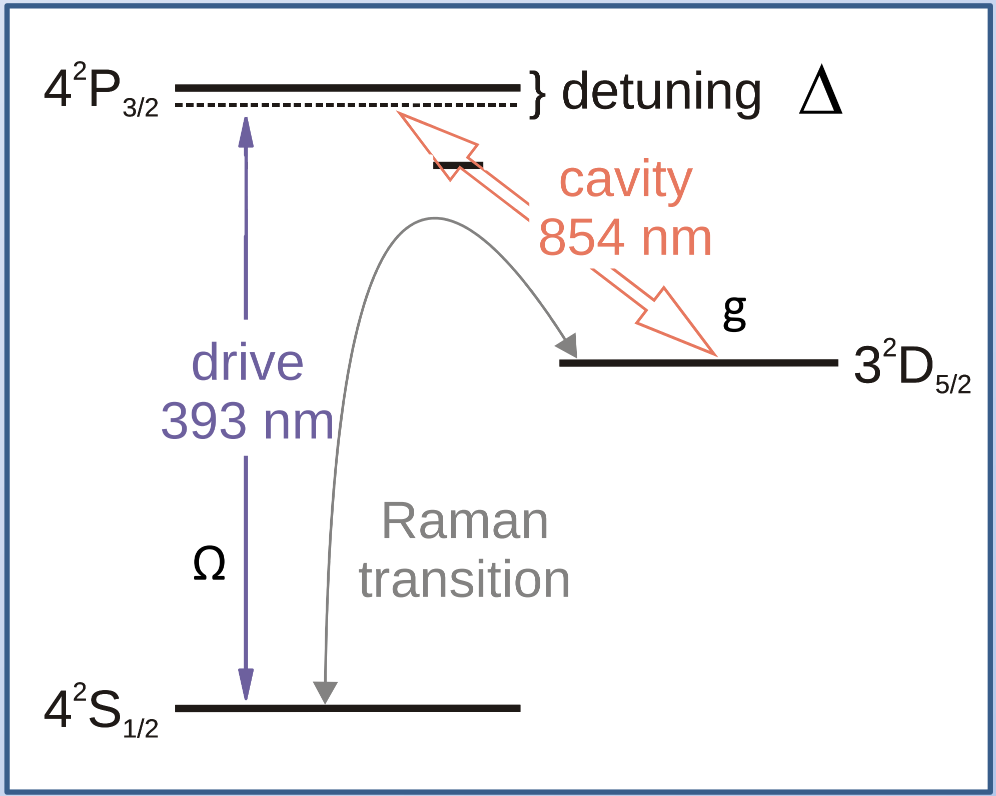
atomic decay γ



Cavity mediates Raman transfer

Keller et al., Nature, **431**, 1075 (2004).

$^{40}Ca^+$



vacuum-stimulated Raman transfer is coherent and reversible

generates cavity photon

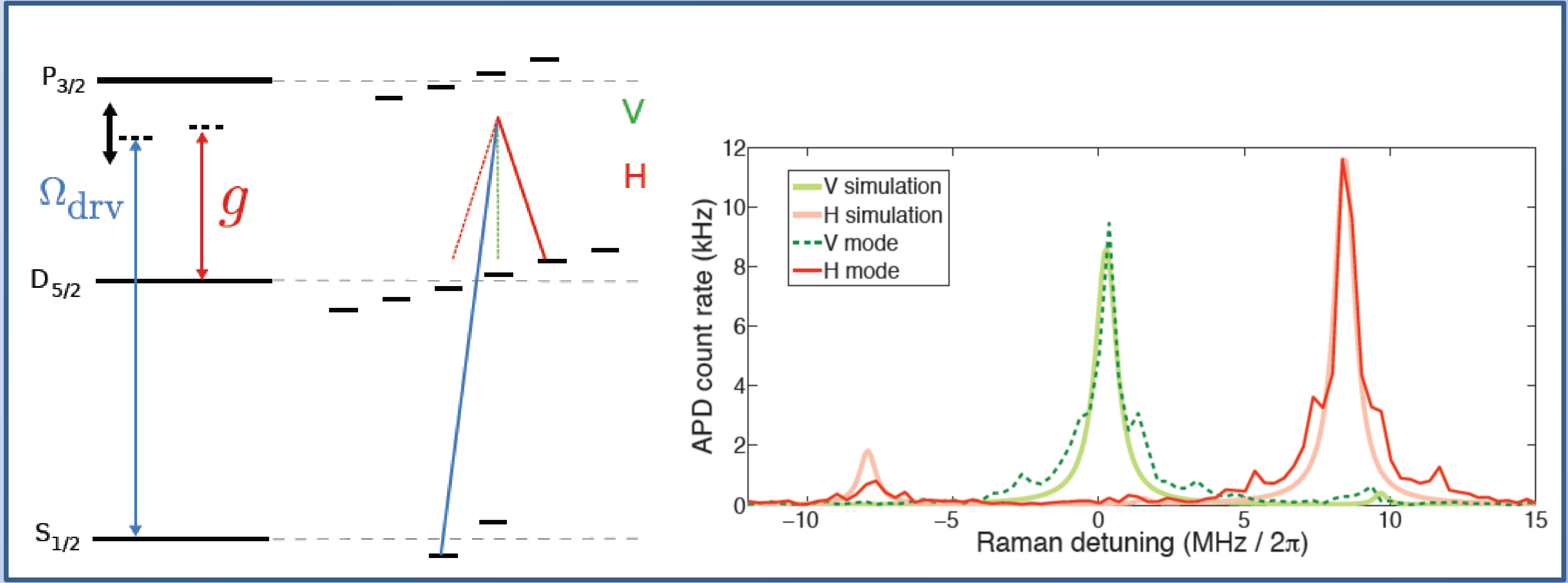
Deterministic single photon generation

McKeever et al., Science **303**, 1992 (2004).

magnetic field splits up Zeeman states

Raman transfer addresses one transition

↳ photon polarization depends on transition



Stute et al., Appl. Phys. B **107**, 1145 (2012).

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Atom-photon entanglement as network protocol

resource for

- distant entanglement

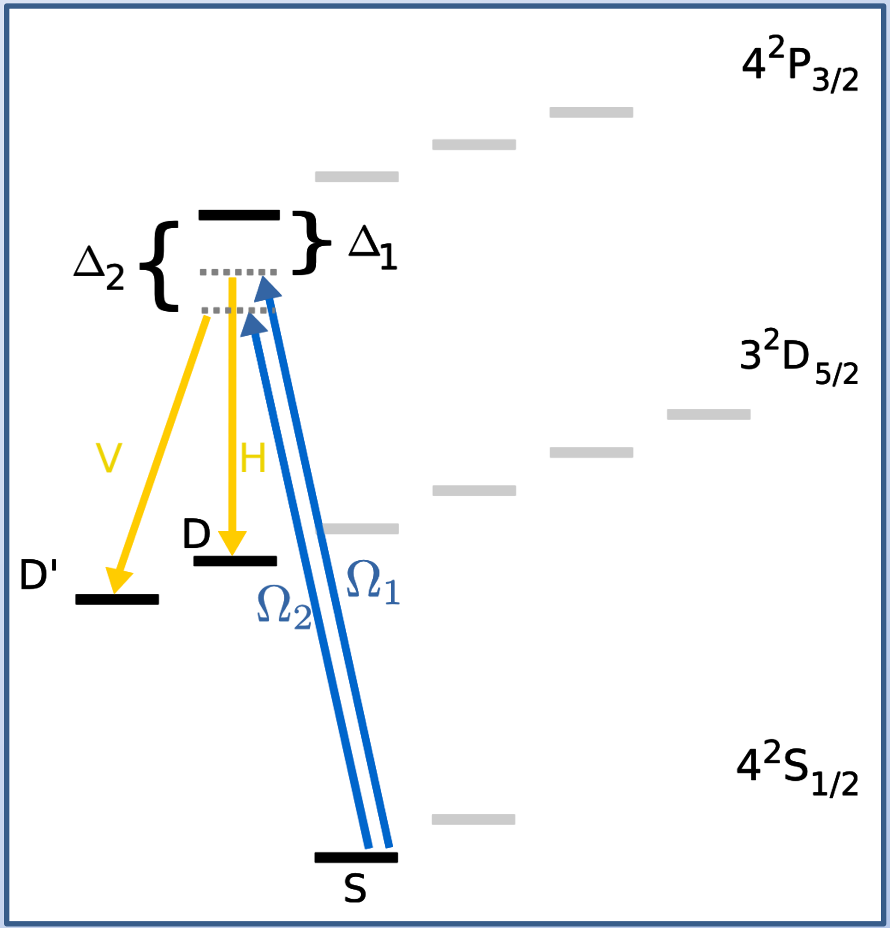
  Moehring et al., Nature **449**, 68 (2007).

- teleportation

$$\cos\alpha|D, H\rangle + e^{i\varphi}\sin\alpha|D', V\rangle$$

Bichromatic Raman field generates entanglement

$$|S,0\rangle \longrightarrow \cos\alpha|D,H\rangle + e^{i\varphi}\sin\alpha|D',V\rangle$$

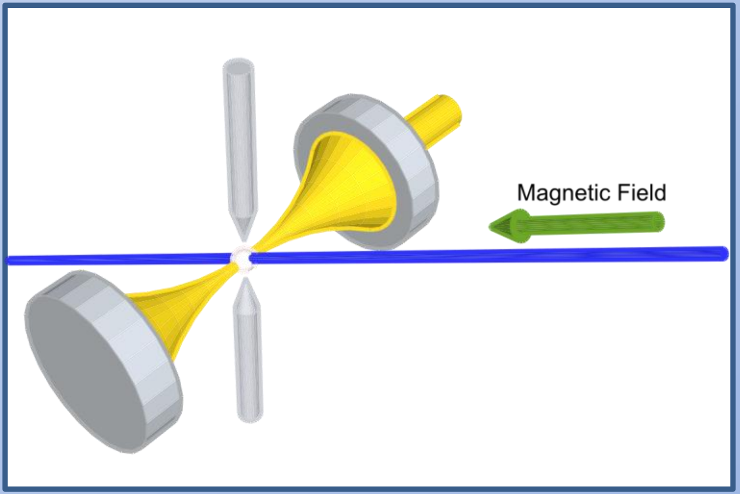


magnetic field splits Zeeman states
bichromatic field drives two Raman transitions

fully tunable phase and amplitude
set by bichromatic field

deterministic

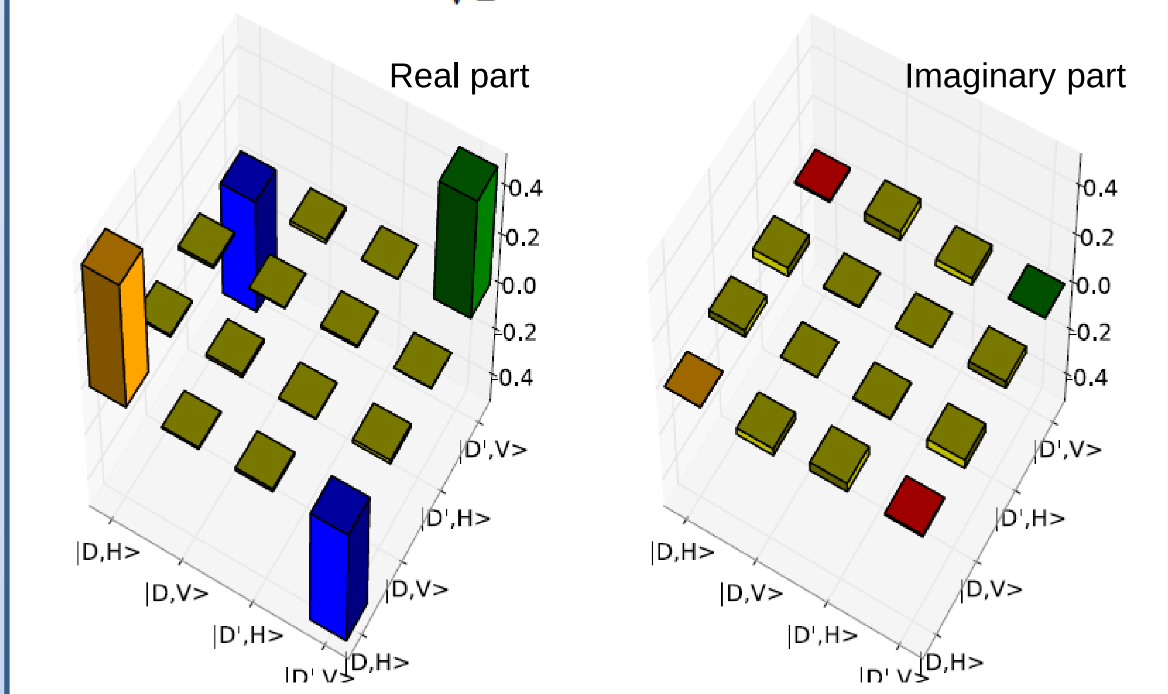
scheme robust to scattering (only limits efficiency)



High-fidelity entanglement

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

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|D,H\rangle - |D',V\rangle)$$



fidelity with respect to $|\psi\rangle$:

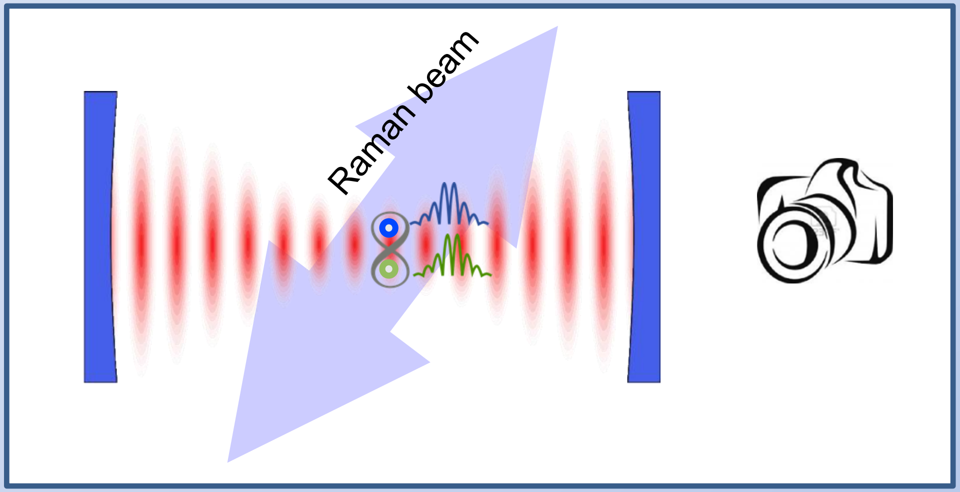
97.4(2)%

efficiency:

5.7%

Let´s repeat the entanglement protocol for two ions

Casabone et al., PRL **111**, 100505 (2013).



one ion:
two ions:

$$|\psi\rangle = (|DH\rangle + |D'V\rangle) \otimes (|DH\rangle + |D'V\rangle)$$

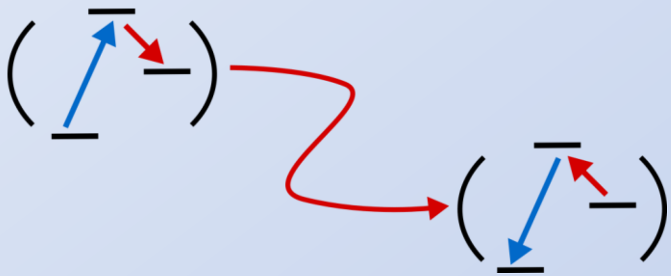
detect photons →	project ions:
HH	*DD*
VV	*D'D'*
HV	*DD'*
VH	*D'D*

indistinguishability→

$$|\psi\rangle = |DD'\rangle + |D'D\rangle$$

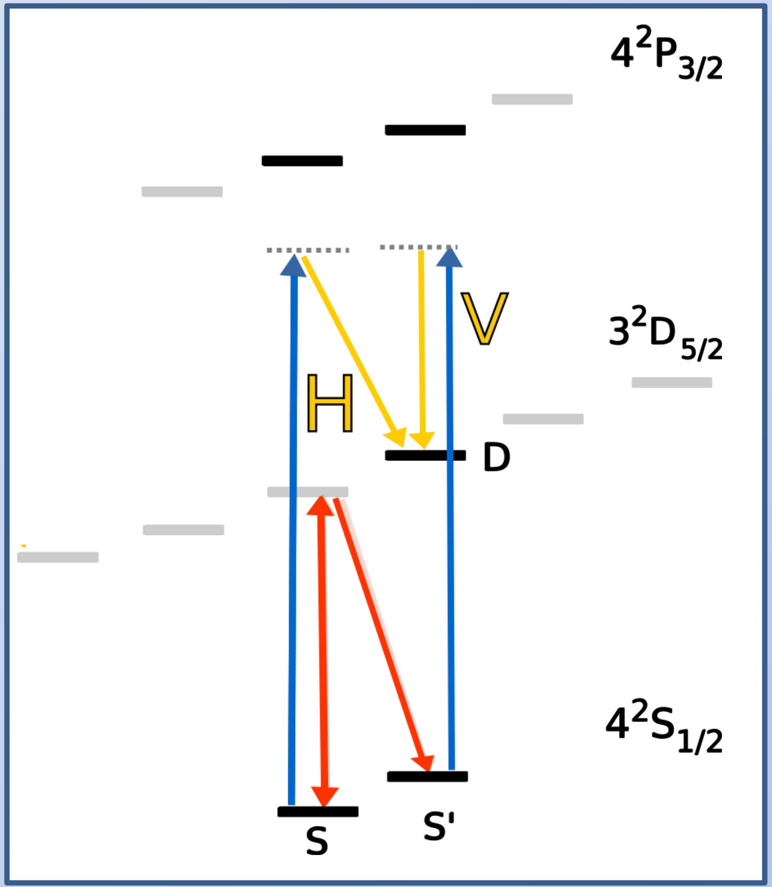
$F_{\Psi+} \geq 0.88 \pm 0.03$ at repetition rate of 0.2 events per second

Direct state transfer via state-mapping



deterministic via cavity

Cirac et al., PRL **78**, 16 (1997).



maps arbitrary quantum state from ion onto photon

$$(\cos\alpha|S\rangle + e^{i\varphi}\sin\alpha|S'\rangle)\otimes|0\rangle$$
$$\longrightarrow |D\rangle\otimes(\cos\alpha|V\rangle + e^{i\varphi}\sin\alpha|H\rangle)$$

drive two Raman transitions simultaneously to same final state

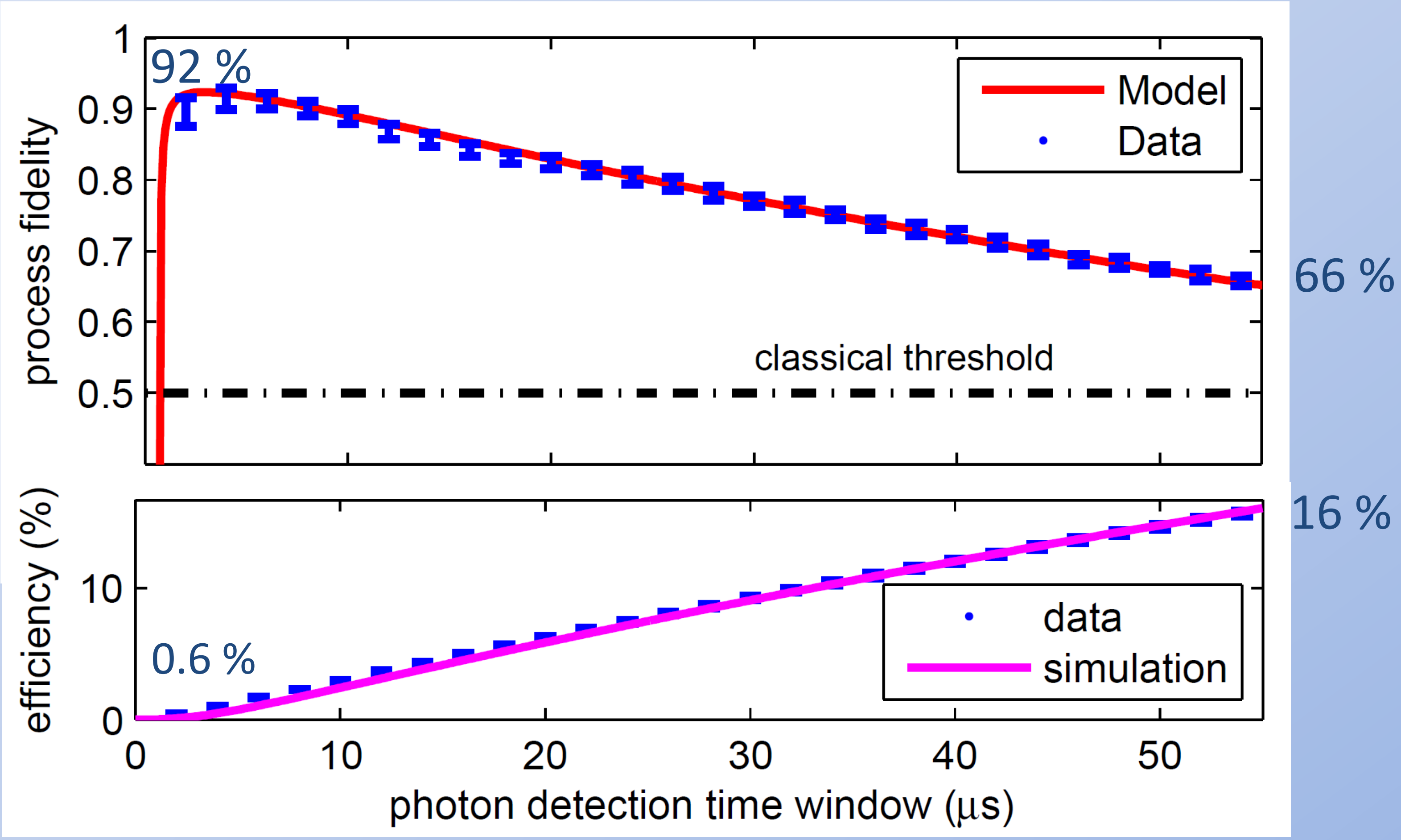
High fidelity at the cost of efficiency

Stute et al., Nature Photonics **7**, 219 (2012).

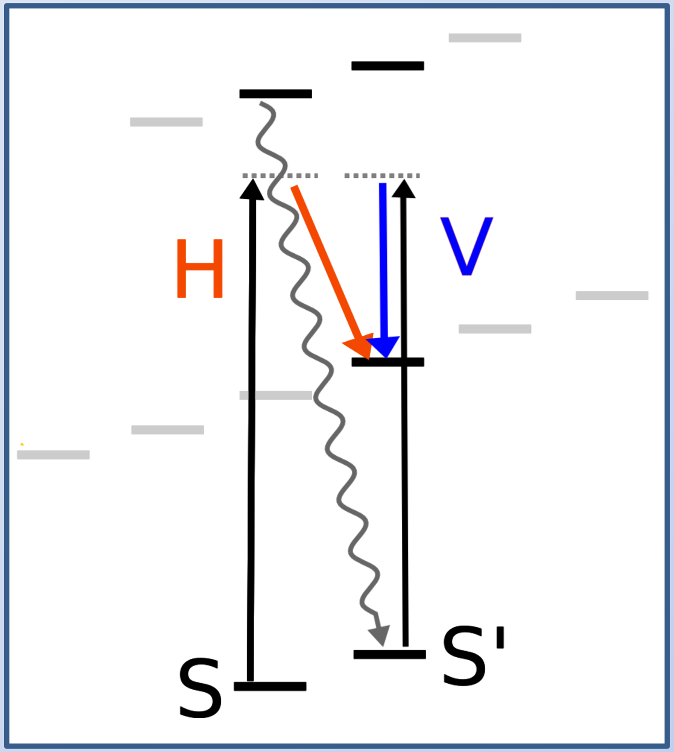
experiment and simulation: (g, κ, γ) = 2π (1, 0.05, 11) MHz

simulations: quantum optics toolbox in Matlab

master equation simulations



Scattering introduces decoherence



spontaneous decay destroys initial quantum state

scattering probability increases over time

fidelity can be increased

at cost of efficiency and vice versa

for high fidelity and efficiency coherence must be preserved

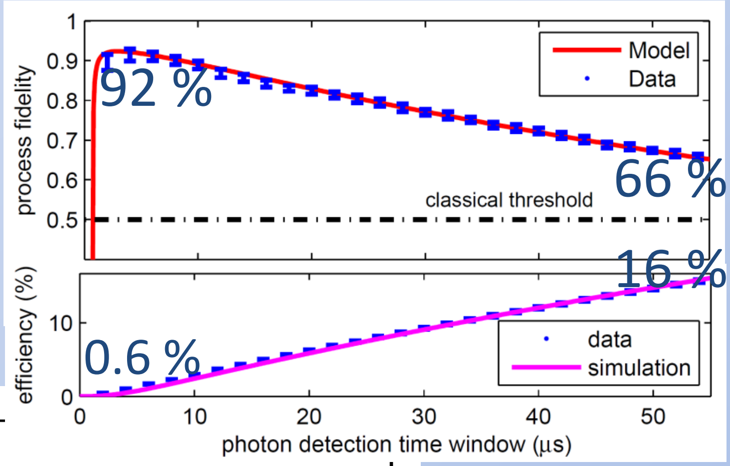
→ decay rate γ must be smaller than coupling g

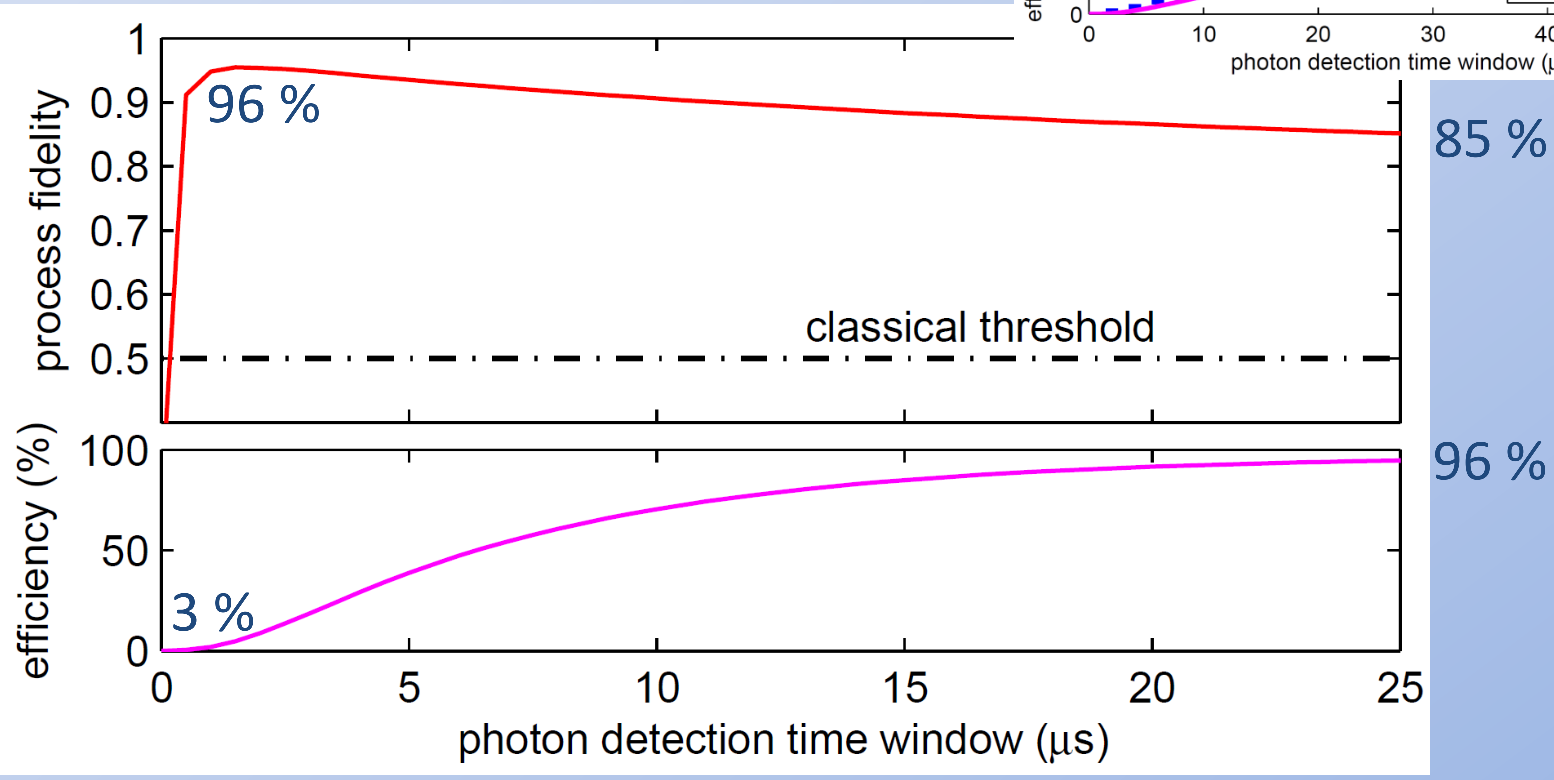
State mapping with system of high coupling rate

simulation: (g, κ, γ) = 2π (40, 9, 11) MHz

higher maximum process fidelity

almost unit efficiency!





A setup with better coherence

the goal:

strongly couple ion to cavity mode, $g \gg \kappa, \gamma$

shown in neutral atom experiments ✓

ion experiments ✗

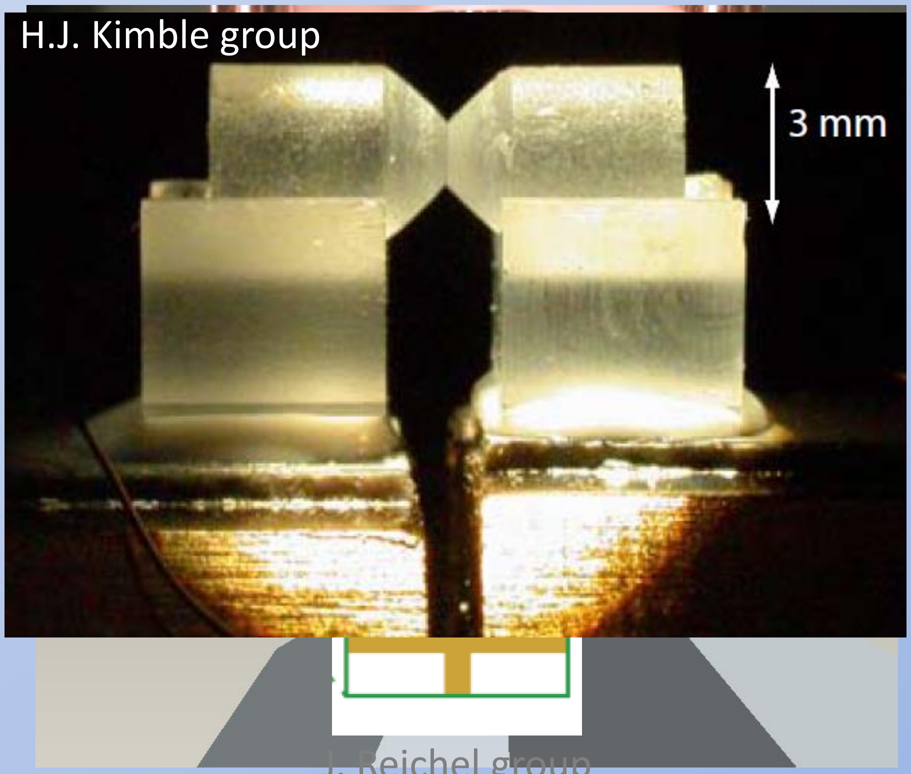
the idea:

produce mirrors on fibers

implemented with neutral atom experiments ✓

the challenges:

- bring fibers close to ions
- develop fiber cavities suitable for implementation with ions



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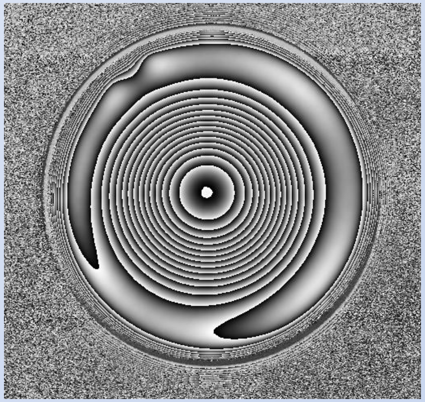
Fabrication of fiber cavities

J. Reichel group

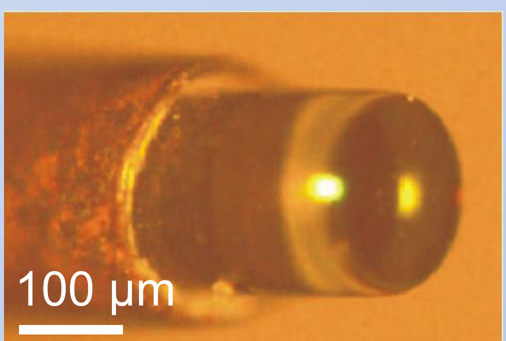


laser ablation

- position cleaved fiber
- CO_2-laser pulse
- analysis with interferometer

coat surfaces with high-reflective coating

align and characterize fiber cavities



Fiber cavity characterization

How good can fiber cavities be?

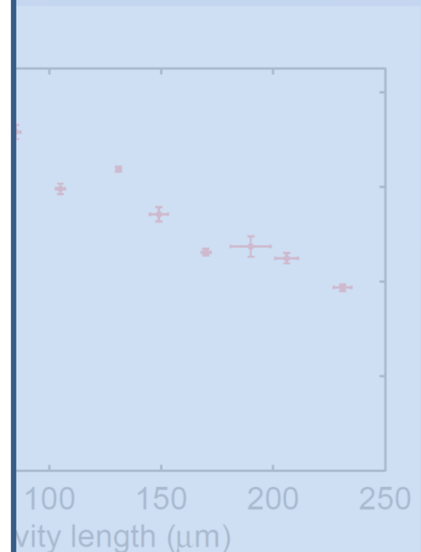
no additional

How long can we ma

finesse decre

Does it hurt to bake r

heating mirro



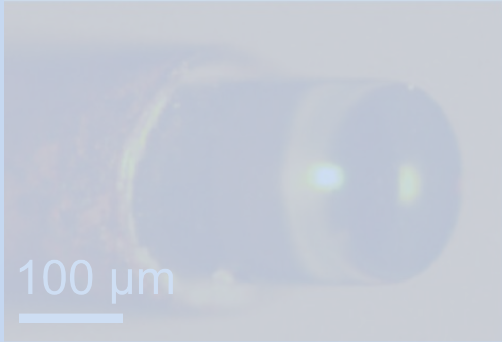
our fiber cavities

$g = 2\pi \cdot 40$ MHz

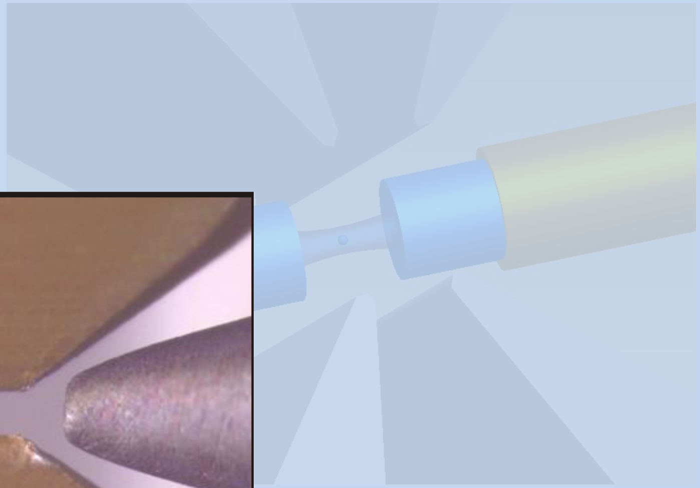
$\kappa = 2\pi \cdot\ 9$ MHz

$\gamma = 2\pi \cdot 11$ MHz

suited for strong coupling



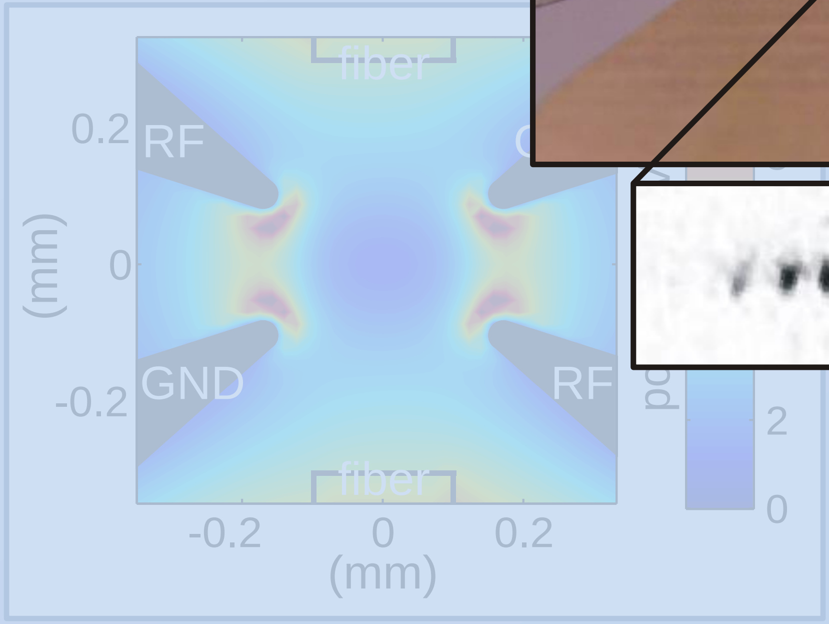
New ion trap for fiber cavities

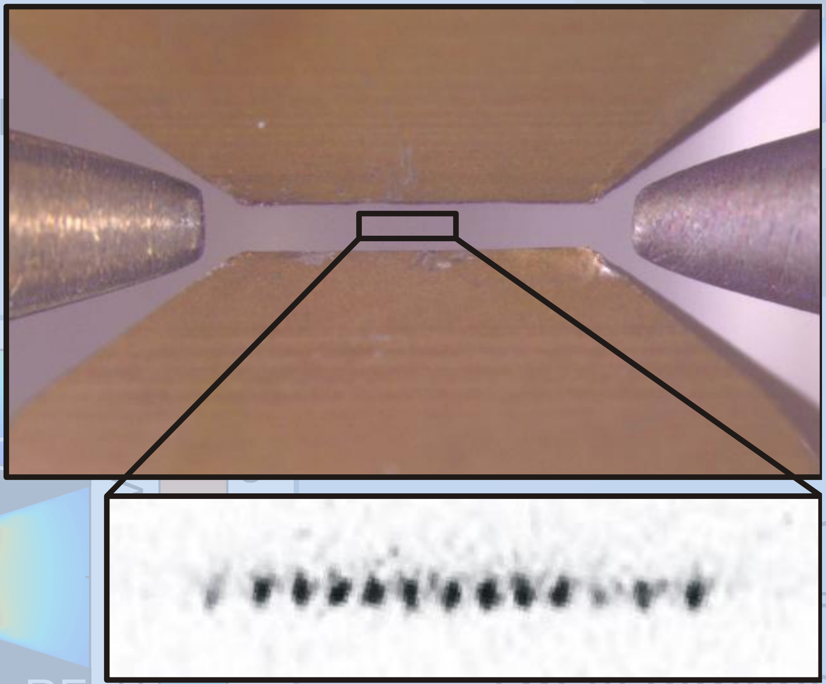


trap dimensions comparable to fiber-cavity dimensions

has to provide cle

unusual angl





ng potential

f 1 eV

- small dimensions

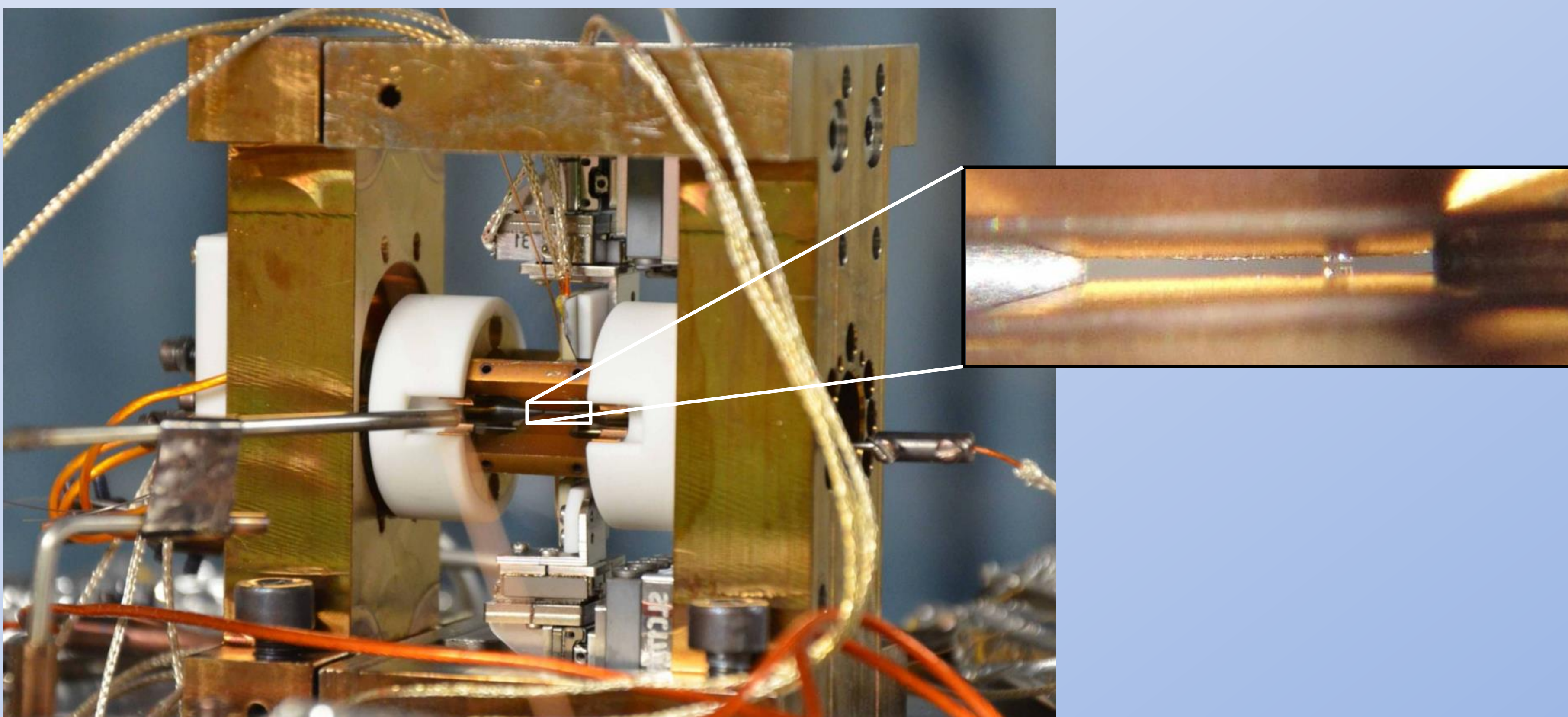
technologically challenging

Trap and cavity mounted together

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

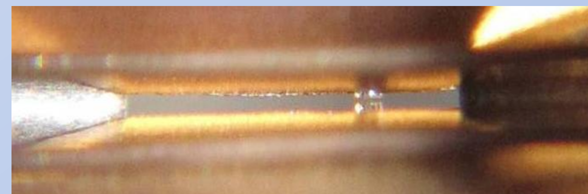
robust: cavity and trap fixed on same holder

fibers sit on three-axis micropositioning system



Presence of fibers influences ions

trap ions with fibers recessed



test influence of fibers on ions

observed when 1 mm away

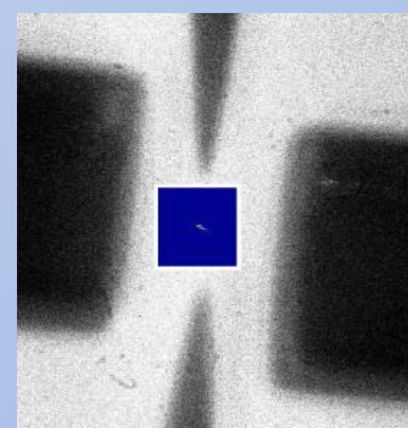
charges of fibers

no trapping and reloading possible at around 300 µm

solutions:

discharge fibers

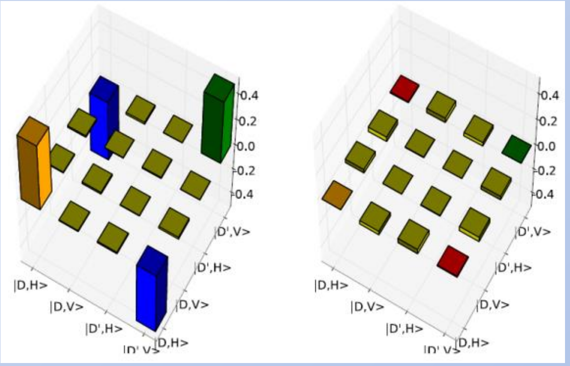
build longer fiber cavities



Steiner et al., PRL **110**, 043003 (2013).

Summary

cavity as ion-photon quantum interface

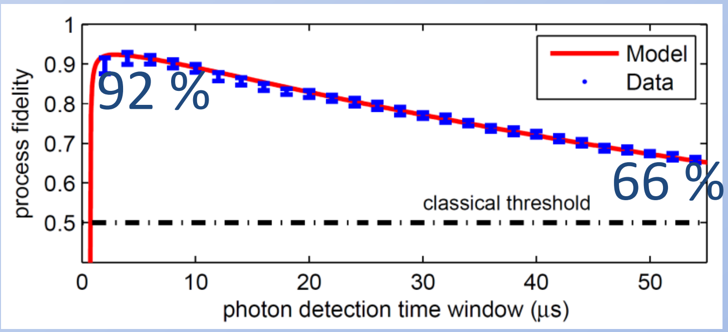


ion-photon entanglement

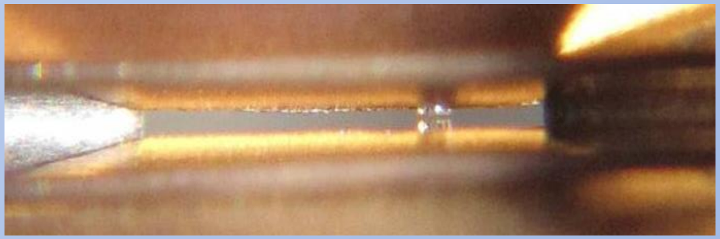
- fidelity 97.4(2)%

ion-photon state mapping

- process fidelity 92(2)%



setup of a fiber-cavity ion-trap system



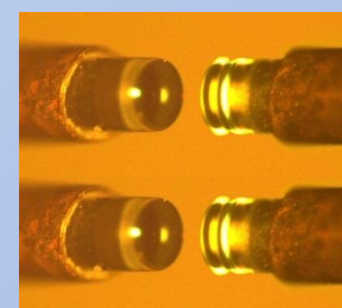
Outlook

fiber-cavity ion-trap system

- realization of an elementary quantum network with trapped ions

scale up system

- large ion-based quantum computer network



use cavity and network schemes for quantum communication to connect distant or different devices

The Innsbruck team:

European Research Council

Österreichische Akademie der Wissenschaften

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