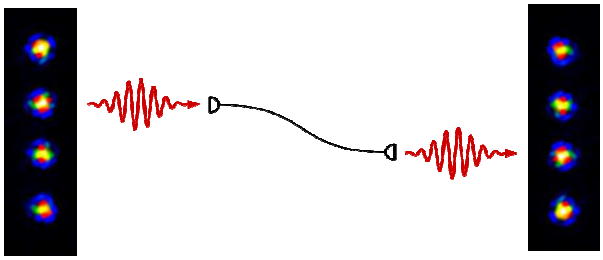
Ion-photon quantum networking tools

Jürgen Eschner

QIPA, HRI Allahabad, India, 12/2015

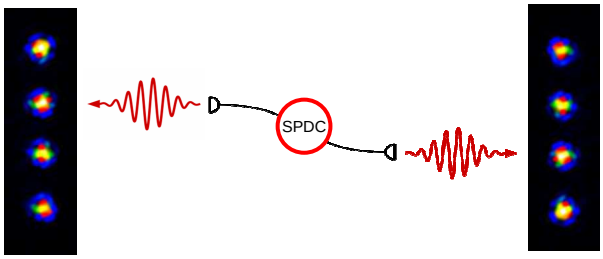
Ion-photon quantum network

- Single atomic ions as nodes that generate, process and store quantum information
- Single photons as quantum channels for **quantum state transfer** between nodes



Ion-photon quantum network

- Photon-to-atom **entanglement transfer** by simultaneous single-photon absorption.
- Quantum repeaters for transmission of quantum information over long distances - **telecom**

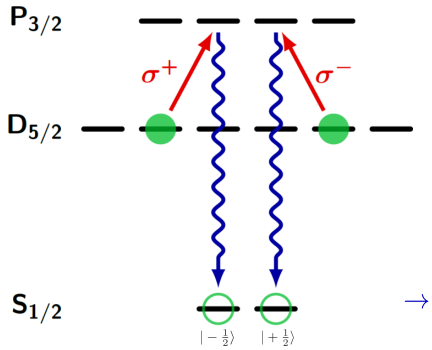


Quantum interfaces

- Mapping an atomic state onto a photon
  - *A. Stute, B. Casabone, B. Brandstätter, K. Friebe, T. E. Northup, R. Blatt, „Quantum-state transfer from an ion to a photon“, Nat. Phot.* ***7****, 219-222 (2013)*
  - *T. Wilk, S. C. Webster, A. Kuhn, G. Rempe, „Single-atom single-photon quantum interface“, Science* ***317****, 488-490 (2007)*
  - *D. N. Matsukevich, A. Kuzmich, „Quantum state transfer between matter and light“, Science* ***306****, 663-666 (2004)*

Quantum interfaces

- Mapping a photonic state onto an atom – heralded protocol
  - *Lloyd et al., PRL **87**, 167903 (2001)*
  - *Sangouard et al., NJP **15**, 085004 (2013)*
  - *P. Müller et al., APB **114**, 303 (2014)*



$$\psi_{\text{photon}} = \alpha|\sigma^+\rangle + \beta|\sigma^-\rangle$$

$$\rightarrow \quad \psi_{\text{atom}} = \alpha|-\tfrac{1}{2}\rangle + \beta|+\tfrac{1}{2}\rangle$$

Deterministic vs. heralded

- **No deterministic single-atom to single-photon coupling**

→ **Success probability limits fidelity !**

→ **Heralded operations**

- **Examples**
  - **SPDC single photons – heralded by partner**
  - **Remote entanglement – heralded by Bell m'ment**
  - **Single photon absorption**
    - **– heralded by quantum jump**
    - **– heralded by scattered photon**

} HERE

- **Figures of merit**
  - **Conditional probabilities between process and herald**
  - **Action of herald on system**

Outline

photonik quanten

The main players

Earlier results

Heralded photon-to-atom state transfer

Programmable ion-photon interface

Telecom-ion interfaces

Outline

photonik quanten

The main players

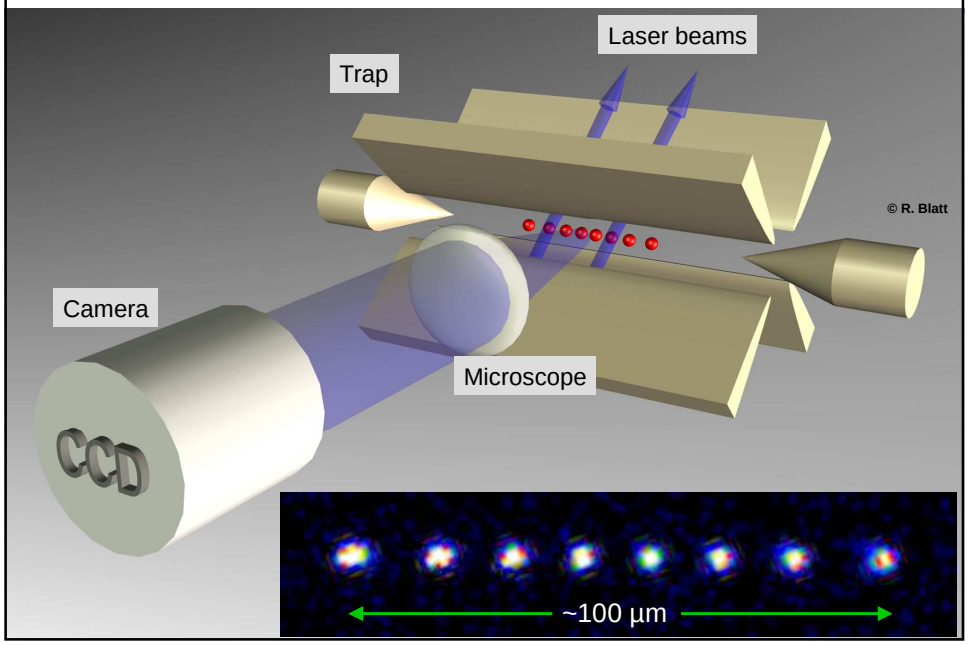
Earlier results

Heralded photon-to-atom state transfer

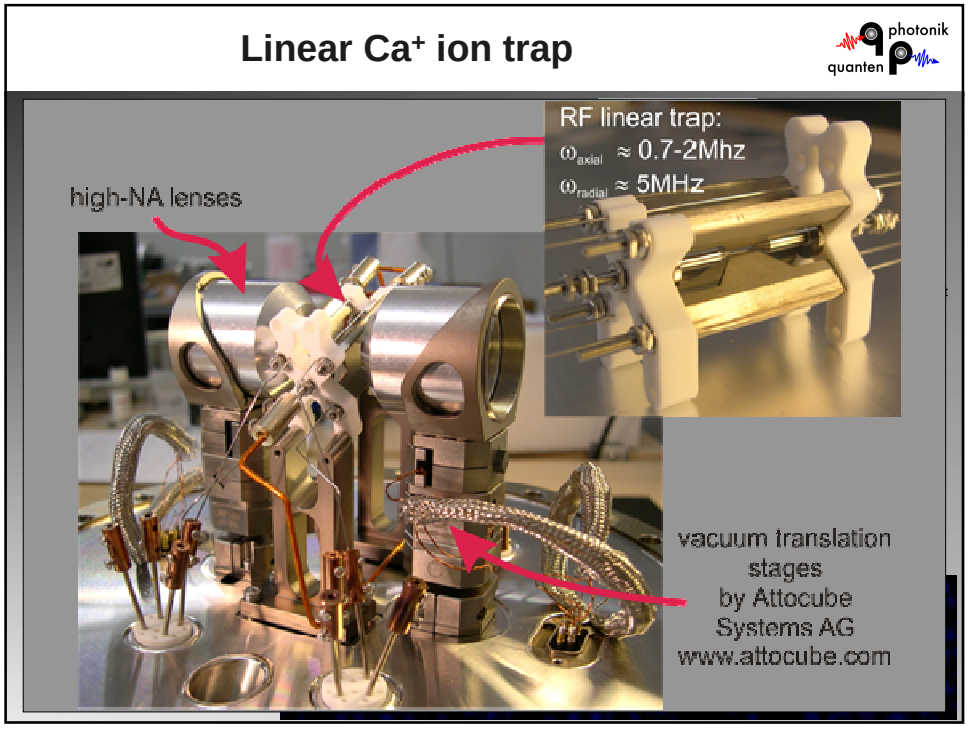
Programmable ion-photon interface

Telecom-ion interfaces

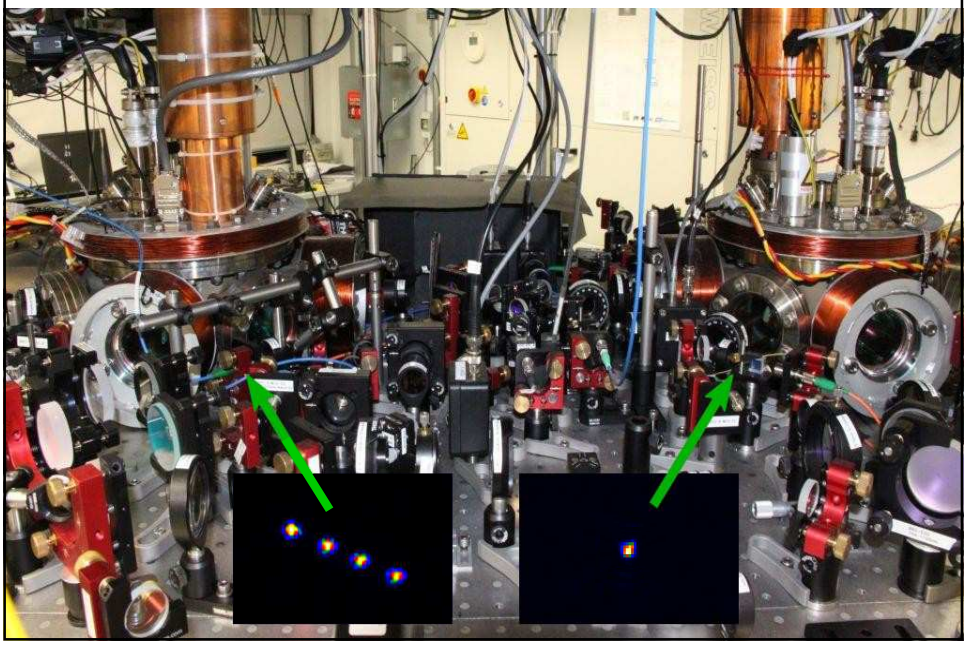
Linear Ca⁺ ion trap



Linear Ca⁺ ion trap

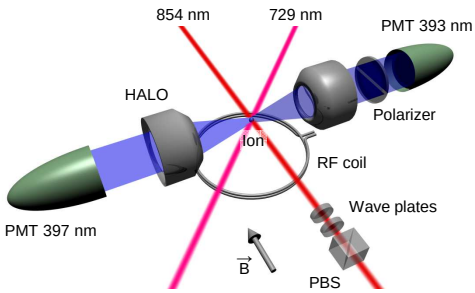


Double ion trap apparatus

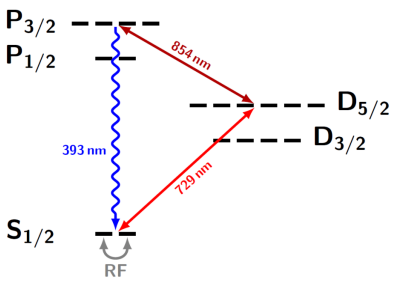


Atomic qubits

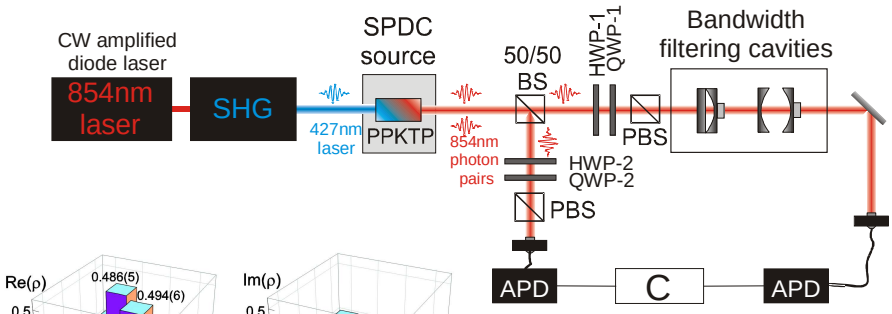
Experimental setup:

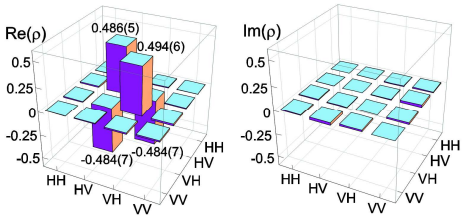


Level scheme: $^{40}Ca^{+}$



Narrowband entangled photon pairs



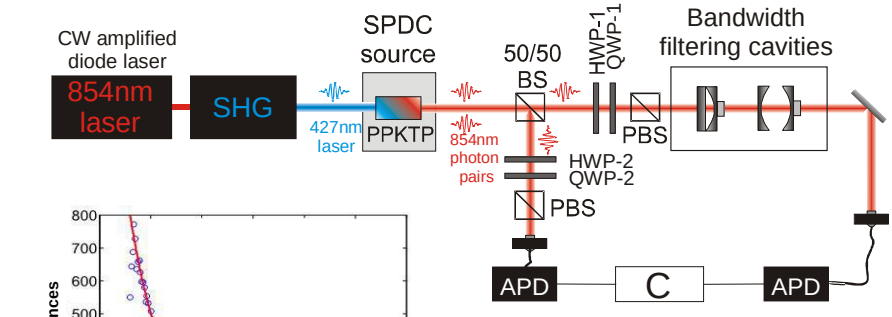


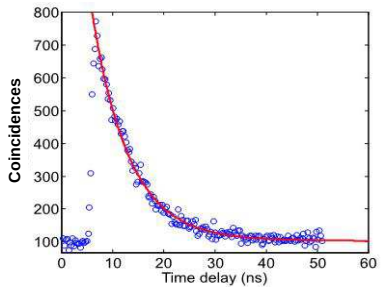
- **Fidelity to singlet Bell state:**

$$F = \langle \Psi^- | \rho | \Psi^- \rangle = 97.6 \pm 1.1\%$$

A. Haase et al., Opt. Lett. 2009; N. Piro et al., J. Phys. B 2009

Narrowband entangled photon pairs





- **Fidelity to singlet Bell state:**

$$F = \langle \Psi^- | \rho | \Psi^- \rangle = 97.6 \pm 1.1\%$$

- **Bandwidth:**

$$\delta\nu = 22.0 \pm 0.5 \text{ MHz} \approx \delta\nu_{\text{ion}}$$

A. Haase et al., Opt. Lett. 2009; N. Piro et al., J. Phys. B 2009

Outline

The main players

Earlier results

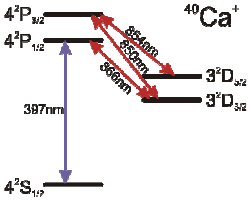
Heralded photon-to-atom state transfer

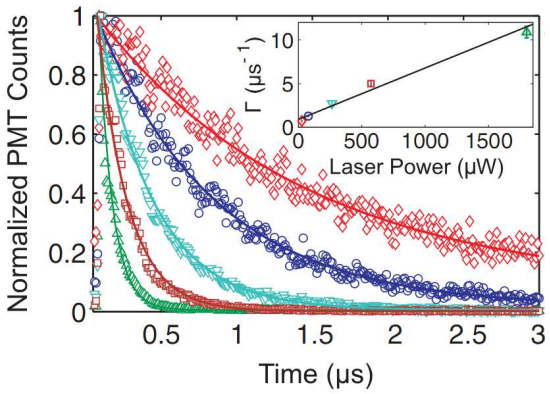
Programmable ion-photon interface

Telecom-ion interfaces

Single photons with tailored properties

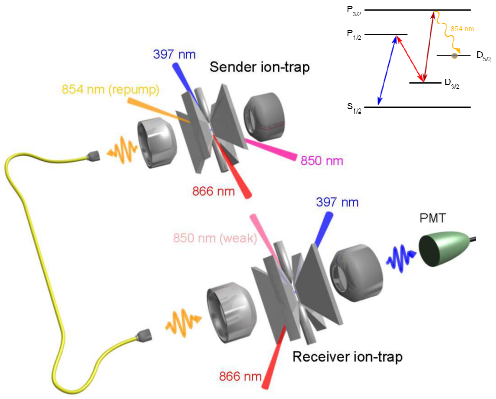
- **Variable wave packet (arrival time distribution after trigger)**
- **Near Fourier limited photons → pure quantum state**
- **Polarization control**



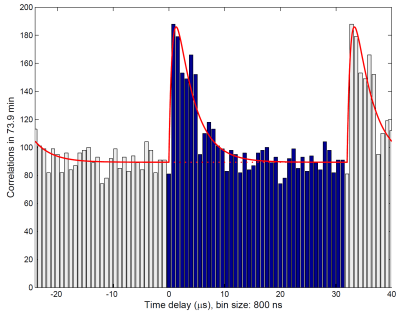


Almendros et al., PRL 2009; Kurz et al., NJP 2013

Absorption of photon from other ion



$g^{(2)}(\tau)$ between trigger and quantum jump



- **30 kHz repetition rate (now > 1 MHz possible)**
- **1.1 μs duration single-mode photons @ ~1 kHz**
- **$2.5 \cdot 10^{-4}$ absorption probability per photon**

M. Schug et al., PRL 2013

Outline

The main players

Earlier results

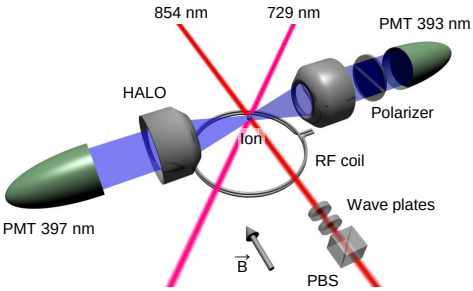
Heralded photon-to-atom state transfer

Programmable ion-photon interface

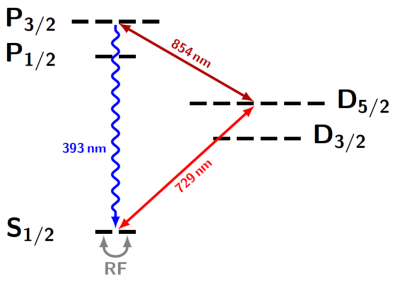
Telecom-ion interfaces

Experimental arrangement

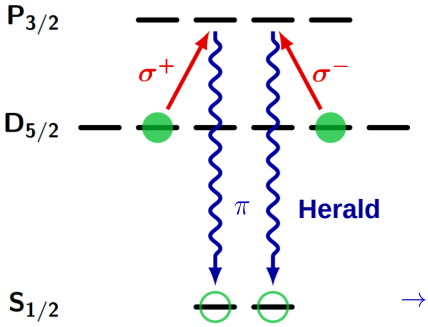
Experimental setup:



Level scheme: $^{40}Ca^{+}$



Heralded transfer protocol

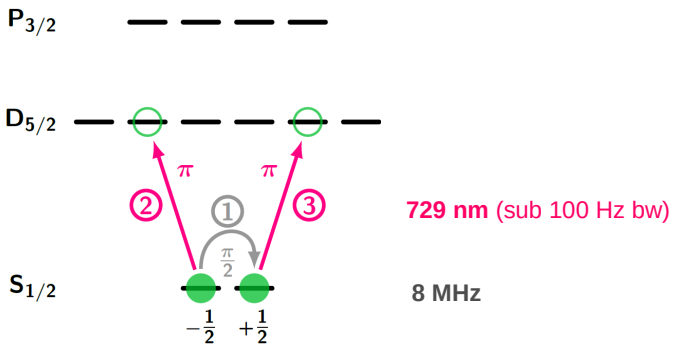


$$\psi_{\text{photon}} = \alpha|\sigma^+\rangle + \beta|\sigma^-\rangle$$

$$\rightarrow \quad \psi_{\text{atom}} = \alpha|-\tfrac{1}{2}\rangle + \beta|+\tfrac{1}{2}\rangle$$

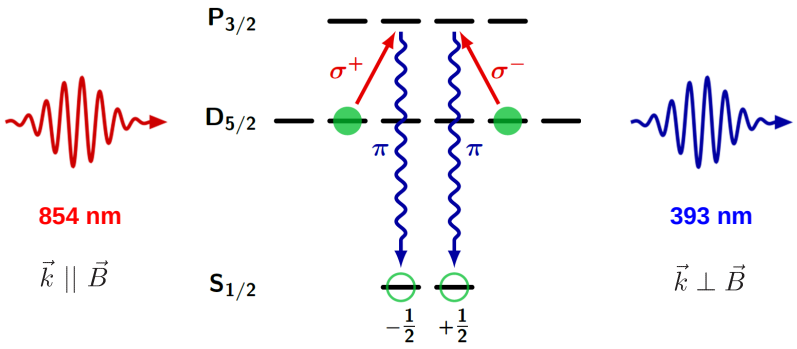
Experimental sequence I

- State preparation (following optical ground-state pumping)



Experimental sequence II

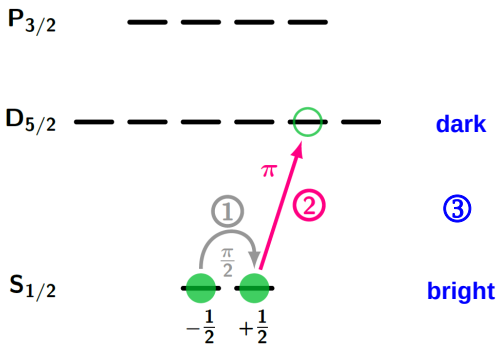
- Heralded photon absorption (single photon Raman scattering)



$$\psi_{\text{photon}} = \alpha|\sigma^+\rangle + \beta|\sigma^-\rangle \quad \rightarrow \quad \psi_{\text{atom}} = \alpha|-\tfrac{1}{2}\rangle + \beta|+\tfrac{1}{2}\rangle$$

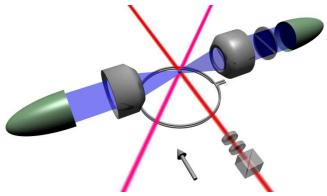
Experimental sequence III

- Atomic state read-out (rotation + state-selective fluorescence)



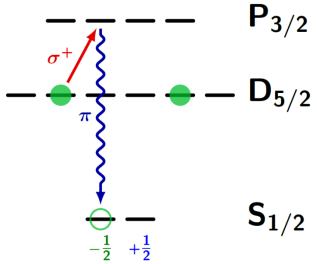
Results

- 854 nm polarization: **circular (R)**



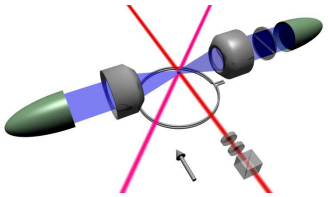
$\psi_{\text{photon}} = |\sigma^+\rangle$

$\rightarrow \quad \psi_{\text{atom}} = |-\tfrac{1}{2}\rangle$

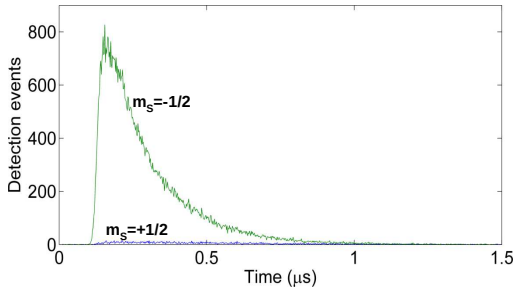


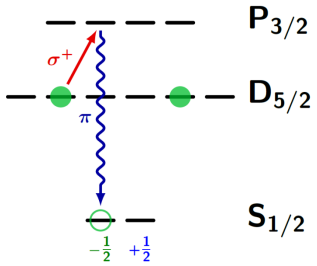
Results

- 854 nm polarization: **circular (R)**



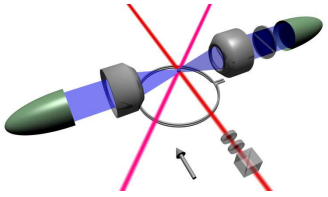
Conditional photon arrival times



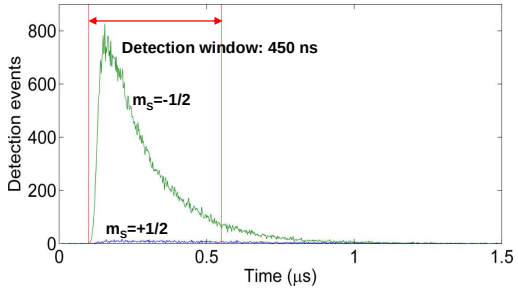


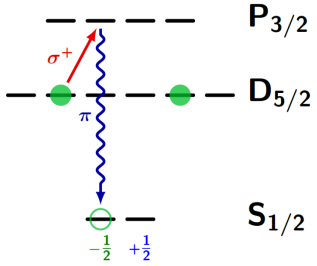
Results

- 854 nm polarization: **circular (R)**



Conditional photon arrival times





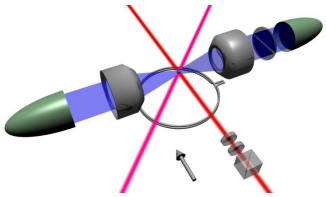
Heralding probability: 0.438(1)%

Fidelity $\langle -\frac{1}{2}|\rho_{ion}|-\frac{1}{2}\rangle$: 0.978(1)

Results

photonik quanten

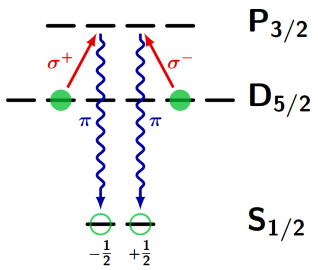
- 854 nm polarization: **linear**



Zeeman splitting!

$$\psi_{\text{photon}} = \frac{1}{\sqrt{2}}(|\sigma^+\rangle + e^{i\Phi}|\sigma^-\rangle)$$

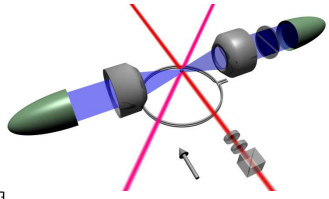
$$\rightarrow \quad \psi_{\text{atom}} = \frac{1}{\sqrt{2}}(|-\tfrac{1}{2}\rangle + e^{i(\Phi+\omega_L t)}|+\tfrac{1}{2}\rangle)$$



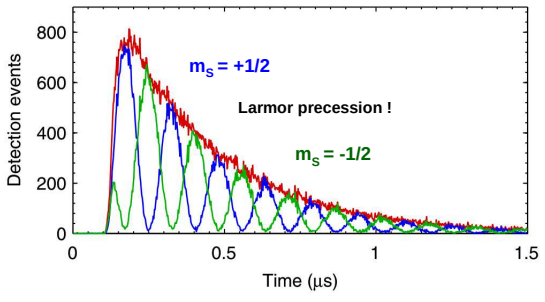
Results

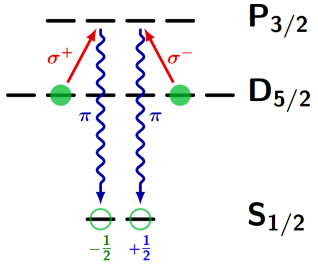
photonik quanten

- 854 nm polarization: **linear (V)**



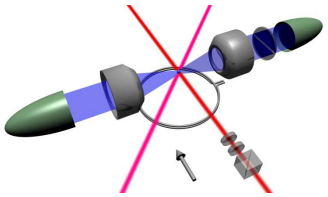
Photon arrival times conditioned
on state detection result (after π/2)



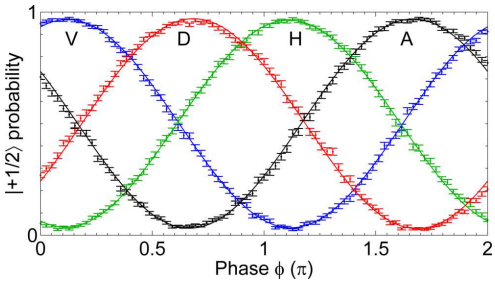


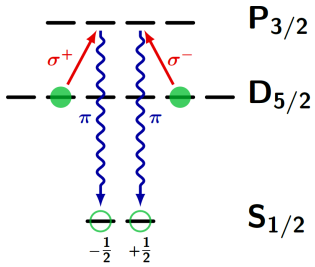
Results

- 854 nm polarization: **(V, H, D, A)**



Conditional photon arrival times



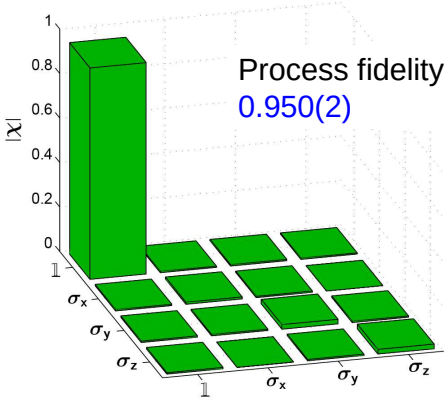


Average fidelity (from contrast): 0.969(1)

C. Kurz et al., Nat. Comm. 2014

Quantum-process tomography

- Characterization how photon state is mapped onto ion state



Process fidelity (identity contribution): 0.950(2)

C. Kurz et al., Nat. Comm. 2014

Outline

The main players

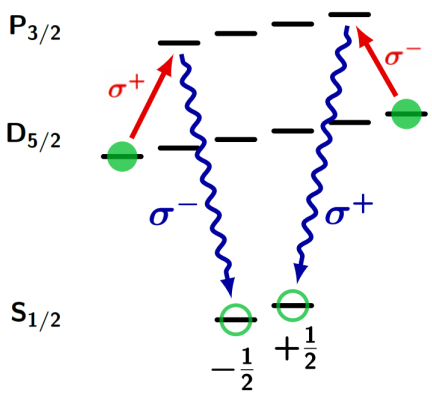
Earlier results

Heralded photon-to-atom state transfer

Programmable ion-photon interface

Telecom-ion interfaces

Programmable atom-photon interface



$|\psi\rangle_{\text{atom-photon, in}}$

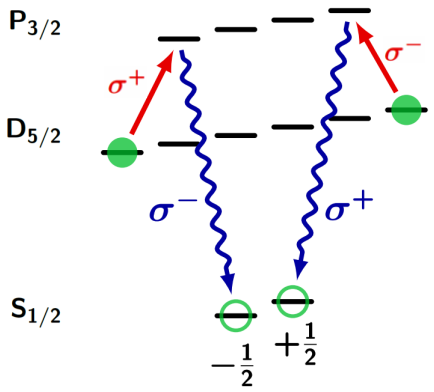
$= |\psi\rangle_{\text{D}}\ |\psi\rangle_{854}$

$\rightarrow \quad |\psi\rangle_{\text{atom-photon, out}}$

$= |\psi\rangle_{\text{S}}\ |\psi\rangle_{393}$

Programmable atom-photon interface

- **Photon-to-atom state transfer**



$|\psi\rangle_{\text{atom-photon, in}}$

$|\psi\rangle_{\text{D}}$ fixed

$|\psi\rangle_{854}$ **qubit**

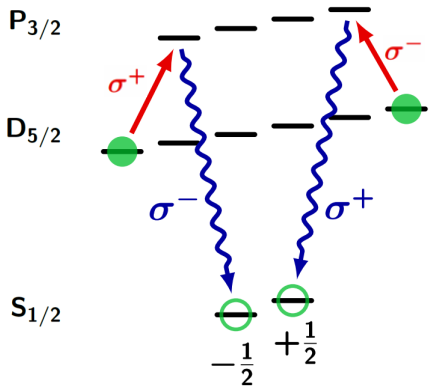
$\rightarrow$ $|\psi\rangle_{\text{atom-photon, out}}$

$|\psi\rangle_{393}$ fixed polarisation

$|\psi\rangle_{\text{S}}$ **mapped qubit**

Programmable atom-photon interface

- **Atom-to-photon state transfer**



$|\psi\rangle_{\text{atom-photon, in}}$

$|\psi\rangle_{\text{D}}$ **qubit**

$|\psi\rangle_{854}$ fixed

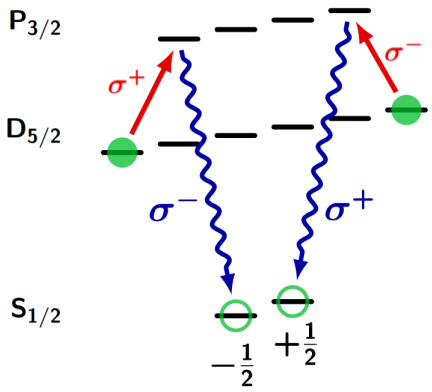
$\rightarrow$ $|\psi\rangle_{\text{atom-photon, out}}$

$|\psi\rangle_{393}$ **mapped qubit**

$|\psi\rangle_{\text{S}}$ projected

Programmable atom-photon interface

- **Atom-photon entanglement**



$|\psi\rangle_{\text{atom-photon, in}}$

$|\psi\rangle_{\text{D}}$ fixed

$|\psi\rangle_{854}$ fixed

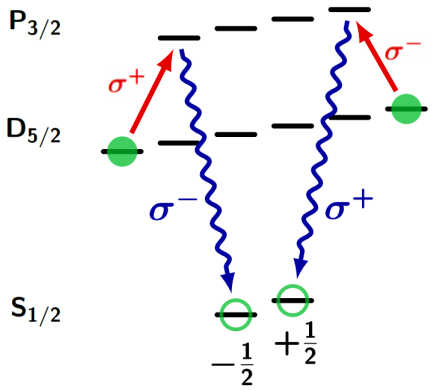
$\rightarrow$ $|\psi\rangle_{\text{atom-photon, out}}$

$|\psi\rangle_{393}$

$|\psi\rangle_{\text{S}}$ } **entangled**

Programmable atom-photon interface

- **Photon-photon conversion**



$|\psi\rangle_{\text{atom-photon, in}}$

$|\psi\rangle_{\text{D}}$ fixed

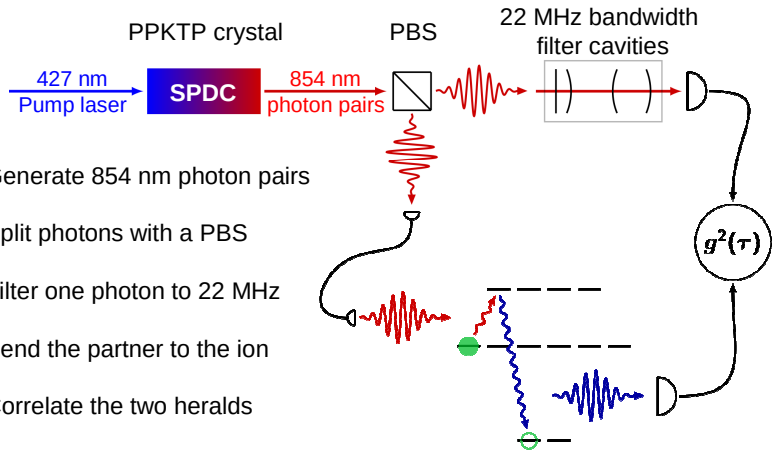
$|\psi\rangle_{854}$ **qubit**

$\rightarrow$ $|\psi\rangle_{\text{atom-photon, out}}$

$|\psi\rangle_{393}$ **qubit**

$|\psi\rangle_{\text{S}}$ projected

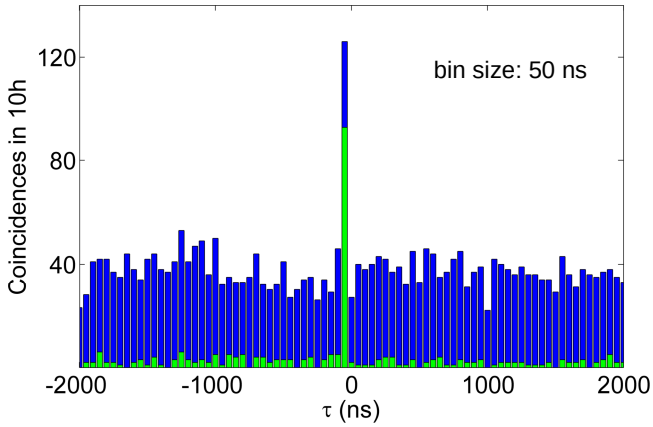
Photon-to-atom state transfer



- Generate 854 nm photon pairs
- Split photons with a PBS
- Filter one photon to 22 MHz
- Send the partner to the ion
- Correlate the two heralds

J. Brito et al., APB (2015)

Photon-to-atom state transfer



SNR = 14.2
SBR = 2.3

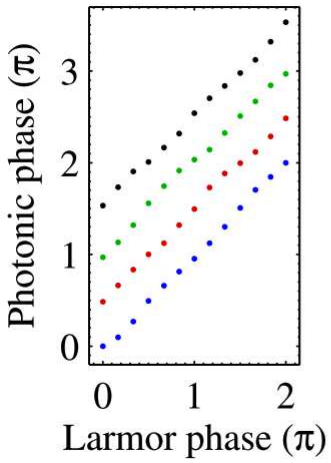
SNR = 61.5
SBR = 40.7

- Green: with applied atomic state discrimination

J. Brito et al., APB (2015)

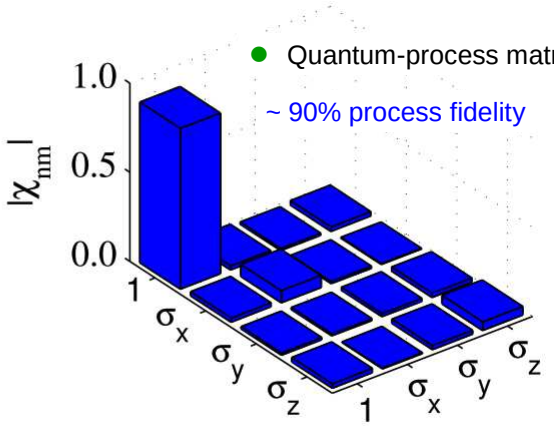
Atom-to-photon state transfer

- **Phase mapping**



- Quantum-process matrix

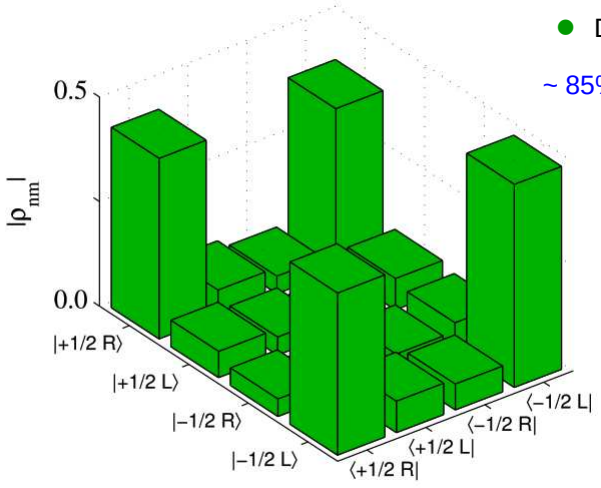
~ 90% process fidelity



Atom – photon entanglement

- Density matrix

~ 85% fidelity to $\Psi^{(-)}$



Outline

The main players

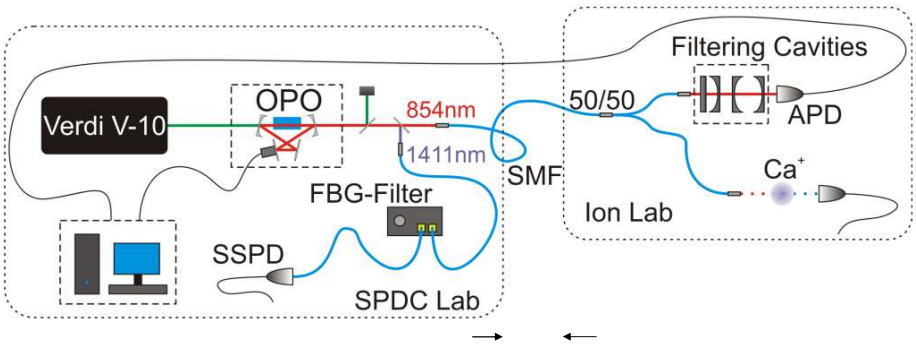
Earlier results

Heralded photon-to-atom state transfer

Programmable ion-photon interface

Telecom-ion interfaces

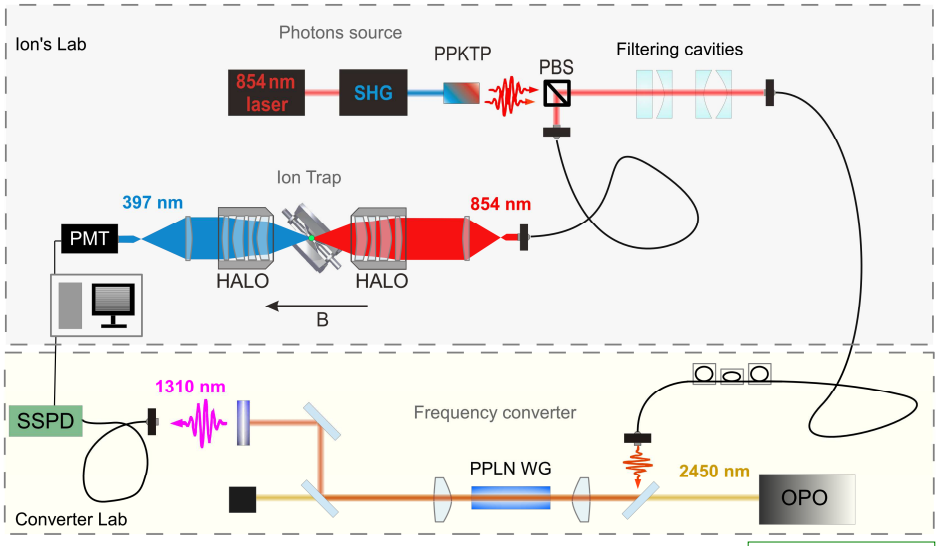
Ion – telecom interface



C. Becher's lab — 90 m — our lab

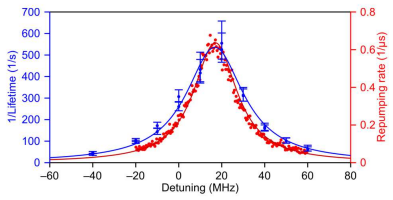
A. Lenhard et al., PRA, soon

Single photon conversion to telecom



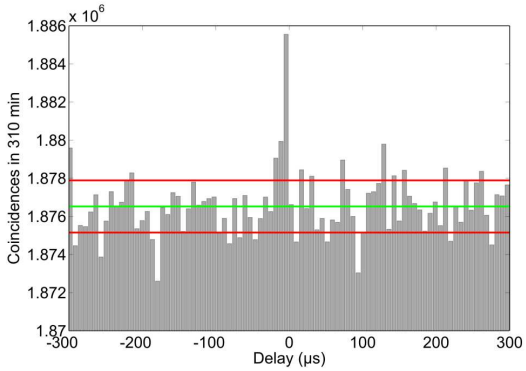
J. Brito et al., t.b.p.

Telecom-heralded absorption



- Single-photon spectroscopy

- Telecom-heralded single-photon absorption



A. Lenhard et al., PRA, soon

Summary

Ion-photon networking tools

- **Single-photon generation**
- **Heralded photon-to-atom state transfer**
- **Atom-photon entanglement**
- **Atom-to-photon state transfer**
- **Telecom-heralded single-photon absorption**

www.uni-saarland.de/lehrstuhl/eschner

The Team

Funding: UdS, BMBF (QuOReP, QSCALE), EU, AvH, Conicyt, Krupp-Stiftung