Controlled emission and absorption of single photons by single atoms

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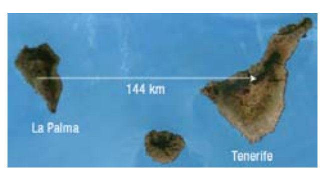
QIPA-2011, Allahabad, India, 19. Feb. 2011

Quantum Optical Information Technology

- **Quantum Computing & Simulation**
  - Factorization, data base search

- **Quantum Cryptography (QKD)**
- **Quantum Random Number Generation**

- **Quantum Communication**
  - Entanglement over large distance

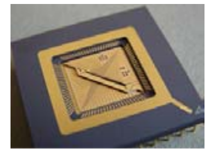


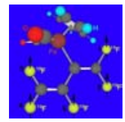
- **Quantum Metrology (clocks, sensors)**

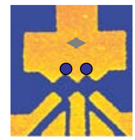
Quantum processors - various approaches

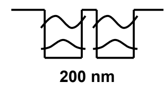
COLD SINGLE QUANTUM SYSTEMS WITH CONTROLLED INTERACTION

- **Ion traps**
- Neutral atoms in traps (opt. traps, opt. lattices, microtraps)
- Neutral atoms and cavity QED
- NMR (in liquids)
- Superconducting qubits (charge-, flux-qubits)
- Solid state concepts (spin systems, quantum dots, etc.)
- Optical qubits and LOQC (linear optics quantum computation)
- Electrons on L-He surfaces or in Penning trap
- Ion-doped crystals or colour centers
- Rydberg atoms
- …and more





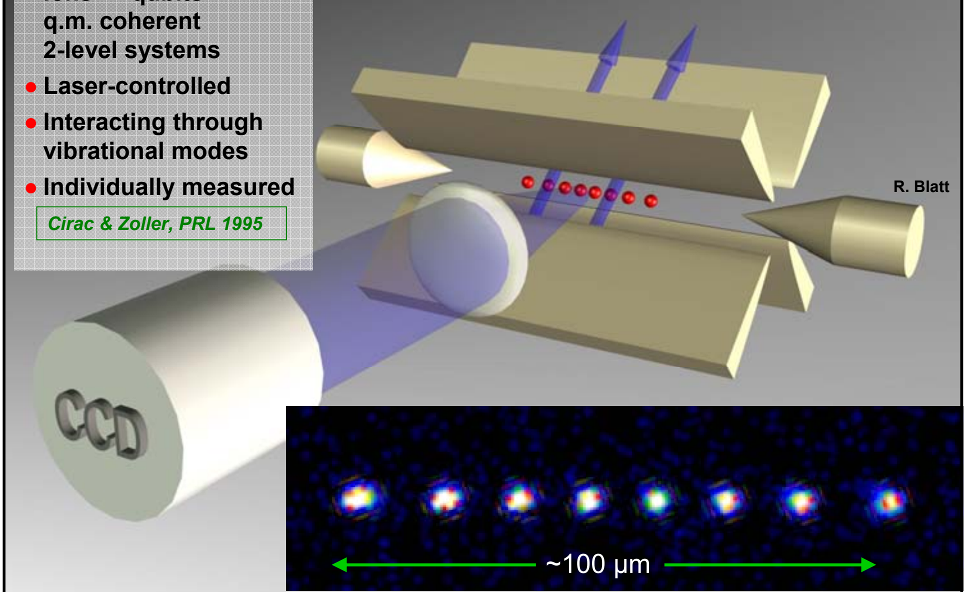




QIP workhorse : linear Paul trap

- **Ions = "qubits" = q.m. coherent 2-level systems**
- **Laser-controlled**
- **Interacting through vibrational modes**
- **Individually measured**

Cirac & Zoller, PRL 1995



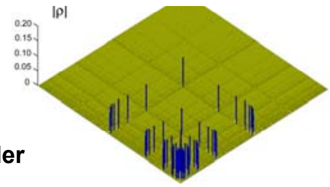
Highlights

- **Entangled W state of 8 ions @ Innsbruck**

$$|\mathrm{W}\rangle = \frac{1}{\sqrt{N}}\left(|D\ldots D\,S\rangle + |D\ldots D\,S\,D\rangle + \ldots + |S\,D\ldots D\rangle\right)$$

Fidelity of density matrix 72%

Nature 2005

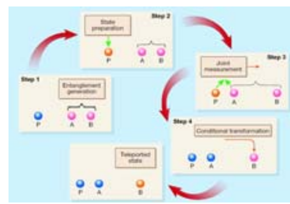


- **Entangled GHZ state of 6 ions @ NIST Boulder**

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}\left(|D\,D\ldots D\rangle + |S\,S\ldots S\rangle\right)$$

- **Quantum teleportation between ions @ Ibk & NIST**

Nature 2004



- **High-fidelity gate, quantum simulations, etc**

… lots of recent Nature, Science, PRL …

Quantum Optical Information Technology

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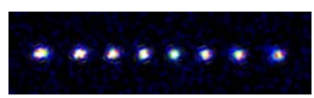
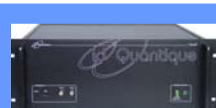
  - Factorization, data base search



- **Quantum Cryptography (QKD)**

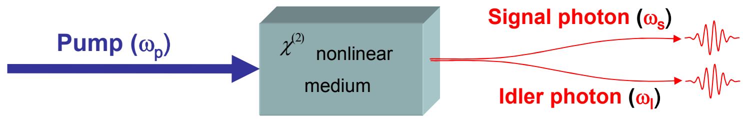


- **Quantum Random Number Generation**
- **Quantum Communication**
  - Entanglement over large distance

- **Quantum Metrology (clocks, sensors)**

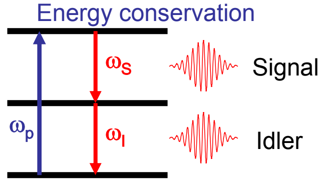
Quantum communication workhorse : SPDC

Spontaneous Parametric Down-Conversion



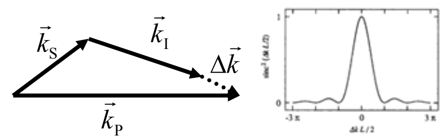
Phase matching conditions

Energy conservation



$$\omega_P = \omega_S + \omega_I$$

Momentum conservation

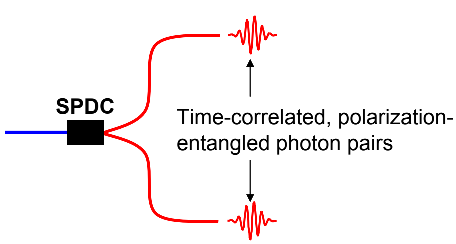


$$\vec{k}_P = \vec{k}_S + \vec{k}_I + \Delta\vec{k}$$

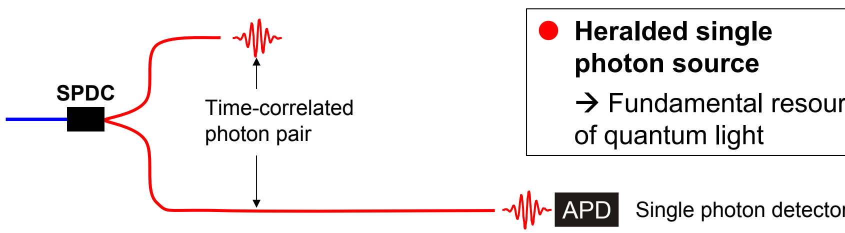
Type II phase matching: $\mathrm{H} \rightarrow \mathrm{H+V}$

Polarization entanglement: $|H_S\rangle|V_I\rangle - |V_S\rangle|H_I\rangle$

SPDC photons in QC



- **Entangled photon pair source**
  → Fundamental resource of entanglement



- **Heralded single photon source**
  → Fundamental resource of quantum light

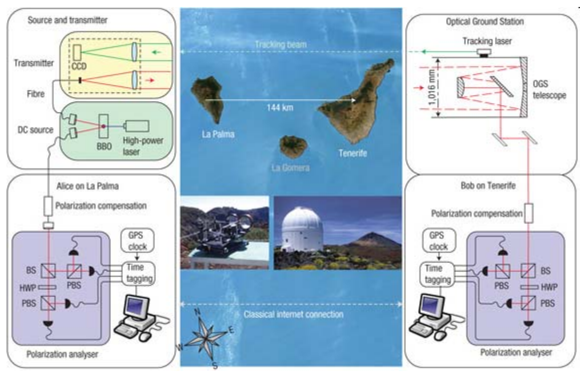
Highlights

- **Quantum key distribution**

  Toshiba 2010 – secure bit rate > 1 Megabit/sec over 50 km of fibre

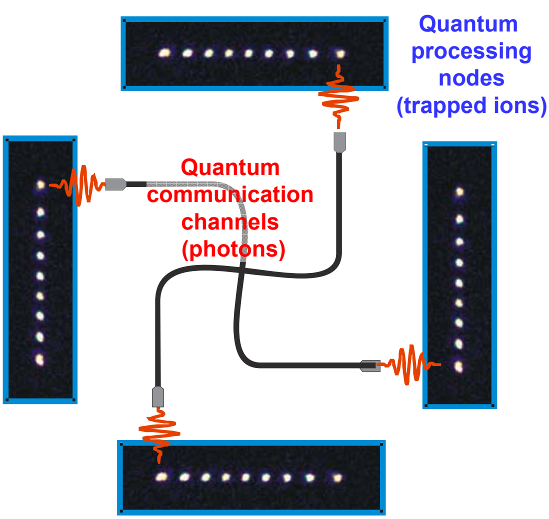
  Vienna 2009 – QKD network connecting various platforms

- **Entanglement distribution over 144 km**



Ursin et al., Nature Physics 2007

Integration : Quantum Network



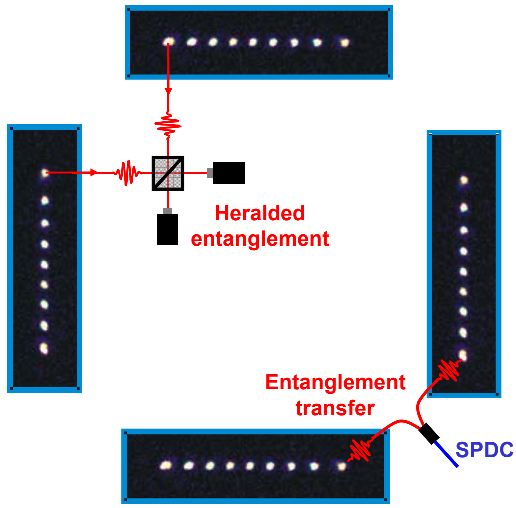
Need:

Atom - photon interfaces:
Coherently map states from one to the other

Distribute entanglement between distant nodes:
allows to scale up computing power of the system

Cirac et al., PRL 1997
Kimble, Nature 2008

Entanglement distribution



By interference of photons from two atoms

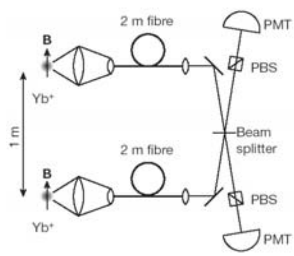
Simon et al. PRL (2003)
Cabrillo et al. PRA (1999)
Moehring et al. Nature (2007)

By absorption of entangled photon pairs

Lloyd et al., PRL (2001)

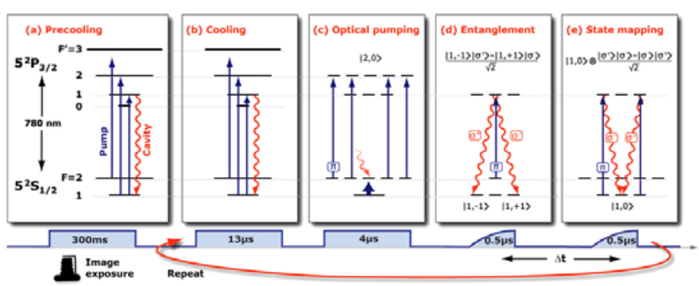
Highlights

- **Distant atomic entanglement**
  - Fidelity 63 %
  - 1 pair / 39 s



Moehring et al., Nature 2007

- **Single atom as source of entangled photons**

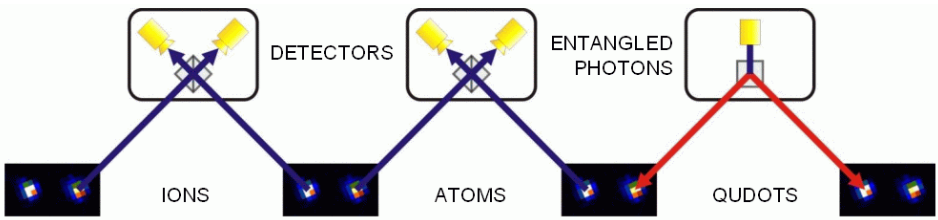


Weber et al., PRL 2009

Integration of platforms

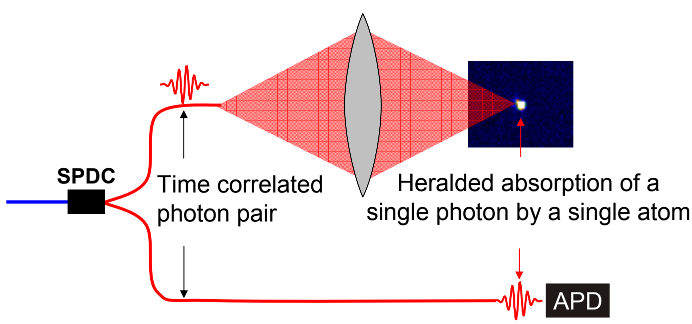
- Linear ion string : Quantum Information Processing
- SPDC entangled photon pairs : Quantum Communication

Seminal results from individual systems, but coupling not demonstrated.



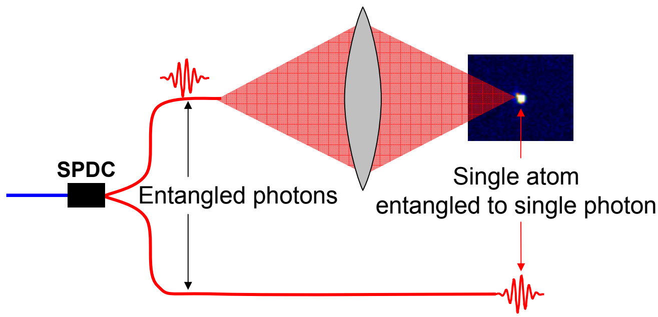
Coupling ions and SPDC

➔ **Controlled absorption of single photons**



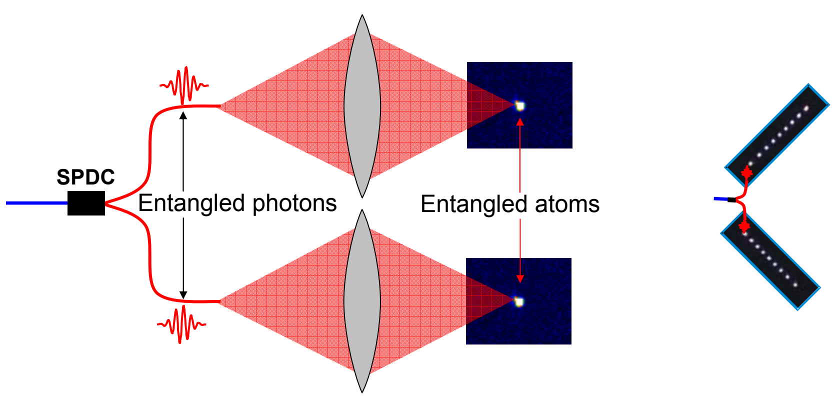
Coupling ions and SPDC

➔ **Quantum state transfer from photon to atom (remote state preparation)**



Coupling ions and SPDC

➔ **Entanglement transfer from photon to atom pairs (remote entanglement)**



Outline

Ion trap

Entangled photon pair source

Single photon – single atom interaction

Entanglement-preserving absorption

Controlled photon emission

Conclusions and outlook

Outline

Ion trap

Entangled photon pair source

Single photon – single atom interaction

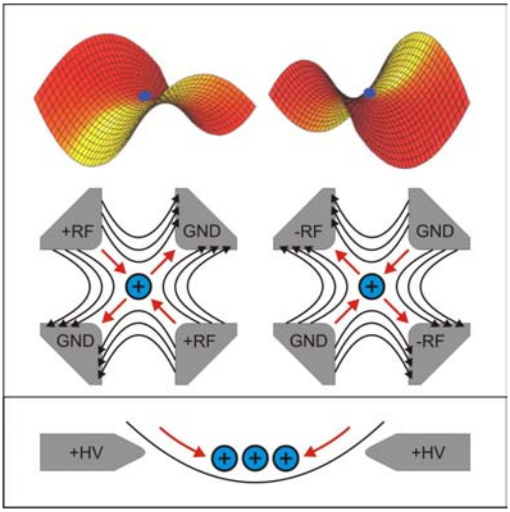
Entanglement-preserving absorption

Controlled photon emission

Conclusions and outlook

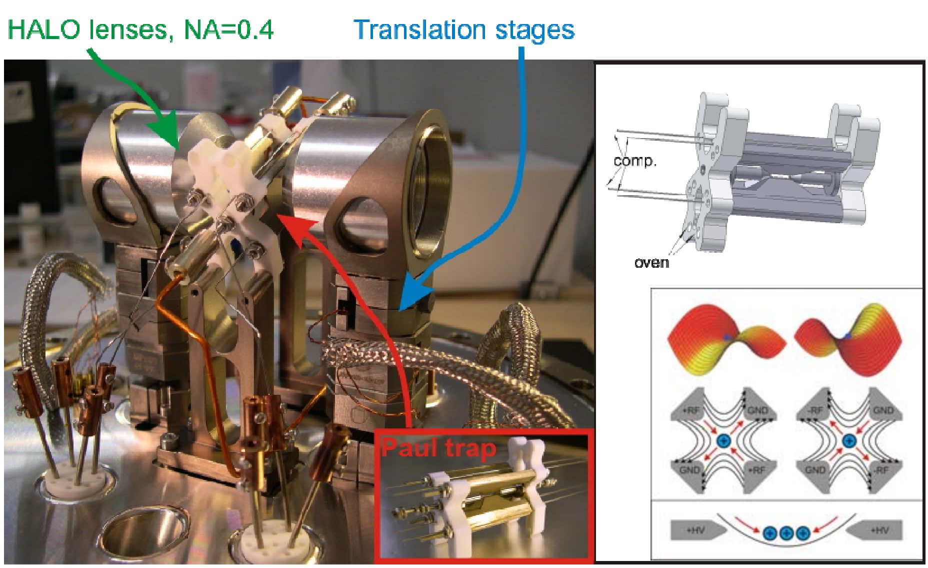
S. Gerber et al., NJP 2009
F. Rohde et al., J. Phys. B 2010
C. Schuck et al., J. Phys. B 2010

Trapping ions

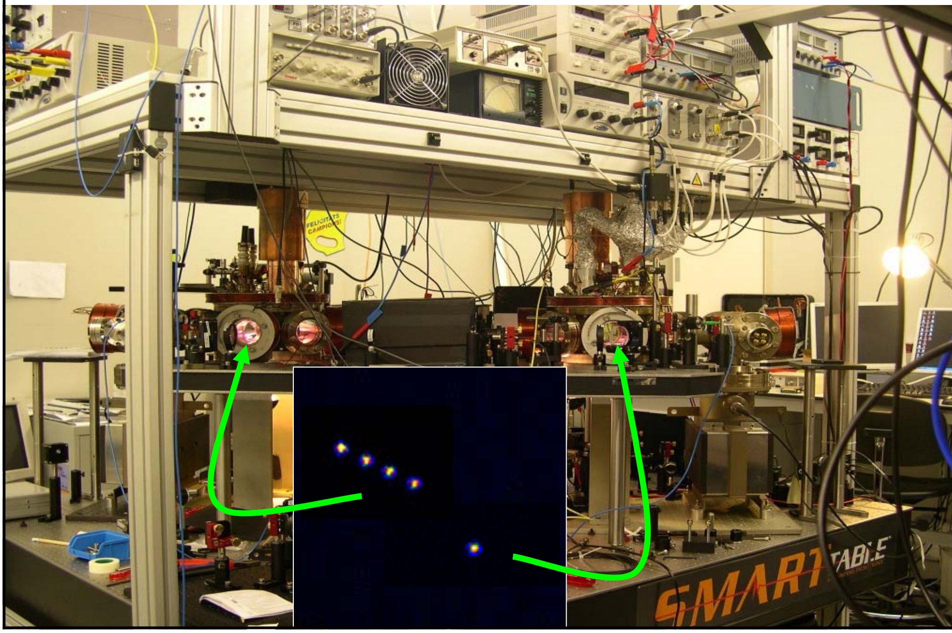


- Paul trap mechanism
  → Trapped charged particles
- Linear trap ~1 mm size
  → Ion strings
- Laser cooling
  → Localization << λ_{Laser}
- Coulomb repulsion
  → Interaction by common modes of motion

Ion trap setup



Double trap apparatus



Outline

Ion trap

Entangled photon pair source

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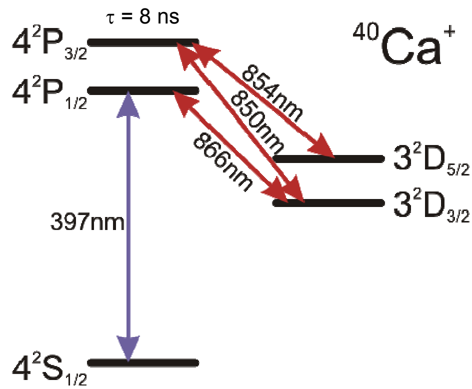
Conclusions and outlook

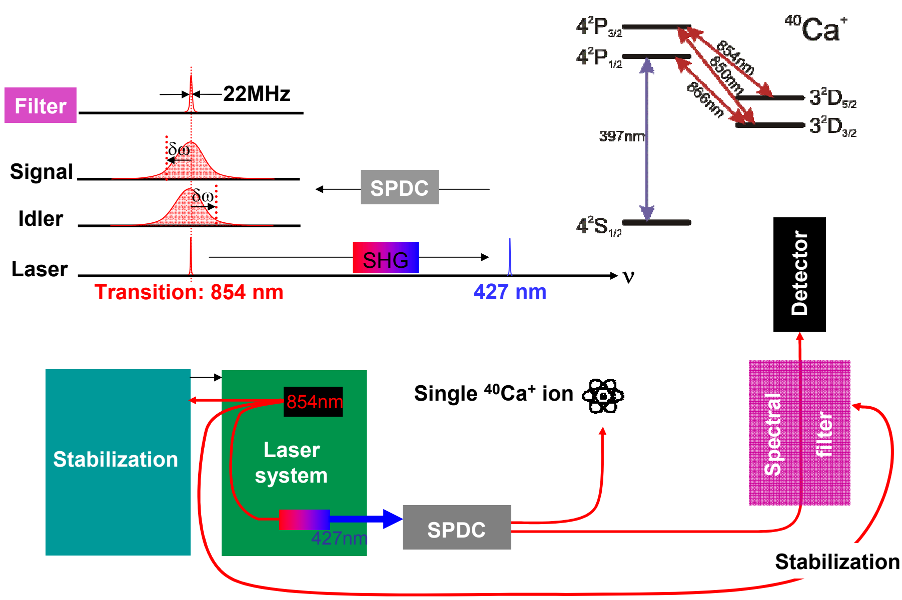
A. Haase et al., Opt. Lett. 2009
N. Piro et al., J. Phys. B 2009
Collab.: M. Mitchell

Design parameters for photon pair source

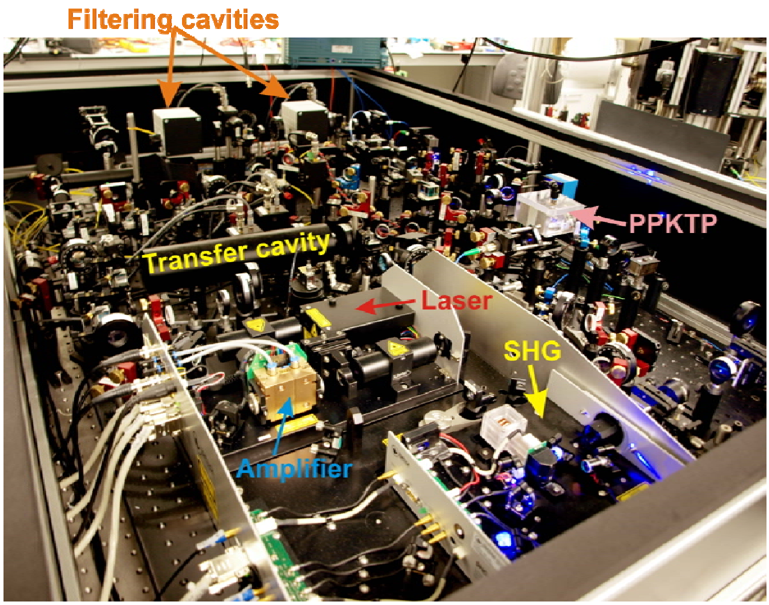
- Time correlated photon pairs
- Tunable to 850-854 nm and stable
- Small bandwidth: 22 MHz (for heralded photons)
- High brightness (>100 photon pairs/s)
- Polarisation entanglement



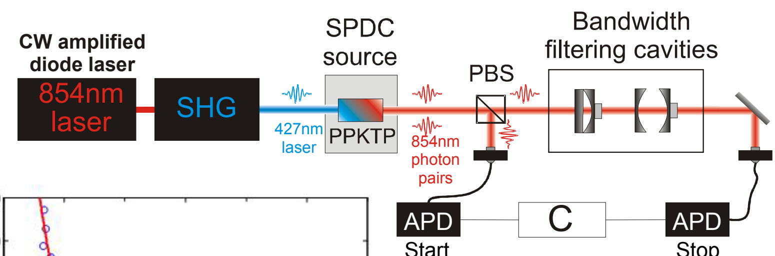
Schematic design

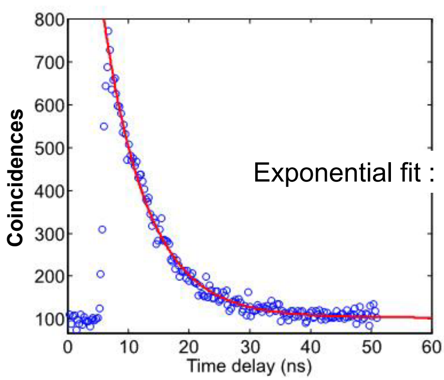


The setup in real life



Characterization : time correlation

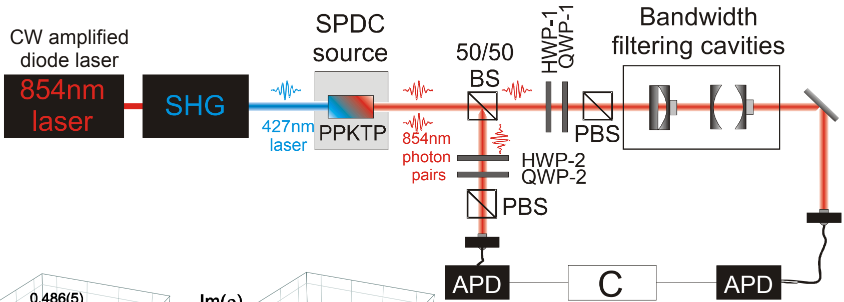


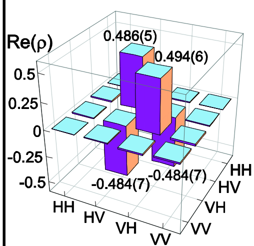


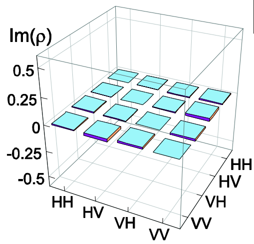
Exponential fit : $\delta\nu = 22.0 \pm 0.5$ MHz

(from 17700 coincidences in 2900 s)

Polarization state tomography





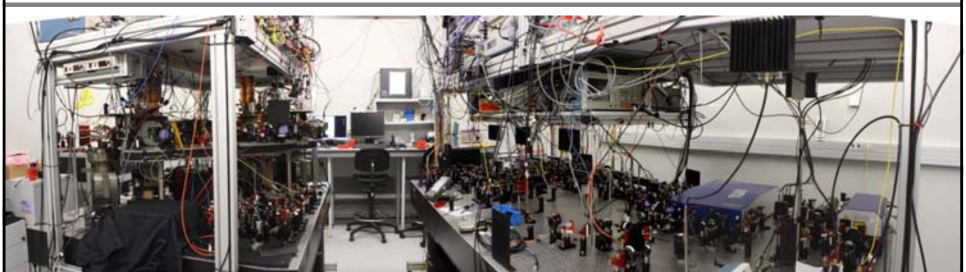


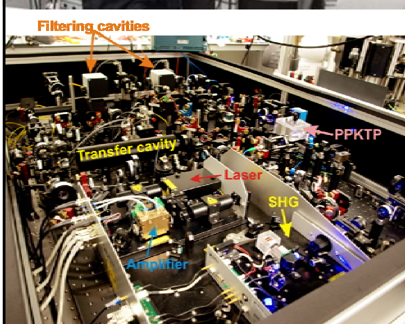
- **Fidelity to the singlet state:**

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|H,V\rangle - |V,H\rangle)$$

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

Single photon – single atom interaction





Let's combine the setups!

Outline

Ion trap

Entangled photon pair source

Single photon – single atom interaction
- Detecting the absorption event

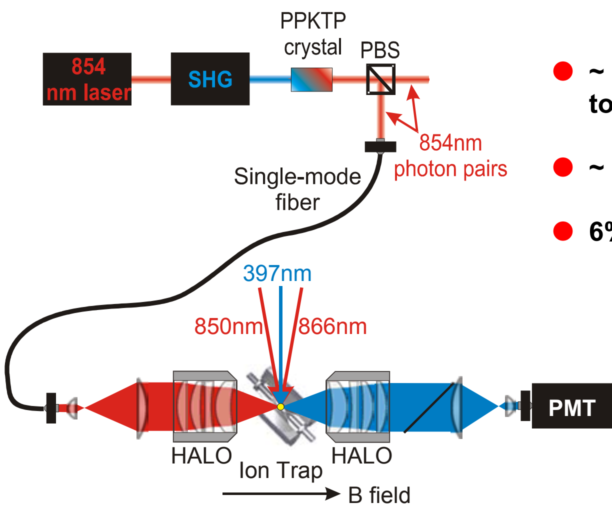
Entanglement-preserving absorption

Controlled photon emission

Conclusions and outlook

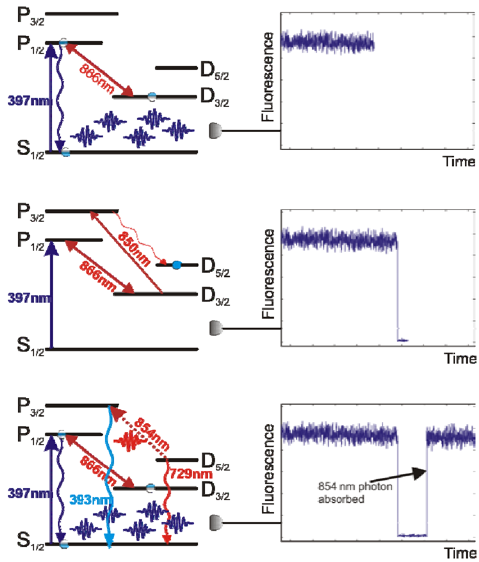
C. Schuck et al. PRA 2010

Signature of absorption of SPDC photons



- ~ 5000 photons/s to single ion
- ~ 1% mode overlap
- 6% oscillator strength

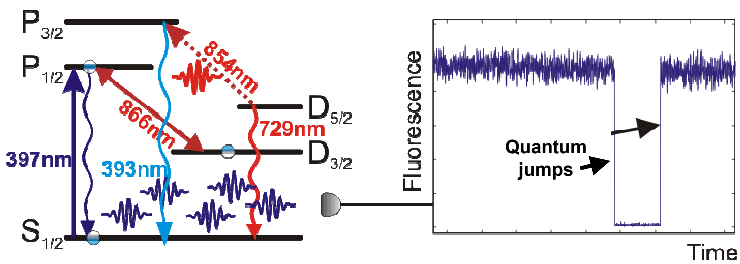
Quantum jump scheme



- Two indistinguishable processes :

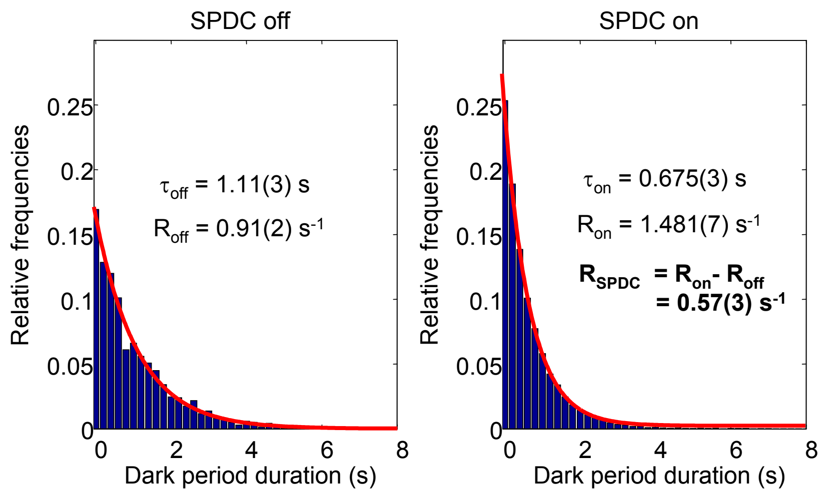
  854 nm absorption
  729 nm spontaneous decay

Quantum jumps



Signature of absorption of SPDC photons

- Plot histograms of dark time durations



Outline

Ion trap

Entangled photon pair source

Single photon – single atom interaction
- Heralding the absorption event

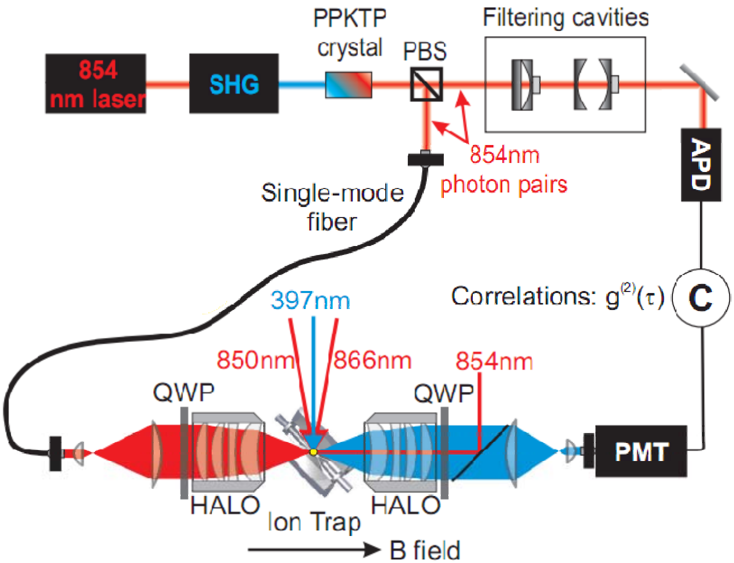
Entanglement-preserving absorption

Controlled photon emission

Conclusions and outlook

N. Piro et al. Nature Physics 2011

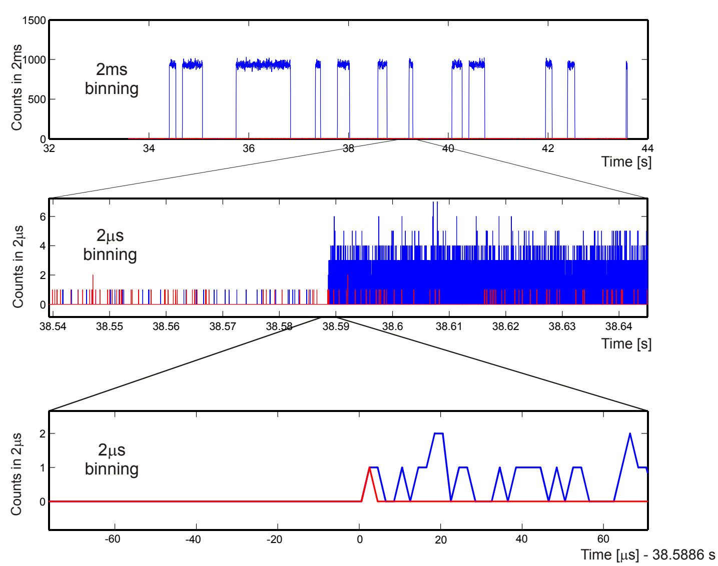
Heralding the absorption event



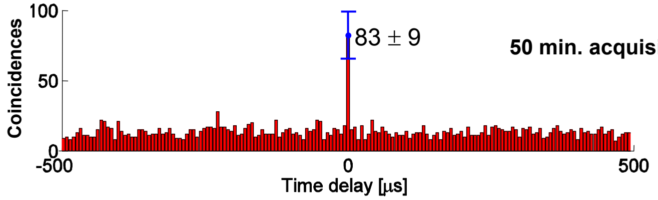
Heralding the absorption event

PMT counts (397 nm fluorescence)

APD counts (filtered trigger photons)



Absorption-trigger coincidences

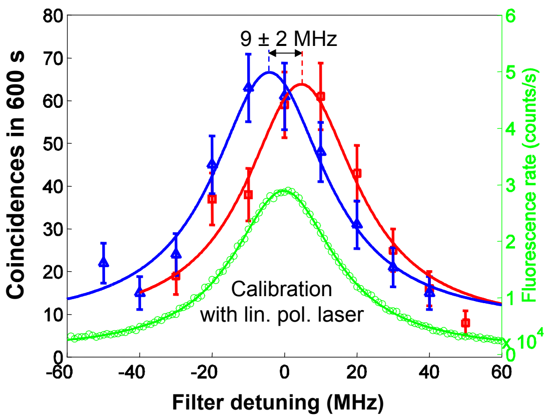


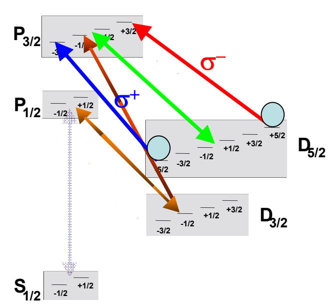
50 min. acquisition time

- **Absorption rate = 1.57 s^{-1}**
- **Absorption efficiency > $3\cdot10^{-4}$**
- **175 – 20 = 155 coincidences in 30 min.**
- **7% correlation probability**

Heralded single photon spectroscopy

- **After preparing ion in opposite Zeeman substates of $D_{5/2}$**





- **Only filter is detuned!**

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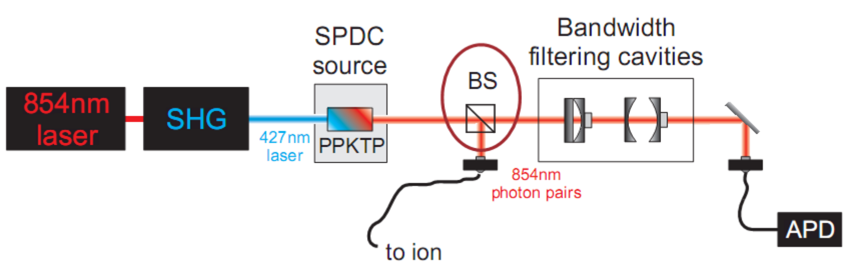
To be published

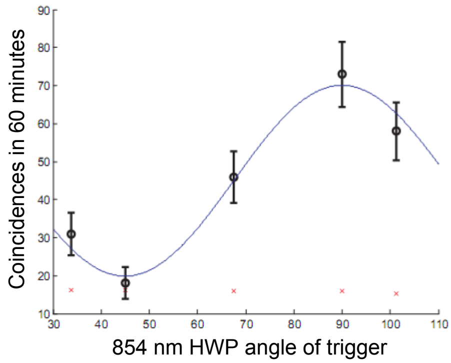
Transferring photon entanglement

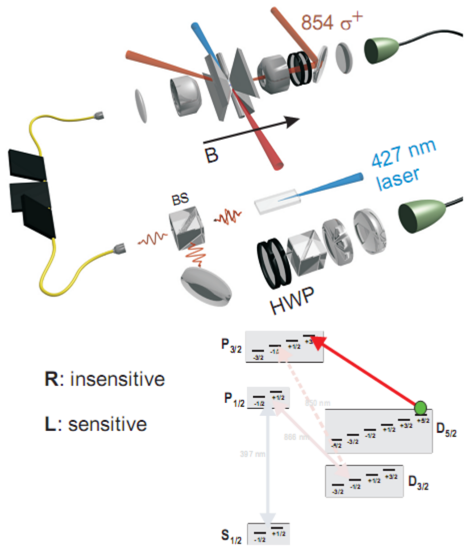
- PBS replaced by non-polarizing BS
- Only 50 % of photon pairs are split



Single-ion polarization analyser

Circular (R-L) basis
(excitation along B-field)



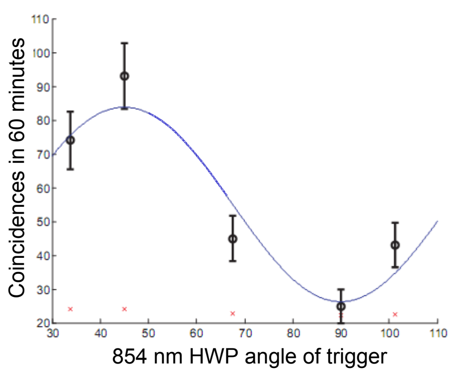


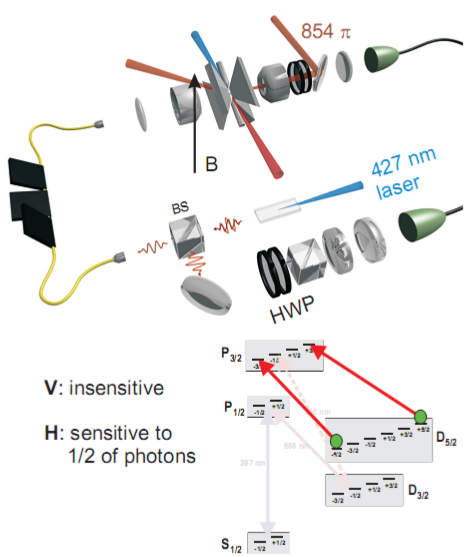
R: insensitive

L: sensitive

Single-ion polarization analyser

H-V basis
(B-field rotated 90º)



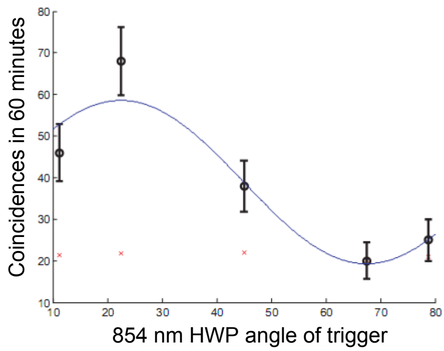


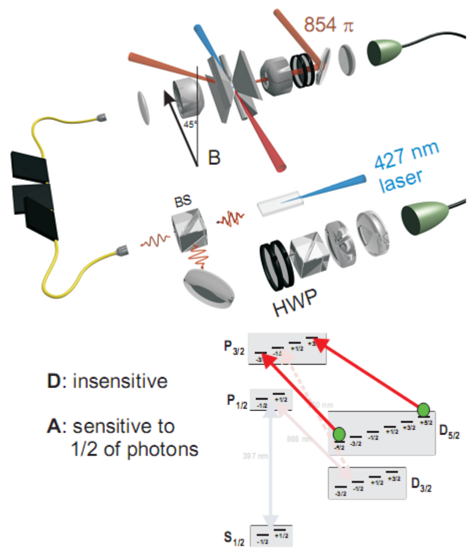
V: insensitive

H: sensitive to
1/2 of photons

Single-ion polarization analyser

Diagonal (D-A) basis
(exciting photon rotated 45º)

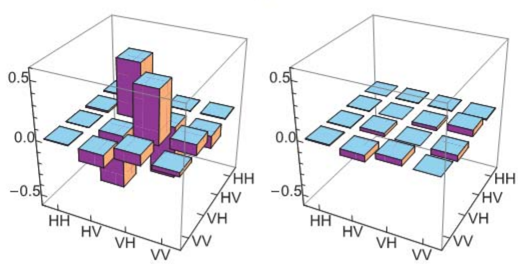




Quantum² tomography

Correlation measurements in 16 independent basis states.

Density matrix reconstruction using Maximum Likelihood approach:



Maximally entangled singlet state : $|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H,V\rangle - |V,H\rangle\right)$

Measured overlap fidelity : $F = \langle\Psi^-|\rho|\Psi^-\rangle \approx 95\%$

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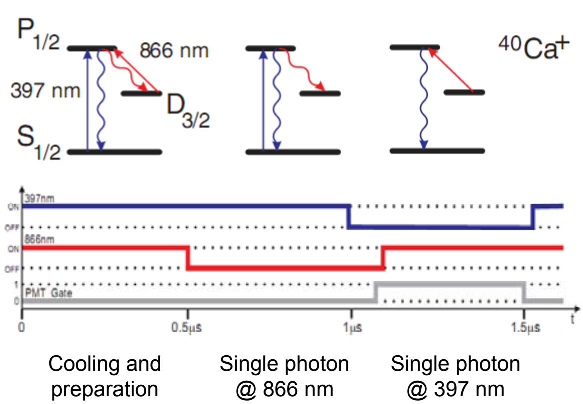
M. Almendros et al., PRL 2009

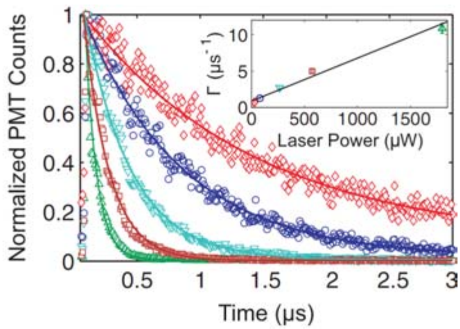
Tunable single photon generation



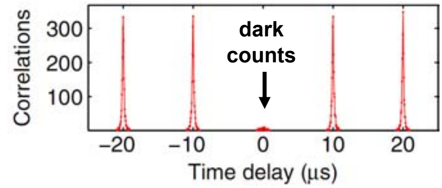
- **Objective: efficient creation of transform-limited single photons with widely variable bandwidth (for multiplexing)**

Single photons from one ion

- Arrival time distribution



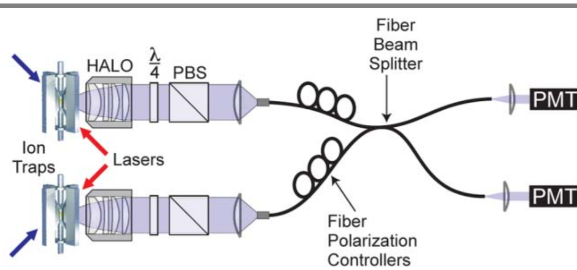
- Auto-correlation of source

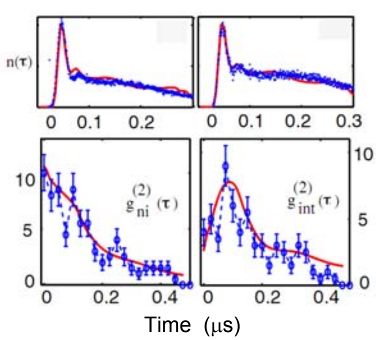


- Controlled photon wave packet between 70 ns and 2 μs
- Brightness ~ 2000/s multi mode, ~ 100/s single mode (now x 10)
- No cavity, no 4π collimation

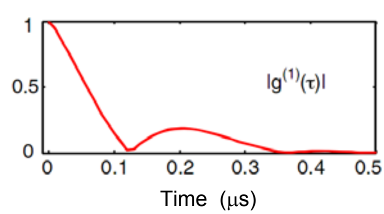
Indistinguishability & Fourier limit

- Single photons from two ions





- 50% HOM suppression
- $T_1 \approx 230$ ns, $T_2 \approx 250$ ns



Outline

Ion trap

Entangled photon pair source

Single photon – single atom interaction

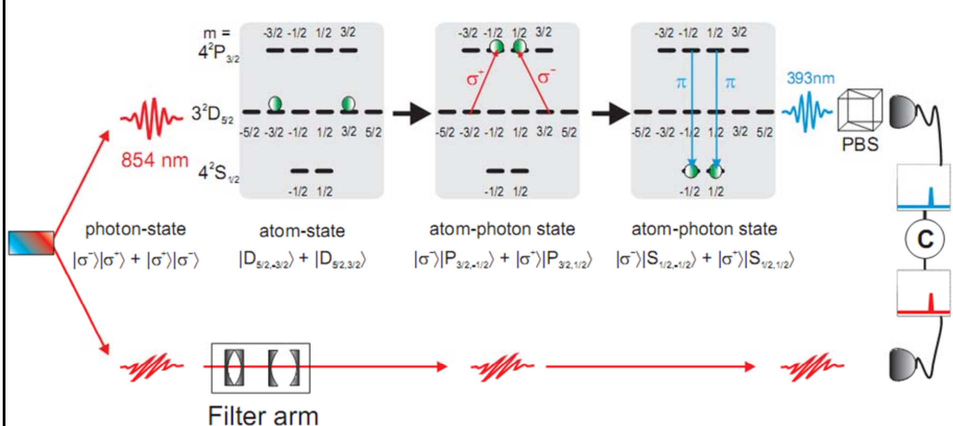
Entanglement-preserving absorption

Controlled photon emission

Conclusions and outlook

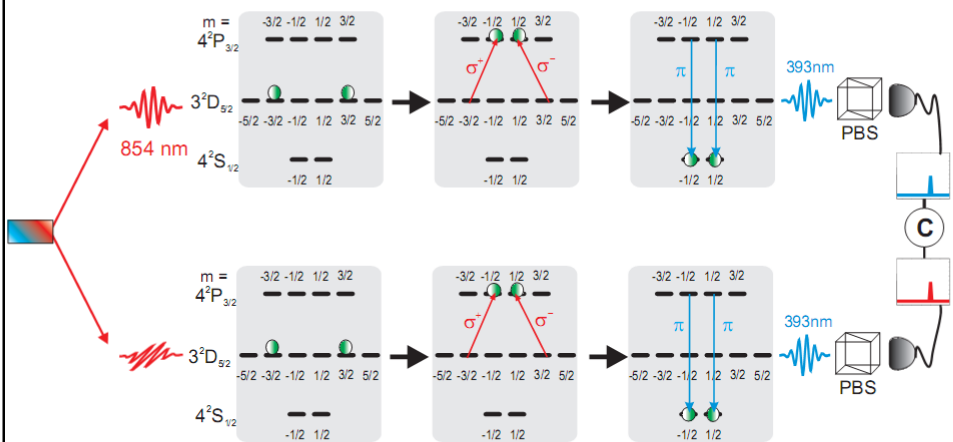
Outlook: entanglement transfer scheme

- **Photon - Photon to Photon - Atom entanglement transfer**



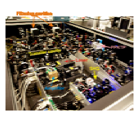
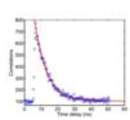
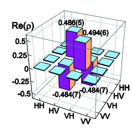
Outlook: entanglement transfer scheme

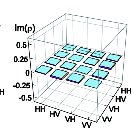
- **Photon - Photon to Atom - Atom entanglement transfer**



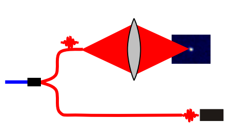
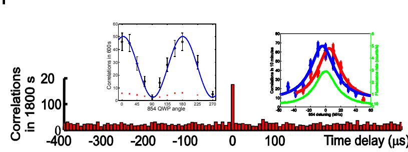
Conclusions

- Source of entangled photon pairs, suitable for interaction with single $^{40}Ca^{+}$ ions



- Coupled source photons to single trapped ion :
  Heralded single photon absorption

- Contribution to quantum optical information technology
- Interaction of most fundamental quantum optical systems

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