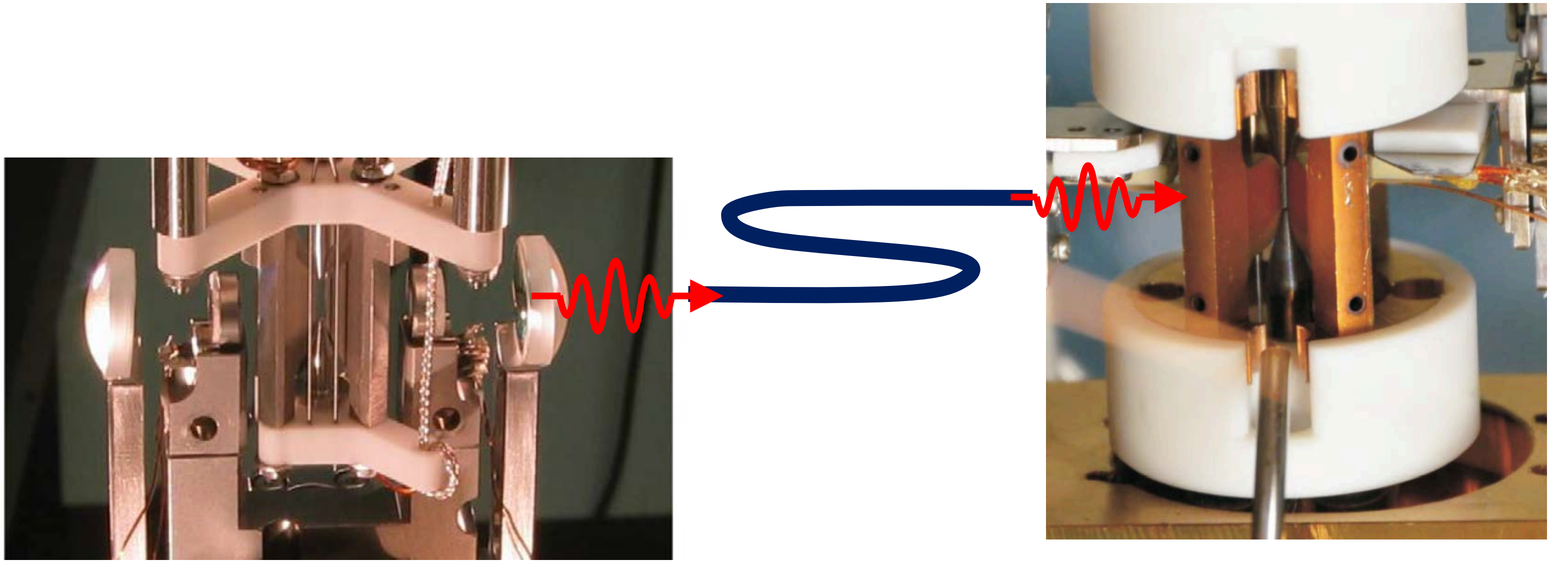
Towards a Quantum Network with Trapped Ions in Optical Cavities



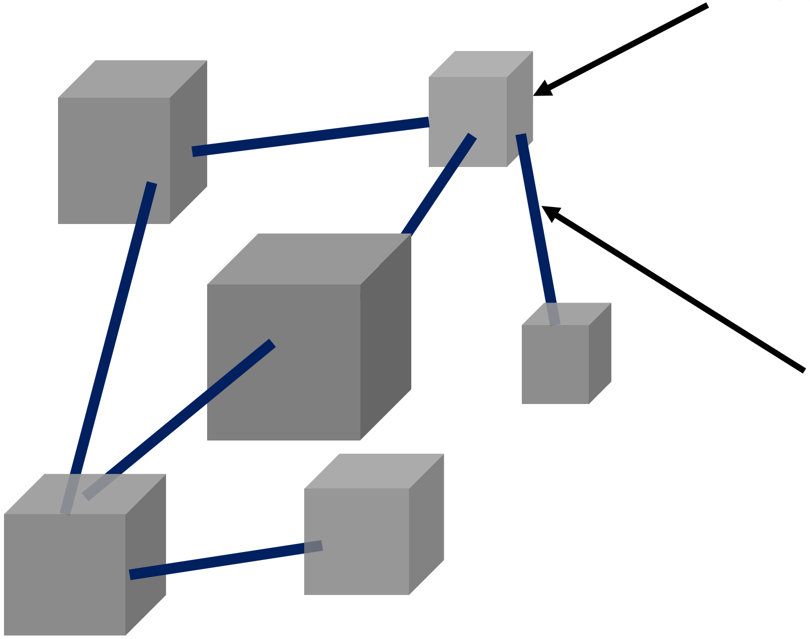
Florian Ong, University of Innsbruck

30 years of Quantronics, June 24th 2015

Horizon 2020
European Union Funding
For Research & Innovation

Quantum networks

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



Node → stationary qubit

- quantum emitter(s)
- light-matter interface

Channel → flying qubit

- entangle distant emitters
- transfer quantum information

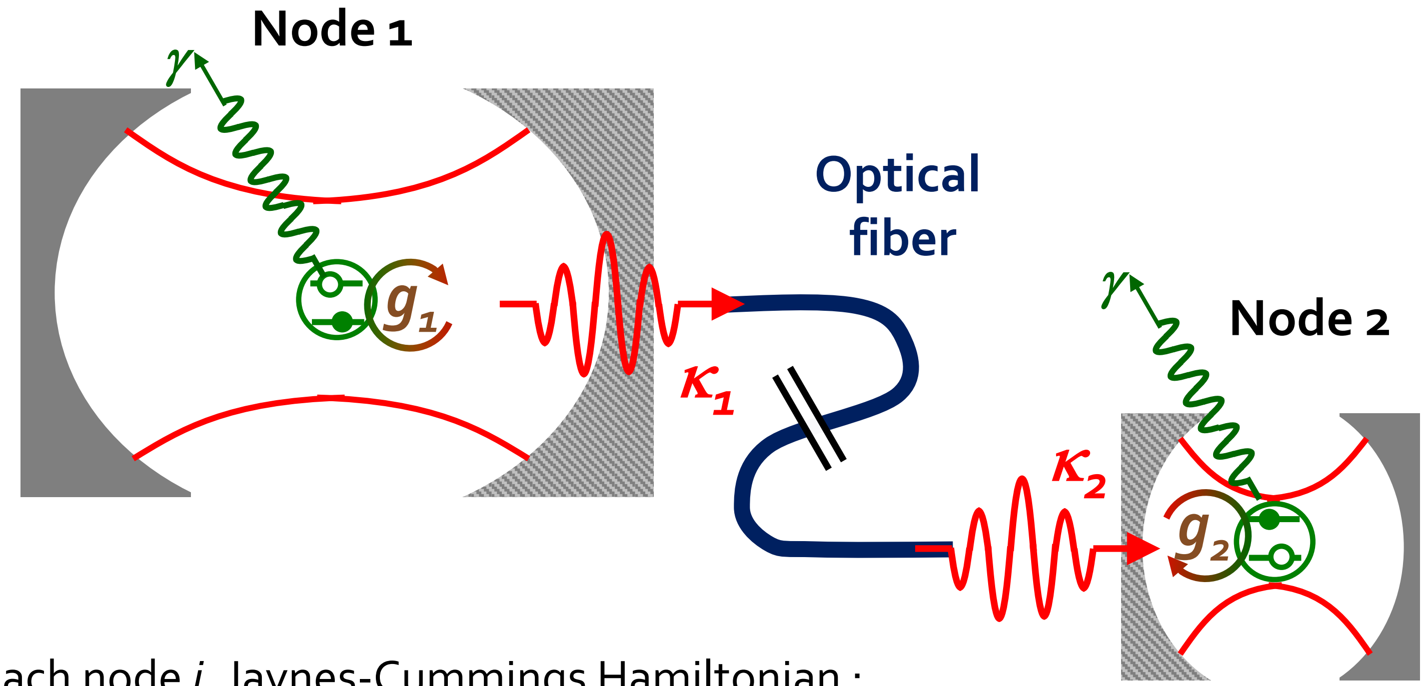
A versatile architecture for :

- distributed QIP
- communication (quantum repeaters)
- quantum simulators (arbitrary connectivities and interactions)
- metrology (distributed atomic clocks)

Elementary network based on cQED

Cirac, Zoller, Kimble, Mabuchi, PRL(1997)
Ritter, ..., Rempe, Nature(2012)

Two atoms in high finesse cavities :



At each node *i*, Jaynes-Cummings Hamiltonian :

$$H_\mathrm{i} = \hbar\omega_\mathrm{a}\sigma_\mathrm{z} + \hbar\omega_\mathrm{c}a^\dagger a + \hbar g_i\left(\sigma^- a^\dagger + \sigma^+ a\right)$$

coherent light-matter interface -> *deterministic* protocols

(and also cavity-enhanced *probabilistic* networking)

"going back" to "real" atoms ?

starting 2004 : *circuit*-QED copied and (quickly) overtook *cavity*-QED

- huge non-linearities without loss
- exotic photon states
- quantum computing

… but *condensed matter* emitters still face challenges

- coherence times
- MW photons are not ideal (superconducting qubits)
- limited reproducibility

-> *hybrid* systems welcome

isolated atoms still have advantages

- reproducibility + coherence
- *trapped ions* : outstanding for QIP + precise/stable localization in cavity
- optical and/or MW frequencies : communication, interface with circuits

Now let’s talk about *ions*

1) cavity QED with 3-level systems

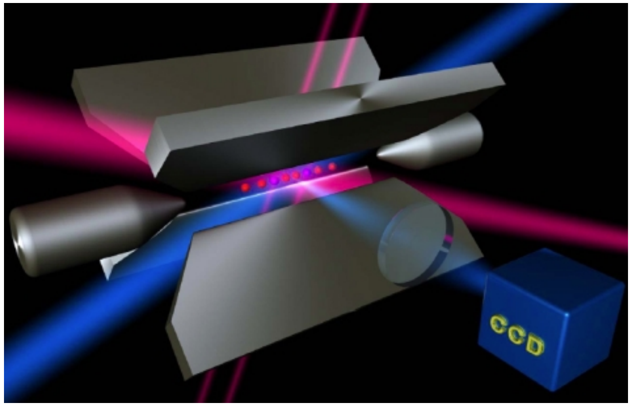
2) examples of quantum communication schemes

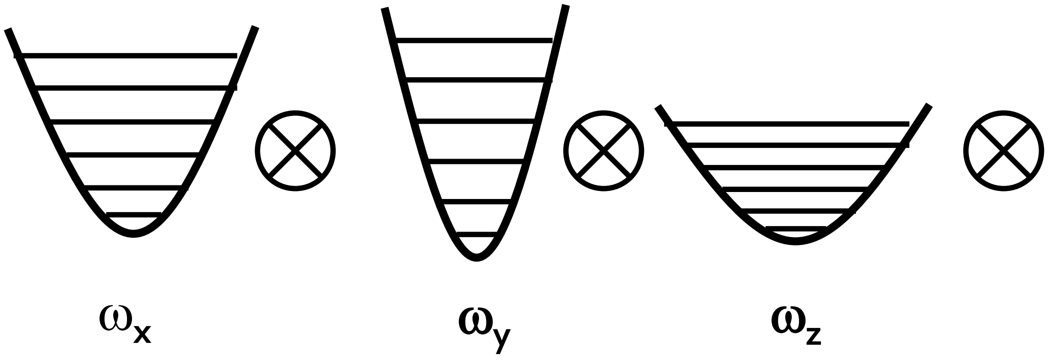
3) towards an elementary network in Innsbruck

Trapped ions energy levels

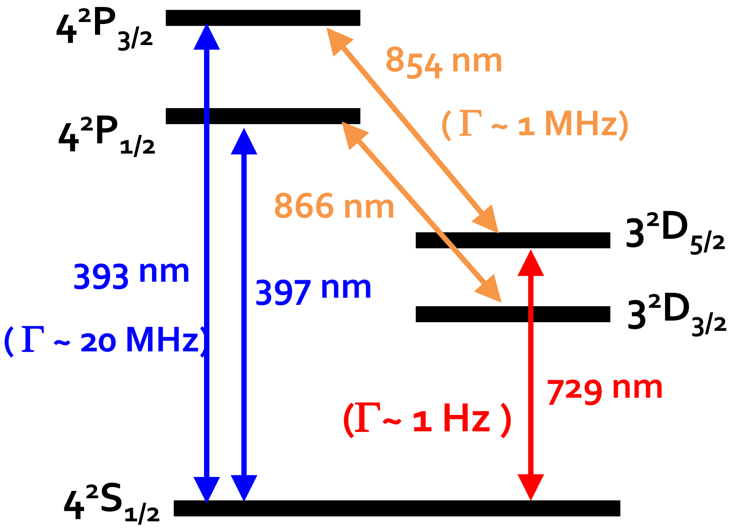
Ion in Paul trap :

3D confinement,
ω_i typ. 100 kHz to 10 MHz




ω_x $\otimes$ ω_y $\otimes$ ω_z $\otimes$

external (motion) states:
harmonic oscillators


$4^2P_{3/2}$

$4^2P_{1/2}$

$3^2D_{5/2}$

$3^2D_{3/2}$

$4^2S_{1/2}$

854 nm (Γ ~ 1 MHz)

866 nm

393 nm (Γ ~ 20 MHz)

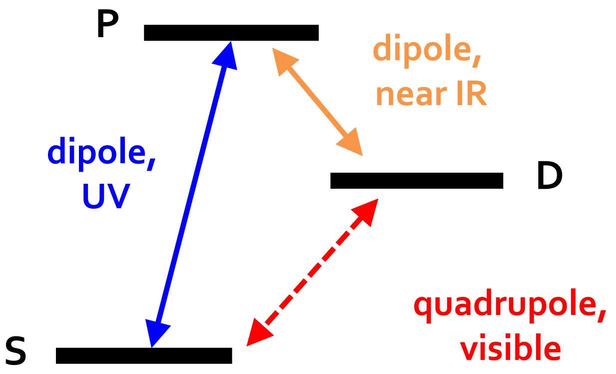
397 nm

729 nm (Γ ~ 1 Hz)

internal (electronic) states
(example of $^{40}Ca^+$)

Cavity QED with a 3-level system

more generally (also Ba$^+$, Sr$^+$…)



Doppler cooling / optical pumping

(with repump)

Optical qubit

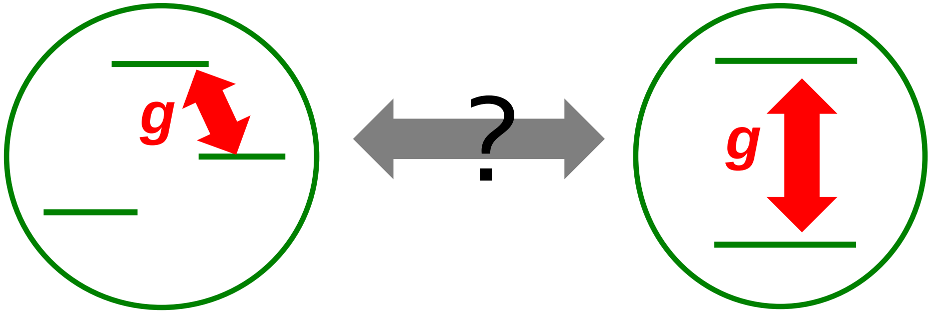
sideband cooling to motional GS

Qubit state readout (detection of fluorescence)

Where to put a cavity ?

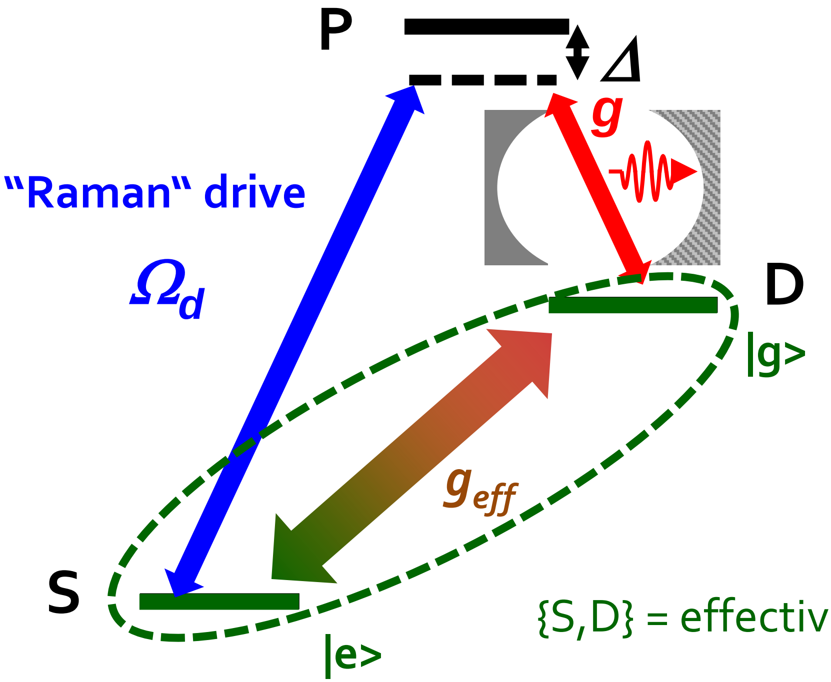
- S-D : too weak ($g \ll \gamma$)
- S-P : no good mirror in UV
- P-D : good compromise

How does this relate to Jaynes-Cummings ?



Cavity QED with a 3-level system

vacuum-assisted Raman transition
-> elimination of P level



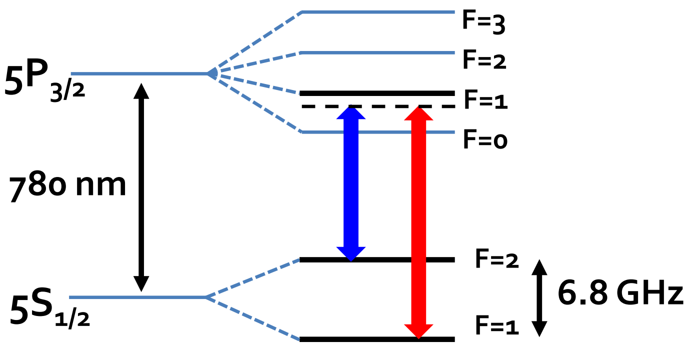
{S,D} = effective TLS with

tunable effective decay rate $\gamma_{\text{eff}} \approx \gamma \left(\frac{\Omega_\text{d}}{2\Delta}\right)^2$

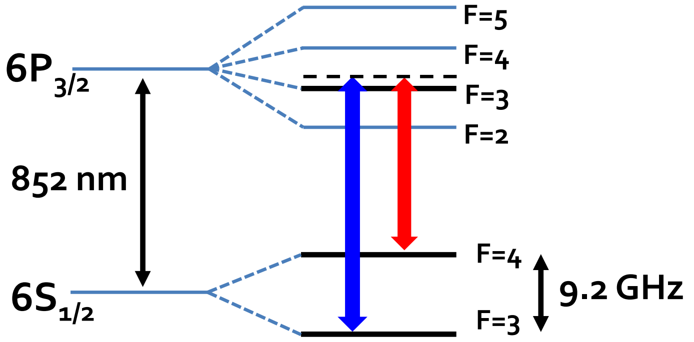
and *tunable* coupling strength $g_{\text{eff}} \approx g \left(\frac{\Omega_\text{d}}{2\Delta}\right)$

Common for cQED with neutral atoms in optical range :

^{87}Rb (eg Rempe, Kuhn...) :



^{133}Cs (eg Kimble):



Coherent ion/photon operations

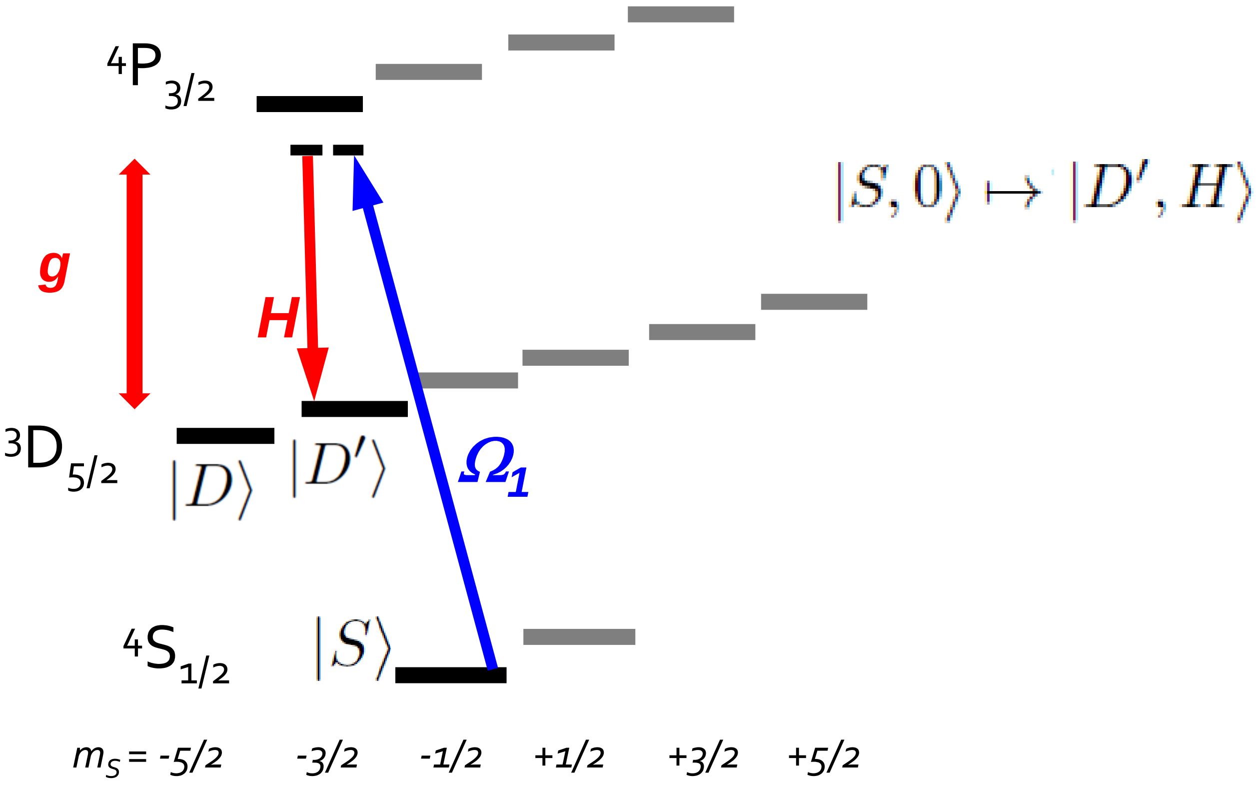
3-level system : ⟨ α |g> + β |e> can be mapped onto ⟨ α |no photon> + β |photon>

<u>but</u> not robust against lossy environment!

Encode photons in polarization instead :

→ apply B field

→ apply **two Raman drives simultaneously**



$$|S,0\rangle \mapsto |D',H\rangle$$

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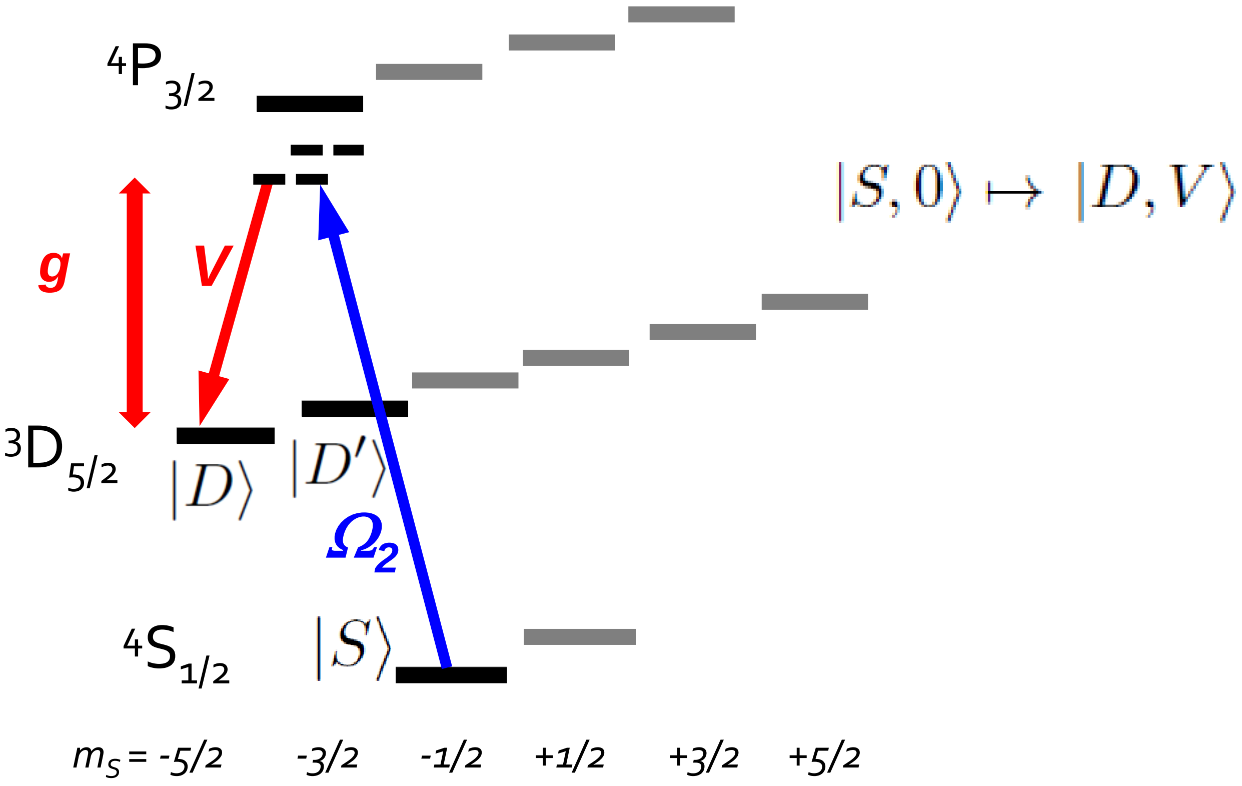

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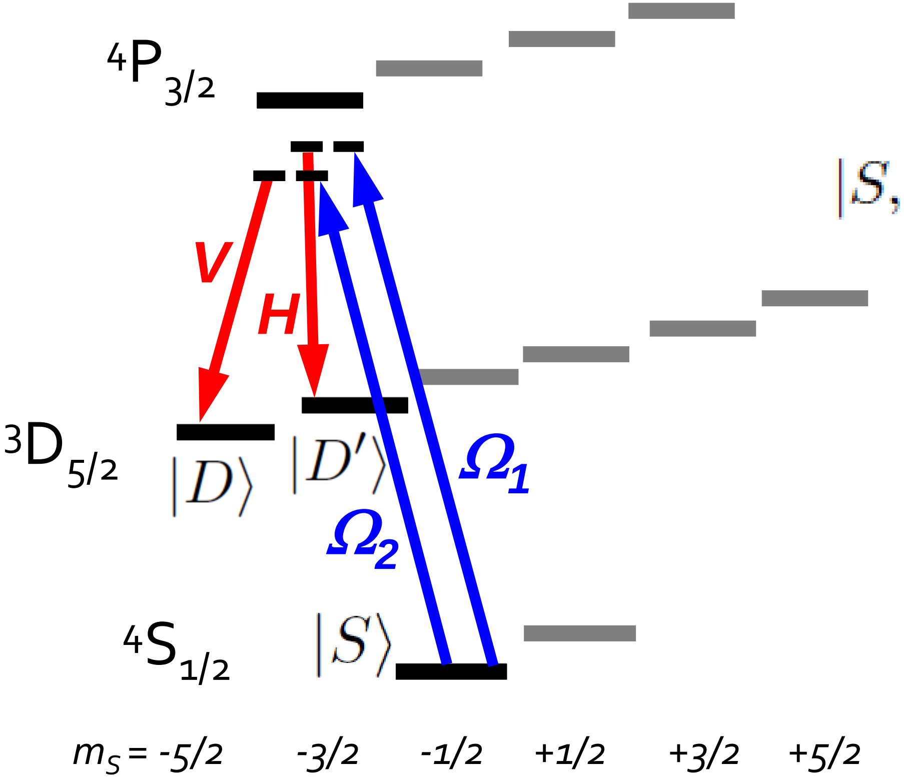


Tunable entanglement between the ion and a photon

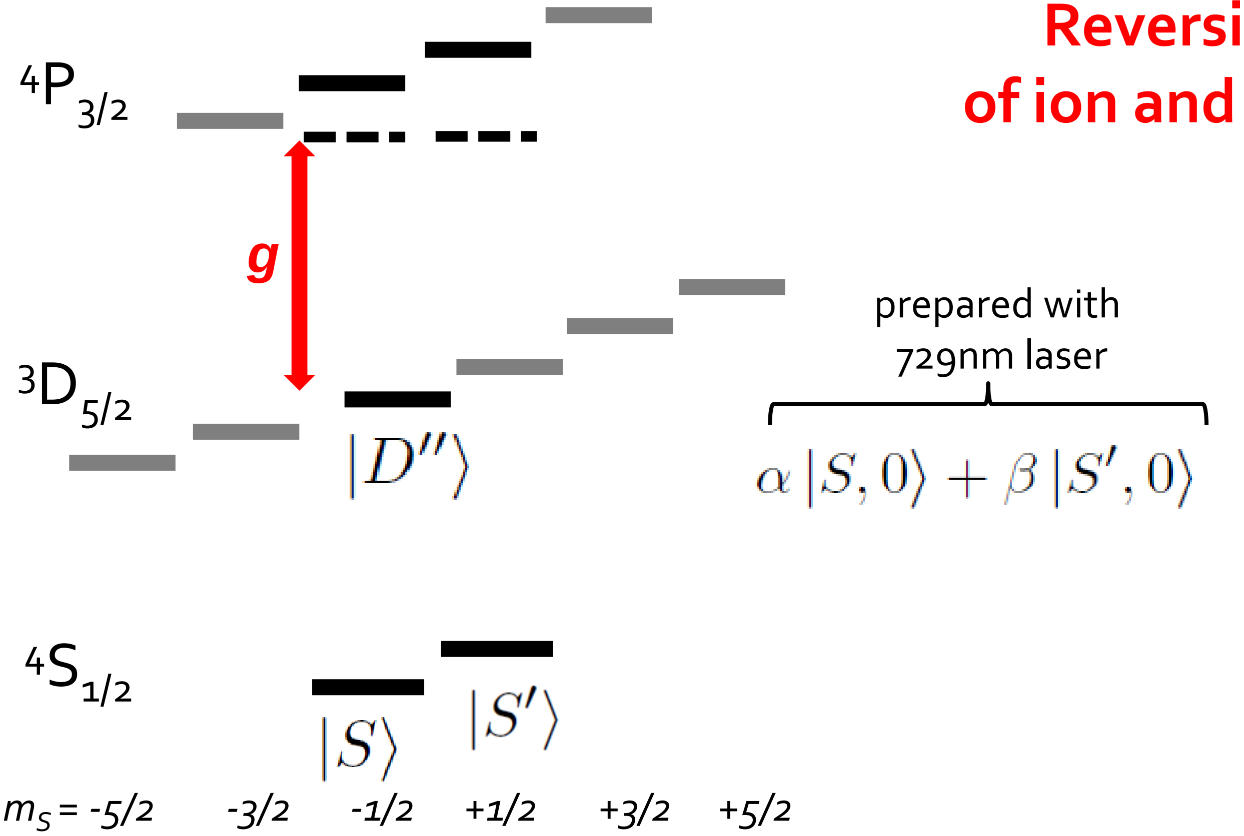
$$|S,0\rangle \mapsto \cos\alpha\,|D,V\rangle + \sin\alpha\; e^{\phi}\,|D',H\rangle$$

$$\alpha \equiv \tan^{-1}\left(g_2^{\mathrm{eff}}/g_1^{\mathrm{eff}}\right)$$

ϕ = relative phase of Raman fields

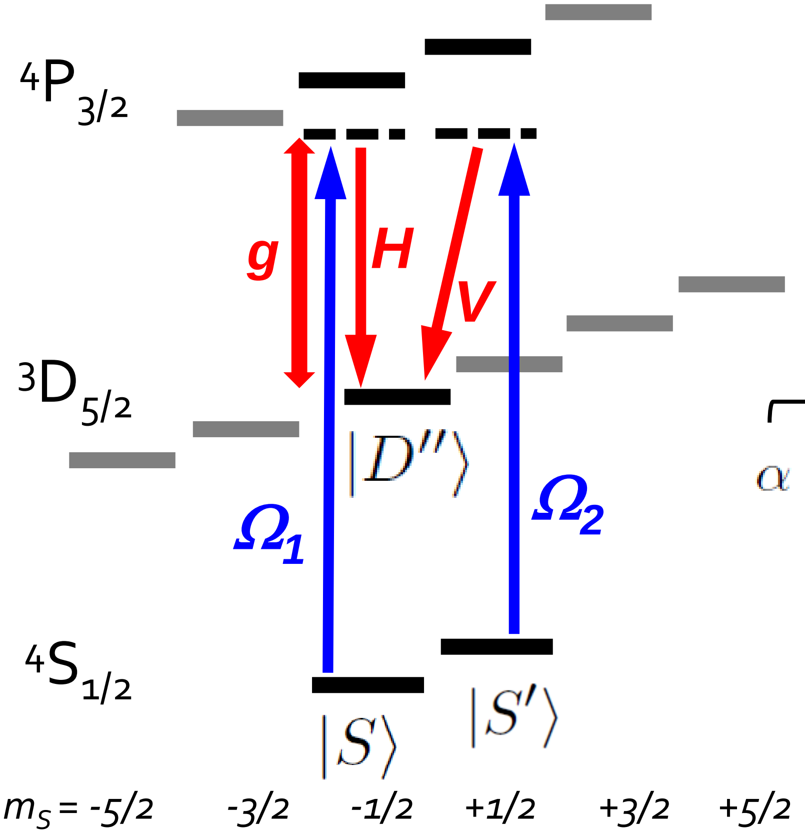
A. Stute … R.Blatt, Nature **485**, 482 (2012)

Coherent ion/photon operations



Reversible mapping of ion and photon states:

Coherent ion/photon operations



Reversible mapping of ion and photon states:

$$\underbrace{\alpha\,|S,0\rangle + \beta\,|S',0\rangle}_{\text{prepared with 729nm laser}} \mapsto \alpha\,|D'',H\rangle + \beta\,|D'',V\rangle$$

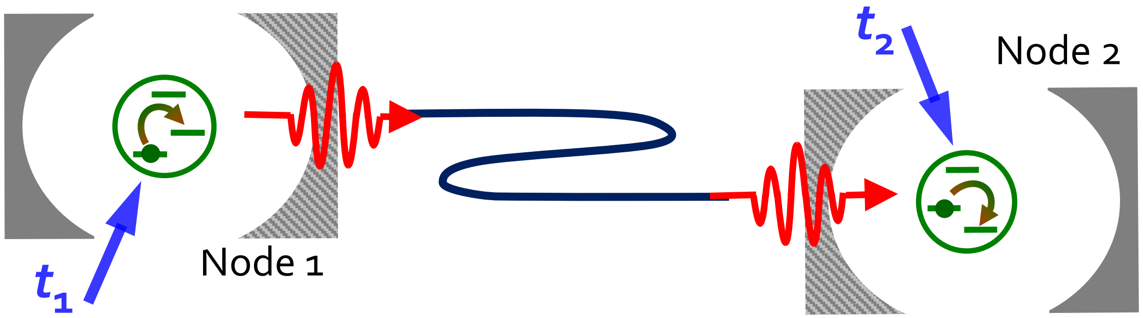
A. D. Boozer … H.J.Kimble, PRL **98**, 193601 (2007)

A. Stute … R.Blatt, Nat. Phot. **7**, 219 (2013)

Elementary network protocols

Deterministic protocols :

-> coherent emission at Node 1 (t_1) followed by coherent absorption at Node 2 (t_2)



Quantum state transfer from ion to ion :

t_1: ion(1) → photon mapping

$$\alpha\,|S_1, D_2, 0\rangle + \beta\,|S_1', D_2, 0\rangle \mapsto \alpha\,|D_1, D_2, H\rangle + \beta\,|D_1, D_2, V\rangle \mapsto \alpha\,|D_1, S_2, 0\rangle + \beta\,|D_1, S_2', 0\rangle$$

t_2: photon → ion(2) mapping

Entanglement of two remote ions :

t_1: ion(1) - photon entanglement

$$|S_1, D_2'', 0\rangle \mapsto |D_1, D_2'', V\rangle + |D_1', D_2'', H\rangle \mapsto |D_1, S_2', 0\rangle + |D_1', S_2, 0\rangle$$

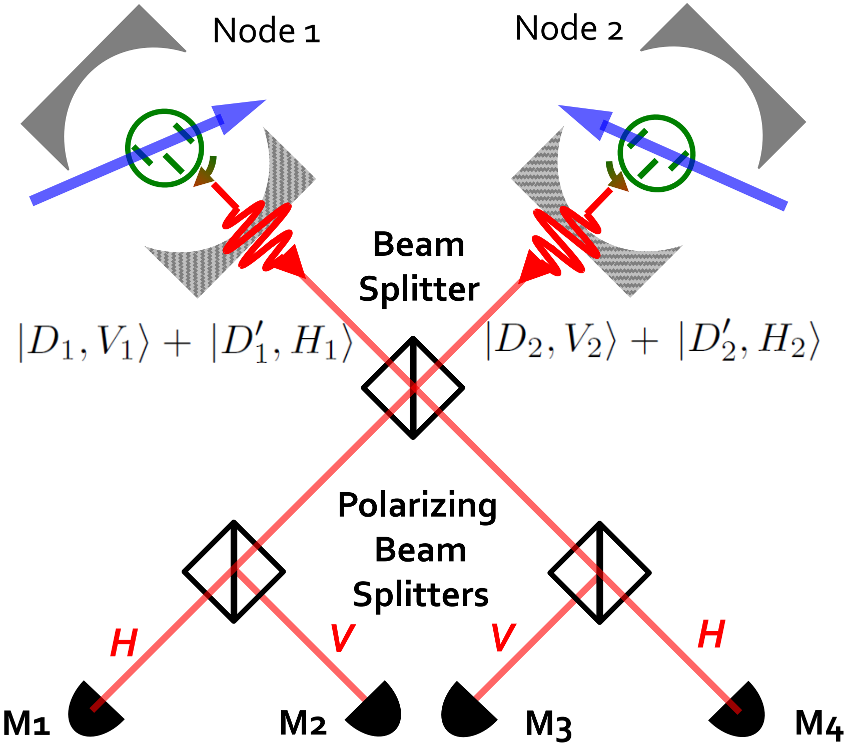
t_2: photon → ion(2) mapping

Cirac, Zoller, Kimble, Mabuchi, PRL(1997)
Ritter, …, Rempe, Nature(2012)

Elementary network protocols

Probabilistic entanglement :

-> heralded entanglement of 2 remote ions by photon interference and measurement
(building block of *teleportation*)



Click of	happen with proba	projects ions onto
M1 **AND** M2	25 %	$\lvert D_1 D'_2\rangle + \lvert D'_1 D_2\rangle$
M3 **AND** M4		
M1 **AND** M3	25 %	$\lvert D_1 D'_2\rangle - \lvert D'_1 D_2\rangle$
M2 **AND** M4		
M1 **OR** M4	25 %	$\lvert D'_1 D'_2\rangle$
M2 **OR** M3	25 %	$\lvert D_1 D_2\rangle$

Free space experiments :

<u>Trapped ions</u> :

Moehring ... Monroe, Nature **449**, 68 (2007)
-> **1 event/ 8.5 min**

Hucul ... Monroe, Nat. Phys. **11**, 37 (2014)
-> **4.5 events/sec**

<u>NV centers</u> :

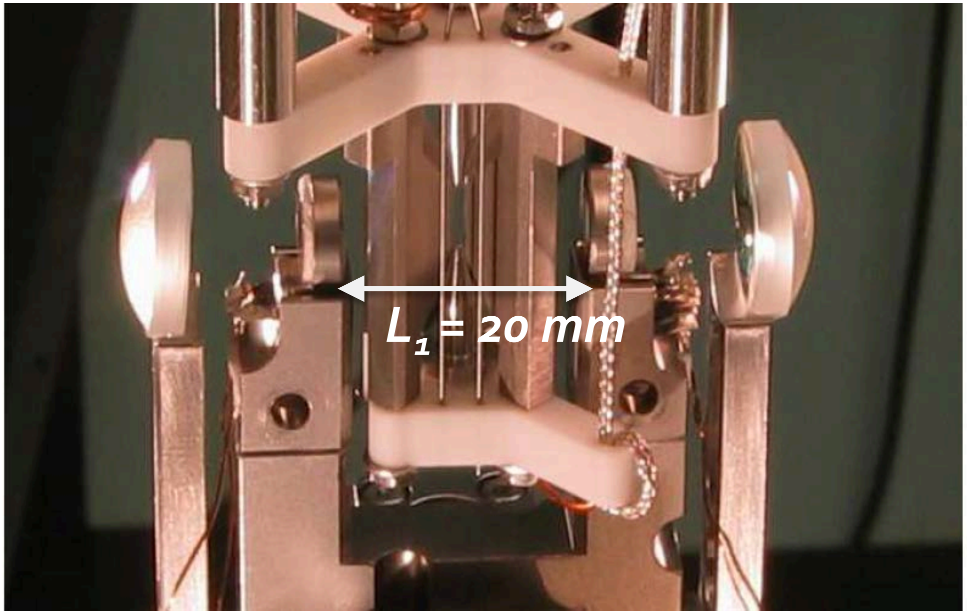
Bernien, ..., Hanson, Nature **497**, 86 (2012)
-> **1 event/10 min**

cQED -> enhancement of photon collection efficiency
(and thus of entanglement rate)

The Innsbruck setup

Towards a 2-node elementary network with $^{40}Ca^+$ ions in cavities

Node 1 (up and running) with “big cavity“ : two mm-size superpolished mirrors



L_1 = 19.9mm ; ROC = 10mm

Finesse $= \frac{\mathrm{FSR}}{2\kappa} = \frac{2\pi}{\mathcal{L}_{\mathrm{tot}}}$ = 77 000

→ $(g,\kappa,\gamma)=2\pi\,(1.4,\ 0.05,\ 11.4)$ MHz

→ ***C* = 1.7** (***intermediate*** regime)

- on-demand single photon (88% efficiency) [Barros *et al*, NJP **11**, 103004 (2009)]
- tunable entanglement (40 events/sec, F=97%) [Stute *et al*., Nature **485**, 482 (2012)]
- state mapping ion->photon (F = 92% at 0.6% efficiency) [Stute *et al*., Nat. Phot. **7**, 219 (2013)]

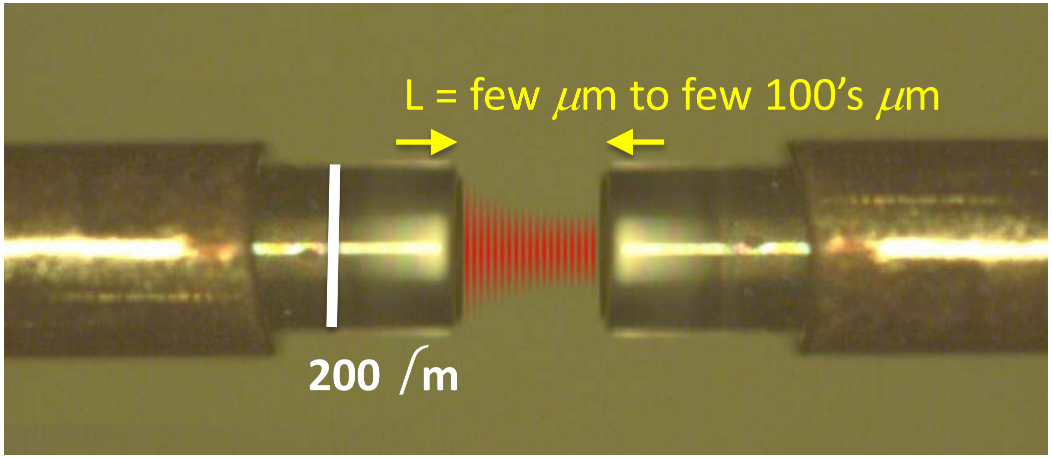
2 ions in the cavity :

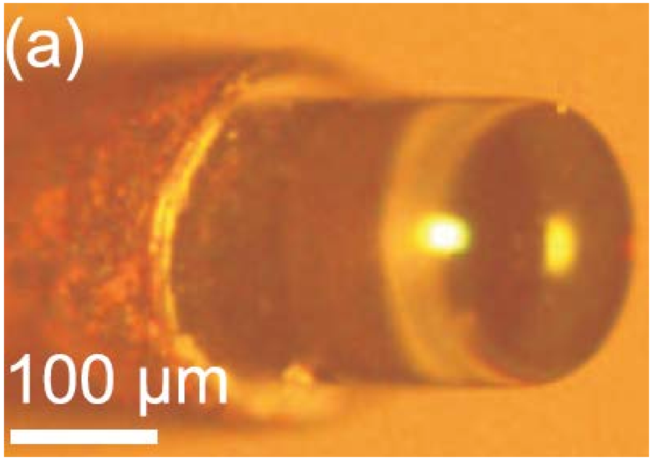
- heralded entanglement (~0.2 to 4 events/sec, F >92%) [Casabone *et al*, PRL **111**, 100505 (2013)]
- sub/superradiance [Casabone *et al*, PRL **114**, 023602 (2015)]

The Innsbruck setup

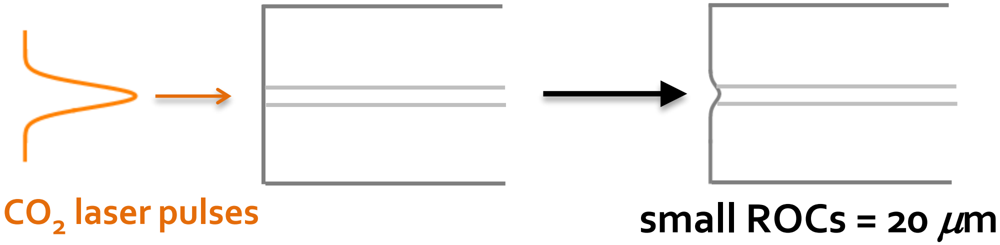
Node 2 : a miniaturized setup aiming at strong coupling

-> need for smaller mode volume -> ***"fibre-based Fabry-Pérot cavity" (FFPC)***





- laser ablation of fibre tip (coll. J. Reichel, ENS-Paris)

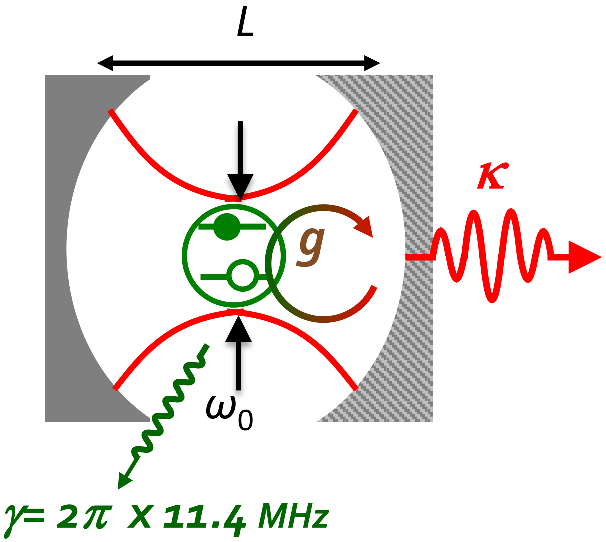


Steinmetz *et al.*, APL**89**, 111110 (2006)
Hunger *et al.*, NJP **12**, 065038 (2010)

small ROCs = 20 μm to 2 mm
roughness ~ 0.2 nm rms

- then coat with high-reflectivity multilayer dielectric stack (ATF, Boulder)

Towards strong coupling : go small



$$g \propto \sqrt{\frac{1}{V_{\mathrm{m}}}} \propto \frac{1}{w_0\sqrt{L}}$$

$$w_0 \propto (L(2R-L))^{1/4}$$

$$\kappa \propto \frac{1}{L\mathcal{F}}$$

$$C = \frac{g^2}{2\gamma\kappa} \propto \frac{\mathcal{F}}{\sqrt{L(2R-L)}}$$

-> the smaller the better (*R* and *L*)

...but how small ?

- neutral atoms : no limits

  pioneering experiment: Reichel group, on-chip cQED with Rb, L~40 μm

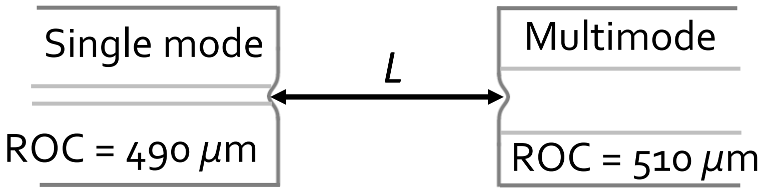
  (g,κ,γ)=2π (215, 53, 3) MHz [Colombe et al. Nature **450**, 272 (2007)]

- ions : dieletric substrate perturb trapping potential !

  -> mirrors need to be at least 100 μm away from ion

  strong coupling not reached yet with single ion !

Testing FFPCs

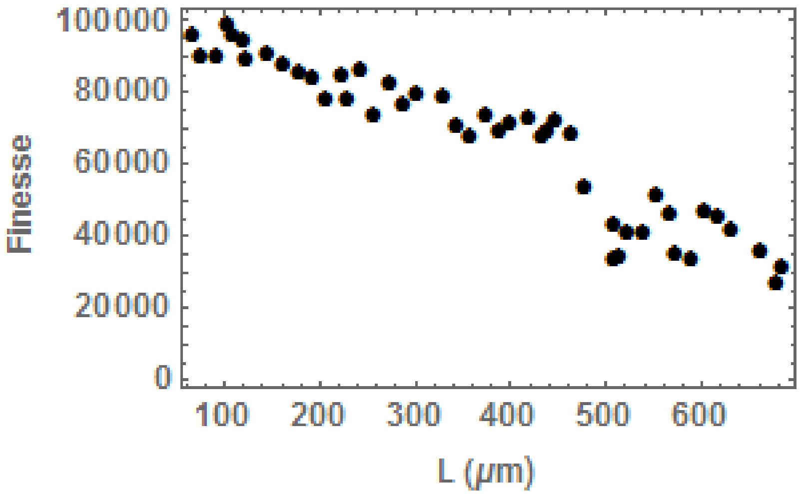

Single mode

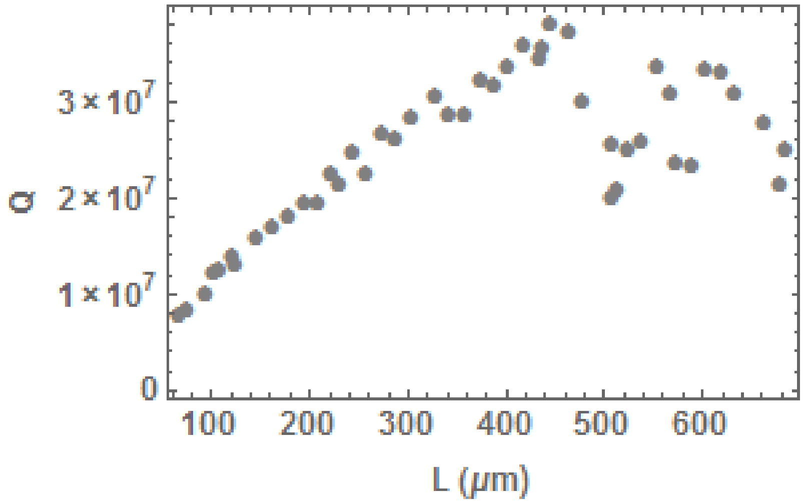
ROC = 490 μm

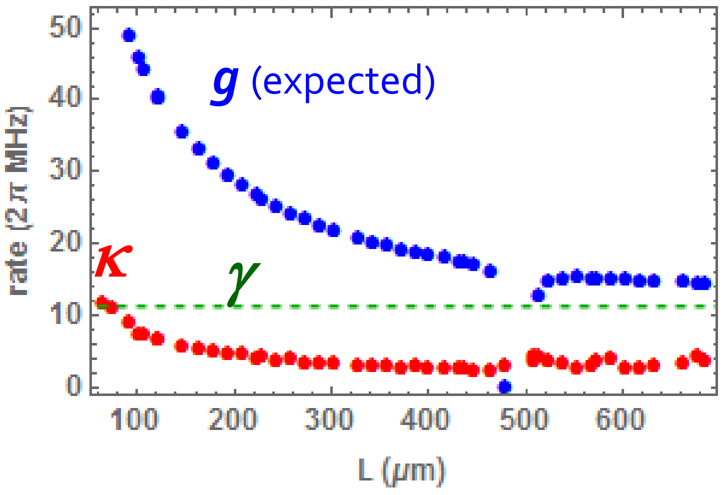
L

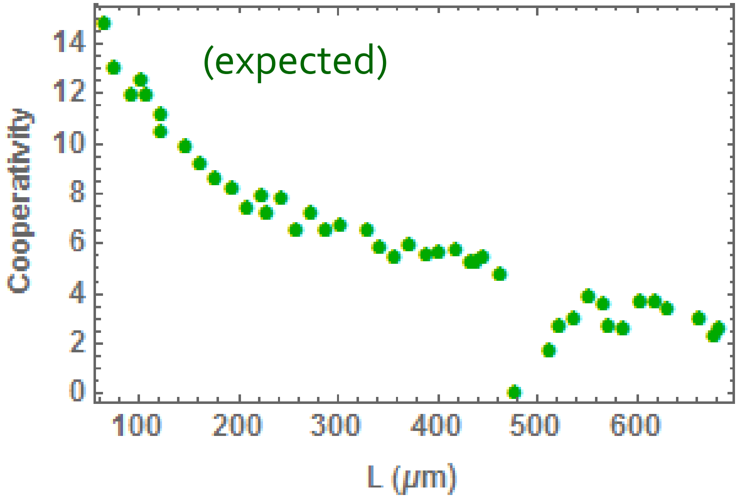
Multimode

ROC = 510 μm

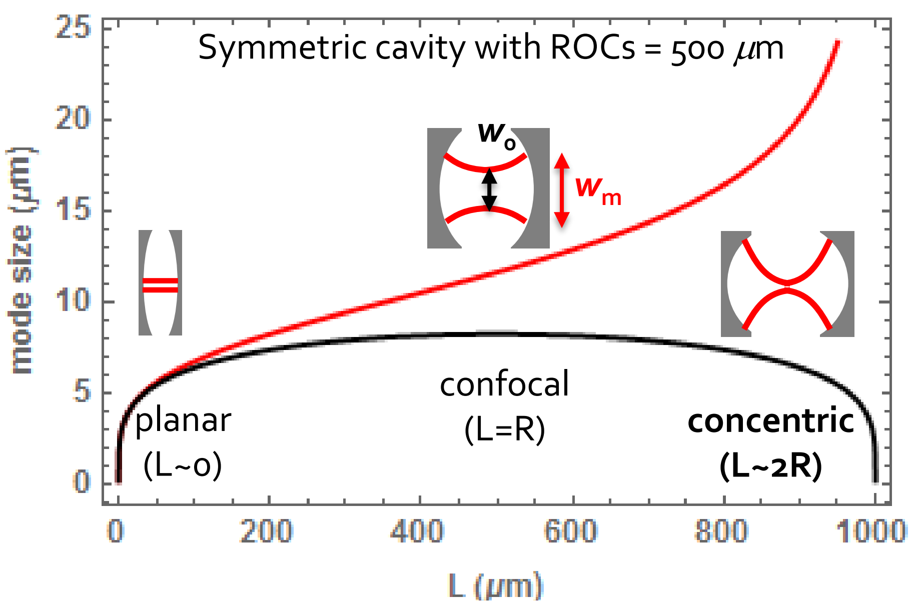


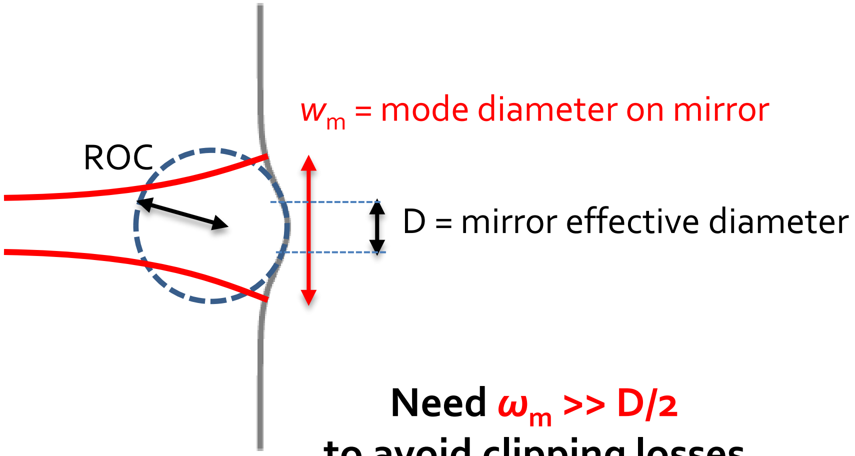




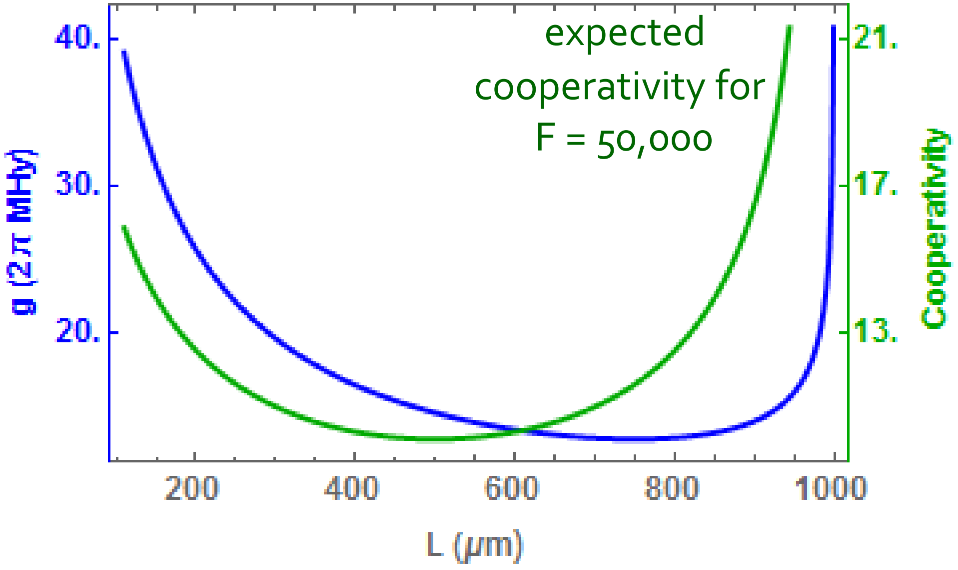


Concentric cavity tempting but…





Need ω_m >> D/2
to avoid clipping losses



Fiber mirror :

D ~ 10 to 45 μm with *single* shot
~ up to 100 μm with *multi* shot

+ other challenges :

- **outcoupling efficiency**

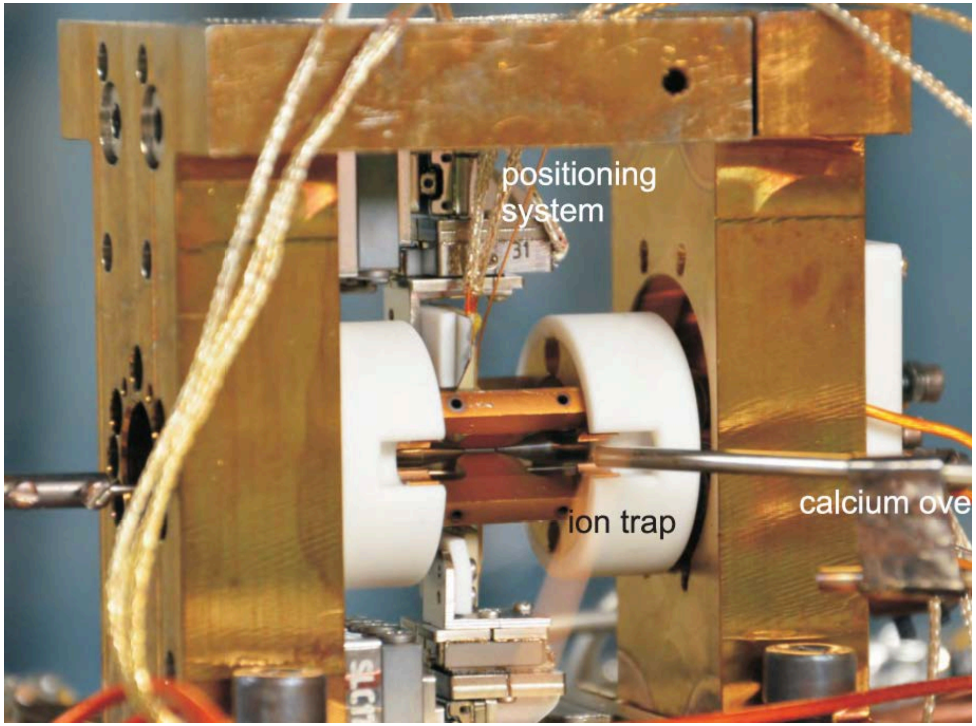
-> use PCF fibers (large mode diameter)

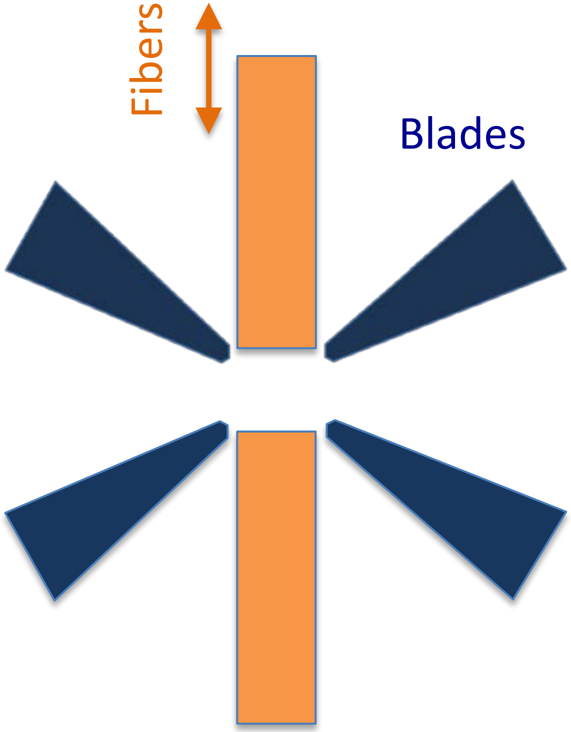
- **sensitivity to misalignement**

Integration of FFPC with a Paul trap

current setup :

[Brandstätter *et al*, RSI **84**, 123104 (2013)]





Linear trap :

- Asymmetric : 60° and 120°
- Miniaturized : 170 um ion-blade
- Axial + radial optical access

FFPC :

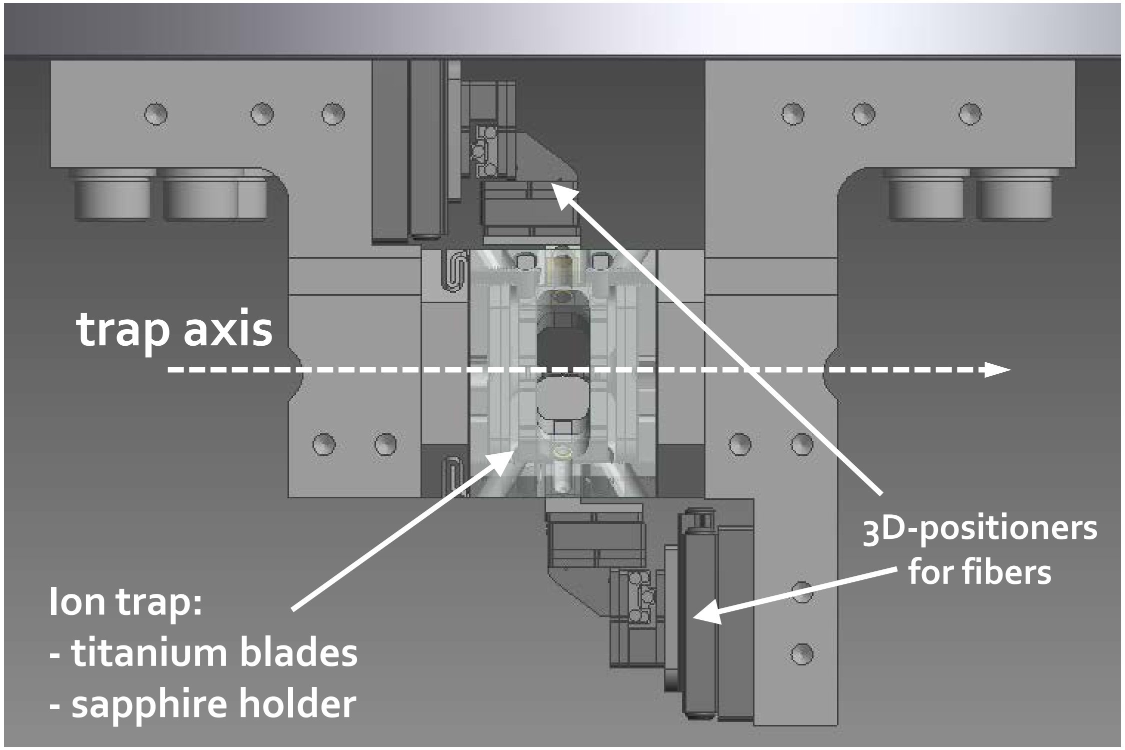
- SM / MM fibers, copper cladded
- Nanopositioning stages (Smaract)
- Active length stabilization (sheer piezos)

... but problems with the trap... no cQED yet ! ☹

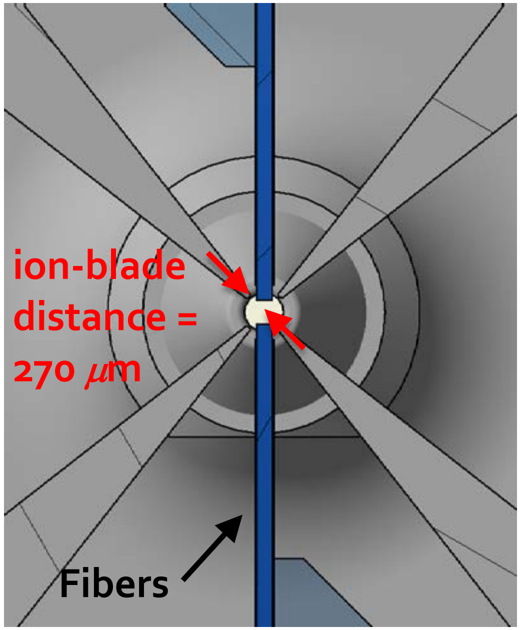
Integration of FFPC with a Paul trap

coming up:

similar design but (hopefully) better trap, more conservative dimensions, and better FFPC



View along trap axis:



... in progress !

Conclusions, perspectives

real atoms are not dead

- nodes : trapped ions outstanding for QIP
- channels :optical photons for long distance quantum communication

strong coupling to single ion still to be demonstrated

- fibre-based Fabry-Perot cavities for smaller mode volumes
- still some technical challenges ...

elementary quantum network based on cQED

- versatility : deterministic AND probabilistic protocols
- (registers of) ions: ideal platform to test more advanced protocols
  (eg error correction, entanglement purification...)

universität innsbruck

Thank you !

AG Quantenoptik und Spektroskopie

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FWF Der Wissenschaftsfonds.

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