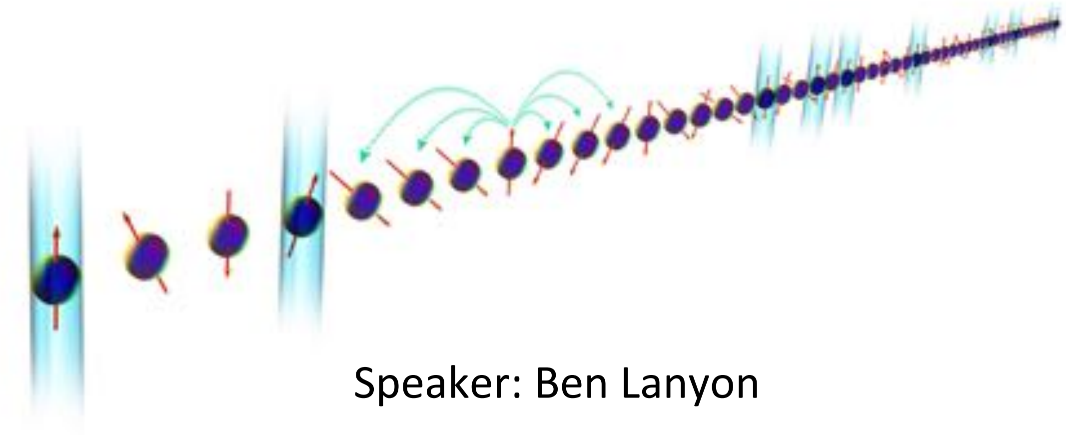
Quantum simulations and networks with Trapped ions

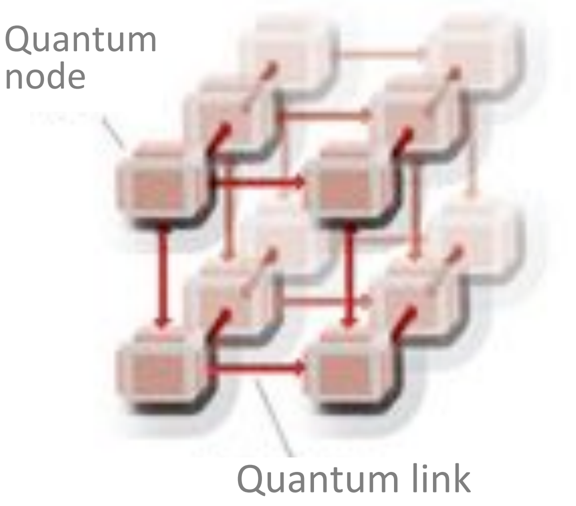


Speaker: Ben Lanyon

Institut für Quantenoptik und Quanteninformation (IQOQI)
Innsbruck, Austria

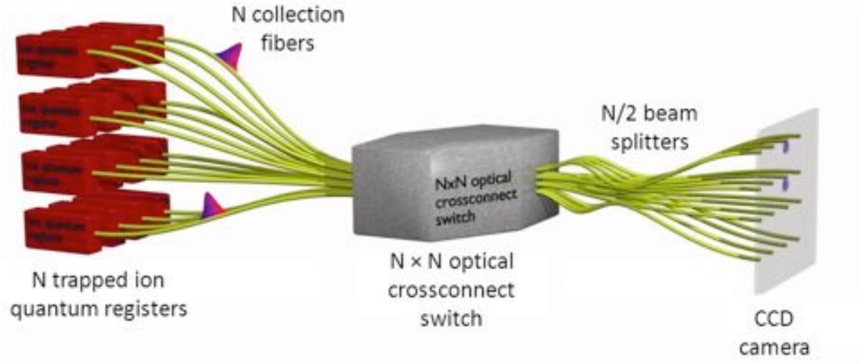
Photons beyond qubits, 2018, Czech

Ongoing research effort to develop light-matter quantum networks



- **Matter-based nodes** for q. information storage & manipulation, connected with **photonic quantum links**
- Unique feature: **entanglement** (correlations)
- Applications from table-top to inter-continental scale

Emerging consensus that this is way to scale up engineered quantum devices:



Modular ion-trap quantum information processor, (Group of C. Monroe)

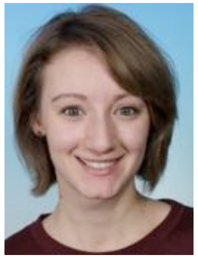
This talk, our current work on:

1. Developing ion trap nodes (context: quantum simulation)
2. Developing ion-photon interfaces for networks

Quantum simulation with trapped ions


C. Roos


C. Maier


T. Brydges


P. Jurcevic


M. Joshi

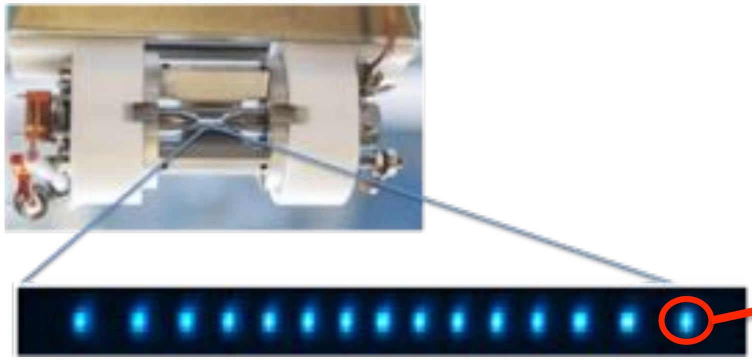

C. Steinlechner


A. Fabre

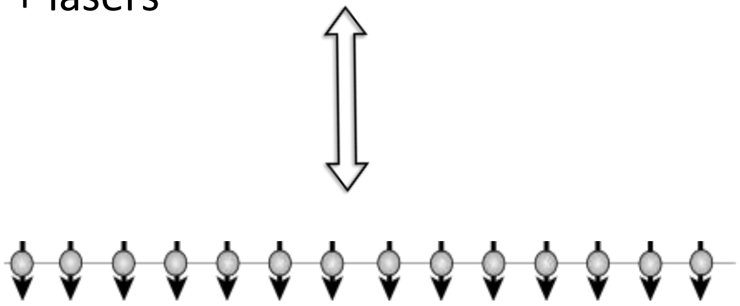

B. Lanyon


R. Blatt

Our quantum many-body system



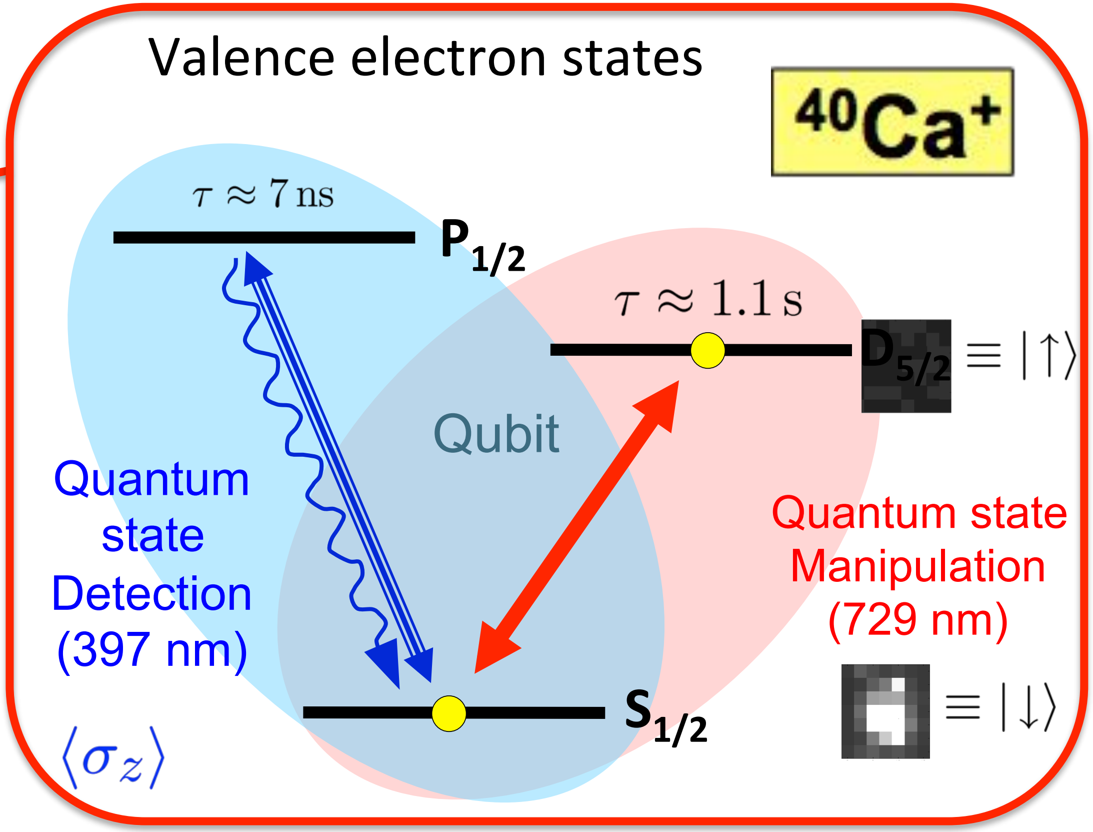
1D string of atomic-ions in 3D trap
+ lasers



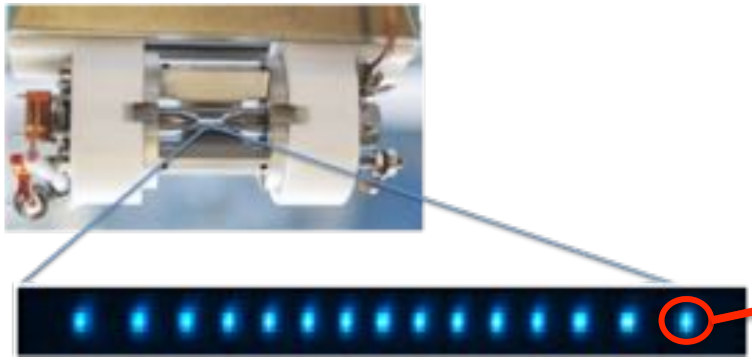
1D chain of spin-1/2 particles
that we can individually measure &
manipulate

Quantum degrees of freedom:

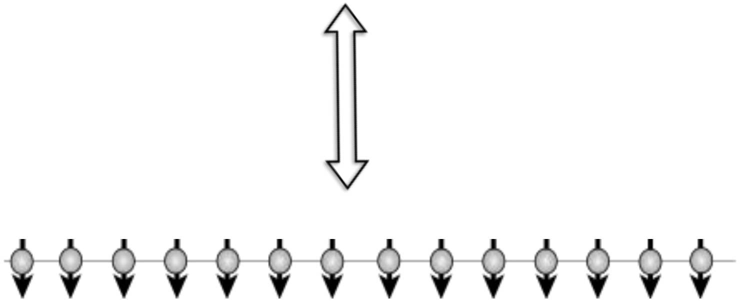
- n ions = n spins
- 3n harmonic oscillators



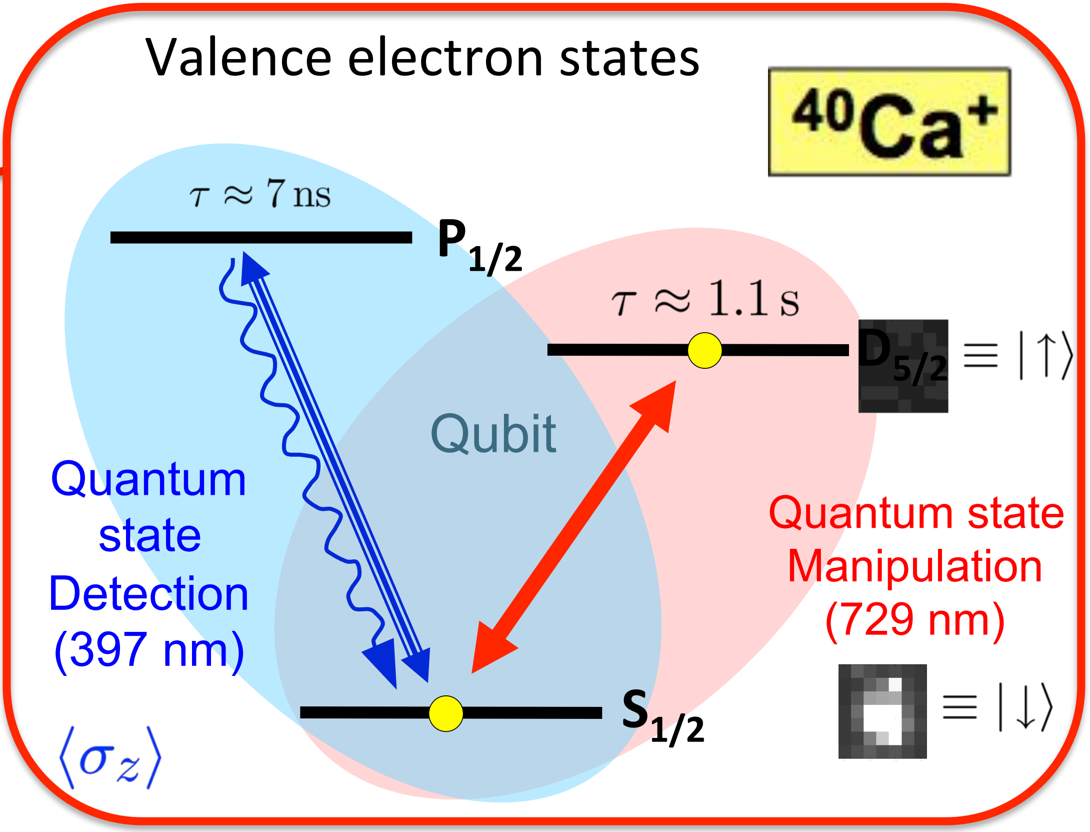
Our quantum many-body system



1D string of atomic-ions in 3D trap (15)



1D chain of spin-1/2 particles
that we can individually measure



Valence electron states

$^{40}\mathrm{Ca}^+$

$\tau \approx 7\,\mathrm{ns}$

$P_{1/2}$

$\tau \approx 1.1\,\mathrm{s}$

$D_{5/2} \equiv |\uparrow\rangle$

Qubit

Quantum state Detection (397 nm)

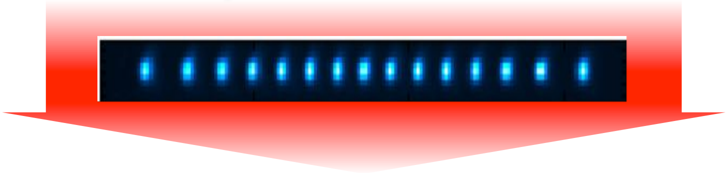
$\langle \sigma_z \rangle$

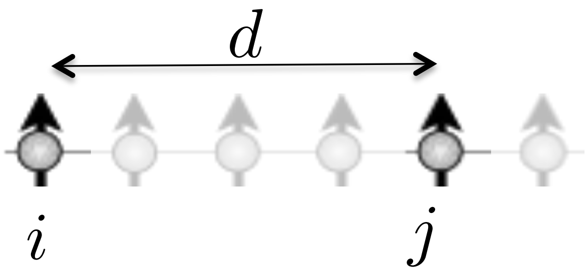
Quantum state Manipulation (729 nm)

$S_{1/2}$

$\equiv |\downarrow\rangle$

Lasers ⇨ spin-spin interactions

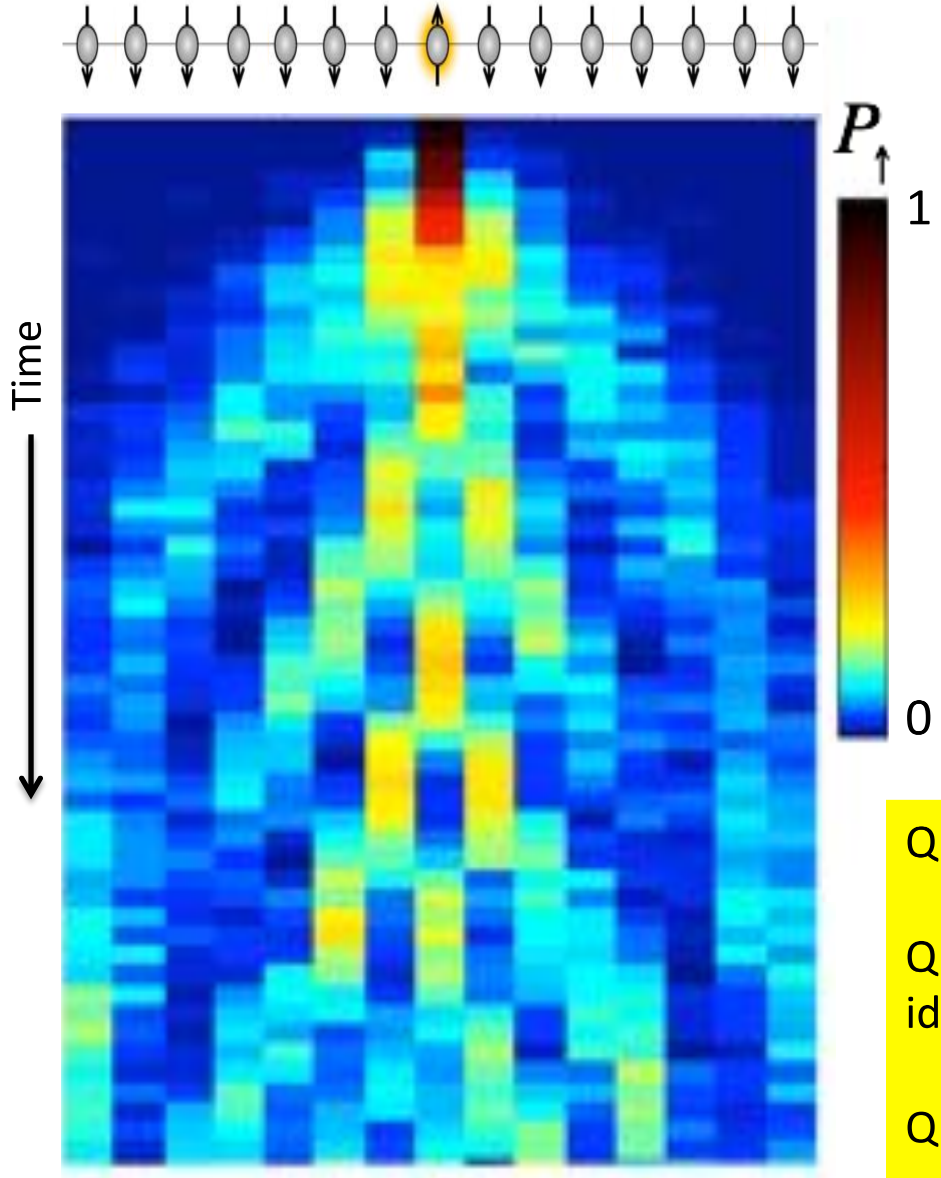




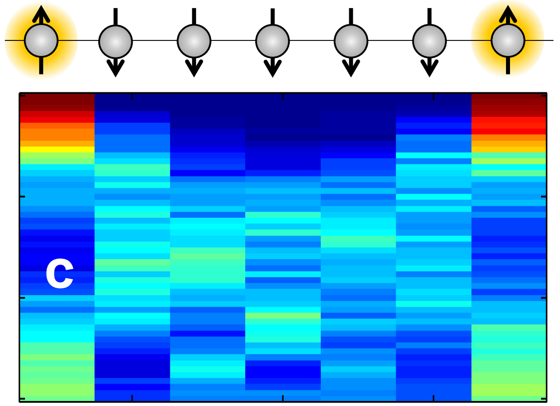
$$J \sim \frac{1}{d^{\alpha}}$$

Power-law

Observation of coherent many-body quantum dynamics



P. Jurcevic et al., Nature **511**, 202 (2014)



- 50 spin version of our system could perform dynamics where entanglement grows too fast to follow with classical computers
  Schachenmayer *et al*, PRX, 3, 031015 (2015)

Q. How scale up to larger numbers of spins?

Q. How to predict what system should do in ideal case?

Q. How to find out in the lab what the system is actually doing (how to verify a quantum simulator)?

MPS tomography: an efficient tool to verify your quantum system

Collaboration with group of M.Plenio (Ulm) & group of A. Daley (Strathclyde)

"Efficient tomography of a quantum many-body system"
B. P. Lanyon, C. Maier, M. Holzäpfel, T. Baumgratz, C. Hempel, P. Jurcevic,
I. Dhand, A. S. Buyskikh, A. J. Daley, M. Cramer, M. B. Plenio, R. Blatt, C. F. Roos
Nat. Phys. 13, 1158 (2017), arXiv:1612.08000,

Core result: There are a broad class of entangled quantum states for which one can determine what the state is in the lab (can do state tomography) with effort that increases slowly in system size

Application: to verify engineered quantum devices, get them to make these kinds of entangled states and see how well they perform.

Quantum State Tomography

Goal: Get reliable estimate for wavefunction ρ of system in lab

Full state tomography

$$\rho = \sum_i Tr(\rho \hat{O}_i) \hat{O}_i$$

- Gold standard for QIP
- No. of *parameters*, *measurements* & *post-processing time* increases exponentially with particle number ☹
- e.g. 20 particles ~ few billion observables

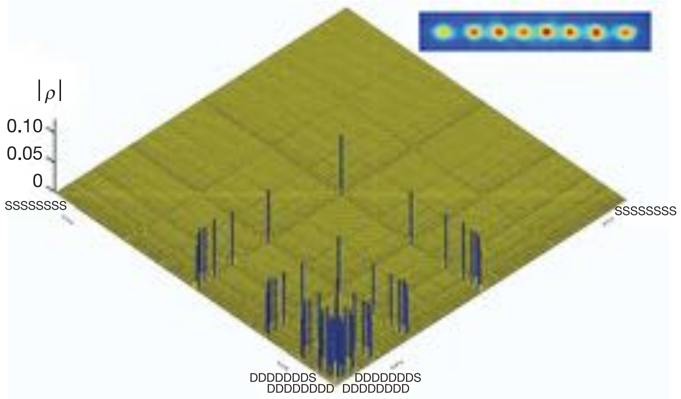


Figure 1 | **Absolute values, $|\rho|$, of the reconstructed density matrix of a $|W_8\rangle$ state as obtained from quantum state tomography.**

M. Cramer et al, Efficient quantum state tomography, Nat. Commun. 1:149 (2010)

Matrix Product State Tomography

Efforts scale *polynomially* with particle number ☺

Broad class of states for which it works

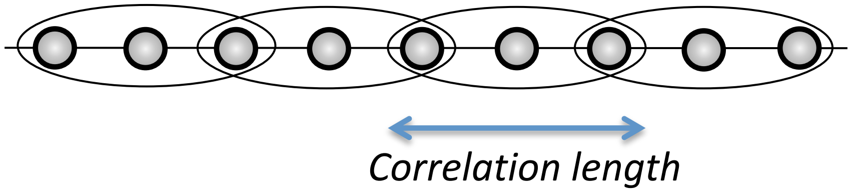
Params	~ Poly(N)
Measurements	~ N
Post Processing	~ Poly(N)

Intuition to MPS tomography

Entanglement (correlation) makes q.states & dynamics difficult to describe and verify in the lab

However, if N particle state has a finite correlation length:

e.g



⇨ *Accurate state description with only poly(N) parameters using MPS formalism*

⇨ *Chance to identify state by measuring only small number of local observables*

Which states?

- ***States generated by systems with local interactions****
- Many important states for Q. computing and Q. metrology e.g. cluster and graph states

*Local interactions = interactions with finite range (e.g. between neighbors)

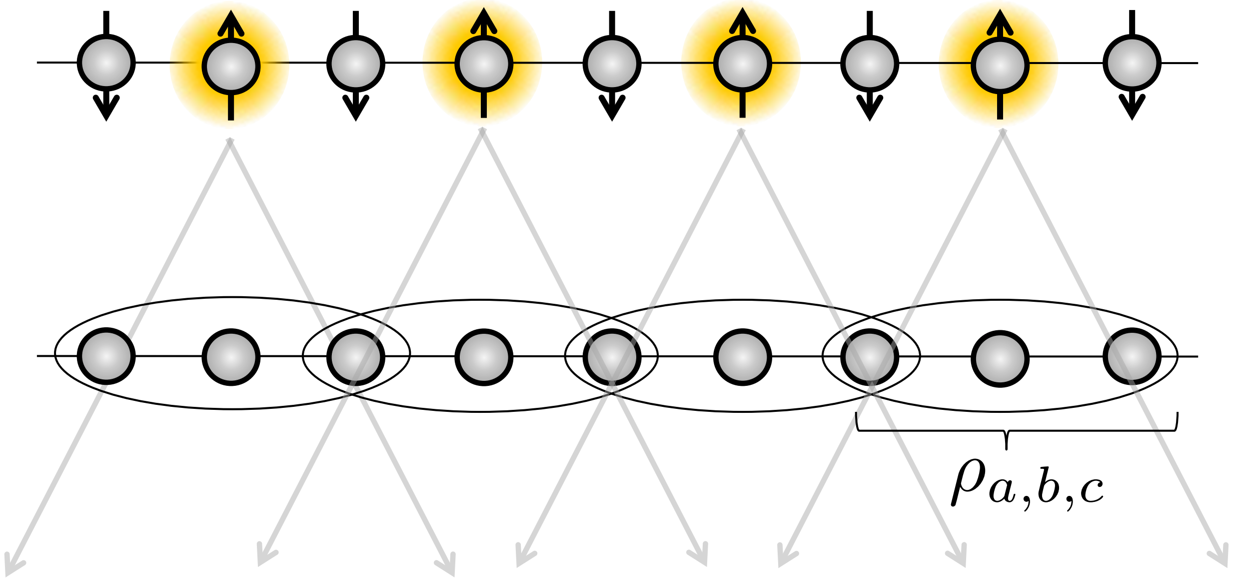
Our application: tracking the state of a quantum simulator

A simulator with local interactions generates correlations that spread at a finite speed, therefore:

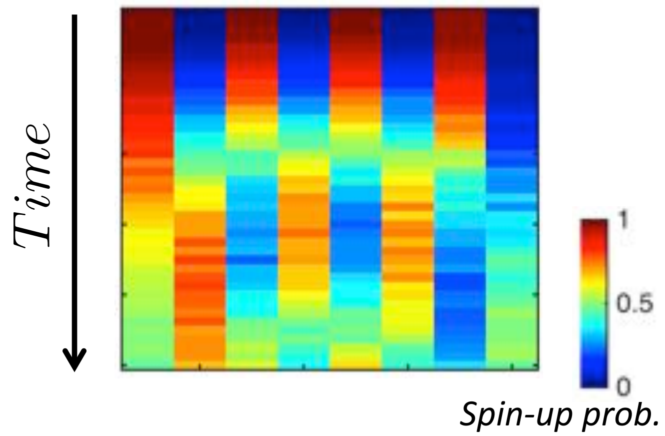
- After finite evolution time, correlations only gone so far *-> efficient description via MPS*
- All info. about correlations contained over those distances *-> local measurements enough*

Example:

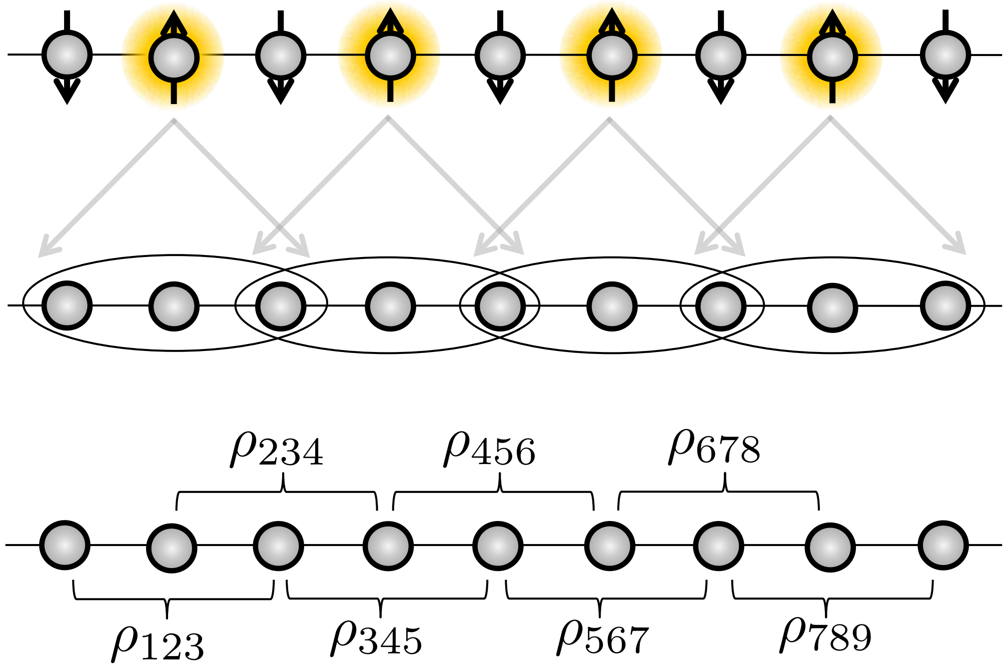
Some initial excited *product* state of spins



Lab results from such experiment



Our implementation with trapped ions



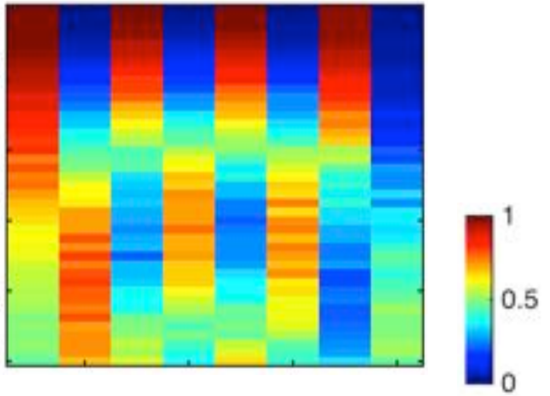
1. Prepare initial product state, then turn on interactions
2. Turn off at desired point in evolution
3. Do enough measurements to reconstruct all local reductions that we think might span the correlation length
4. Give measurement data to classical search algorithm which finds an MPS estimate $\left|\Psi^{est}_{mps}\right\rangle$

   Baumgratz, *et al* New J. Phys. 15, 125004 (2013).
5. Certification step to confirm that the output state is a good description of the lab state $\langle\Psi^{est}_{mps}|\rho_{lab}|\Psi^{est}_{mps}\rangle$

This technique is efficient in space (qubit number), but not in time.

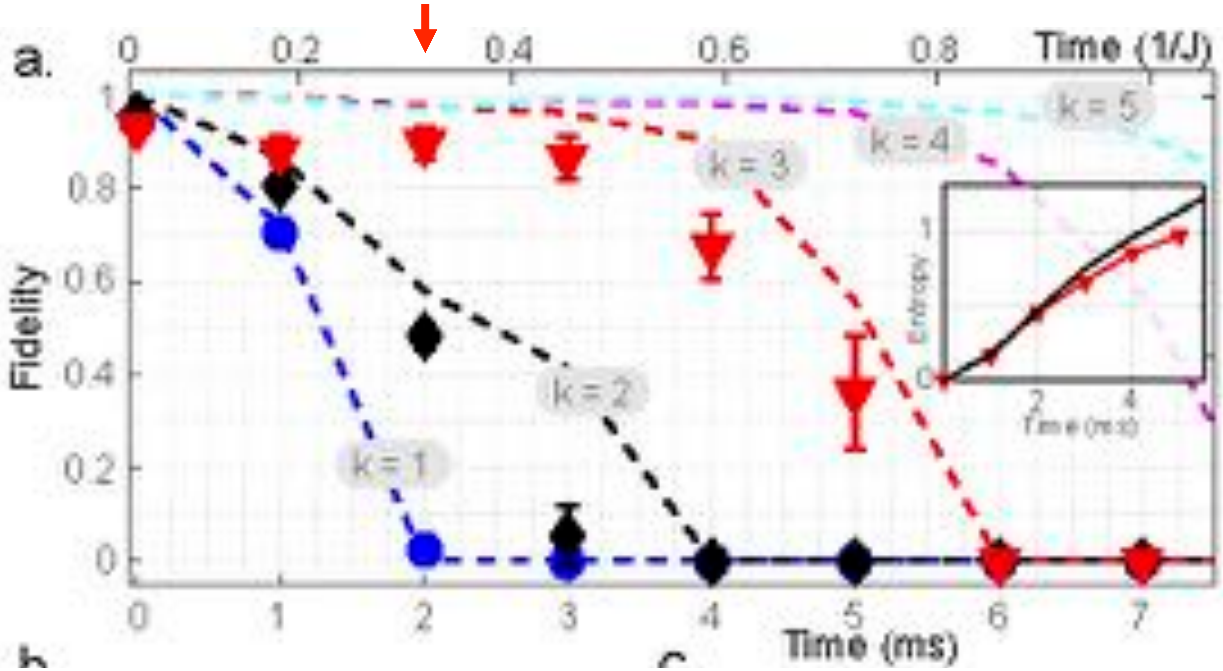
MPS tomo results for 8 spin case

$$\langle \Psi^{est}_{mps} | \rho_{lab} | \Psi^{est}_{mps} \rangle$$



Spin-up prob.

All neighbors strongly entangled



As time goes on, system is better described by increasingly complex entangled pure states ☺

Can follow simulators evolution into complexity, up to some limit, in a way efficient in qubit number ☺

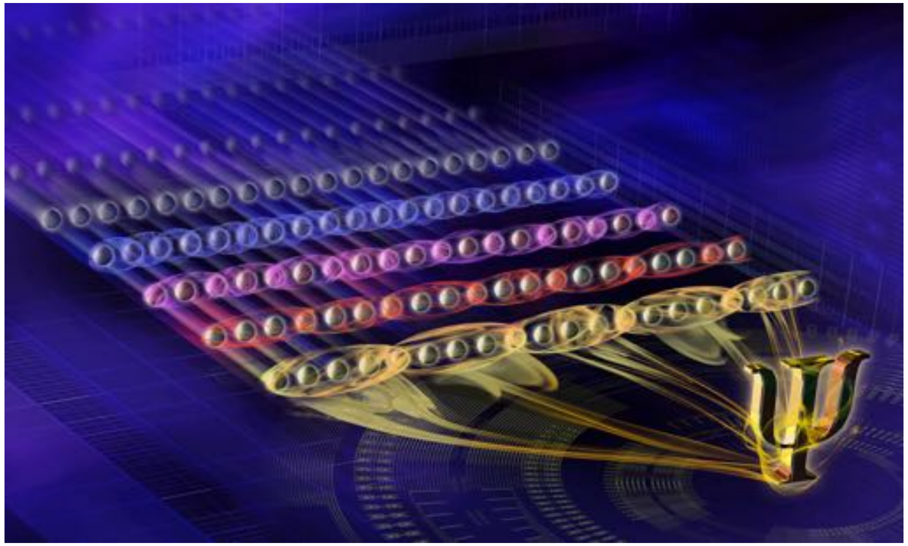
After e.g. 2ms, lab state has ≥ 90% fid with 8-body entangled pure state ☺

10 minutes for each point (vs 10 hours for full state tomo)

Observation of entangled states of a fully-controlled 20-qubit system

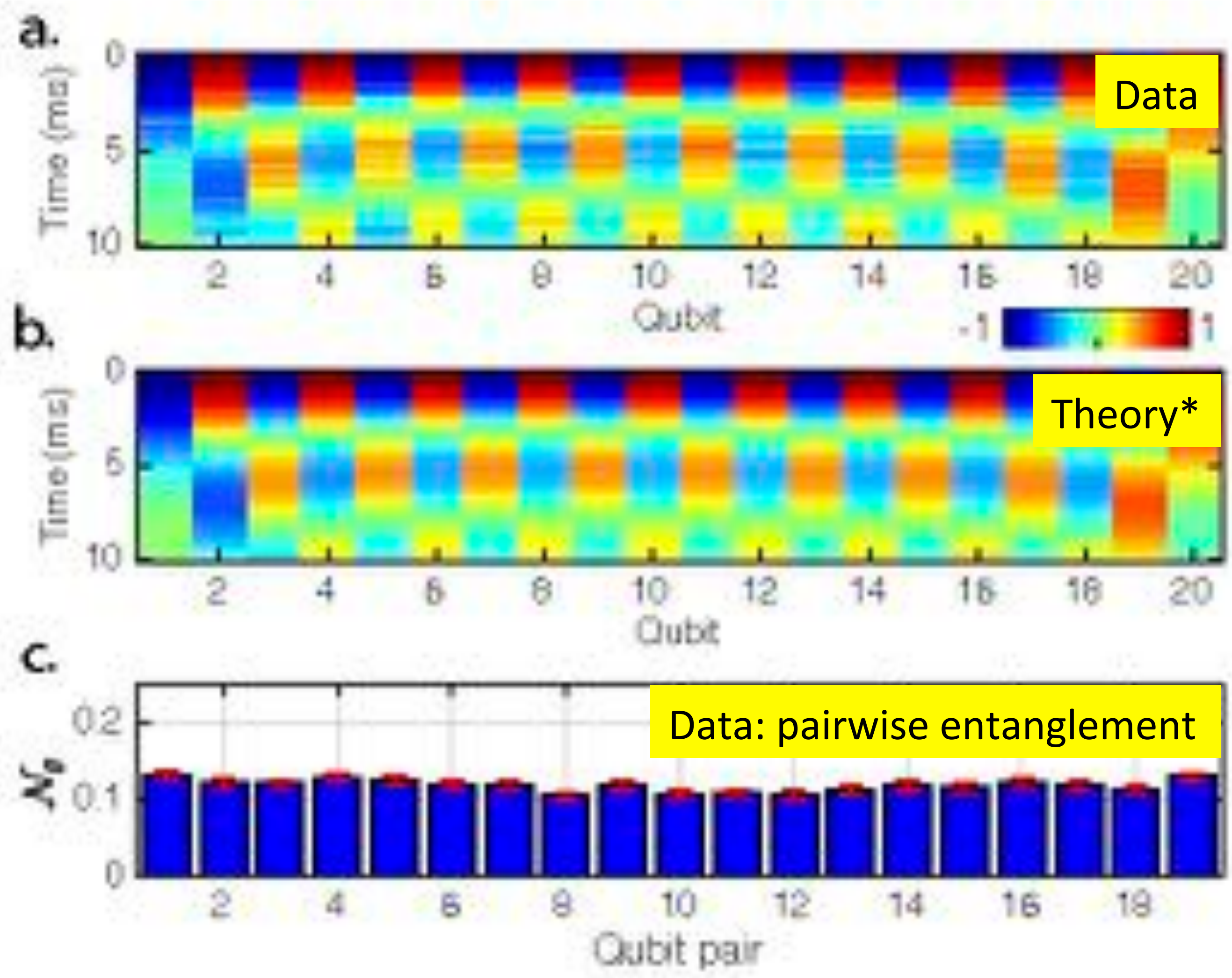
N. Friis, O. Marty, C. Maier, C. Hempel, M. Holzapfel, P. Jurcevic, M. Plenio, M. Huber, C. Roos, R. Blatt, B. Lany
[Phys Rev X.8.021012, arXiv:1711.11092]

Collaboration with group of M. Plenio (Ulm) and of M. Huber (Vienna)



Core result: By designing entanglement witnesses, we could directly observe the generation of multipartite entanglement in a 20-qubit system

- 20-qubit dynamics looks great ☺

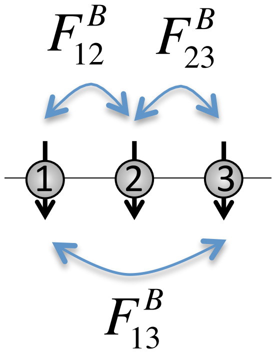


- MPS tomography produced very low fidelities ☹
- Q: Can we directly probe higher-order q. correlations from measurements that we have?

*A. Daley & A. Buyskikh

Analytical witnesses, based on average Bell state fidelities

O. Gühne and G. Tóth, Phys. Rep. 474, 1 (2009).



if $$\frac{F_{12}^{B}+F_{23}^{B}+F_{13}^{B}}{3} > 0.57$$ then 3-partite entangled

- Analytical expression for extension to arbitrary qubit numbers
- Violated in our *ideal* system by all neighbouring triplets

Witnesses found by numerical search

Exhaustive search for witness operators Q^k

$$Q^{k} = \sum_{i} c_{i} M_{i}^{k}$$

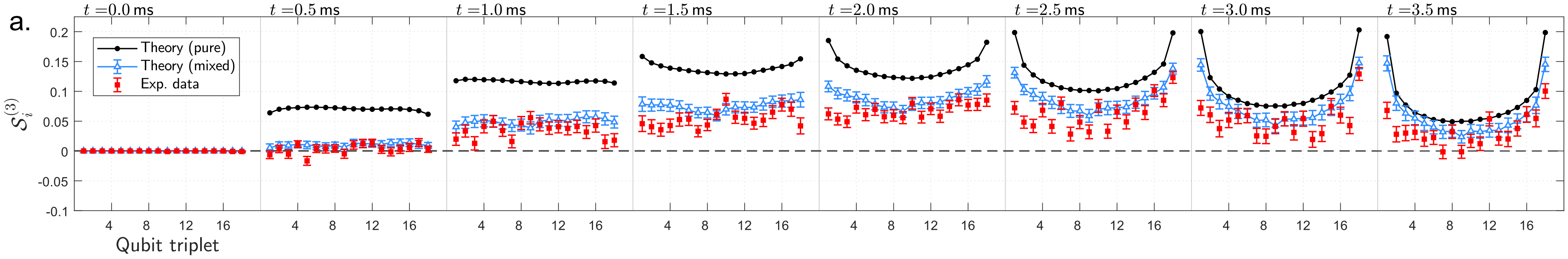
Measurements
we carried out

Where $$Tr\left(Q^{k}\rho^{k}\right) > 0$$ Proves k-partite GME

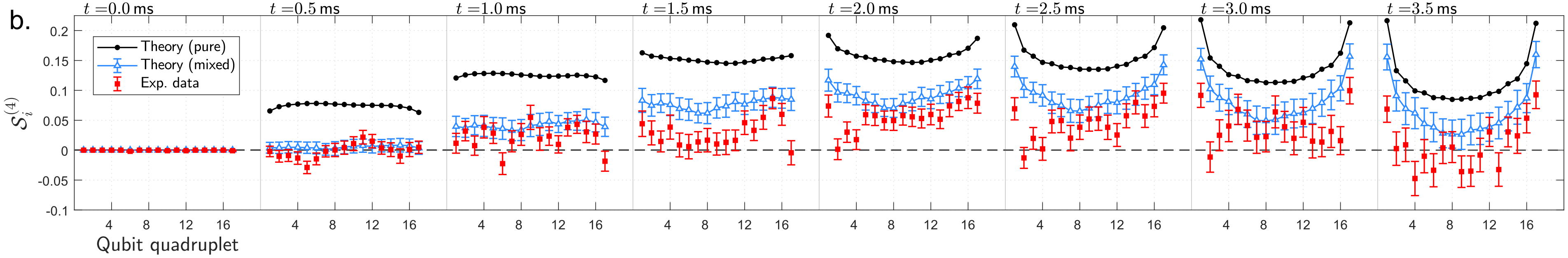
Lab state of k qubits

- Limited to 5-qubit groups by vastness of search
- Violated in our *ideal* system by all neighbouring groups of 5

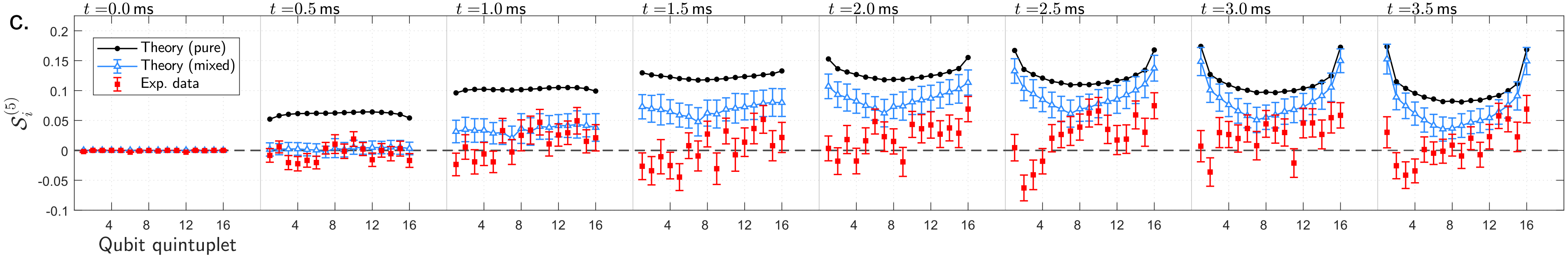
All neigbouring triplets multipartite entangled



Almost all neighbouring quadruplets multipartite entangled



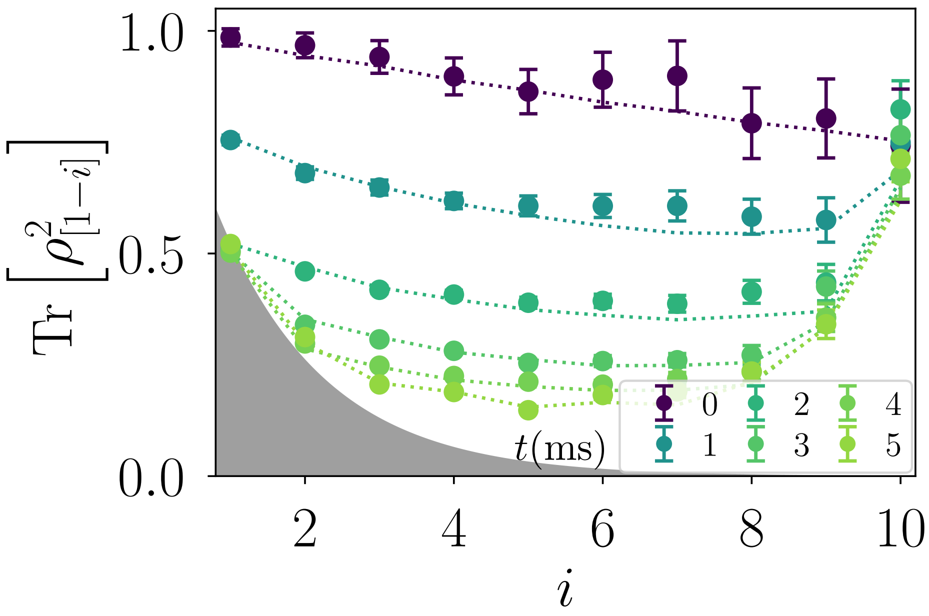
Some neighbouring quintuplets multipartite entangled



‘5th-order’ q. correlations are generated in our simulator, but exhibit larger deviations from ideal
Provides feedback method to improve our system

Measuring entropy via random measurements

in collaboration with A. Elben, B. Vermersch and P. Zoller



Core result: New method to measure the entropy of engineered quantum systems of up to a few tens of qubits, works for all states and dynamics.

Application: tool to determine global coherence of ~20 qubit partitions of a many-body system & to detect entanglement between parts

Entropy

$$\rho = |\psi\rangle\langle\psi|$$

Pure state

$$Tr\left(\rho^2\right) = 1$$

Entropy = 0

$$\rho \neq |\psi\rangle\langle\psi|$$

mixed state

$$Tr\left(\rho^2\right) < 1$$

Entropy > 0

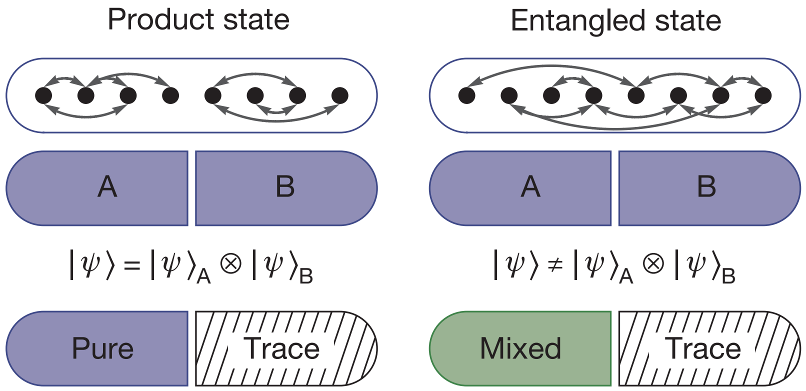
Renyi Entropy

$$S^n \propto \log\left[Tr\left(\rho^n\right)\right]$$

S^2

- Log(purity)
- Bounds Von Neumann entropy

Connection to entanglement



Entanglement across partition if:

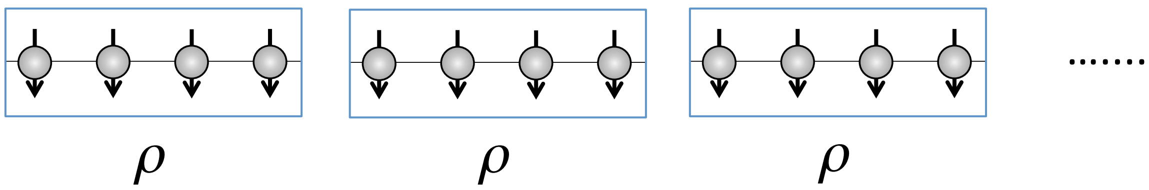
$$\mathrm{Tr}(\rho_A^2) < \mathrm{Tr}(\rho_{AB}^2)$$

- Quantity that tells you how globally coherent a system is, and how much bipartite entanglement is generated between its parts
- Very challenging to measure

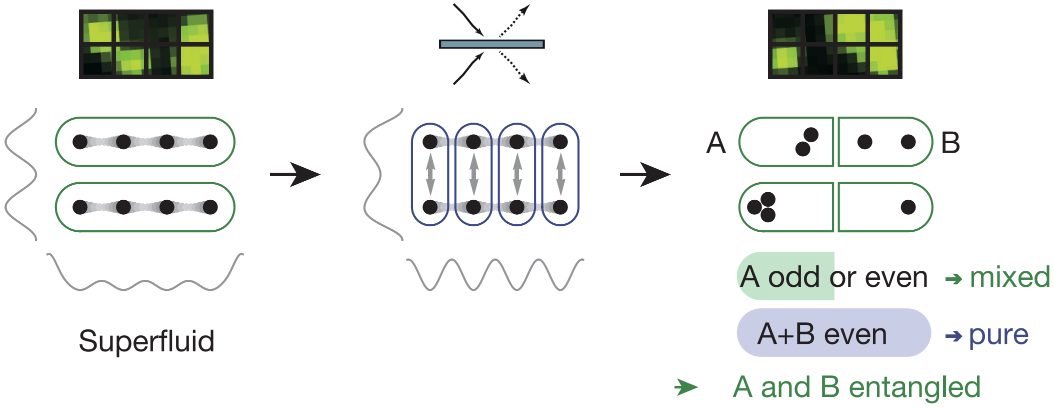
Renyi entropy via copies

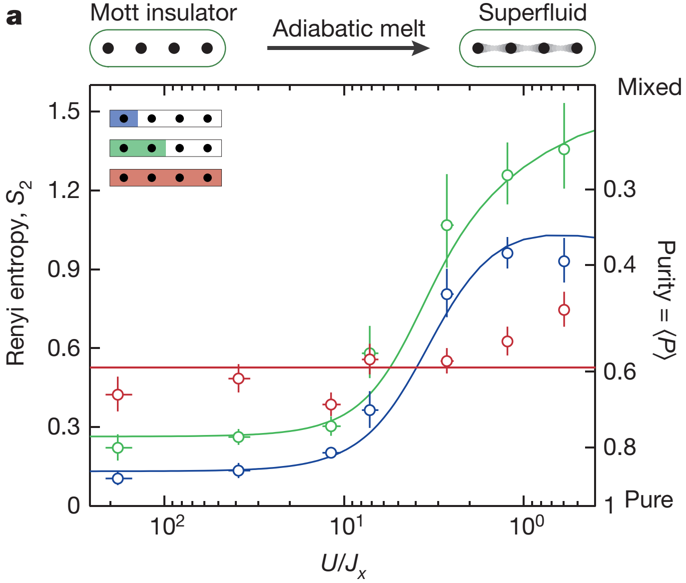
Given n identical copies, can measure S^n via joint measurements

Ekert *et al*, PRL 88 217901 (2002)



Experiment with atoms in optical lattice, by Greiner group.
Islam *et al*, Nature 528 (2017) 4 atoms, 2-copies.





Experiment: 2 ions, 2 copies, Yb+ ion trap. Linke *et al*, arXiv:1712.08581 (2017)

Renyi entropy via randomized measurements on one copy

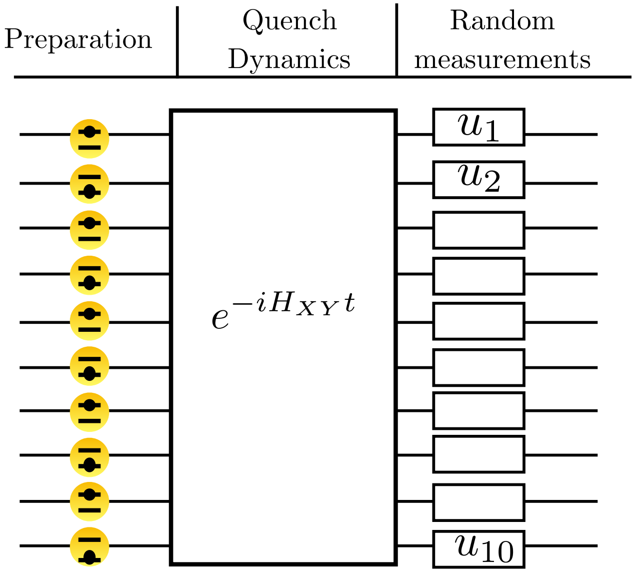
Key insight:

S^n obtained via nth order moments of local outcome probabilities *P*, when averaged over many random instances

$$S^2 = fn\left[P^2\right]$$

$$S^3 = fn\left[P^3\right]$$

Entropy information lies in statistical fluctuations of measurement outcomes

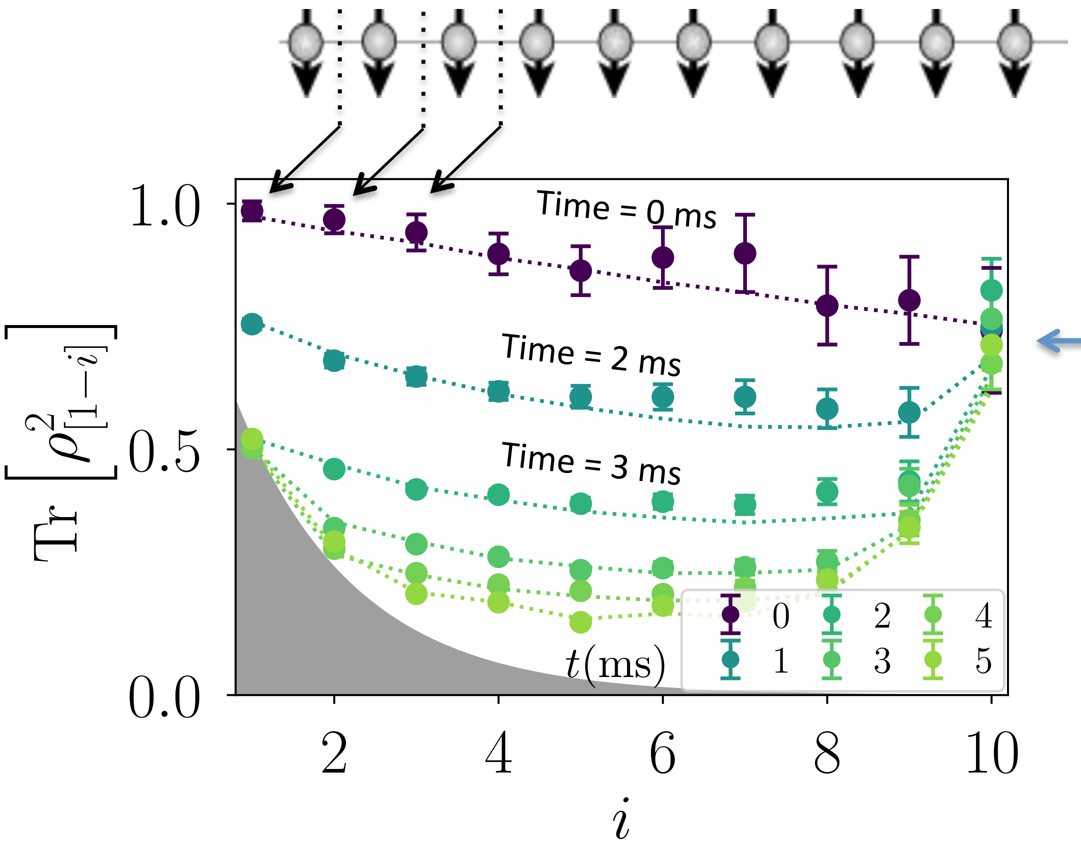


A. Elben, *et al*, Rényi Entropies from Random Quenches in Atomic Hubbard and Spin Models Phys. Rev. Lett. **120**, 50406 (2018)

Experimental effort scales exponentially in qubit number (as expected), but seems feasible to apply to at least 20-qubit partitions

Works for **all states, no assumptions**, **no need for identical copies**

Experimental results: evolution of entropies in 10 qubit ion-trap simulator dynamics



global purity remains high

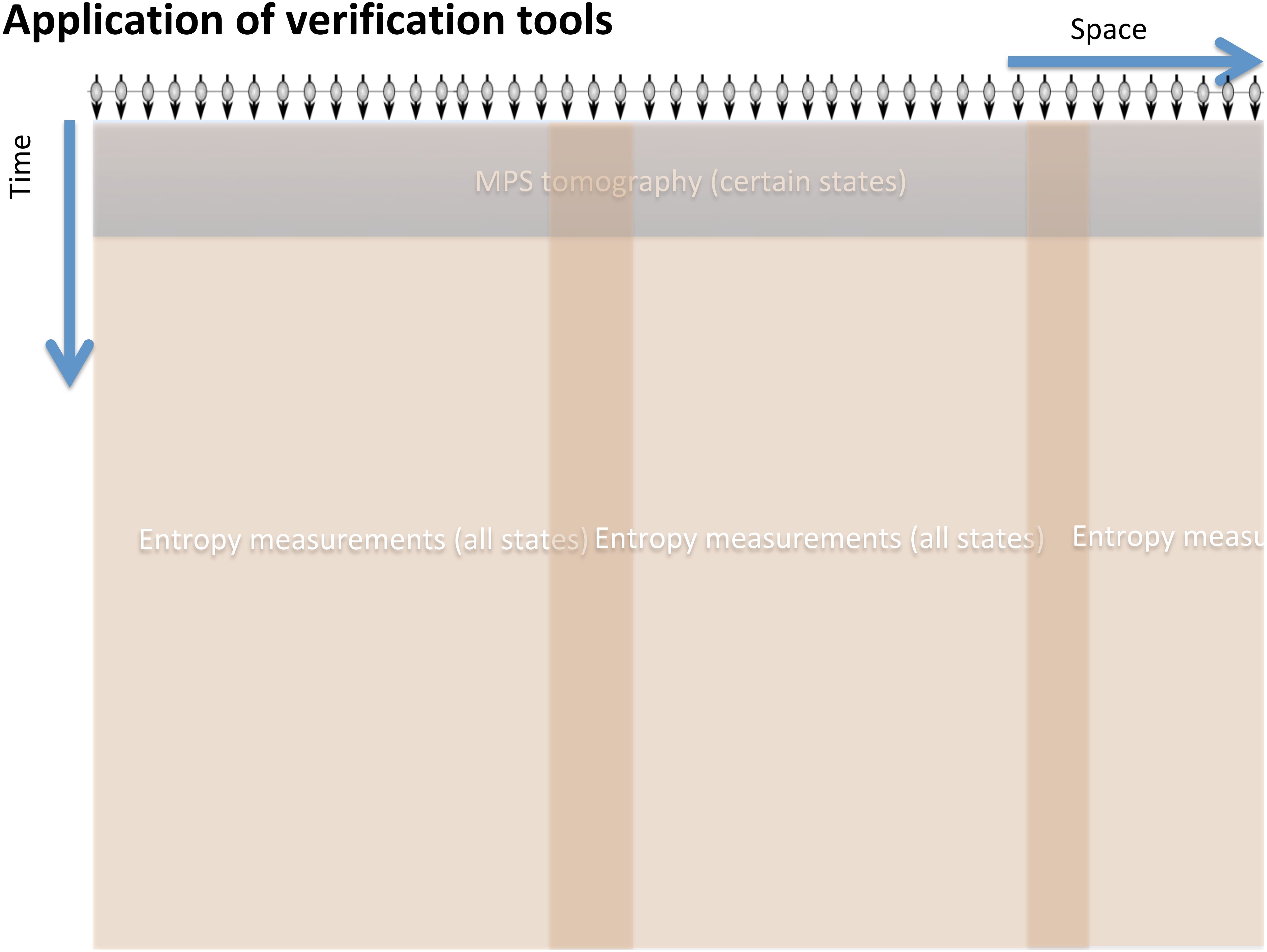
From 3 ms of interaction time onwards, all shown bi-partitions are entangled

7500 copies used for each point (consisting of 500 different random Us, 250 runs each)
$1\text{x}10^9$ copies would be required for state tomography

Allowed us, for the first time, to determine the purity of our quantum dynamics for 10 spins (20 spins feasible given technical improvements)

Future application: study thermalization and localisation effects in long-time Q. dynamics

Application of verification tools



MPS tomography (certain states)

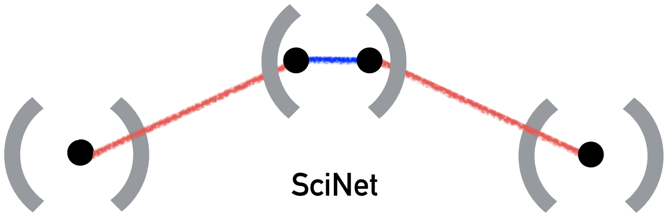
Entropy measurements (all states)

Entropy measurements (all states)

Entropy measu

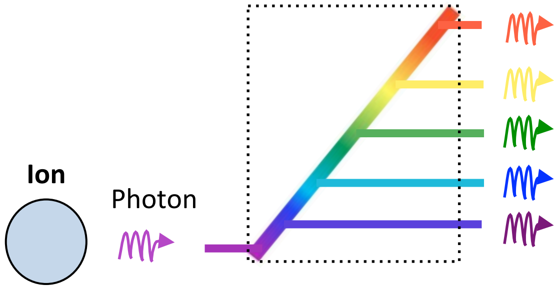
Light-matter interfaces and networking of trapped ions

Innsbruck ion-trap quantum network



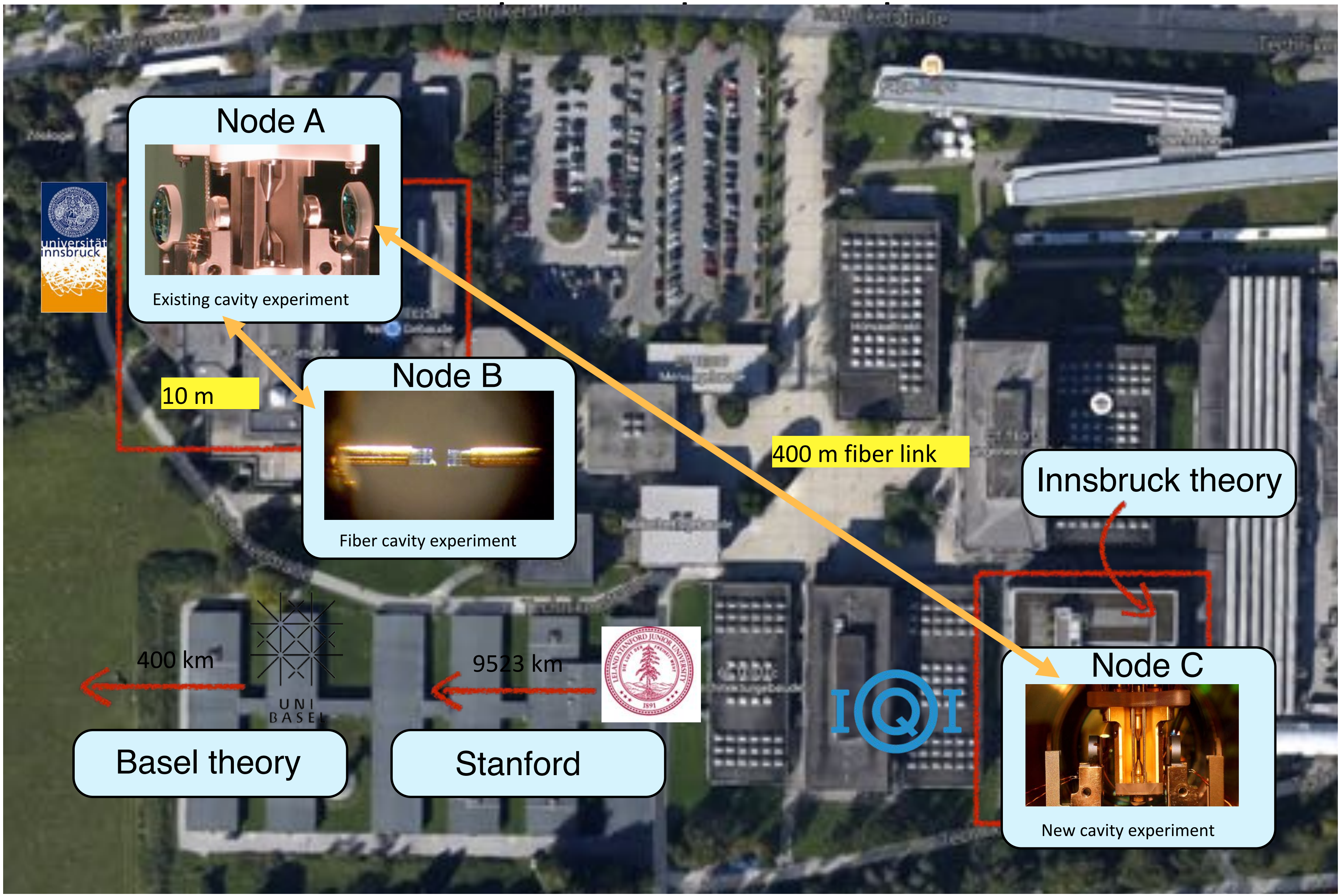
ARL

Photonic frequency converter



FWF
START

Innsbruck ion-trap quantum network



Node A

Existing cavity experiment

Node B

Fiber cavity experiment

10 m

400 m fiber link

Innsbruck theory

Node C

New cavity experiment

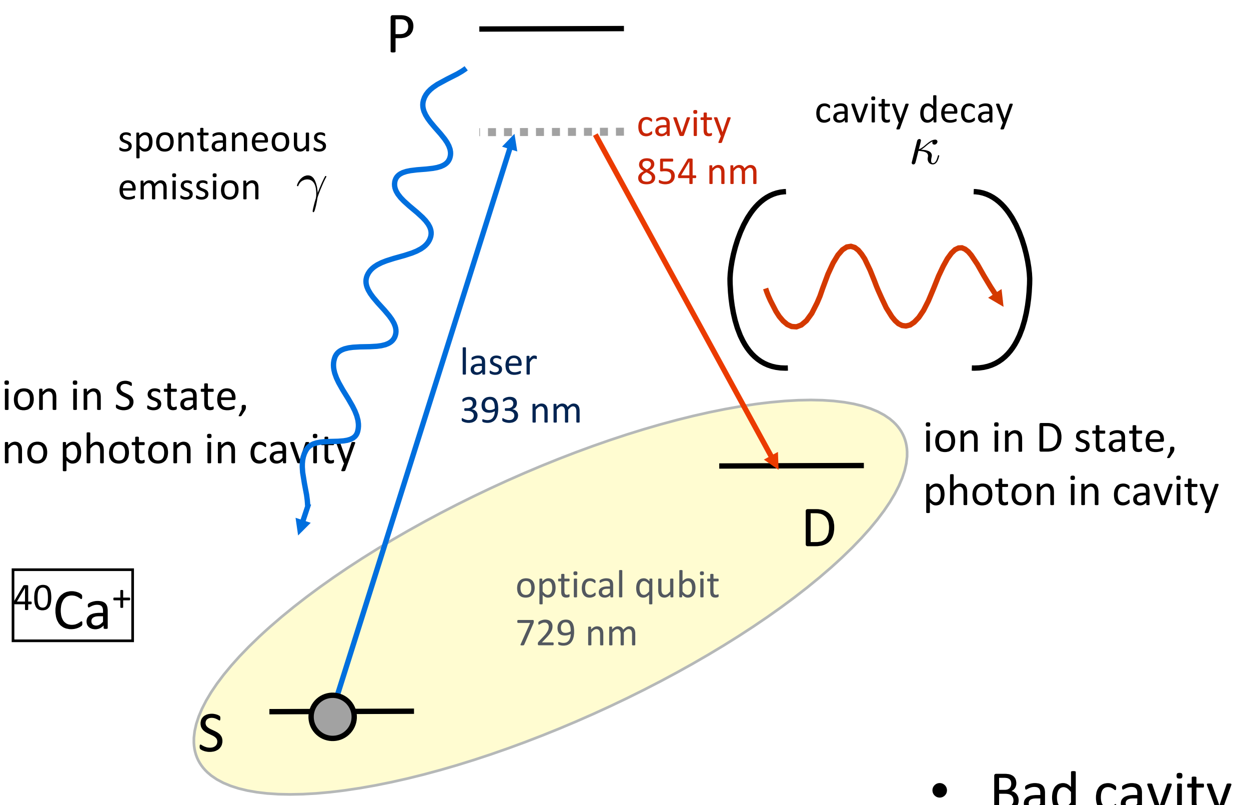
400 km

Basel theory

9523 km

Stanford

Light-matter interface: cavity-mediated Raman transition



P

spontaneous
emission γ

cavity
854 nm

cavity decay
κ

laser
393 nm

ion in S state,
no photon in cavity

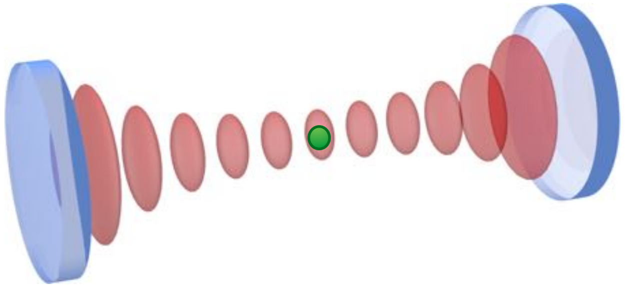
ion in D state,
photon in cavity

D

$^{40}Ca^{+}$

optical qubit
729 nm

S



- Bad cavity regime
- 100 kHz bandwidth photons
- 854nm photons (3 dB/km loss)

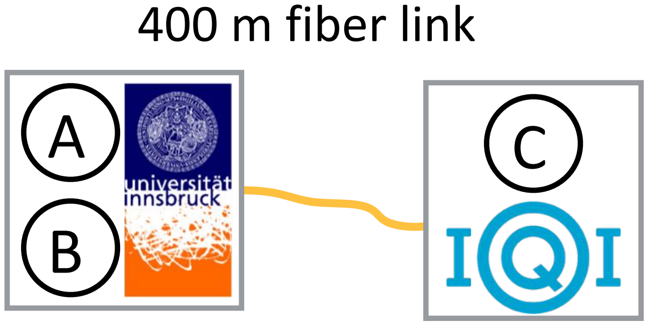
Tunable ion–photon entanglement
A. Stute et al., Nature 485, 482 (2012)

Quantum state transfer
A. Stute et al., Nature Photon. 7, 219 (2013)

Quantum networking team at IQOQI

Broad goals:

- Develop an remote ion-trap node, optimised for quantum networking
- Develop techniques to frequency-convert networking photons to telecom
- Entangle ions between the buildings



400 m fiber link

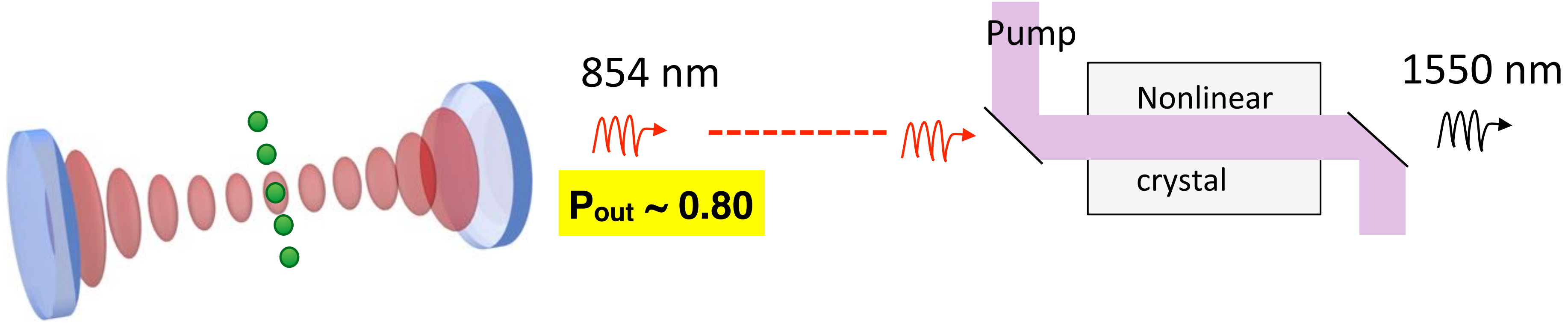
A

B

C

Trapped Ca^+ with optical cavity

Photon conversion via DFG



854 nm

P_{out} ~ 0.80

Pump

Nonlinear crystal

1550 nm

H. Hainzer

V. Krcmarsky

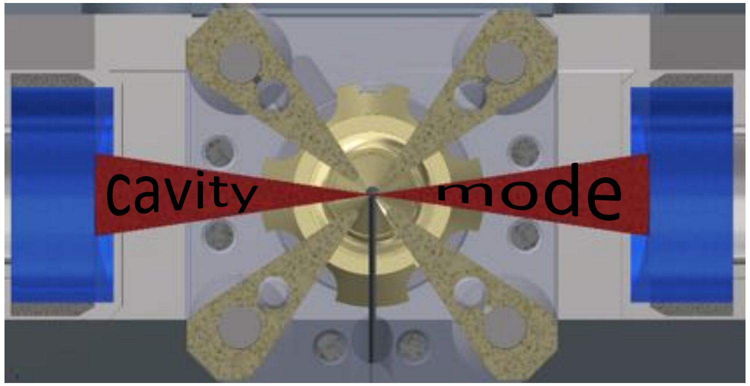
V. Krutianskii

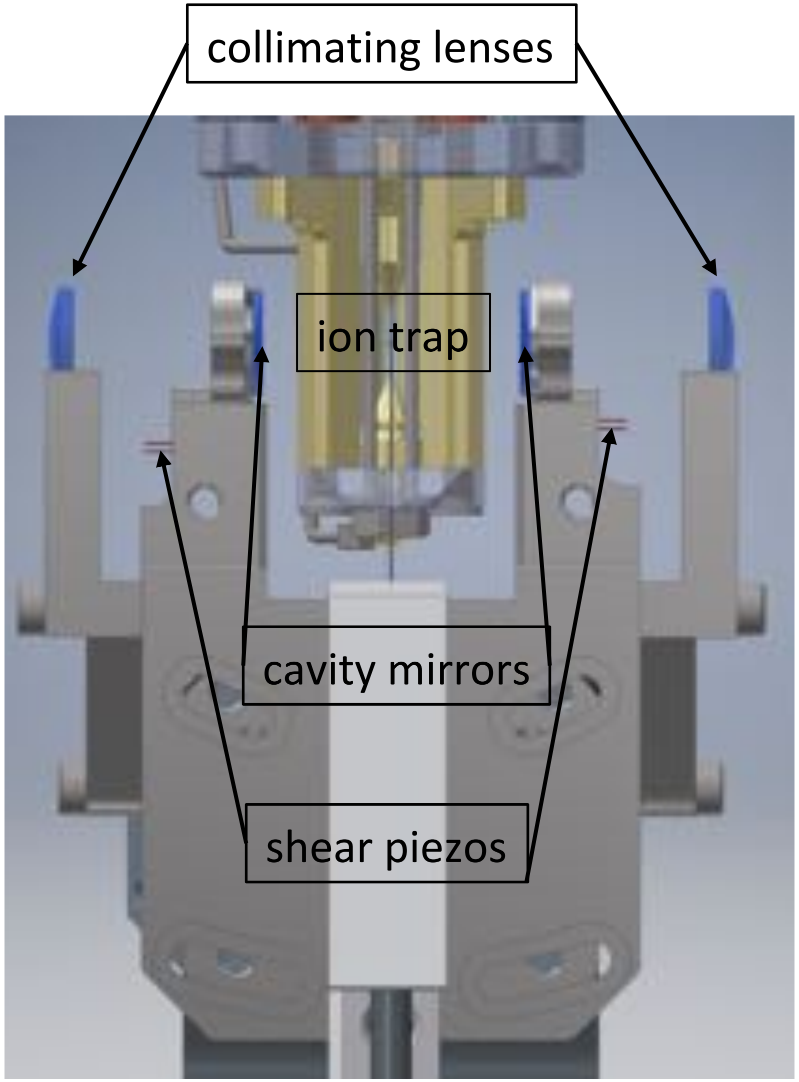
M. Meraner

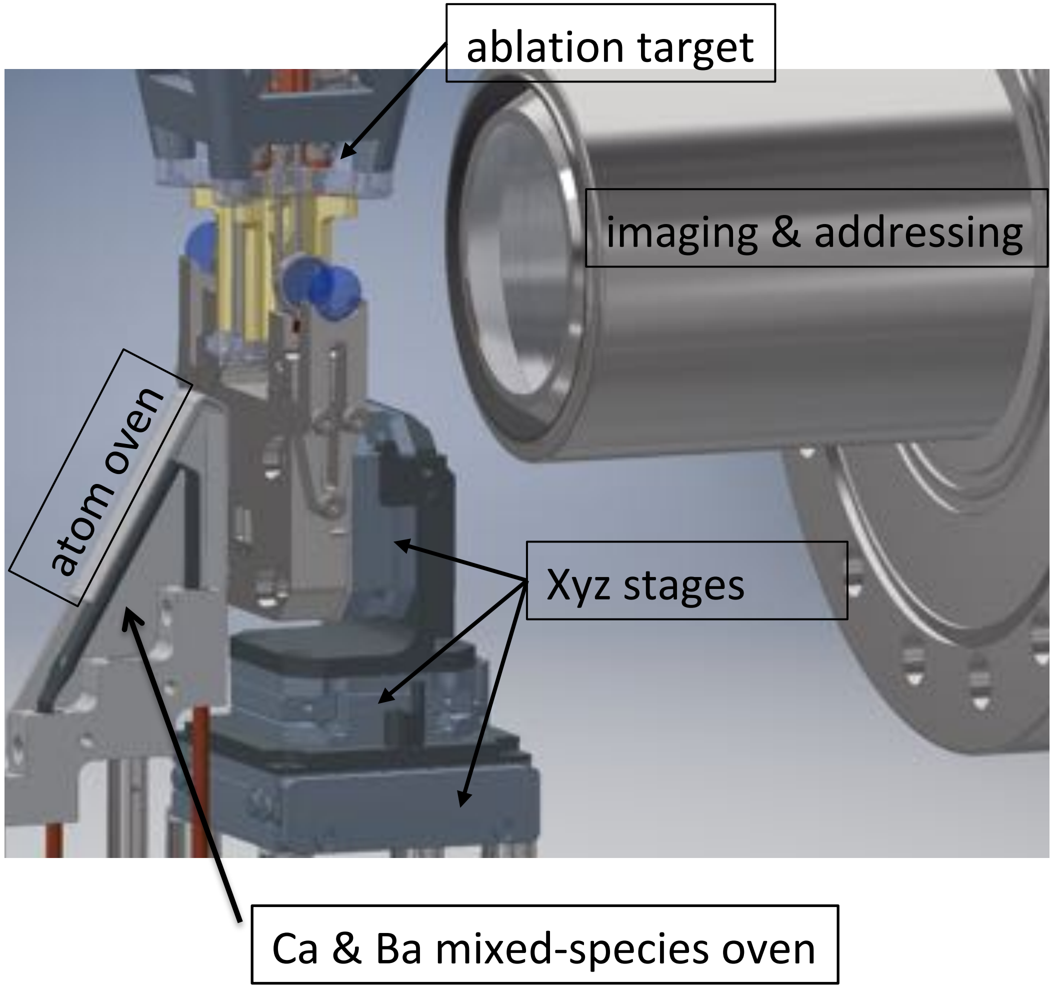
J. Schupp

B. Lanyon

Network node design

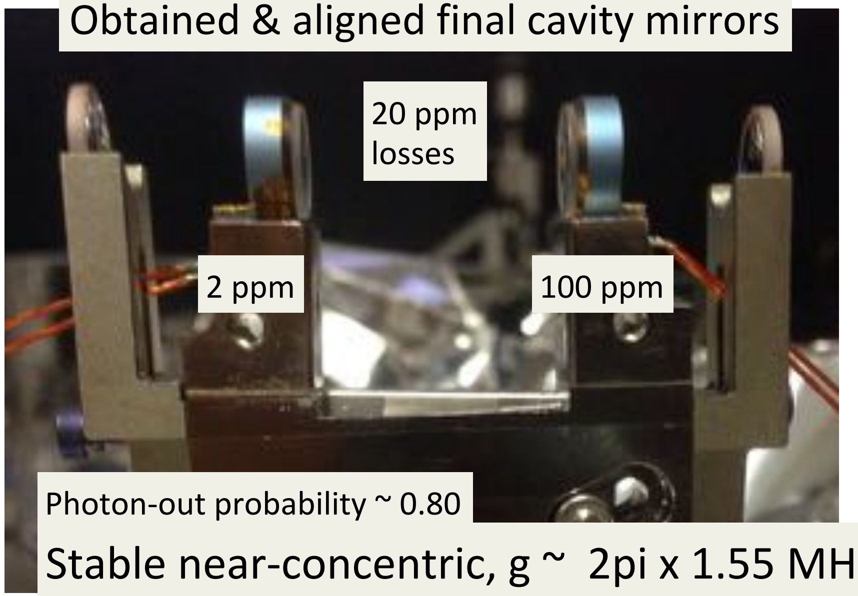






Manufacturer, testing and assembly last year

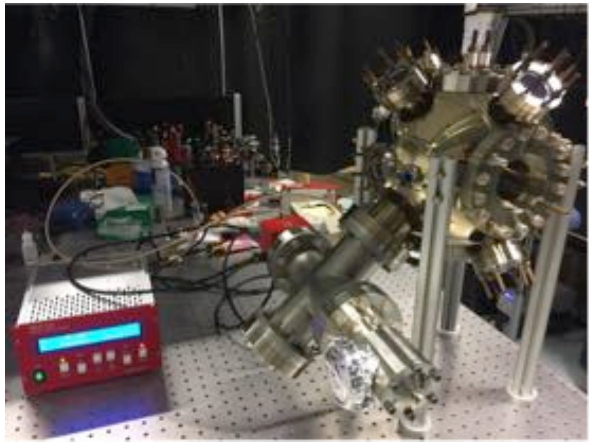
Obtained & aligned final cavity mirrors

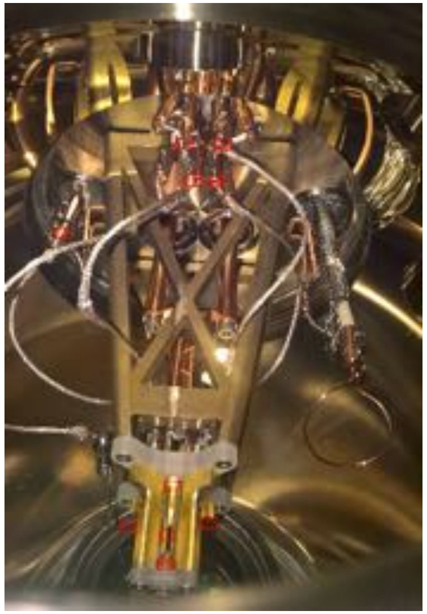


Photon-out probability ~ 0.80

Stable near-concentric, g ~ 2pi x 1.55 MHz

Manufacture, assembly & bake-out of ion trap system

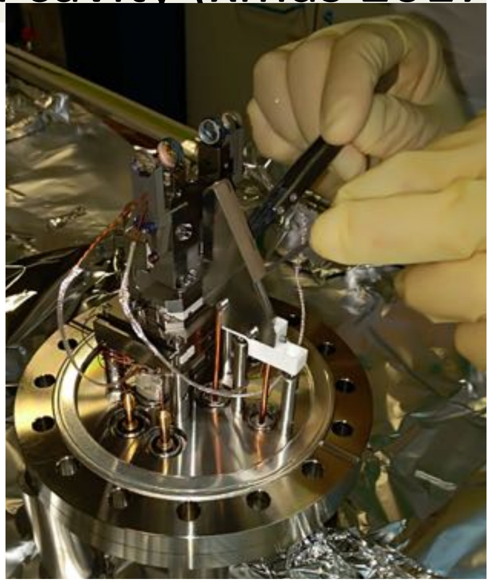




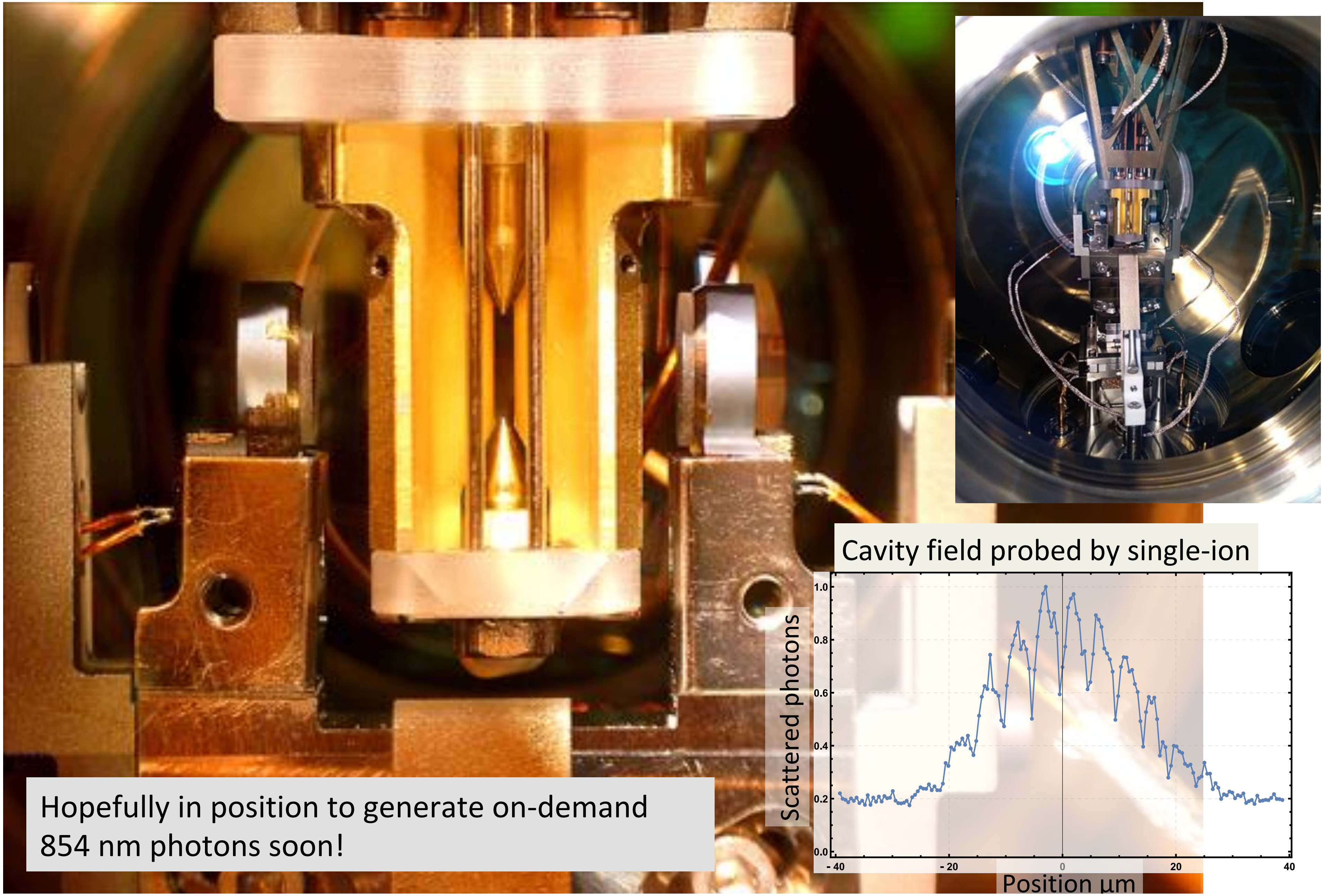
Ions trapped in new Node C

- Stable ion strings ✓
- Doppler cooling ✓
- Low Micromotion ✓
- Qubit Rabi flops ✓

Integration of optical cavity (xmas 2017



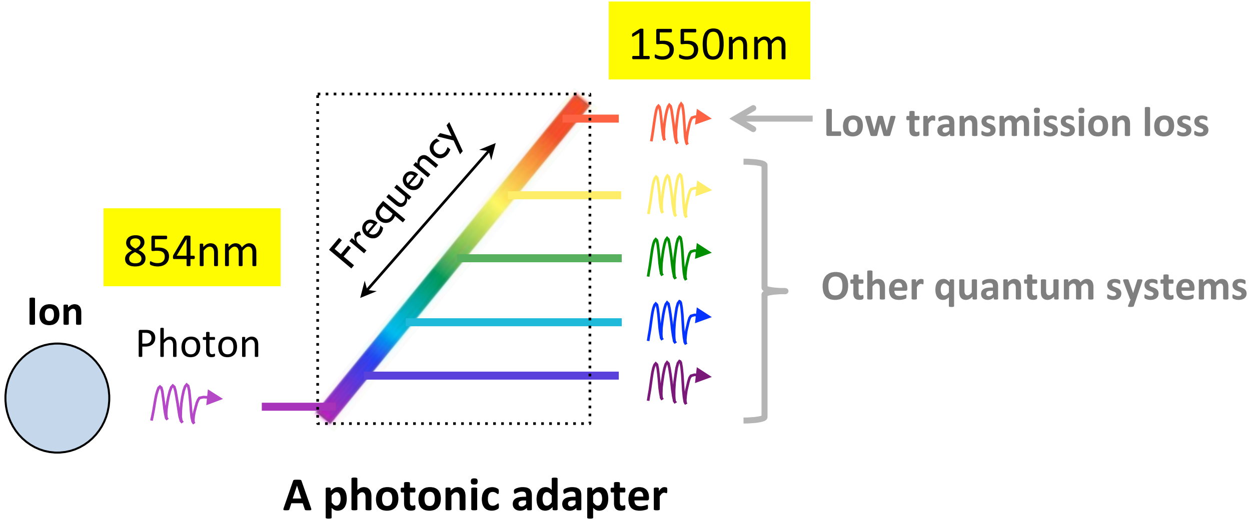
Ion-cavity system, January this year



Cavity field probed by single-ion

Hopefully in position to generate on-demand 854 nm photons soon!

Goal: develop a **photonic quantum interface for trapped ions:**

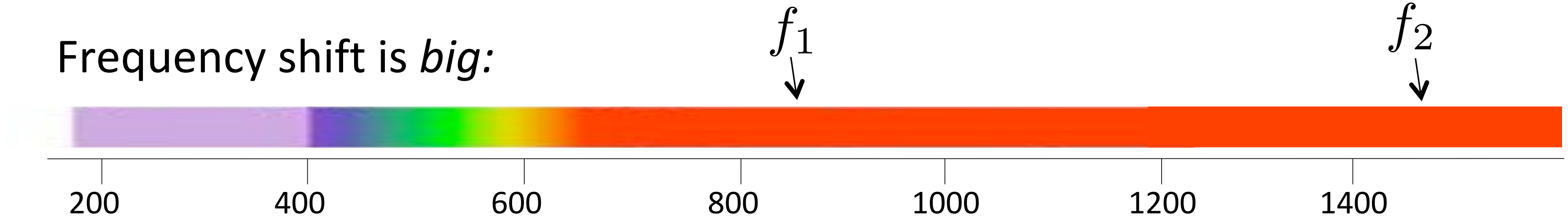


A photonic adapter

First experimental goal:

- Observe entanglement between ion and 50 km photon

Frequency shift is *big:*



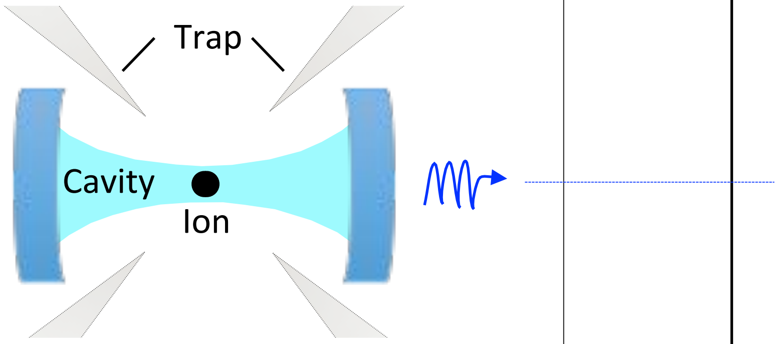
Wavelength	Loss in optical fiber dB/km	400 m transmission probability	50 km transmission probability
854 nm	3	0.5	1×10^{-15}
1550 nm	0.2	0.96	0.1

Several other examples of other quantum matter have been or will be coupled to telecom:

- Q. Dots
- Rb atomic ensembles
- Solid-state ensembles
- Solid-state Defect centers

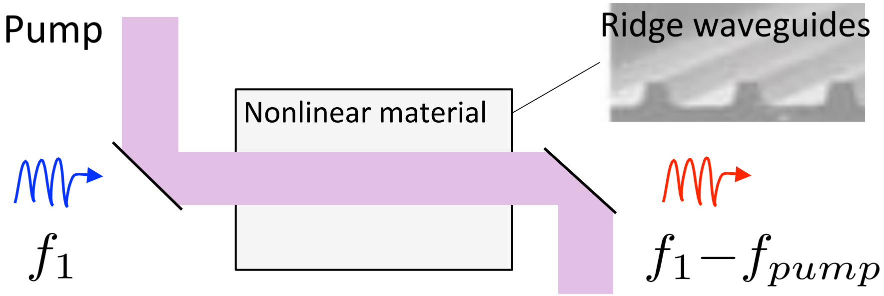
Basic Methods & Challenges

Photon source



- High rate & efficiency
- On demand

Photon conversion via DFG (SFG)



- Frequency reduced by that of a strong pump
- Waveguide-integrated nonlinear material

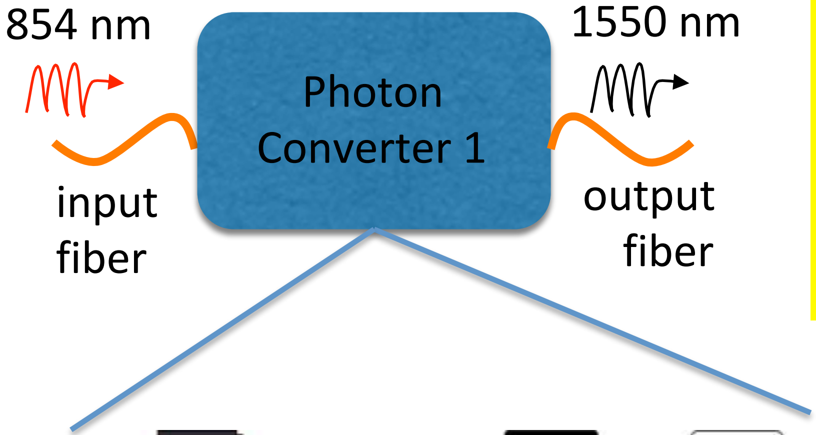
Key challenges:

- Noise filtering below the single photon level
- Preserving classical and quantum photon properties (correlations with matter qubit)
- Efficiency

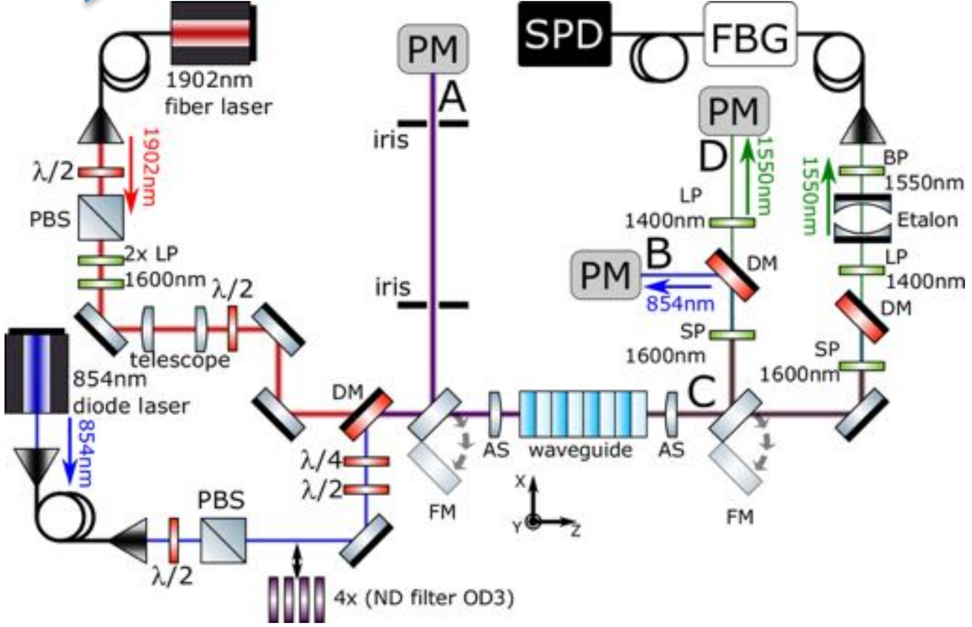
Note 1: Not just any ion or any photon transition

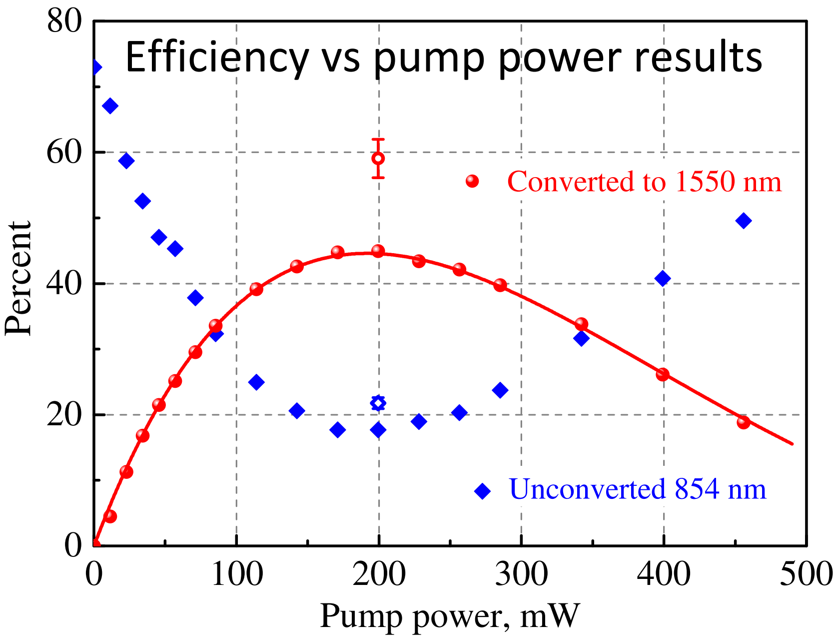
Note 2: C. Becher, C. Silberhorn, K. Kim, M. Lobino, Q. Quraishi, M.Keller

Results with laser light attenuated to single-photon level:



- 45% total efficiency for fixed polarisation
- 30 Hz added telecom photon noise
- 250 MHz bandwidth
- Time bin photonic qubits

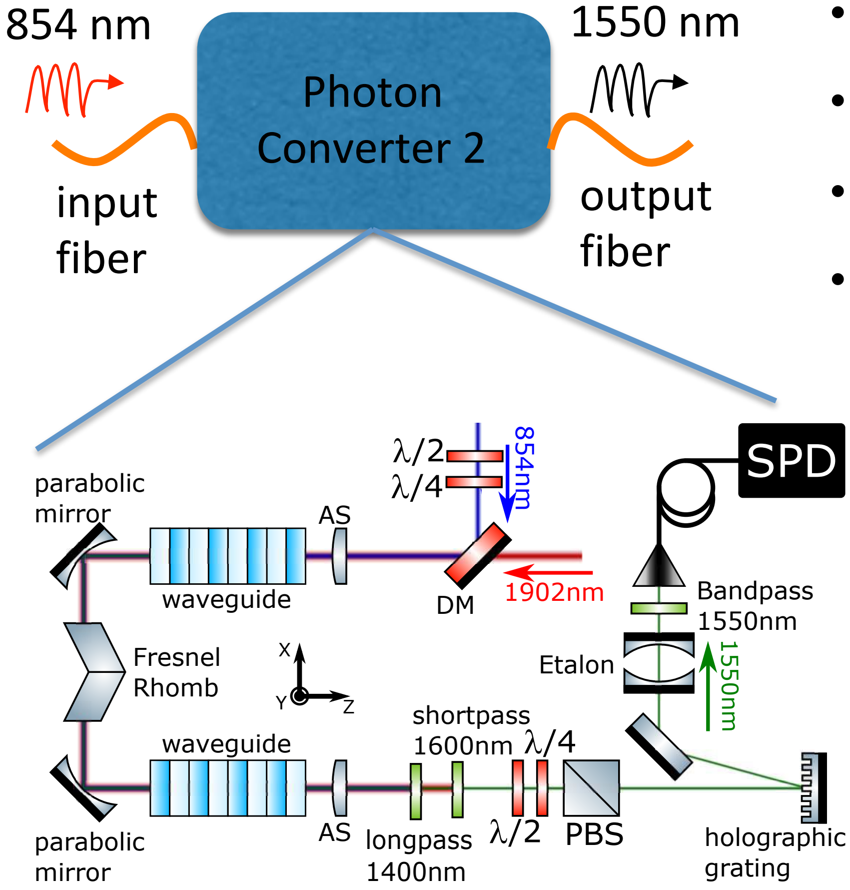




- 50 mm PPLN ridge waveguides
- 200 mW 1900nm pump laser

- Volume-holographic Bragg grating filters
- Cavity filtering

Results 2: **Polarisation-independent** conversion



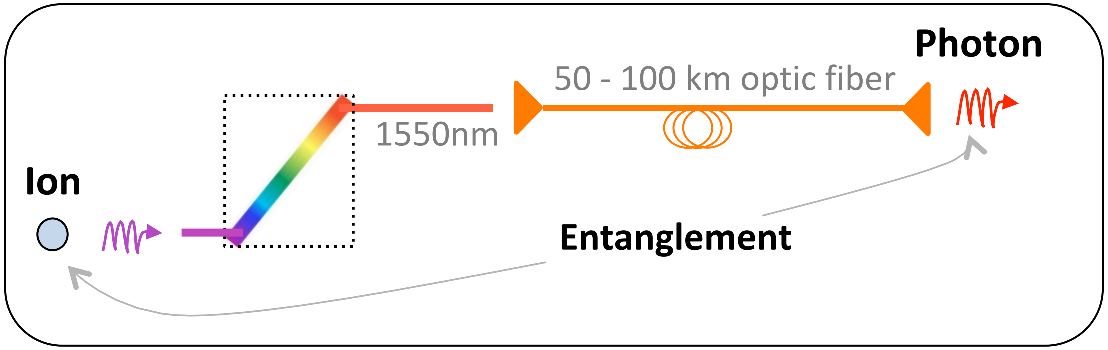
- 30% total efficiency for any polarisation
- > 0.93 fidelity polarisation preservation
- 50 Hz added telecom photon noise
- Polarisation qubits

- Two-converters in series
- Intrinsically-stable multi-wavelength polarization interferometer

Krutianski *et al*, Appl. Phys. B 123 (2017)

Next steps

- We have pieces to allow 50 km+ light-matter entanglement distribution (84 km)
- Next step: photons from ion



- Practical distances to start building large-scale light-matter q.networks, with full quantum logic capability.

- Possibility of new ion-hybrid systems

Summary and outlook

1. Now possible to engineer and precisely-probe quantum states of systems of 20 individually addressable quantum particles (trapped ions).

2. Some new methods to characterize and build-confidence in engineered quantum systems

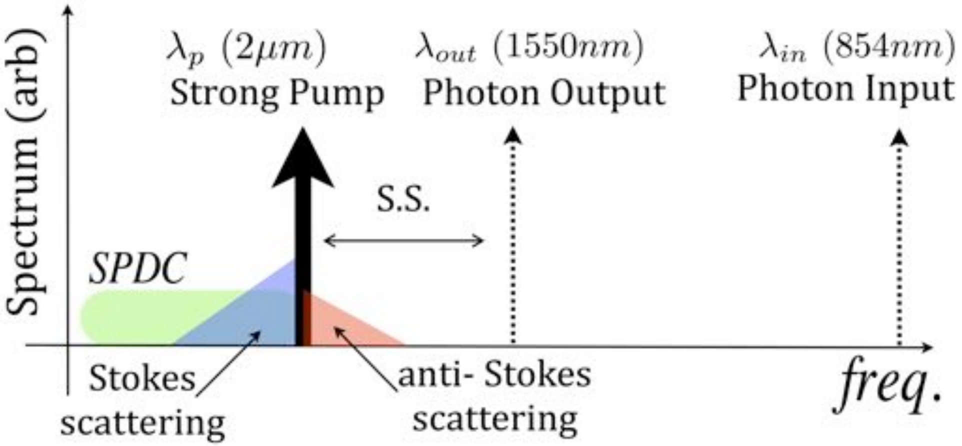
    - MPS tomography: scalable for broad class of quantum states
    - Witnesses for direct access to high-order correlations
    - Method to measure entropy via randomized measurements

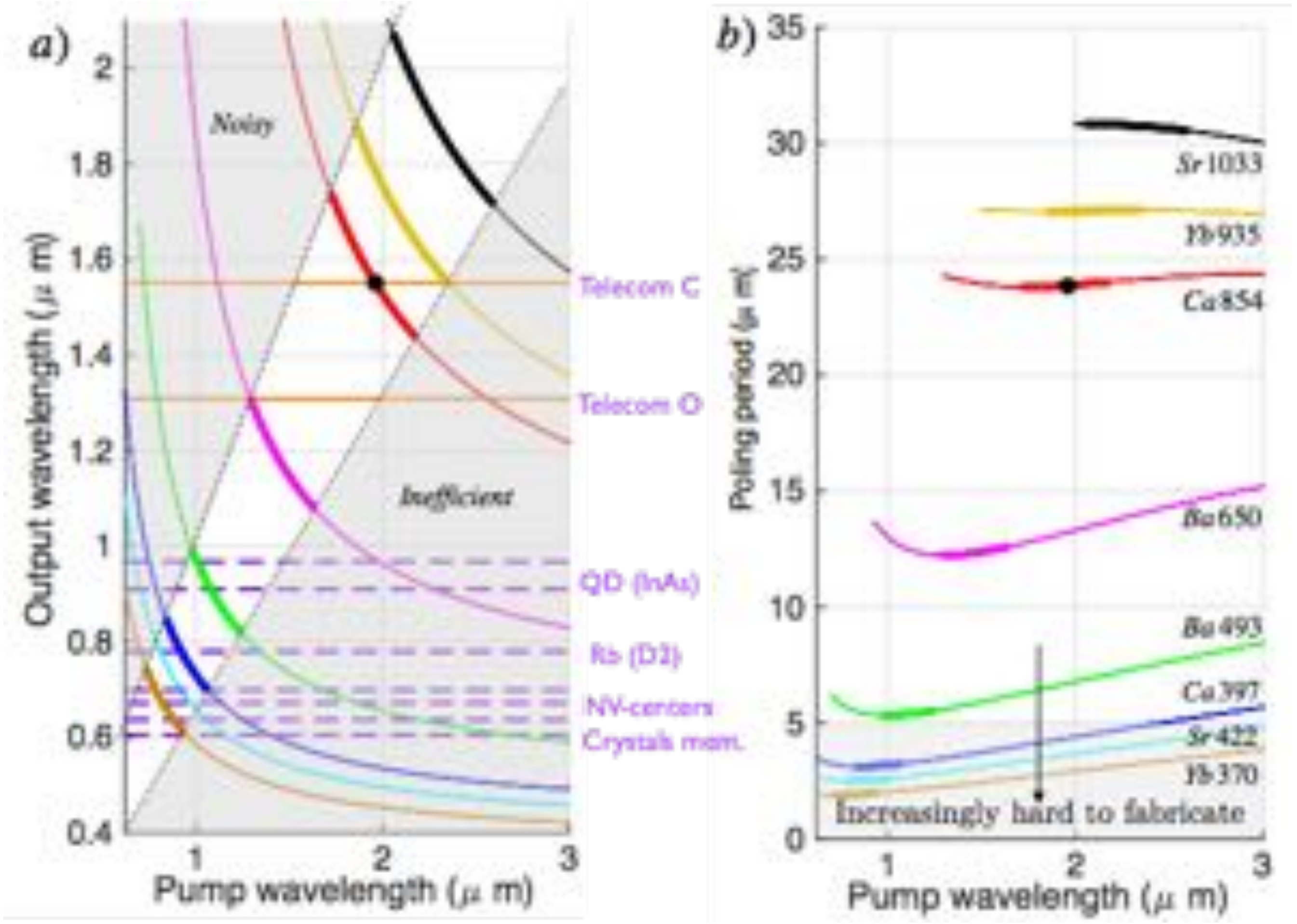
3. Our plans to realise a three-node light-matter q. network in Innsbruck (photons between buildings this year)

4. Using photon conversion, seems soon feasible to distribute long-lived entanglement over large distances between small quantum processors (~50 qubits) and between new ion-hybrid systems

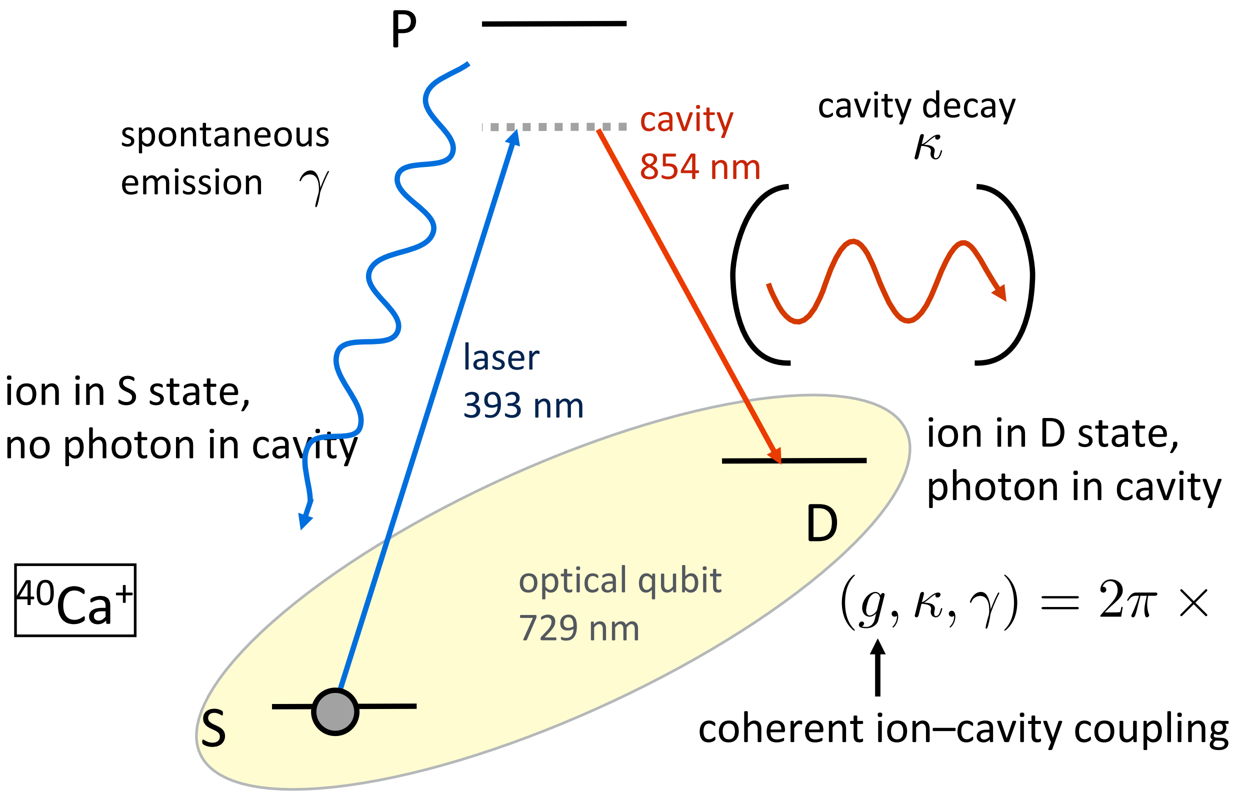
SPARE SLIDES

The 854nm transition in Ca+ is special





Light-matter interface: cavity-mediated Raman transition



P

spontaneous emission γ

cavity 854 nm

cavity decay κ

laser 393 nm

ion in S state, no photon in cavity

ion in D state, photon in cavity

D

optical qubit 729 nm

S

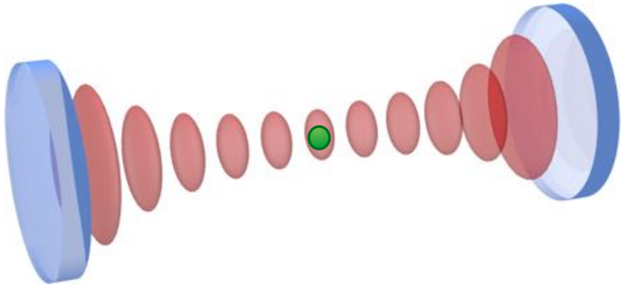
$^{40}\mathrm{Ca}^{+}$

$$(g, \kappa, \gamma) = 2\pi \times (1.4, 0.05, 11.5)\ \mathrm{MHz}$$

↑ coherent ion–cavity coupling

↓ detuning

$$(g_{\mathrm{eff}}, \kappa, \gamma_{\mathrm{eff}}) = 2\pi \times (18, 50, 6)\ \mathrm{kHz}$$



We operate in the “bad cavity” regime which is well suited for quantum networks.

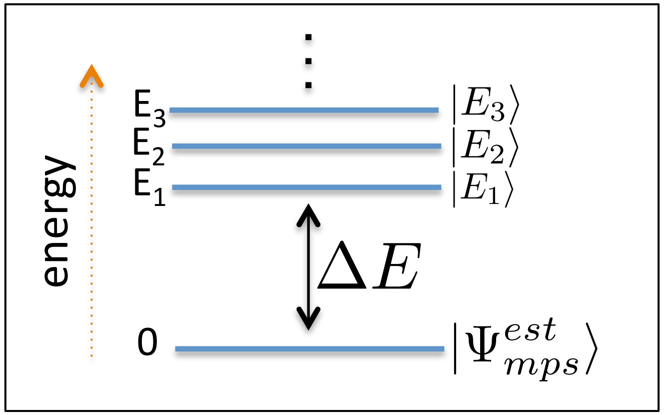
Tunable ion–photon entanglement
A. Stute et al., Nature 485, 482 (2012)

Quantum state transfer
A. Stute et al., Nature Photon. 7, 219 (2013)

Certificate

But is the MPS estimate close to the state in the lab? $\langle \Psi^{est}_{mps} | \rho_{lab} | \Psi^{est}_{mps} \rangle$

Suppose $|\Psi^{est}_{mps}\rangle$ is the unique ground state of a gapped local Hamiltonian *H*



$$Tr(H\rho) \geq \Delta E(1 - \langle \Psi^{est}_{\text{mps}} | \rho | \Psi^{est}_{\text{mps}} \rangle)$$

- Hamiltonian acts as witness for its own ground state
- Since *H* is local, Tr(*H p*) efficient to measure

So what?

Generic MPS states ***are*** the unique ground states of gapped local……..
Can determine overlap of MPS estimate, with state in lab, in straightforward way:

1. Get MPS estimate
2. Find parent H
3. Use local measurements to estimate Tr(Hp)
4. Calculate 'certified' fidelity lower bound

$$Fid \geq 1 - \frac{Tr(H\rho)}{\Delta E}$$

Next steps

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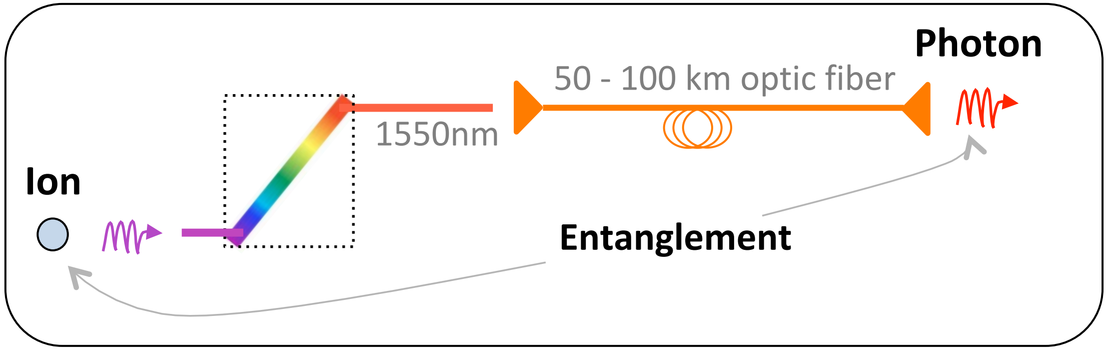
- Next step: photons from ion



- Practical distances to start building large-scale light-matter q.networks, with full quantum logic capability.
- Possibility of new ion-hybrid systems

Q. What are the applications of distributed quantum information and entanglement?

- Unconditionally secure communication (lots of papers on topic..)
- Enhanced precision time-keeping (Q. networks of clocks, *Komar et al, Nat. Phys.***10**, (2014))
- Scalable quantum information processing (Hucul et al, *Nat. Phys.* **11**, (2015))
- Enhanced long-baseline imaging of faint stellar objects (M. Lukin group, in preparation)
- …….?