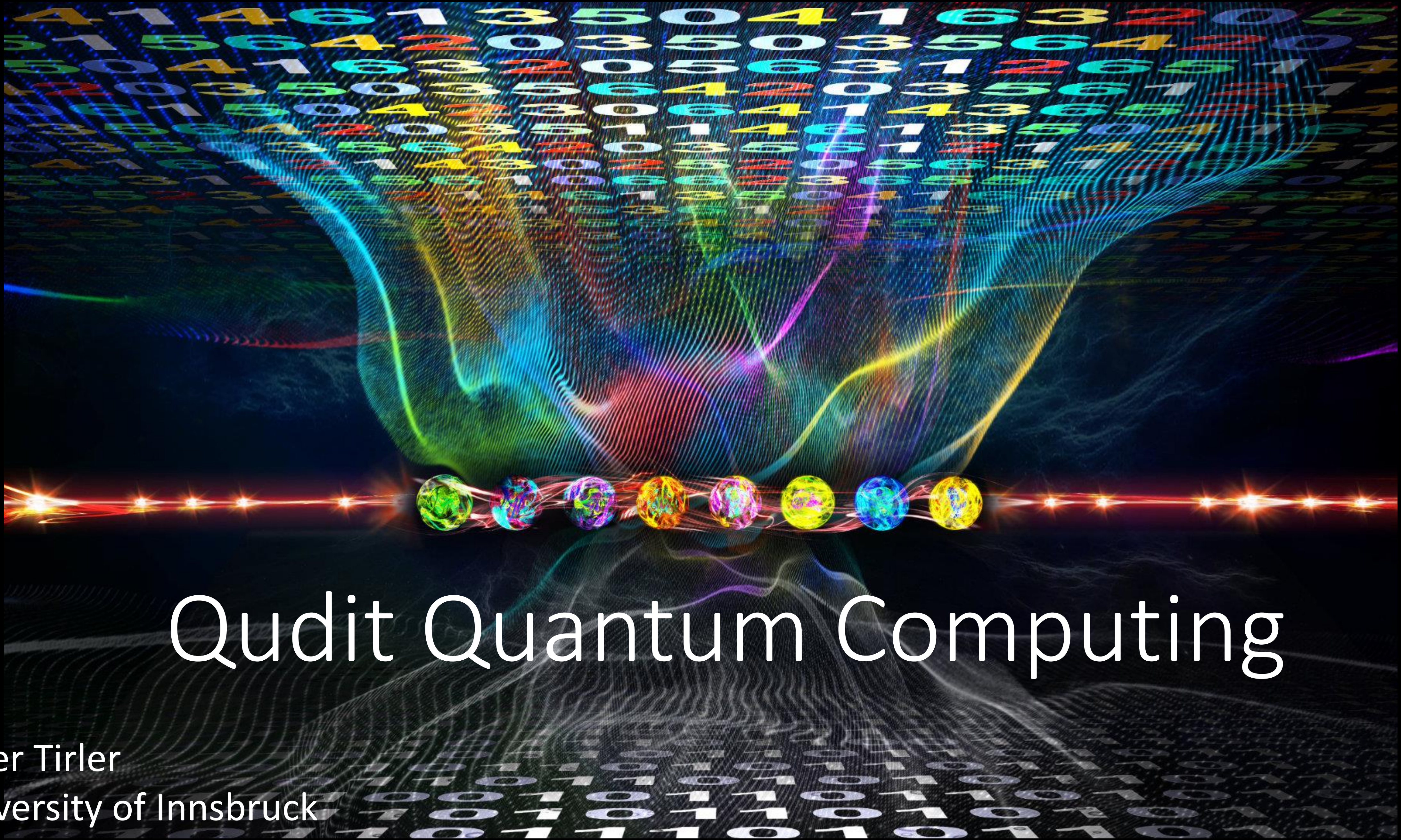
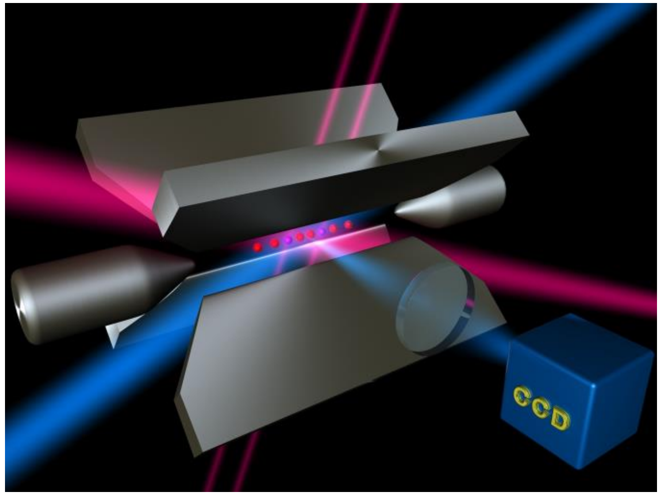


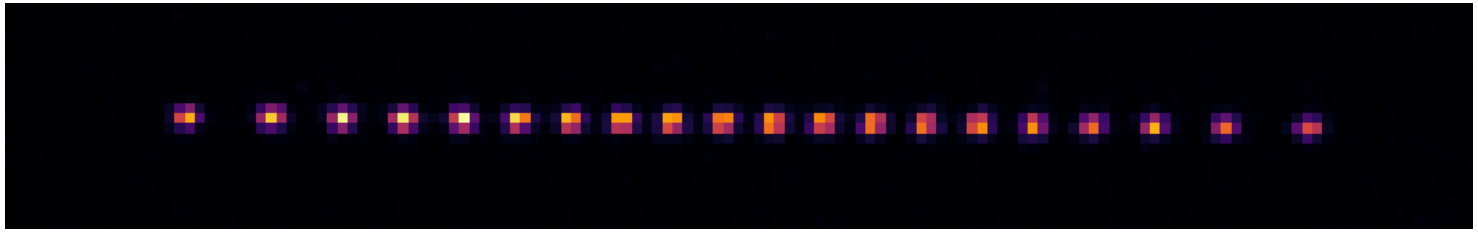
Qudit Quantum Computing

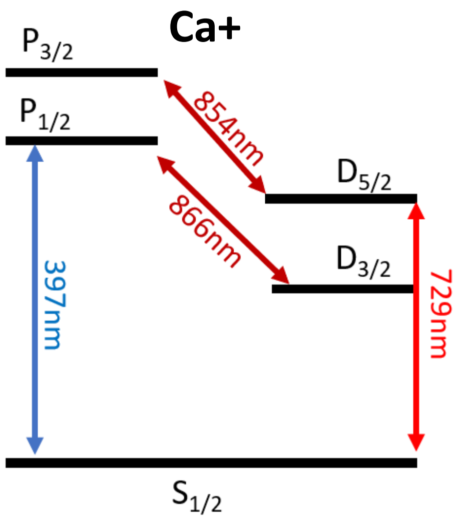
Peter Tirler
University of Innsbruck

Quantum Computing with Trapped Ions

We trap multiple Calcium Ions in a Linear Paul Trap and store quantum information in their electronic levels, using lasers that drive the quadrupole transition.





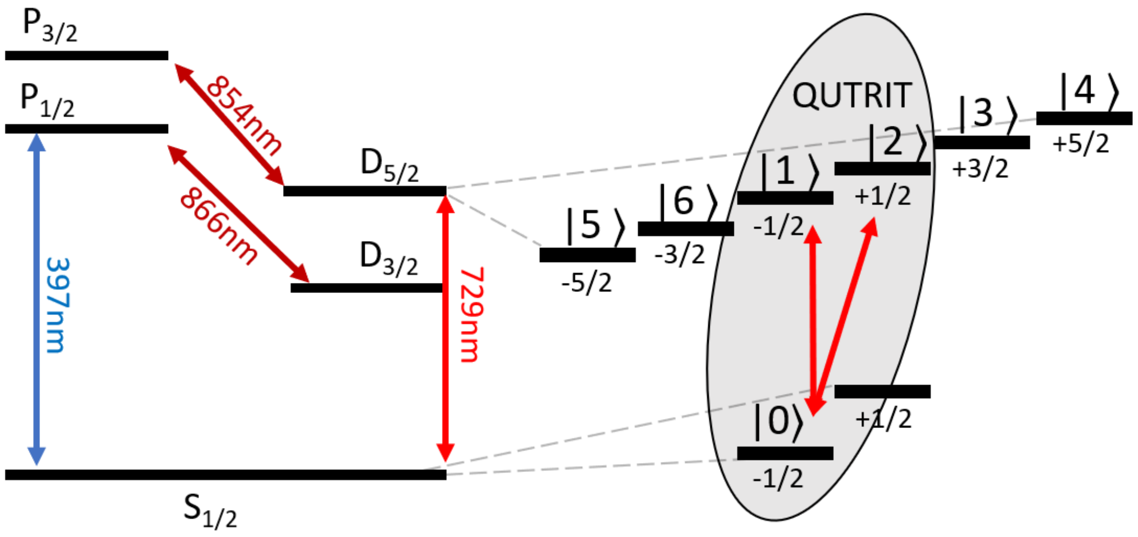


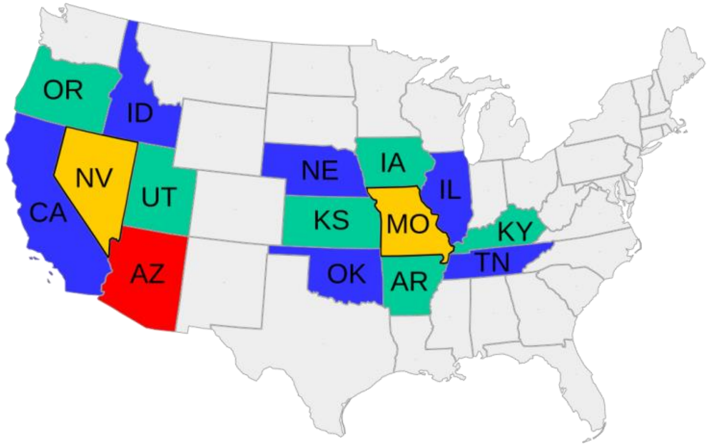
P. Schindler et al., New. J. Phys. 15, 123012 (2013)

Qudit Quantum Information Processing

Instead of restricting us to a 2-dimensional subspace of the available Hilbert space, we store more information in one ion by using bigger subspaces.

- Is this useful? - depends…



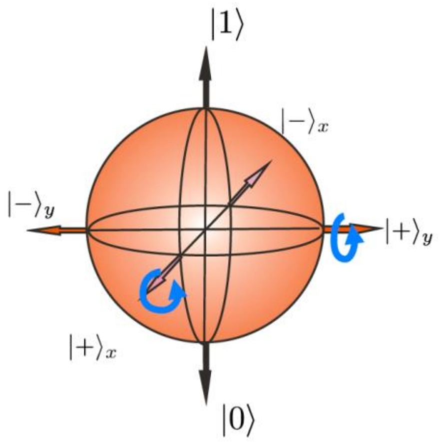


Intricacies of Qudit QIP I

Now we have to implement arbitrary unitaries on d-dimensional quantum systems.
This can be done by decomposition into 2-level operations.

$$\begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

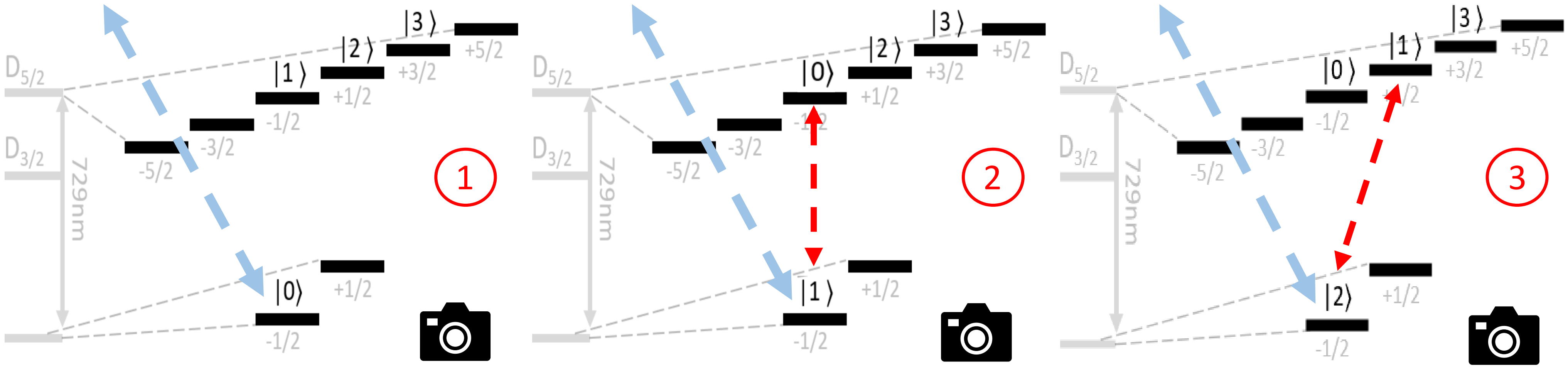
$$\begin{pmatrix} i & 0 & 0 \\ 0 & -i & 0 \\ 0 & 0 & 1 \end{pmatrix} \neq \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Ringbauer et al. Nat. Phys. 2022

Intricacies of Qudit Quantum Computing II

Readout is always projective into „bright“ or „dark“. Since this is fundamentally qubit-based, d-dimensional readout has to be done iteratively, which creates overhead.

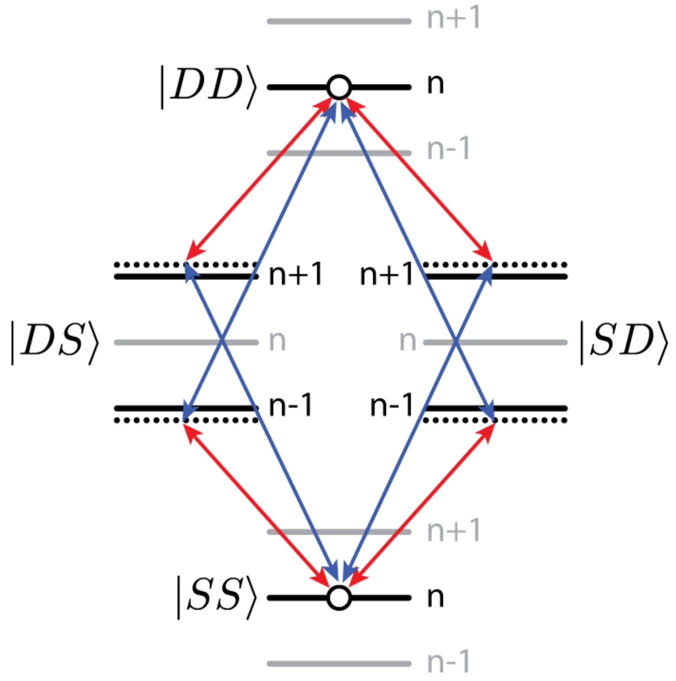


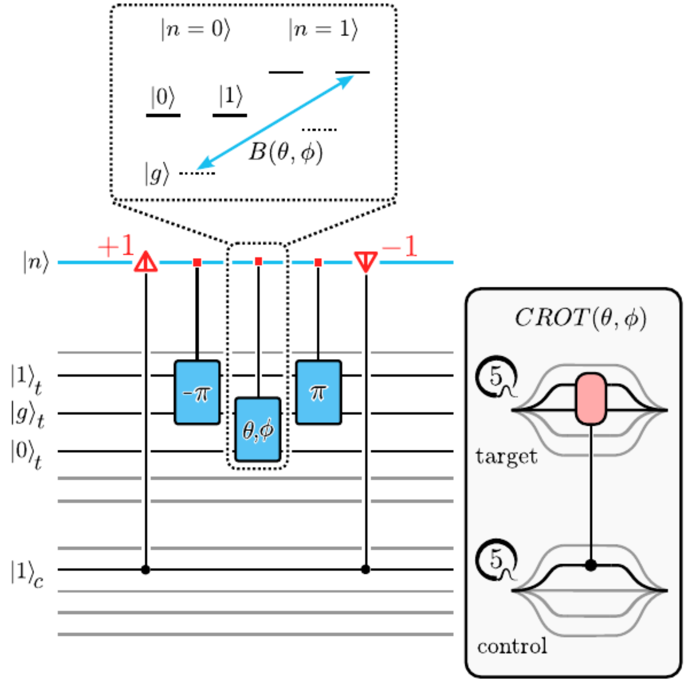
universität innsbruck

Intricacies of Qudit Quantum Computing III

Entangling gates are still universal, but not equivalent. This calls for multiple different entangling gates to be used for different applications. E.g:

- Mølmer-Sørensen
- Cirac-Zoller
- Light Shift Gate



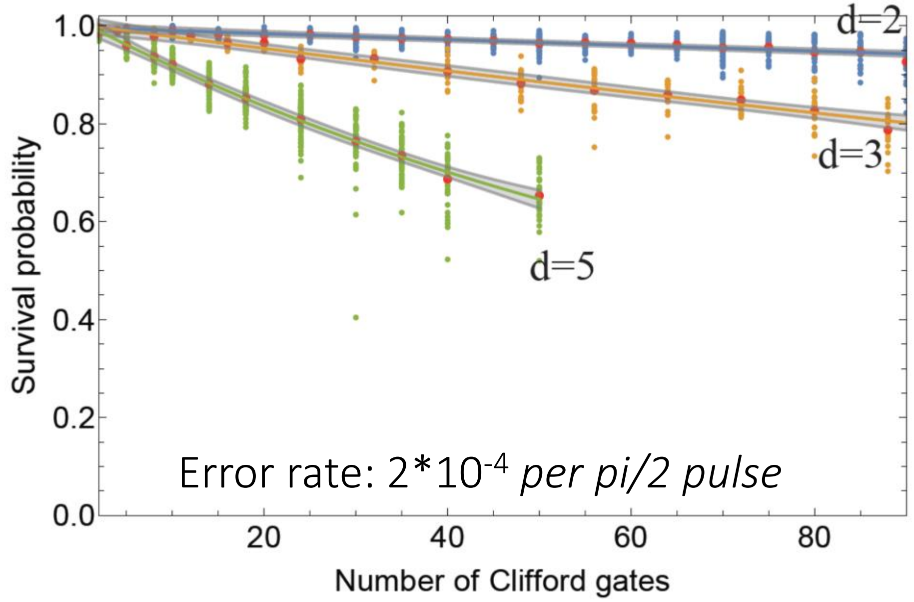


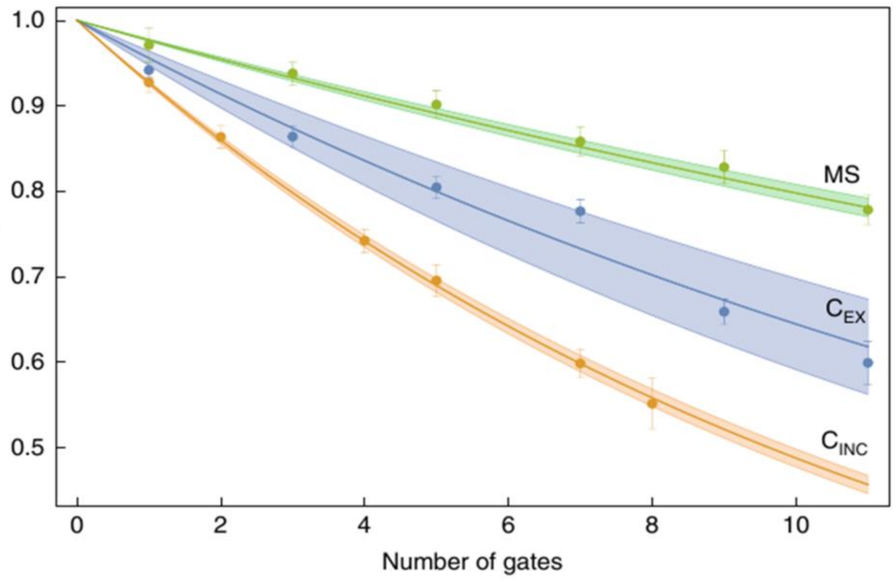
Meth et al. arXiv:2310.12110

K. Mølmer and A. Sørensen, PRL 82, 1835 (1999)

State of the Art

We can use an existing experiment in Innsbruck to benchmark qudit gates. Going to larger dimensions, the fidelity per pulse remains constant and gate fidelities scale accordingly.

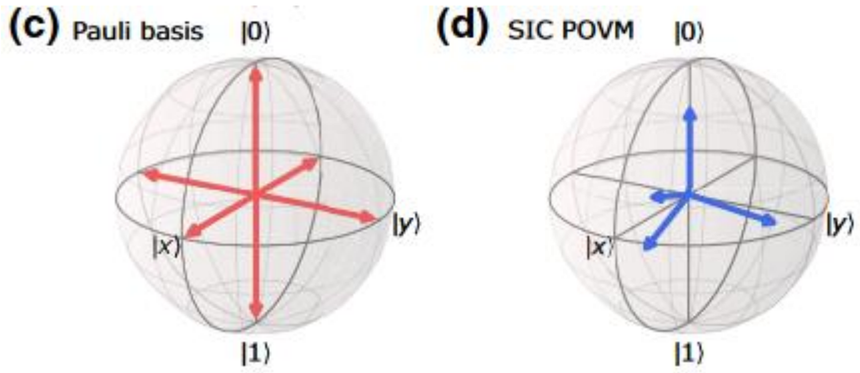


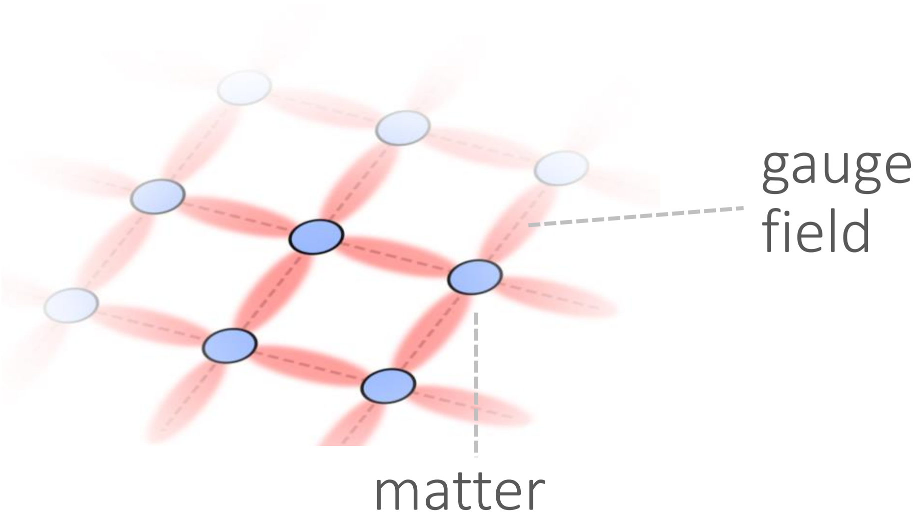


Ringbauer et al. Nat. Phys. 2022

Is this useful?

Already, some problems are better suited for qudit-based computation. Examples that were demonstrated here in Innsbruck include single-setting tomography and quantum simulations of two-dimensional lattice gauge theories.



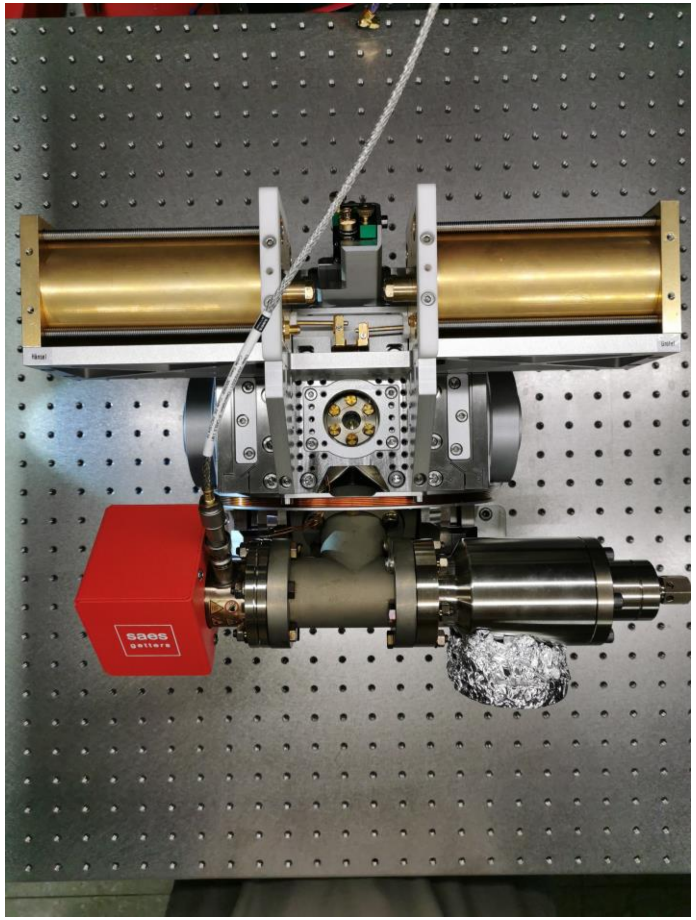


R. Stricker, et al., PRX Quantum **3**, 040310 (2022)
M. Meth, et al., arxiv:2310.12110 (2023)

The Real World: Building a New Hardware Setup

Our current focus is to build a new experiment, that is specifically geared toward state-of-the-art QIP with qudits. This in particular includes:

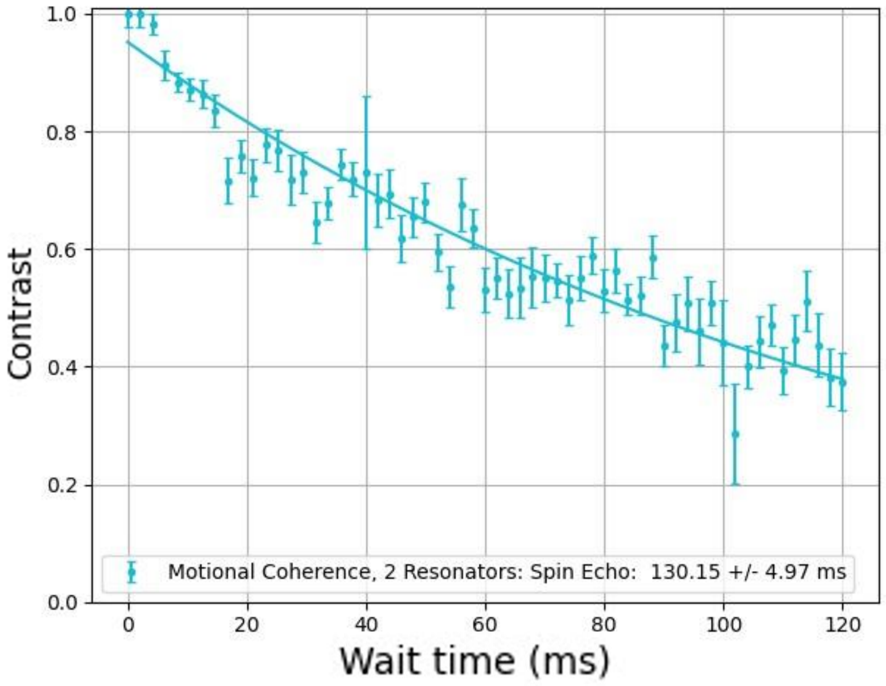
- Dual desonator drive
- Two sided orthogonal addressing
- High NA objective
- Titanium Chamber



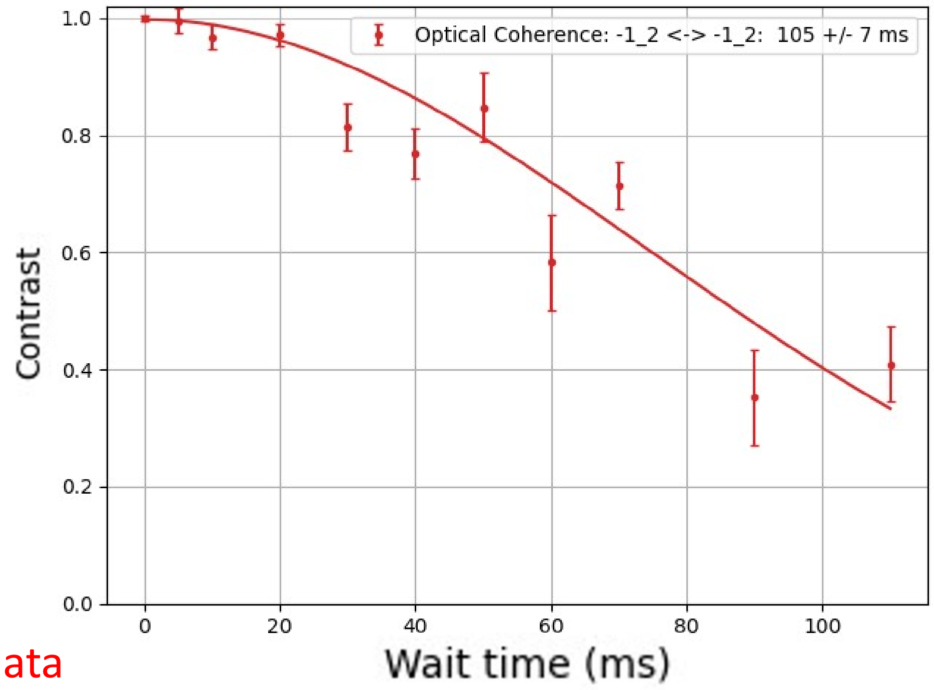
Current Status

We are currently installing a single ion addressing unit for the quadrupole laser

Motional Coherence: 130 ms



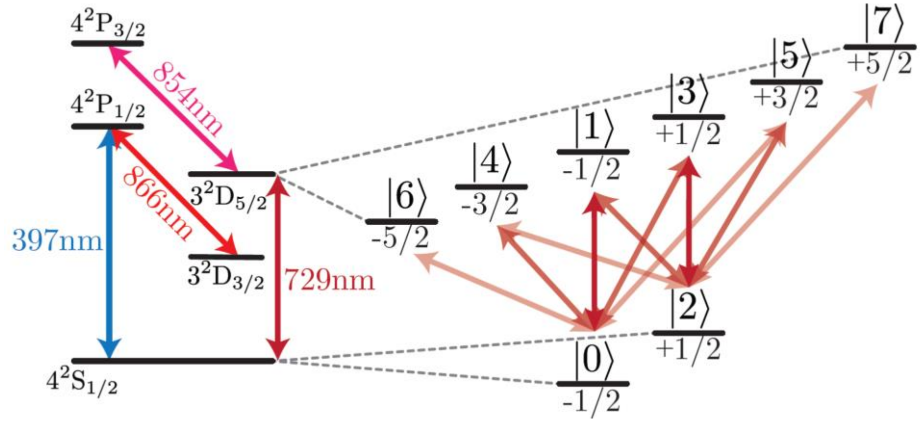
Optical Coherence: 105 ms

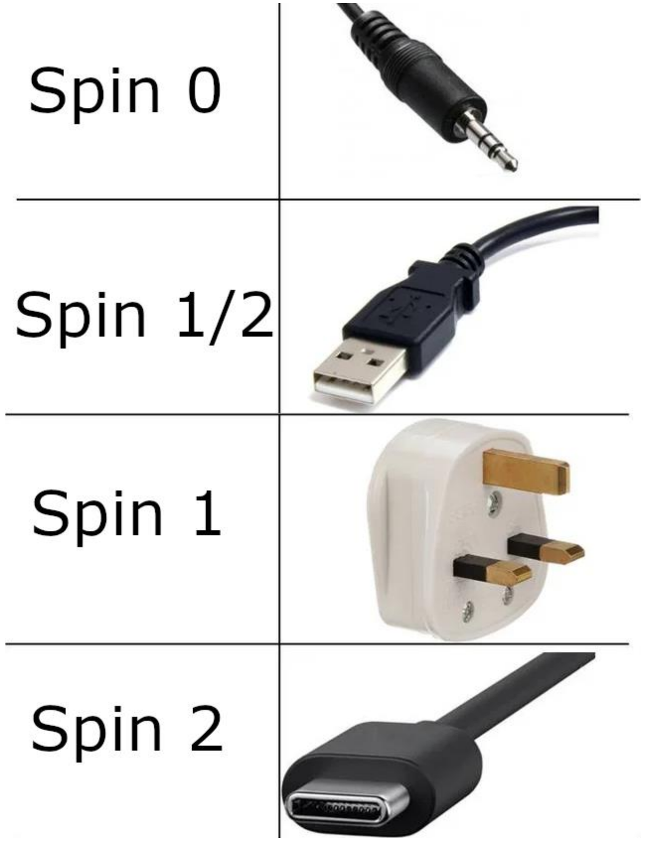


preliminary data

Future applications:

- Quantum Simulation beyond spin ½
- Developing a Qudit computing framework
- Pushing the limits of what is classically simulatable



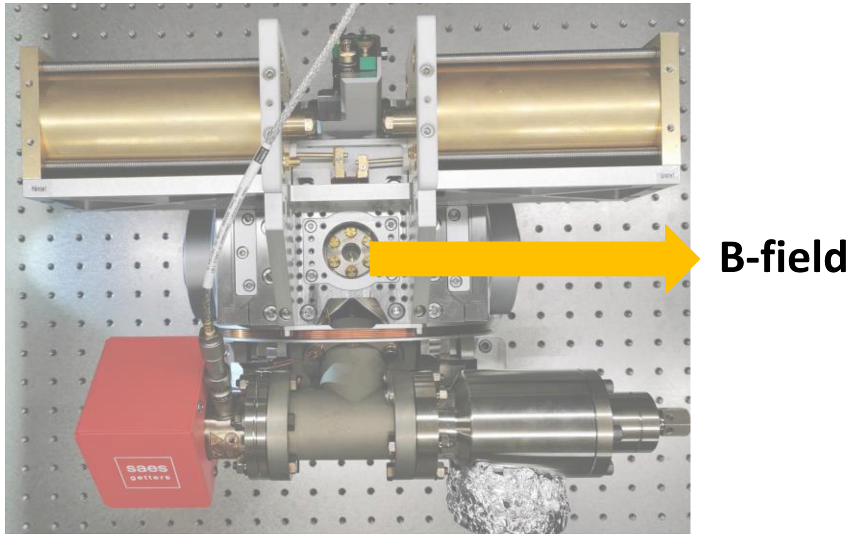


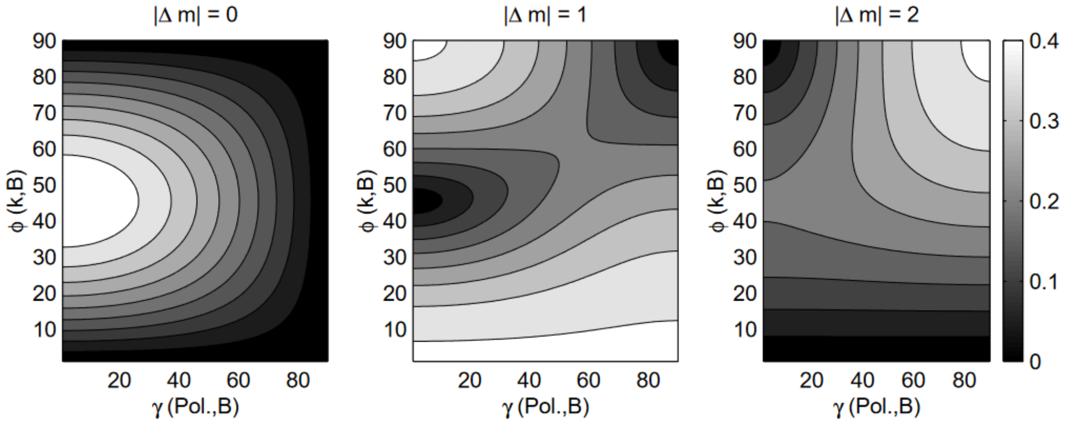
Credit: reddit u/Dabman2006

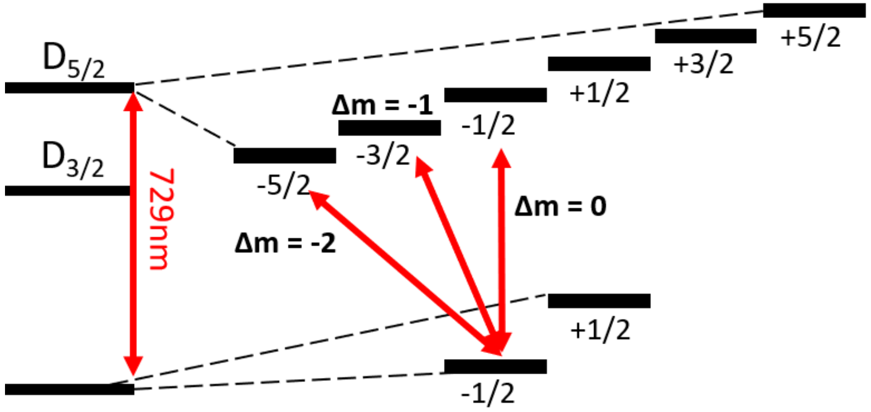
Thanks!

Problem 1: Magnetic field direction

For the direction of the quantisation axis, an equal coupling for all carriers has to be considered. This limits the set of available polarisation-dependent cooling schemes.



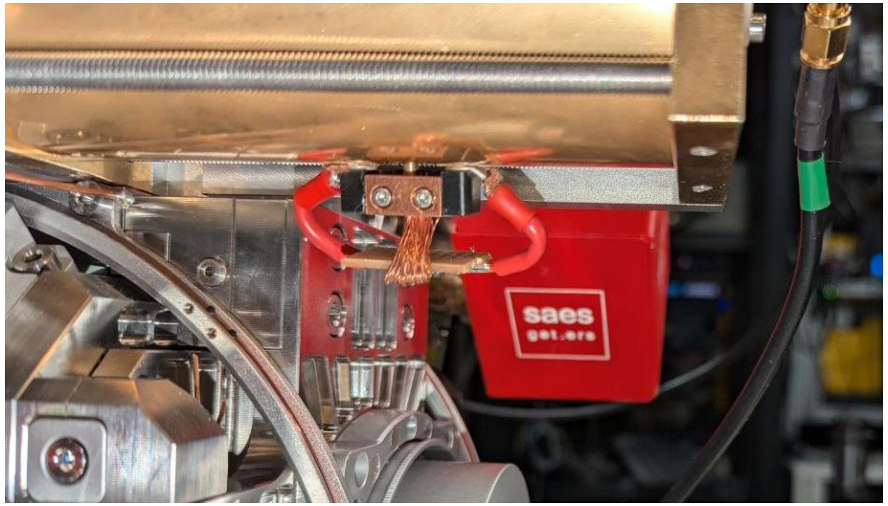


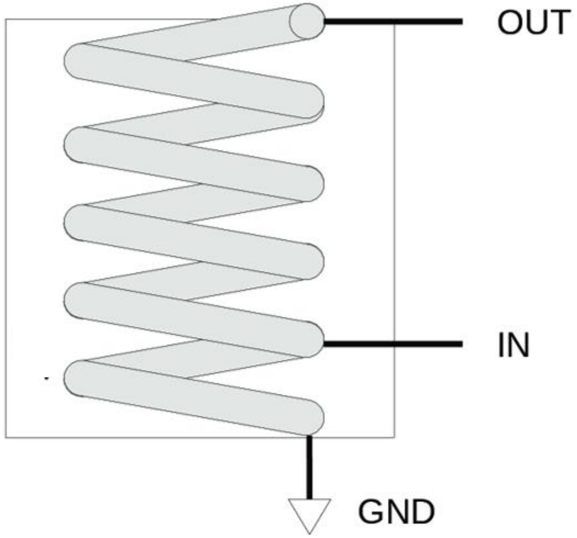


Christian Roos, PhD Thesis, 2000, University of Innsbruck

Problem 2: Dual Resonator Configuration

Degeneracy splitting of radial modes cannot be achieved with two helical resonators that galvanically connect the helix to the shield.





E. Martines et al. Applied Sciences, 2021

Problem 3: Coherences

Coherences are very sensitive to ground loops. Here‘s a list of friends we made over the last year:

https://www.thorlabs.com
https://www.cmple.com/wavenet

Problem 3: Coherences

Coherences are very sensitive to ground loops. Here‘s a list of lessons we learned over the last year:

- Some are unavoidable
- They like to mix and merge
- Larger loops are worse