OPTICA
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Technical Groups

Rack-Mounted Quantum Computation

Thomas Monz, CEO at Alpine Quantum Technologies

08 April 2022

A Quick Zoom Tutorial

– Submit a question by clicking on “Q&A”

– Like a question that’s been submitted?
Click the “thumbs up” icon to vote for it.

– Share your feedback in the survey.

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Question & Answer

Rack-Mounted Quantum Computation

Thomas Monz, CEO Alpine Quantum Technologies

09.04.22

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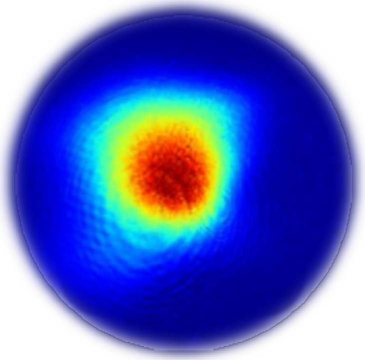


Could be you?
Please contact us!

About Our Technical Group

Our technical group focuses on the physics of laser cooling, electromagnetic trapping and other radiative manipulation of neutral atoms, ions, dielectric particles and nanostructures.

Applications are new kinds of physics measurements and processes such as high resolution spectroscopy, clocks, optics, interferometry.

Our mission is to connect the members of our community through technical events, webinars, networking events, and social media.

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

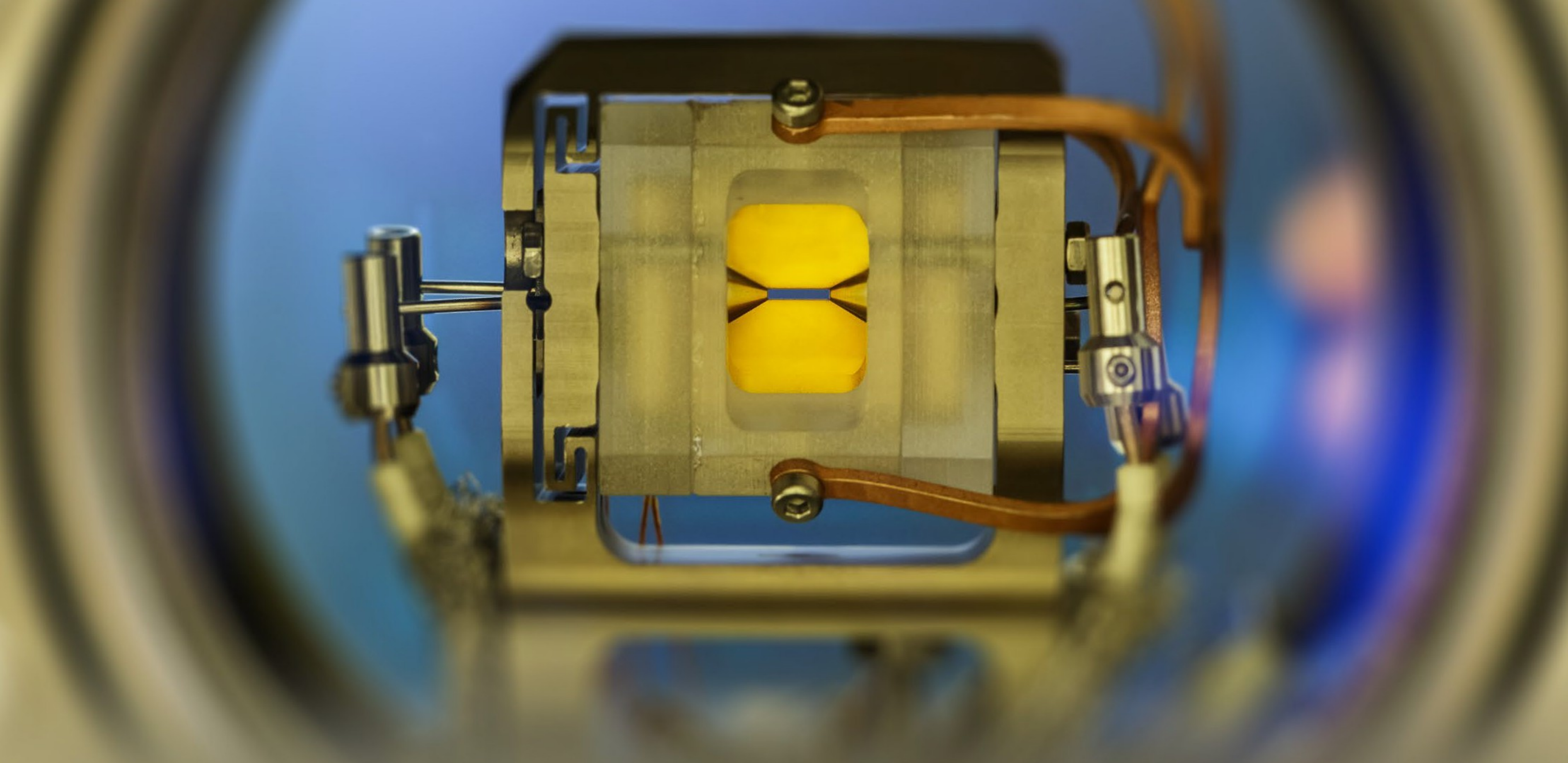
Ways to connect with us:

- Our website at www.osa.org/ot
- On LinkedIn at https://www.linkedin.com/groups/5081944/
- Email us at TGactivities@osa.org (or markus.krutzik@fbh-berlin.de)

Today's Speaker

- Thomas Monz
- *Alpine Quantum Technologies GmbH*

- Monz started on ion-trap quantum information processing during his Masters degree, focusing on ion-photon interfaces. He moved on to quantum information processing, realizing the first Toffoli gate, pushed for a new world-record on entangling 14 ion-qubits, and implemented the first Shor algorithm without pre-computations.
- After a detour in Scotland working as product specialist for a laser company, he returned to Innsbruck focusing on engineering aspects. He realized the first ion-trap quantum computing fully inside a 19" rack, which holds the new world record on entangling 24 qubits. The latest achievement of his products includes the demonstration of a universal logical gate-set, besides proof of concepts in finance, chemistry, and security.



Rack-Mounted Quantum Computation

Rack-Mounted Quantum Computation with Trapped Ions

Thomas Monz,

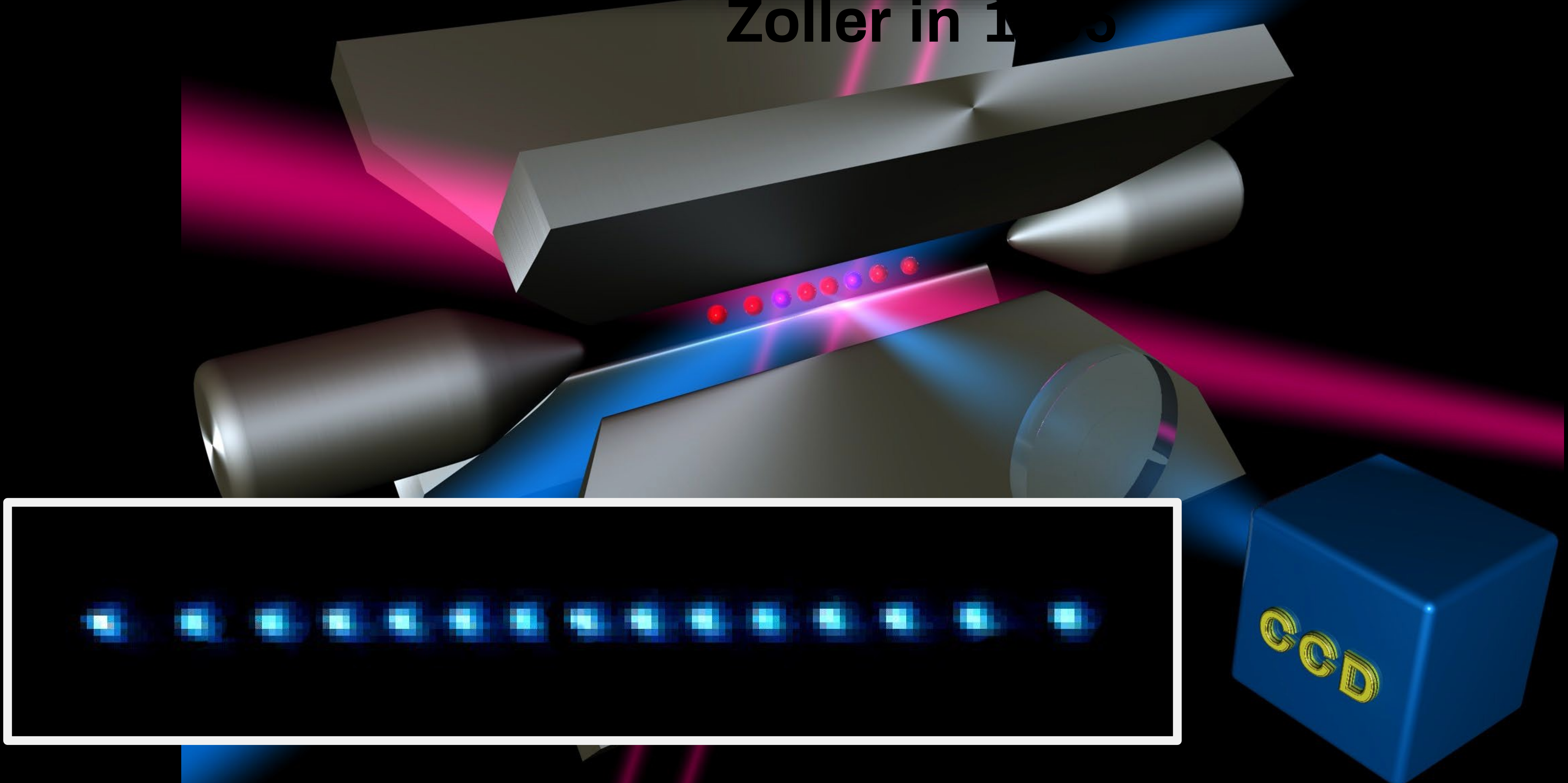
Institute for Experimental Physics, University of Innsbruck, Austria
AQT, Innsbruck, Austria

- Quantum Computing with Trapped Ions
- Lab achievements
- From „proof-of-concept“ to commercial devices
- Rack-based achiements

Take-away message

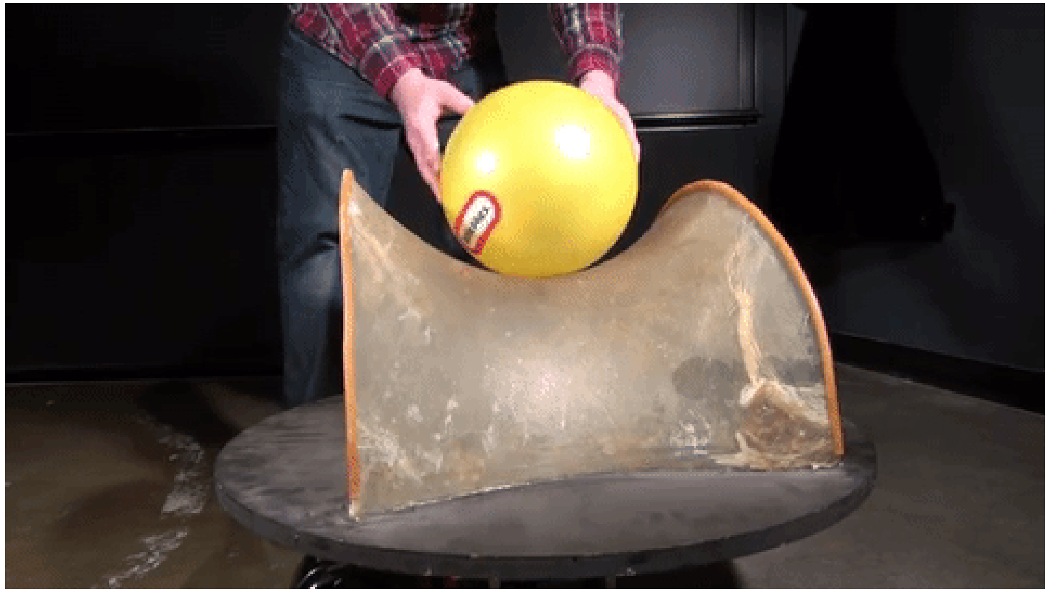
- Ion-trap quantum computing achieves **fault-tolerant performance levels**
- Error correction, topological qubits, even a **universal gate-set for logical qubits** has been implemented
- Progress in enabling-technologies allowed to transfer the systems **from an optical table into a rack**
- Which **performs better than (our) lab-devices.**

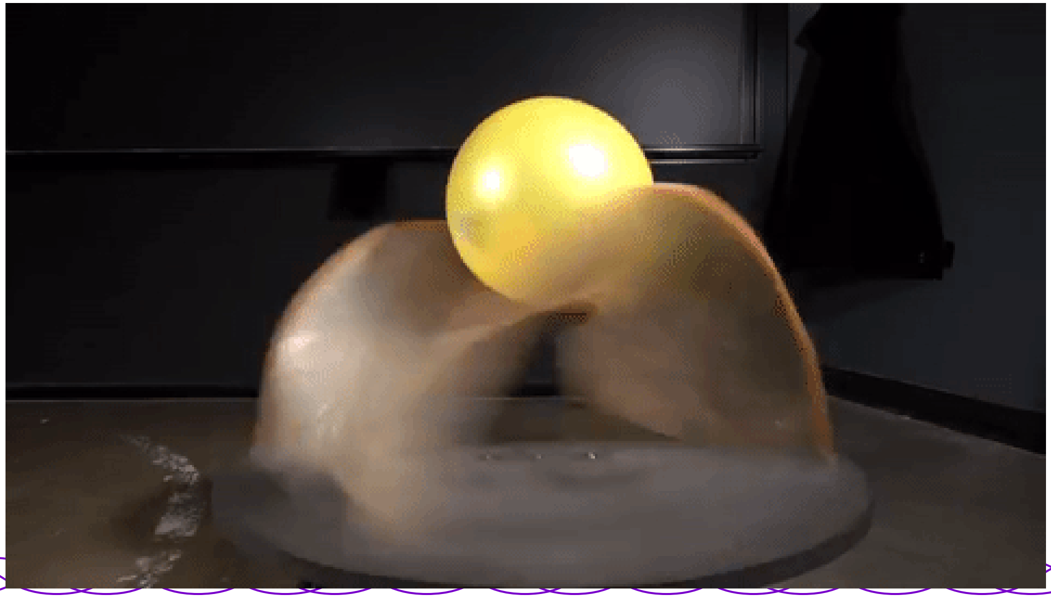
The Quantum Processor with Trapped Ions Vision by P. Zoller in 1[illegible]



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

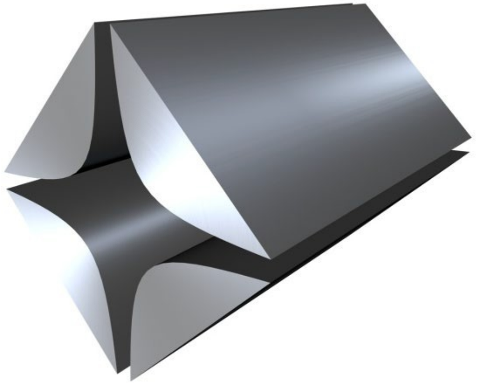
Electric fields to trap charged particles

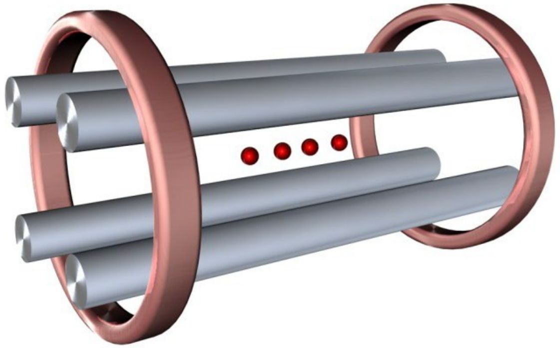




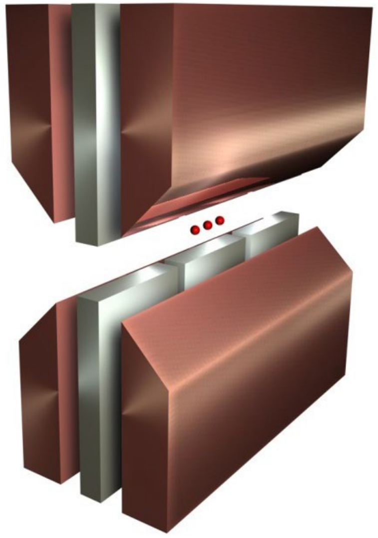
Linear ion-traps

Paul mass-filter

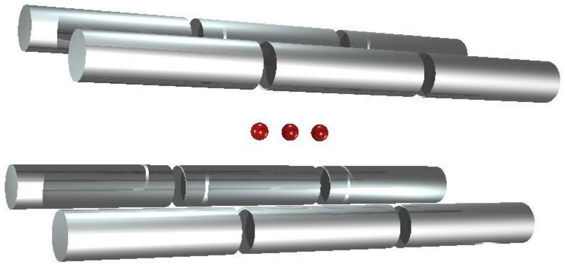




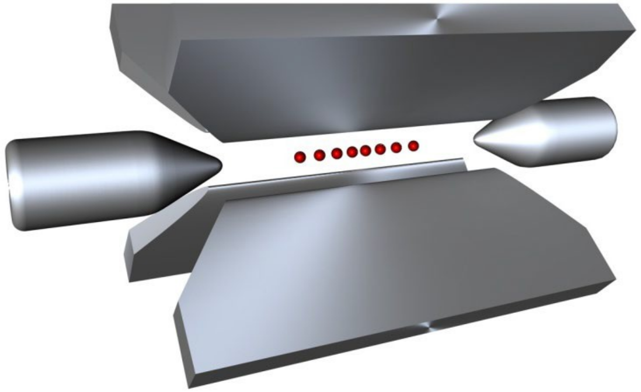
Innsbruck
Ann Arbor



Munich,
Sussex

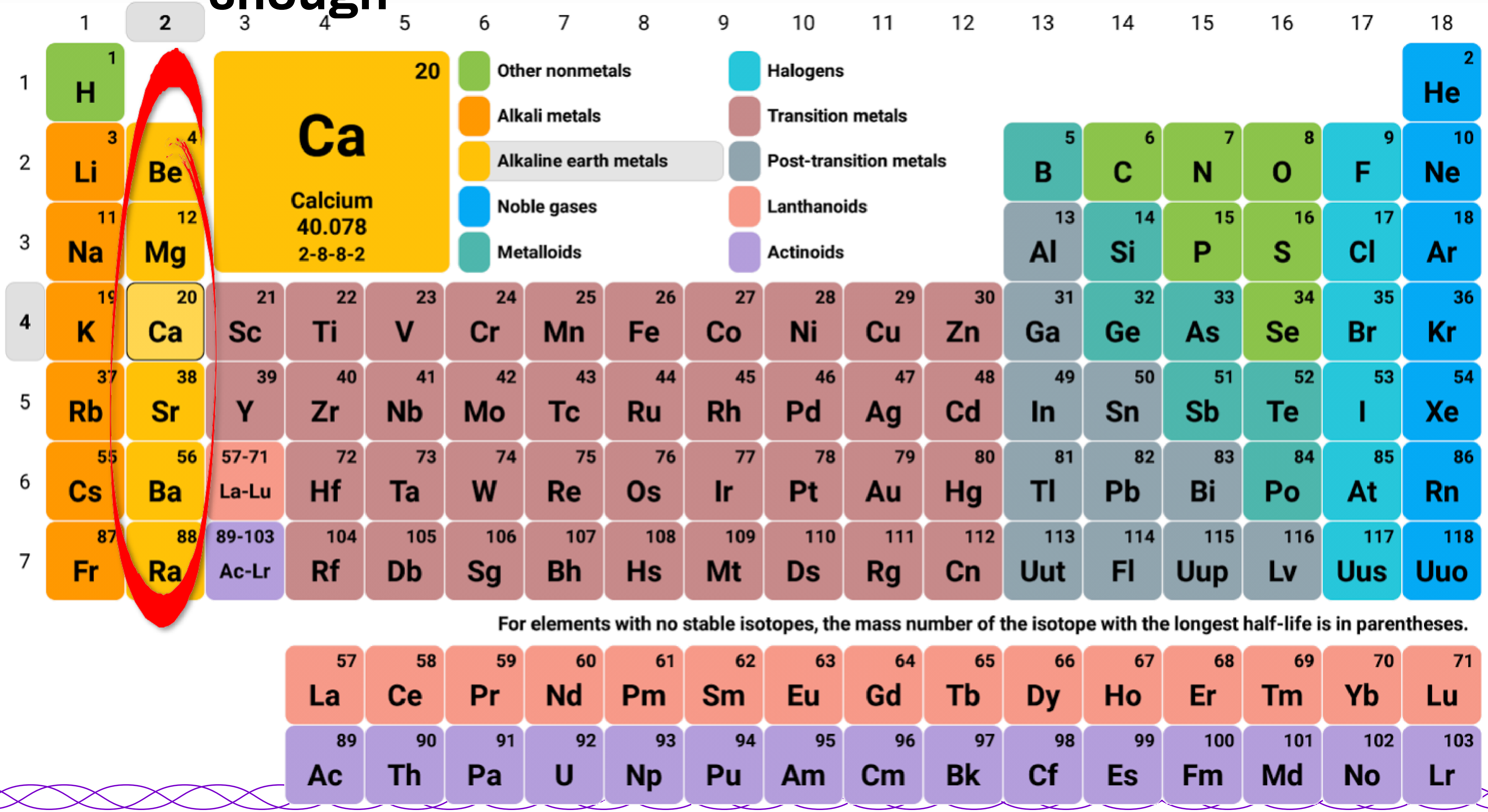


Boulder, Mainz, Aarhus

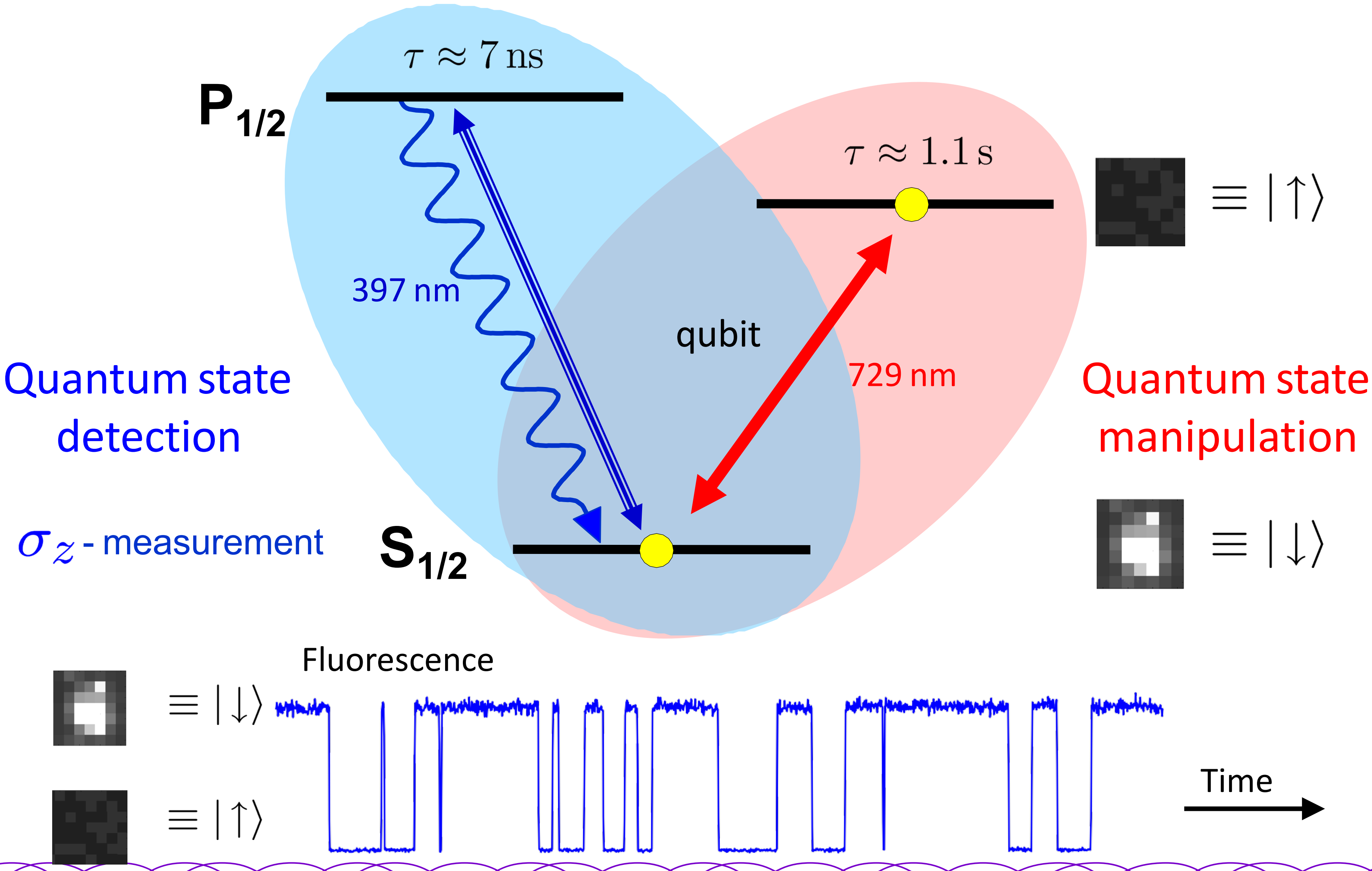


Innsbruck, Oxford

Pick your poison: “simple is already complex enough”



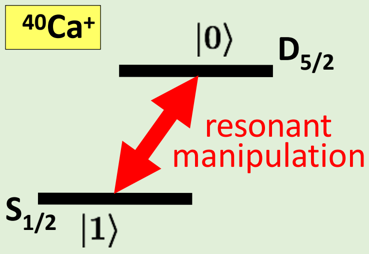
Ion-trap quantum computing basics



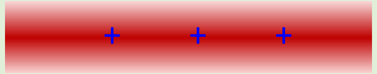
Universal gate-set to implement arbitrary quantum algorithms

Global

Collective Local Operations



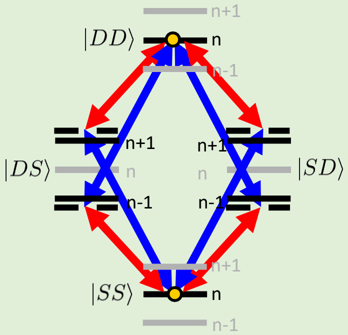
$S_{x,y}(\theta)$



τ = 20μs

F > 99.5%

Global Mølmer- Sørensen entangling gate



$S^2_{x,y}(\theta)$

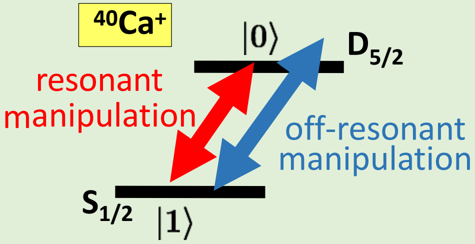
τ = 50μs

F_2 > 99%

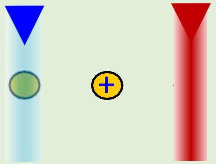
Local

Individual (and parallel) local operations

New!



$S_z(\theta)$ $S_{x,y}(\theta)$



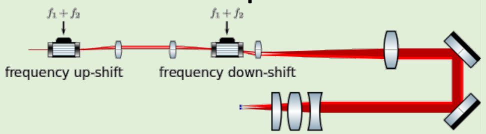
τ = 20μs

F > 99%

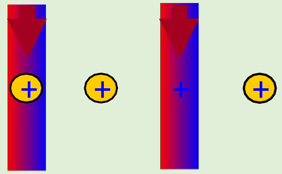
<u>Local</u> Mølmer- Sørensen entangling gate

New!

Simultaneous addressing of multiple ions



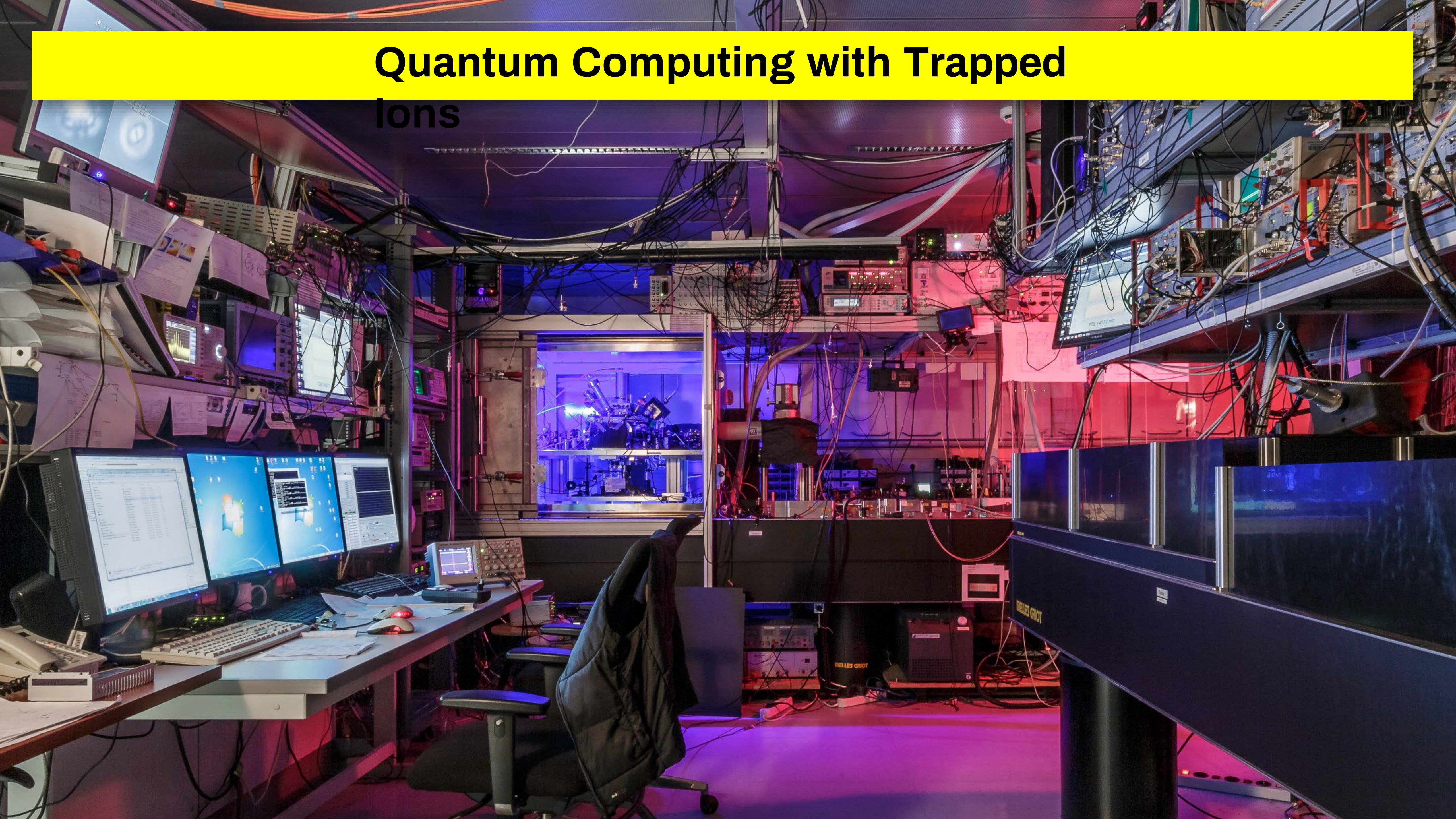
$S^2_{x,y}(\theta)$

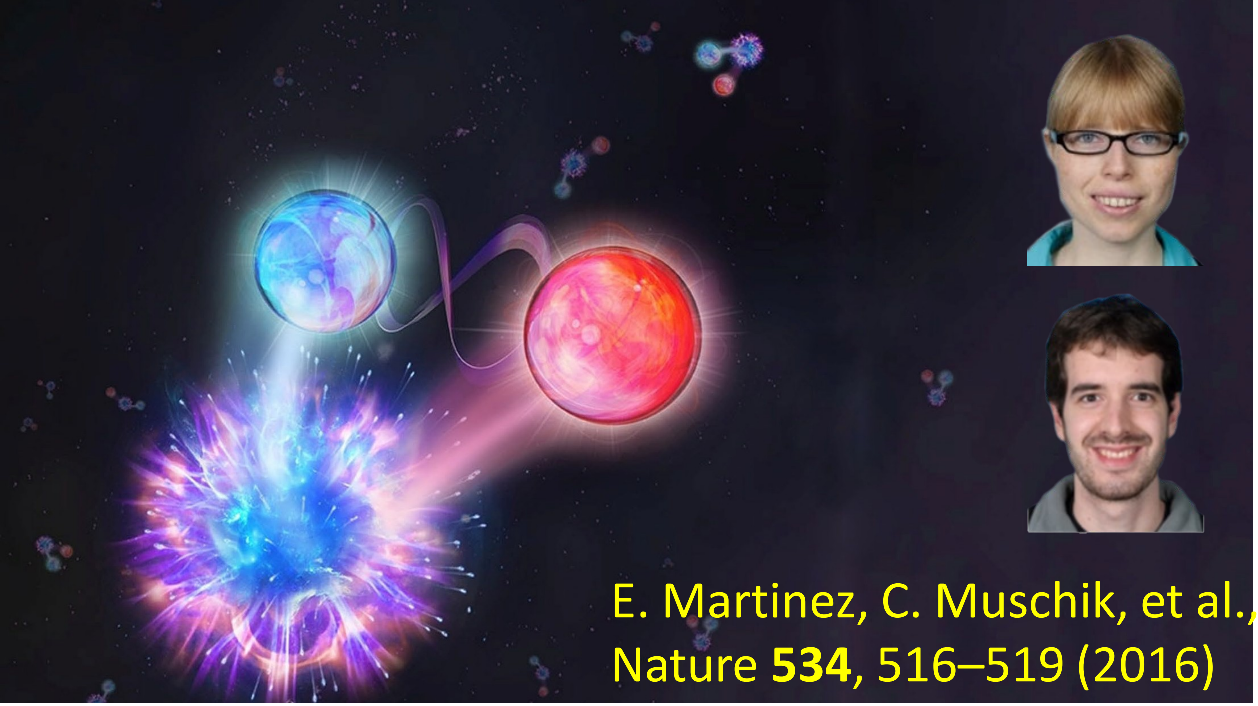


τ = 100μs

F ~ 99%

Quantum Computing with Trapped Ions

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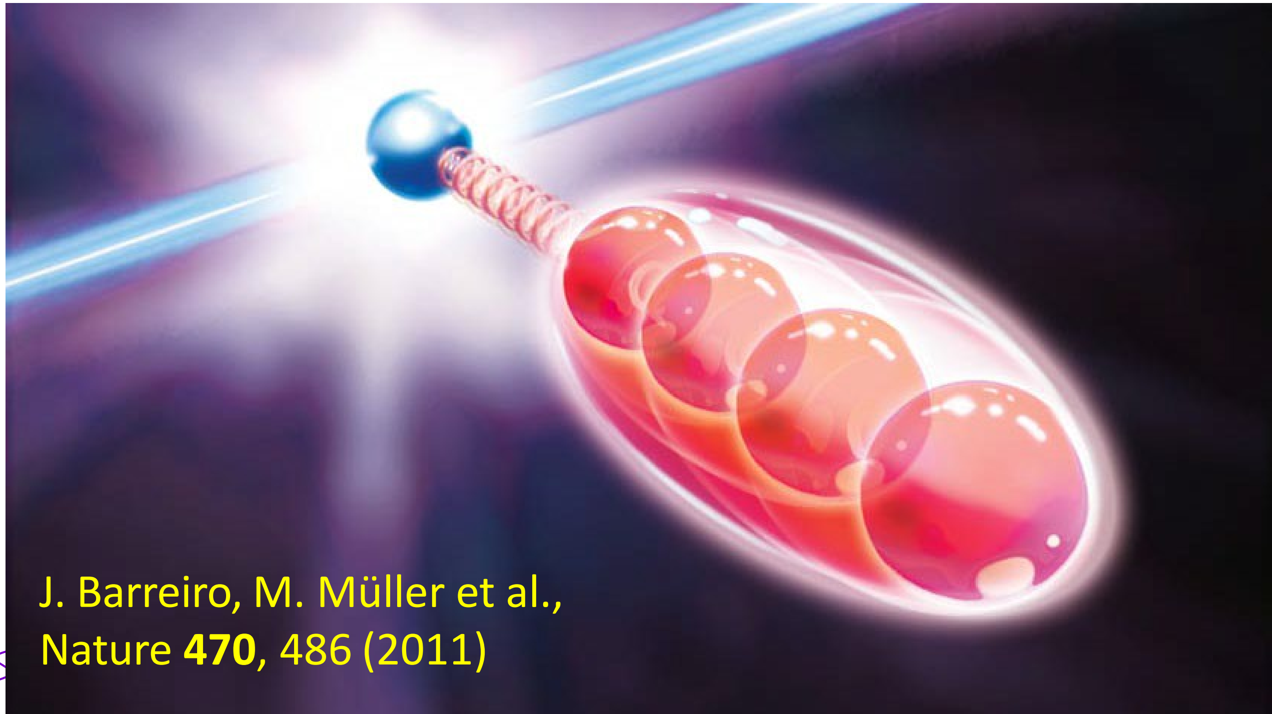
Science **334**, 6052 (2011)


J. Barreiro, M. Müller et al.,
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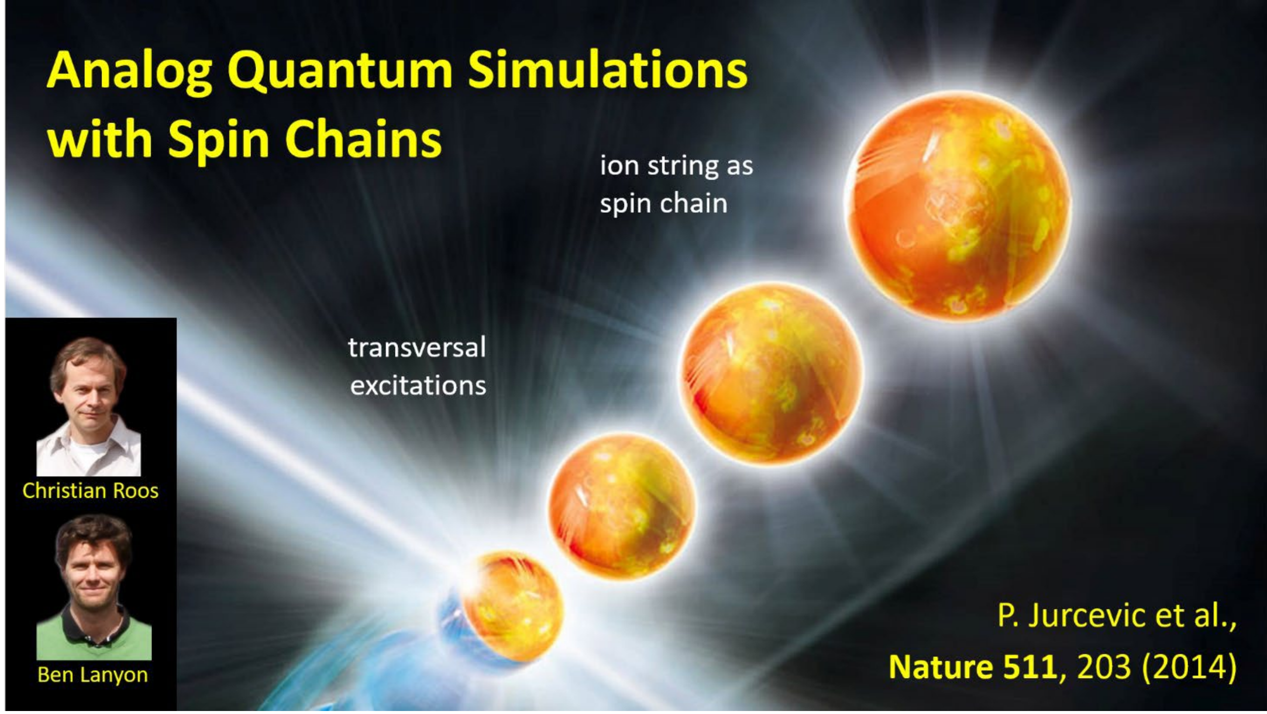
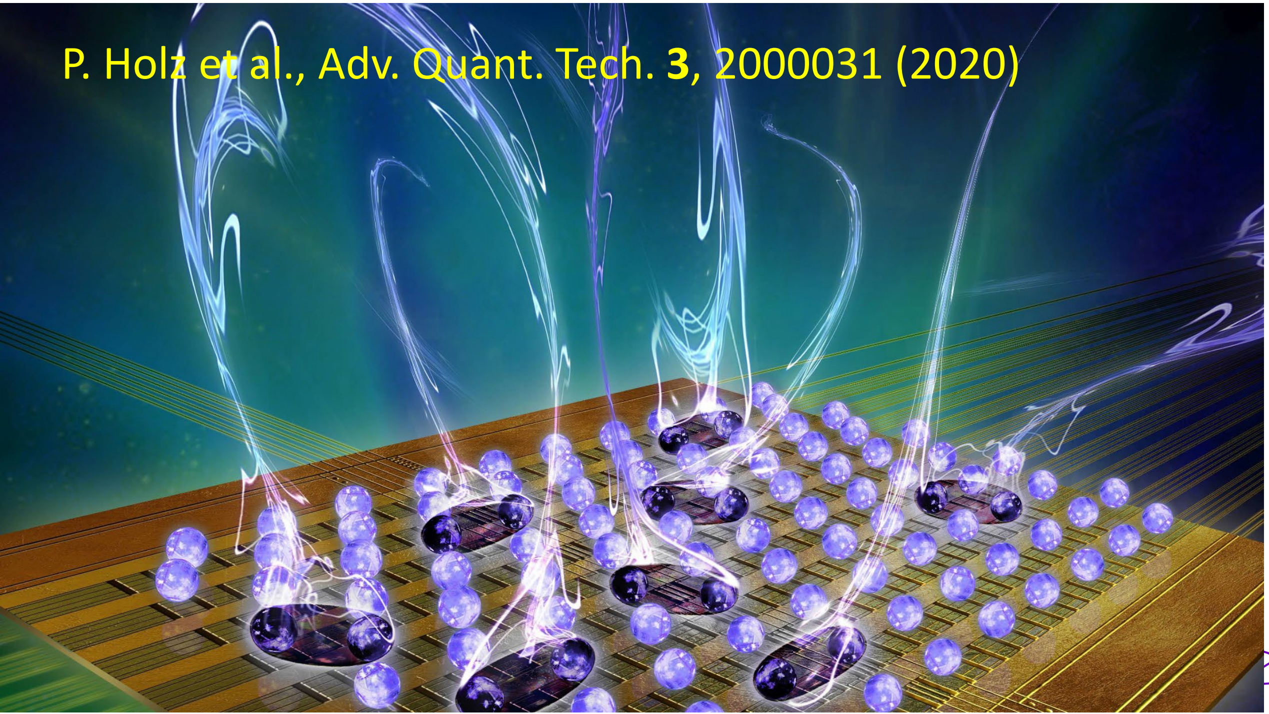
D. Nigg, M. Müller et al.,
Science **345**, 302 (2014)


Analog Quantum Simulations with Spin Chains
ion string as spin chain
transversal excitations
Christian Roos
Ben Lanyon
P. Jurcevic et al.,
Nature 511, 203 (2014)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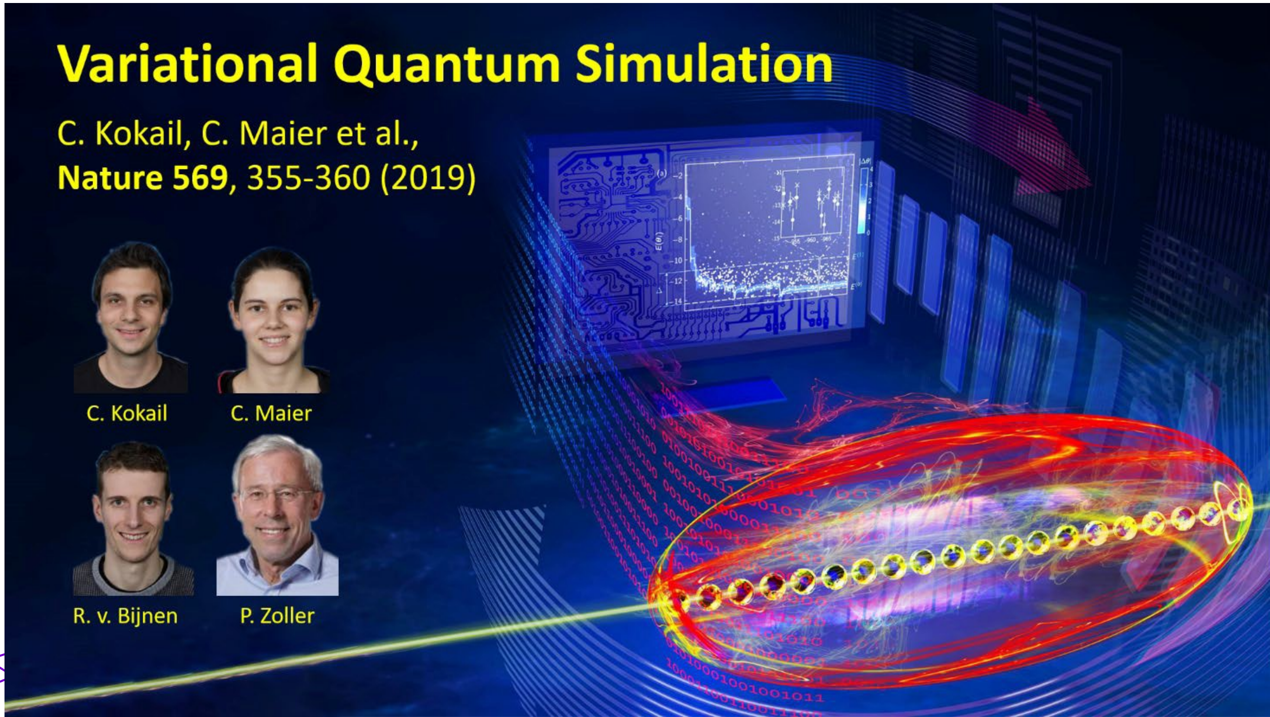
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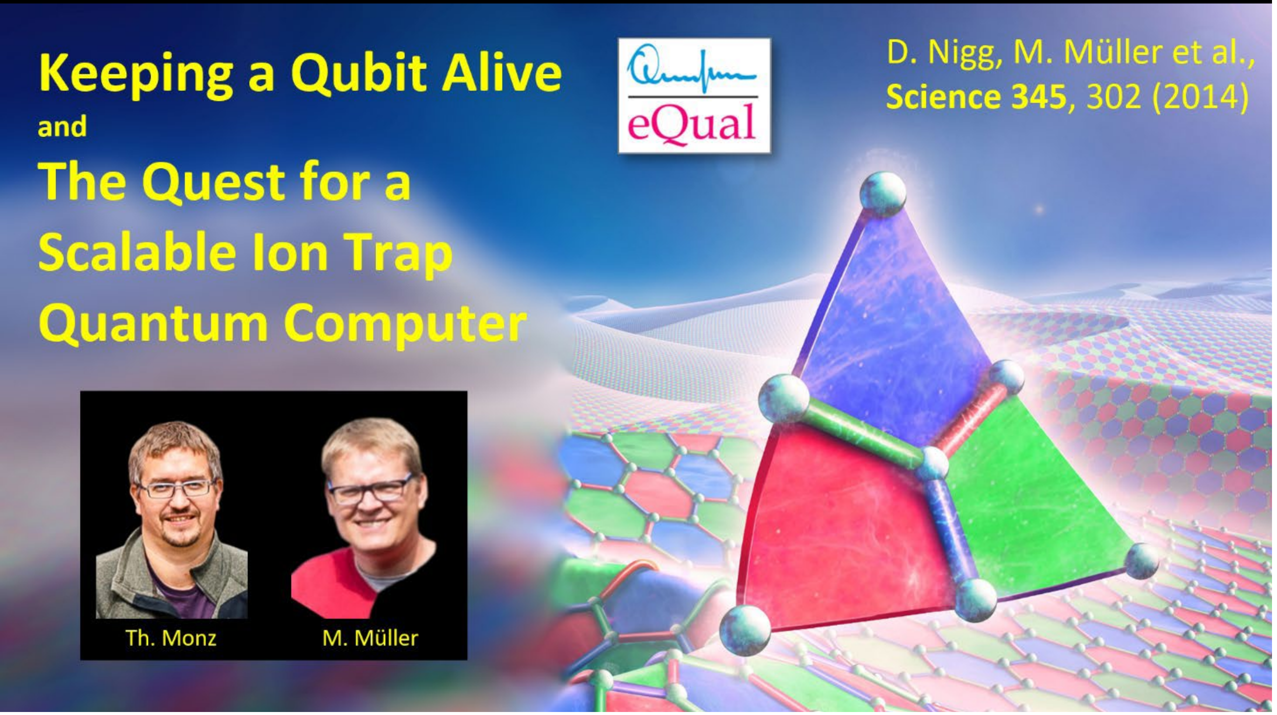
P. Zoller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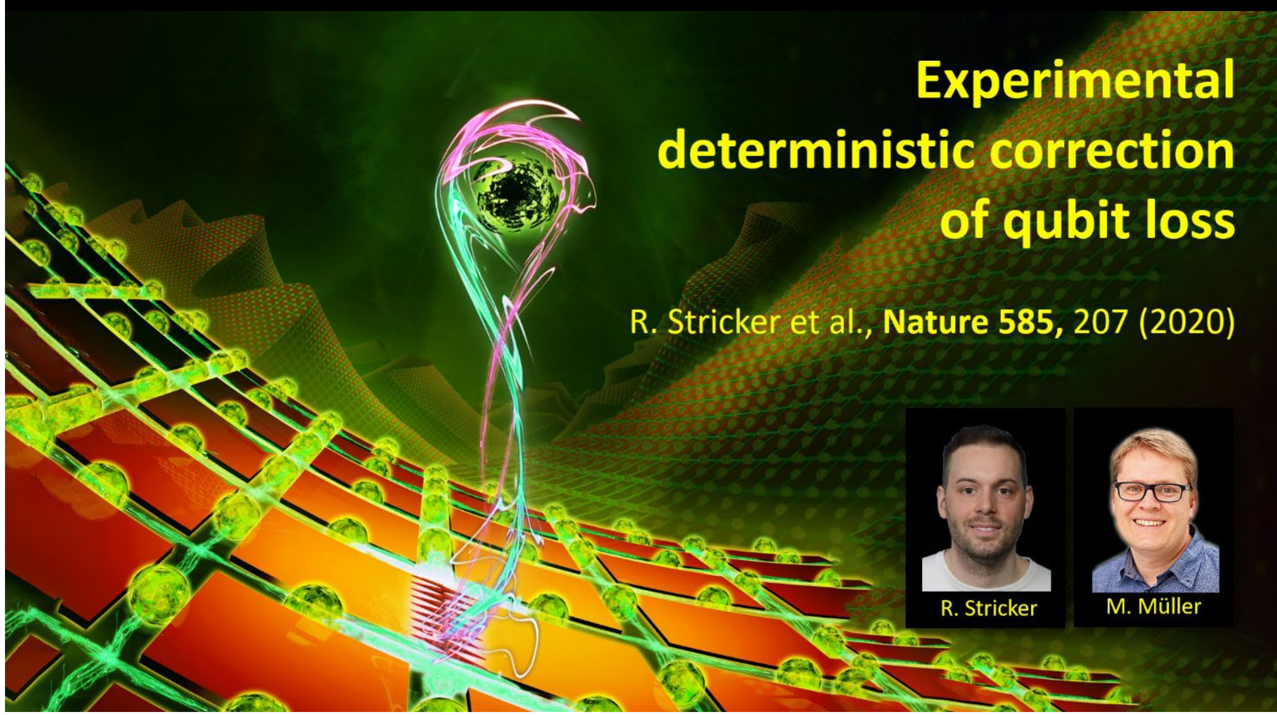
Th. Monz
M. Müller


Experimental
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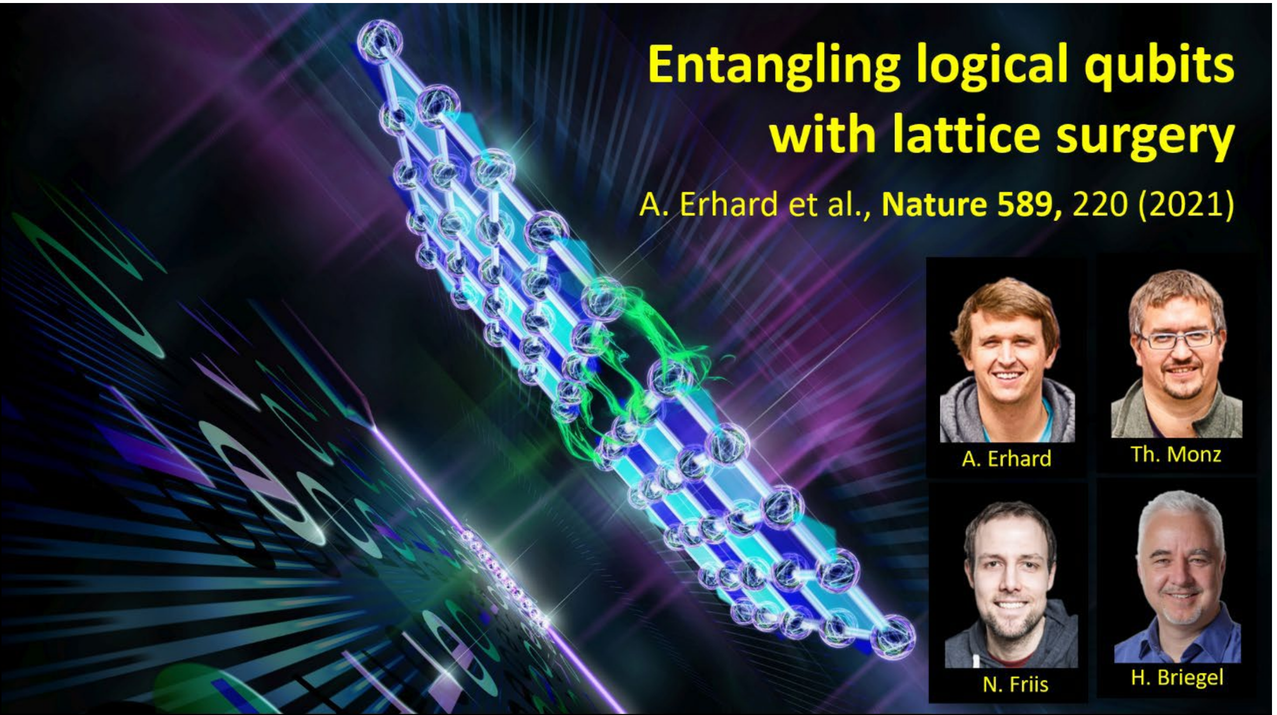
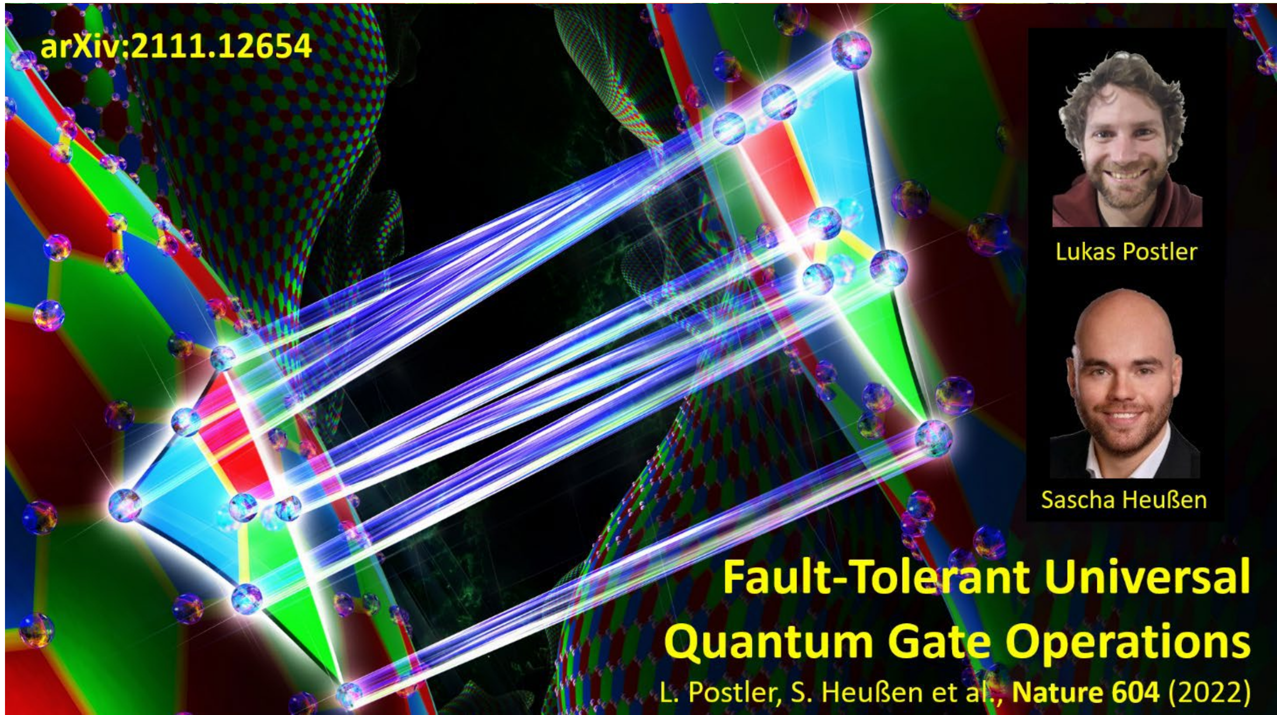
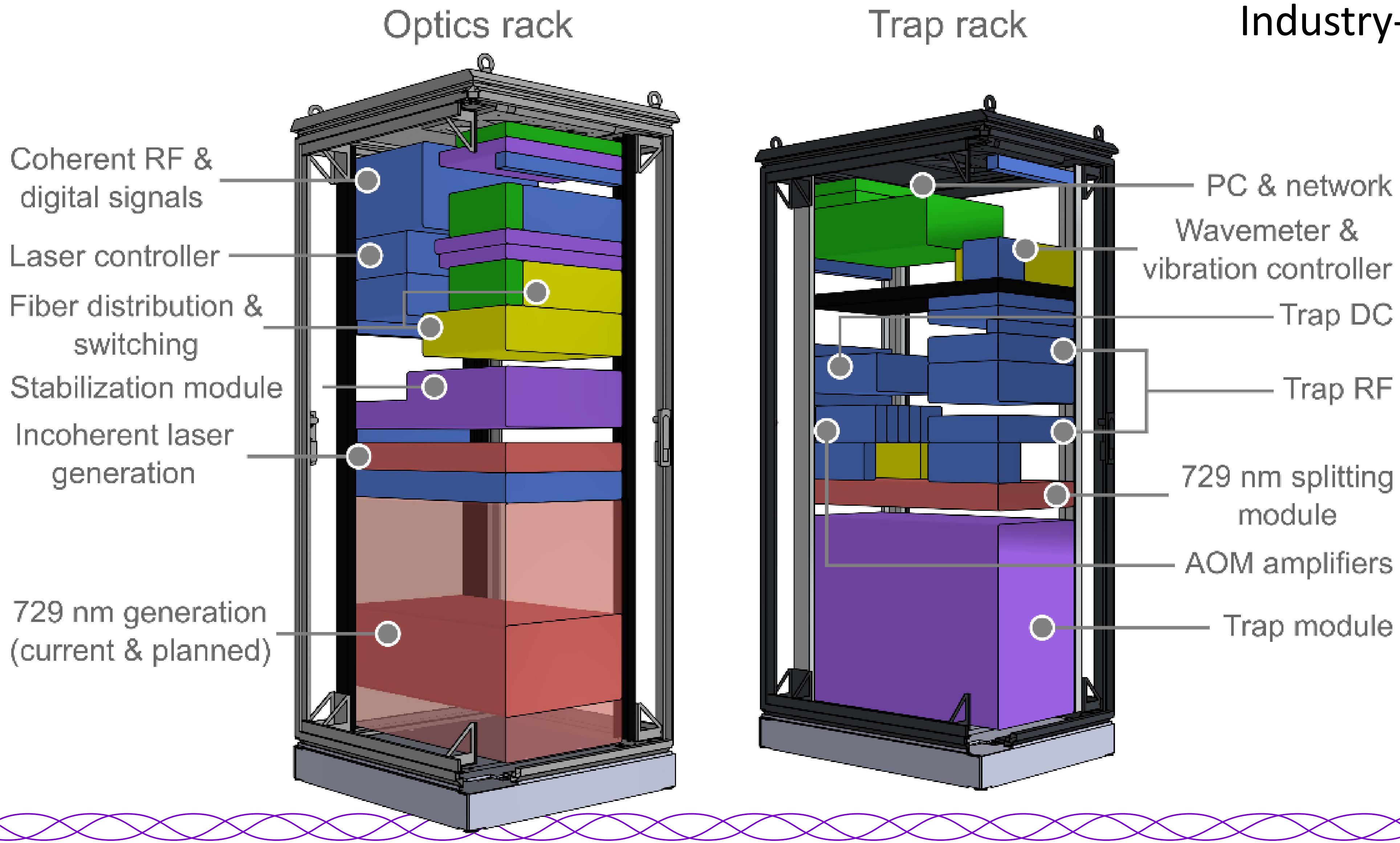
R. Stricker et al., Nature 585, 207 (2020)
R. Stricker
M. Müller


Entangling logical qubits
with lattice surgery
A. Erhard et al., Nature 589, 220 (2021)
A. Erhard
Th. Monz
N. Friis
H. Briegel


arXiv:2111.12654
Lukas Postler
Sascha Heußen
Fault-Tolerant Universal
Quantum Gate Operations
L. Postler, S. Heußen et al., Nature 604 (2022)

Compact ion-trap quantum computing demonstrator designed @ AQT

Industry-Standard 19'' Rack



C. Marciniak I. Pogorelov

I. Pogorelov, et al., PRX Quantum **2**, 020343 (2021)

AQTION

Compact ion-trap quantum computing demonstrator

AQTION

consortium

universität innsbruck

TOPTICA PHOTONICS

Atos

JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

Swansea University Prifysgol Abertawe

UNIVERSITY OF OXFORD

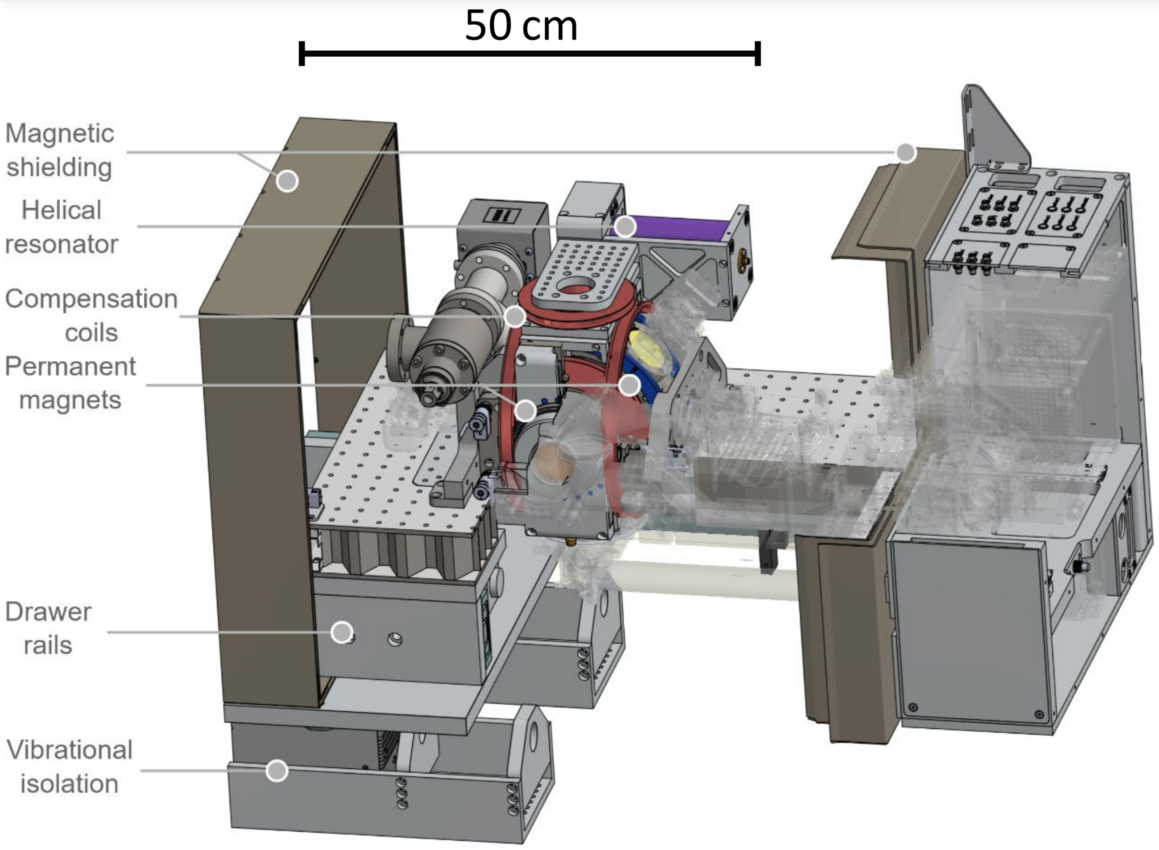
ETH zürich

AKKA Digital

trap module

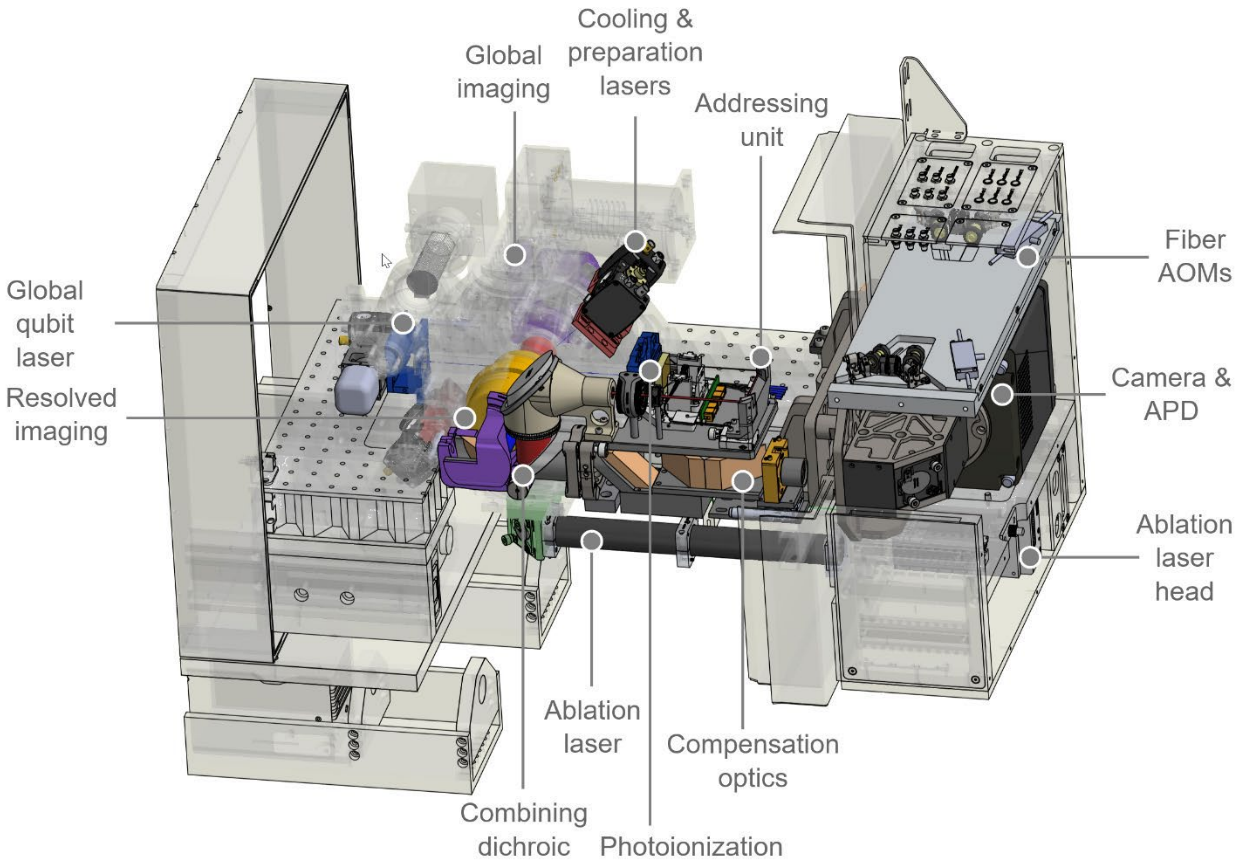
C. Marciniak I. Pogorelov

Compact ion-trap quantum computing demonstrator



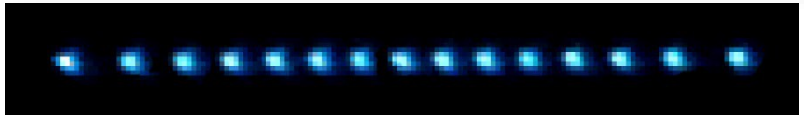
Ion trap module, mechanical

Ion trap module, optical

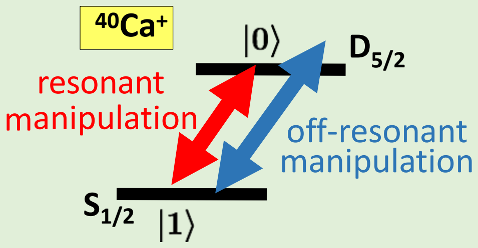


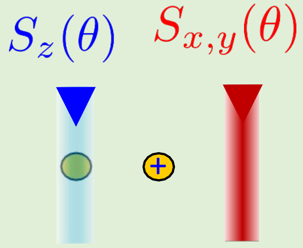
I. Pogorelov, T. Feldker et al.,
PRX Quantum **2**, 020343 (2021)

The new workhorse at UIBK …



Individual (and parallel) local operations





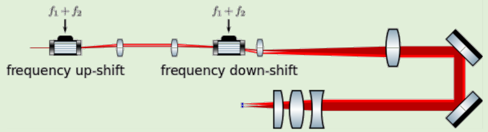
τ = 20µs
F > 99%

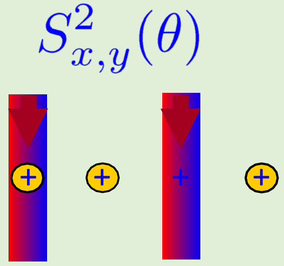
Control capabilities

- T1 approx 1s
- T2 approx 500 ms
- Routinely work with 20+ ions
- Demonstrated 24q-GHZ state
- Supports Qiskit/Cirq/…

Local Mølmer- Sørensen entangling gate

Simultaneous addressing of multiple ions





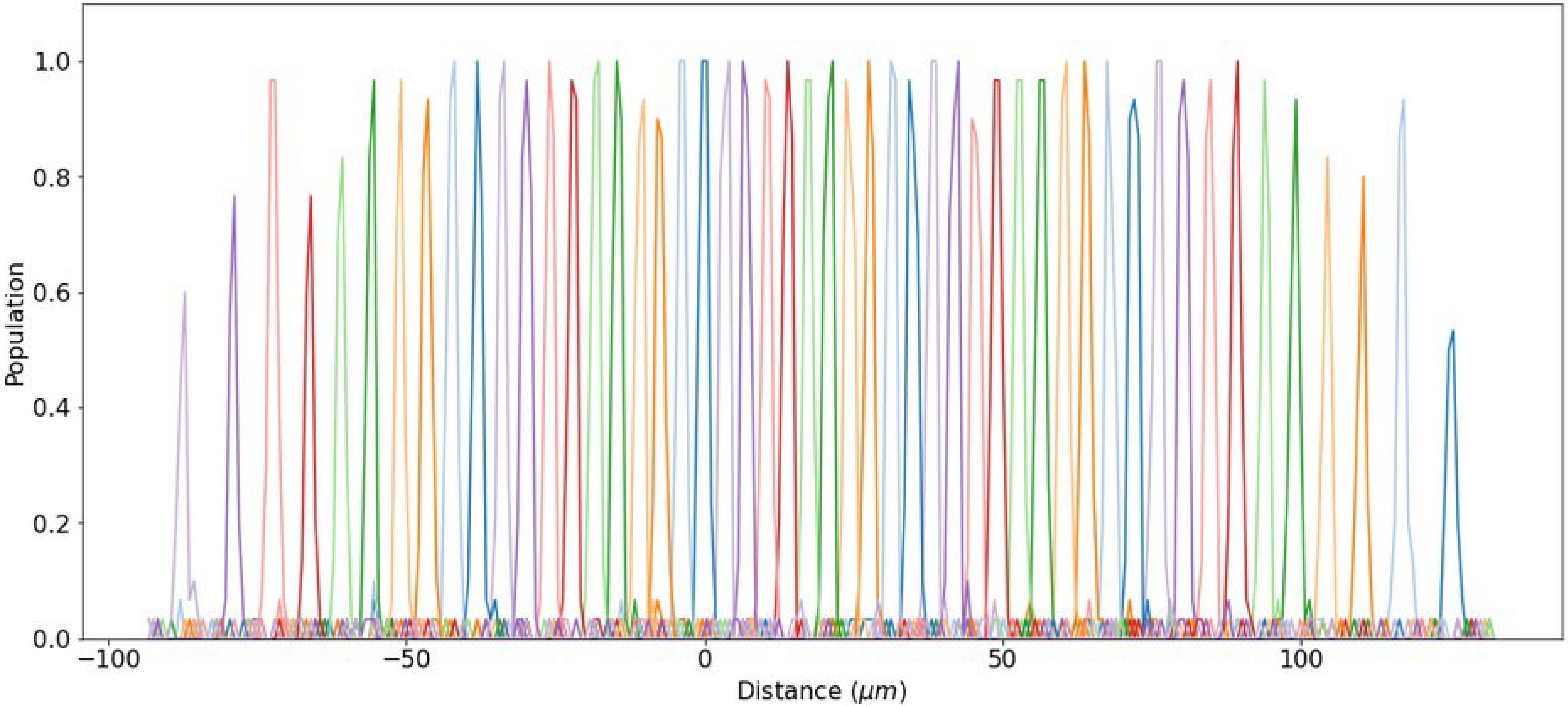
τ = 100µs
F ~ 99%

Automated tune-up

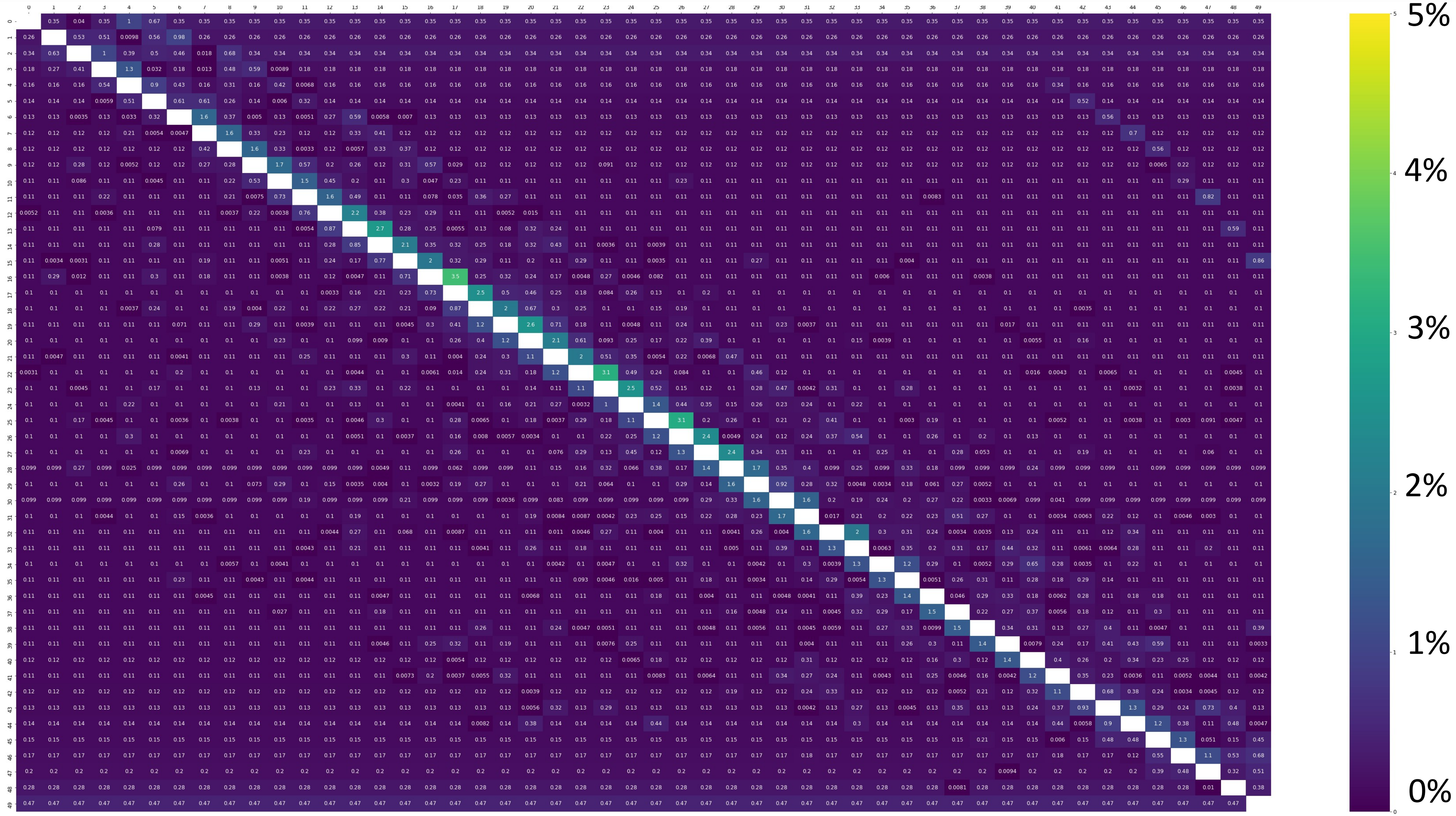
- Single-qubit control
- Single-setting MS up to 20 q despite full connectivity
  N^2 speed-up
- Tune-up to > 99% in 30 sec

PRX Quantum 2, 020343 (2021)

State-of-the-Art



Cross-talk, resonant



max x-talk 3.5%; avg NN-x-talk 1.2%, avg x-talk <0.2%

Cross-talk using addressing error correction

Resonant

	1	2	3	4	5	6	7	8	9	10
1		0.46	0.17	0.0037	0.0022	0.16	0.0032	0.51	0.16	0
2	0.23		0.37	0.21	0	0.15	0.21	0.2	0.4	0.16
3	0.19	0.25		0.48	0.32	0.14	0.19	0.23	0.007	0.41
4	0.084	0.27	0.34		0.98	0.13	0.24	0.23	0	0.12
5	0.19	0.32	0.13	0.48		0.67	0.23	0.091	0.27	0
6	0.19	0.27	0.33	0.26	0.42		0.78	0.46	0.21	0.19
7	0.14	0.24	0.14	0.2	0.38	0.4		0.46	0.37	0.23
8	0.22	0.21	0.016	0	0.17	0.25	0.28		0.29	0.0025
9	0.22	0.12	0.22	0.17	0.0026	0.27	0.21	0.28		0.8
10	0.088	0.2	0.093	0.2	0	0	0.22	0.23	0.78	

max = 0.98%
min < 0.1%
avg on all = 0.22%
avg on NN = 0.49%

Correctable

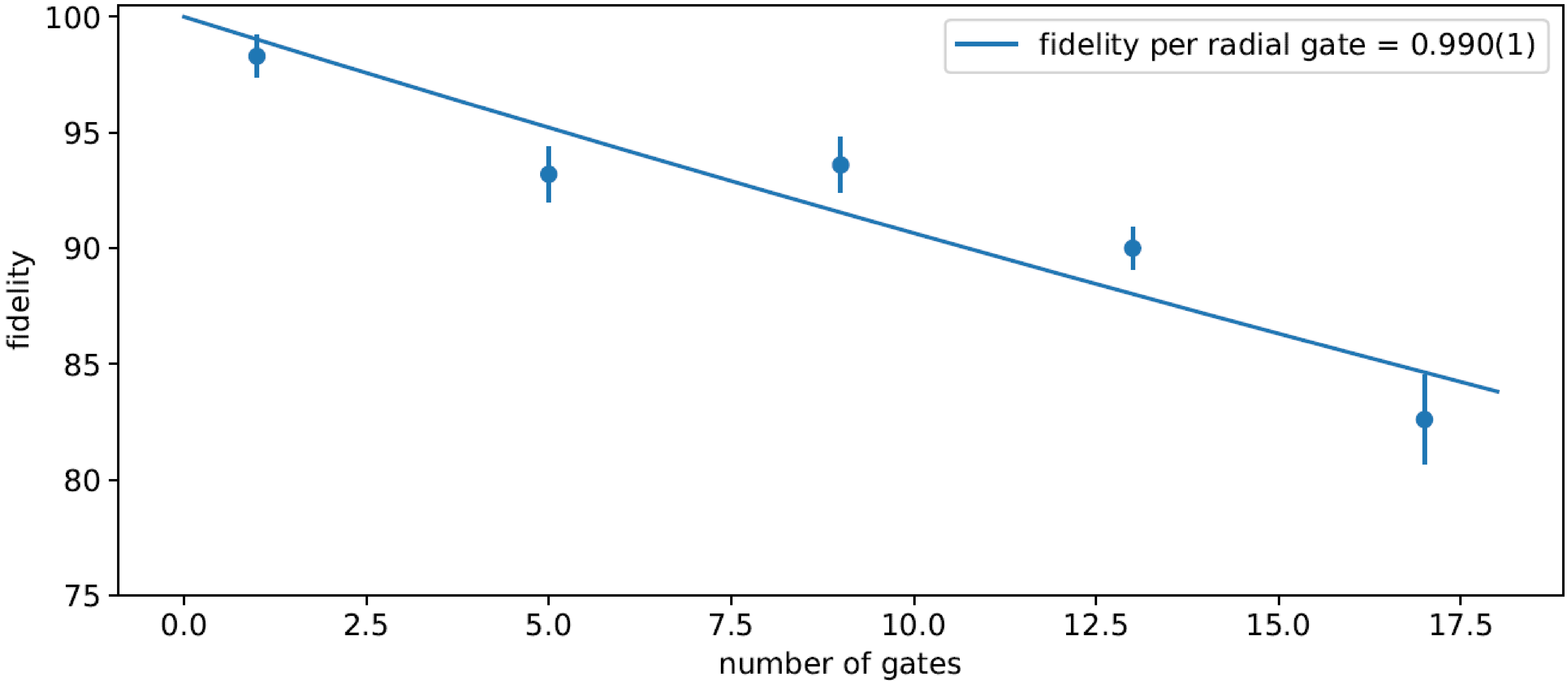
Off-resonant

	1	2	3	4	5	6	7	8	9	10
1		0	0	0	0	0	0	0	0	0
2	0.0087		0.00011	0	0	0	0	0	0	0
3	0	0.014		0.0098	0	0	0	0	0	0
4	0	0	0.017		0.017	0	0	0	0	0
5	0	0	0	0.018		0.025	0	0	0	0
6	0	0	0	0.0063	0.017		0.014	0	0	0
7	0	0	0	0	0	0.012		0.011	0	0
8	0	0	0	0	0	0	0.018		0.0044	0
9	0	0	0	0	0	0	0	0.022		0.0002
10	0	0	0	0	0	0	0	0	0.015	

max = $2.5*10^{-4}$
min < $5*10^{-5}$
avg on NN = $1.25*10^{-4}$
or **10^{-8} error rate**

Negligible errors @ 10^{-6}

2-qubit gate performance



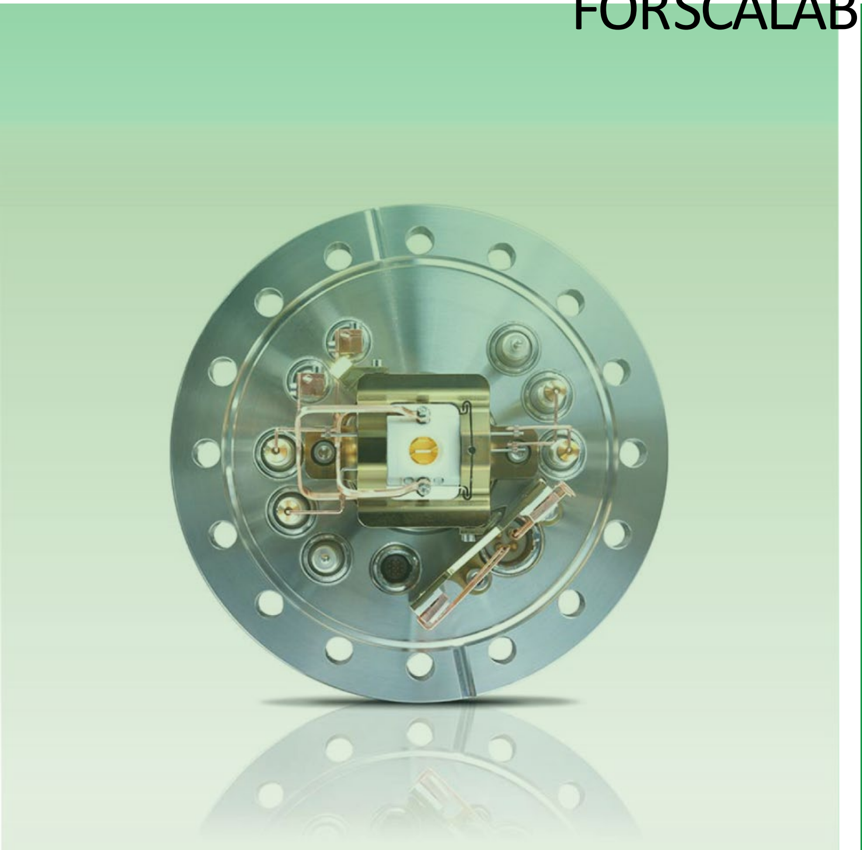
- Same setting confirmed for any subset of 2-qubits, here for 12 qubit-register
- Fidelity of 99.0(1)% with automated tune-up routines

GHZ state generation w/ global interactions

Quantencomputing – Made in Austria

TIERED PRODUCT STRATEGY

FOR SCALABLE VALUE GENERATION



STAND-ALONE 19" QUANTUM INSTRUMENTS
Production & sales

CLOUD-ACCESS TO FULL SYSTEMS
Software-as-a-Service

ON-PREMISE 19'' QUANTUM COMPUTERS
Hardware-as-a-Service

AQT

PROGRAMMING

AND SOFTWARESOLUTIONS

CIRQ

QISKIT

QUEST

PENNYLANE

PYTKET

CLOUD ACCESS

CAMBRIDGE QUANTUM COMPUTING LIMITED

JoS QUANTUM

Qu & Co

HQS QUANTUM SIMULATIONS

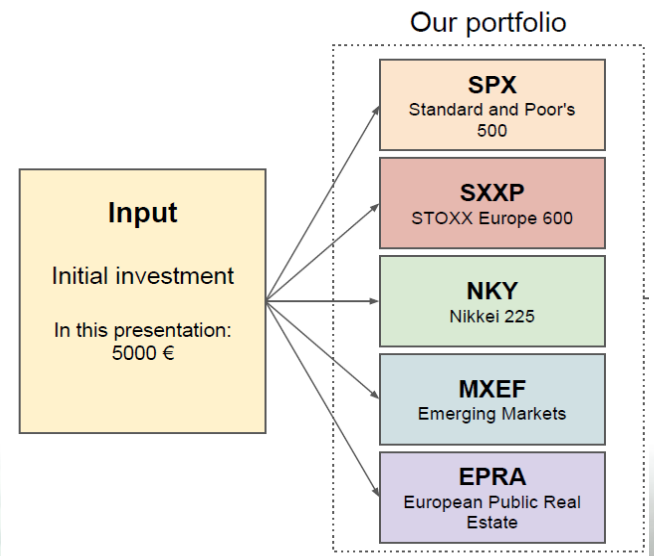
RIVERLANE

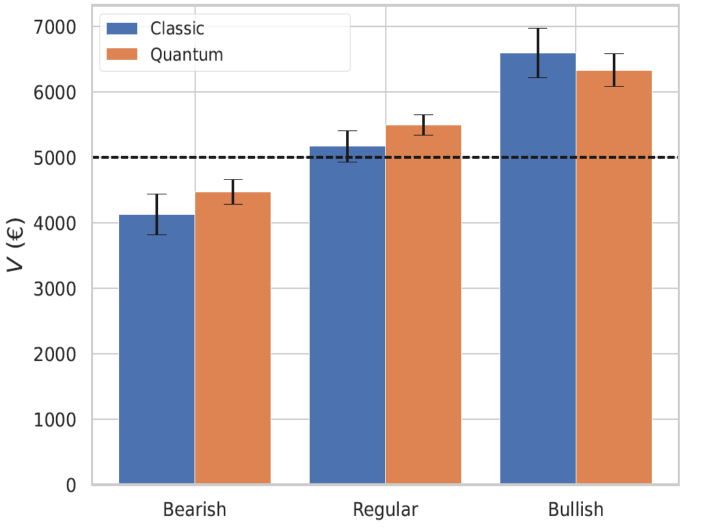
USE-CASE: Finance

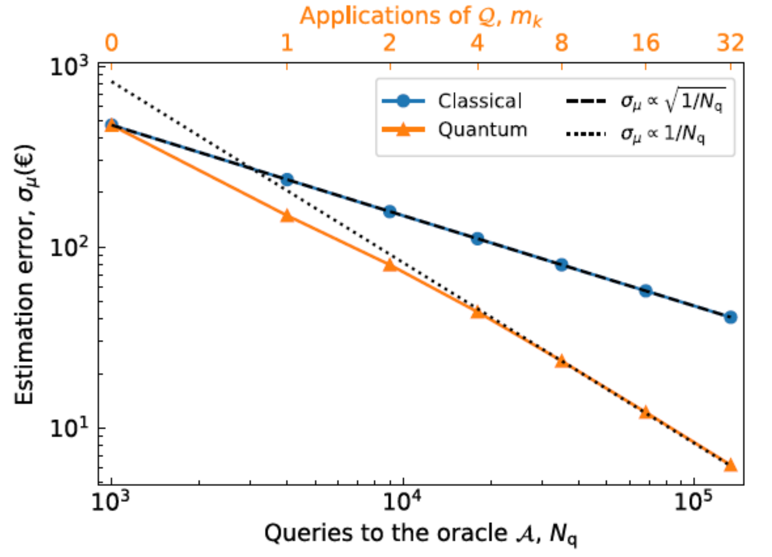
2-5 BUSD market by 2030, according to BCG (2019)

PORTFOLIO OPTIMISATION

Quantum computers provide a quadratic speed-up over classical solutions. This speed-up can be used to either make more precise predictions for the same amount of iterations, or provide as-good-as-classical statements quadratically faster – which we demonstrated with our partner Multiverse.







Roman Orus, Multiverse, CTO and Co-Founder:

We predict the market faster and will less uncertainty than classically possible.

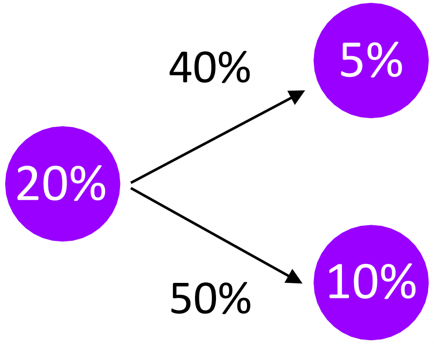
Reference: arXiv:2111.14970 (2021)

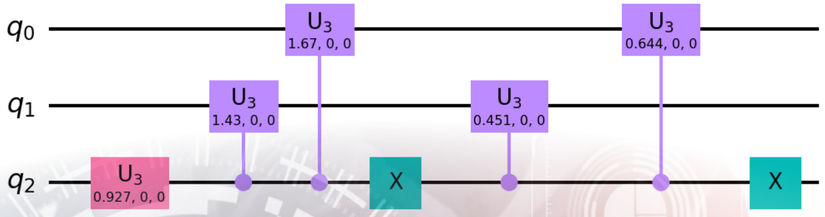
USE-CASE: RISK

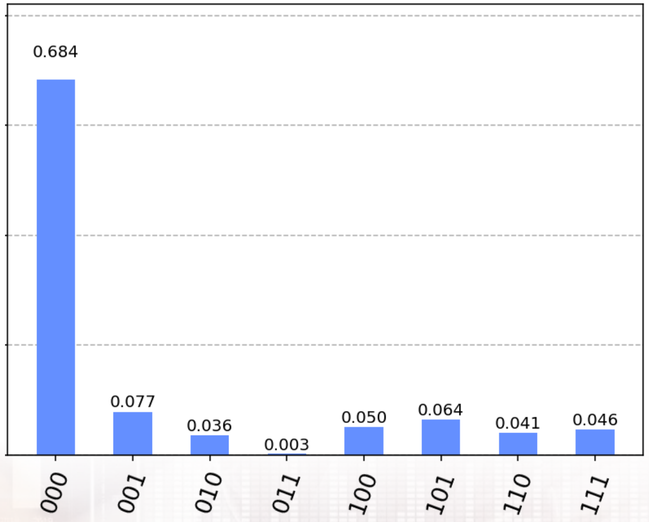
2-5 BUSD market by 2030, according to BCG (2019)

RISK ANALYSIS

The evaluation of scenarios is usually implemented by time-consuming Monte-Carlo simulations. The principle of superpositions allows quantum computers to predict the most likely outcomes significantly faster than classical computers – in particular useful in the context of insurance and risk evaluations.







Markus Braun, JoS, CEO:

Risk analysis can be shorten from days to minutes.

Reference: internal project (2021)

AQT

USE-CASE: CYBER - SECURITY

CQC
CAMBRIDGE QUANTUM COMPUTING

1-2 BEUR market by 2030, according to McKinsey (2021)

ENCRYPTION

In data-centers, the trustworthyness of the hardware and routines may be questioned – in particular processes for encryption purposes.

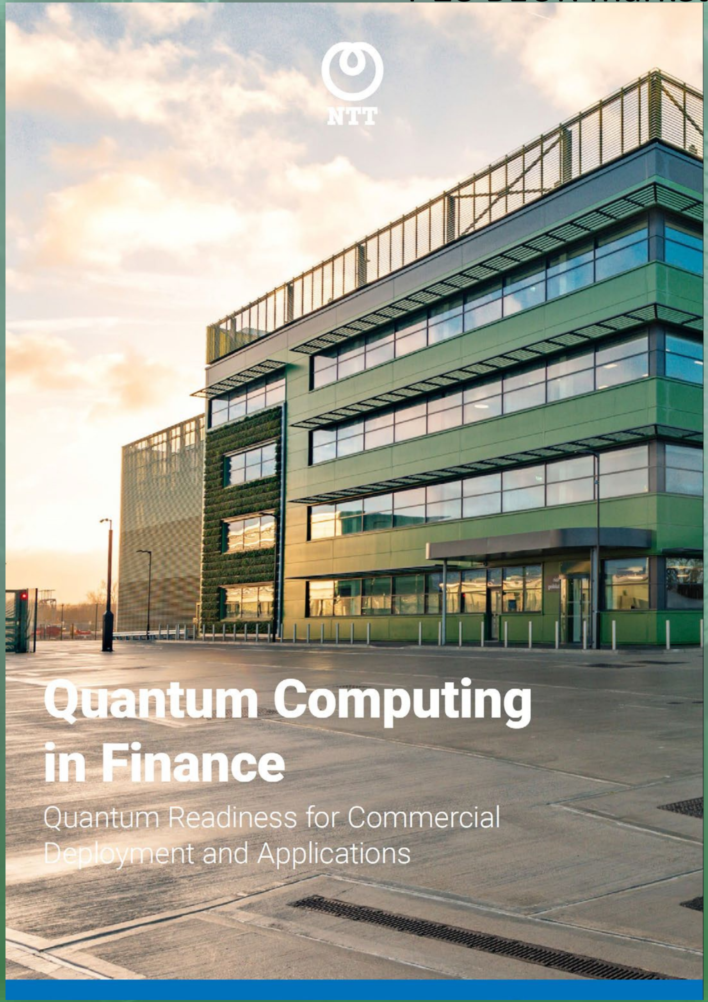
Quantum computers offer proofably secure random numbers for trusted encryption and security.

Duncan Jones, CQC, Head of Quantum Cybersecurity:
We are comfortable describing that [AQT device] as "world-class".

Reference: to be submitted for review (2022)

USE-CASE: DATA CENTERS

4-28 BEUR market in 2030, according to McKinsey (2021)



How to Get Started?

The key to develop quantum-enhanced applications is to tailor use cases - respectively algorithms - to financial situations with real data. Since programming quantum computers is so fundamentally different from programming classical computers, new intuition and development skills need to be learned and acquired. More precisely, by creating interdisciplinary teams of domain specialists and quantum specialists, expertise can be built to understand and transform the specific use-cases into an application. A good starting point can be a workshop that is used to identify interesting use-cases.

Fortunately, there is already a number of available frameworks providing different functionality for quantum computing. For development purposes, the programming language Python with packages like Cirq[2] or Qiskit[3] has become dominating. Most importantly, the frameworks offer a high-level description of the underlying computation, allow to compose small scale circuits, and learn about quantum algorithms. As most of the frameworks are developed as open-source software (Apache License 2.0), providing access to privately-managed hardware resources is easily possible.

To prevent the leakage of acquired intellectual property and protect sensitive data, it is necessary to use a private cloud development infrastructure located in Europe. This infrastructure provides access to the quantum hardware, located in the same data center, and a platform for collaborative development. The core of this collaboration platform is an interactive browser-based development tool allowing for collaborative development, simulation of circuits, and productive use-case development. As circuits are first tested on a small scale, powerful simulators are necessary which can be extended by hardware emulators to consider noise. Later on, quantum circuits can be executed on real hardware in a data safe environment. Furthermore, access to classical high-performance simulators is given.

After developing use-case scenarios and implementing proof-of-concept like technology demonstrators, the question of productive environments typically arises. On the road to productive usage of quantum computing in business, operational and regulatory requirements need to be considered.

In current frameworks so-called quantum assembly languages (e.g., QASM[4]) are used to translate high-level Python code to assembly instructions for quantum hardware. Pre- and post-processing routines need to be implemented as well to manipulate input, model, and gate parameters.

Figure 4. Top: ion-trap quantum processing module in a 19-inch rack; Bottom: Photograph of an AQT quantum computer system

2 https://cirq.readthedocs.io/en/stable/
3 https://qiskit.org/
4 https://github.com/QISKit/openqasm

Contact

Alpine Quantum Technologies GmbH (AQT) - Quantum computing hardware for on-site integration using industry standards

AQT is a quantum computer hardware startup located in Innsbruck. Building on decades of experimental and theoretical expertise in the field of quantum information processing, our goal at AQT is to get quantum technologies out of the laboratory environment and turn them into everyday products. The long-term goal is a quantum computer based on trapped ions, that is installed in normal IT infrastructure and can be readily operated from any PC or laptop.

Representative: Thomas Monz

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Location: Technikerstraße. 17, 6020 Innsbruck, Austria

JoS QUANTUM (JSQ) - Quantum solutions for capital and energy markets

Founded in 2018 in Frankfurt, Germany, JoS QUANTUM is developing models and algorithms for usage in optimization and simulation with applications in financial and energy markets. Together with innovative workshops and prototyping of relevant use cases, JSQ provides a managed development environment with access to simulators and hardware.

Representative: Niklas Hegemann

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Homepage: https://jos-quantum.de/

Location: TechQuartier, Platz der Einheit 2, 60327 Frankfurt am Main, Germany

SVA System Vertrieb Alexander GmbH (SVA) - IT Service Integrator

SVA System Vertrieb Alexander GmbH is one of the leading German system integrators. The corporate objective of SVA is the combination of high-quality IT products of different vendors with the project know-how and flexibility of SVA to achieve optimum solutions for customers. SVA experts combine twenty years of IT infrastructure experience with know-how about modern demands such as data center security 2.0, big data & analytics, workspace of the future, cloud, and agile IT and software development.

Representative: Christopher Zachow

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Location: Borsigstraße 26, 65205 Wiesbaden, Germany

NTT Global Data Centers EMEA GmbH (NTT) - Co-Location Data Center Services

The Global Data Centers division of NTT Ltd. designs and operates over 160 high-quality, mission-critical data centers across 500,000 sqm. We understand that every business - large and small - has its own unique needs and goals when it comes to its data center infrastructure. Through our tailored local expertise, our worldwide connected platform, and NTT's portfolio of global technology solutions, we are an enabler of growth and innovation for our clients - wherever they are in the world.

Representative: Dominik Friedel

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Reference: White-paper on quantum computer data centers (2022)

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Questions & Discussion