# QUANTUM COMPUTING WITH TRAPPED IONS

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Bundesministerium für Bildung und Forschung

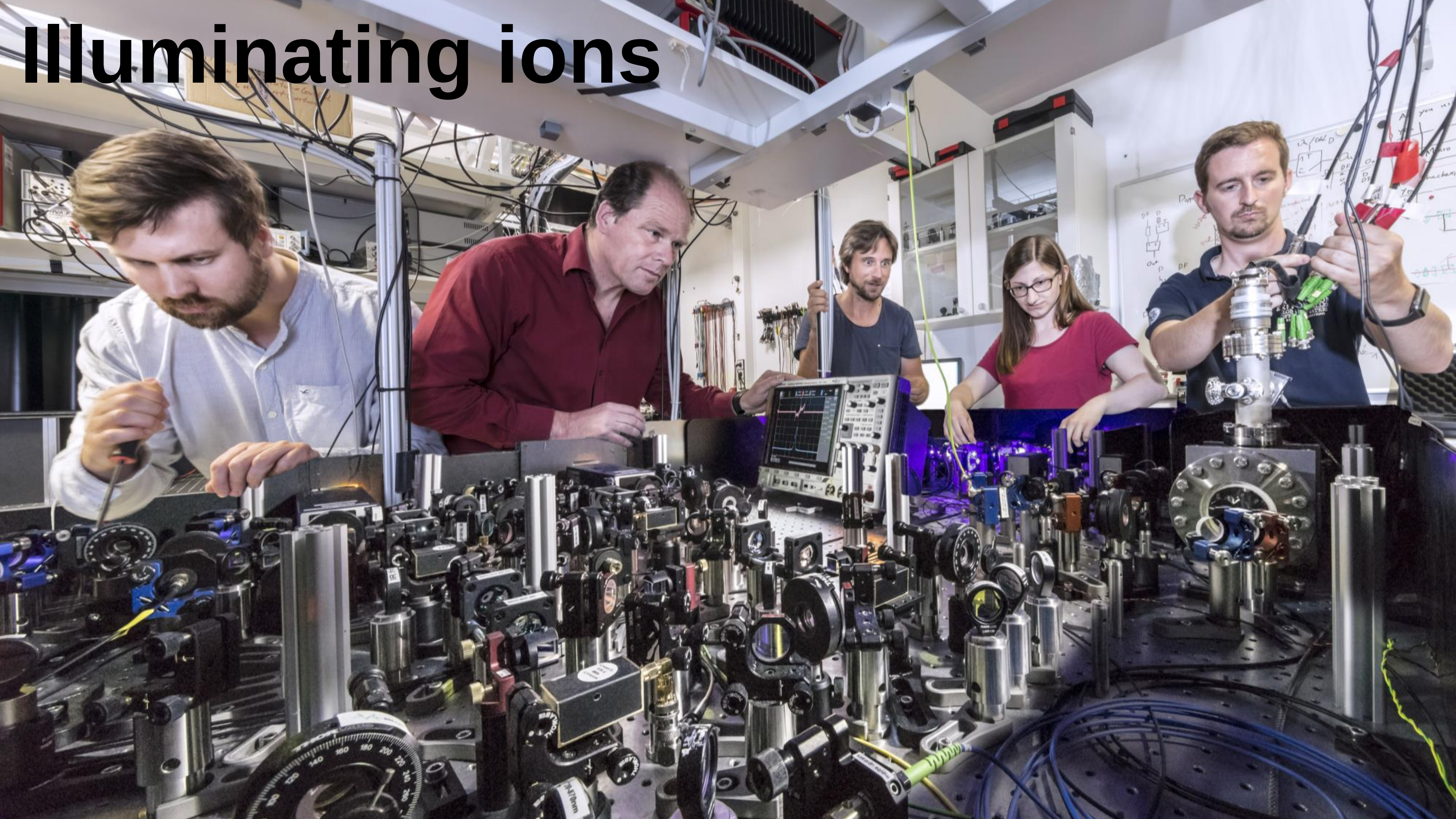
iRyd

AQTION

IQuAn

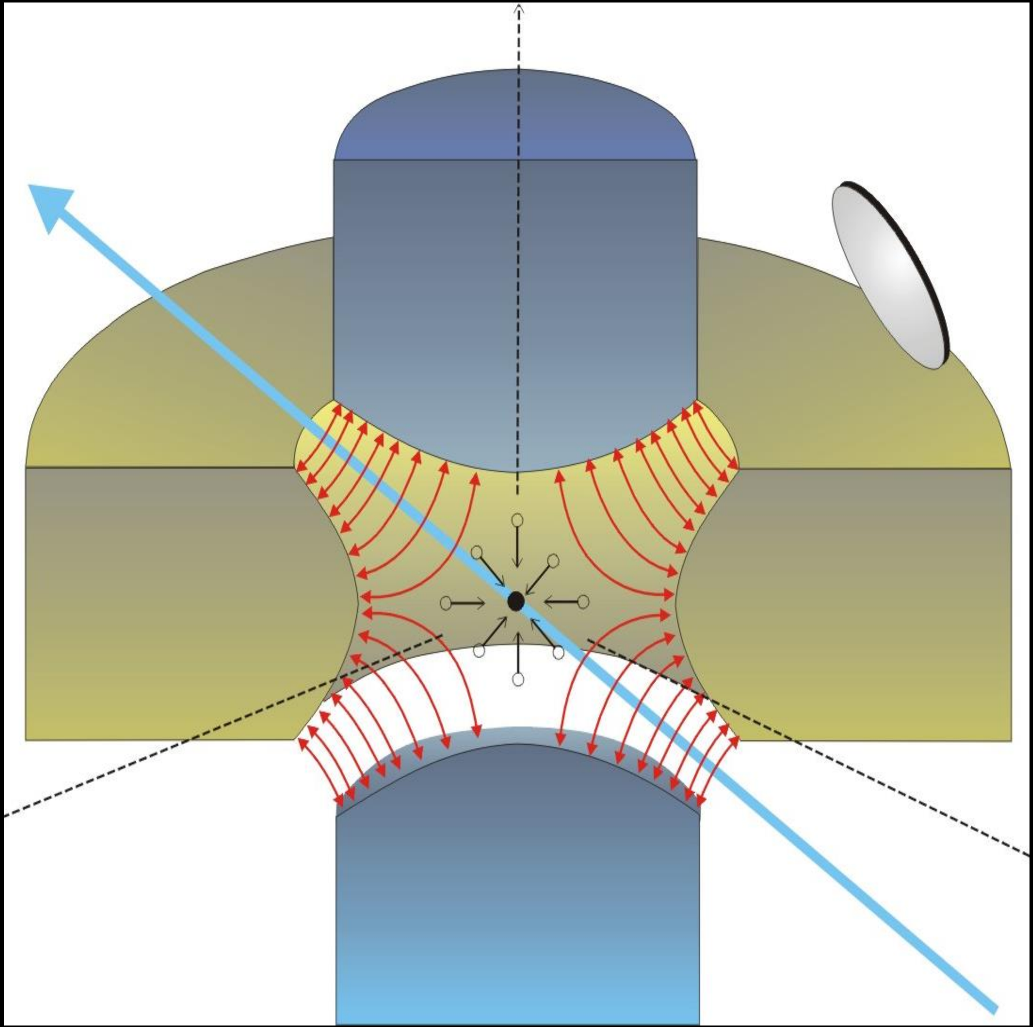
ATIQ

# Illuminating ions

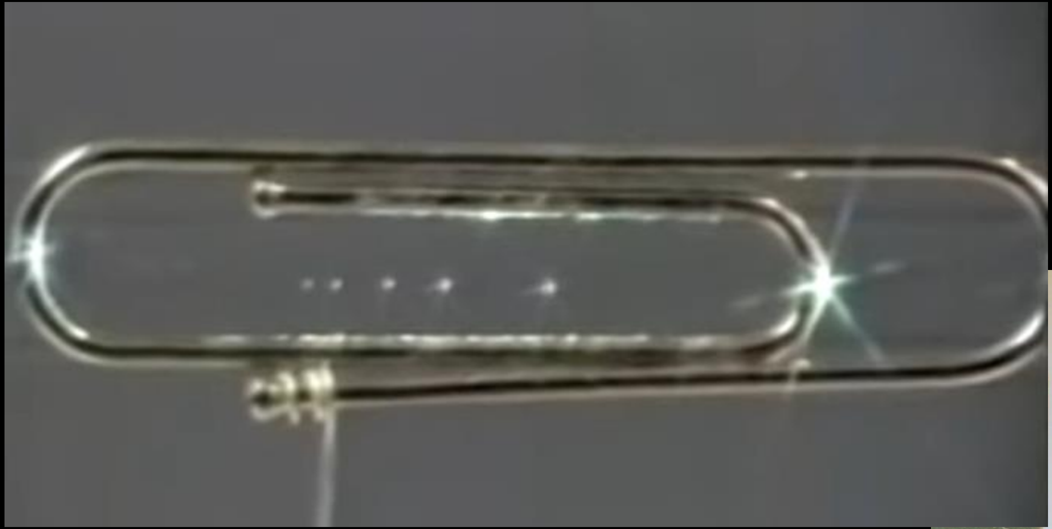


# Trapping ions

Wolfgang Paul (1989), Nobel Prize
for inventing of the Paul trap

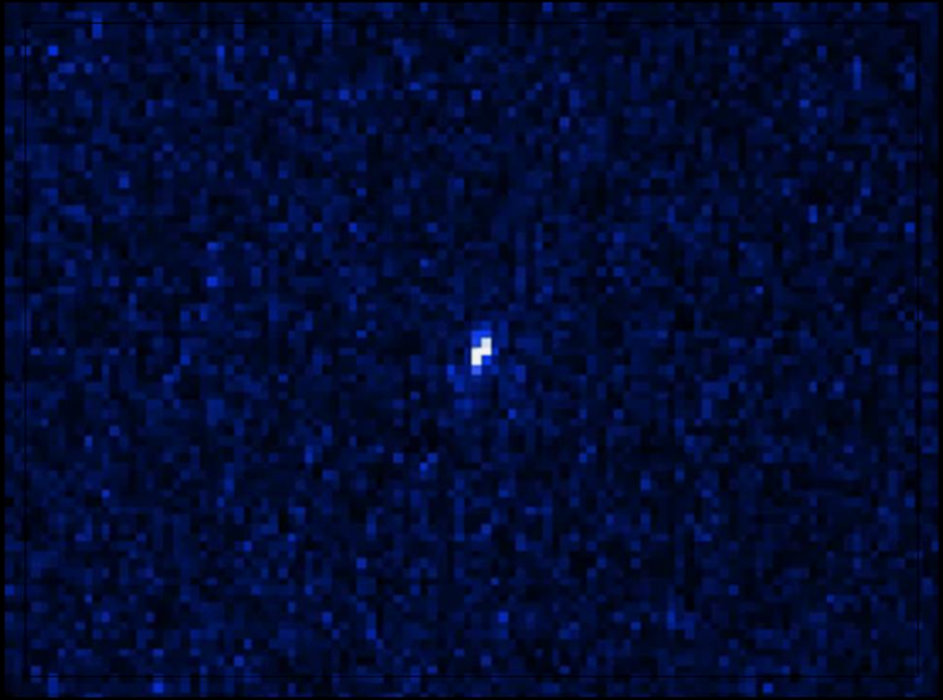


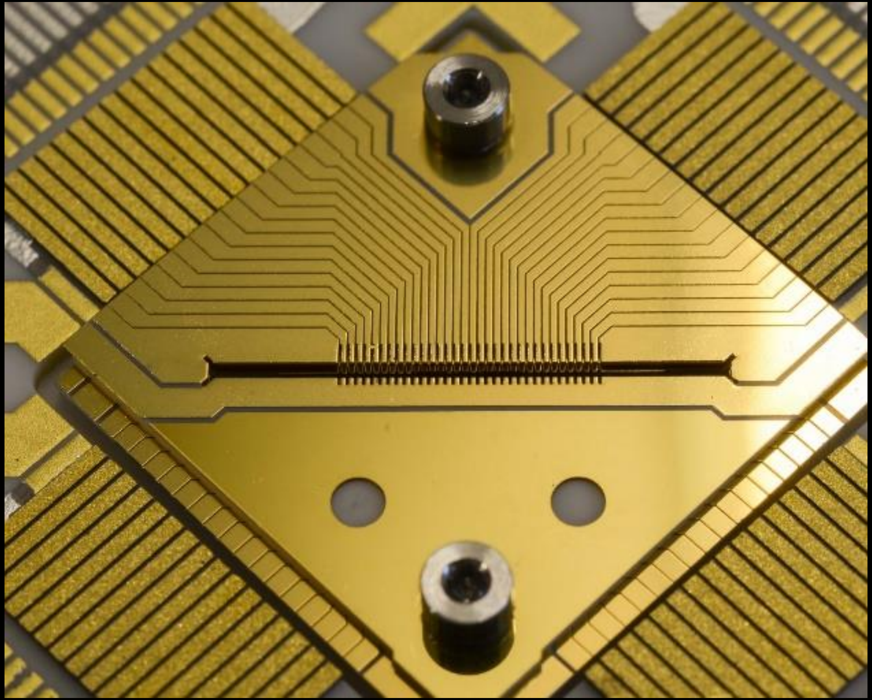
# Theodor Hänsch celebrates Wolfgang Paul



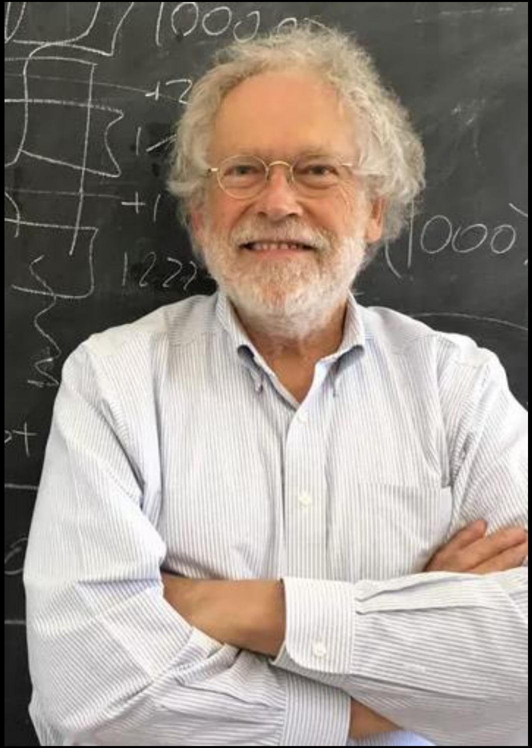
https://www.youtube.com/watch
?v=bkYX[illegible]eJ8IP0

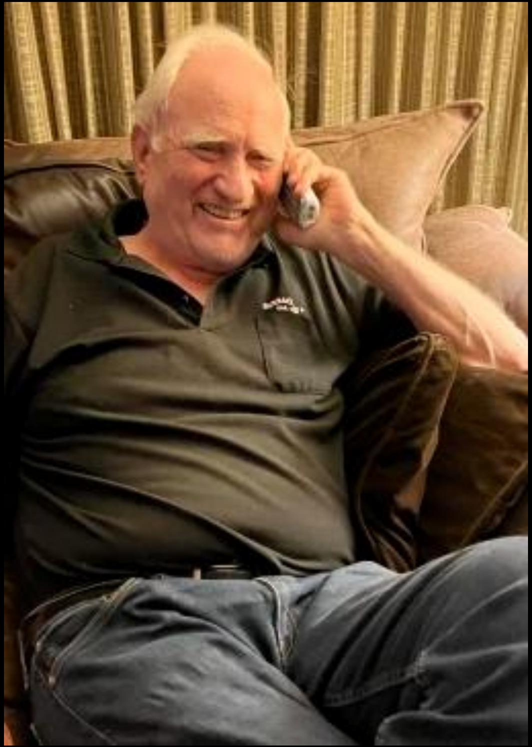
# Loading Calcium Ions / Micro-structured trap





# Exploring the quantum world of entanglement

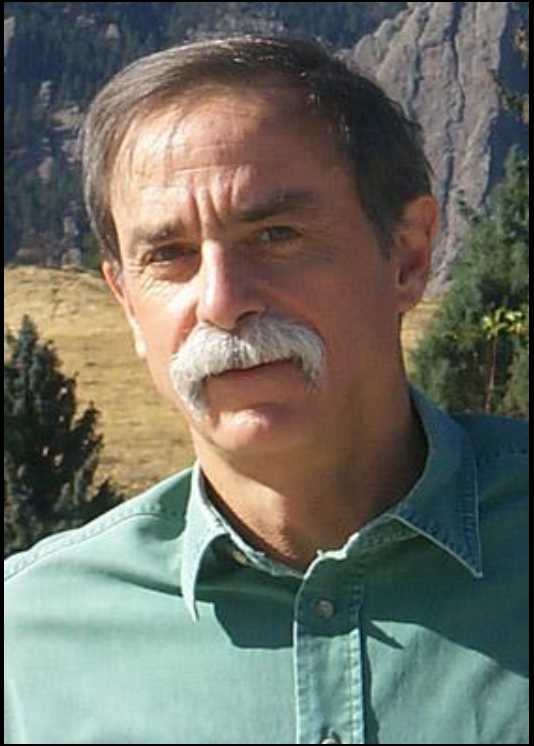




Anton Zeilinger, John Clausner and Alan Aspect

Nobel Preis (2022) for entangled Photons, Bell-experiments and Quantum information

# Controlling single quantum systems



Serge Haroche and Dave Wineland

Nobel Preis (2012) for measurement and control of single quantum systems

# The experimental requirements for quantum computing

*DiVincenzo, Quant. Inf. Comp. 1, 1 (2001)*

Qubits store superposition information, scalable physical system

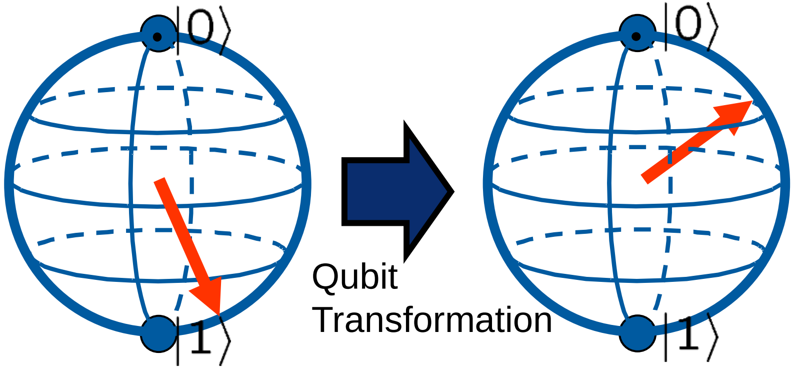
Ability to initialize the state of the qubits $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Universal set of quantum gates: Single bit and two bit gates

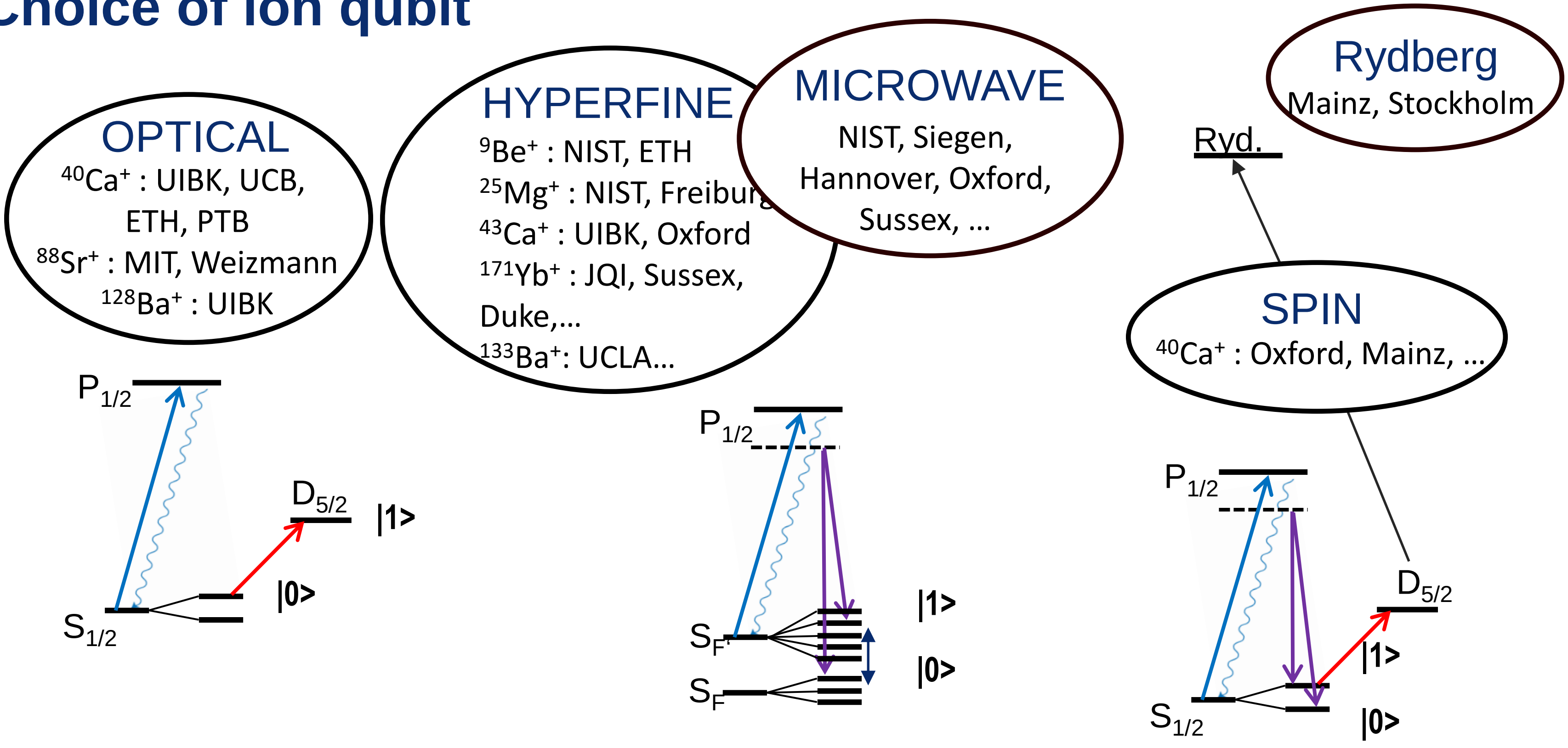
Long coherence times, much longer than gate operation time

Qubit-specific measurement

Qubit connectivity



# Choice of ion qubit



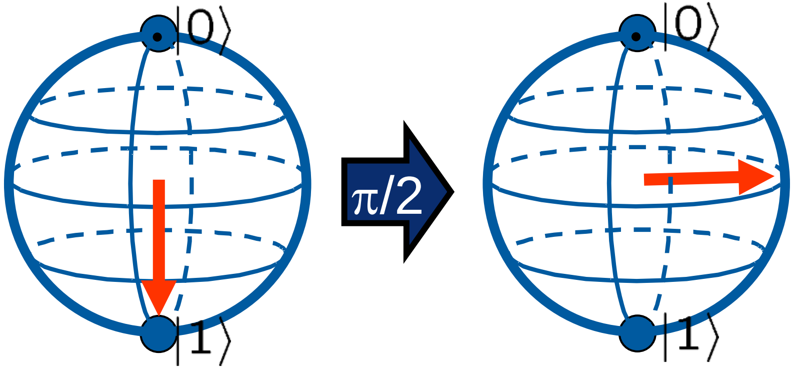

Easy readout
Requires optical phase stability
Limited by metastable lifetime

Infinite $T_1$
only scattering errors
complicated level scheme

Infinite $T_1$
only scattering errors
readout overhead

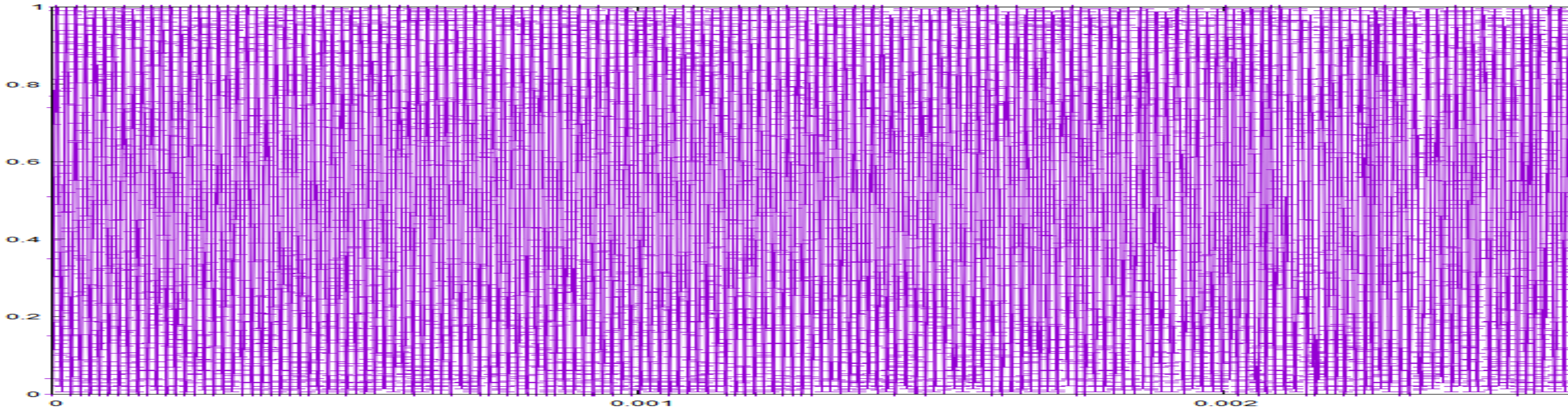
# Rotation of an ion qubit

- Driven by laser beams
- >99,99% fidelity gates
- Gate time few µs



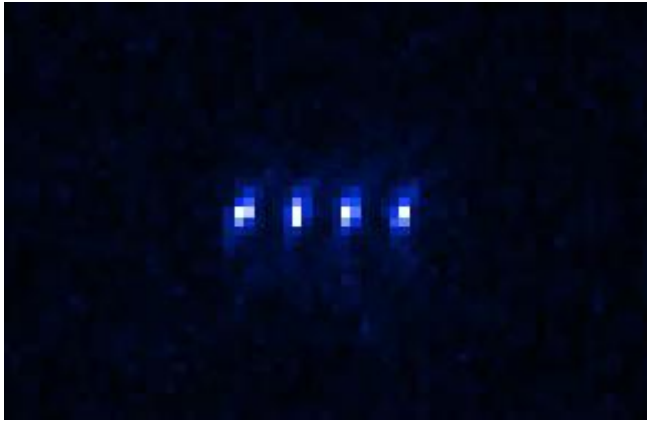

Randomized benchmarking:

average EPG: $7.8\ 10^{-5}$



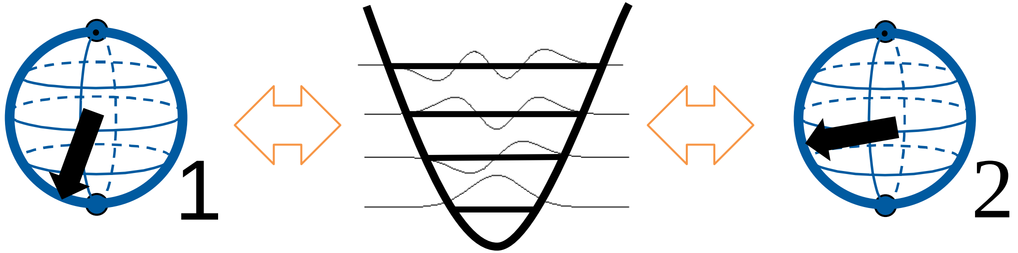
# Key figures in trapped ion QC

Quantum jumps



long-range Coulomb interaction:

- All-to-all connectivity
- Single shot read-out of spin state better than 1 - $10^{-4}$
- Single gate fidelity better than 1 - $10^{-4}$….$10^{-5}$
- Two qubit gate fidelity 1 – $10^{-3}$….$10^{-4}$
- Two-qubit gate operation times ~ 30 … 50 µs




Qubit coupling is mediated by laser light interactions to one or many modes

# Various platforms for quantum computers

Trapped ion qubits: highest fidelities for gates and qubit preparation, longest coherence

Superconduction circuits: highest speed in gates and qubit detection

Neutral atoms: highest number of qubits

Photonic devices: fast, interconnectivity of nodes

Quantum dots, single donors: connecting to solid state processor fab. technology

# Scalable quantum computing architectures

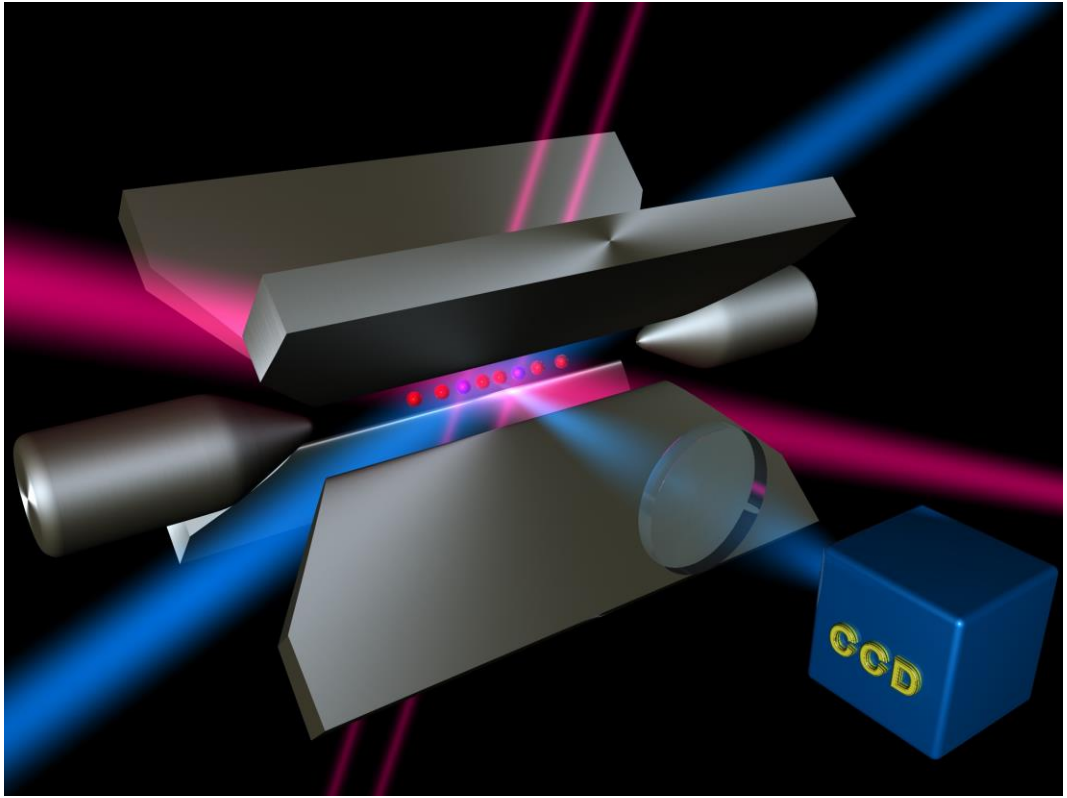
- Number of qubits
- Qubit-connectivity
- Fidelity of gate operations

→ Quantum-volume

Number of qubits & connectivity ⟷ architecture ⟷ Controllability & crosstalk & dephasing

# Linear crystal processor

Static trapped ion registers >20 qubits




AQT IONQ

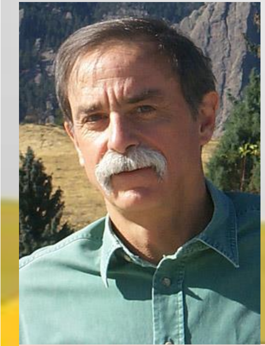
- ❑ Long linear crystals
- ❑ Individual single ion addressing for gates

*Nägerl, et al, PRA 60, 145 (1999)*
*Friis, et al, Phys Rev X. 8 021012 (2018)*
*Korenblit et al, NJP 14, 095024 (2012)*
*Egan et al., Nat. 598, 281 (2021)*

# Quantum-CCD architecture

- ❑ Laser pulses generate entanglement
- ❑ Segmented micro trap allows controlling the ion positions

**DIVIDE ET IMPERA**



*Kielpinski et al., Nat. 417, 709 (2002)*

Dave Wineland – vision of scalabe QC using shuttles in segmented ion traps

Honeywell Quantum Solutions

Our quantum computing future is built on our technology heritage.

# Ion movement – qubit register reconfiguration

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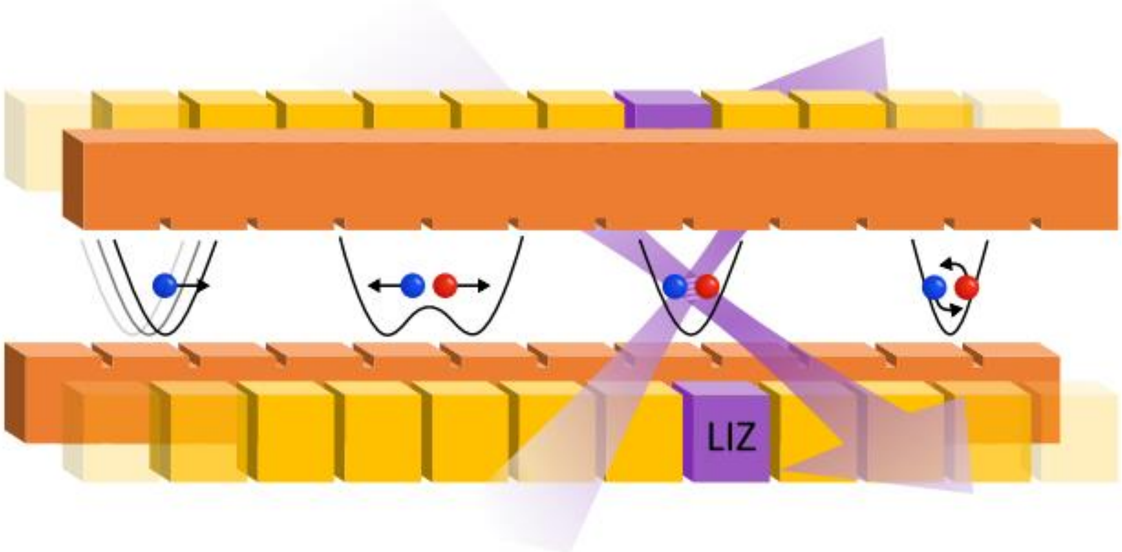


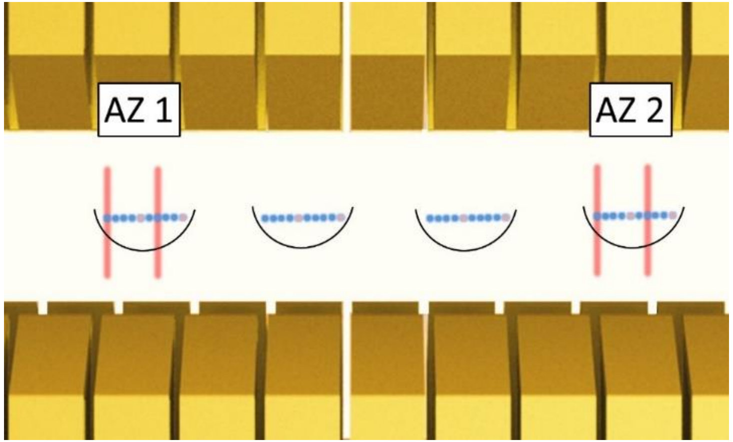

Geometric phase gate with 99.85% fidelity on **radial** mode

Single qubit rotation with average EPG of 7.8 $10^{-5}$

- ❑ Shuttle single ion
- ❑ Shuttle ion crystal
- ❑ Separate two-ion crystal
- ❑ Merge into two-ion crystal
- ❑ Swap ion positions


*Kielpinski et al., Nat. 417, 709 (2002)*
*Walter et al., PRL109, 080501 (2012)*
*Kaufmann et al, NJP 16, 073012 (2014)*
*Kaufmann et al, RPA 95, 052319 (2017)*
*Kaufmann et al, PRL 119, 150503 (2017)*
*Kaustal et al, Adv. At. Mol. Opt. Phys. 69, 233 (2020)*

# IQuAn - Architecture





- Multiple zones for individual optical addressing for gates
  *combined with*
- Reconfiguration of registers, 50 ..100
- Paralell excecution of gates and reconfiguration

- Scalable, industry standard optical and electrical control units
- HPC connection

- Funding started 2021

Bundesministerium für Bildung und Forschung

# Quantum computer control room

# IQuAn / ATIQ access

https://www.iquan.de

IQuAn

Bundesministerium für Bildung und Forschung

Consortium:
**Ionen-Quantenprozessor mit HPC-Anbindung** (IQuAn)

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

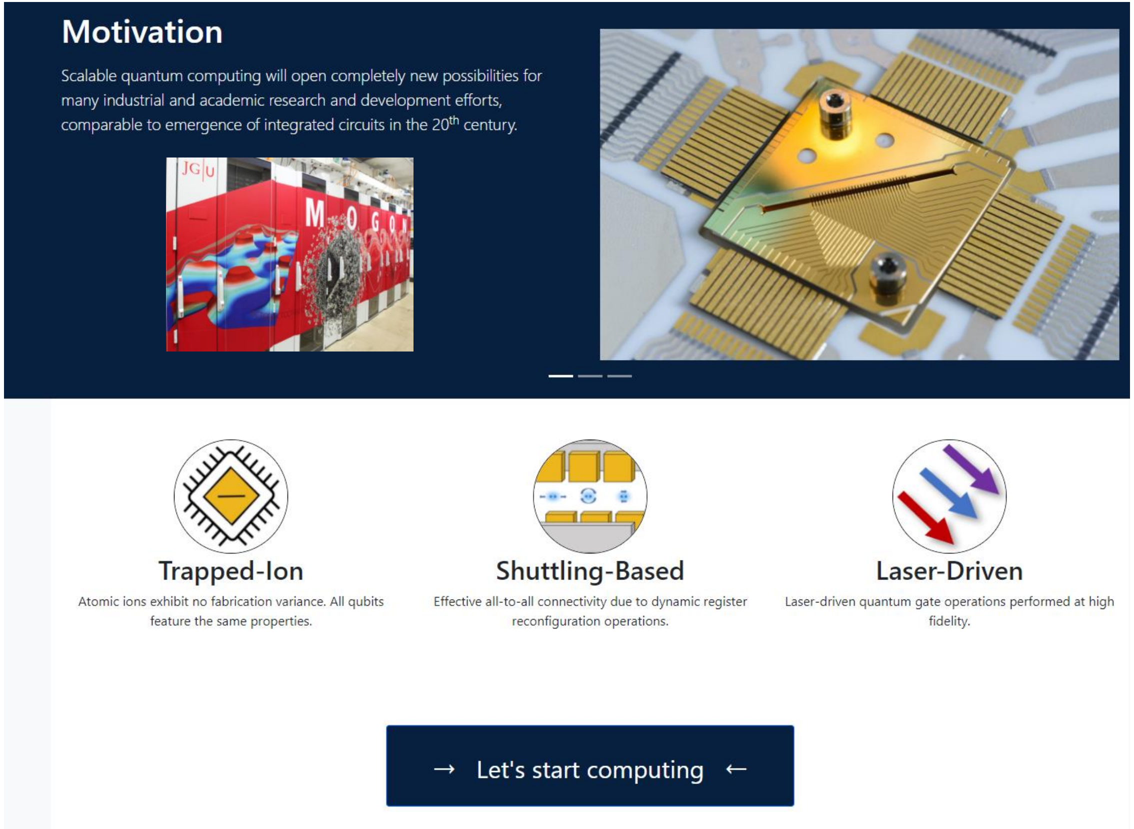
JÜLICH Forschungszentrum

Fraunhofer ILT
Fraunhofer-Institut für Lasertechnik ILT

Fraunhofer IOF
Fraunhofer-Institut für Angewandte Optik und Feinmechanik IOF

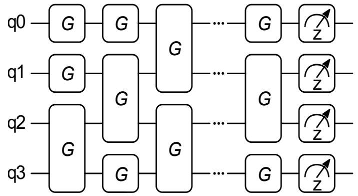
TOPTICA PHOTONICS

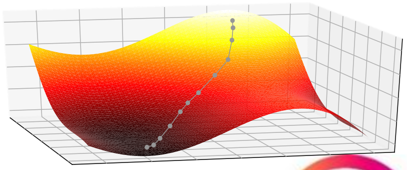
AKKA PASSION FOR TECHNOLOGIES



# Applications and cooperations

## VQE - Hybrid Variational Quantum Eigensolver

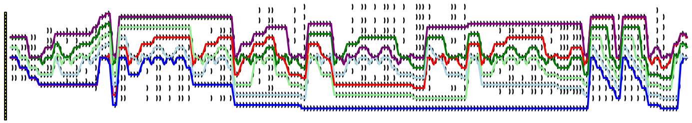


Determine the ground state of a molecule

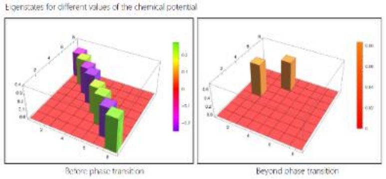
## ParityQC Architecture

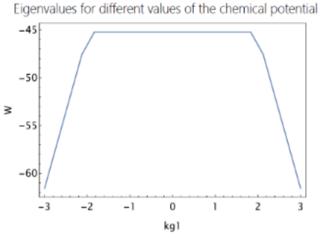
Map optimization problem to parallelizable design of four-qubit interactions



## VQS for High-Energy Physics — K. Jansen, GSI

Variational Quantum Simulation of Multi-Flavor Schwinger Model

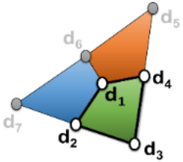


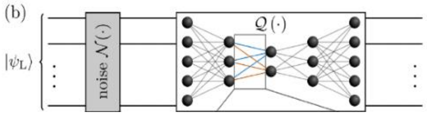




## Beyond NISQ — T. Monz / M. Müller

Ongoing work on:

- QEC – Quantum Error Correction
- QAE – Quantum Auto Encoder
- Logic operations with logic qubits



# Quantum Computing Team @ JGU Mainz

Want to join?


Jonas Vogel


Daniel Pijn

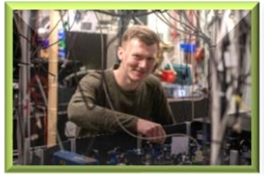

Janine Hilder

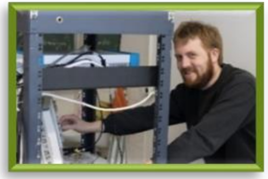

Björn Lekitsch


Ulrich Poschinger


Ferdinand Schmidt-Kaler


Felix Stopp

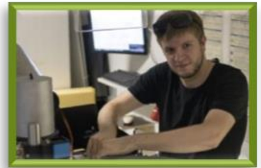

Jan Müller

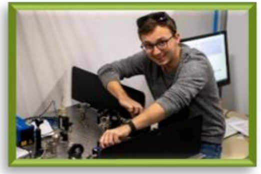

Alexander Stahl


Maximilian Orth


Christian Melzer


Janis Wagner


Alexander Müller


Robin Strohmaier


Daniel Wessel

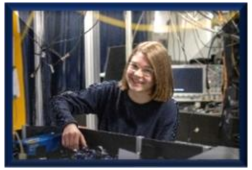

Diego Olvera Millán


Andreas Conta


Sahori Jiménez


Helin Özel


Dario Moreira


Pauline Wagner


Lukas Klein

Fabian Kreppel

André Brinkmann