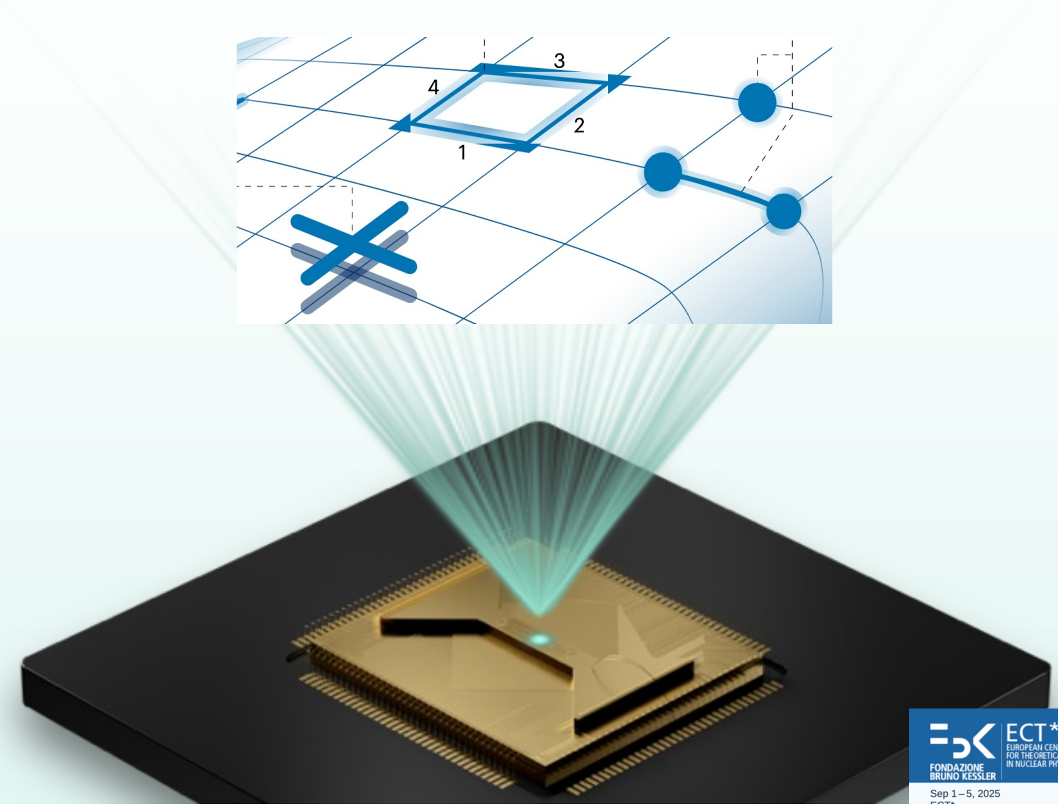
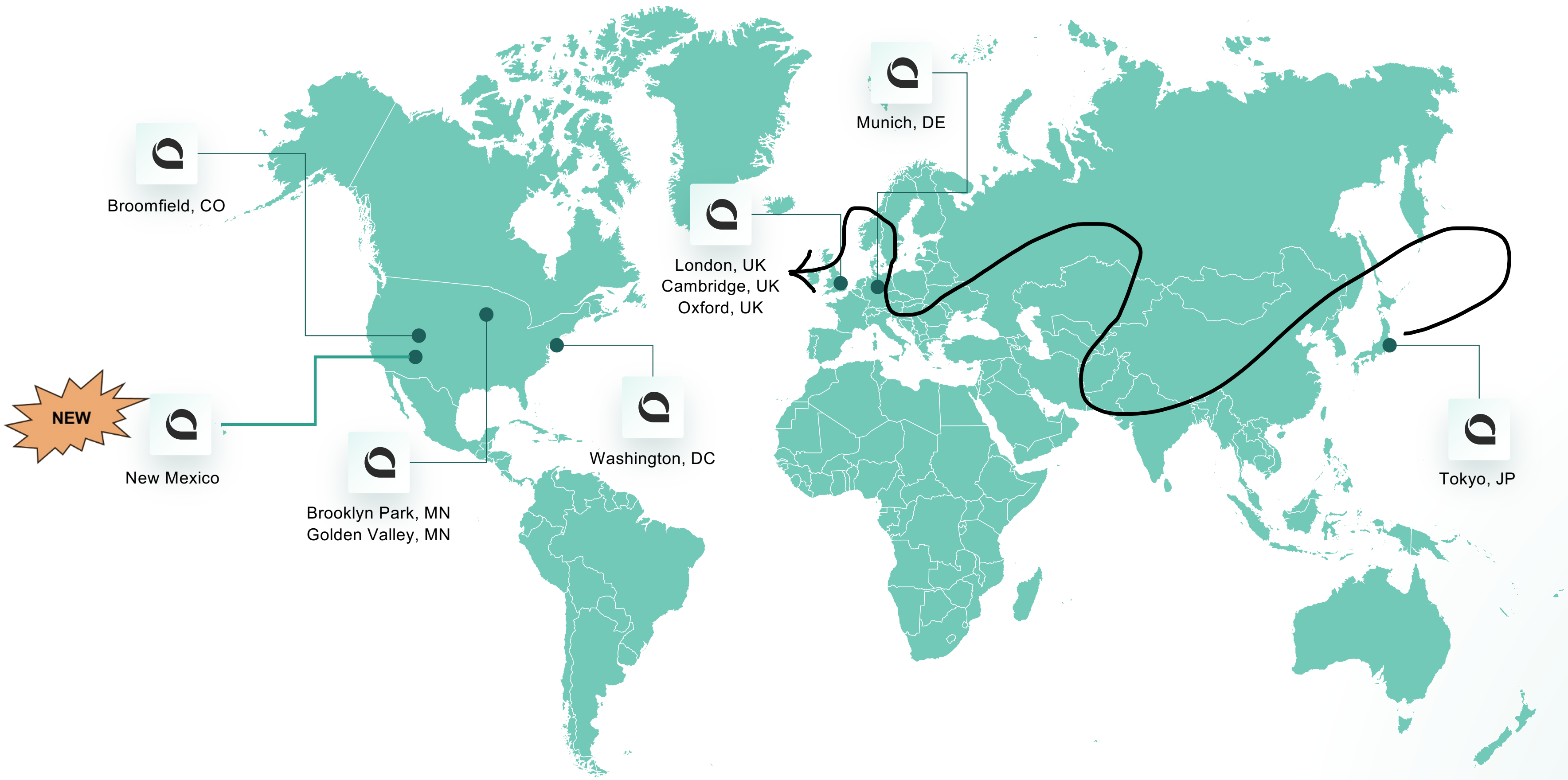
# The QCCD trapped-ion architecture and its benefits for Lattice Gauge Theories




Enrico Rinaldi
Lead R&D Scientist
QUANTINUUM

# Quantinuum's Global Team



# Quantinuum

## the **clear leader** in quantum technology

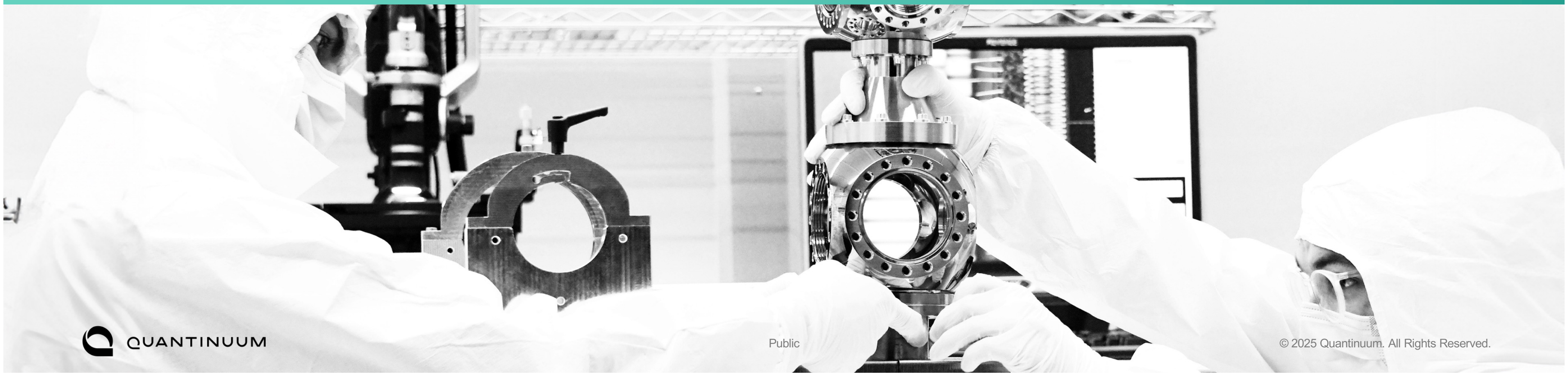
**550+**
employees across 8 offices

**420+**
PhDs and Masters
Largest concentration of quantum experts outside of academia

**140+**
global patents

**~200**
scientific papers

**Cross-domain subject matter expertise:**
Chemistry | Materials science
Artificial intelligence | Machine learning
Condensed matter | Cybersecurity
Encryption | Finance



# Supporting the quantum ecosystem at every level

**Cybersecurity**
**Quantum Origin:** Enterprise-grade quantum computing-enable cryptographic solutions

**Quantum Chemistry**
**InQuanto:** transforming the discovery of new materials and novel processes

**Quantum AI**
Aiming to solve commercial and specific problems that cannot be solved using today's classical computers

**Ecosystem Platforms**
Enables other partners to leverage the power of quantum via open-source access

TKET — **High-performance quantum software development kit**
Multi-platform | Open-source

QUANTINUUM NEXUS — **Full Stack SaaS Platform | Cloud Native**
Complete software platform that allows developers to build and deploy algorithms with minimum effort and maximum flexibility

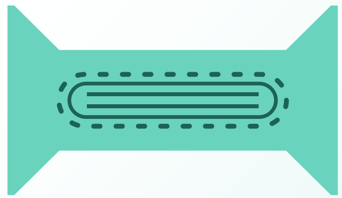
QUANTINUUM SYSTEMS — The world's highest-performing quantum hardware

Ecosystem Quantum Processors

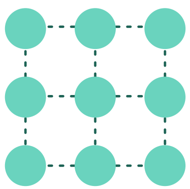
# Quantinuum Hardware – Highest Fidelity, Most Capability

QCCD architecture on a commercial device

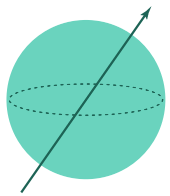
**SYSTEM MODEL H1**



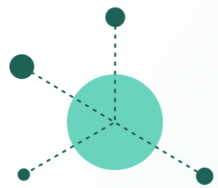
**SYSTEM MODEL H2**



**Unparalleled quality**



**Proven to scale**

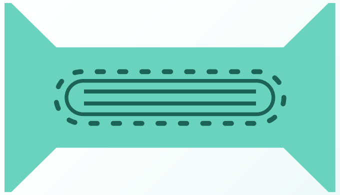


**Solving complex problems**

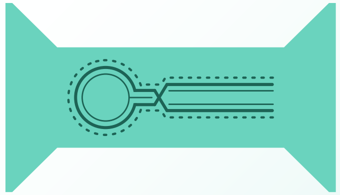
# Quantinuum Hardware – Highest Fidelity, Most Capability

QCCD architecture on a commercial device – a scalable path to fault tolerance

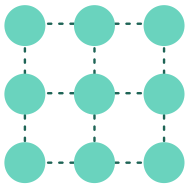
SYSTEM MODEL H1



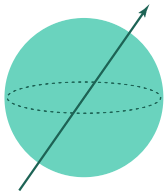
SYSTEM MODEL H2



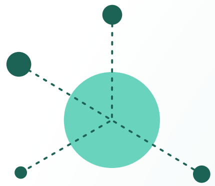
QUANTINUUM HELIOS



**Unparalleled quality**

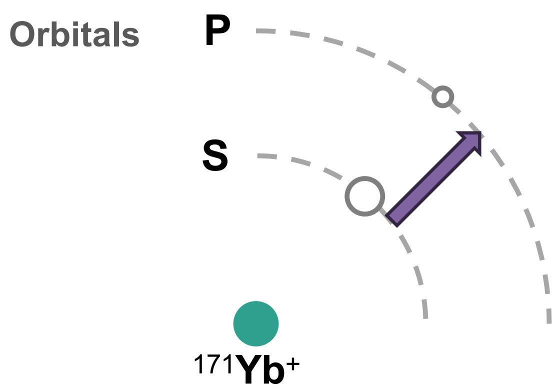


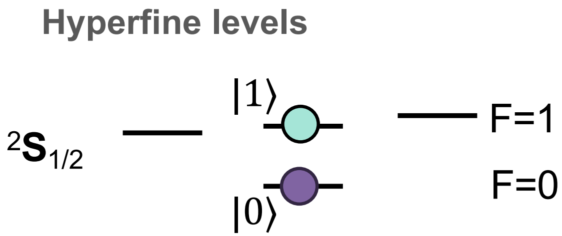
**Proven to scale**



**Solving complex problems**

# Atomic ions are ideal quantum 'bits'




- Quantum information is stored in electronic state
- Each atom is identical, each qubit is identical
- Strong interaction via positive charge and valence electron resonance
- Errors are fundamentally understood
- We precisely capture, control, and manipulate ions for quantum operations

- **initialize into well-defined & determinate state**
- maintain coherence
- provide sets of universal quantum gates
- devise non-destructive qubit state readout

# Architecture for a Large-Scale Quantum Computer

Known as QCCD - **Quantum Charge-Coupled Device**

## Key Concepts

**Qubits** through ions

**Connectivity** by physical transport

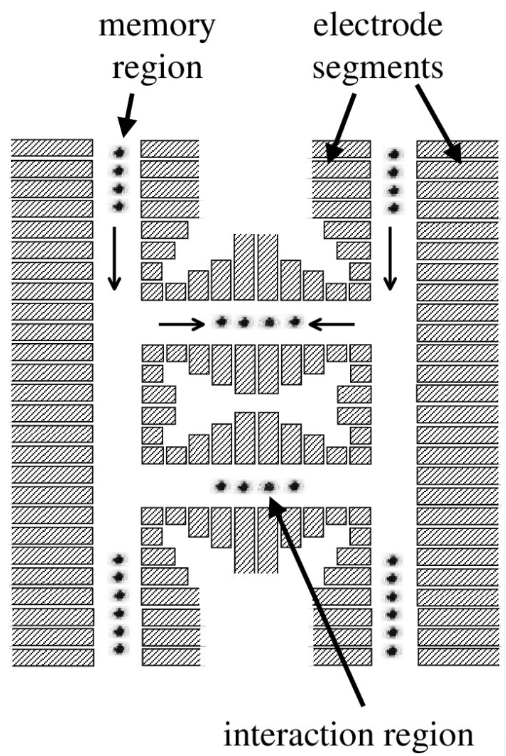
**Dedicated zones** for logic/initialization/measure

**High-fidelity gates** via laser gates on short ion chains

**Scalability** enabled by micro-fabricated traps

Volume 103, Number 3, May–June 1998
Journal of Research of the National Institute of Standards and Technology
[J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)]

*Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions*

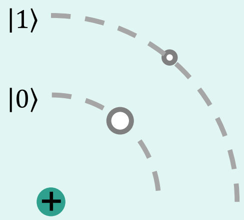



Additional references:
D.J.Wineland, C. Monroe, et. al., Entangled states of atomic ions. for quantum metrology and computation, Atomic Physics 15, pp. 1-474 (1997)
Kielpinski, D., Monroe, C. & Wineland, D. Architecture for a large-scale ion-trap quantum computer. Nature 417, 709–711 (2002).

# QCCD architecture

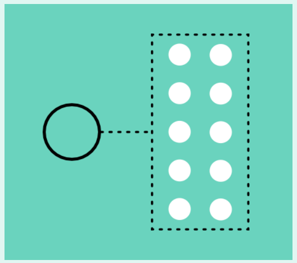
differentiating features

## Robust Coherence



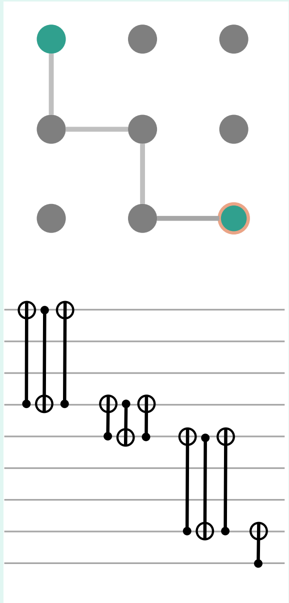

## Flexible and reconfigurable

MCMR and conditional logic

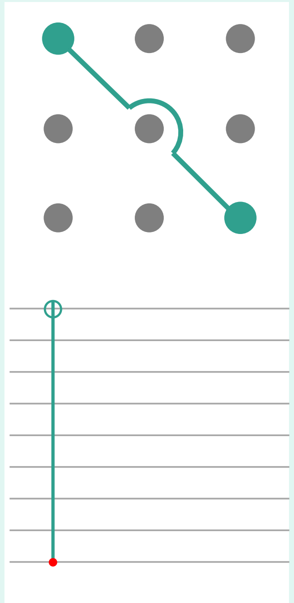


## All-to-All Connectivity

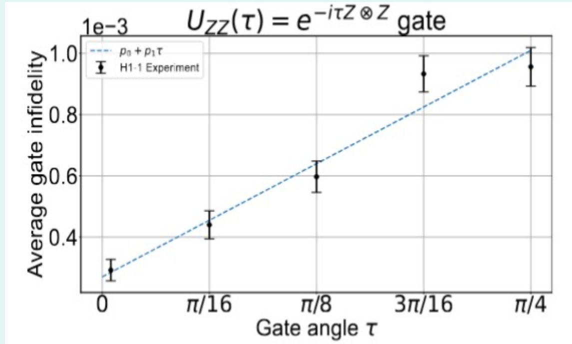
Nearest Neighbor



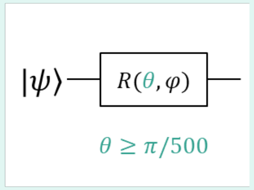
**All-to-All**



## High-Fidelity Ops



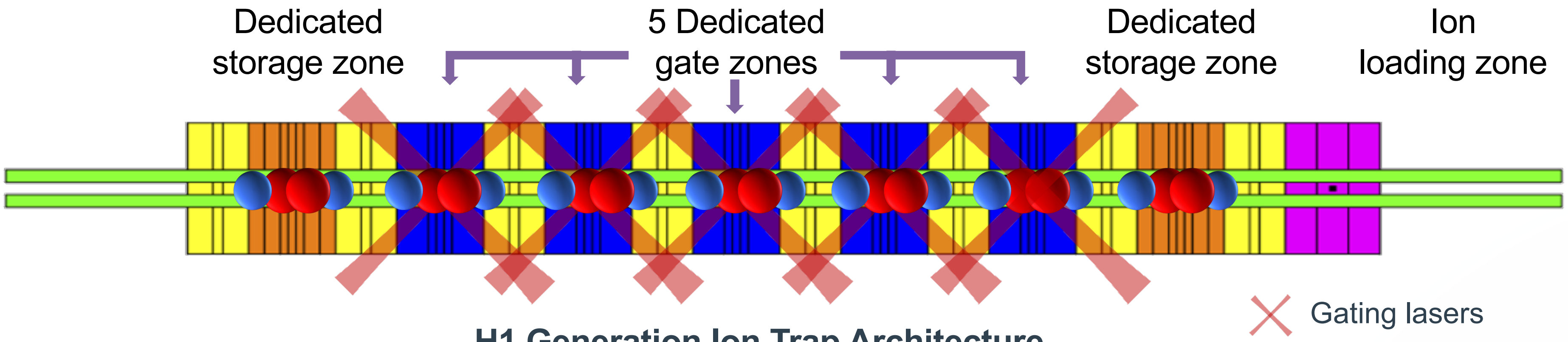

Parameterized Angle
SQ and TQ gates




$$RZZ(\theta) = e^{-\frac{i\theta}{2}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\theta} & 0 & 0 \\ 0 & 0 & e^{i\theta} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

# QUANTINUUM QCCD Trapped-Ion Architecture

## Quantum Charge Coupled Device (QCCD) Architecture




**H1 Generation Ion Trap Architecture**

Quantum bits (qubits) are stored in the electronic states of **IDENTICAL** $Yb^{+}$ ions

$^{171}Yb^{+}$ $|1\rangle$ $|0\rangle$ Hyperfine qubit

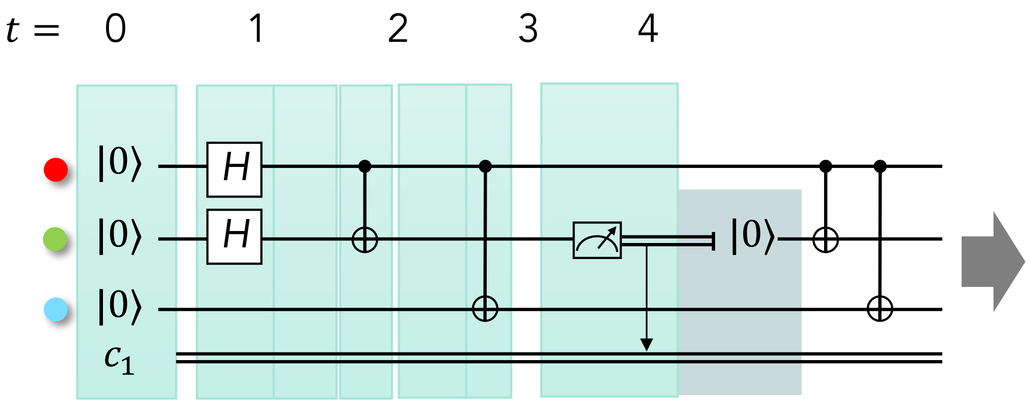
QCCD architecture enables using **gate zones**

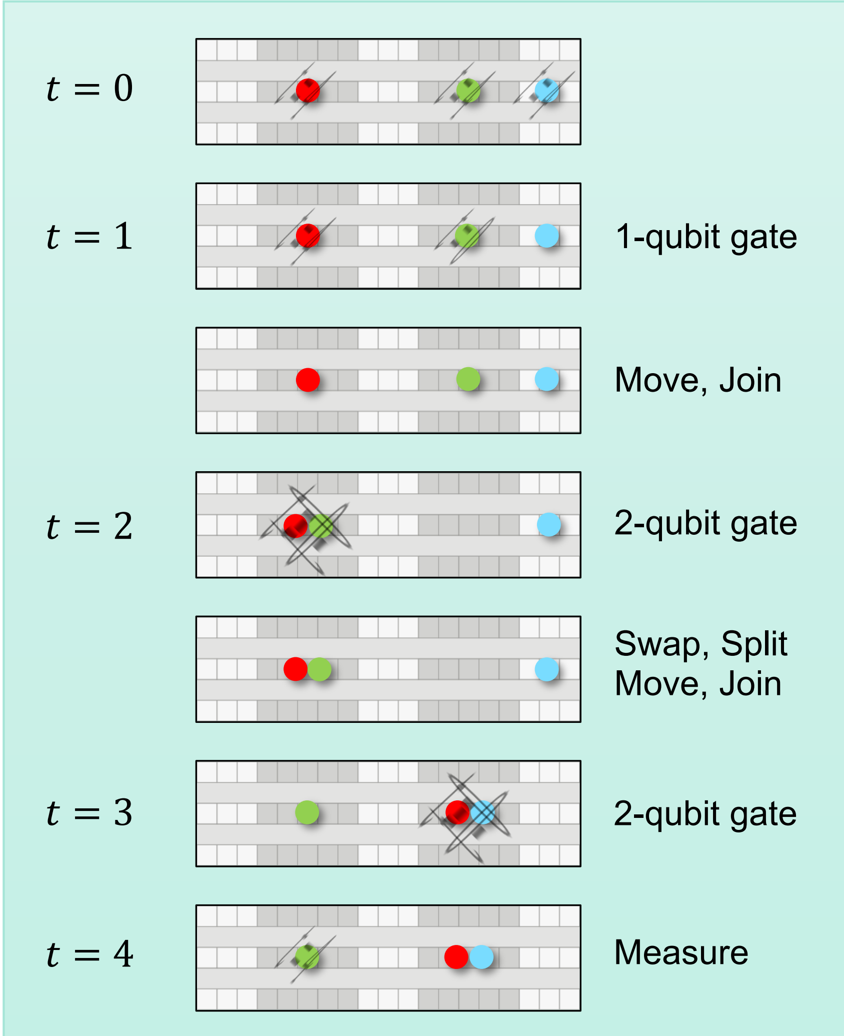
- Minimal and frequent calibrations
- All-to-all connectivity
- High fidelity operations

Cooling ions provide mid-circuit cooling, maintaining circuit fidelity throughout circuit

$^{138}Ba^{+}$ Cooling ion

# Physical Implementation



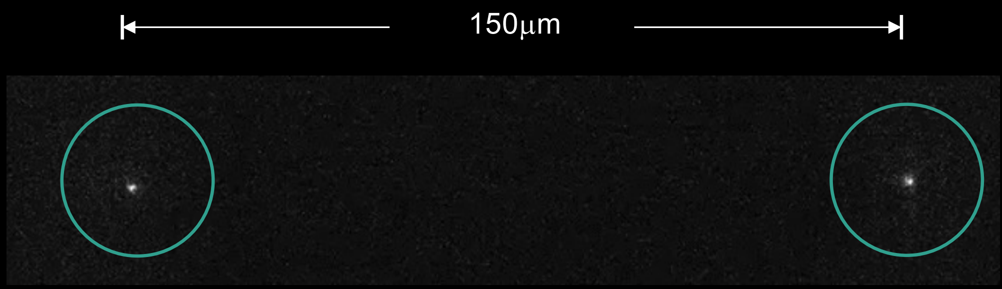



# Transport Primitives

## Split and Combine

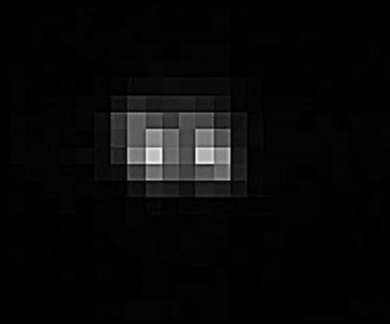
Ion is transported into the same zone

Ions are combined into a single potential well and then re-separated




## Swap

Ions are carefully manipulated to reorder positions



QUANTINUUM


**56**
FULLY-CONNECTED QUBITS

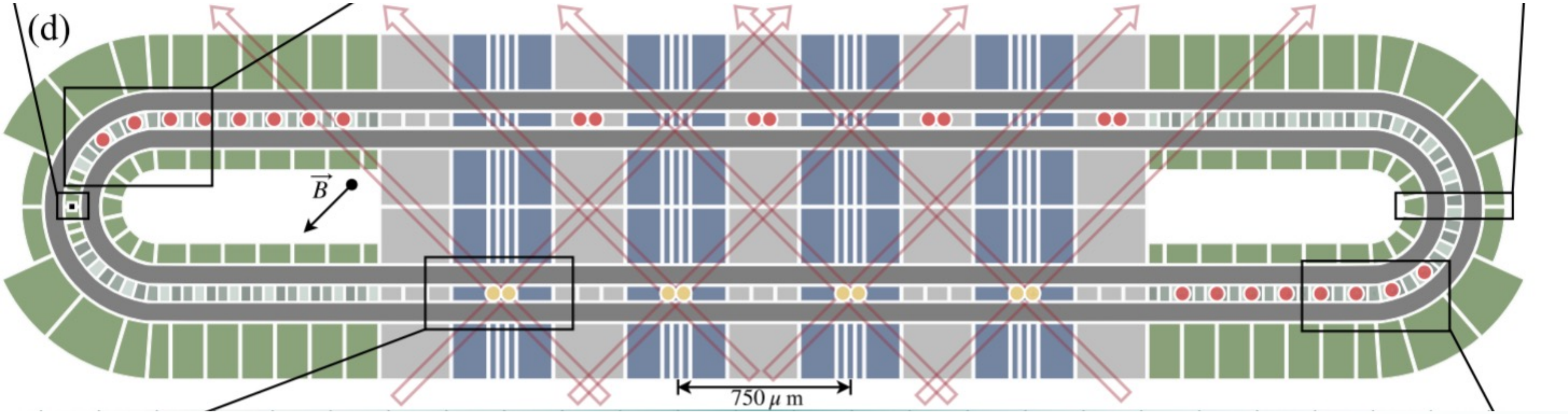
**8,388,608 ($2^{23}$)**
QUANTUM VOLUME

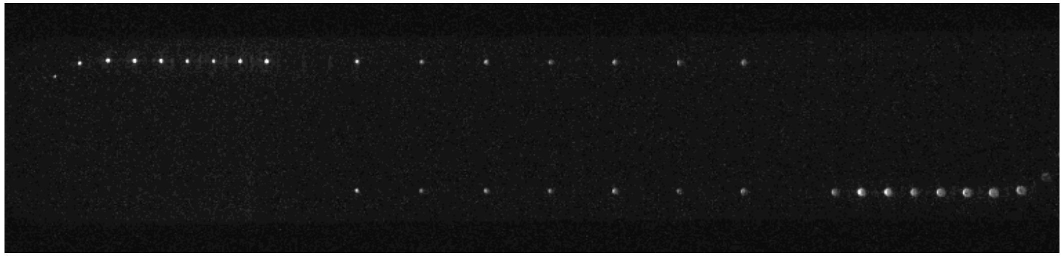
**99.997%**
SINGLE-QUBIT GATE FIDELITY

**99.895%**
TWO-QUBIT GATE FIDELITY

# A Race Track Trapped-Ion Quantum Processor

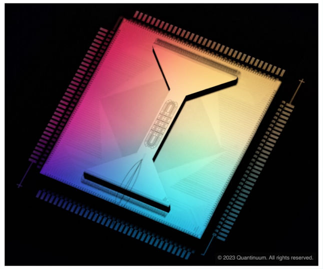
## System Model H2 with N=56 qubits



video: 32 qubits in the trap

*Moses, S. A., et. al., A Race Track Trapped-Ion Quantum Processor, Phys. Rev. X 13, 041052 (2023).*

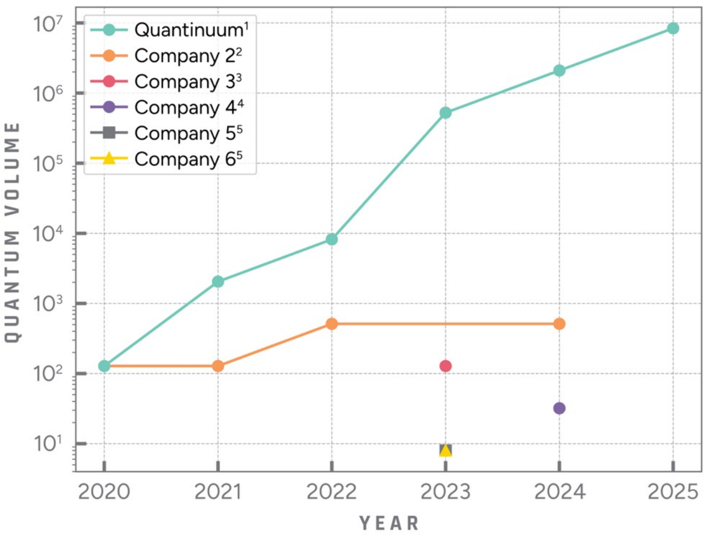


QUANTINUUM

# Performance - Consistently demonstrating differentiation

Consistently demonstrating separation from other systems

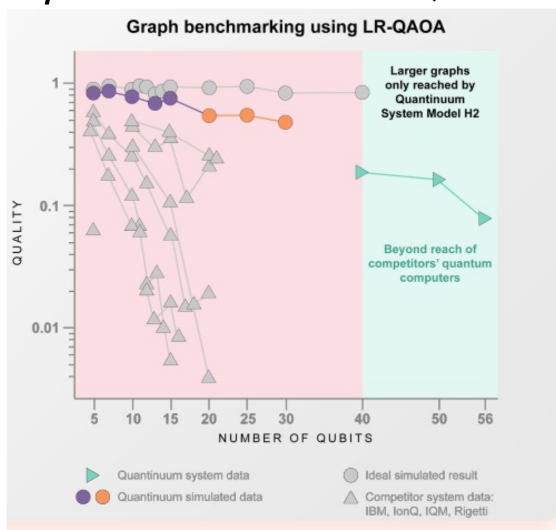
2020 – 2025: 13 records in setting new quantum volume high water marks, 16000x better than next best




https://www.quantinuum.com/blog/quantum-volume-milestone

Feb 2025 – Julich Supercomputing center benchmarking results on IBM, IQM, Rigetti, IonQ, QNTM

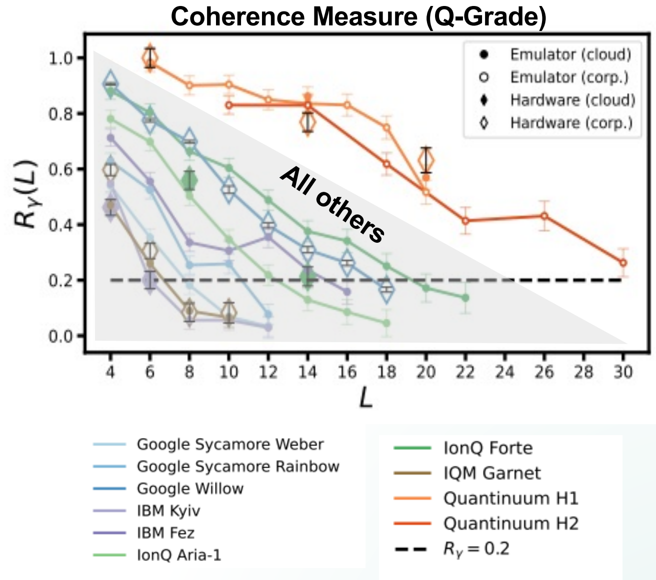
***"The performance of Quantinuum… is superior to that of the other QPUs"***




Evaluating the performance of quantum process units at large width and depth


J. A. Montañez-Barrera,[1,*] Kristel Michielsen,[1,2,3] and David E. Bernal Neira[4]
[1]Jülich Supercomputing Centre, Institute for Advanced Simulation, Forschungszentrum Jülich, 52425 Jülich, Germany
[2]AIDAS, 52425 Jülich, Germany
[3]RWTH Aachen University, 52056 Aachen, Germany
[4]Davidson School of Chemical Engineering, Purdue University, 47907, West Lafayette, Indiana, USA


April 2025 - Researchers in Cambridge benchmarking results Google, IBM, IonQ, IQM and Quantinuum



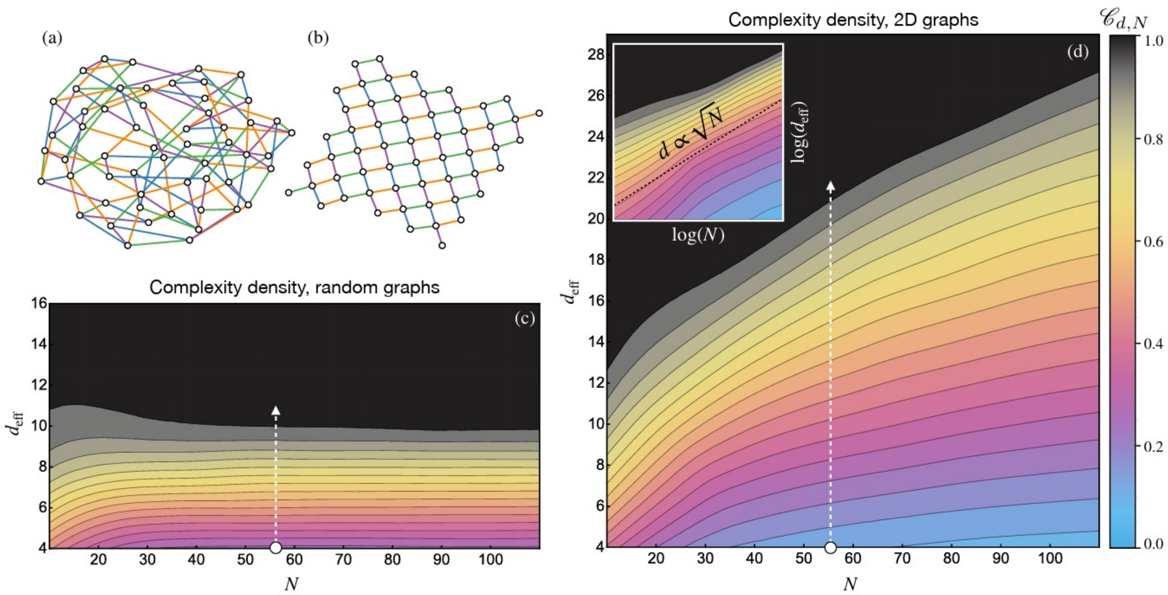

Standardized test of many-body coherence in gate-based quantum platforms


Yi Teng,[1] Orazio Scarlatella,[1] Shiyu Zhou,[2] Armin Rahmani,[3] Claudio Chamon,[4] and Claudio Castelnovo[1]
[1]TCM Group, Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
[2]Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada N2L 2Y5
[3]Department of Physics and Astronomy and Advanced Materials Science and Engineering Center, Western Washington University, Bellingham, Washington 98225, USA
[4]Department of Physics, Boston University, Boston, MA, 02215, USA

# Beyond the classical frontier

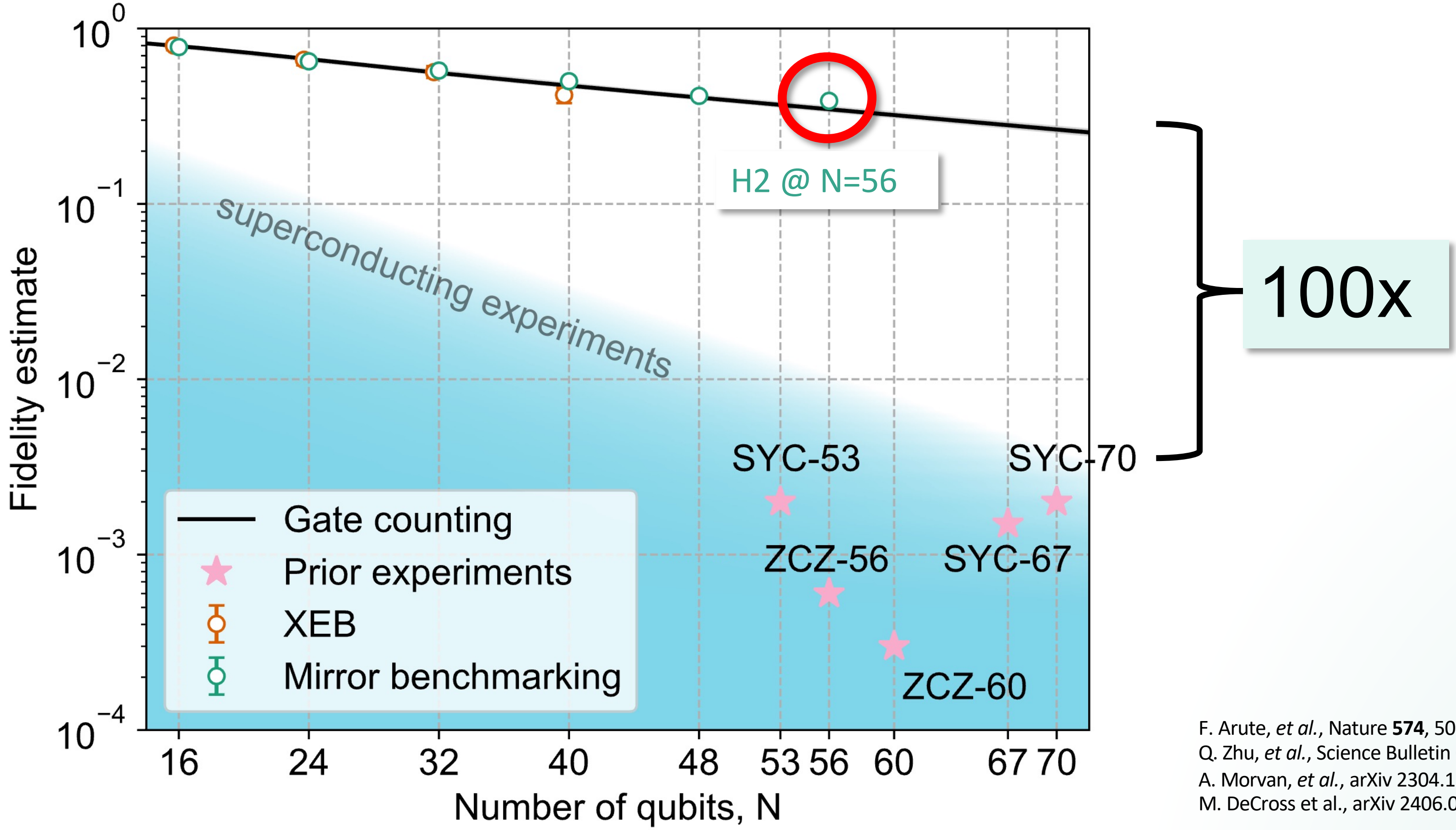
Random Circuit Sampling performance advantage enhanced by all-to-all connectivity

- All-to-all connectivity means the complexity of these random circuits grows faster than for a nearest-neighbor-connected circuit
- Nearest-neighbor connectivity: for higher qubit numbers, deeper circuits must be run to achieve maximum complexity
  - Deeper circuits = more gates = worse fidelity
- All-to-all connectivity: shallower circuit required to maximize complexity density
  - Increasing qubit number does *not* necessitate deeper circuits
- This effect combined with higher-fidelity gates leads to large fidelity improvements over competitors




"The computational power of random quantum circuits in arbitrary geometries." DeCross et al., arXiv 2406.02501

# RCS fidelities compared to competitors





F. Arute, *et al.*, Nature **574**, 505 (2019).
Q. Zhu, *et al.*, Science Bulletin **67**, 240 (2022).
A. Morvan, *et al.*, arXiv 2304.11119 (2023).
M. DeCross et al., arXiv 2406.02501

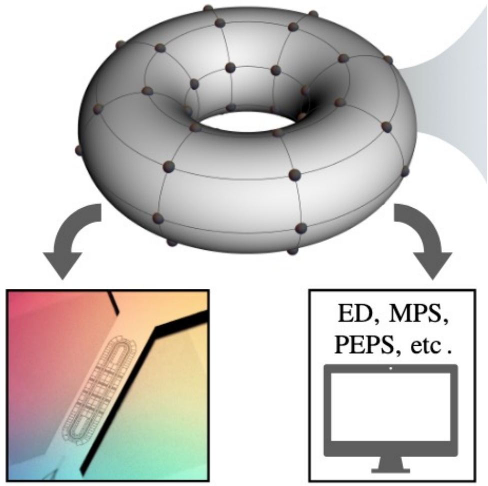
# Studying quantum matter with H2-1 Quantum Ising model

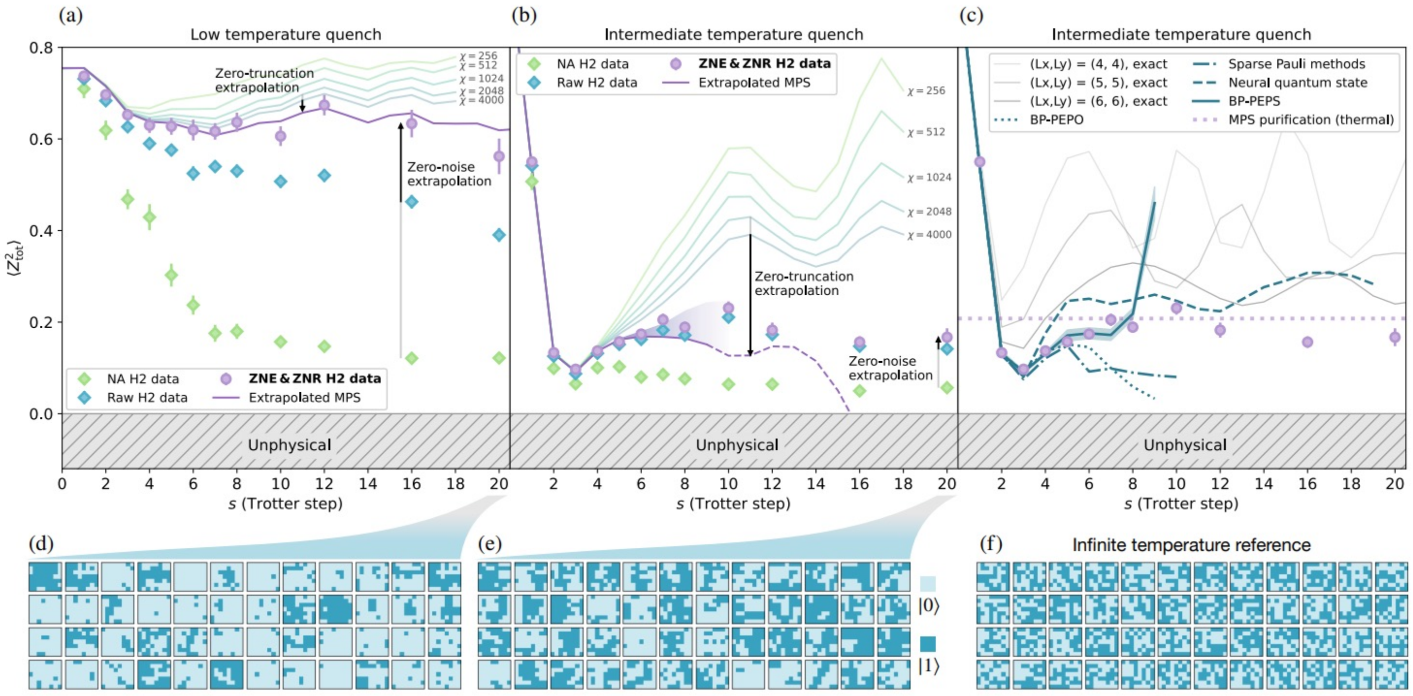
"Digital quantum magnetism at the frontier of classical simulations" arXiv:2503.20870

## Simulate 2D Ising model on 7 x 8 rectangular lattice using H2

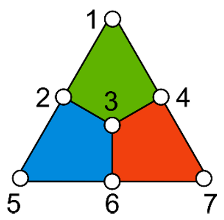
## Partial entangler fidelities of 99.94(1)% enable circuits with > 2,000 two-qubit gates

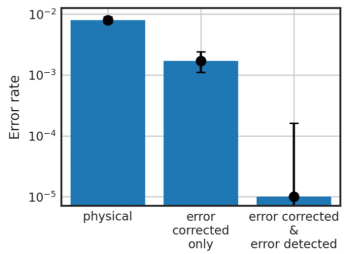
$$H = J\sum_{\langle j,k\rangle} Z_j Z_k + h\sum_j X_j$$

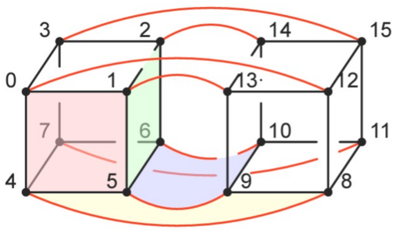


# Some QEC research milestones at Quantinuum



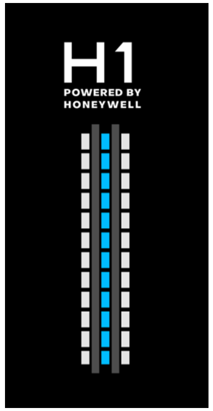



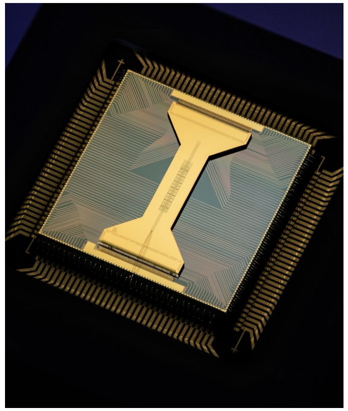




- First to demonstrate real-time error correction (July 2021, demonstrated on H1-1 (10 qubits at the time, now 20), https://arxiv.org/abs/2107.07505)
- First to demonstrate break-even logical error rates (August 2022, demonstrated on H1-1, https://arxiv.org/abs/2208.01863)
- First to demonstrate teleportation of a logical qubit (April 2024, demonstrated on H2-1, https://arxiv.org/abs/2404.16728)
- Beyond Break Even (April 2024, demonstrated on H2-1, collaboration with Microsoft, https://arxiv.org/abs/2404.02280)
- Leading in Demonstrations of high-dimensional QEC codes (Aug-Sept 2024, demonstrated on H2-1, https://arxiv.org/abs/2408.08865, https://arxiv.org/abs/2409.04628)

# Some HEP works on Quantinuum System H1

- Neutrino oscillations:
  - https://arxiv.org/abs/2210.08656
  - http://arxiv.org/abs/2407.13914
- Nuclear beta decay:
  - https://arxiv.org/abs/2209.10781
- Quantum gravity in the lab:
  - https://arxiv.org/abs/2205.14081
- Scattering wave packets of hadrons:
  - https://arxiv.org/abs/2402.00840
- Shear viscosity of SU(2) LGT:
  - https://arxiv.org/abs/2402.04221
- (2+1)D QED ground state:
  - http://arxiv.org/abs/2411.05628
- SYK model simulations
  - http://arxiv.org/abs/2507.07530



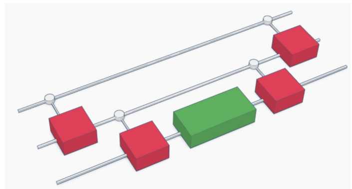


- *20 fully-connected qubits*
- *5 parallel gating zones*
- *TQ gate fidelity 99.91%*
- *SQ gate fidelity > 99.998%*
- *SPAM fidelity > 99.7%*
- *Measurement cross talk error < 0.01%*

http://arxiv.org/abs/2411.05628

# Example of workflow used for (2+1)D QED calculation

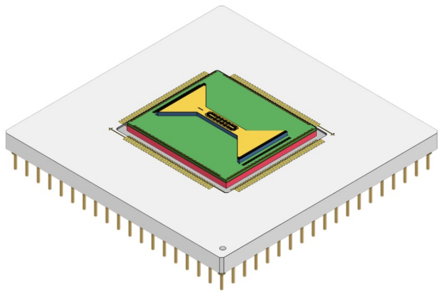
**Quantinuum Nexus orchestration platform:**
- Manage circuits
- Submit jobs to multiple backends
- Share results within organizations



**Quantinuum TKET toolkit:**
- Design circuits in a compositional way
- Optimize and reduce gate count
- Compile to any gate set and architecture

INQUANTO™

**Quantinuum quantum chemistry library:**
- Define arbitrary Hamiltonians (bosons and fermions)
- Define circuit ansatze
- Efficient re-usable protocols for quantum observables



**Quantinuum Systems:**
- Emulators with realistic noise models
- Support Mid-Circuit-Measurments-and-Reset and qubit reuse
- Arbitrary angle ZZ and SU(4) gates

# Some LGT works on Quantinuum System H2

D4 LGT

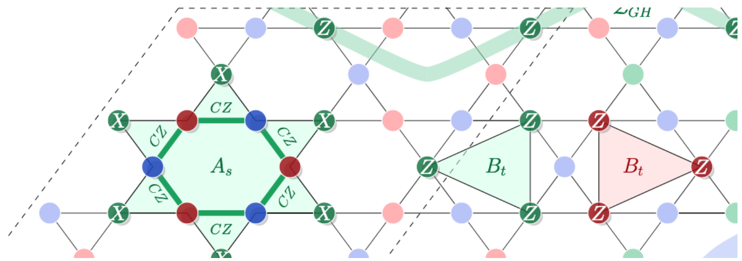
Article | Published: 14 February 2024

## Non-Abelian topological order and anyons on a trapped-ion processor

Mohsin Iqbal, Nathanan Tantivasadakarn, Ruben Verresen, Sara L. Campbell, Joan M. Dreiling, Caroline Figgatt, John P. Gaebler, Jacob Johansen, Michael Mills, Steven A. Moses, Juan M. Pino, Anthony Ransford, Mary Rowe, Peter Siegfried, Russell P. Stutz, Michael Foss-Feig, Ashvin Vishwanath & Henrik Dreyer

*Nature* **626**, 505–511 (2024) | Cite this article





Article | Open access | Published: 08 July 2025

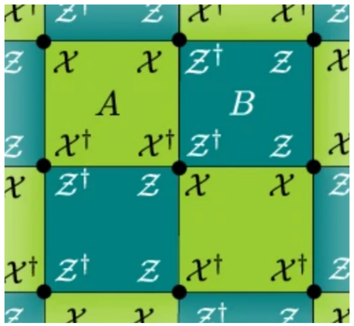
## Qutrit toric code and parafermions in trapped ions

Mohsin Iqbal, Anasuya Lyons, Chiu Fan Bowen Lo, Nathanan Tantivasadakarn, Joan Dreiling, Cameron Foltz, Thomas M. Gatterman, Dan Gresh, Nathan Hewitt, Craig A. Holliman, Jacob Johansen, Brian Neyenhuis, Yohei Matsuoka, Michael Mills, Steven A. Moses, Peter Siegfried, Ashvin Vishwanath, Ruben Verresen & Henrik Dreyer

*Nature Communications* **16**, Article number: 6301 (2025) | Cite this article



Z3 LGT



# Quantinuum Hardware Roadmap

| | Today | | Tomorrow | | |
|---|---|---|---|---|---|
| | 2020 | 2023 | 2025 | 2027 | 2029 |
| SYSTEMS: | SYSTEM MODEL H1 | SYSTEM MODEL H2 | QUANTINUUM HELIOS | QUANTINUUM SOL | QUANTINUUM APOLLO |
| PHYSICAL QUBITS: | 20 | 56 | 96 | 192 | 1000's |
| PHYSICAL 2-QUBIT GATE ERROR: | $1 \times 10^{-3}$ | $1 \times 10^{-3}$ | $< 5 \times 10^{-4}$ | $< 2 \times 10^{-4}$ | $1 \times 10^{-4}$ |
| LOGICAL QUBITS: | | > 12 | ~ 50 | ~ 100 | 100's |
| LOGICAL ERROR RATES: | | $1 \times 10^{-3}$ | $< 10^{-4}$ | $\sim 10^{-5}$ | $1 \times 10^{-5}$ to $1 \times 10^{-10}$* |

QUANTINUUM

# HELIOS

**New chip design:**

improved performance

**More physical qubits:**

~50 logical qubits

**Higher-fidelity:**

more accurate operations

**Faster circuit times:**

quicker time to solution

**Power consumption:**

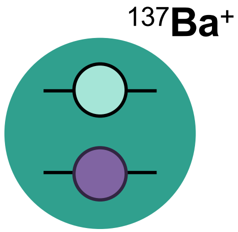
less than 40kW

**Provides all Quantinuum Systems features, including:**

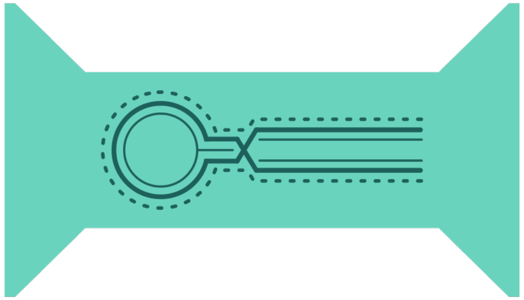
- All-to-all connectivity
- Parameterized 2-qubit operations
- Mid-circuit measurement & reset
- Conditional Operations
- QEC decoder toolkit
- Application-level leakage detection
- Qubit Reuse Compiler
- Emulation and debugging (Selene)
- Real-time Random Number Generator

# Helios – Our Next Gen System

**$^{137}Ba^{+}$ qubit**

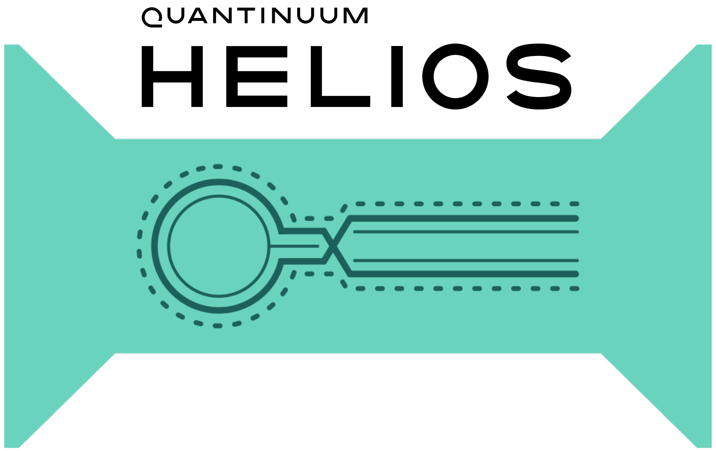



Helios Processor Architecture



Quantum Programming Stack

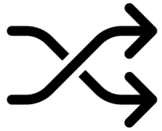
# Helios QPU – QCCD junctions changes topology




First commercial
QCCD junction

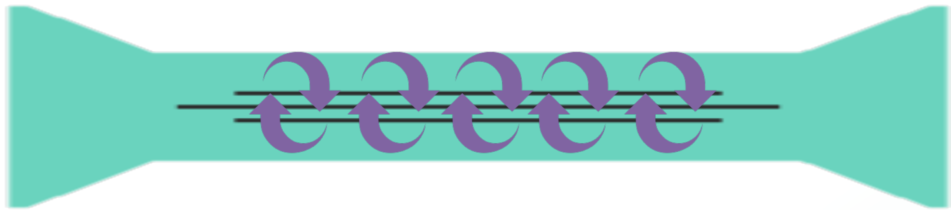
# What is a QCCD junction?

First commercial
QCCD junction



Linear ion trap geometry

Swap sorting time grows out of control

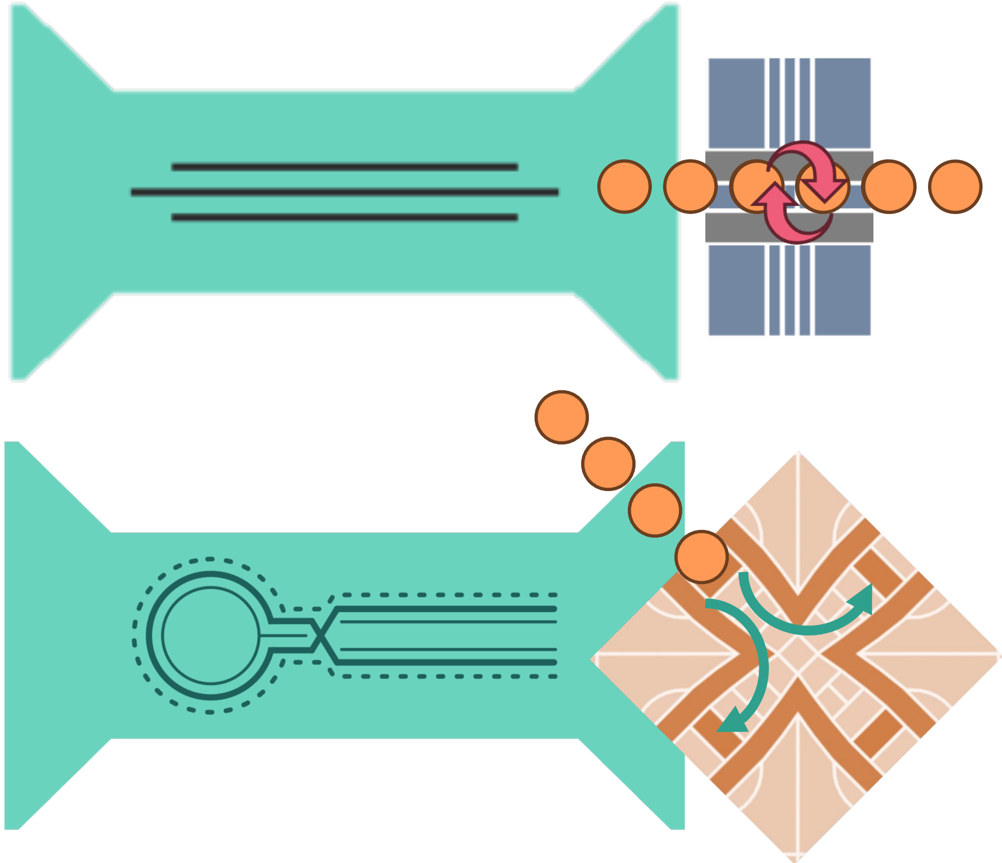


Junctions merge short linear traps

Swap sorting replaced by junction sorting

# Junctions speed up qubit routing

First commercial QCCD junction



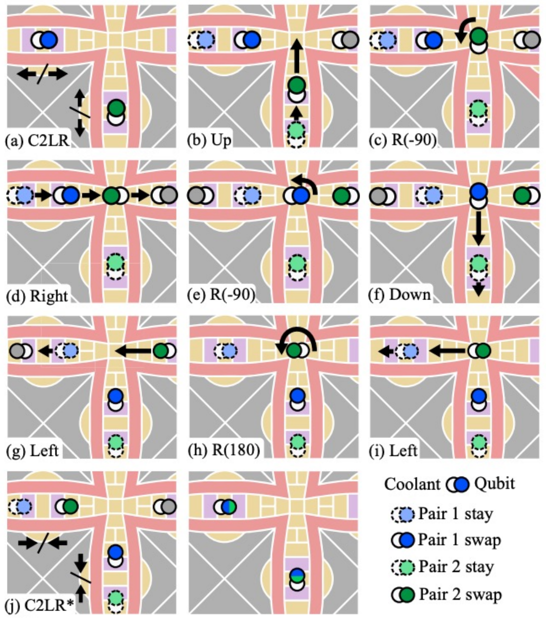
**Swap sorting is $O(N^2)$**

**Junction sorting is O(N)**

# Junctions scale to future systems

Quantinuum leading in ion trap junction design

First commercial QCCD junction




FEATURED IN PHYSICS | OPEN ACCESS

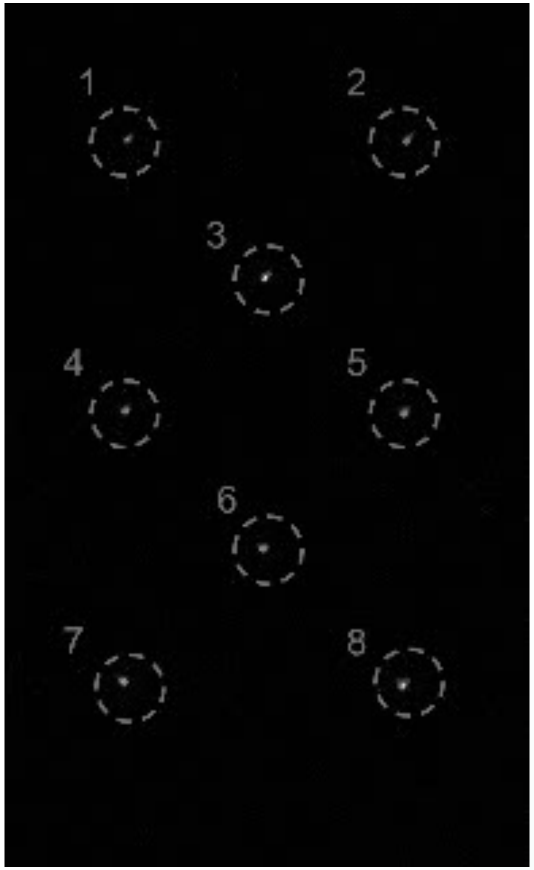
**Scalable Multispecies Ion Transport in a Grid-Based Surface-Electrode Trap**


Robert D. Delaney[1,*], Lucas R. Sletten[2,*], Matthew J. Cich[2], Brian Estey[1], Maya I. Fabrikant[1], David Hayes[1], Ian M. Hoffman[1], James Hostetter[2], Christopher Langer[1] *et al.*


Show more

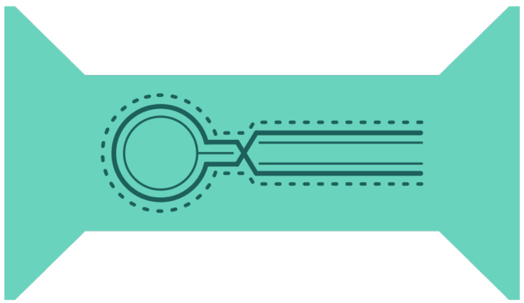

Phys. Rev. X **14**, 041028 – **Published 1 November, 2024**

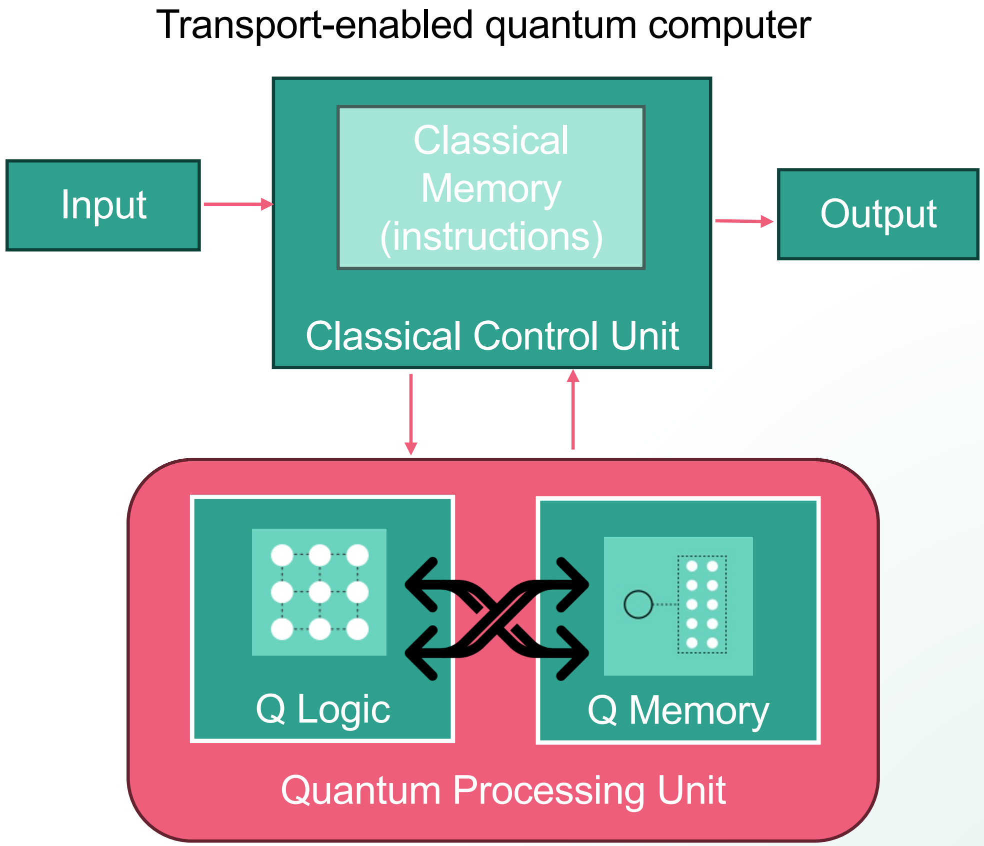
DOI: https://doi.org/10.1103/PhysRevX.14.041028

# A “2x" system

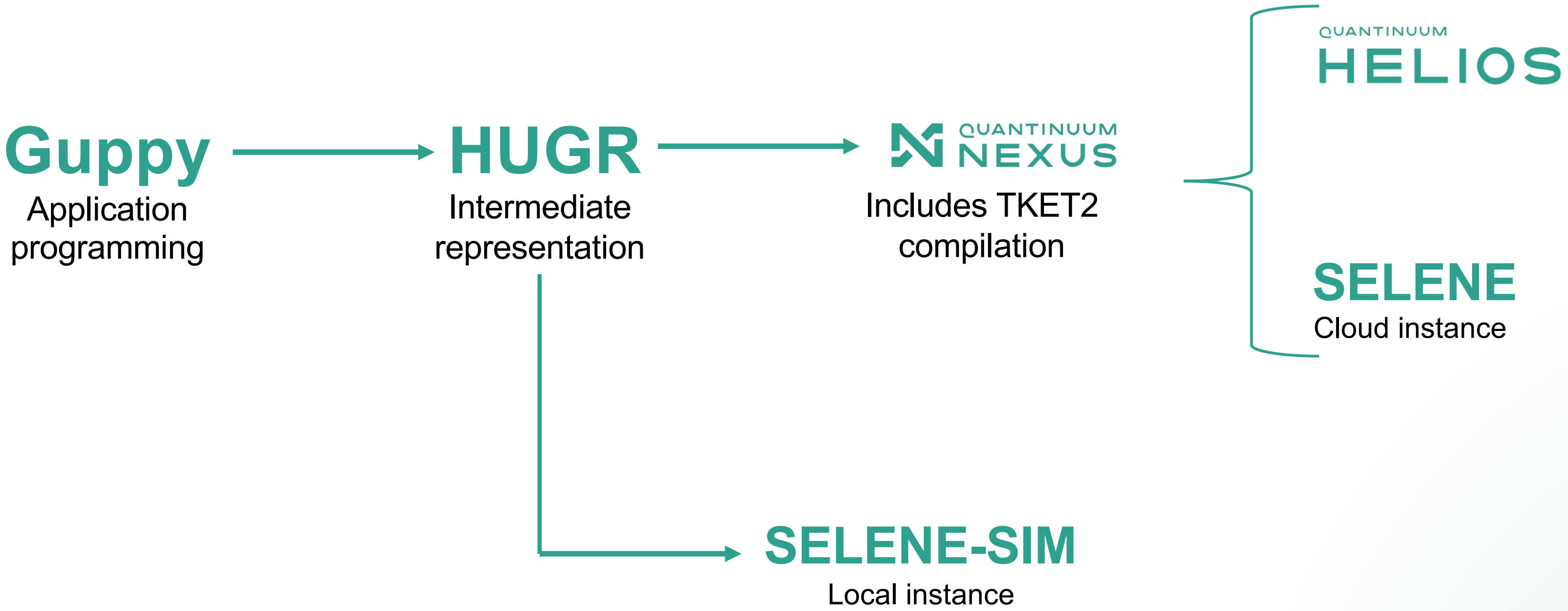
**Helios will offer roughly 2x <u>more</u> qubits with 2x <u>lower</u> two-qubit gate errors, while operating more than 2x <u>faster</u> than System Model H2.**






- 96 high fidelity $Ba^{+}$ qubits
- Junction speeds up on-the-fly qubit routing
- Scales to future fault-tolerant systems

# Quantinuum Next-Generation Software



# GUPPY

Quantum-first programming language, embedded in Python.

Get Started

```
pip install guppylang
```

- Arbitrary control flow
- Arbitrary classical compute
- Quantinuum native operations
- Automated system qubit resource management
- Static compiling and safety

```
from guppylang.decorator import guppy
from guppylang.std.quantum import qubit, cx, h

@guppy
def bell() -> tuple[qubit, qubit]:
    q0, q1 = qubit(), qubit()
    h(q0)
    cx(q0, q1)
    return q0, q1
```

```
from guppylang.std.quantum import measure
from guppylang.std.builtins import result

@guppy
def main() -> None:
    q0, q1 = bell()
    v0 = measure(q0)
    v1 = measure(q1)
    result("q0", v0)
    result("q1", v1)
```

```
hugr = guppy.compile_module()
```

```
from selene_sim.build import build
from selene_sim import Stim
from hugr.qsystem.result import QsysResult

runner = build(hugr)
shots = QsysResult(runner.run_shots(Stim(), n_qubits=2,
n_shots=10))
```

# Guppy Control Features

- For/While loops
- Arrays
- Lists
- Structures
- Generics
- Higher-order functions

```
from guppylang import guppy
from guppylang.std.quantum import qubit, toffoli, s, measure
from guppylang.std.quantum.functional import h

@guppy
def repeat_until_success(q: qubit, attempts: int) -> bool:
    """
    Repeat-until-success circuit for Rz(acos(3/5))
    from Nielsen and Chuang, Fig. 4.17.
    """
    for i in range(attempts):
        a, b = h(qubit()), h(qubit())
        toffoli(a, b, q)
        s(q)
        toffoli(a, b, q)
        if not (measure(h(a)) | measure(h(b))):
            result("rus_attempts", i)
            return True
    return False
repeat_until_success.check() # type check
```

# Our next generation quantum ecosystem

Built for applications in the post-NISQ era

### Cybersecurity
**Quantum Origin:** Enterprise-grade quantum computing-enable cryptographic solutions

### Quantum Chemistry
**InQuanto:** transforming the discovery of new materials and novel processes

### Quantum AI
Aiming to solve commercial and specific problems that cannot be solved using today's classical computers

### Ecosystem Platforms
Enables other partners to leverage the power of quantum via open-source access

### Guppy
Pythonic Domain-Specific programming embedded within Python | Open-source

### Nexus – Quantum Operating System
Complete software platform that allows developers to build and deploy algorithms with minimum effort and maximum flexibility

### TKET2
Retargetable Guppy program optimization whilst matching baseline TKET1 performance

Ecosystem Quantum Processors

### Quantinuum Systems
Quantum Computers

### Selene
A digital twin for Helios and beyond, supporting emulation, debugging and metrics estimation.

QNTM Current-gen | Third-party | QNTM Next-gen

# Access to Quantinuum Systems

https://www.quantinuum.com/

QUANTINUUM SYSTEMS

Purchase a subscription directly with Quantinuum to access our trapped-ion quantum computers, the world's leading quantum hardware

START WITH DIRECT ACCESS ↗

INQUANTO™

Perform quantum chemistry research with InQuanto, state of the art platform utilizing Quantinuum systems for complex molecular and materials simulations

START WITH AN INQUANTO LICENSE ↗

Microsoft Azure

Purchase a subscription on Microsoft Azure with access to Quantinuum systems. Researchers can apply for an Azure Quantum Credits Grant worth $10,000

START WITH MICROSOFT AZURE ↗

**Oak Ridge National Laboratory**

Researchers in the United States may apply for a quantum credits grant on Quantinuum systems through their Quantum Computing User Program (QCUP)

START WITH ORNL ↗

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## Technical Documentation

Explore the documentation, tutorials, and knowledge articles for our software, toolkits and H-Series hardware at the links below.

docs.quantinuum.com