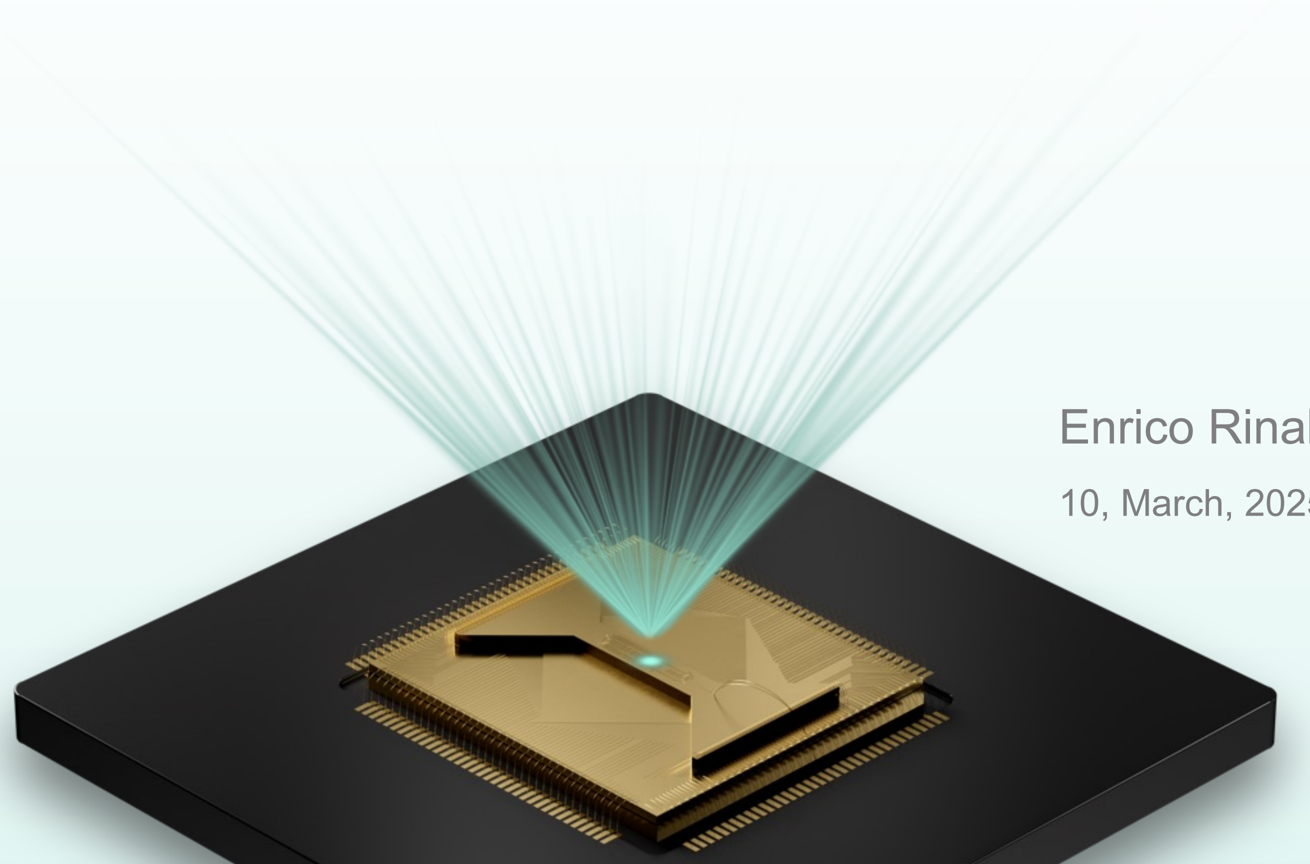
Quantinuum Systems with NVIDIA CUDA-Q



Enrico Rinaldi and Kentaro Yamamoto

10, March, 2025 @ SCA25, Singapore

Quantinuum at a glance

550+
employees across 8 offices

420+
PhDs and Masters

Largest concentration of quantum experts outside of academia

130+
global patents

~200
scientific papers

Cross-domain subject matter expertise:

Chemistry | Materials science
Artificial intelligence | Machine learning
Condensed matter | Cybersecurity
Encryption | Finance

QUANTINUUM

Our business model is

differentiated and resilient: *a true full stack*

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 | Open-sourced

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

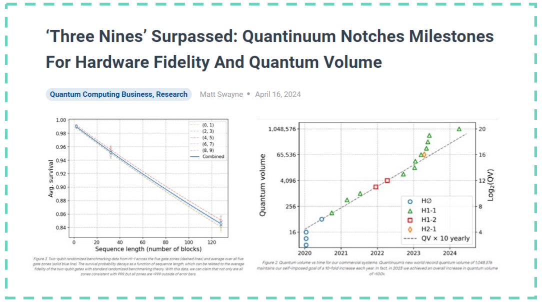
Ecosystem Quantum Processors

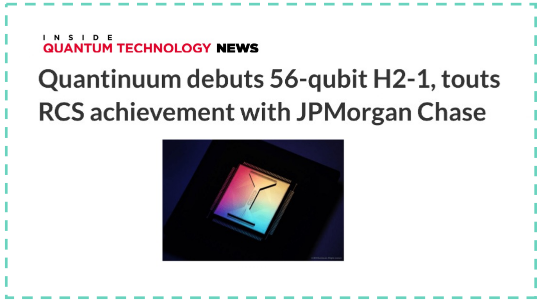
Quantinuum Systems
Quantum Computers

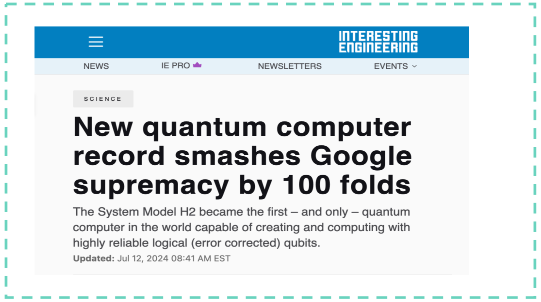
Ecosystem Quantum Processors

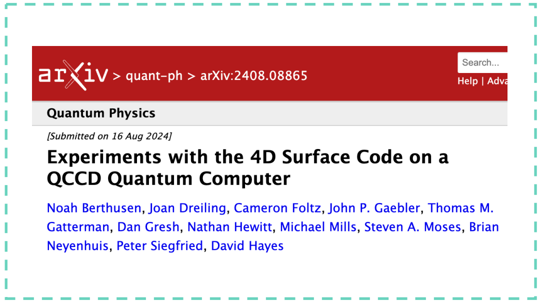
Quantinuum Products | Partner/Ecosystem Products

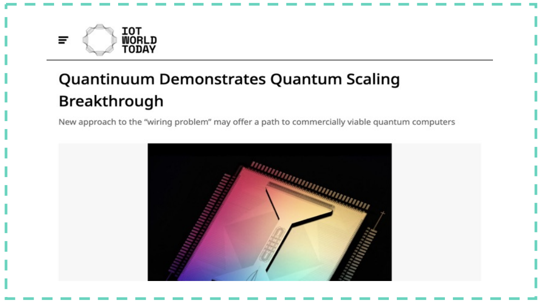
Leading research with our partners…



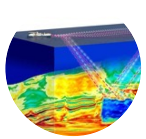






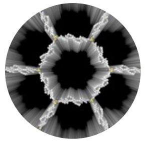


BMW, Airbus
Fuel cell catalytic reactions

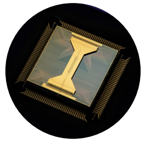


BP
Seismic imaging

HSBC
Fraud detection

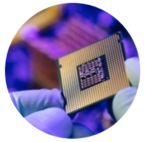


TotalEnergies
Carbon capture materials



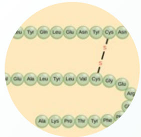
Riken
Integrating HPC with quantum

Singapore
Computational biology



JSR
Semiconductor defects

Thales
Stronger cryptography



AMGEN
QNLP for peptide binding

JPMorgan Chase
Financial Operations

Honeywell
Efficient synthesis of refrigerants

Equinor
Ammonia catalysis

QUANTINUUM

Our roadmap

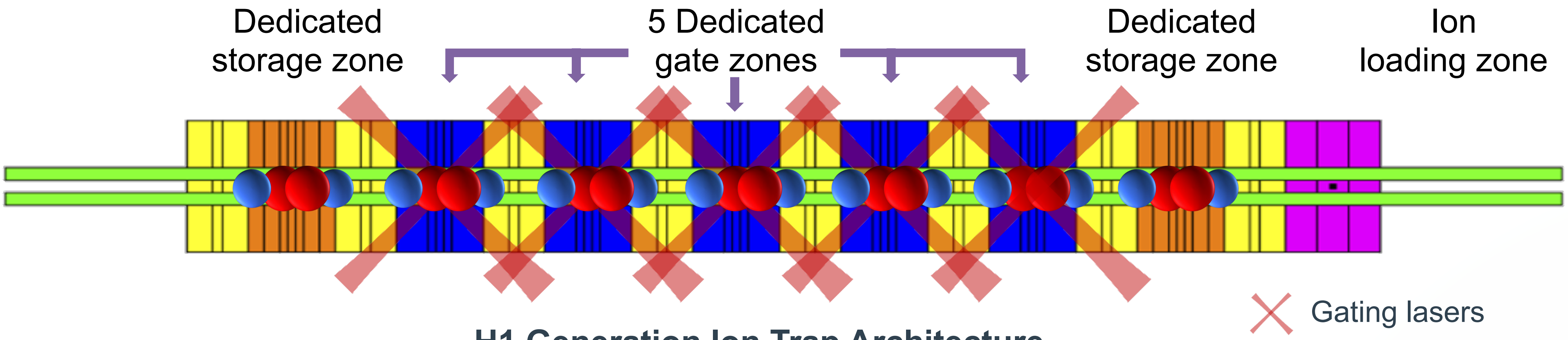
to universal, fault-tolerant quantum computing

	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	1×10^{-3}	1×10^{-3}	$< 5 \times 10^{-4}$	$< 2 \times 10^{-4}$	1×10^{-4}
LOGICAL QUBITS		> 12	~ 50	~ 100	100's
LOGICAL ERROR RATES		1×10^{-3}	$< 10^{-4}$	$\sim 10^{-5}$	1×10^{-5} to 1×10^{-10}*

*analysis based on recent literature in new, novel error correcting codes predict that error could be as low as 1E-10 in Apollo (ref: arXiv:2403.16054, arXiv:2308.07915).

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

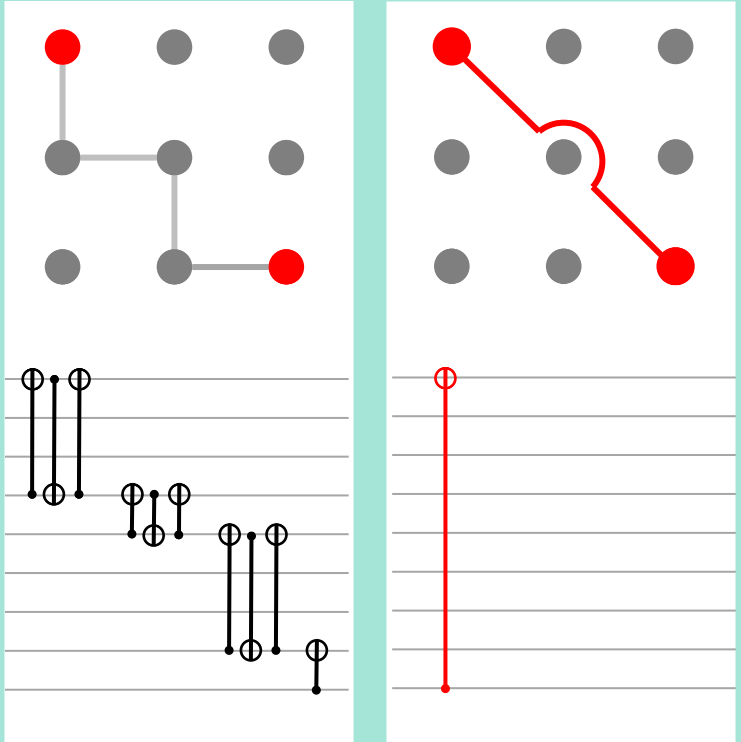
Cooling ions provide mid-circuit cooling, maintaining circuit fidelity throughout circuit

$^{138}Ba^+$ Cooling ion

QCCD Architecture Differentiating Features

All-to-All Connectivity

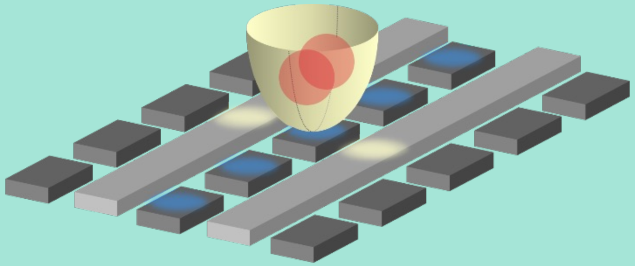
Nearest Neighbor | All-to-All



Significantly lower # of gates

High-Fidelity Gates

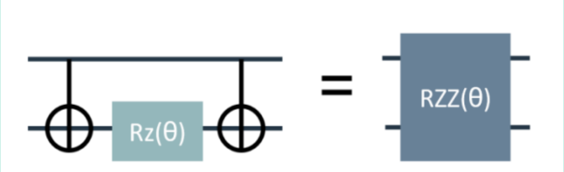
Isolated Gates = Scalable Gates

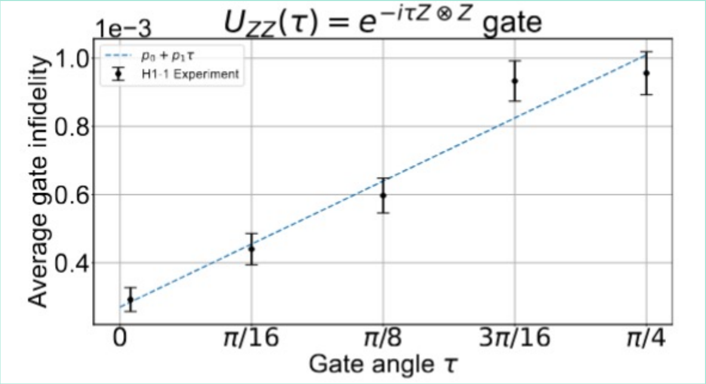


1Q fidelity	> 99.997%
2Q fidelity	> 99.87%
State preparation and measurement	> 99.7%
Measurement cross-talk error	< 0.01%
Memory error per qubit at average depth-1 circuit	< 0.04%

Arbitrary Angle two-qubit gate

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





Quantum Phase Estimation

On Quantinuum Systems with Nvidia CUDA-Q

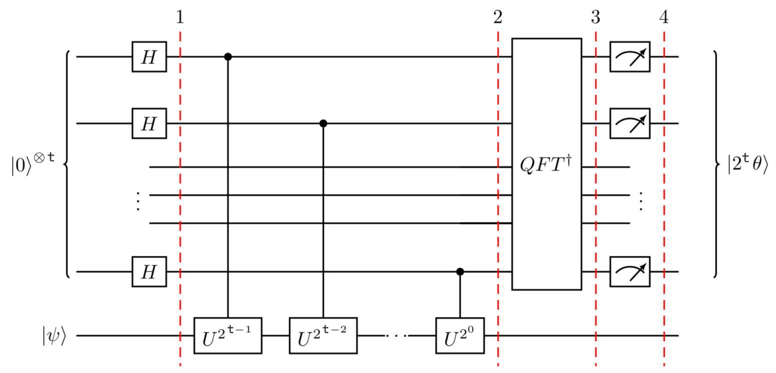
Quantum Phase Estimation (QPE)

An important subroutine of many quantum algorithms (e.g., Shor's algorithm and quantum chemistry).

- QPE infers eigenphase ϕ of a given unitary U and its eigenstate $|\phi\rangle$ satisfying

$$U|\phi\rangle = e^{i\phi}|\phi\rangle$$

- QPE is scalable. For the desired precision ε:
  - QPE: depth $O(1/\varepsilon)$ circuit with $O(1)$ measurements
  - Pauli meas.: depth $O(1)$ circuit with $O(1/\varepsilon^2)$ measurements



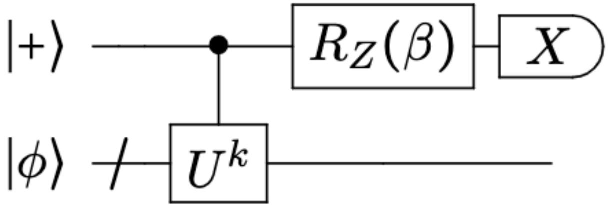
Deeper circuit → higher precision

Single ancilla QPE

Classical signal processing replaces quantum Fourier transform (QFT) in the canonical QPE.

How does it work?

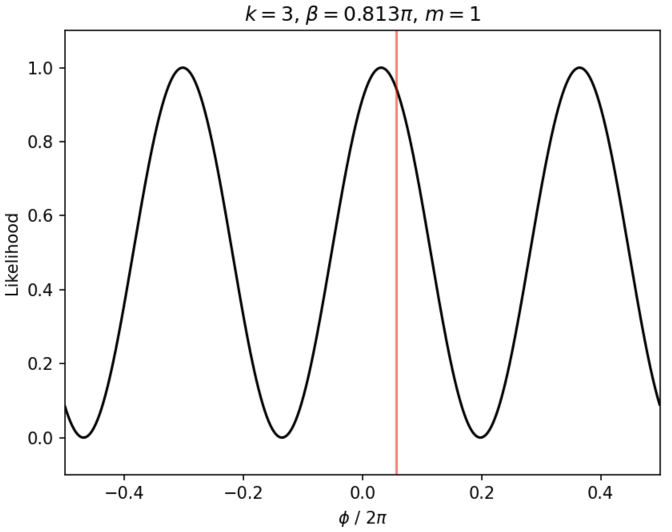
- Run a **single-ancilla** QPE circuit multiple times



Parameters: $k \in \mathbb{N}, \beta \in [0, 2\pi)$

- The probability to measure $m \in \{0, 1\}$ is expressed as

$$P(m|\phi; k, \beta) = \frac{1 + \cos(k\phi + \beta - \pi m)}{2}$$



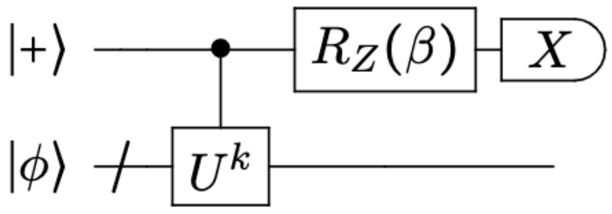
- **Classically** post-process the outcomes $\{m\}$ to infer the phase ϕ

QUANTINUUM

Information theoretic QPE [1] as an example

Basic stochastic QPE algorithm using single-ancilla QPE circuits

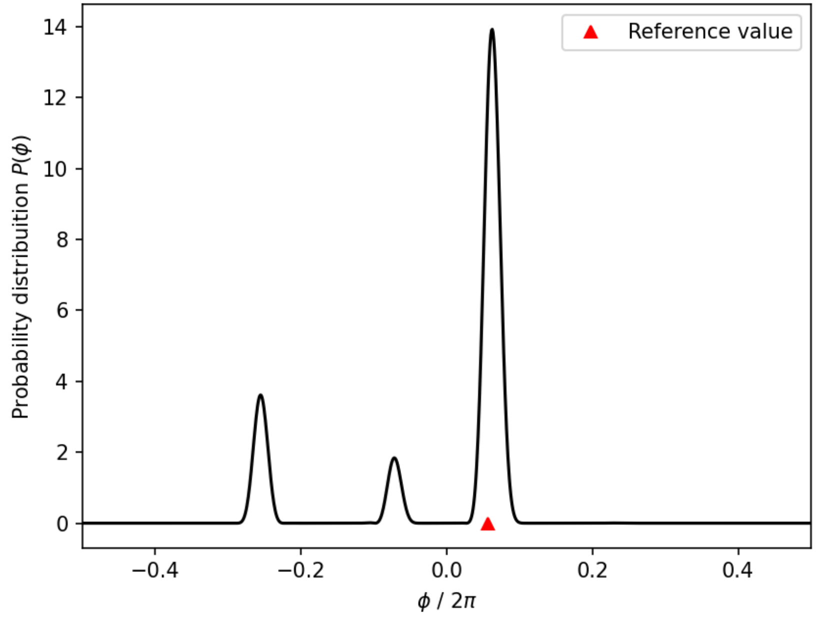
- Randomly generate parameters $k \in [1, k_{\max}]$ and $\beta \in [0, 2\pi)$
- Build the QPE circuit with those parameters to measure the ancilla
- Miximize the likelihood to obtain the resulting bit string



Parameters: $k \in \mathbb{N}, \beta \in [0, 2\pi)$

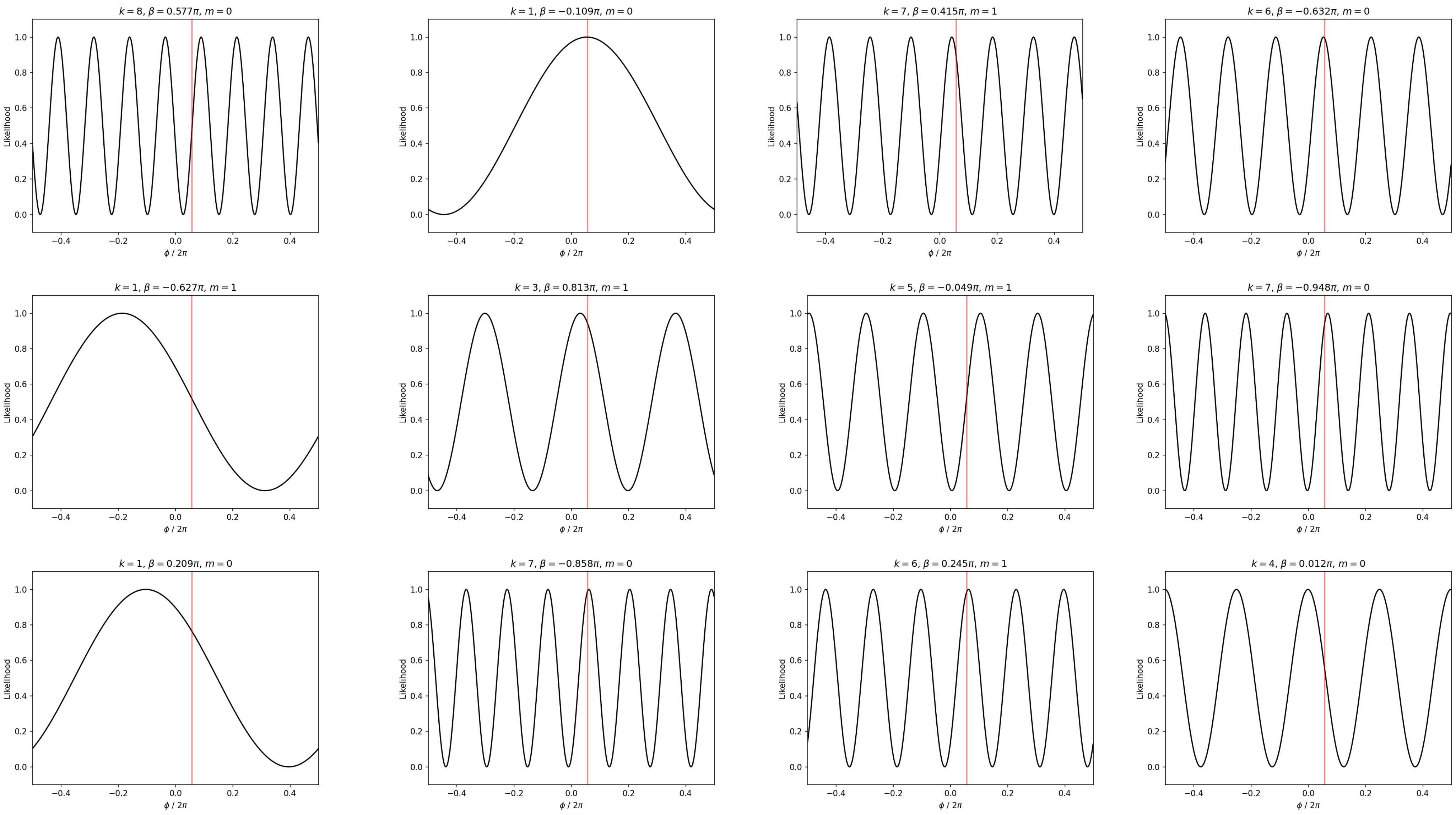
Maximum likelihood estimate

$$P(\boldsymbol{m}|\phi; \boldsymbol{k}, \boldsymbol{\beta}) = \prod_{j}^{N} P\left(m_j|\phi; k_j, \beta_j\right)$$



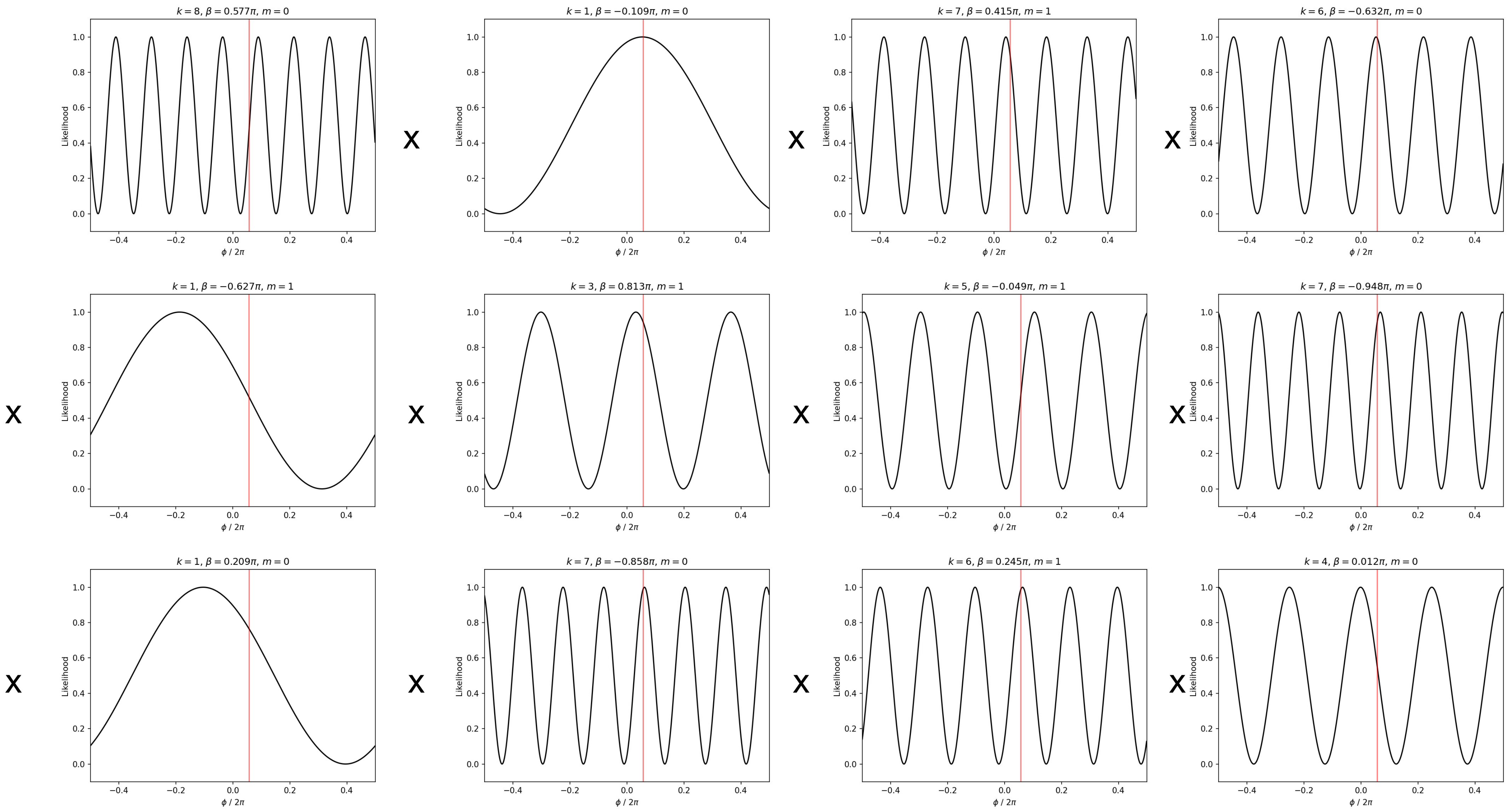
[1] K. M. Svore *et al.*, Quantum Inf. Comput. **14**, 306 (2014).

$$P(m|\phi; k, \beta) = \frac{1 + \cos(k\phi + \beta - \pi m)}{2}$$



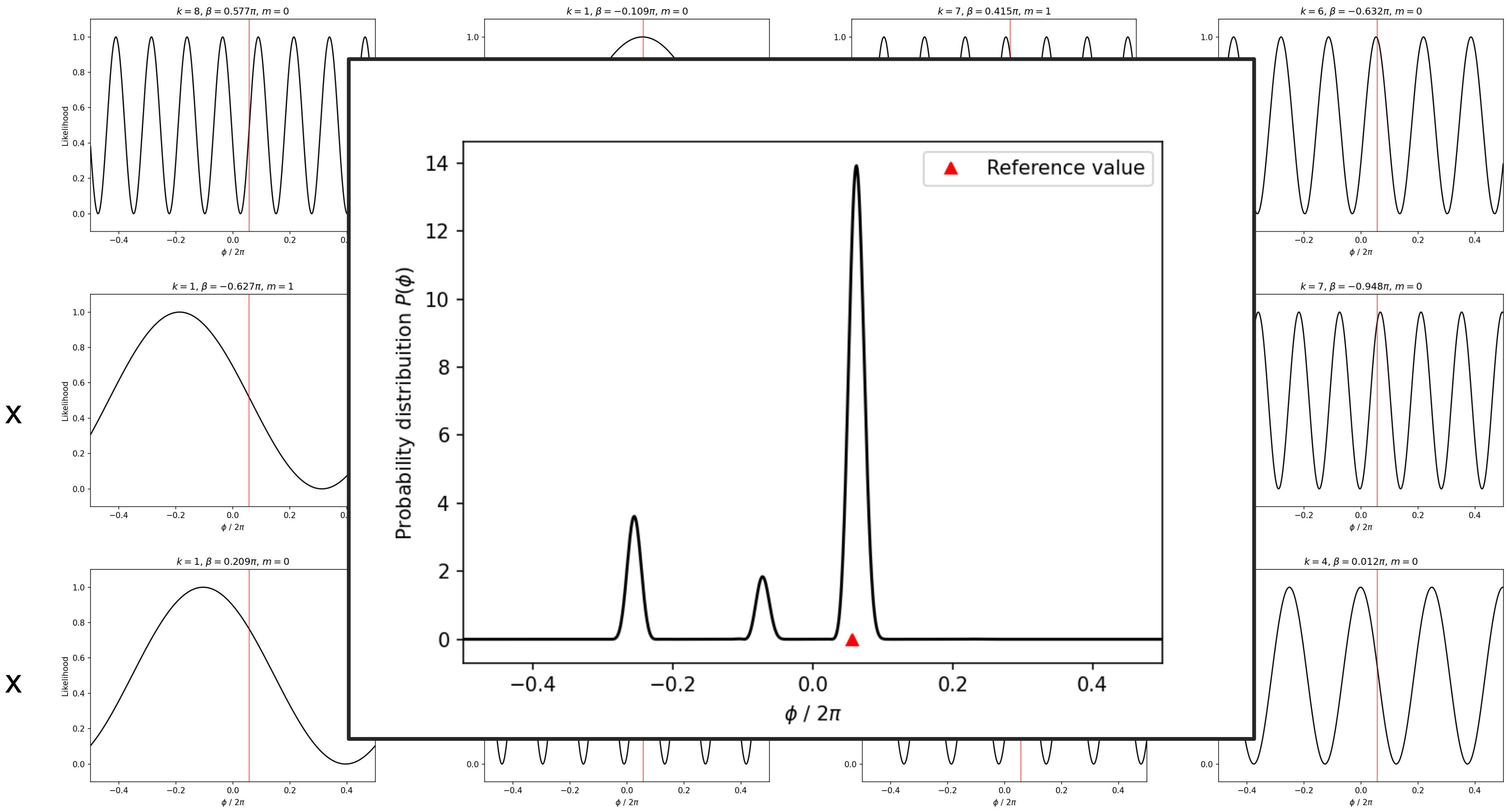
QUANTINUUM

$$P(\boldsymbol{m}|\phi;\boldsymbol{k},\boldsymbol{\beta}) = \prod_{j}^{N} P(m_j|\phi;k_j,\beta_j)$$



QUANTINUUM

$$P(\boldsymbol{m}|\phi;\boldsymbol{k},\boldsymbol{\beta}) = \prod_{j}^{N} P\left(m_j\middle|\phi;k_j,\beta_j\right)$$

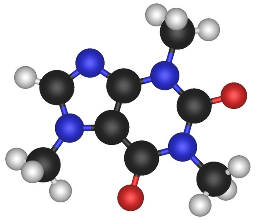


QUANTINUUM

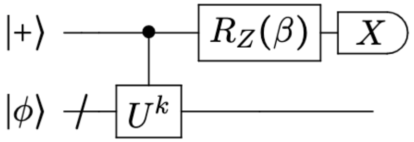
Overview of QPE experiments for chemistry

Bayesian QPE workflow:

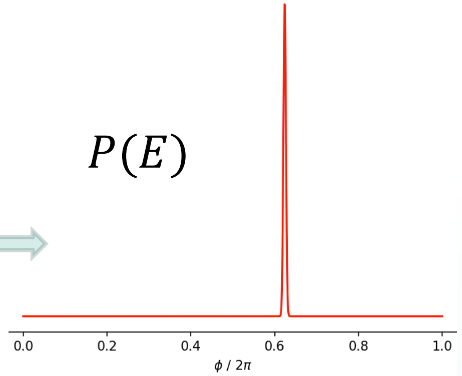
Bayesian update of $P(E)$



$U = e^{-\mathrm{i}Ht}$



Parameters: $k \in \mathbb{N}, \beta \in [0, 2\pi)$



Choose a molecule

Build a QPE circuit

Hardware execution

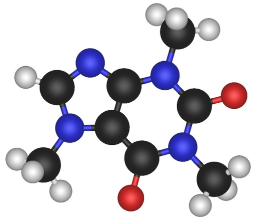
Estimate the energy

QUANTINUUM

Overview of QPE experiments for chemistry

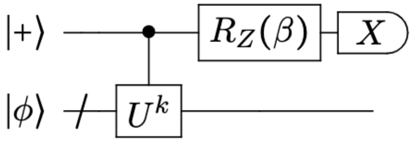
Bayesian QPE workflow:

Bayesian update of $P(E)$



Choose a molecule

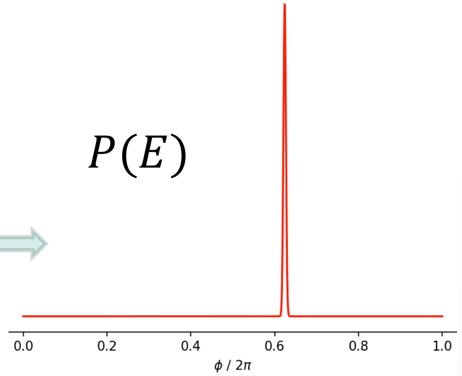
$U = e^{-\mathrm{i}Ht}$



Parameters: $k \in \mathbb{N}, \beta \in [0, 2\pi)$

Build a QPE circuit

Hardware execution



Estimate the energy

Encoding

QEC/QED

Interpretation

Logical qubits
by the QEC/QEC code

QEC = (quantum error **correction**)

QED = (quantum error **detection**)

Error correction is required to implement QPE

Quantum error correction

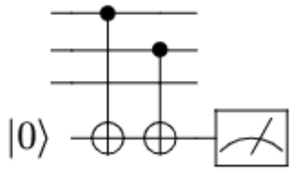
Detect, identify, and correct the error by exploiting the redundancy.

- Shor's $[\![3,1,1]\!]$ code for example:
    - The encoded states are "stabilized" by $S = \{ZZI, IZZ\}$:

$$|\bar{0}\rangle = |000\rangle,\ |\bar{1}\rangle = |111\rangle, \quad \bar{X} = XXX,\ \bar{Z} = ZZZ = ZII \text{ (up to stabilizer)}$$

    - The error may be detected by the syndrome measurements:

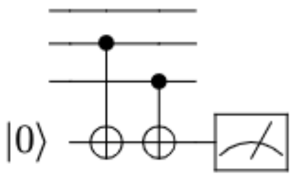
ZZI sydrome:



$0 \rightarrow |00?\rangle$ or $|11?\rangle$

$1 \rightarrow |10?\rangle$ or $|01?\rangle$ error

IZZ sydrome:



$0 \rightarrow |?00\rangle$ or $|?11\rangle$

$1 \rightarrow |?01\rangle$ or $|?10\rangle$ error

Decoding the error by the lookup table

$ZZI \setminus IZZ$	0	1
0	III	IIX
1	XII	IXI

X error can be detected, but not *Z*

Build "logical qubits" with quantum error detection code

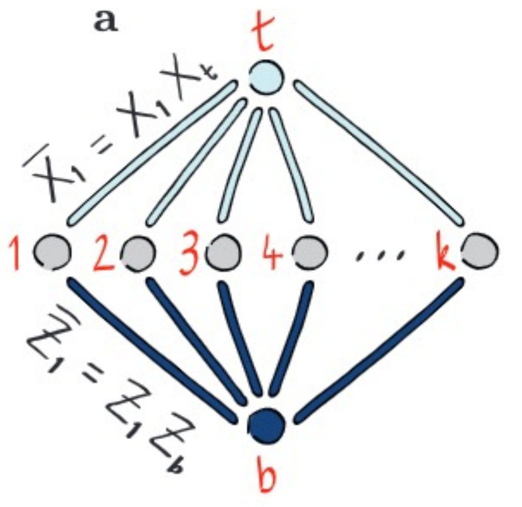
Improve the logical fidelity at the cost of the shot overhead by post-processing measurement outcomes.

Employ $[\![n+2, n, 2]\!]$ error detection code (**Iceberg code)** [1]

- Add two qubits (*t* and *b*) to introduce redundancy for error detection. Stabilizers are:

$$S_X = X_b X_1 \cdots X_n X_t, \qquad S_Z = Z_b Z_1 \cdots Z_n X_t$$

- Any **weight-one errors may be detected** by exploiting the redundancy.
- The shot is discarded when an error is detected.
- Hardware experiments have been done on Quantinuum devices [1,2,3]

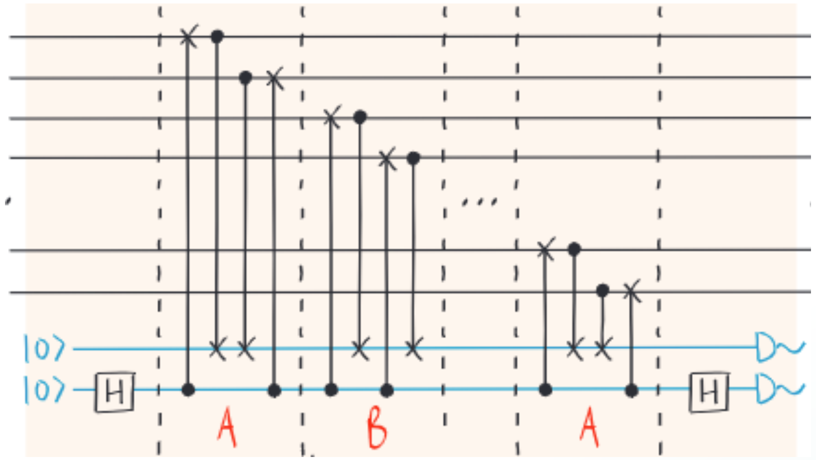


[1] C. N. Self *et al.*, Nat. Phys. **20**, 219 (2024).
[2] K. Yamamoto *et al.*, Phys. Rev. Res. **6**, 013221 (2024).
[3] Z. He *et al.*,, arXiv:2409.12104.

Error detection code tailored to Quantinuum hardware

Exploit the unique features of the Quantinuum hardware stack

- All-to-all connection
  - Ancilla qubits for error detection are connected to all the data qubits.
- Mid-circuit measurement and qubit reuse
  - Recycle the ancilla qubits for the syndrome measurements.
- Conditional logic
  - Early exit if an error is detected.



Syndrome measurement
(Mid-circuit error detection)

All these features will also be useful for quantum error correction.

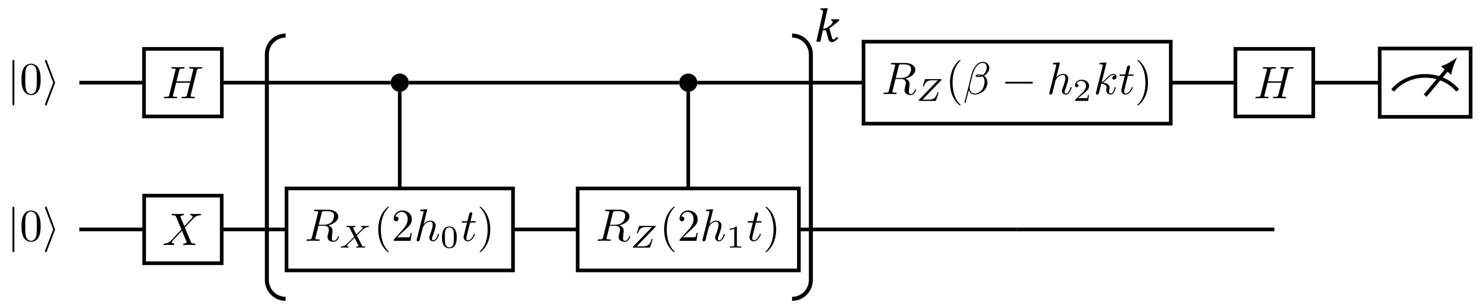
Demonstration

QPE with quantum error detection on Quantinuum backends

- Take a one-qubit Hamiltonian representing a hydrogen molecule:

$$H = h_0 X + h_1 Z + h_2 I$$

- Use the information theory QPE (maximum likelihood estimate)



- Use the $[\![4, 2, 2]\!]$ quantum error detection (iceberg code) to encode the logical circuit

- Execute this with CUDA-Q on Quantinuum backends

Quantinuum Documentation

Demo Time

SCA25-NVIDIA-Quantum-Workshop GitHub

The future of computing is here:

Where quantum and classical merge
to explore new use cases.

CUDA-Q, NVIDIA's cutting-edge quantum-classical hybrid platform, seamlessly integrates with **Quantinuum's industry-leading quantum hardware**, unlocking computational capabilities for scientific discovery, optimization, and AI.

Sign up here

to apply for promotional access

Seamless Hybrid Computing
Leverage CUDA-Q to build, optimize, and deploy quantum-classical workloads effortlessly.

Superior Quantum Performance
Run quantum circuits on Quantinuum's high-fidelity trapped-ion processors, delivering the accuracy and flexibility needed for real-world applications.

Accelerate Innovation
From materials science to financial modeling, push the boundaries of what's possible with the combination of CUDA-Q and Quantinuum.

QUANTINUUM

QUANTINUUM