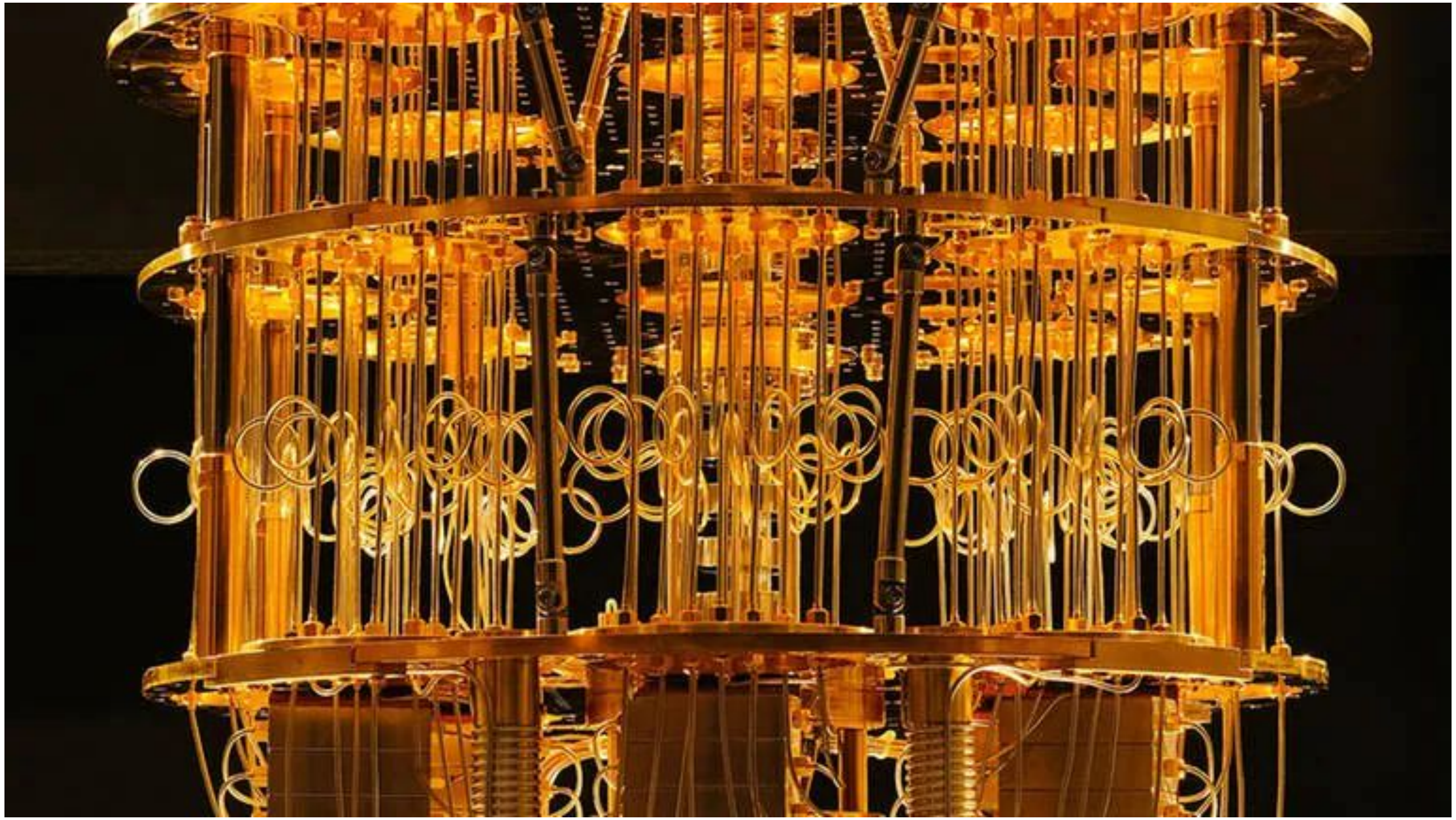
Feature Talk: Quantum Computing



Source: [1]

FTX Meeting

David Spataro
23/1/2024

HELMHOLTZ

Applications

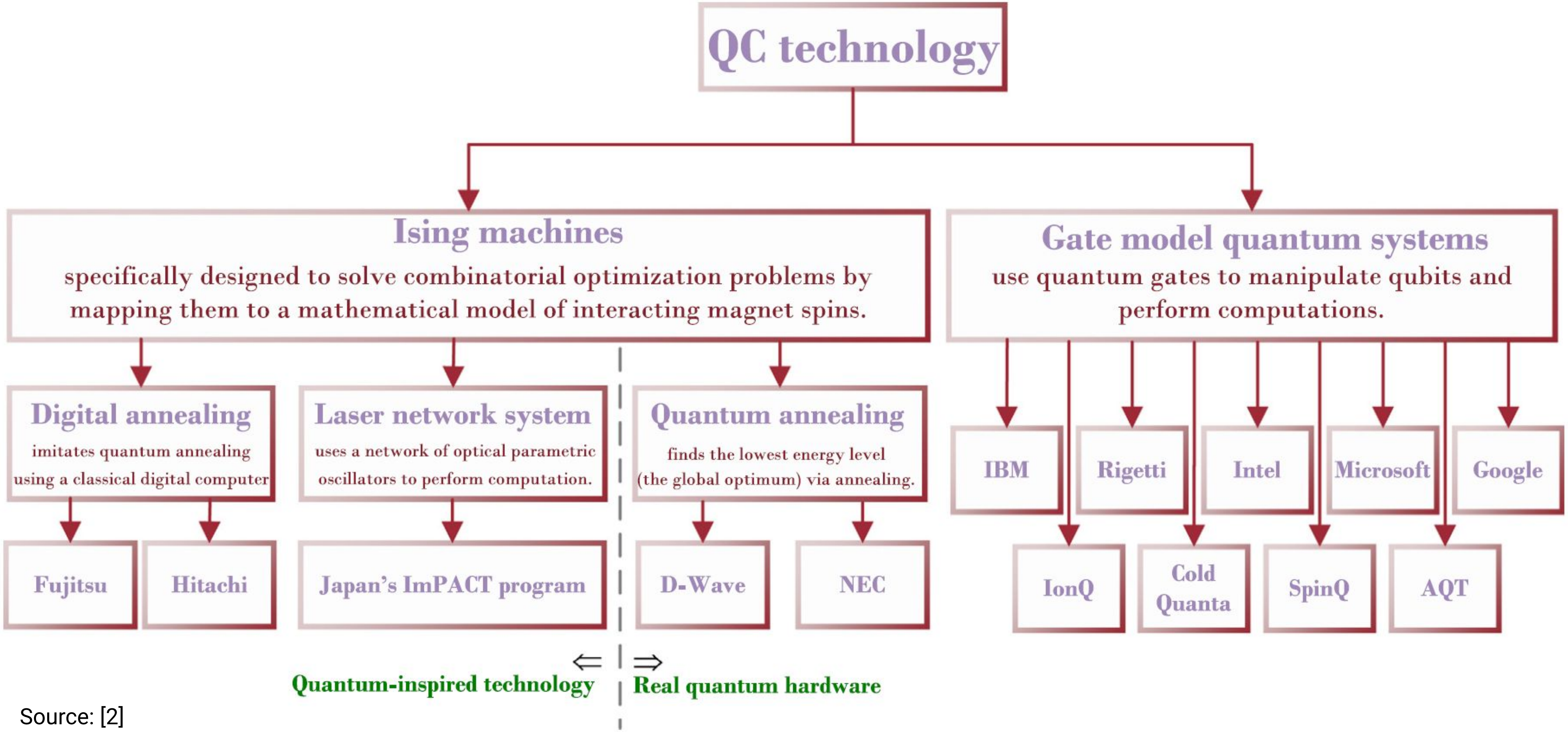
- **Polynomial-Time Algorithms** → Shor
- **Search** → Grover
- **Optimisation** → Variational Quantum Eigensolver, Annealing, …

…

- **Cryptography** → Quantum Key Distribution
- **Climate Science** → Weather forecast
- **Drug Discovery and Materials Science** → Protein folding, batter development
- **Machine Learning and AI** → Quantum (enhanced) Machine Learning
- **Finance** → Portfolio optimisation
- **Quantum Computing in HEP** → Lattice Gauge Theories, reconstruction algorithms, simulation, …

…

Technologies



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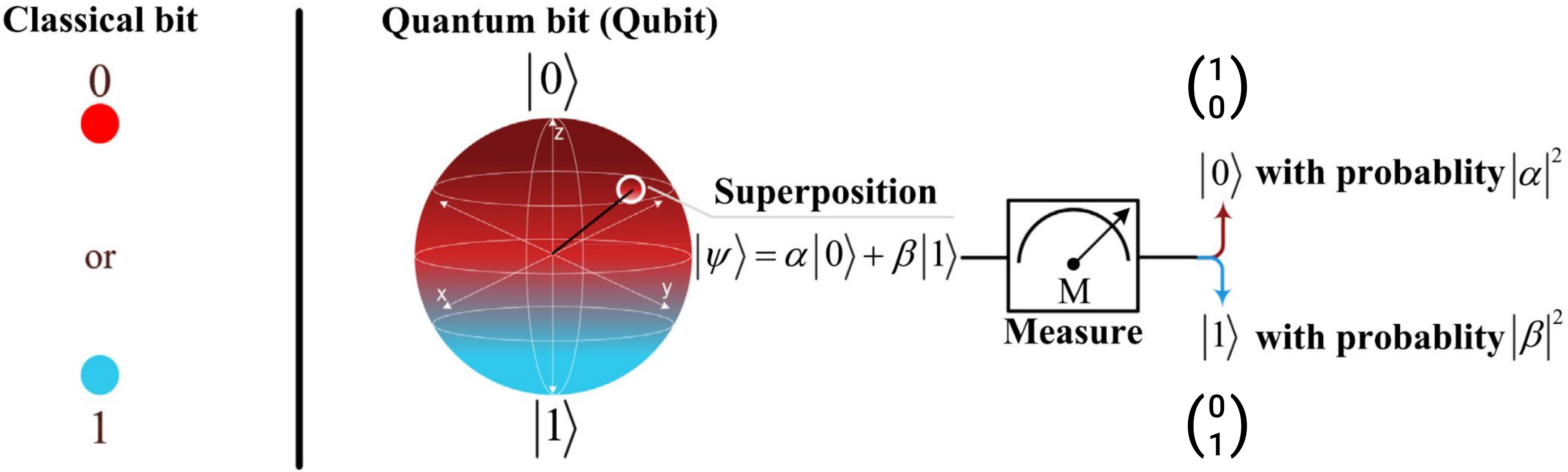
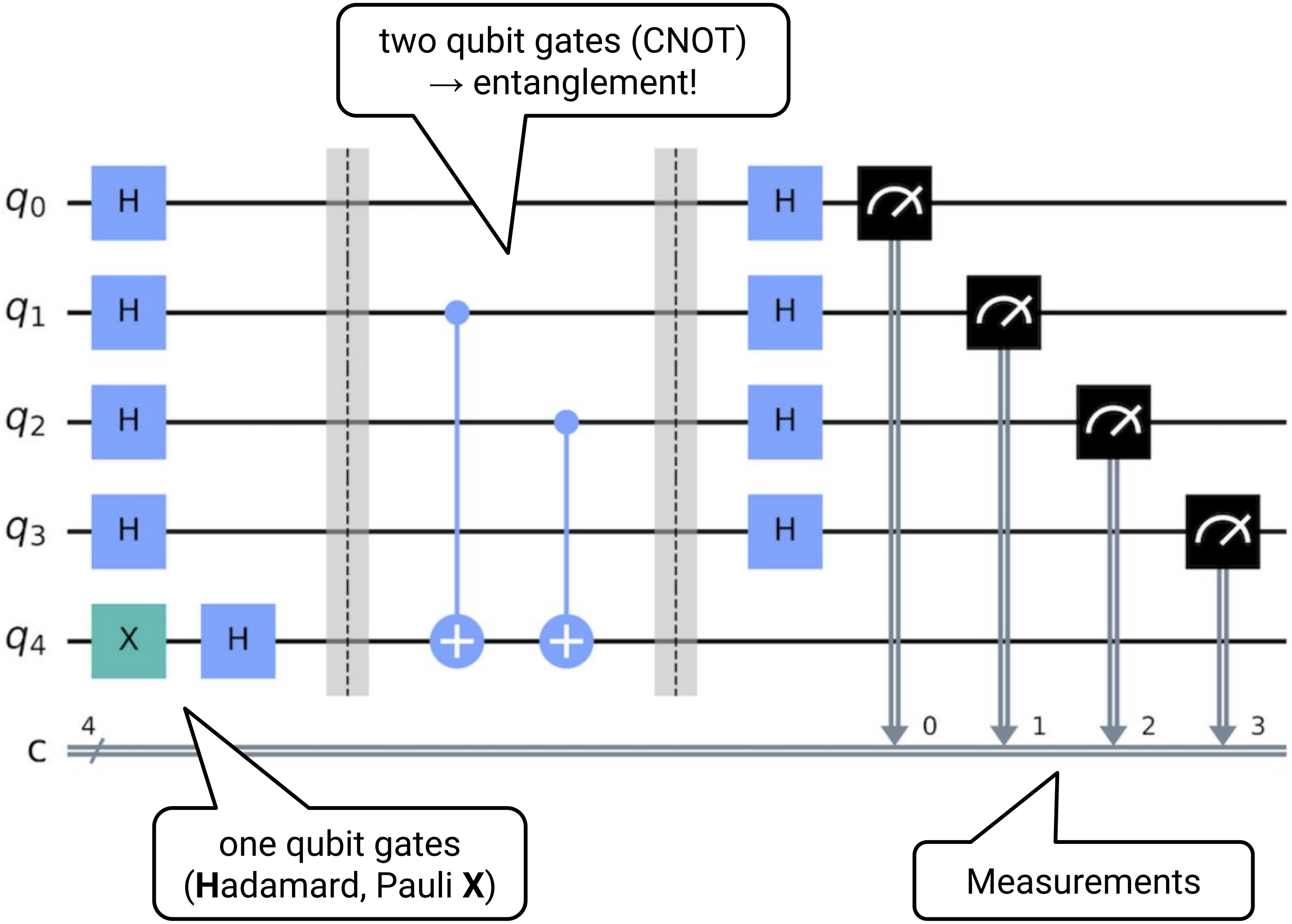
Qubits



Source: [2]

Quantum circuits

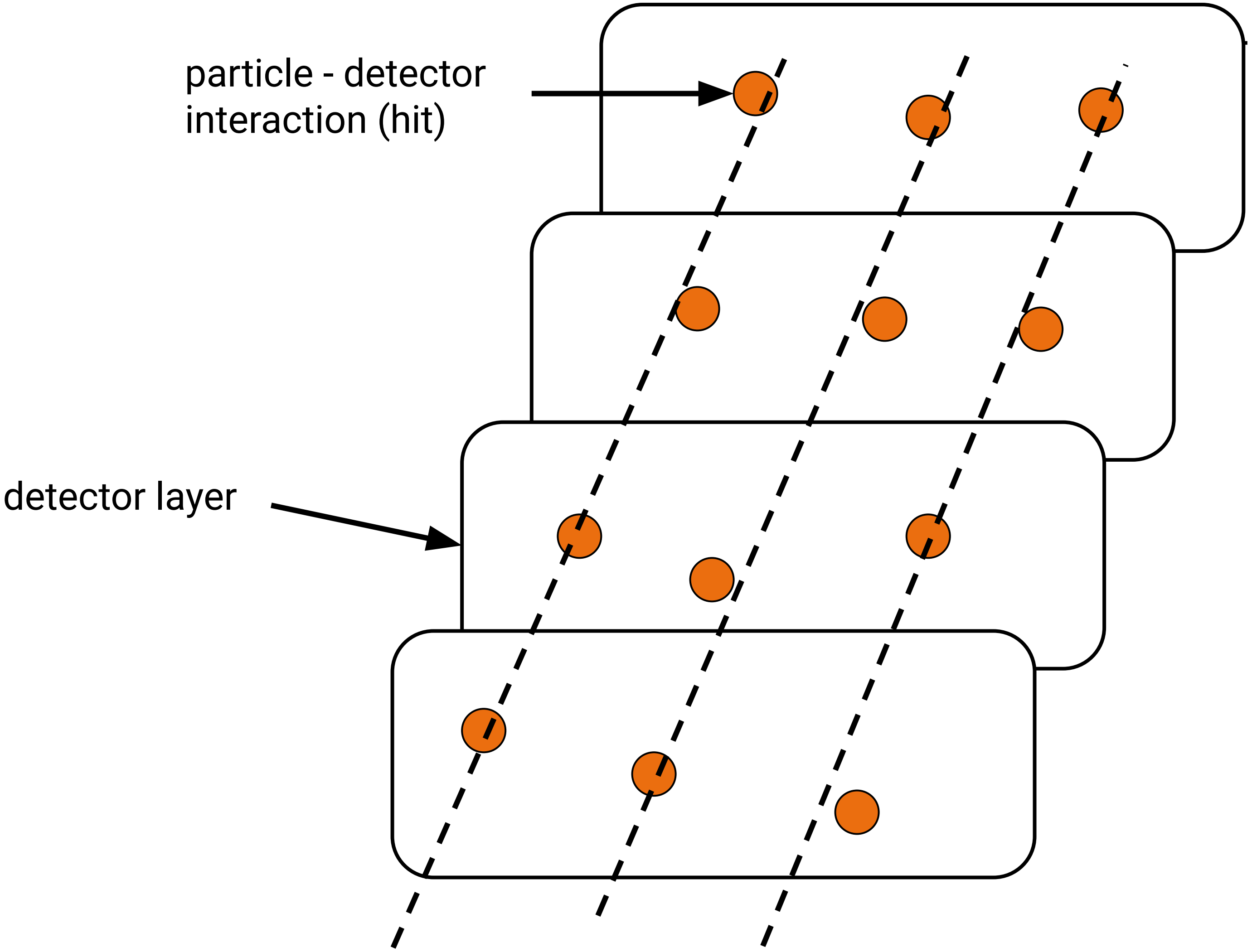


Operator	Gate(s)		Matrix
Pauli-X (X)	**X**	$\oplus$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	**Y**		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	**Z**		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	**H**		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	**S**		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	**T**		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)	$\bullet$ / $\oplus$		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

Source: [3]

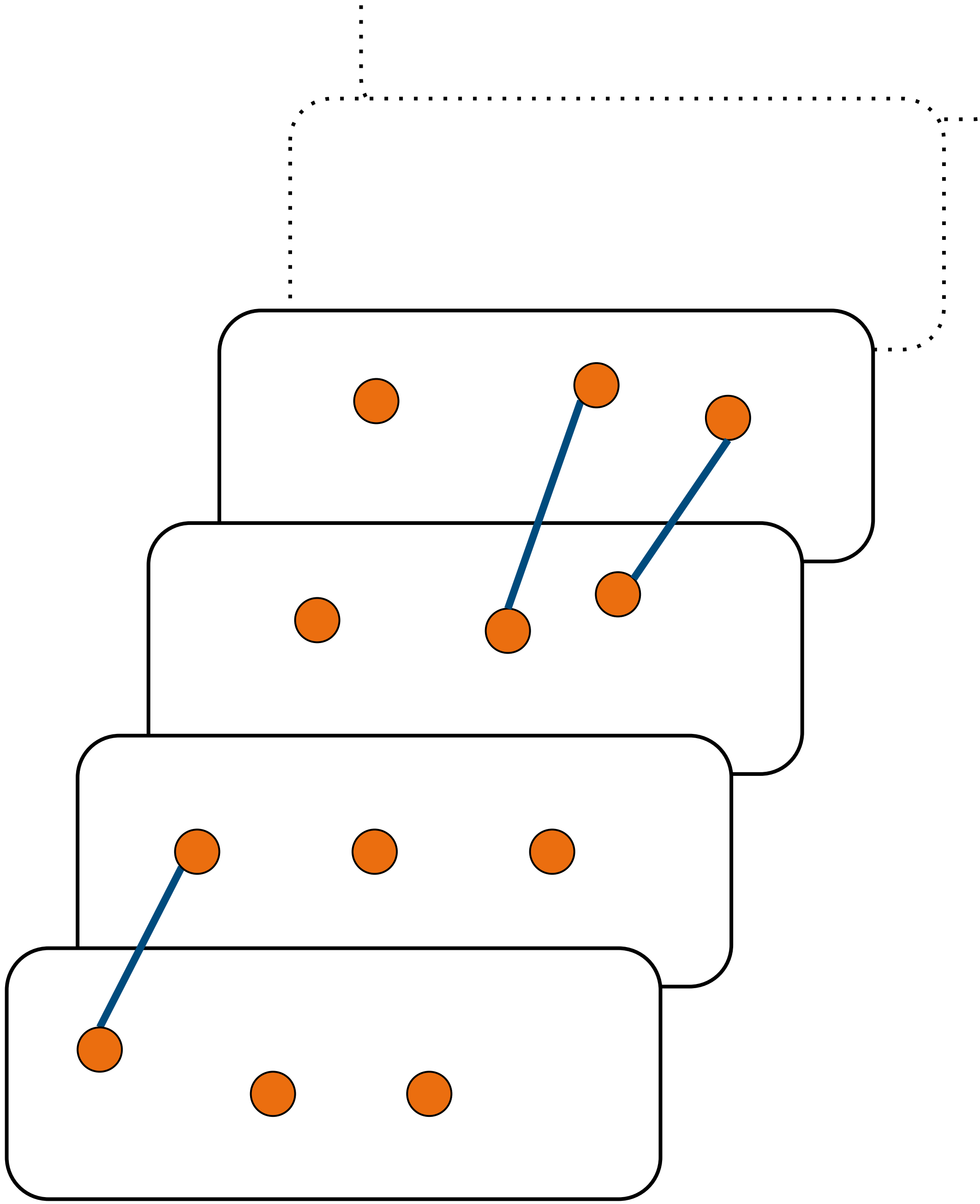
Application: Pattern Recognition for particle tracking using quantum algorithms

Procedure: Connect hits from different detector layers and fit the space points to reconstruct particle tracks



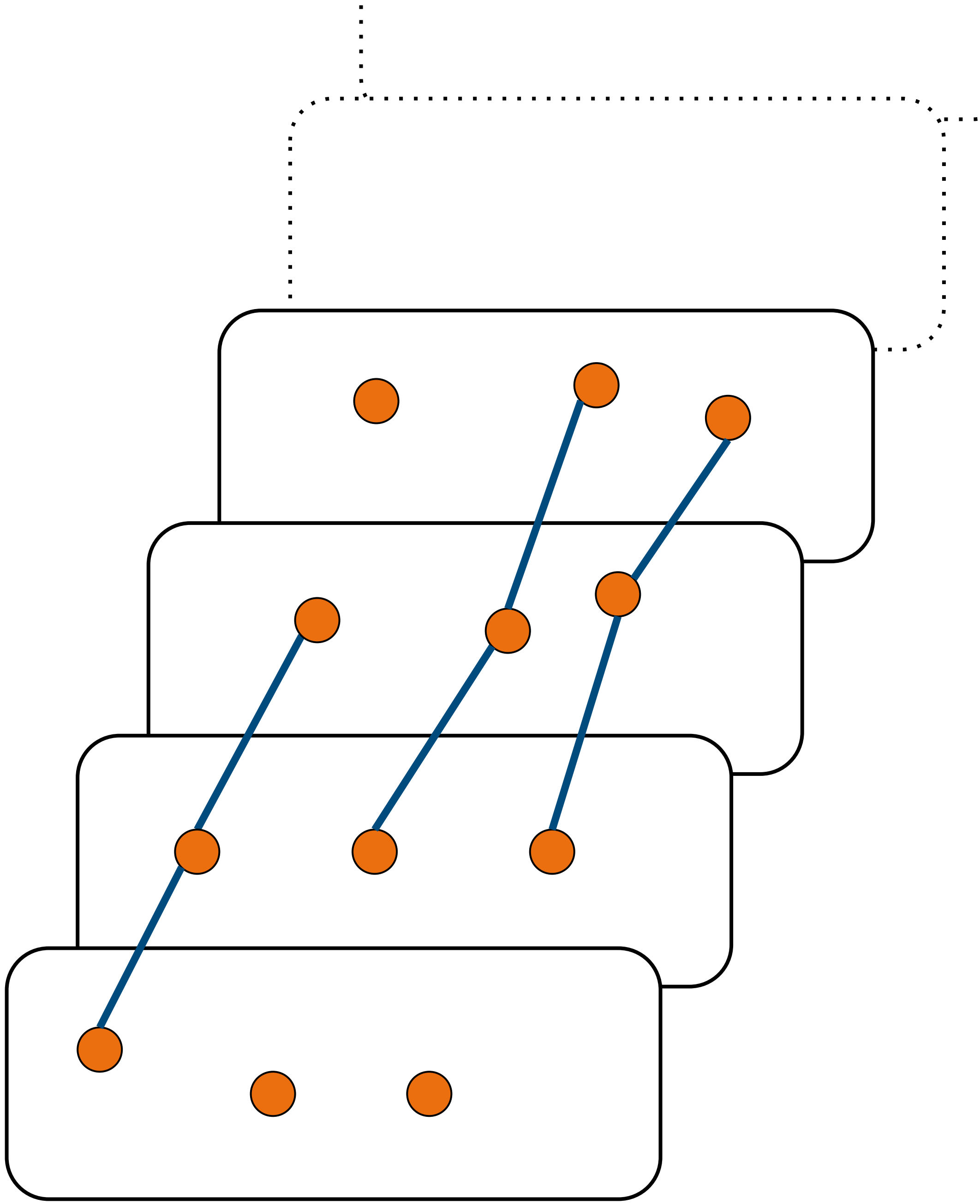
Pattern Recognition

- **Doublets** are created by combining hits from successive layers



Pattern Recognition

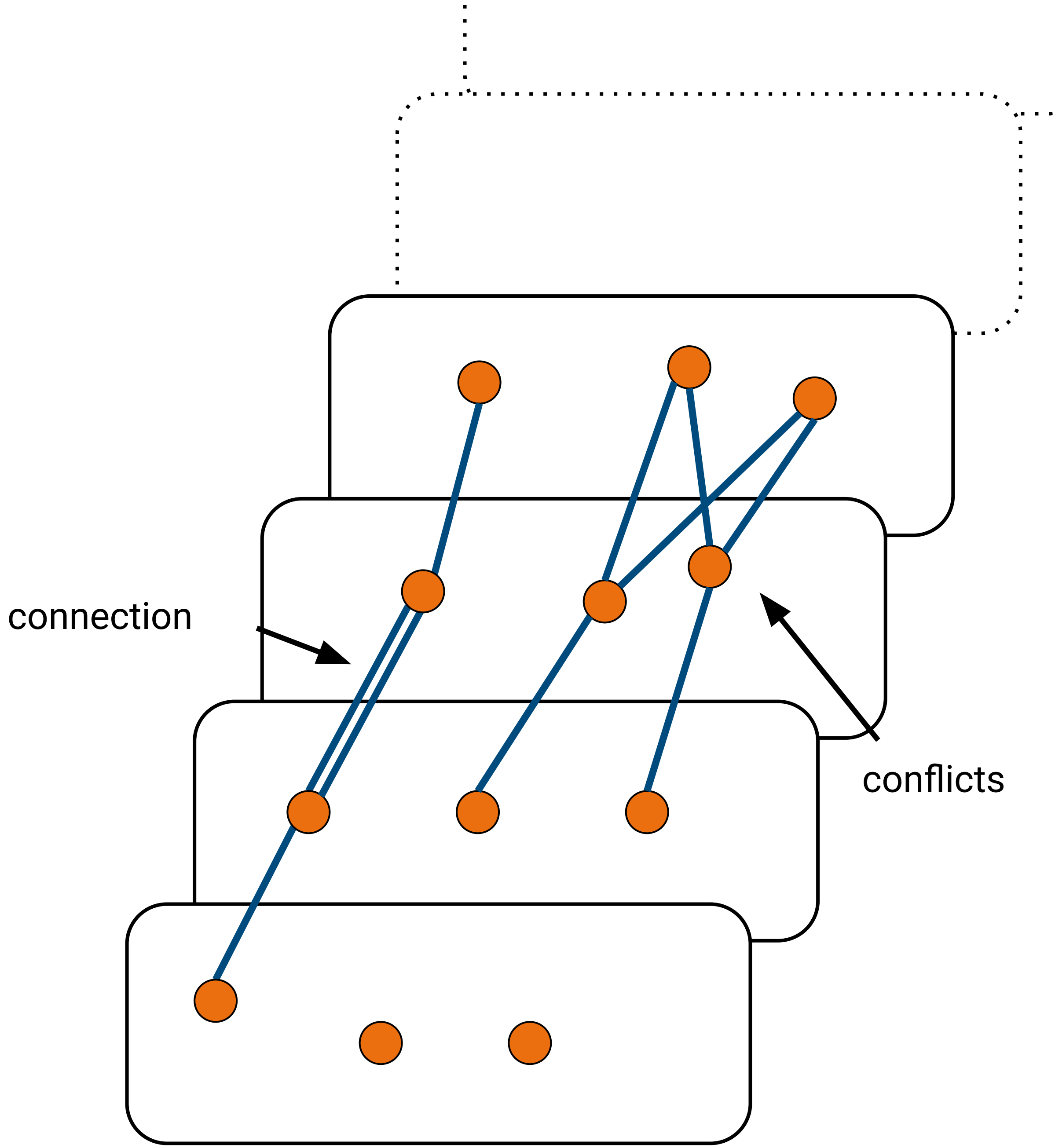
- **Doublets** are created by combining hits from successive layers
- **Triplets** are created by combining doublets



Pattern Recognition

- **Doublets** are created by combining hits from successive layers
- **Triplets** are created by combining doublets
- **Relations** of triplets as key feature

Goal: Identify triplets stemming from a single particle (“matched”) and combine them to tracks



QUBO

Quadratic Unconstrained Binary Optimisation

- Triplets $\mathbf{T_i} \in \{0, 1\}$

$$\hat{H} = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i \qquad \text{(QUBO)}$$

QUBO

Quadratic Unconstrained Binary Optimisation

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- Triplets $\mathbf{T_i} \in \{0, 1\}$

- System with two types of parameters:
  - **Conflicts**: $\mathbf{b_{ij} > 0}$
  - **Connections**: $\mathbf{b_{ij} < 0}$
  - **Individual term**: $\mathbf{a_i}$

QUBO

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- Triplets **T_i** $\in \{0, 1\}$

- System with two types of parameters:
  - **Conflicts**: **$b_{ij} > 0$**
  - **Connections**: **$b_{ij} < 0$**
  - **Individual term**: **a_i**

Goal: Minimising the QUBO cost function (Hamiltonian) of the system

QUBO

Quadratic Unconstrained Binary Optimisation

$$\hat{H} = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i \qquad \text{(QUBO)}$$

Minimise QUBO cost function

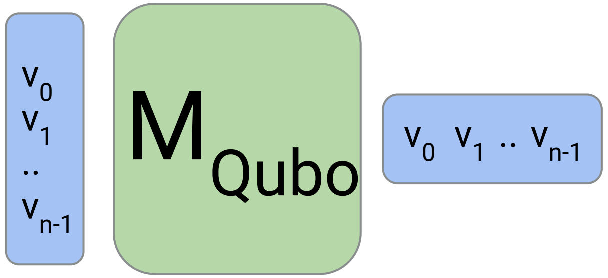
- Ground state → best set of triplets to keep
- $\mathbf{v}_{\mathbf{binary}}$: $[T_1, T_2, T_3, \ldots, T_N] \rightarrow [0, 1, 1, \ldots, 0]$
- Large QUBOs need to be split into sub-QUBOs

  → sequentially minimised and combined to global solution

Computation:

- Matrix diagonalisation (analytic solution)
- Hybrid quantum-classical algorithm (VQE)

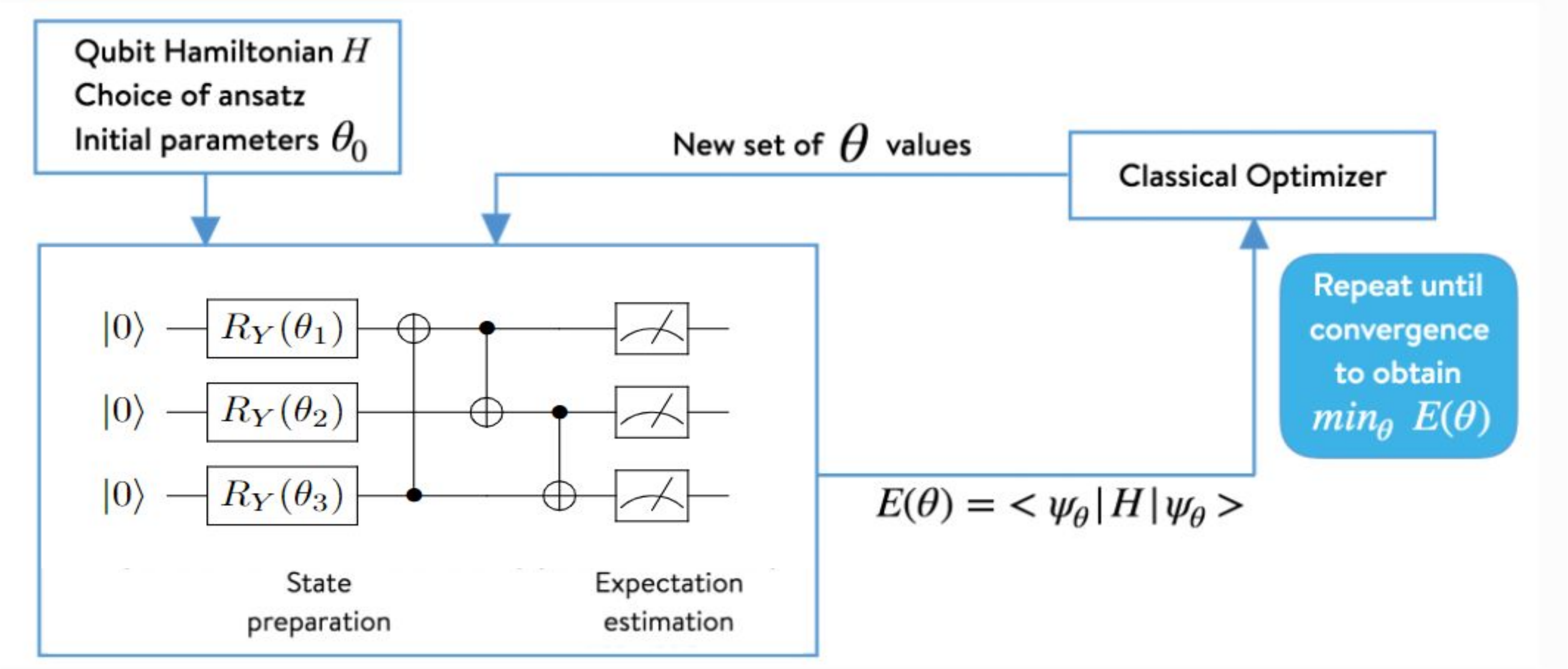
  …



$$\min(\hat{H}) = \min_{v_i \in v}(v^T M v)$$

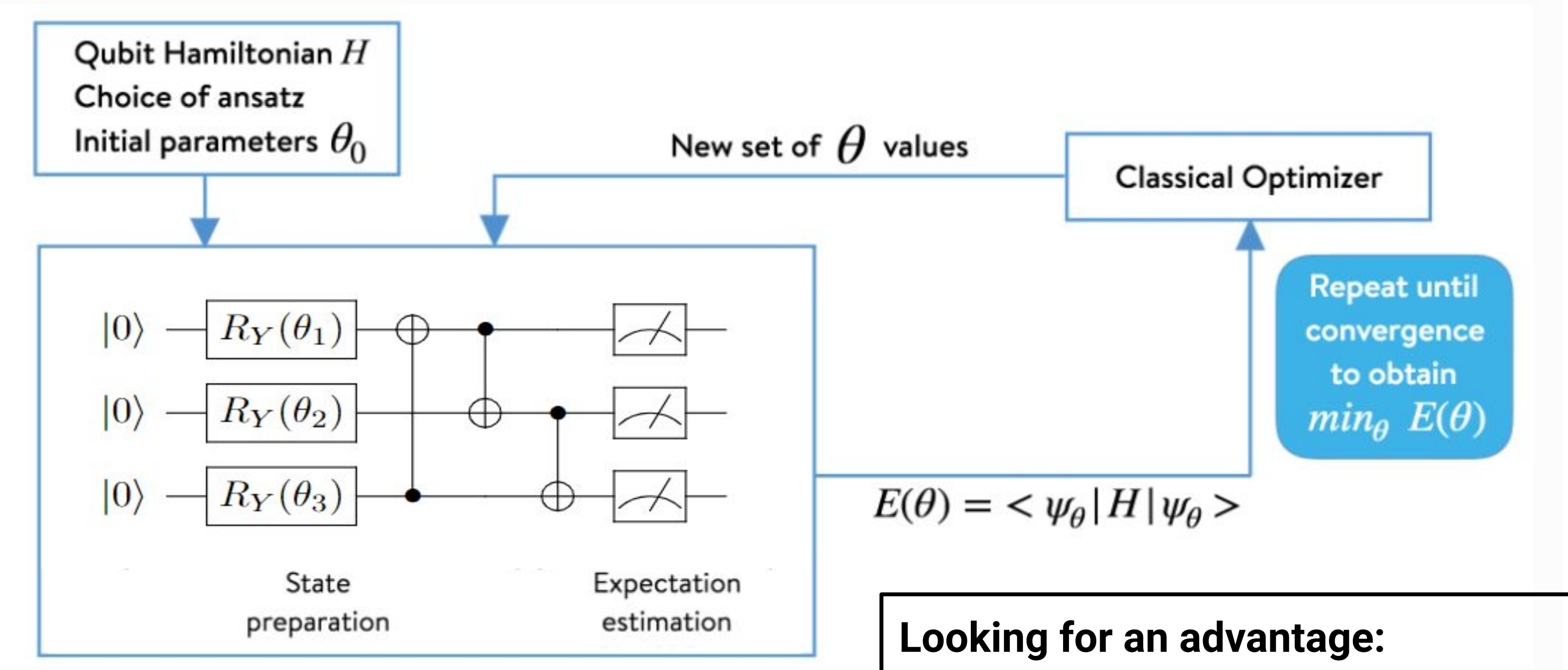
VQE

Variational Quantum Eigensolver



VQE

Variational Quantum Eigensolver



$$H = \sum_{a=1}^{\mathcal{O}(Poly(N))} w_a P_a$$

$$P_a \in \{I, X, Y, Z\}^{\otimes N}$$

Looking for an advantage:

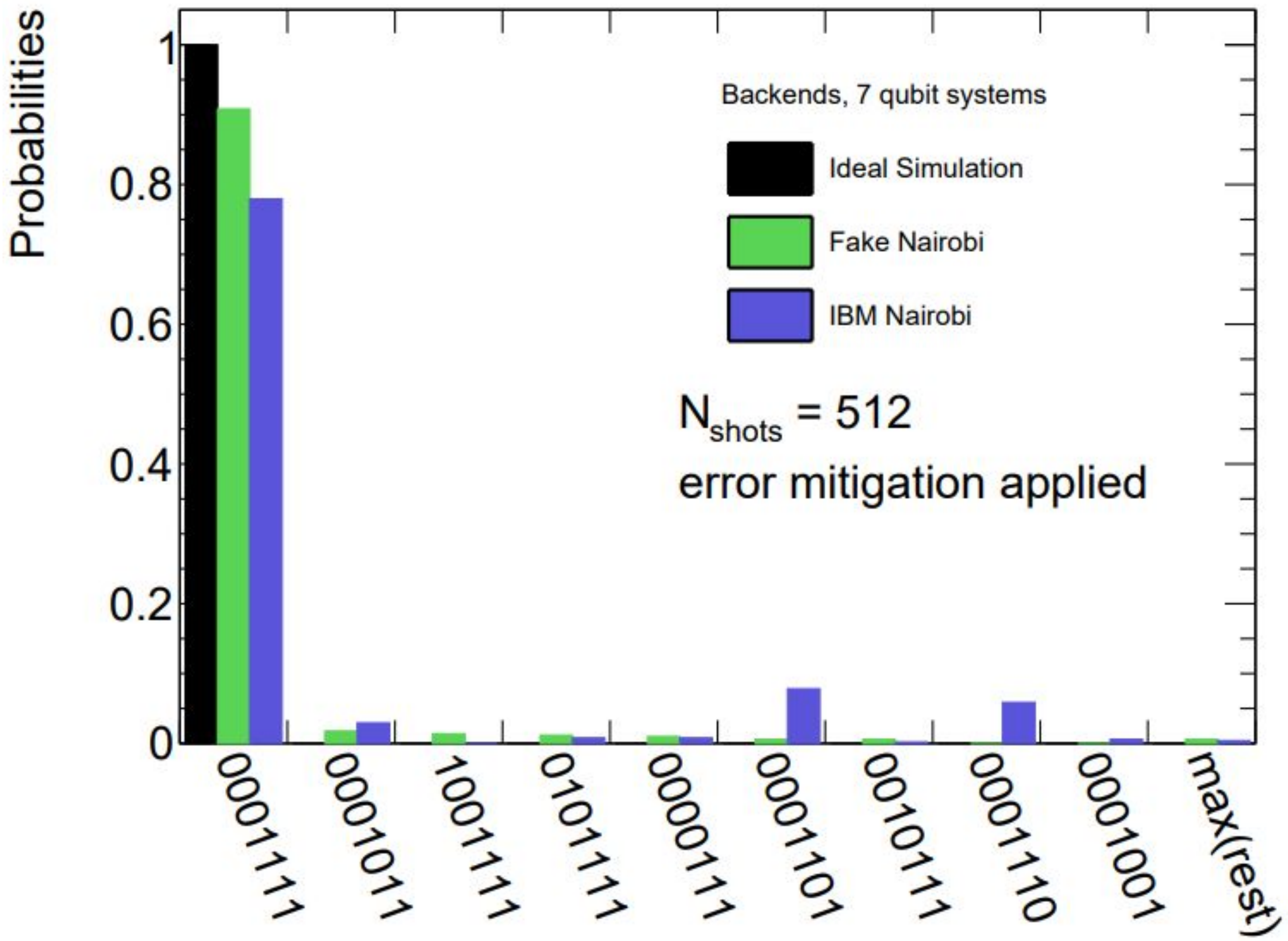
dim(H) = 2^n x 2^n, then $<\psi|H|\psi>$ needs:

- $O(2^{2n})$ operations classically
- Possibly only O(Poly(n)) operations with a quantum computer

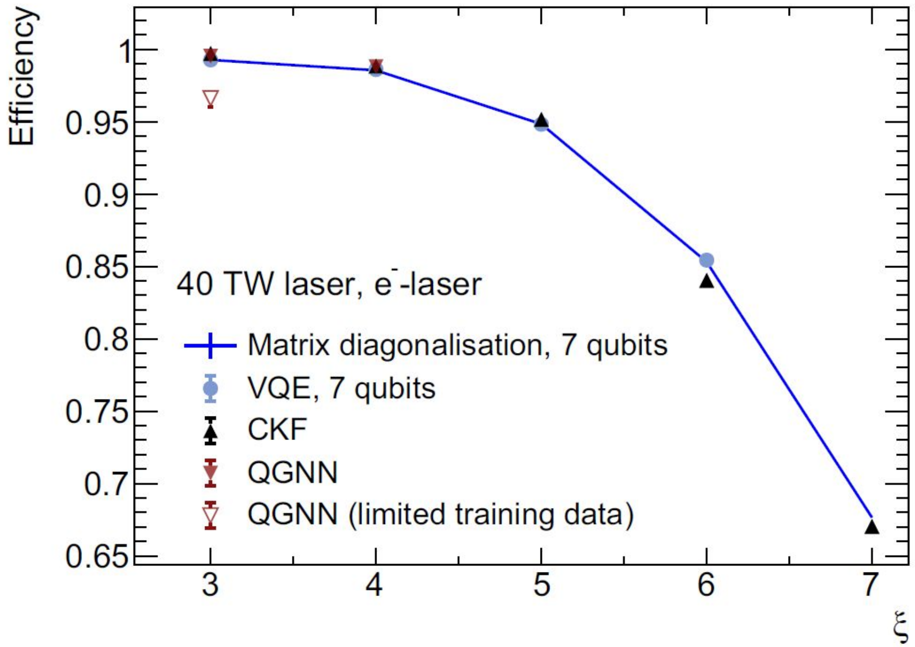
Quantum computing result example

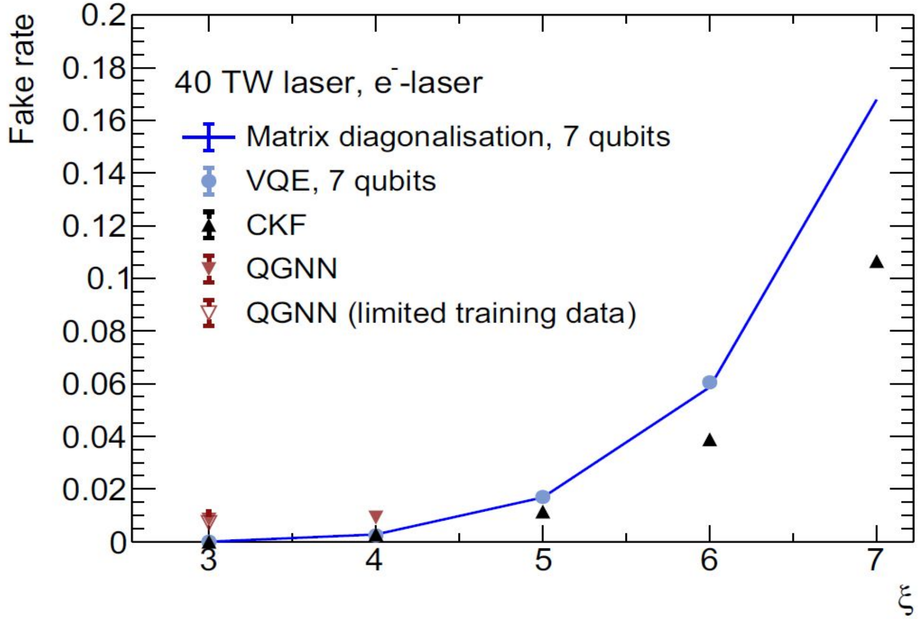
- Calculations on a quantum device are noisy:
  → Error mitigation and error correction

- 10 shots (number of circuit evaluations) sufficient for 99% success rate



Example: Positron tracking at LUXE





- Performance of quantum algorithms compared to classical track reconstruction algorithms
- Similar performance in efficiency, slightly higher fake rate

Laser intensity parameter ξ	3	4	5	6	7
Average number of positrons	140	2100	10500	30000	67000

Source: [4]

Thank You!

References

- [1] https://de.newsroom.ibm.com/ibm-dach-special-coverage-Fraunhofer-IBM
- [2] “Quantum computation in power systems: An overview of recent advances”, doi:10.1016/j.egyr.2022.11.185
- [3] https://qiskit.org/
- [4] “Quantum Algorithms for Charged Particle Track Reconstruction in the LUXE Experiment”, Comput Softw Big Sci 7, 14 (2023). https://doi.org/10.1007/s41781-023-00109-6
- [5] http://openqemist.1qbit.com/