Scalability and Universality of Quantum Benchmarks

Perspectives from C12

Chloe Ai, C12 Quantum Electronics

24 Juin 2025, TQCI Seminar, Palaiseau

We are transforming carbon nanotubes into "Quantum transistors"

Founded in 2020

Paris-based quantum hardware startup

Spin-off Ecole Normale Supérieure in Paris

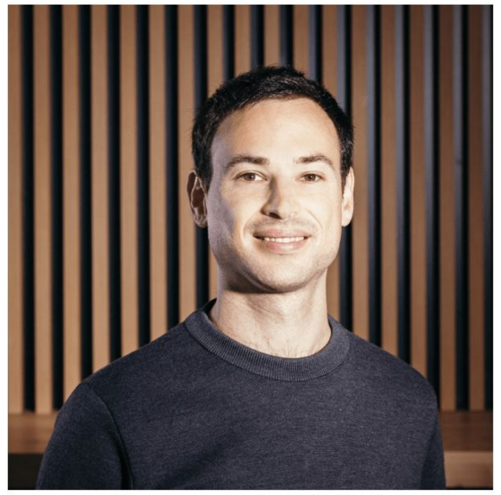
55+ employees

8+ patents

Pilot production line in Paris

First application-specific chips for quantum chemistry in development

Pierre Desjardins
CO-FOUNDER & CEO



Dr. Matthieu Desjardins
CO-FOUNDER & CTO

360 CAPITAL

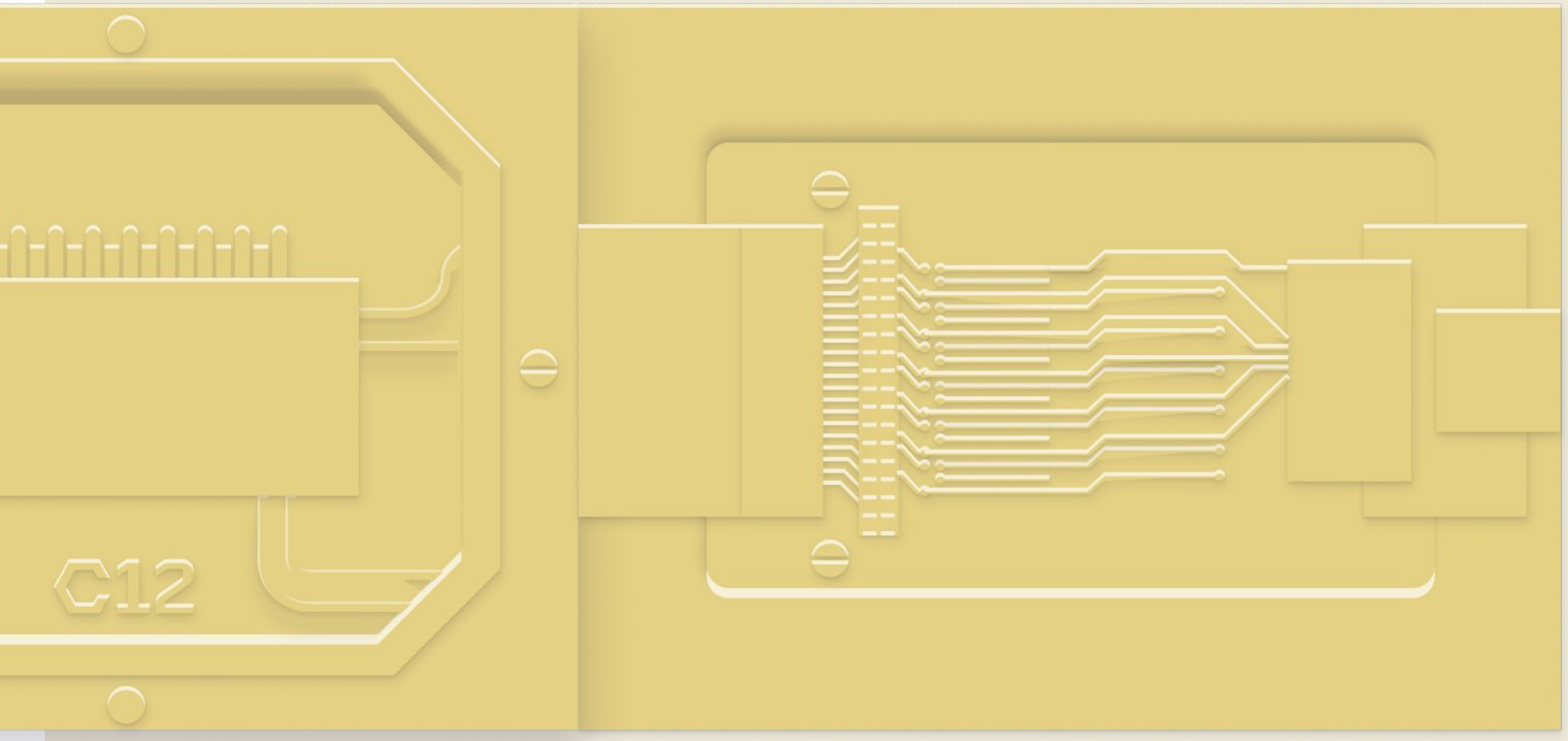
bpifrance DIGITAL VENTURE

BNP PARIBAS DÉVELOPPEMENT

Varsity

VERVE VENTURES

C12, a unique approach to build a universal quantum processor



Ultra-clean material

DEMONSTRATED

- Lowest charge noise
- Isotopic purity
- Longest 1Q coherence times*

High Connectivity

FOCUS

- Long-distance 2Q gate > 99.9%
- Efficient error correction

At large scale

DEMONSTRATED

- Foundry process

Our vision

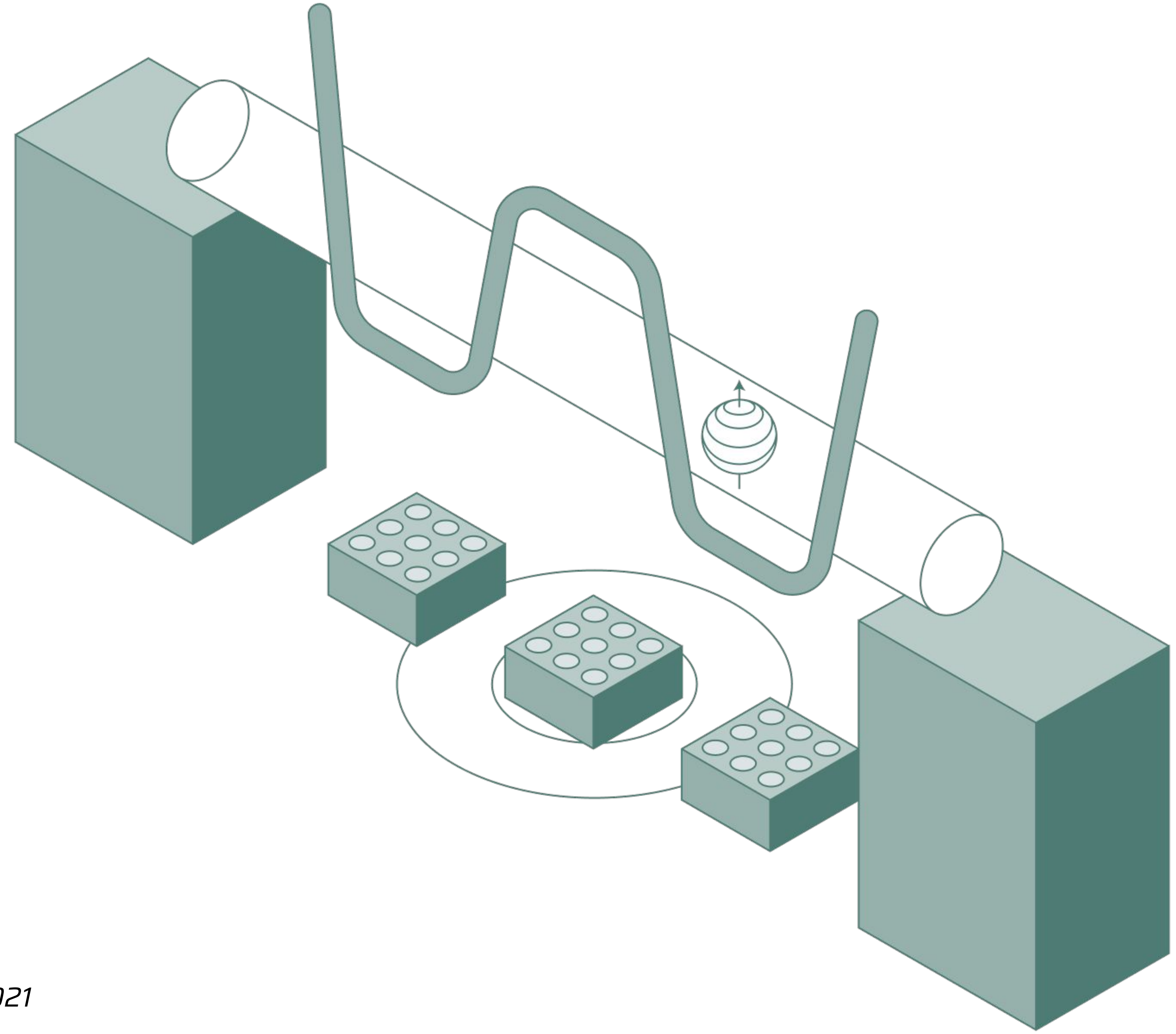
We need
high-quality qubits

And errors come from
defects in qubit material

C12

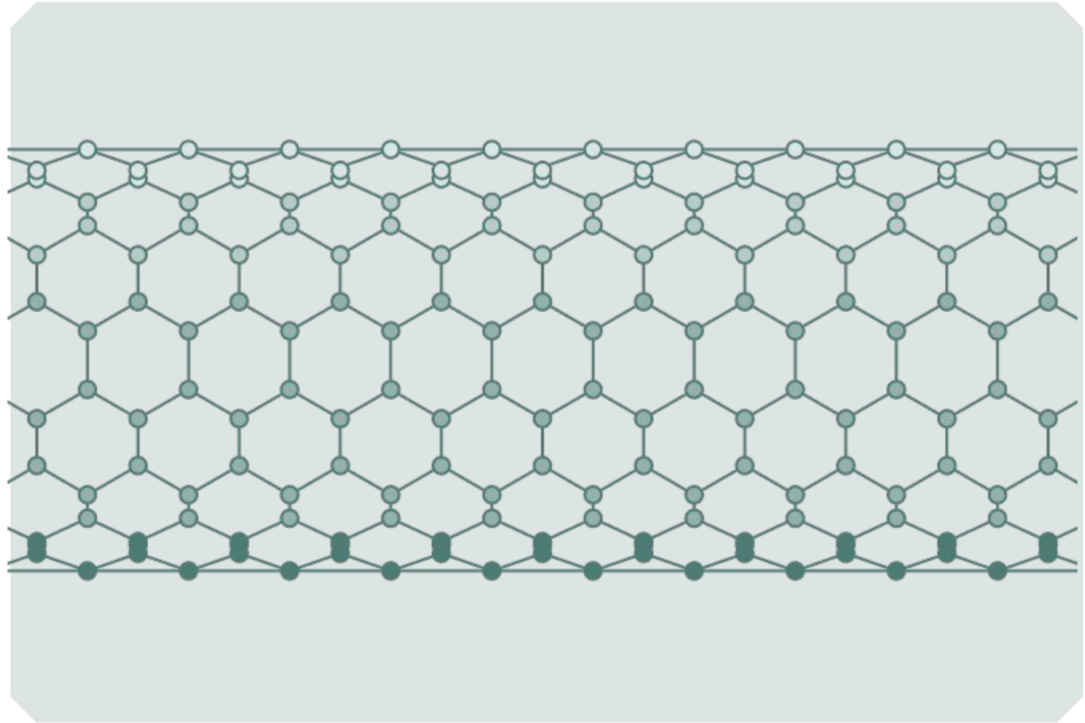
C12’s qubit is a spin qubit hosted in a **single carbon nanotube**

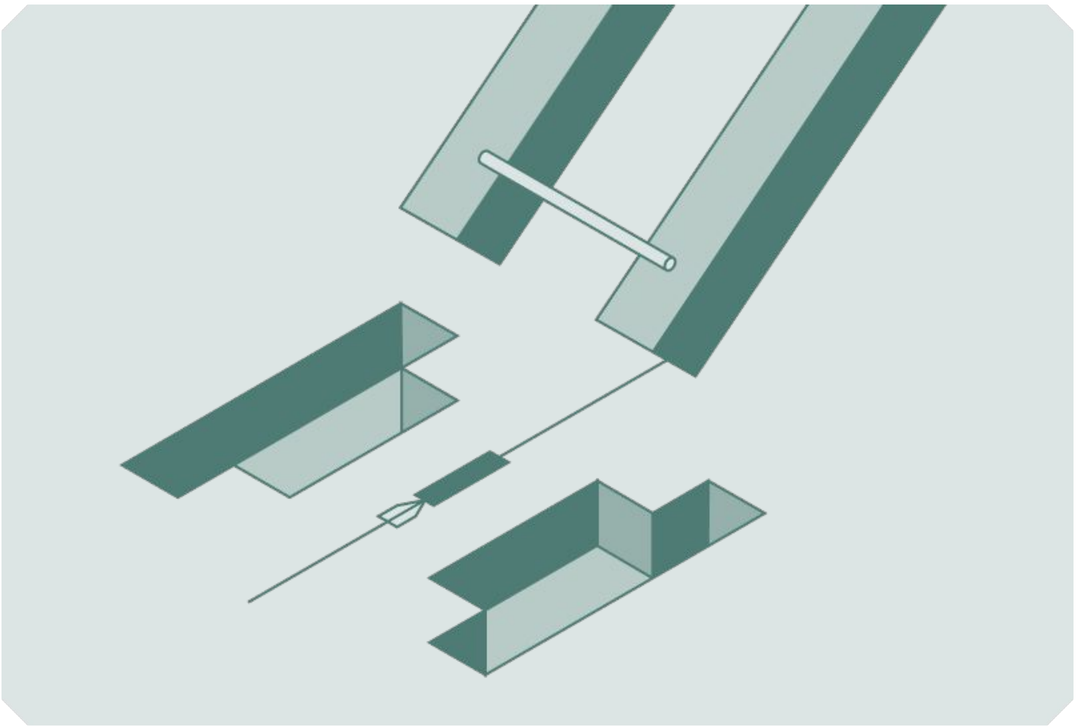
- Ultra-pure carbon nanotube, connected between electrical contacts, is suspended above an array of gate electrodes
- Gate electrodes manipulate a single electron within a double quantum dot
- Local magnetic field entangles the electronic spin with the charge dipole in the double quantum dot
- This spin qubit is addressed via microwave pulses

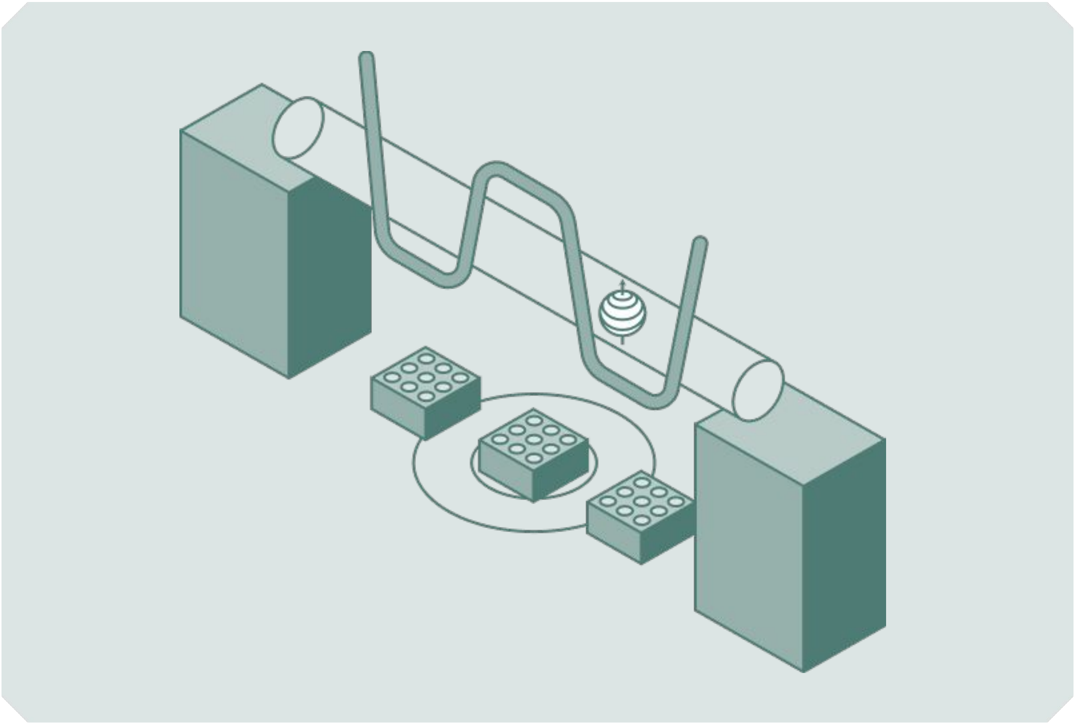


T. Cubaynes et al. NPJ, 2019, F. Borjans et al, Nature, 2020, P. Harvey-Collard, 2021

Building a quantum computer still needs technological breakthroughs







Breakthrough in material science

Carbon nanotubes as an **ultra-pure** hosting material for the spin

Ultra-clean 1D material: highly tunable system for fast control of the spins with reduced decoherence channels

J. Waissman et al. Nature Nano, 2013

Breakthrough in manufacturing

Patented fabrication process based on the **nano-assembly** of carbon nanotubes on a silicon chip

Method and device for depositing a nano-object, US Patent App. 17/285,369, 2021

T. Cubaynes et al, Appl. Phys. Lett. (2020)

Breakthrough in quantum computing architecture

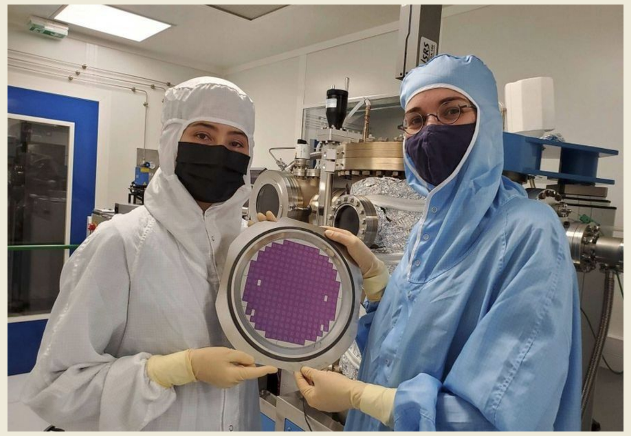
Quantum processors based on **spin qubits** coupled through a quantum bus

Long range coupling of individual spins, isolated yet addressable

T. Cubaynes et al. NPJ, 2019, F. Borjans et al, Nature, 2020, P. Harvey-Collard, 2021

A functional production line inside C12’s quantum foundry

Inside C12's quantum foundry



Nanofabrication

- Wafer-scale fabrication
- Magnetic gate (2nd generation)
- Patent for 3rd generation

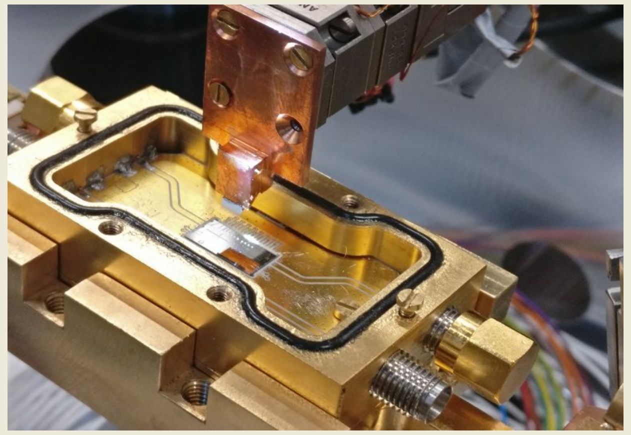
CNT Growth

- Localized deposition
- Stable growth

CNT Characterization

- Optical characterization to select single tubes vs bundles
- In situ electrical detection

CNT Nano-assembly



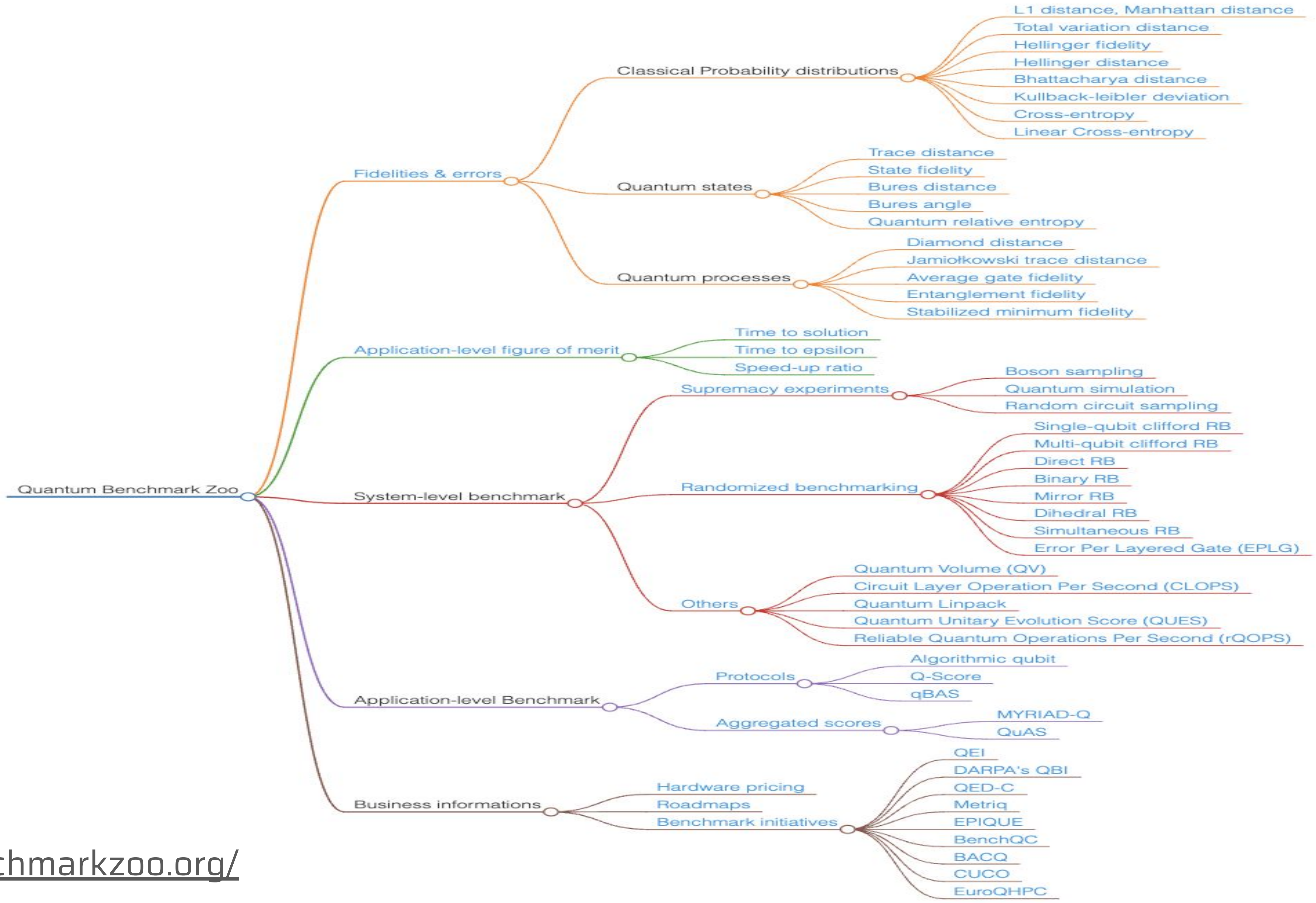
- High throughput
- Quality check

Scalable for universal quantum computing

- Semiconductor integration enables small qubit and high qubit density
- Qubit pre-selection ensures quality
- High qubit density, connectivity and quality → efficient quantum error correction

We need **scalable** and **universal** benchmarks as guide to improve hardware development for achieving practical quantum advantage

Various quantum benchmarks



https://quantumbenchmarkzoo.org/

Performance Metrics for Quantum Computers

M1. HARDWARE ARCHITECTURE PROPERTIES

M1.1. Number of usable qubits
M1.2. Pairwise connectivity
M1.3. Native gate set
M1.4. Capability to perform mid-circuit measurements

M2. - M5. QUALITY METRICS

HARDWARE MANUFACTURER → *END-USER*

M2. QUBIT QUALITY METRICS

M2.1. Qubit relaxation time (T_1)
M2.2. Qubit dephasing time (T_2)
M2.3. Idle qubit purity oscillation frequency

M3. GATE EXECUTION QUALITY METRICS

M3.1. Gate set tomography-based process fidelity
M3.2. Diamond norm of a quantum gate
M3.3. Clifford randomized benchmarking average gate error
M3.4. Interleaved Clifford randomized benchmarking gate error
M3.5. Cycle-benchmarking composite process fidelity
M3.6. Over- or under-rotation angle
M3.7. State preparation and measurement fidelity

M4. CIRCUIT EXECUTION QUALITY METRICS

M4.1. Quantum volume
M4.2. Mirrored circuits average polarization
M4.3. Algorithmic qubits
M4.4. Upper bound on the variation distance

M5. WELL-STUDIED TASK EXECUTION QUALITY METRICS

M5.1. Variational Quantum Eigensolver metric
M5.2. Quantum Approximate Optimization Algorithm metric
M5.3. Fermi-Hubbard model simulation metric
M5.4. Quantum Fourier Transform metric

Lall et al, A Review and Collection of Metrics and Benchmarks for Quantum Computers- definitions, methodologies and software, 2025

HARDWARE COMPONENTS → *APPLICATIONS*

Application-level benchmarks

Current status

Several protocols dedicated to several promising problems

- Combinatorial optimisation, e.g. Q-Score
- Quantum chemistry simulation e.g. McCaskey2019*
- Learning problem, e.g. qBAS-Score

*A.McCaskey *et al*, Quantum Chemistry as a Benchmark for Near-Term Quantum Computers. npj Quantum Information, 5(1):1–10, 2019.

Application-level benchmarks

Current status

Execution quality metrics

- Quantum Approximate Optimisation Algorithm (QAOA) metric
- Variational Quantum Eigensolver metric
- 1D Fermi-Hubbard model simulation metric

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Variational quantum algorithms on NISQ devices

Application-level benchmarks : Observations

- These benchmarks depend on the chosen metrics and the chosen algorithm for a particular problem.

- So both **metric** and **algorithm** have important impact on the performance of benchmarking of quantum devices.

Questions :

Representativity: is the problem chosen representative of testing the applicability of quantum computing for practical application in the domain?

Expressivity: is the execution quality metric expressive for measuring the performance of the quantum device?

Application-level benchmarks : bitter fact

No industrially-relevant and practically-useful problem has been identified.

We only have a few domains in which quantum computing is **believed** to be available to provide computational advantage/usefulness.

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Encoding challenges: For practical applications, we need efficient encoding of problems into quantum computing framework, especially for NISQ era.

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Belief **v.s.** **Reality**

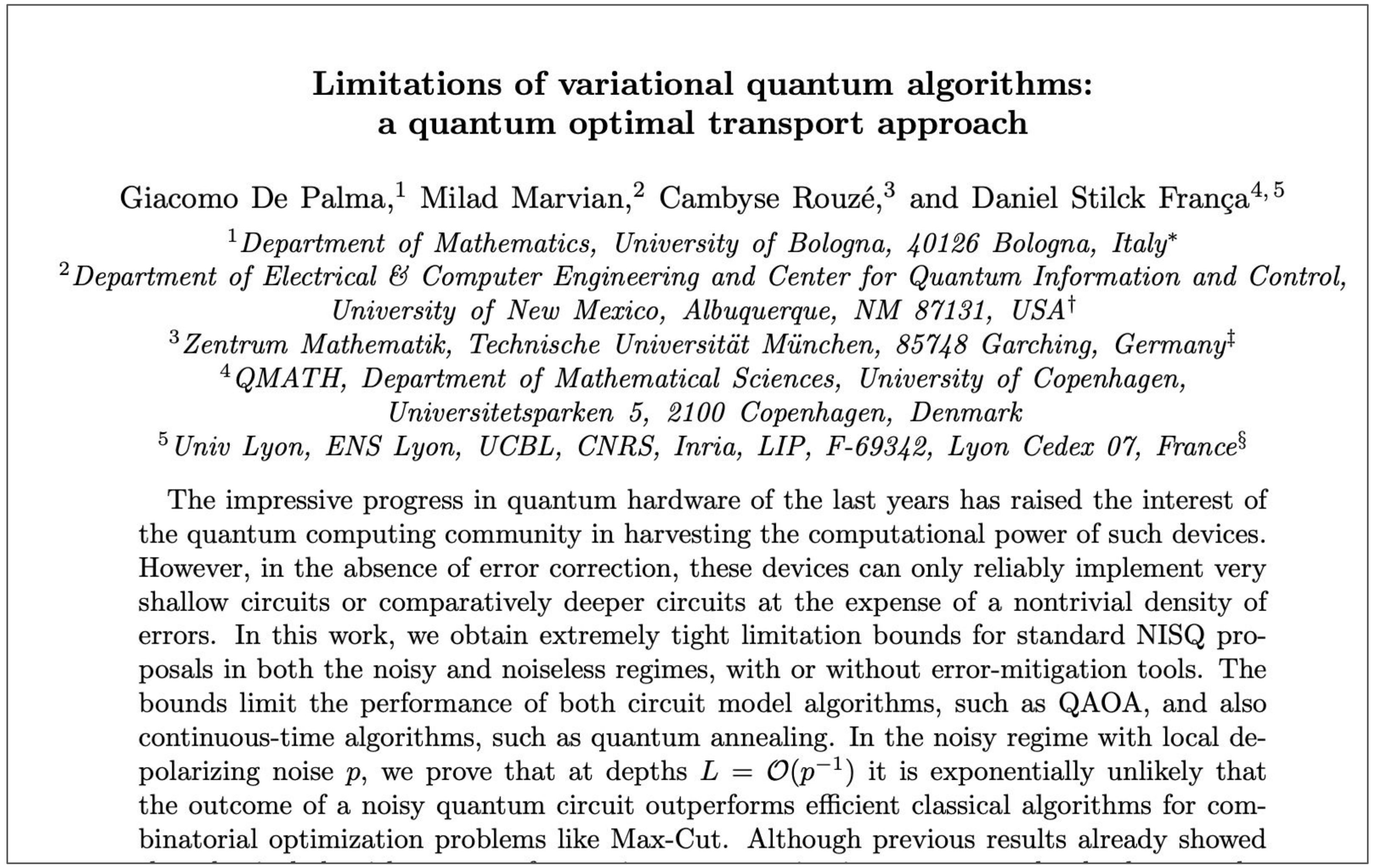
Execution quality metrics

- Impact of algorithms

Limitation of Variational Quantum Algorithms on NISQ

- Trainability issue
- Expressivity of the chosen ansatz
- Scalability of VQA

Scalability of these metrics ??



Limitations of variational quantum algorithms: a quantum optimal transport approach

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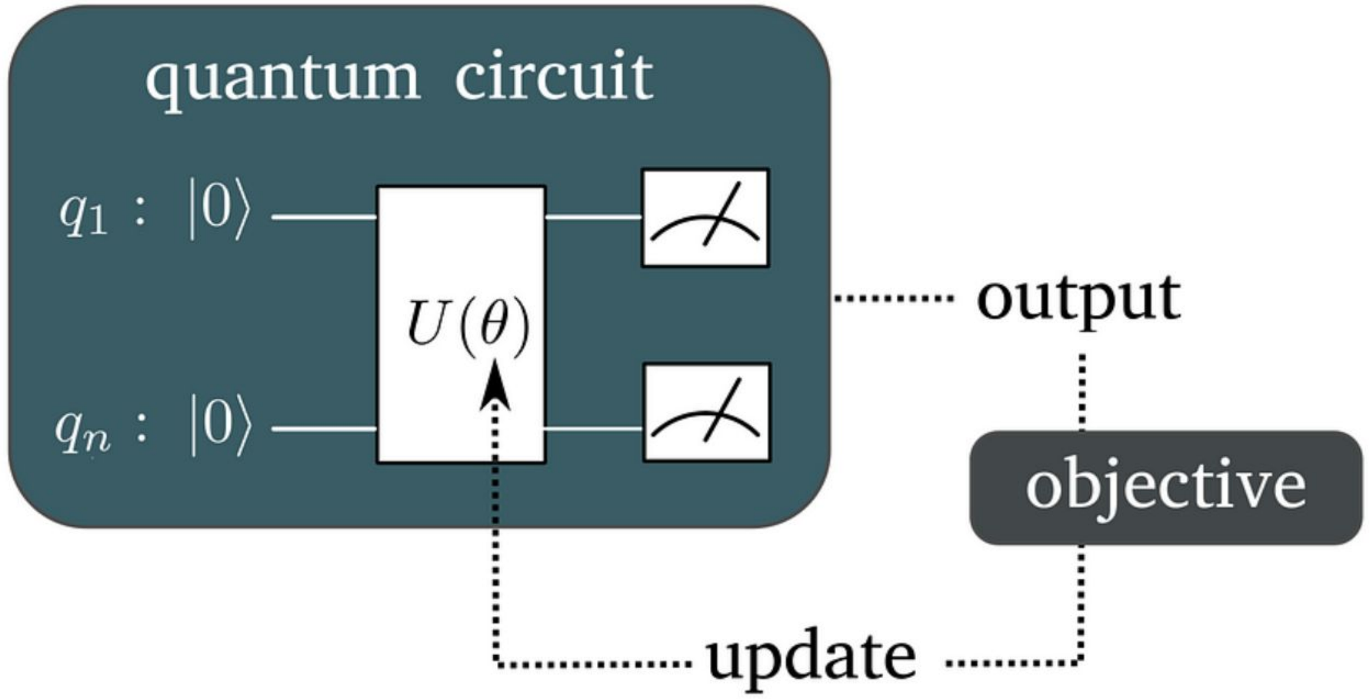
The impressive progress in quantum hardware of the last years has raised the interest of the quantum computing community in harvesting the computational power of such devices. However, in the absence of error correction, these devices can only reliably implement very shallow circuits or comparatively deeper circuits at the expense of a nontrivial density of errors. In this work, we obtain extremely tight limitation bounds for standard NISQ proposals in both the noisy and noiseless regimes, with or without error-mitigation tools. The bounds limit the performance of both circuit model algorithms, such as QAOA, and also continuous-time algorithms, such as quantum annealing. In the noisy regime with local depolarizing noise p, we prove that at depths $L = \mathcal{O}(p^{-1})$ it is exponentially unlikely that the outcome of a noisy quantum circuit outperforms efficient classical algorithms for combinatorial optimization problems like Max-Cut. Although previous results already showed



Execution quality metrics
- Impact of algorithms

NISQ

Benchmarks based on Variational quantum algorithms

Execution quality metrics
- Impact of algorithms

NISQ

Benchmarks based on Variational quantum algorithms

Fault-Tolerant

Benchmarks based on QFT

Execution quality metrics
- Impact of algorithms

NISQ

Benchmarks based on Variational quantum algorithms

?

Transition

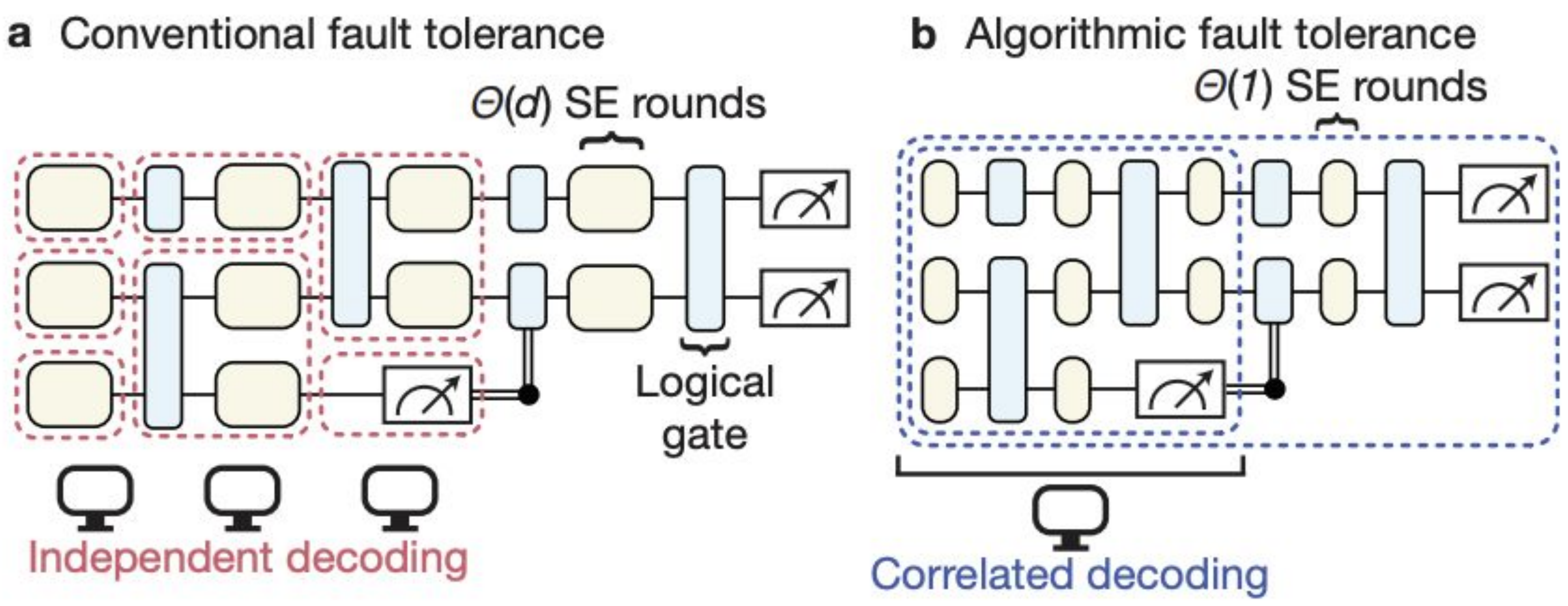
Fault-Tolerant

Benchmarks based on QFT

Potential proposal for the transition

"Algorithmic fault-tolerance"

Can we base on fast and reliable logical operation to design an application-oriented benchmark ?



Algorithmic Fault Tolerance for Fast Quantum Computing

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Fast, reliable logical operations are essential for the realization of useful quantum computers [1–3], as they are required to implement practical quantum algorithms at large scale. By redundantly encoding logical qubits into many physical qubits and using syndrome measurements to detect and subsequently correct errors, one can achieve very low logical error rates. However, for most practical quantum error correcting (QEC) codes such as the surface code, it is generally believed that due to syndrome extraction errors, multiple extraction rounds—on the order of the code distance d—are required for fault-tolerant computation [4–14]. Here, we show that contrary to this common belief, fault-tolerant logical operations can be performed with constant time overhead for a broad class of QEC codes, including the surface code with magic state inputs and feed-forward operations, to achieve "algorithmic fault tolerance". Through the combination of transversal operations [7] and novel strategies for correlated decoding [15], despite only having access to partial syndrome information, we prove that the deviation from the ideal measurement result distribution can be made exponentially small in the code distance. We supplement this proof with circuit-level simulations in a range of relevant settings, demonstrating the fault tolerance and competitive performance of our approach. Our work sheds new light on the theory of quantum fault tolerance, potentially reducing the space-time cost of practical fault-tolerant quantum computation by orders of magnitude.

Conclusion

We need good benchmarks as guide to achieve practical quantum advantage:

Need to identify representative problems for designing application-oriented benchmarks

Need to define universally-applicable metrics based on scalable quantum algorithms

Need to prepare the transition from NISQ to Fault-tolerant era

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Unique at Scale