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Key ingredients for developing superconducting quantum processing units at scale

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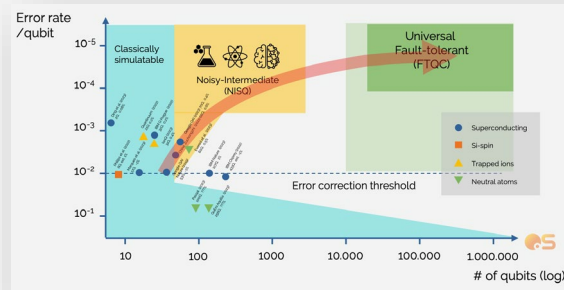
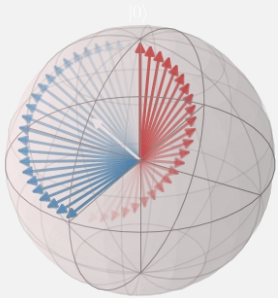
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Outline

1. What is Quantum Computing and why do we care?

2. What is needed to make it useful?

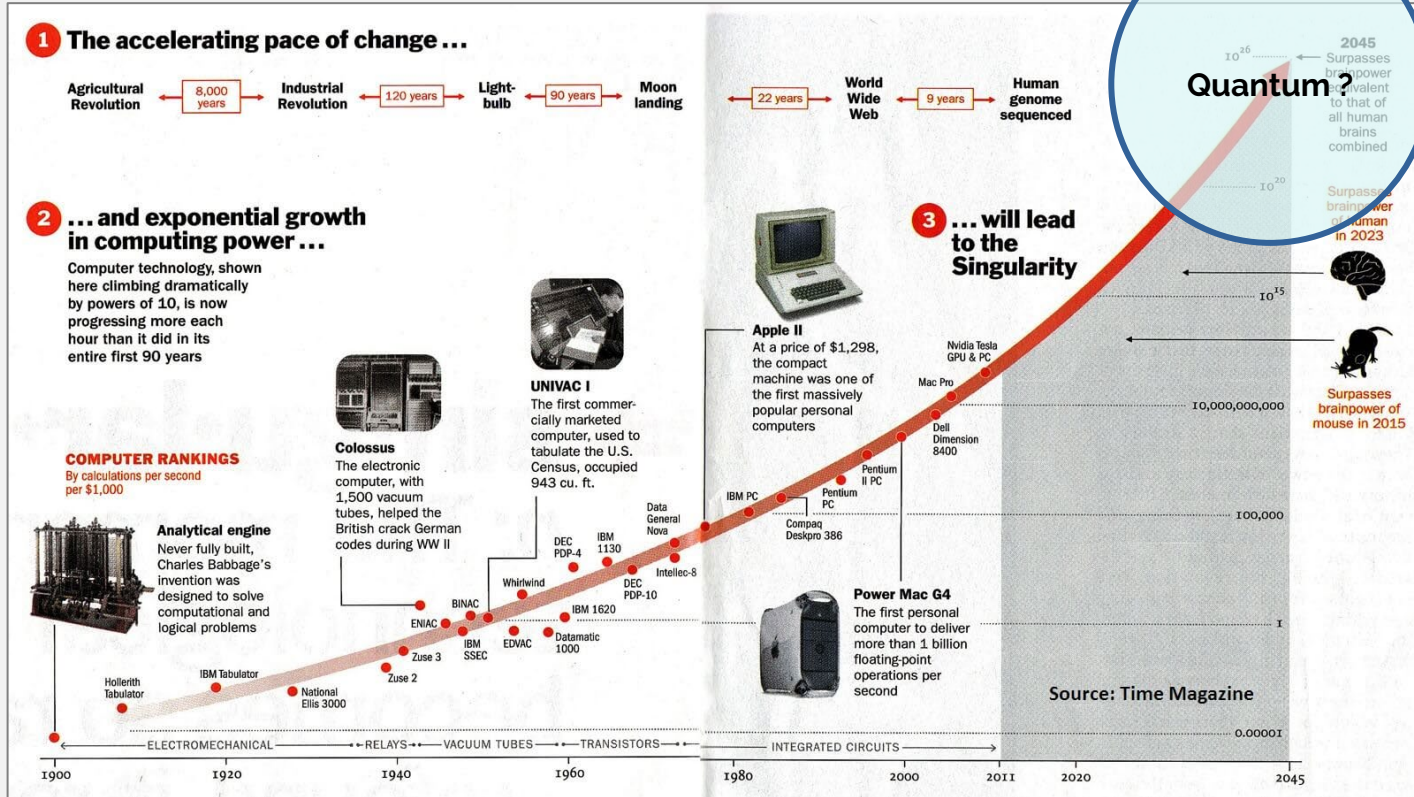
3. What is special about quantum chip testing?



What is Quantum Computing and why do we care?

The Kurzweil plot – More than Moore

Information processing capability (calculation/(sec \$))

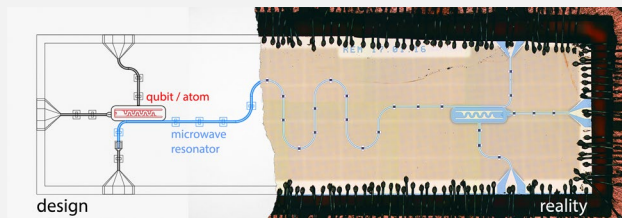


Manipulating quantum systems

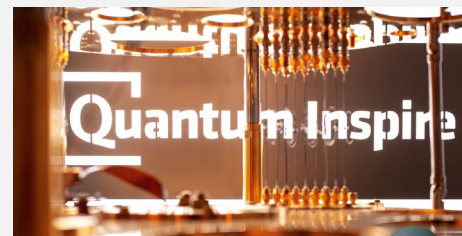
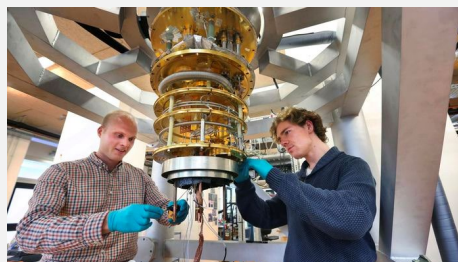
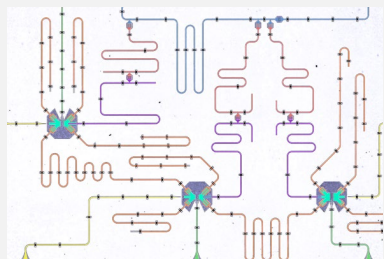


The Next Quantum Revolution

Artificial atoms, e.g., transmons



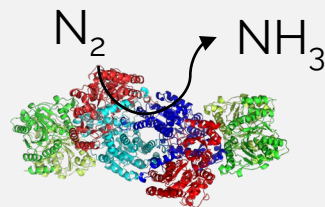
Engineered quantum systems



Quantum Computing



Material design



Chemical simulation



Cryptography

What is needed to make it useful?

First movers in the quantum HW sphere have made consistent progress & quantum technology is going from lab to fab

2019 - Demonstration of quantum supremacy

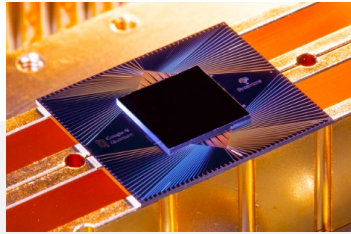
Article | [Published: 23 October 2019](#)

Quantum supremacy using a programmable superconducting processor

[Frank Arute](#), [Kunal Arya](#), ... [John M. Martinis](#)  [+ Show authors](#)

[Nature](#) **574**, 505–510 (2019) | [Cite this article](#)

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2021 - World's first commercial quantum chip



QUANTWARE



2022 - Europe's first quantum chip fabrication facility



2020 - Europe's first cloud-based quantum computer & World's first multi-platform quantum computer



QuTech

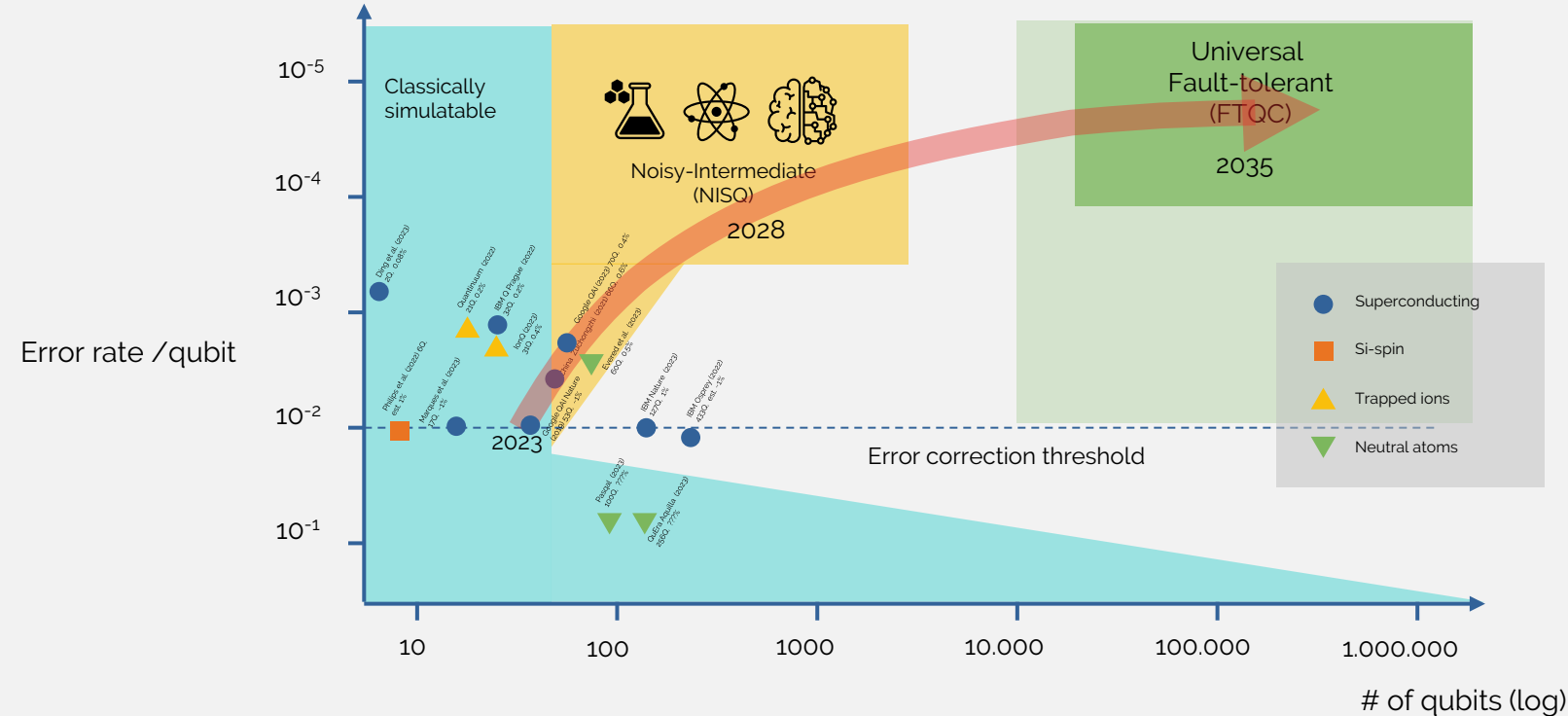


2023 - Demonstration of quantum utility

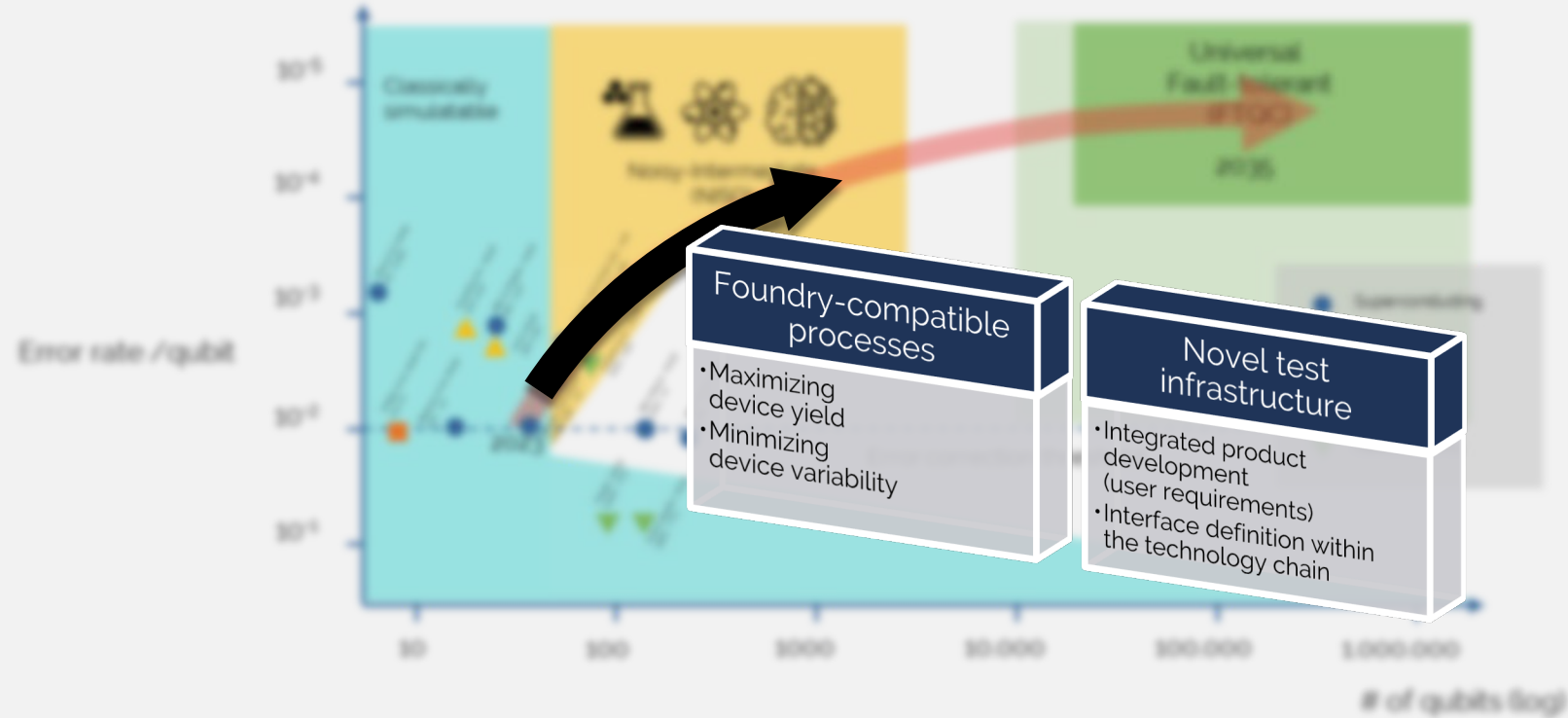
IBM Quantum



But in order to realize a quantum advantage, more, and better qubits are needed.

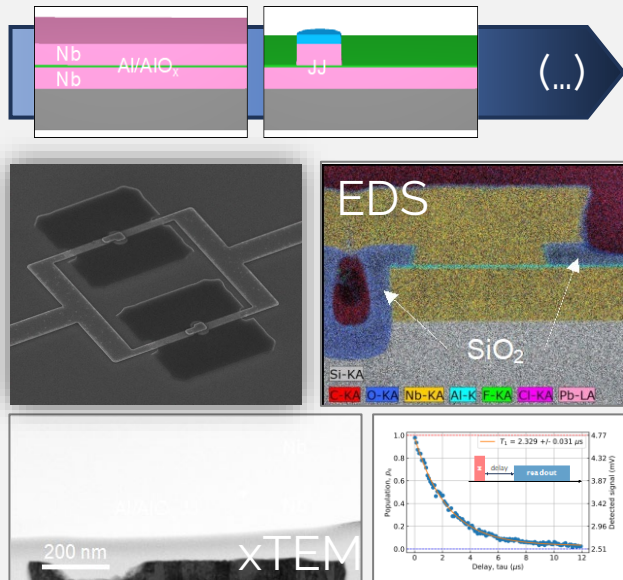


This task cannot be achieved by scientific breakthroughs alone. It requires a combination of scientific breakthroughs, novel approaches and integrated enabling products



Ingredient 1: Transistioning from standard qubit manufacturing towards foundry-compatibility

Process steps detailed out in [1]



Current challenges

Process steps not yet optimized
(example in figure – spacer issue)

Verified coherence times still far below coherence times of SOA qubits

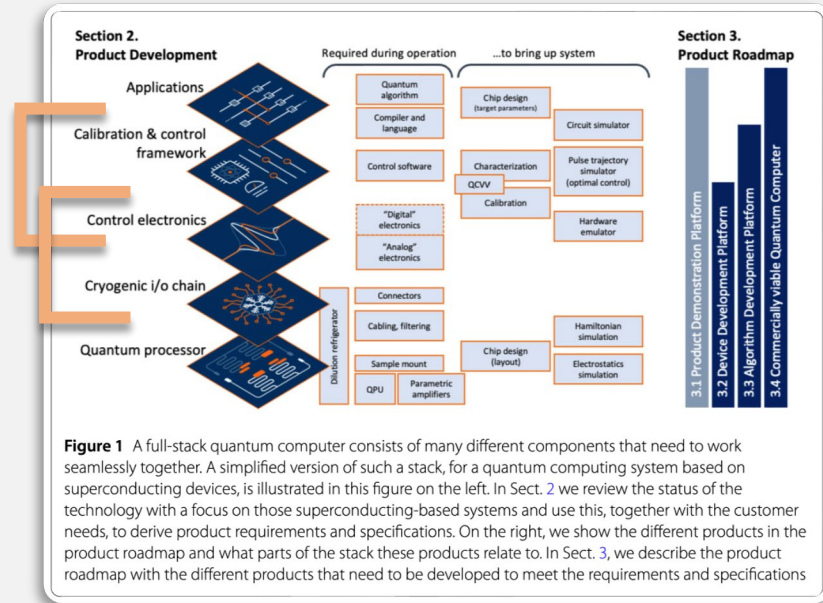
Advantages

Extremely uniform tunnel barrier across the whole wafer can be created

MTJ-inspired BEOL process flow can be applied

Key advantage over conventional pilot lines:
Improved learning cycles can be implemented through tighter process control

INGREDIENT 2: An aspect of novel test infrastructure **is a shift in focus** towards integrated product development alongside R&D activities



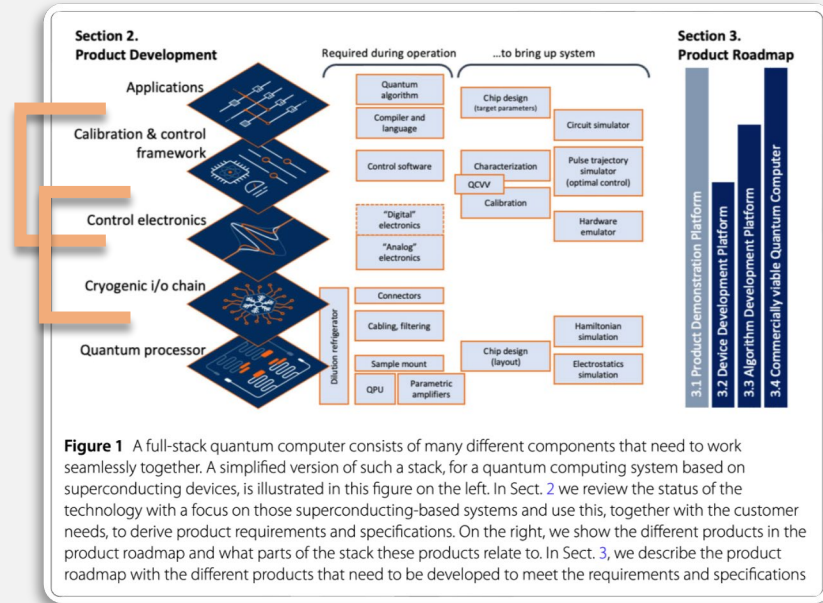
Elements to take into account when controlling, tuning & testing transmon qubits

- A Knowledge of the user requirements (Knowledge of the experiment)
- B Assembly of the key hardware components that can be used
- C HW/SW integration to fulfill the user requirements (control the experiment)



Leads to unwanted delays in R&D activities

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Integrated **product development** will enhance focus on:

- Interface definition of technology chain
- System integration (elements A, B, & C with same high priority)

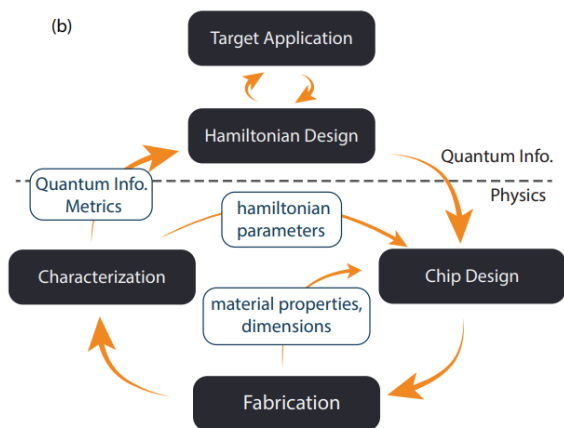


Leads to extendable and easier to use solutions and to an acceleration of QPU test and diagnostics

What is special about quantum chip testing?

What do we need to know?

The Quantum Device Engineering Cycle



Gao, et al. PRXQ (2021)

Alberts, Rol, Last, et al. EPJ Quantum (2021).

- Quantum information properties
 - Gate fidelities, crosstalk, algorithm performance, etc.
 - Measures chip quality
 - Quantum physics properties
 - Frequencies, coupling strengths, coherence times, etc.
 - Measures qubit quality
-
- Material properties
 - Resistances, capacitances, etc.
 - Can be a predictor of device quality

Relevant work: large-scale JJ testing and statistics

- Muthusubramanian et al. APS MM 2022
- Zhang et al. Sci. Adv. 2022

But the test tools to go from lab to fab are missing



Expensive: high-tech equipment
(2-5 Meuro lab)



Slow: manual workflow
(1 chip with 5 qubits per month)

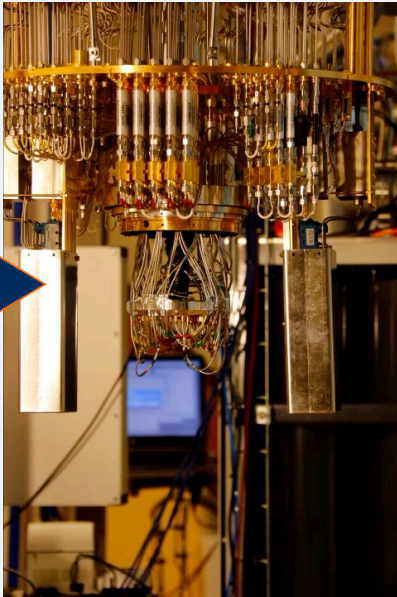


Difficult: PhD level operator

To test quantum chips we need to bring the chip to operating conditions in a quantum environment

Quantum environment:

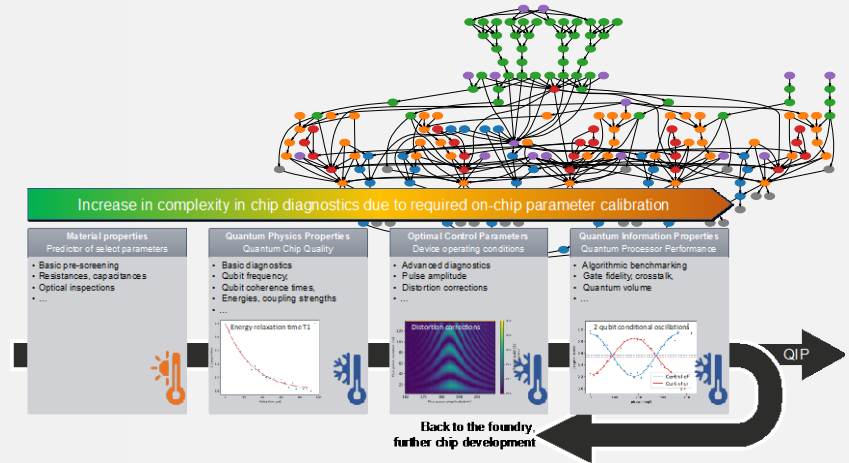
- Cryogenic (milli-Kelvin) temperatures.
- Extensive shielding and filtering.



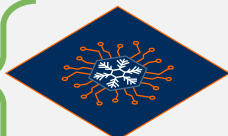
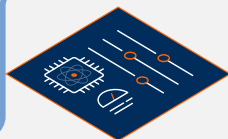
Movie credit: J.C. de Sterke at
DiCarlo Lab TUDelft/QuTech

Bring-up to operating conditions

- No correlations to room-temperature measurements.
- Intricate dependencies between tune-up protocols.



Orange QS is developing **an integrated** and **easy-to-use** **high-throughput industry systems** for **accelerating** quantum chip development



The Industry Diagnostics System: optimized for high-speed qubit testing.



Speed

Optimized for fast testing of quantum chip quality.



Usability

Turn-key operation:
Fully automated qubit testing.



Affordable

Over 2 orders of magnitude reduction in test cost per qubit.

Closing remarks:

- **Synergies** with foundry-compatible approaches need to be considered, and distinct differences evaluated.
- **Integrated test and measurement equipment** will lead to an acceleration of QPU development and will, hence, address the test capacity bottleneck.



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