# quantum technologies roadmaps
## perspective and challenges

#QEI
the quantum energy initiative

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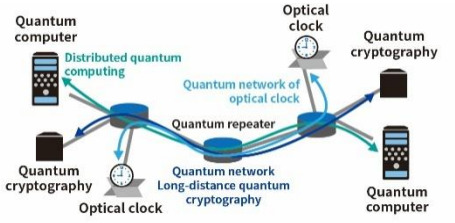
DPG Fall Meeting, Göttingen, September 10th, 2025

# second quantum revolution pillars



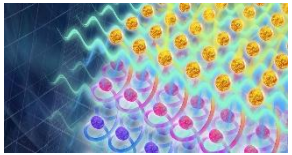

quantum
**computing**

quantum
**communications**

quantum
**sensing**

quantum
**enabling technologies**

quantum
**matter**

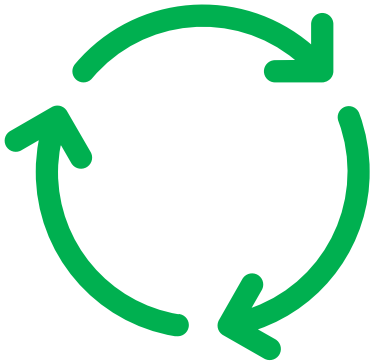


# a virtuous cycle at play

academic research

experiments

theory



engineering

technology development

commercialization

industry

# continuous advances in all fields

**quantum computing**

- reaching 99.9% qubit fidelities.
- qubit number >100 (IBM, QuEra, …).
- efficient error correction codes.
- first logical qubits.
- non-local qubit connectivity.
- progress with all types of qubits.
- solving interesting physics problems.
- NISQ quantum utility (*still debated*).

**quantum enabling technologies**

- cryo-CMOS and SFQ electronics.
- flexible cables.
- qubit readout TWPAs.
- high-power cryogenics.
- fibre lasers.
- low-loss fibres and waveguides.
- higher efficiency SNSPDs and PNRDs.
- deterministic quantum dots photon sources.

**quantum communications**

- longer distance QKD.
- higher sat and terrestrial QKD keyrates.
- QPU interconnect trials.
- telecom-wavelength QKD.
- first memories for entanglement repeaters.

**quantum sensing**

- commercial absolute gravimeters.
- quantum PNT experiments.
- quantum LiDARs.
- $10^{-19}$ s accuracy quantum clocks.
- broad spectrum analysis with cold atoms.

# but it takes time


August 10, 2018

**2025:**
84 qubits (Ankaa)
36 qubits (better fidelities)

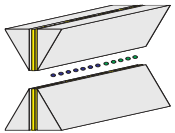
**2025:**
36 qubits (Forte)

IonQ Has the Most Powerful Quantum Computers With 79 Trapped Ion Qubits and 160 Stored Qubits

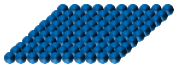
December 11, 2018 by Brian Wang

# an amazing technology diversity

## atoms

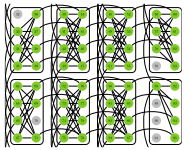


trapped ions

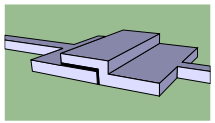


cold atoms

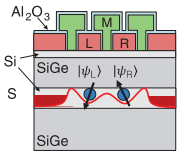
## electrons *controlled spin and microwave cavities*



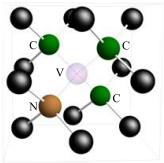
annealing



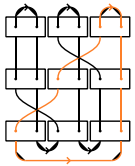
superconducting



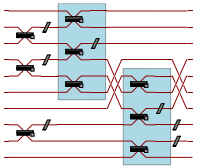

silicon



vacancies



topological



photons

QUANTINUUM · AQT · NEQT · ZuriQ · Quantum Art · FOXCONN · 华翊量子

1

IONQ · eleQtron · QUDORA TECHNOLOGIES

2

CRYSTAL QUANTUM COMPUTING

3

IQuEra · Pasqal · Infleqtion · QUANTier · planqc

4

atom computing

5

Atom Quantum Labs

6

D-Wave The Quantum Computing Company · KILIMANJARO QUANTUM TECH · NEC

IBM · rigetti · IQM · Google · 本源量子 Origin Quantum · ANYON · OQC · FUJITSU · QOLAB · QuamCore · Peak Quantum

7

ALICE & BOB · Nord Quantique · amazon · qci · ATLANTIC QUANTUM

Z-Axis Quantum

8

diraq · ARQUE · quobly · QUANTUM MOTION · QπAI

9

Groove Quantum · equal1.labs · intel

10

Silicon Quantum Computing · EeroQ · C12 · ARCHER

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QUANTUM BRILLIANCE · TURING · XEEA · SaxonQ · Quantum Transistors · FUJITSU

12

photonic

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Microsoft · QUOHERENT · QUANTUM · NOKIA

PsiQuantum · QUANDELA · QUIX QUANTUM · ORCA COMPUTING · DUALITY QUANTUM PHOTONICS · aegiq · TUNDRA SYSTEMS GLOBAL

14

XANADU · QUANFLUENCE

15

QCi · BOSON

16

# what should we have in FTQC roadmaps?

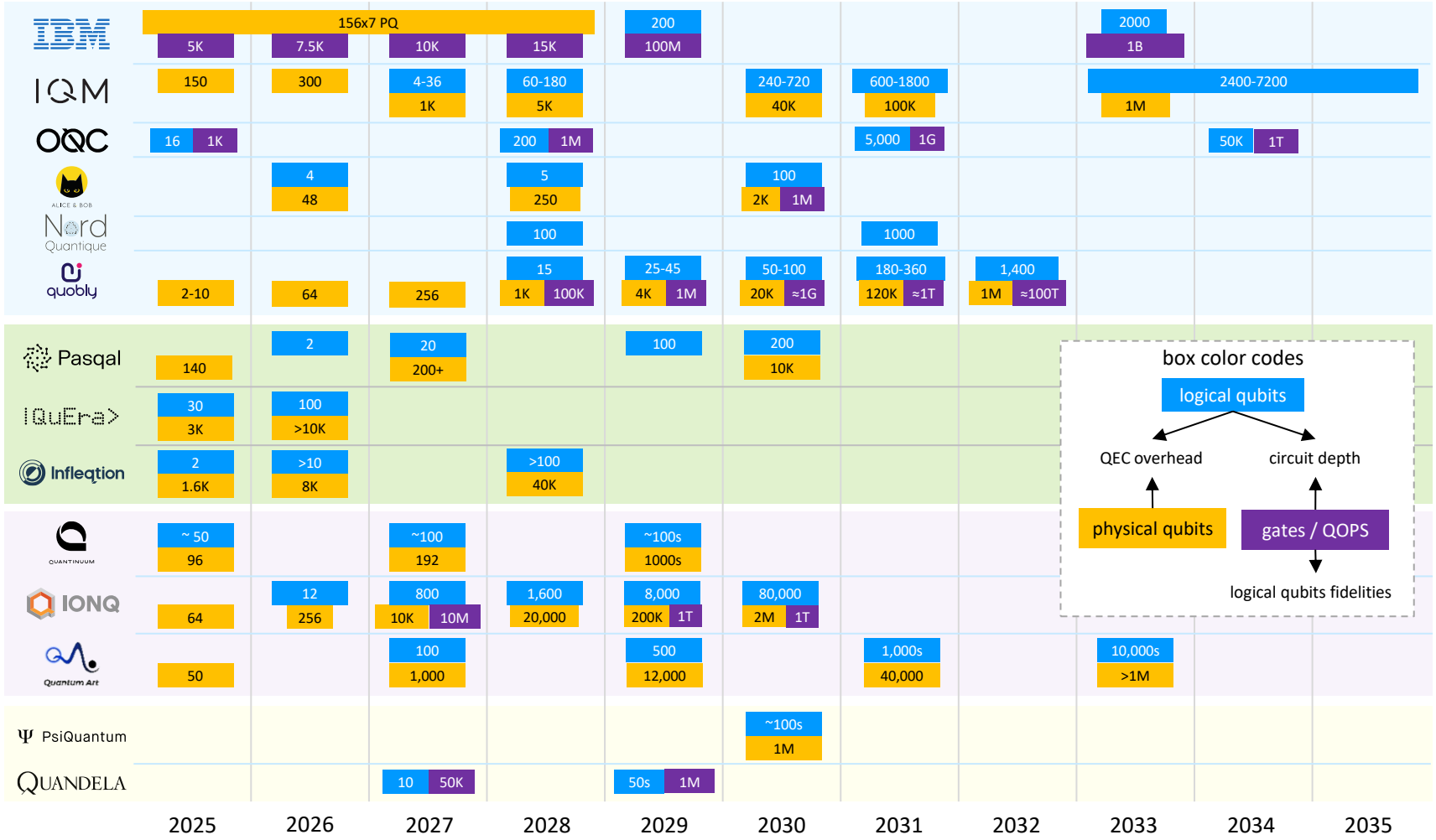
## bare minimum

- # logical qubits.
- supported circuit size / logical error rates.
- # physical qubits.

## nicer to have

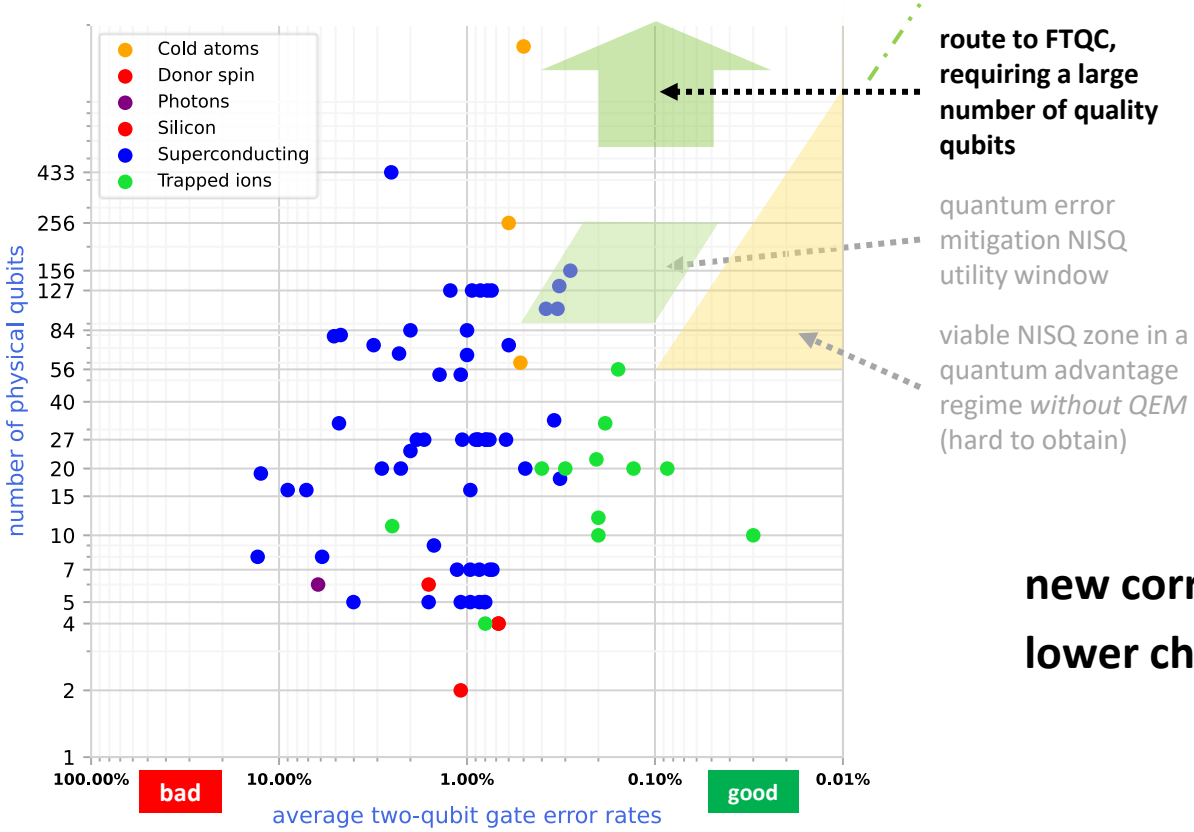
- clock speed and QLOPs/s.
- planned QEC codes and methods.
- processor size & reliance on QPU interconnect.
- peak power consumption in W.
- components operating temperature.
- QPU weight and size.
- operational constraints like temperature variability.
- components MTBF.
- capex/opex cost structure.

**operational metrics**




(cc) Olivier Ezratty, August 2025.

# challenge 1: **qubit *in*fidelities at scale**




**route to FTQC, requiring a large number of quality qubits**

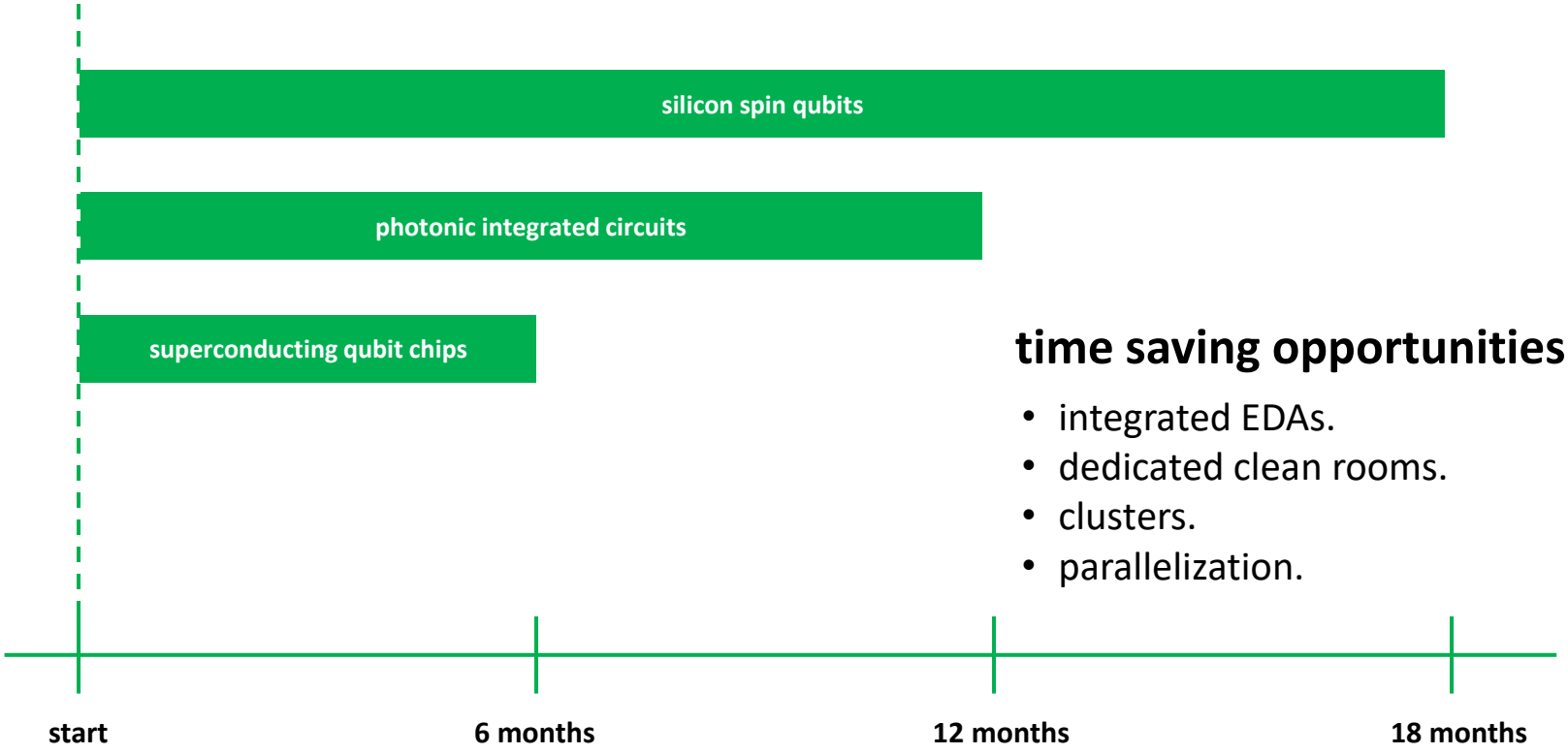
quantum error mitigation NISQ utility window

viable NISQ zone in a quantum advantage regime *without QEM* (hard to obtain)

**new correlated noise sources?**

**lower chips variability?**

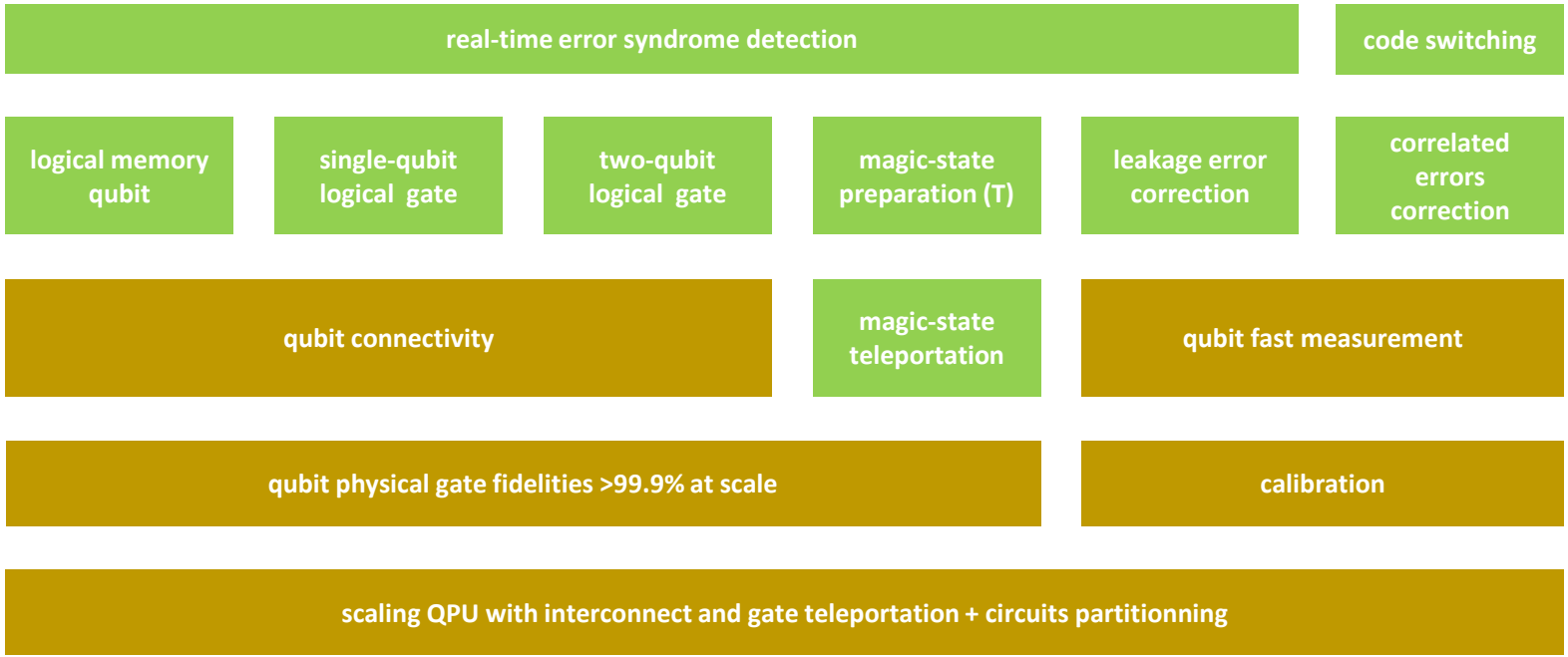
# challenge 2: **chips iteration cycles**




**time saving opportunities**

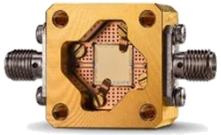
- integrated EDAs.
- dedicated clean rooms.
- clusters.
- parallelization.

# challenge 3: **quantum error correction**




**green**: QEC components.
**orange**: QEC enablers.

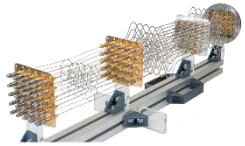
# challenge 4: **enabling technologies**



control and readout signals multiplexing ? control signals quality

room temperature electronics ? cryo-electronics ? cryogenics scaling

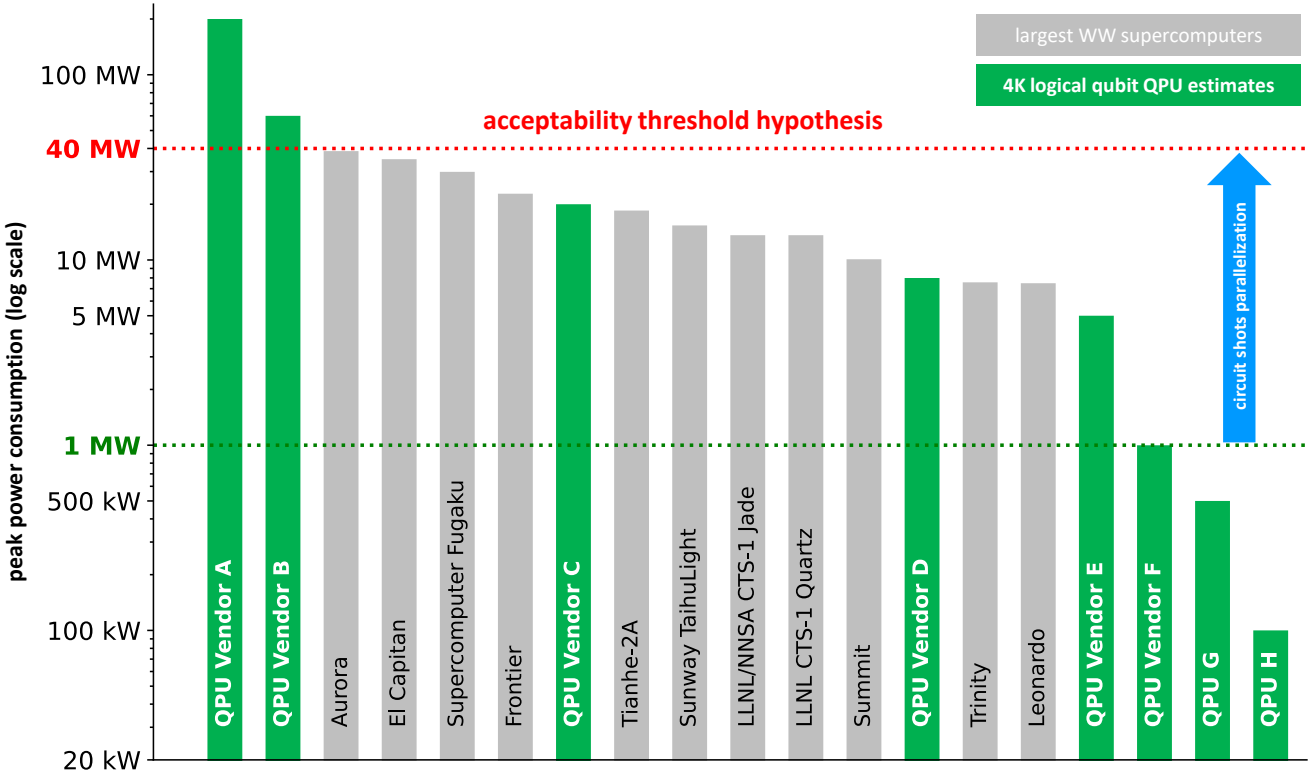
QPU scaling ? cabling scaling



manufacturing quality, crosstalk ? QPU interconnect ? mw/optical photons transduction

more powerful lasers ? laser phase noise

# challenge 5: **energetics**




estimate base power for various QPUs and actual for existing largest HPCs WW.
HPC source: https://www.top500.org/lists/top500/2024/06/.

#QEI
the quantum energy initiative

IEEE

**IEEE P3329 Quantum Energy Initiative (QEI) Working Group**

# challenge 6: **software stacks**

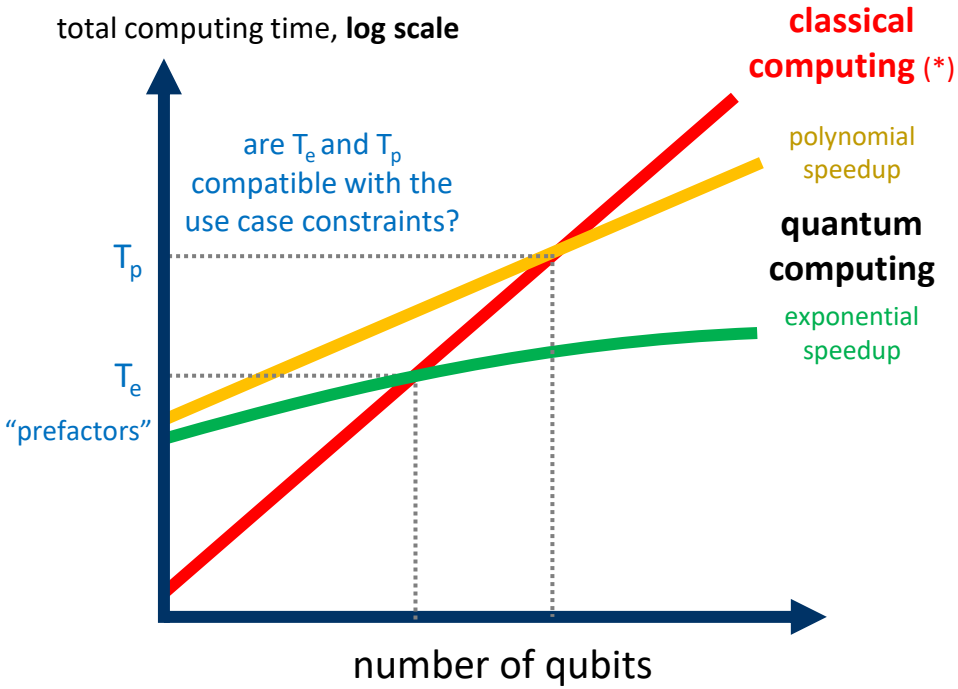
**practical vs theoretical speedups**

**compiler & optimizers scalability**

**classical pre- and post-processing costs** (chemistry)

**verification, certification, benchmarking.**

**classical computing progress** (MPS, DMRG).




inspired by Opening the Black Box inside Grover's Algorithm
by E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.
(*) for a fair comparison, the classical computer can be as expensive and/or energy hungry as the QPU.

# Europe early adopters - evaluators





















EuroHPC
Joint Undertaking





# bonus challenge: **geopolitics**

INDEX DECLARATION LINKS CYBER RISK

European Quantum Act | Updates

DARPA

Quantum Benchmarking Initiative

AFRL AIR FORCE RESEARCH LABORATORY

[dstl]

DIANA

DLR

DGA

ISO International Organization for Standardization

ETSI

CEN CENELEC

IEEE

⟨quantum|gov⟩

Department of Commerce Releases Export Controls on Quantum Technologies

POSTED ON SEPTEMBER 6, 2024

(September 6, 2024) A new rule regarding export controls for advanced technologies, including quantum technologies, has been published in the Federal Register. A brief summary of the key items of interest for quantum technologies is captured below. The controls are effective September 6, 2024, though there is a 60-day delay for some quantum related controls; see the links below for details.

# discussion

**get the slides**

***now***