CSC

The European hybrid HPC+AI+QC ecosystem

Quantum Autumn School 2025, Stockholm
3 Nov 2025 / Mikael Johansson, CSC

Why are we (as HPC centres) interested in quantum computing?

Quantum computers will not replace supercomputers

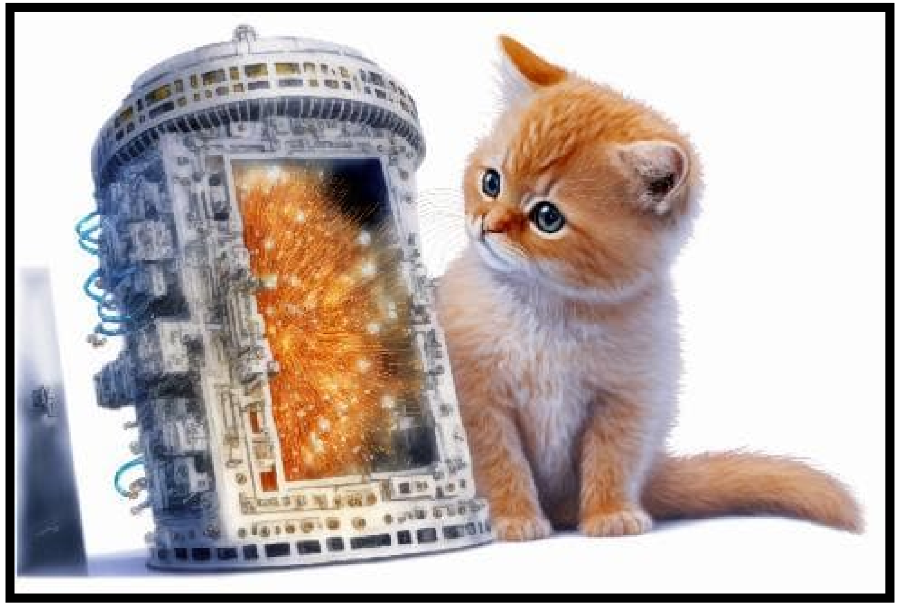
- Instead, the two will merge
- Important to stimulate **co-creation** between the HPC and QC communities

Our end-users will need early-access to HPC+QC in order to make their workflows quantum-ready

- The **transition from classical CPUs/GPUs to quantum QPUs** requires fundamental rethinking of problems and algorithms
- Requires time, resources, and support

HPC centres serve as natural starting points

- All the necessary basic services already in place:
    - User authentication and administration
    - Resource allocation and control
    - Storage, high-speed network, classical resources, …
- **End-users!**



Types of problems for QC

- QC is good with problems with a *moderate* amount of both input and output variables
- The **relation** between input and output should be a **highly complex equation** that can be solved efficiently by some quantum algorithm
    - QC typically excels at problems with a **large potential solution *space***, but only a small set or even **a single solution**
    - Additionally, the input parameters need to be of the same order of magnitude as the number of qubits of the quantum computer

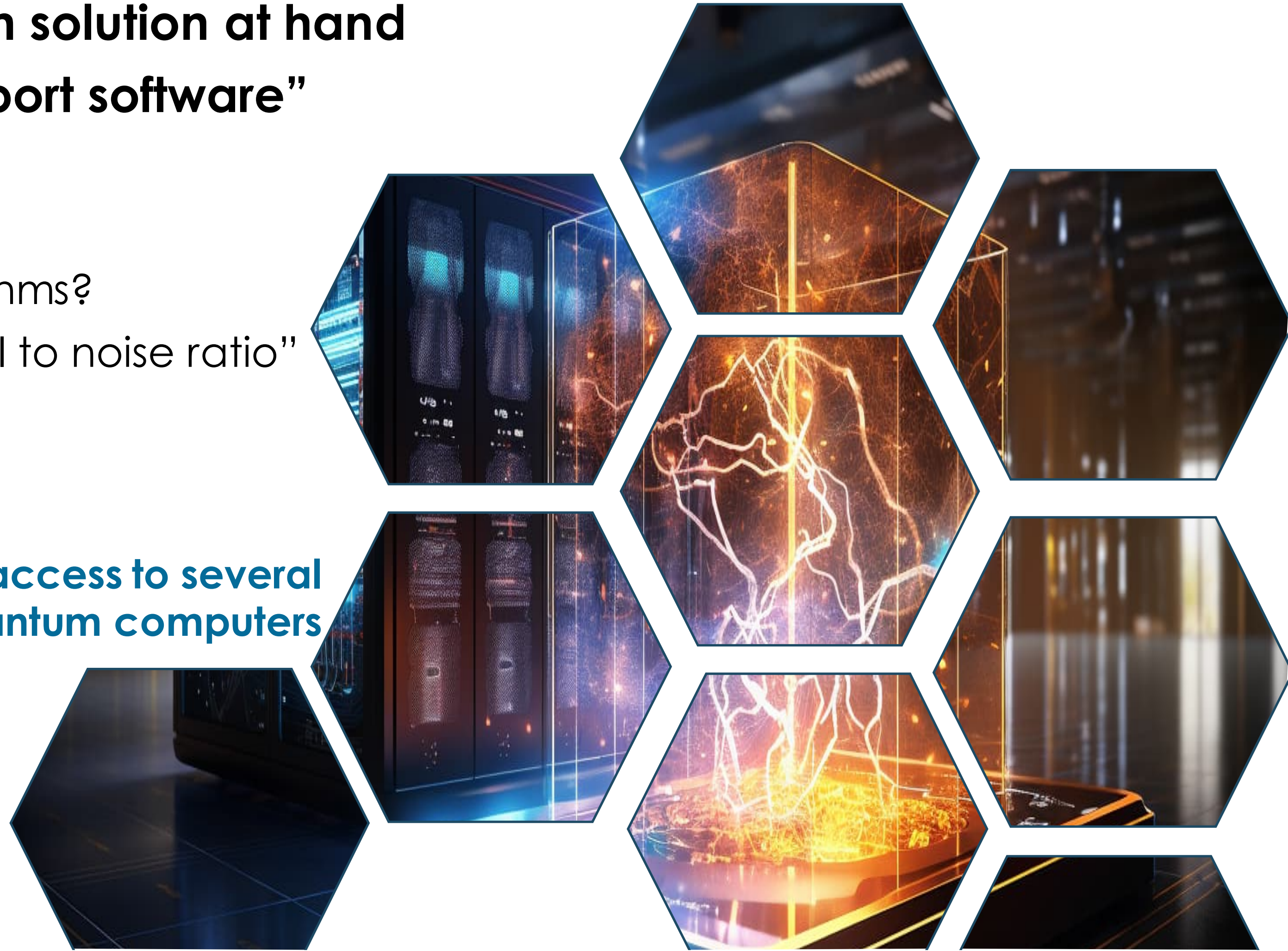
What is needed for quantum advantage

- **Deep understanding of the problem at hand:** classical modelling algorithms have been developed for a hundred years!
  - Need to know what the *actual* bottlenecks for present and future classical methods are and will be!
- **Deep understanding of the possible quantum solution at hand**
- **Understanding how to exploit "classical support software"**
  - **Pre- and postprocessing**
  - Compiling and transpiling quantum algorithms
  - Machine learning for creating quantum algorithms?
  - Error mitigation of the results, enhancing "signal to noise ratio"
- **Access to HPC+AI+QC infrastructure**

Quantum computers are different

- From classical supercomputers
- **From each other**

Users need access to several different quantum computers



CSC

The Role of Quantum Computing in Advancing Scientific High-Performance Computing: A perspective from the ADAC Institute

Gilles Buchs[a,*], Thomas Beck[a], Ryan Bennink[a], Daniel Claudino[a], Andrea Delgado[a], Nur Aiman Fadel[c], Peter Groszkowski[a], Kathleen Hamilton[a], Travis Humble[a], Neeraj Kumar[d], Ang Li[d], Phillip Lotshaw[a], Olli Mukkula[b], Ryousei Takano[e], Amit Saxena[f], In-Saeng Suh[a], Miwako Tsuji[g], Roel Van Beeumen[h], Ugo Varetto[i], Yan Wang[a], Kazuya Yamazaki[j], Mikael P. Johansson[b,*]

[a] *Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[b] *CSC - IT Center for Science, Espoo, Finland*
[c] *Swiss National Supercomputing Centre (CSCS), ETH Zurich, Zurich, Switzerland*
[d] *Pacific Northwest National Laboratory, Richland, WA, USA*
[e] *National Institute of Advanced Industrial Science and Technology (AIST), Tokyo, Japan*
[f] *Centre for Development of Advanced Computing (C-DAC)), Pune, India*
[g] *RIKEN Center for Computational Science, Kobe, Japan*
[h] *Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[i] *Pawsey Supercomputing Research Centre, Kensington, WA, Australia*
[j] *Information Technology Center, University of Tokyo, Tokyo, Japan*

15 Aug 2025

https://arxiv.org/abs/2508.11765

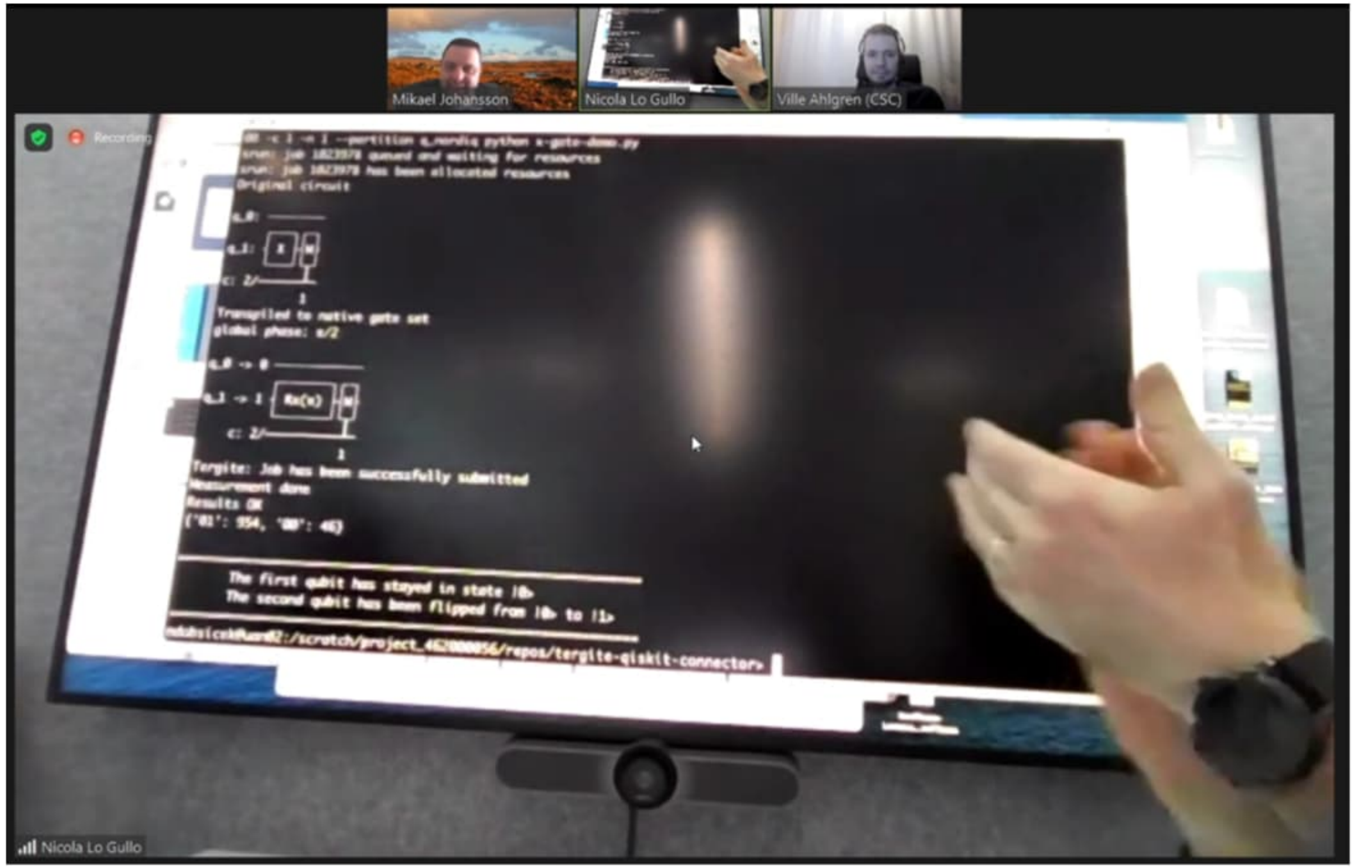
ADAC Members' Survey: One-slide Summary

- The survey reveals a **diverse and evolving landscape of QC infrastructure**
- Only a subset of institutions currently operate their own quantum computers, but many are developing testbeds or accessing quantum systems through cloud platforms
- **User interest** in QC varies significantly between institutions.
  - In some centers, demand is limited to a small group of researchers
  - Others report growing interest in fields such as quantum chemistry, materials science, optimization, and QML.
  - The immaturity of quantum hardware and the lack of clear, demonstrable advantages over classical methods remain significant barriers to broader adoption.
- A recurring theme: the **need for comprehensive training**
- QC is not yet a mainstream component of HPC infrastructure
  - The groundwork is being laid across multiple fronts, from hardware testbeds and cloud access to training programs and hybrid software stacks.
- The **lack of standardized software stacks and interoperability protocols** makes integration with existing HPC workflows complex and resource-intensive.

EuroHPC LUMI <-> Chalmers/WACQT QAL 9000

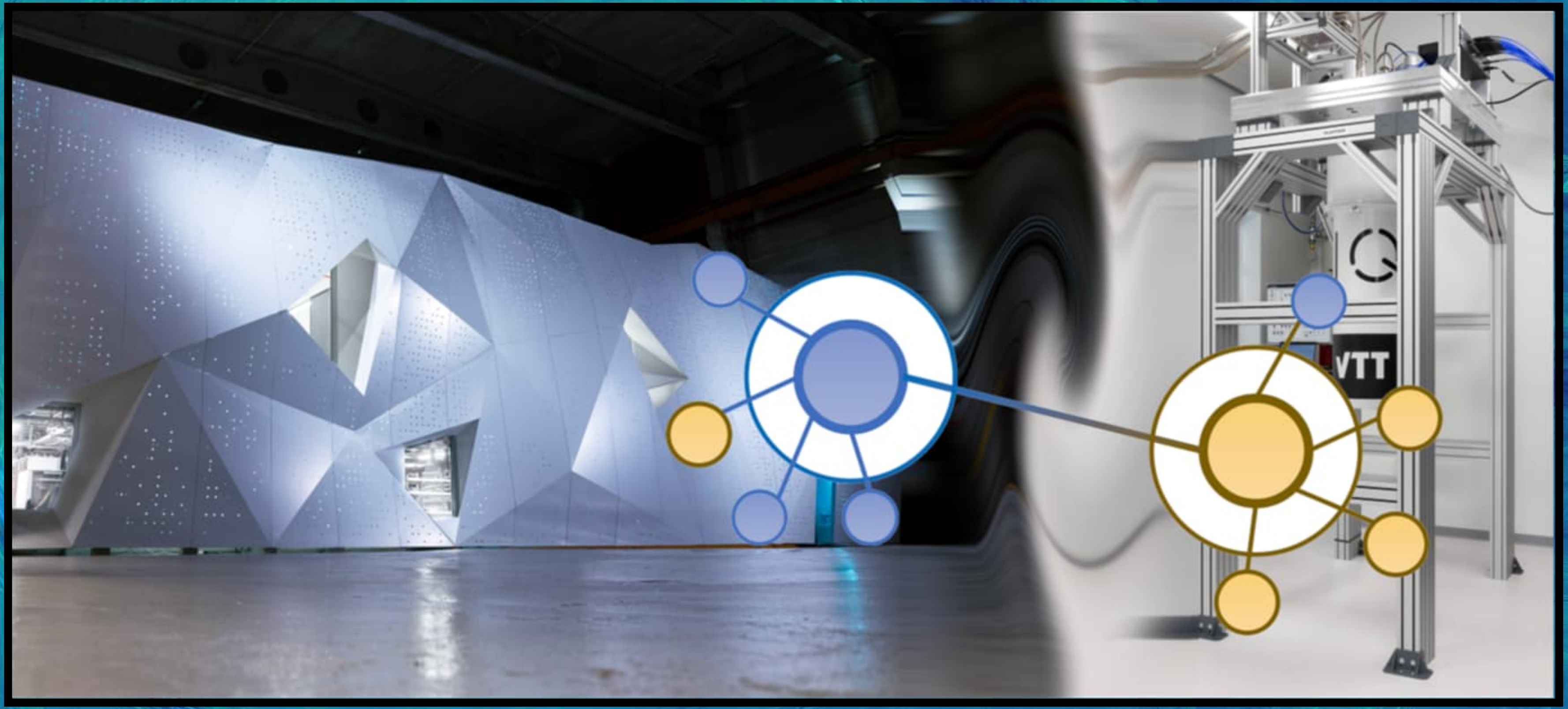
30.3.2022: First quantum job submitted through the LUMI queueing system

- Connected one LUMI-C node in Finland to the QAL 9000 QC in Sweden, and *successfully ran a **cross-border HPC+QC quantum job***



Henrik Nortamo (CSC), Nicola Lo Gullo (VTT/CSC)
Miroslav Dobsicek (Chalmers), Ville Ahlgren (CSC, zoom)

Considerations



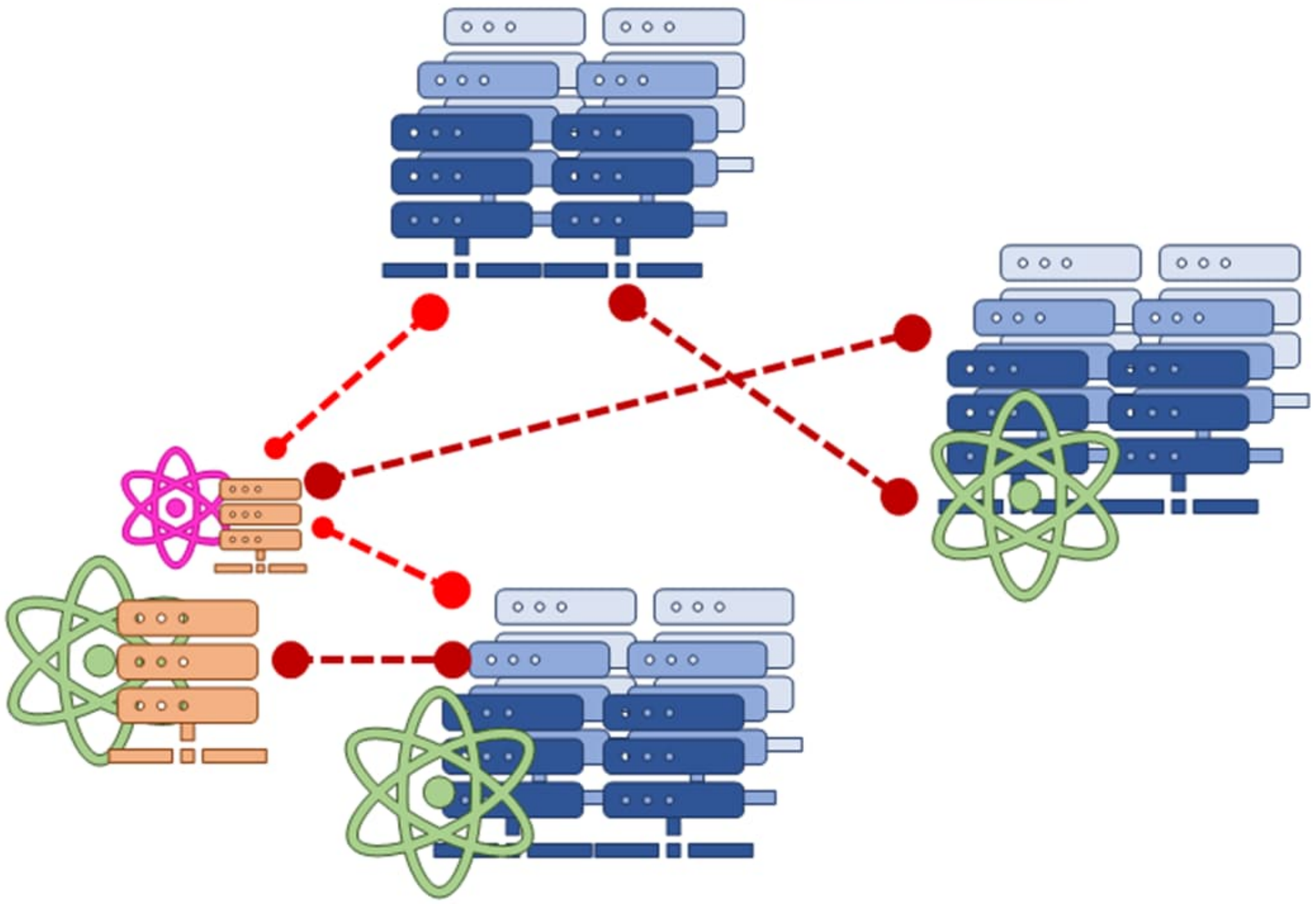
Goal

Set up a *general* protocol for connecting HPC and QC

- Several, generic HPC sites and infrastructures
- Several different quantum computers
- Located all around the globe

The protocol should be transferable with as few assumptions on the HPC or QC as possible

- **Open-source** development highly beneficial for adoption of the software-stack components
- Compare: Qiskit, QIR, CUDA-Q, Linux, …
- Open-source does *not* preclude IP protection!

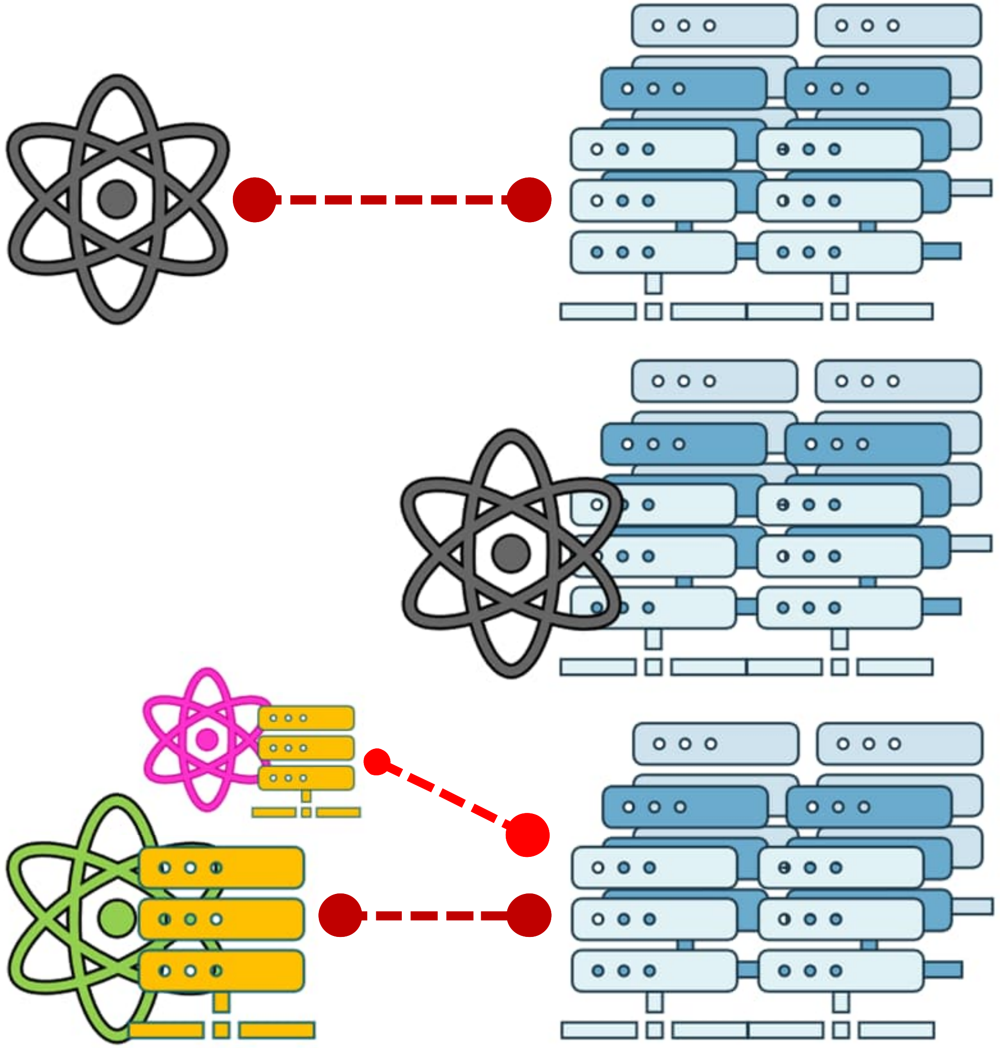


3 different ways of connecting HPC+QC

3 main ways to connect quantum and classical computers:

- **Stand-alone**, cloud access
- **Co-located** in the same premises
- **Distributed**, with QPU and HPC resources physically distant

Come with different levels of complexity for software stack



"Quantum Computing – A European Perspective" *PRACE* (2021)
https://doi.org/10.5281/zenodo.5547407

Importance of latency

DEPARTMENT: EXPERT OPINION

Quantum Computers for High-Performance Computing

Travis S. Humble, Alexander McCaskey, Dmitry I. Lyakh, and Meenambika Gowrishankar, *Quantum Computing Institute, Oak Ridge National Laboratory, Oak Ridge, TN, 37830, USA*

Albert Frisch, *Alpine Quantum Technologies, Innsbruck, 6020, Austria*

Thomas Monz, *Alpine Quantum Technologies, Innsbruck, 6020, Austria and also Institut für Experimentalphysik, Universität Innsbruck, Innsbruck, 6020, Austria*

IEEE Micro, vol. 41, no. 5, pp. 15-23, 1 Sept.-Oct. 2021

DOI: 10.1109/MM.2021.3099140

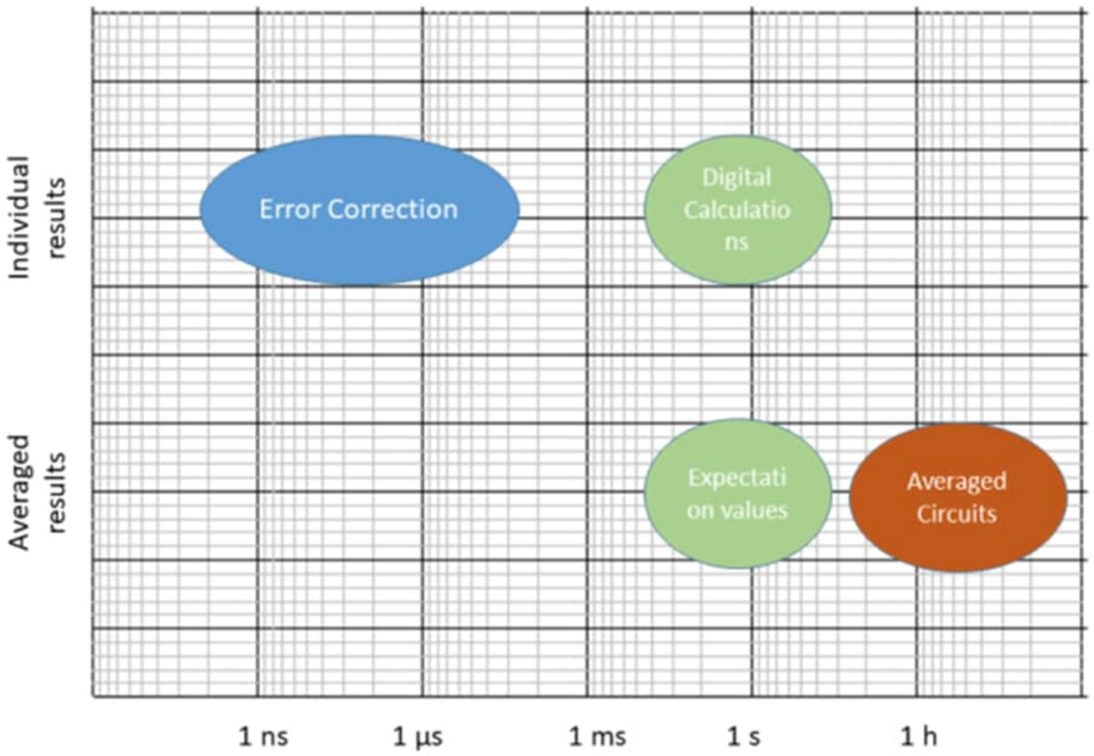


FIGURE 1. Applications of quantum computing categorized by typical execution times. Low-latency, in-sequence processing applications (blue) include quantum error correction and probabilistic state initialization methods that control decisions on nanosecond timescale. Single-circuit applications (green) only return at the end of computation on second timescales. Ensemble-circuit applications (orange), such as application benchmarking or device verification and validation of quantum devices, may take up to hours or more of computational time.

Authentication

Users should be able to submit jobs to the QC without sending identifiable user information from HPC to QC

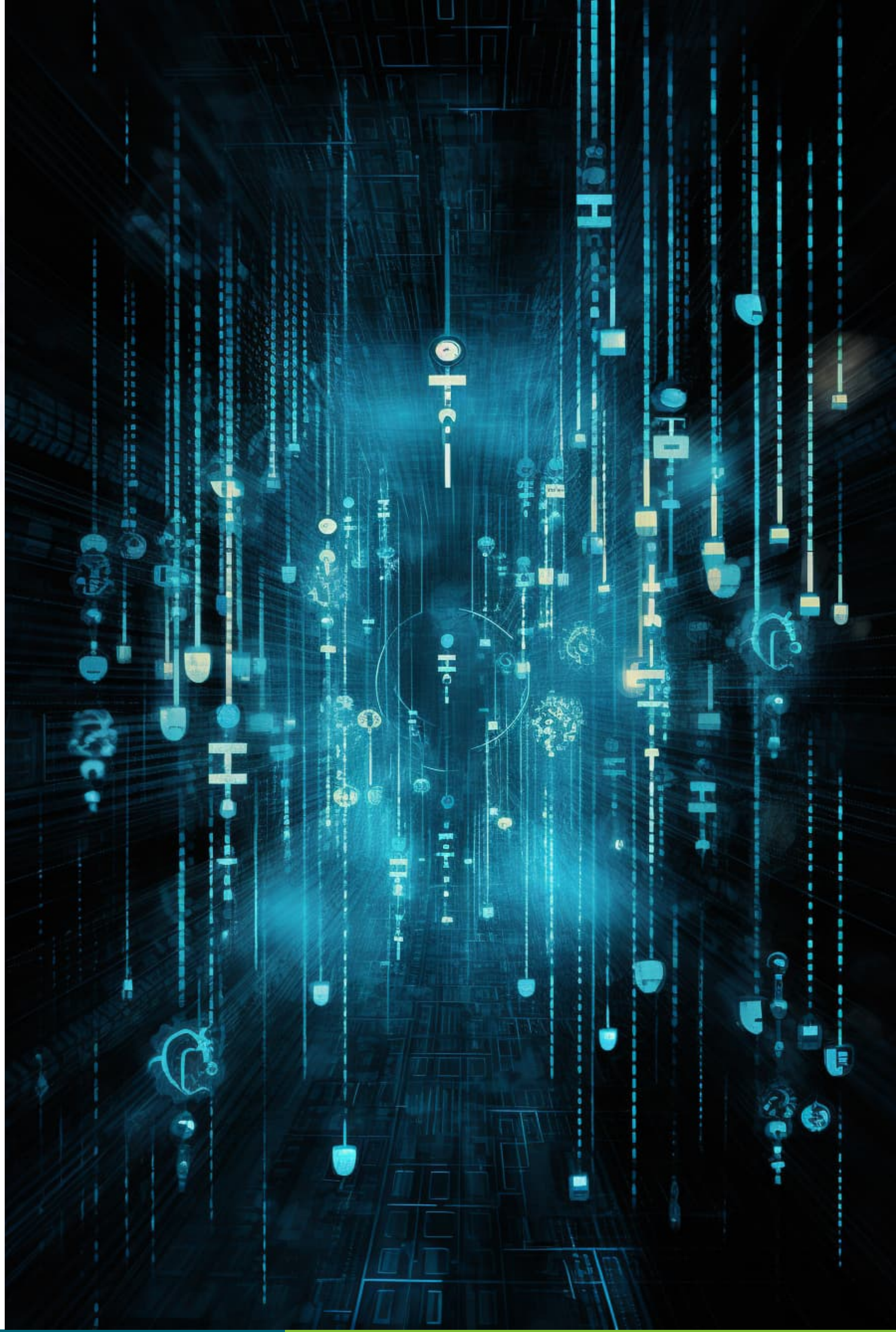
- Still has to allow for account and resource tracking of the HPC system and QC system

A meta-data scheme needed

- Associates an identifier (e.g., user id, job id, HPC site) to be used at QC site scheduling systems and resource tracking
- Calibration information, **Figures of Merit for researchers**

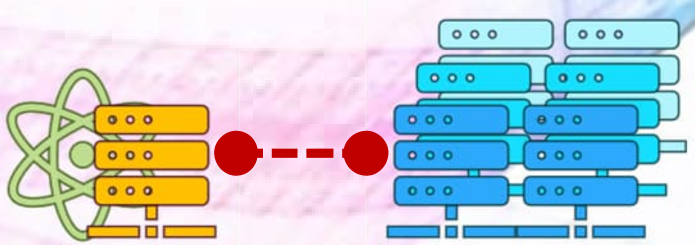
Pollable data

- A health-check of the QC and statistics
- Status: is the QC resource up or not? More details?



Data transfer between HPC <-> QC

Information on what to compute



1. Quantum-only circuit
2. Predefined variational algorithm
3. Fully user defined container to be run on “orange box”, custom variational jobs, intricate pulse configurations

→ **Data size kB to tens of GB**

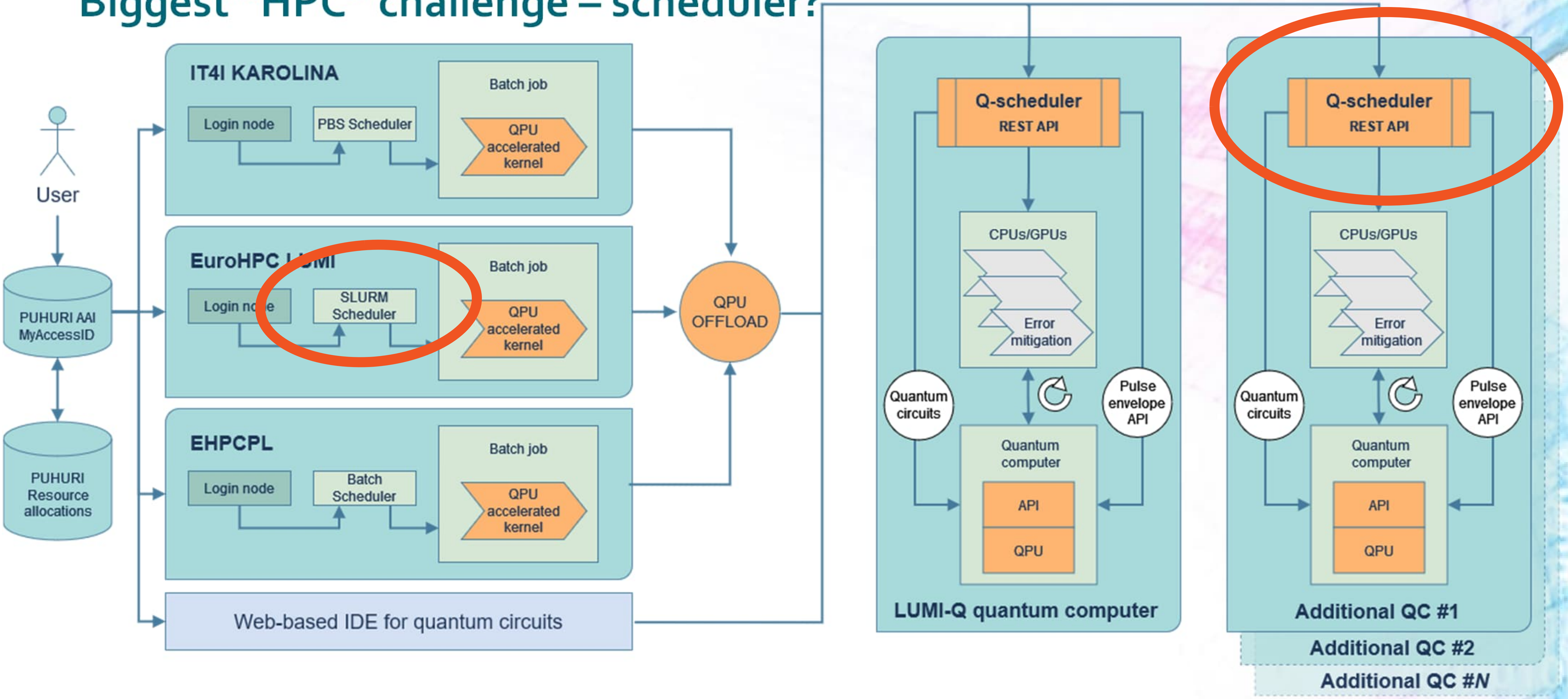
Real-time status

- Job cancelled/crashed on HPC
- Job cancelled/crashed on QC
- Calibration information, **Figures of Merit for researchers**

Resource tracking

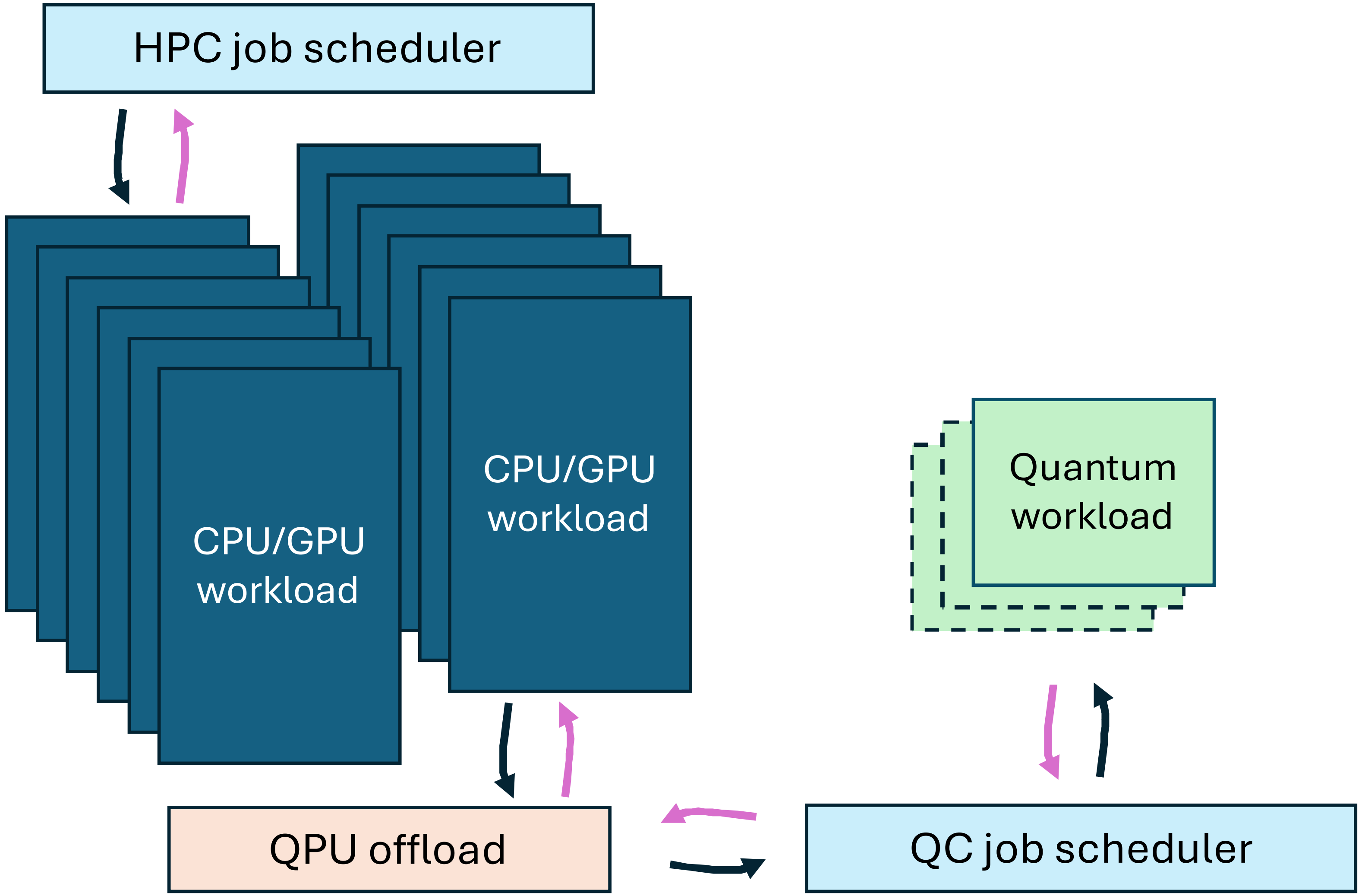
- QC needs to collect data and send to HPC

Biggest "HPC" challenge – scheduler?

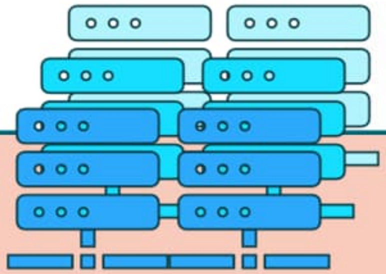


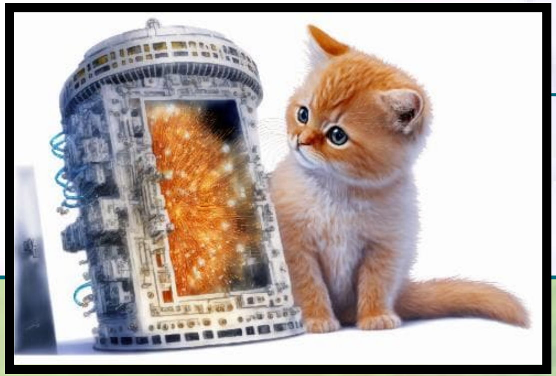
General execution of a hybrid classical HPC+QC task

- Need to couple two schedulers, HPC and QC
  - HPC resources abundant
  - QC resources scarce



Scheduling HPC+QC





HPC jobs

- Long runtimes
  - Scheduler can take its time when dispatching jobs
- Abundant resources
  - Moderate idling time no problem
- Users from one site
- Very diverse user scenarios

QC jobs

- Rather short runtimes
  - Scheduler needs to be very fast to keep up!
- Scarce resources
  - Any idle time a waste
- Users from several sites
- Very diverse user scenarios

Need top-level HPC scheduler and QC-bound meta-scheduler

Different user groups – different needs (and expectations)

1. Short, fully quantum jobs
    - Short circuits, educational use, pulse testing, …

easy

2. Variational HPC+QC loops
    - Rather “well-behaved” from a scheduler POV

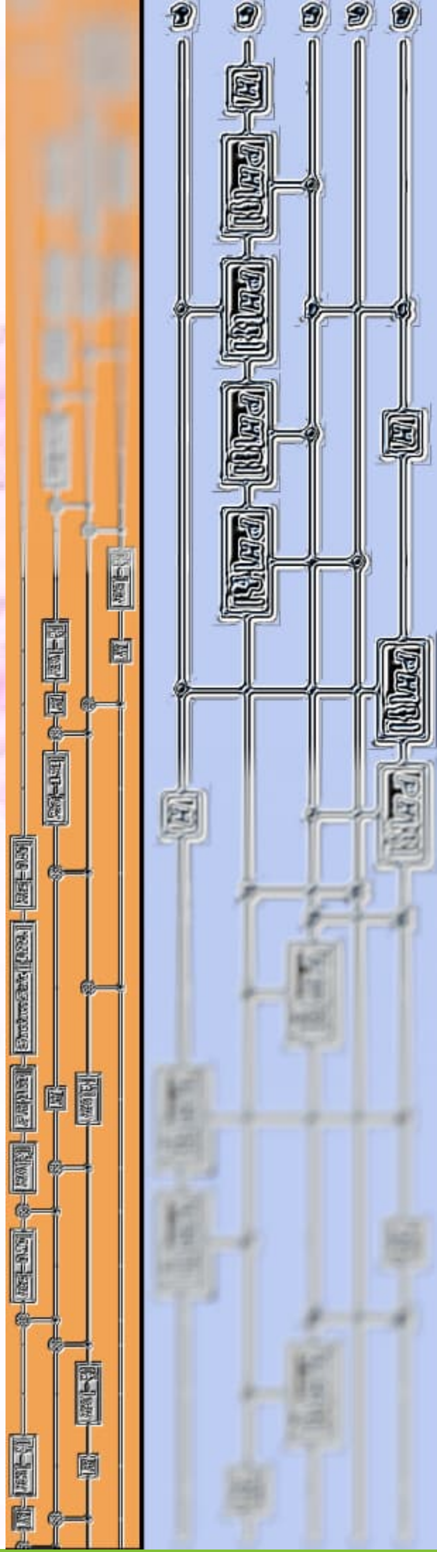
quite easy

3. Hybrid HPC+QC with “unbalanced” HPC/QC consumption
    - Long HPC runs interrupted by calls to QC in one job

difficult

4. Long (even days), almost fully quantum jobs
    - For example, using the QC as a simulator for physics
    - HPC pre- and post-processing

quite easy

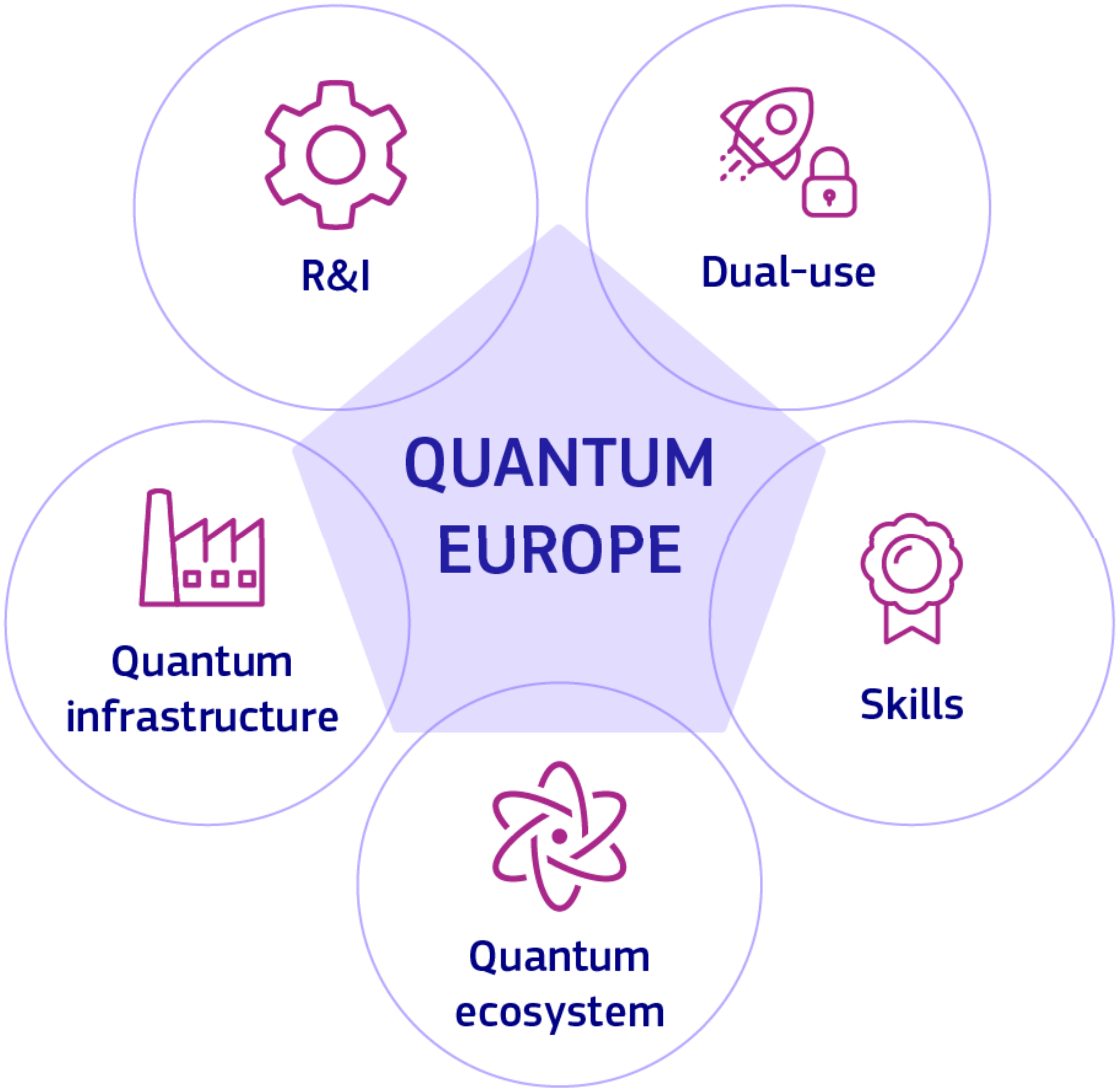


July 2025: Europe's Q Strategy

- The **will** has been expressed
- https://digital-strategy.ec.europa.eu/en/library/quantum-europe-strategy

"Europe is currently lagging behind in translating its innovation capabilities and future potential into real market opportunities."

- The **way** to be defined (Quantum Act, Q2/2026)
- Provides EU level support
- Does not replace more regional efforts!



LUMI-Q

- LUMI-Q consortium
- LUMI consortium
- LUMI-Q quantum computer
- quantum computer
- supercomputer

Inclusive

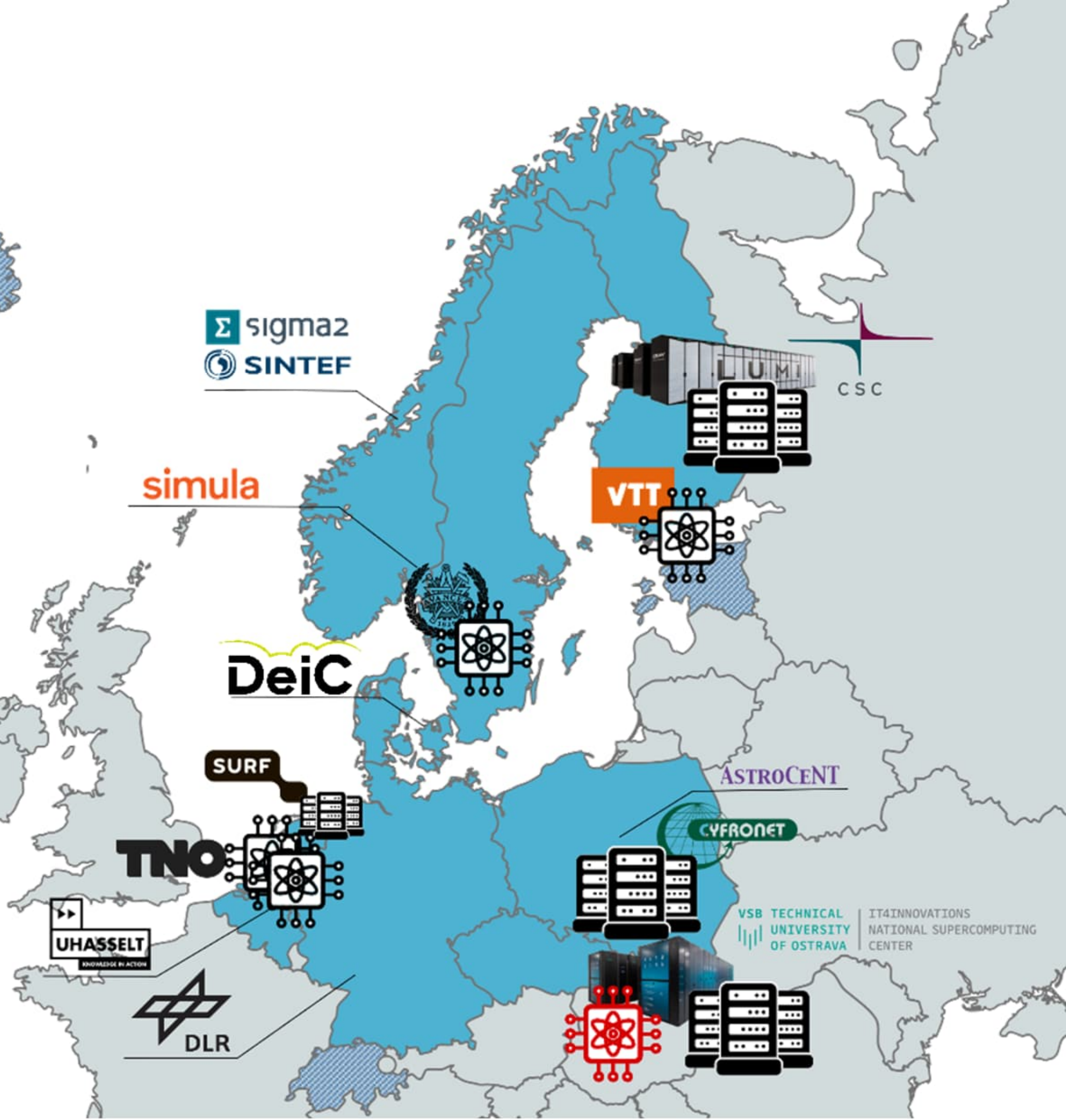
- Builds on the 11-country pan-European LUMI consortium

Diverse

- Getting several QCs to the fingertips of researchers and developers is crucial for catalysing software development.
- Different problems will fit different architectures **and software stack infrastructure** better

Accessible

- By being available through several platforms distributed throughout Europe, LUMI-Q provides a familiar interface to a uniquely large user base



LUMI-Q – A novel topology for highly entangled algorithms

Unique star topology

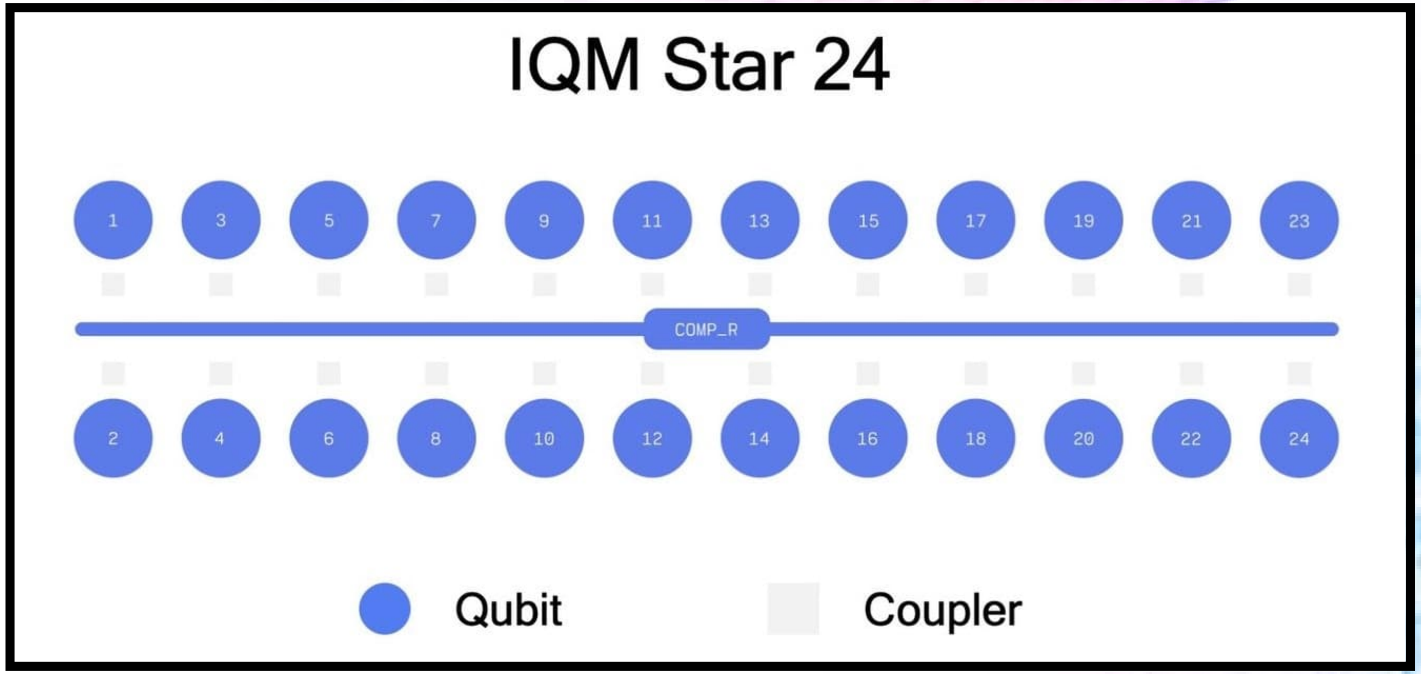
- One-to-all qubit connectivity
- Significantly decreases the number of SWAP gates in quantum circuits

Especially suitable applications

- Highly entangled states
- Needed, *e.g.*, for quantum machine learning (QML) and quantum AI
- Quantum error correction
- Practically *all* quantum algorithms benefit

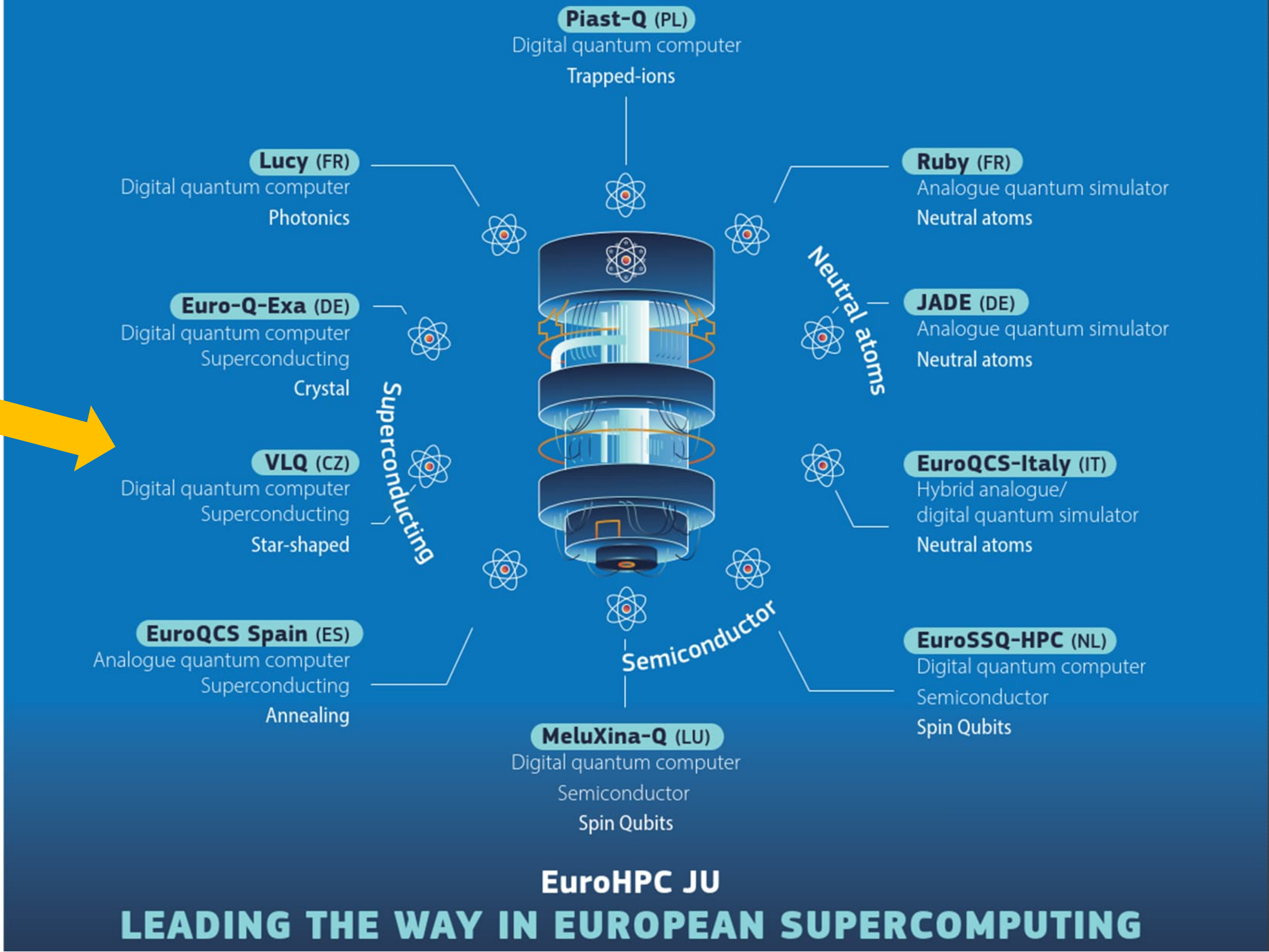
Testing platform

- Provides use-case developers an advanced platform for deploying, testing, and trialing new methods




VLQ
VLQ
VLQ QUANTUM COMPUTER INAUGURATION
23 September 2025

The full EuroHPC QC family will be available to Europe



LUMI AI Factory

LUMI AI Factory

- The three pillars of LUMI AI Factory
  - AI-optimised supercomputer **LUMI-AI**
  - AI Factory **Service Center**
  - Experimental quantum-computing platform **LUMI-IQ**
- CSC (Finland) coordinates consortium with participation from Czechia, Denmark, Estonia, Norway and Poland
  - Other Finnish partners are FCAI (Aalto University, University of Helsinki) and AI Finland (Technology industries)
- Total budget over 612 million euros
  - EU 306.4 M€, FI 250 M€, CZ 11 M€, DK 10 M€, EE 5 M€, NO 20.4 M€, PL 10 M€
  - largest public computing ecosystem investment in Finland, among the largest in Europe
  - largest EuroHPC AI Factory investment
- Significant investment in talent and competence development

LUMI-IQ

Advanced AI-Optimised
Experimental Platform

LUMI-IQ: Quantum-enhanced AI within the LUMI-AI Factory

Set up a world-leading HPC+AI+QC infrastructure

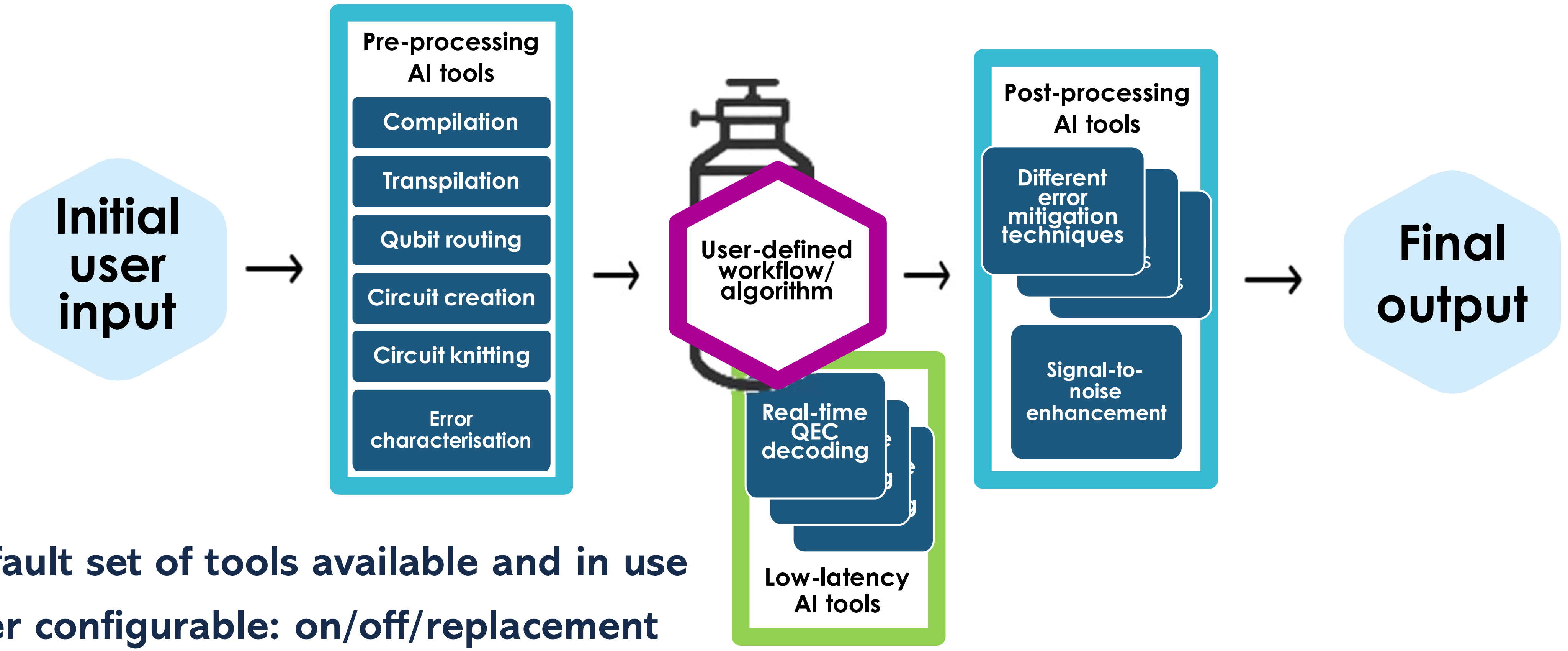
Accelerate AI development	Quantum AI software development and classical AI software development for quantum computing enhancement will get a significant boost from gaining **access to world-class HPC+AI+QC infrastructure.**
Establish new high-value commercial activities	The LUMI-IQ infrastructure, including user support and vetted use case libraries, will **aid industry in adopting quantum-accelerated AI** solutions in their service delivery, research, development, and innovation activities.

Accelerate development and uptake of useful QML and Quantum AI methodology, such as:

- Quantum Neural Networks (QNNs)
- Quantum Reinforcement Learning (QRL)
- Quantum Reservoir Computing (QRC)
- …

AI for QC

Goal: Set up a comprehensive supporting-software framework for quantum computing



- Default set of tools available and in use
- User configurable: on/off/replacement

Towards FTQC

Quantum Error Correction (QEC) is coming

Real-time decoding of the gross code memory with FPGAs.

Thilo Maurer*[1], Markus Bühler[1], Michael Kröner[1], Frank Haverkamp[1], Tristan Müller[1], Drew Vandeth[1], and Blake R. Johnson[1]

[1]IBM Quantum

Oct 24, 2025

Abstract

We introduce a prototype FPGA decoder implementing the recently discovered Relay-BP algorithm and targeting memory experiments on the $[[144, 12, 12]]$ bivariate bicycle quantum low-density parity check code. The decoder is both fast and accurate, achieving a belief propagation iteration time of 24ns. It matches the logical error performance of a floating-point implementation despite using reduced precision arithmetic. This speed is sufficient for an average per cycle decoding time under $1\,\mu$s assuming circuit model error probabilities are less than 3×10^{-3}. This prototype decoder offers useful insights on the path toward decoding solutions for scalable fault-tolerant quantum computers.

Platform Architecture for Tight Coupling of High-Performance Computing with Quantum Processors

SHANE A. CALDWELL, MOEIN KHAZRAEE, ELENA AGOSTINI, TOM LASSITER, COREY SIMPSON, OMRI KAHALON, MRUDULA KANURI, JIN-SUNG KIM, SAM STANWYCK, MUYUAN LI, JAN OLLE, CHRISTOPHER CHAMBERLAND, BEN HOWE, BRUNO SCHMITT, JUSTIN G. LIETZ, and ALEX MCCASKEY, NVIDIA Corporation, USA

JUN YE, Institute of High Performance Computing (IHPC), Agency for Science, Technology and Research (A*STAR), Singapore

ANG LI, Pacific Northwest National Laboratory, USA and University of Washington, USA

ALICIA B. MAGANN, COREY I. OSTROVE, KENNETH RUDINGER, ROBIN BLUME-KOHOUT, and KEVIN YOUNG, Quantum Performance Laboratory, Sandia National Laboratories, USA

NATHAN E. MILLER, Lincoln Laboratory, Massachusetts Institute of Technology, USA

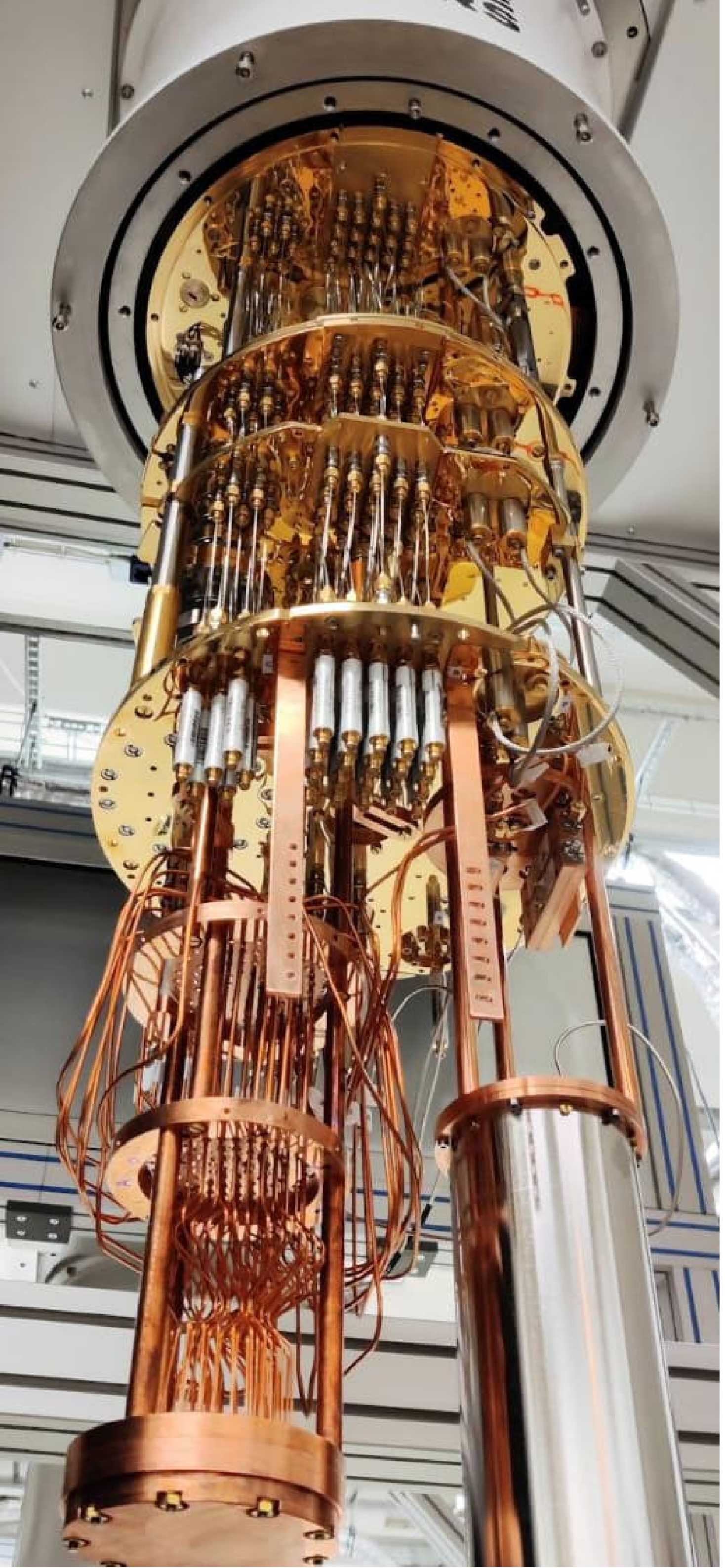
YILUN XU and GANG HUANG, Lawrence Berkeley National Laboratory, USA

IRFAN SIDDIQI, University of California, Berkeley, USA and Lawrence Berkeley National Laboratory, USA

JOHN LANGE, Oak Ridge National Laboratory, USA and University of Pittsburgh, USA

CHRISTOPHER ZIMMER and TRAVIS HUMBLE, Oak Ridge National Laboratory, USA

We propose an architecture, called NVQLink, for connecting high-performance computing (HPC) resources to the control system of a quantum processing unit (QPU) to accelerate workloads necessary to the operation of the QPU. We aim to support every physical modality of QPU and every type of QPU system controller (QSC). The HPC resource is optimized for real-time (latency-bounded) processing on tasks with latency tolerances of tens of microseconds. The network connecting the HPC and QSC is implemented on commercially available Ethernet and can be adopted relatively easily by QPU and QSC builders, and we report a round-trip latency measurement of 3.96 μs (max) with prospects of further optimization. We describe an extension to the CUDA-Q programming model and runtime architecture to support real-time callbacks and data marshaling between the HPC and QSC. By doing so, NVQLink extends heterogeneous, kernel-based programming to the QSC, allowing the programmer to address CPU, GPU, and FPGA subsystems in the QSC, all in the same C++ program, avoiding the use of a performance-limiting HTTP interface. We provide a pattern for QSC builders to integrate with this architecture by making use of multi-level intermediate representation dialects and progressive lowering to encapsulate QSC code.



Summary

- **HPC+AI+QC is the future HPC**
  - For the vast majority of modelling problems, massive need for HPC and AI even with QC
- **Hardware is nothing without software**
  - We need new quantum algorithms, new ways of utilising existing quantum algorithms, and plenty of classical software
- **Complementary to QC cloud offerings: true integration with HPC and AI**
  - Including quantum computing provides two-way synergies
- **We need to be user centric!**
  - Active engagement, training, example use cases, …

CSC

Mikael Johansson

Manager, Quantum Technologies
mikael.johansson@csc.fi

linkedin.com/in/mikael-p-johansson

facebook.com/CSCfi

twitter.com/CSCfi

youtube.com/CSCfi

linkedin.com/company/csc---it-center-for-science

github.com/CSCfi