Introduction to Quantum Computing and hybrid HPC+QC systems
8-9 June 2022

Three different ways of connecting HPC and QC

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NordIQuEst
ENCCS
EuroCC National Competence Centre Sweden

Funded by the European Union
NextGenerationEU

neic
10 YEARS OF NORDIC COLLABORATIONS

What is a quantum computer *not*?

A quantum computer is *not* a super-fast version of a classical computer —
It is *different*

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Supercomputers ♡ quantum

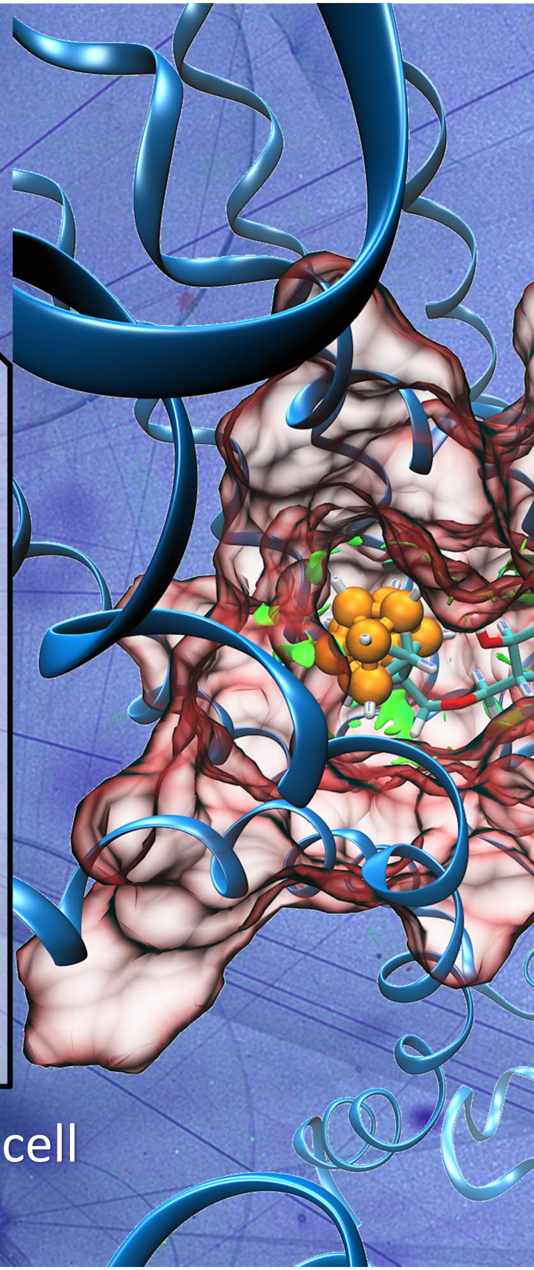
- Quantum computers will not replace supercomputers, but instead the two will *merge*
- LUMI is the most powerful supercomputer in Europe
  - 20% reserved for industry!

The LUMI supercomputer and the Helmi quantum computer
Photos: Fade Creative and VTT

- Through NordIQuEst, researchers will have access to one of the most powerful *hybrid* **HPC+*n*QC** resources in the world, available for **quantum accelerated research and development**
  - Also a real opportunity to raise the level of quantum software know-how in the Nordics!

Typical HPC+QC applications in the near-term

- **Electronic structure problems**
  - Do the best initial guess HPC is capable of, then refine further with quantum computing
  - The electronic structure needs to be very complex for QC to show advantage in the near-term!
- **Optimisation problems**
  - Compare solutions: if QC found a better one, great!
- **Machine learning and big data**
  - Part of ML/AI workflows can be sped-up by QC; in addition to additional computing power, HPC provides storage and bandwidth for large data sets



Drug molecule attacking a cancer cell

HPC and quantum computing

- In the future, quantum computers, QPUs, can accelerate HPC workflows

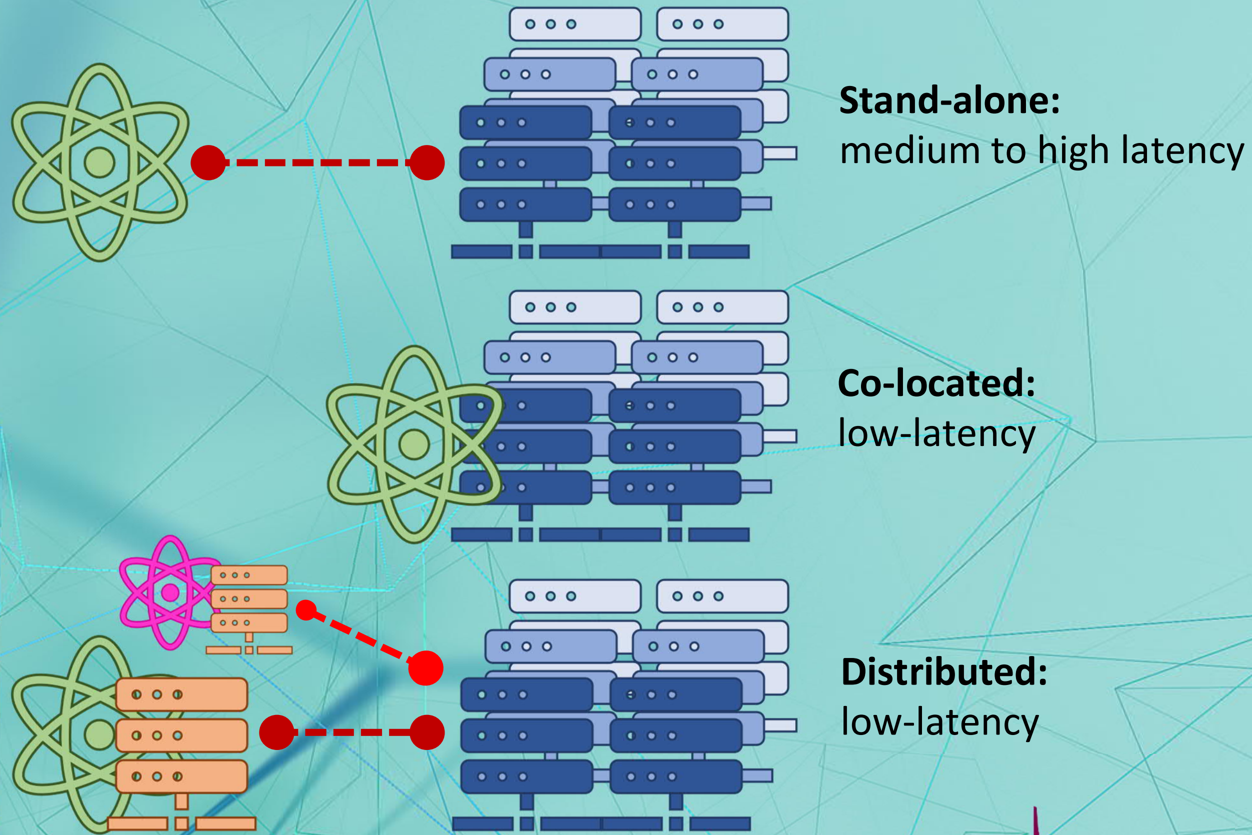
  → **quantum computing resources and HPC resources have to be coupled**
- Coupling HPC and QC resources is already taking place in several European HPC centres: **also NordIQuEst has already run its first quantum job!**
- Expected that the demand for QC resources will become "standard" among users of *most* HPC centres
- Here, a look at three different ways of connecting QC with an HPC centre
- In all, the HPC centre provides the "basic" services: **identity management, resource allocation, HPC capacity, storage solutions, …**

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)
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Latency and hybrid algorithms

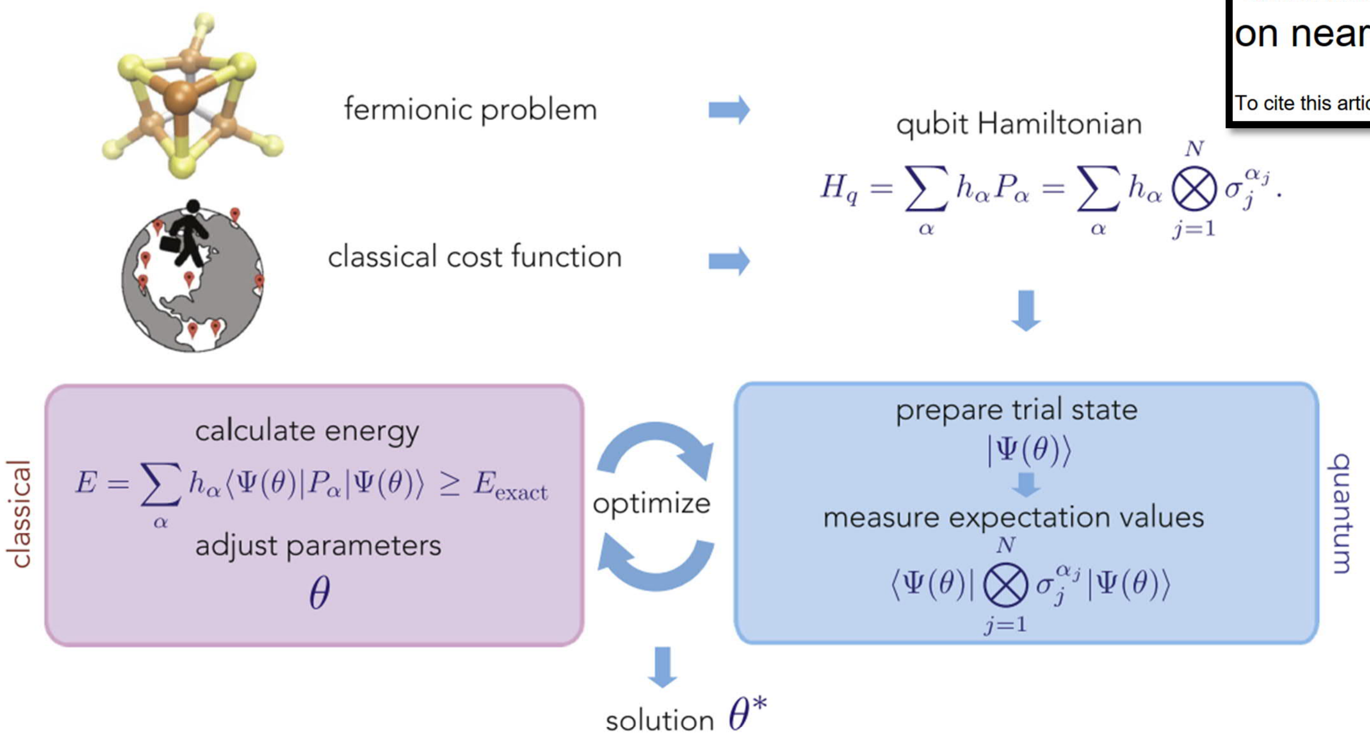


Figure 3. Variational quantum eigensolver method. The trial states, which depend on a few classical parameters $\boldsymbol{\theta}$, are created on the quantum device and used for measuring the expectation values needed. These are combined on a classical computer to calculate the energy $E_q(\boldsymbol{\theta})$, i.e. the cost function, and find new parameters $\boldsymbol{\theta}$ to minimize it. The new $\boldsymbol{\theta}$ parameters are then fed back into the algorithm. The parameters $\boldsymbol{\theta}^*$ of the solution are obtained when the minimal energy is reached.

Quantum optimization using variational algorithms on near-term quantum devices

To cite this article: Nikolaj Moll *et al* 2018 *Quantum Sci. Technol.* **3** 030503

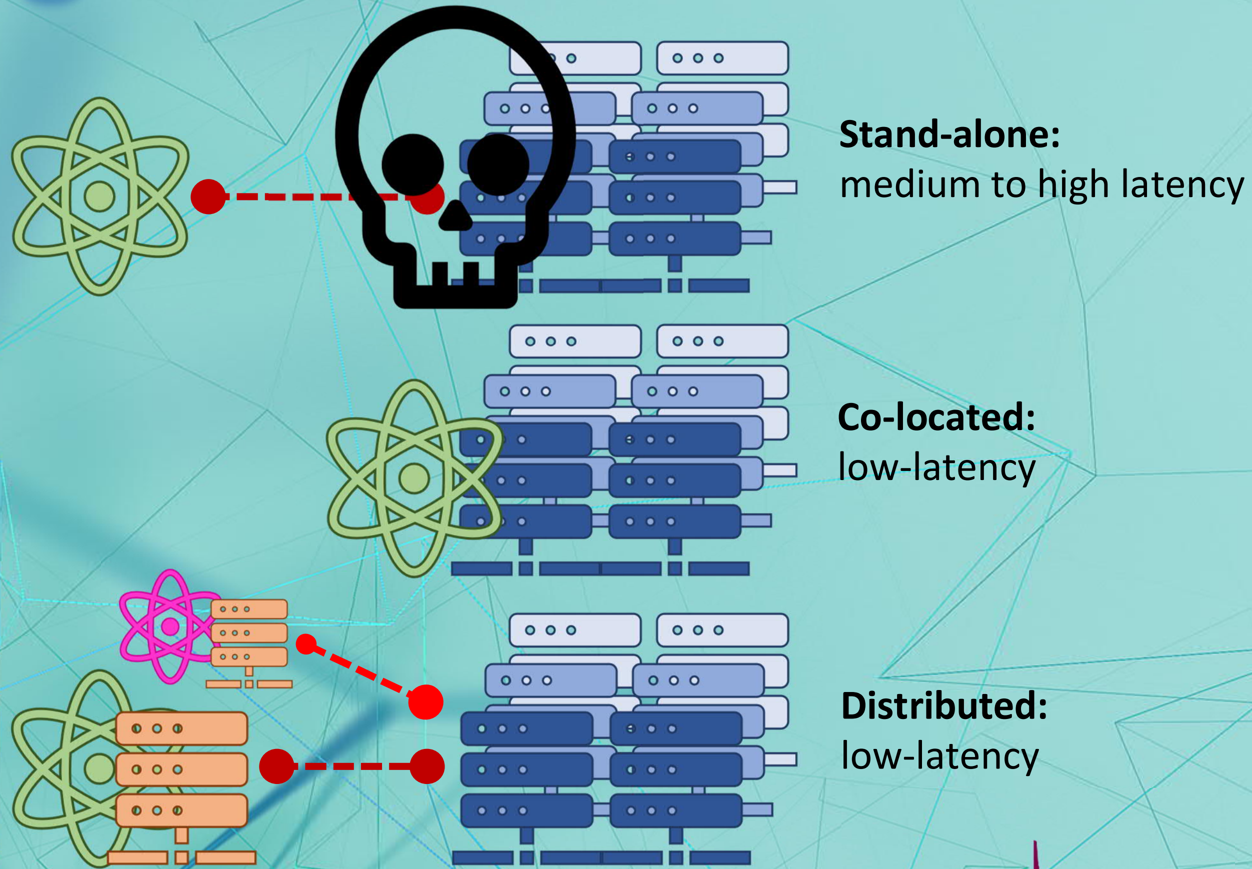
DOI: 10.1088/2058-9565/aab822

- When the quantum block *and* the classical block are fast, communication has to be even faster to avoid bottlenecks!
- **With present QPUs, decoherence *forces* the quantum block to be fast!**

Latency and hybrid algorithms

For quick loops, stand-alone creates too much overhead

- A classical processing unit needs to physically close, to **keep feeding the QPU with new input**
- **This is, however, not an HPC task**, a powerful server is more than enough



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Latency and hybrid algorithms

When QPUs mature to provide actual quantum advantage, run times of the quantum block will increase

For example Quantum Approximate Optimization Algorithms (QAOAs) are expected to require circuit depths well beyond what is presently possible

When they *do* become possible, latency becomes less important

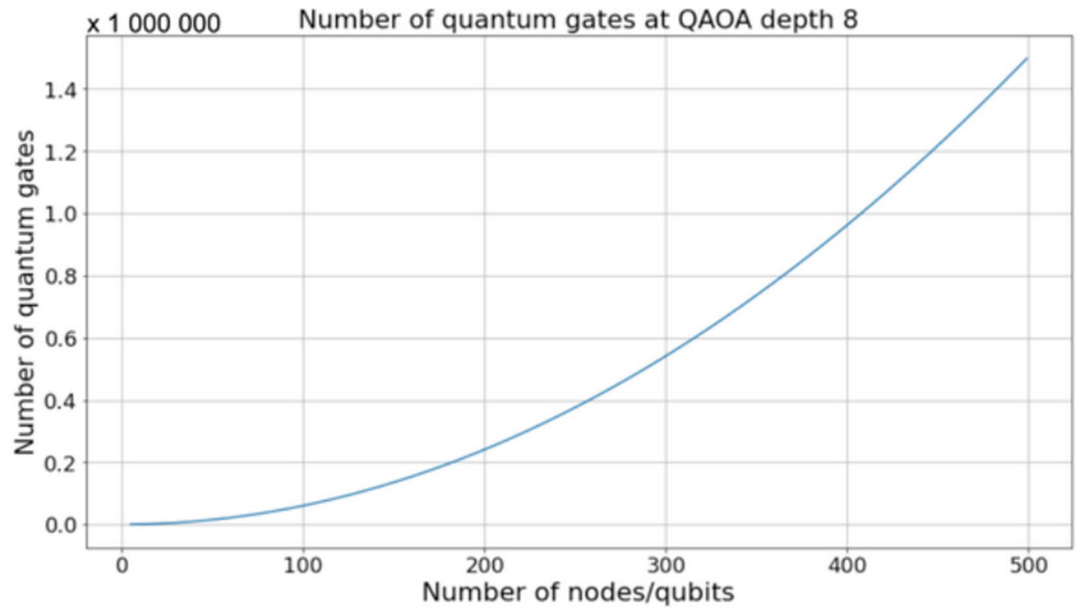
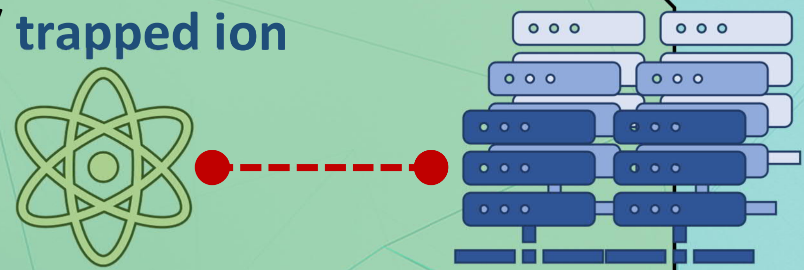


Figure 3. Achieving quantum advantage is likely to require about 500 qubits, rapidly increasing the circuit depth to millions of gates.

https://www.csc.fi/en/-/emulated-quantum-noise

Execution times of algorithms

Execution times of gate operations: superconducting / trapped ion



- 1-qubit gates: 20-25 ns / 15 µs
- 2-qubit gates: 15-300 ns / 66-200 µs

➔ **Execution time of 1,000,000 gates**

- Assuming average of 100 ns/gate: 100,000,000 ns = **100 ms**

This is for just *one* execution of the quantum circuit!

- usually one repeats the run 100-10,000 times for statistically relevant results

Signal in fibre travels at around 200,000 km/s -> around the Earth in 200 ms

➔ **The classical server does not need to be *very* close**

Values kindly provided by Hempel Cornelius / PSI.CH

Co-located and distributed

- Low-latency *can* be important also in the future, when QCs mature
- A separate server or HPC node can take care of the classical computing that requires low-latency
- Straightforward approach: **co-location**
  server = HPC node
- More involved: **distributed**

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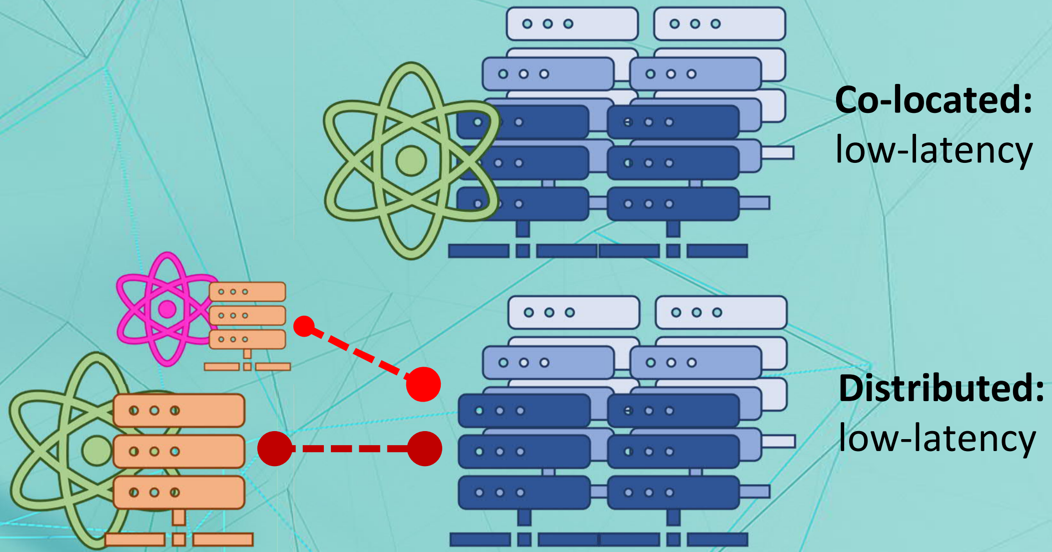
LUMI-Q



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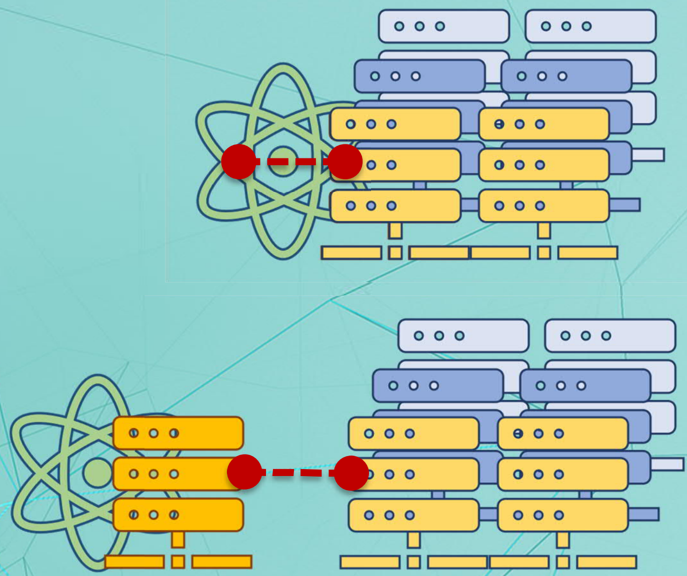

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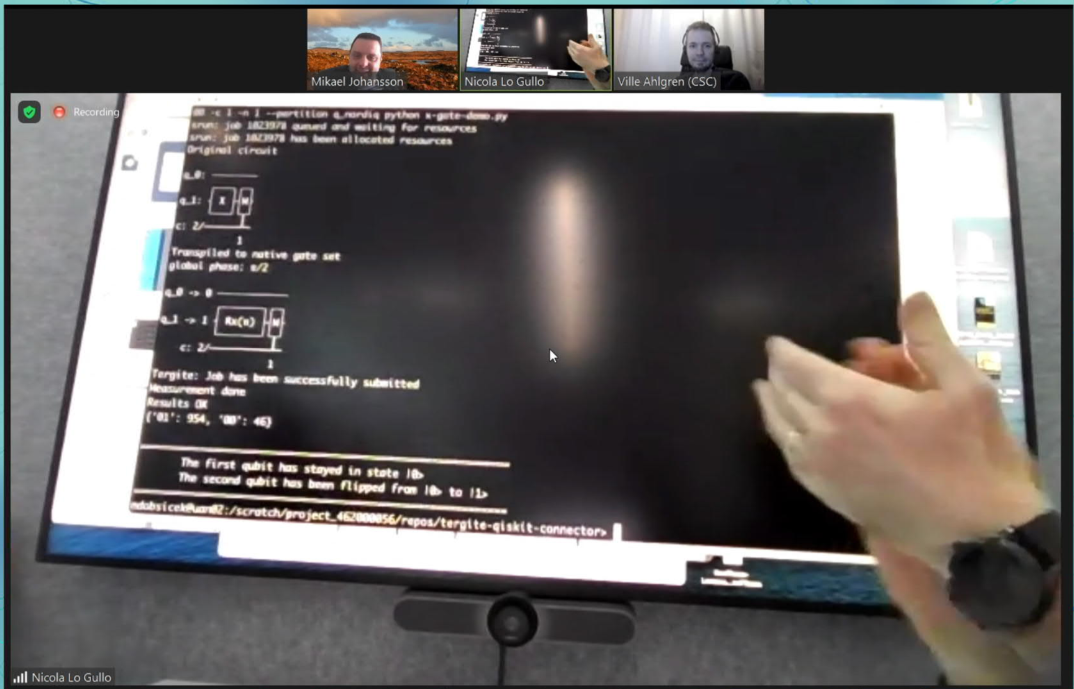
EuroHPC LUMI <-> Chalmers/WACQT QAL 9000

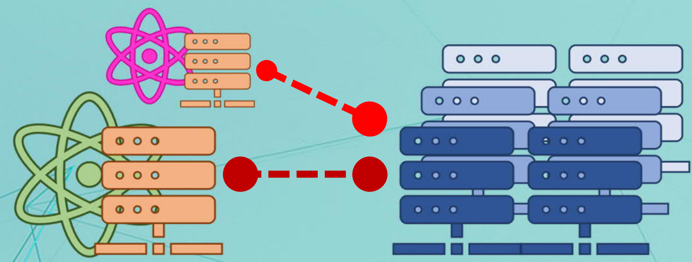
30.3.2022: First quantum job submitted through the LUMI queueing system

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

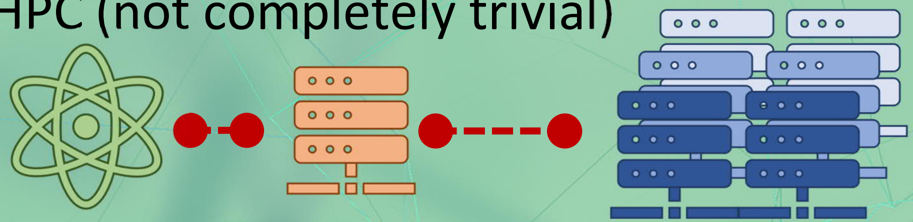


Henrik Nortamo (CSC), Nicola Lo Gullo (VTT/CSC)
Miroslav Dobsicek (Chalmers), Ville Ahlgren (CSC, zoom)

Co-located and distributed



- The **software stack** for a distributed approach requires somewhat more work than the co-located approach
  - Need to take care of one additional communication step between classical and HPC (not completely trivial)



  - User authentication needs to be done twice (rather trivial)
  - Need personnel at more than one physical location

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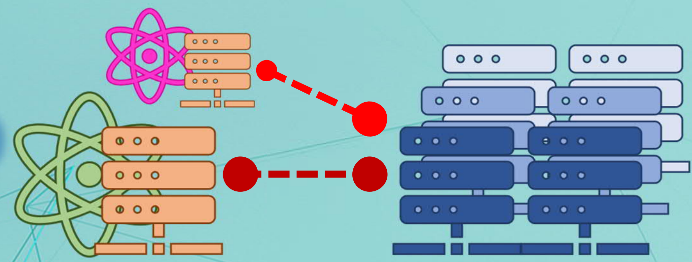
Why make distributed work?



- With the **software stack** in place, ***easy to add additional QC resources***
  - Needs only location of a classical server next to the QPU (+internet)
  - **Increases diversity and inclusiveness**
  - Users can access several QPUs from the same computing environment
  - Facilitates **time-sharing** of QPU resources
- QC and HPC can be optimally located, separately
  - HPC in large data centres with sufficient and affordable electric power
  - QC in shielded environments: temperature, vibrations, other noise sources

Article | Published: 16 June 2021

Correlated charge noise and relaxation errors in superconducting qubits

C. D. Wilen, S. Abdullah, N. A. Kurinsky, C. Stanford, L. Cardani, G. D'Imperio, C. Tomei, L. Faoro, Ioffe, C. H. Liu, A. Opremcak, B. G. Christensen, J. L. DuBois & R. McDermott

Nature **594**, 369–373 (2021) | Cite this article

across the millimetre-scale chip. The resulting correlated errors are explained in terms of the charging event and phonon-mediated quasiparticle generation associated with absorption of γ-rays and cosmic-ray muons in the qubit substrate. Robust quantum error correction will require the development of mitigation strategies to protect multiqubit arrays from correlated errors due to particle impacts.

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