Quantum computing in Sweden in a Nordic and EU perspective

Göran Wendin
Quantum Technology Laboratory – MC2
Chalmers University of Technology
Gothenburg, Sweden

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Why do we need quantum computers ?

→ We need QC for **exponential speed-up** to solve **hard problems**
(only approximately!) with finite resources (time, memory).
(to **reduce energy consumption**, if nothing else ...)

The original "killer application": Shor's algorithm for factorisation (1995)

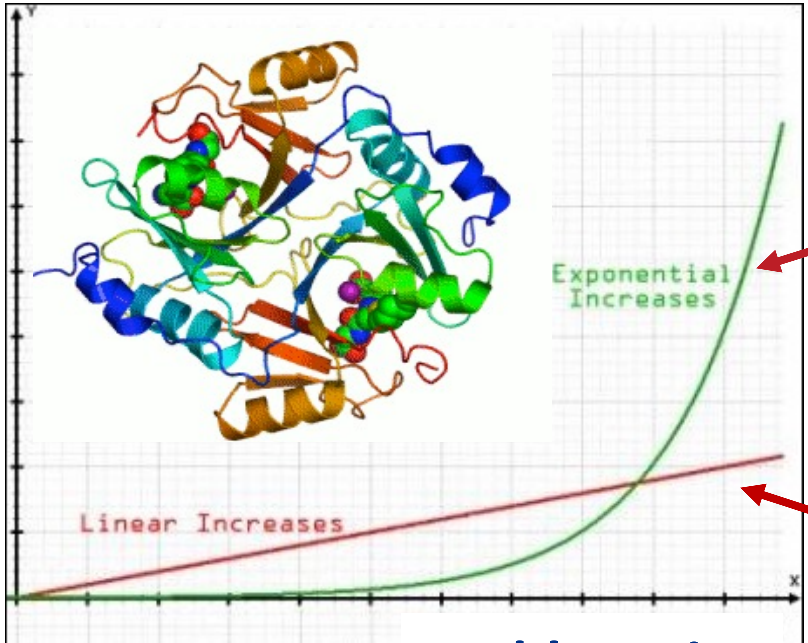
Today, the typical killer applications are "use cases":

- **Quantum Chemistry** – designing enzymes and catalysers; pharma
- **Materials science** – describing strong electron correlations; new materials
- **Optimization** - logistics, scheduling, big data, machine learning, ...

Quantum Advantage

Quantum computers offer, in principle,
exponential speed-up for certain classes of hard problems

time



problem size

TTS for a HPC:
Grows exponentially

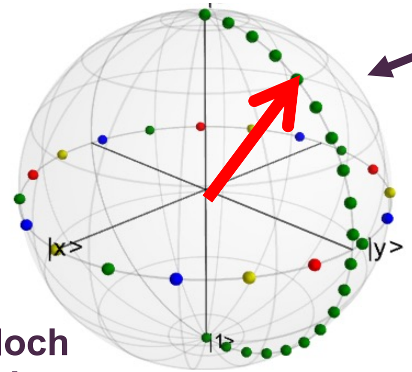
TTS for a quantum computer:
Grows linearly/polynomially

No Quantum Advantage

Quantum Advantage

QC = Linear algebra

|0>



Bloch sphere

|1>

a|0> + b|1>

Qubit

0 and 1

Vector addition

Superposition!

Parallellism!!

One single memory: 1 bit configuration at any given time t:

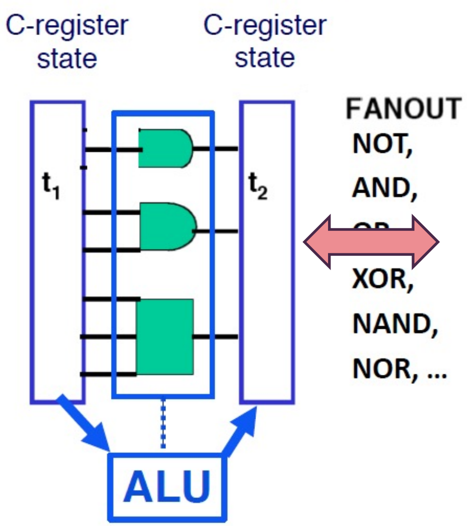
|0 ...00>
|0 ...01>
|0 ...10>

|1 ...11>

Superposition & Entanglement → Quantum Advantage:

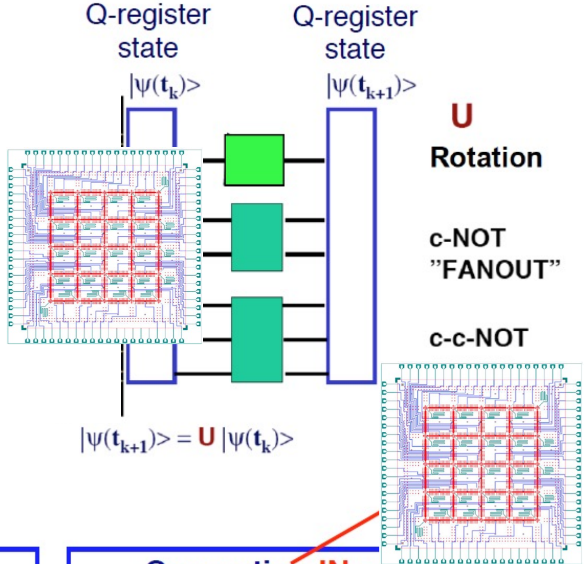
$f_1(t)$ |0...00>
+ $f_2(t)$ |0...01>
+ $f_3(t)$ |0...10>
+ ....
+ $f_n(t)$ |1...11>

CC: Classical gates



Computing FROM/TO memory
The memory is the storage

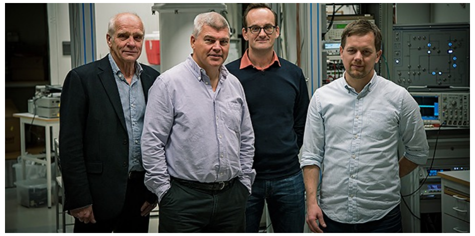
QC: Quantum gates

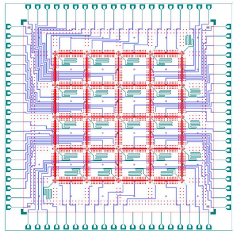


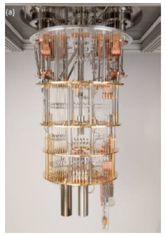
Computing IN memory
The memory is the computer

Long-term projects in Sweden:

2018







WACQT (KAW; 2018-2029)

EU Horizon Europe Q-Flagship
OpenSuperQPlus (2023-2026 (-2029))

Coordinated by Frank Wilhelm-Mauch, Jülich; Chalmers 2 WPs: design, theory
100q+ QPU by 2025; (1000q+ by 2029)

NordIQuEst (2022-2024)

NeIC, NordForsk -->> Nordic HPC+QC ecosystem

ENCCS-WACQT-NordIQuEst
HPC+QC workshop
Hands-on activites
October 25-27, 2023

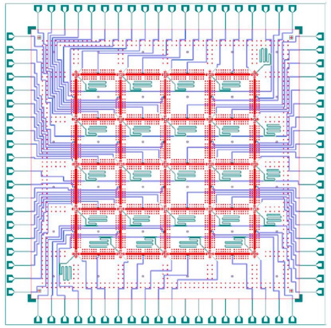
Complete program, exercises and Q&A log available at:
https://enccs.github.io/qas2023/

LUMI-Q (2024-2027)
EuroQHPC-Integration

EuroHPC Joint Undertaking
HPC+QC European ecosystem
QPU procurement

NordiQuEst HPC+QC hybrid ecosystem

NeIC = Nordic e-Infrastructure Collaboration

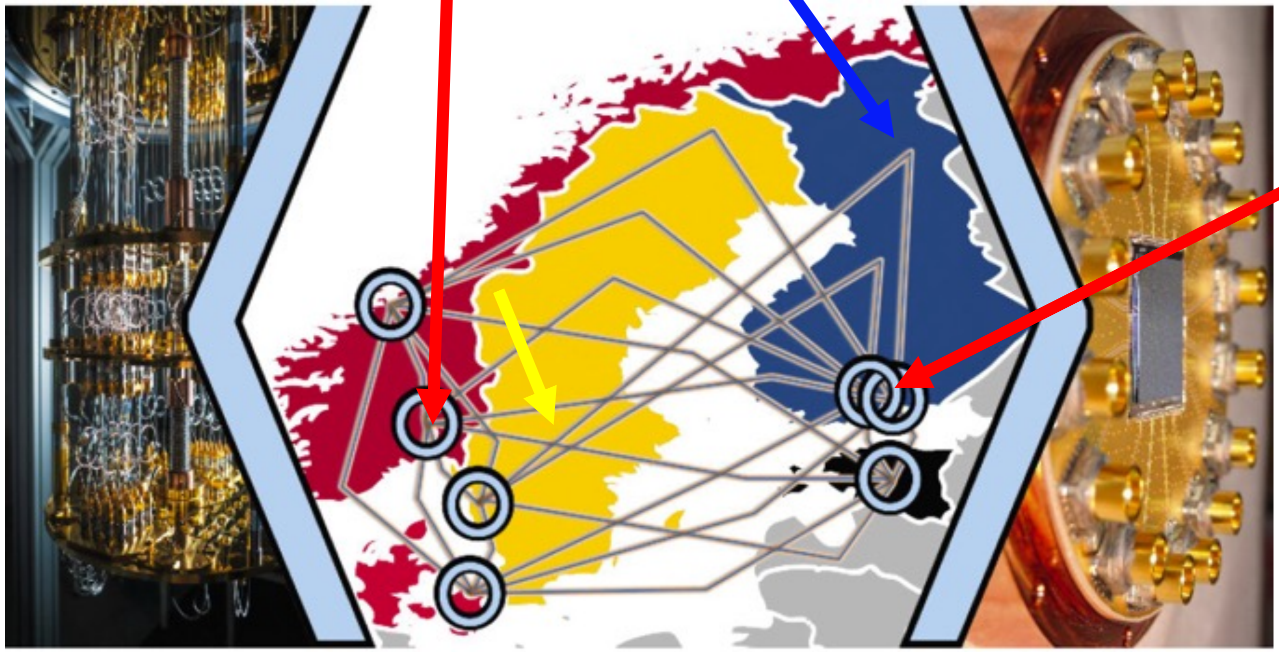


2022-2024

LUMI pre-exascale HPC in Kajaani

Chalmers QPU:
QAL 9000

According to plans:
20-25 qubits by 2023
40-50 qubits by 2025



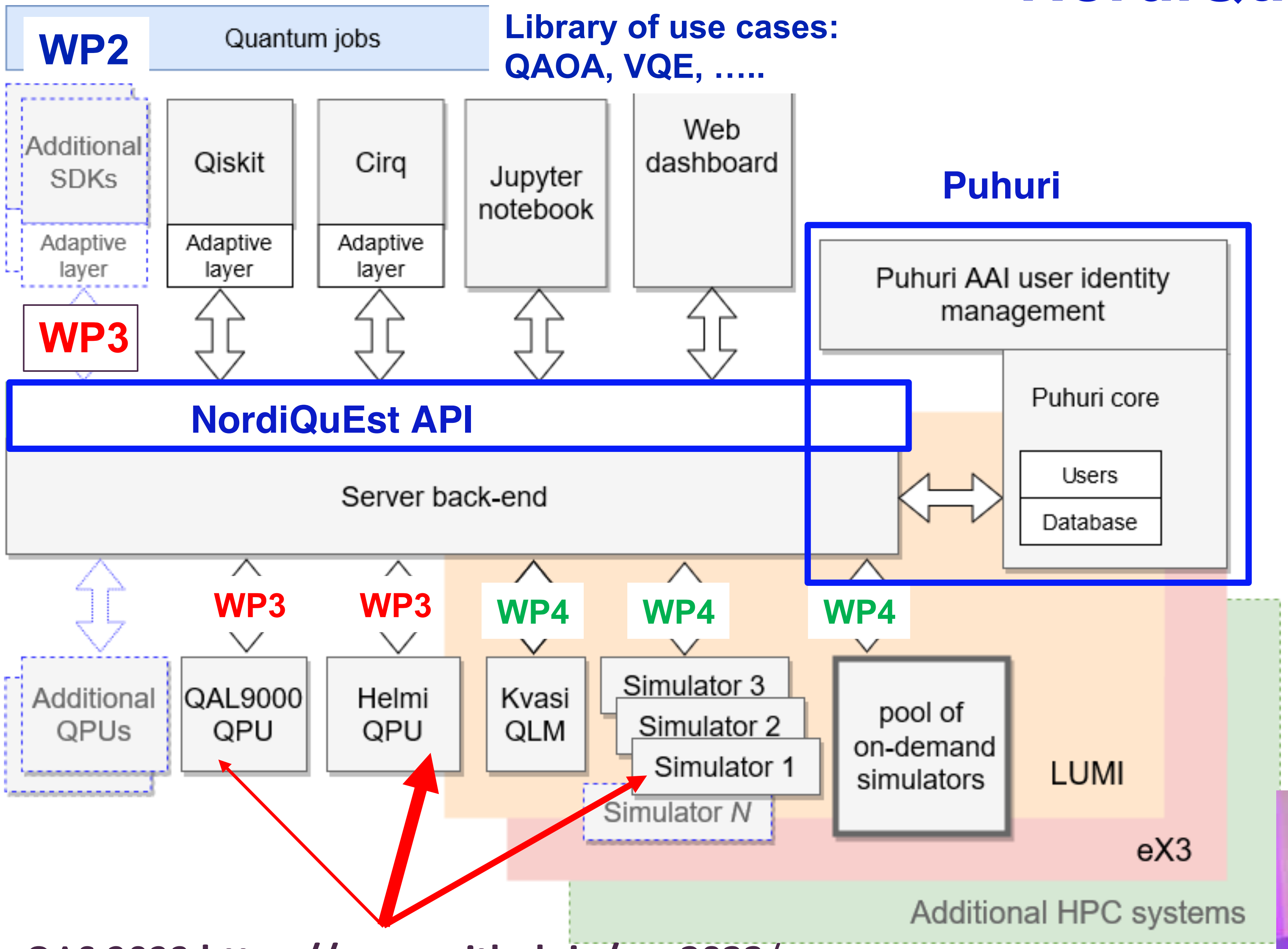
VTT QPU:
HELMI
LEENA

Accessible for users via a LUMI's Puhuri portal

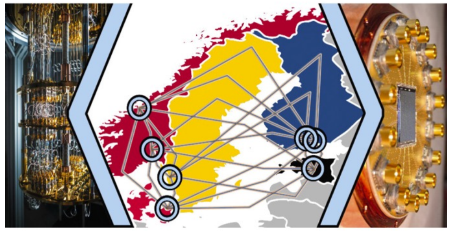
NordIQuEst =
Nordic-Estonian Quantum Computing e-Infrastructure Quest – NeIC/NordForsk

NordiQuEst in a nutshell

Library of use cases: QAOA, VQE, …..



QAS 2023 **https://enccs.github.io/qas2023/**



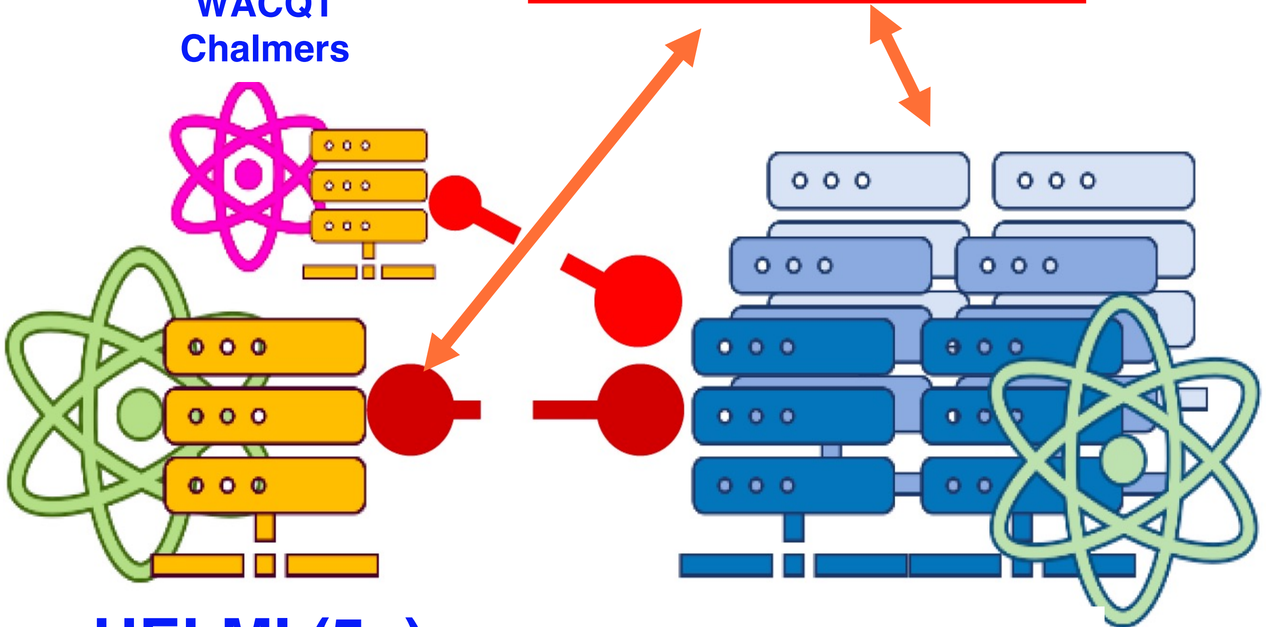
31 March 2022: QAL 900-LUMI contact!

Start of NordIQuEst – 1-5 April 2022

LUMI-Q (2024-2027 ….; EuroHPC JU)

LUMI-Puhuri

QAL9000 (25q)
WACQT
Chalmers



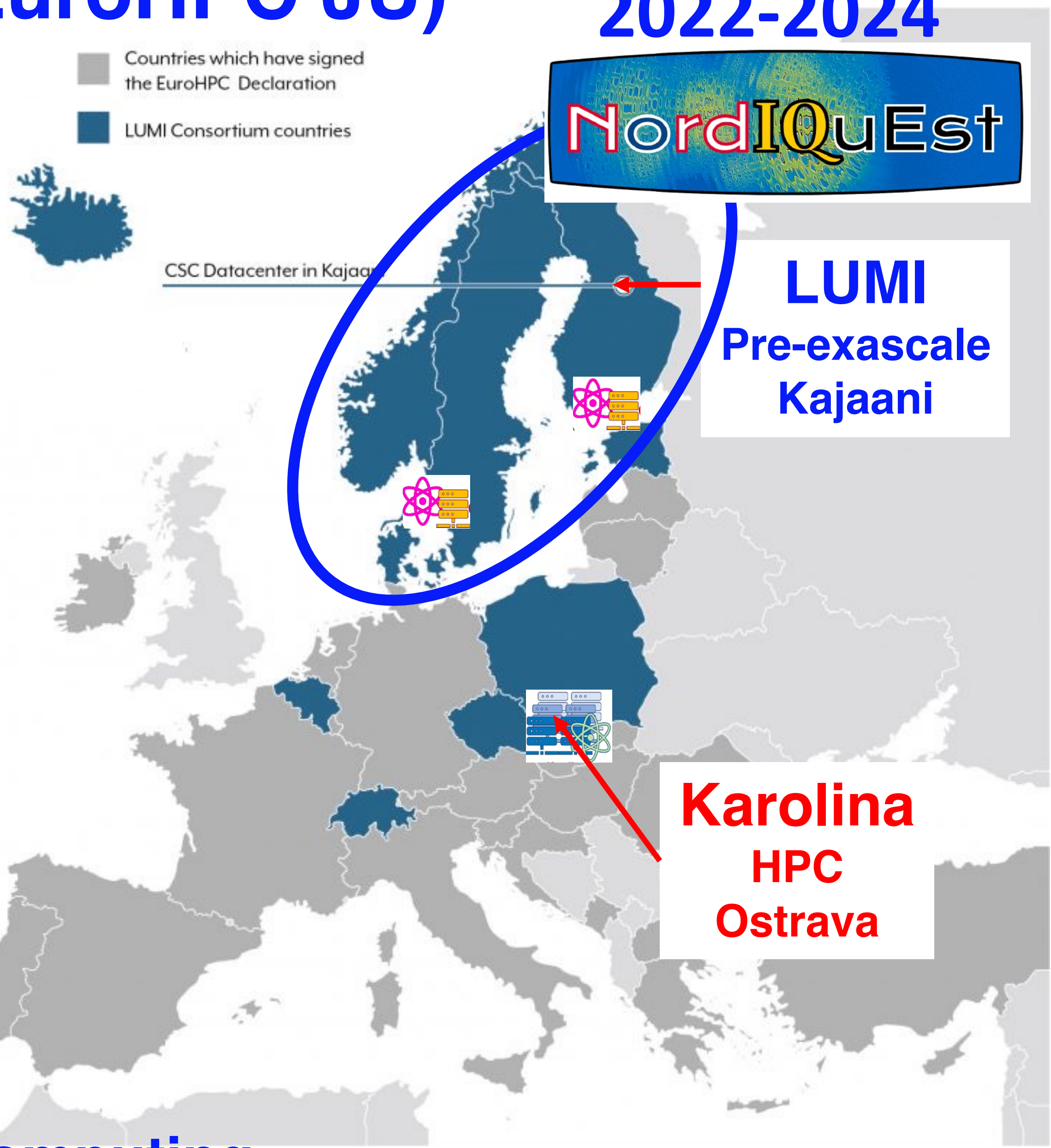
HELMI (5q)
LEENA (20q)
VTT/CSC/IQM

Karolina
Ostrava

QC-centric

HPC-centric

2022-2024



Integrated and distributed HPC+QC hybrid computing

QC computer with
internal ***super-high-speed***
classical (CC) processing

HPC: Cloud access
with high-speed
classical processing

Cloud access

High speed optical link

Floating HPC/QC division

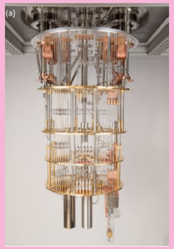
FPGA

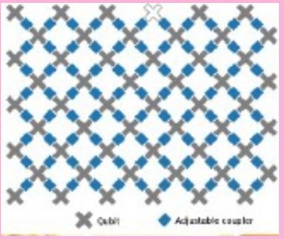
Classical control

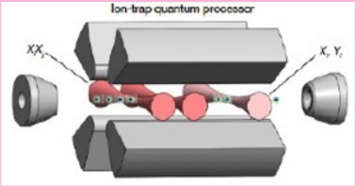
Super-fast CC-QC hybrid processing

Quantum error mitigation (QEM); Quantum error correction (QEC)

Very low latency







Classical pre/post-processing
Fast CC-QC hybrid processing
Quantum error mitigation

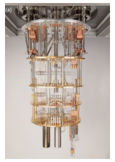
Note: execution of quantum gates in the QC is done by classical code controlling classical electronics.

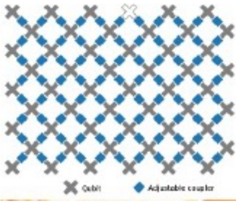
LUMI-Q

6 upcoming HPC+QC sites procuring QCs funded by the EuroHPC JU (2024-2027)

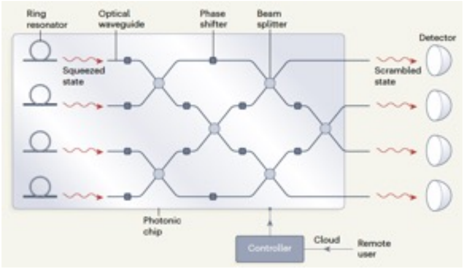
Czechia, IT4I, Karolina (LUMNI-Q): **Superconducting; digital (~ 20q)**

Germany, LRZ:

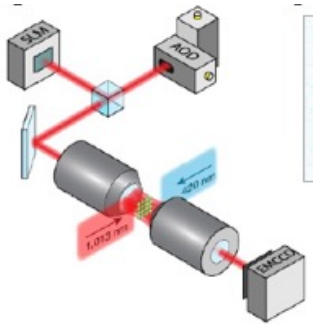




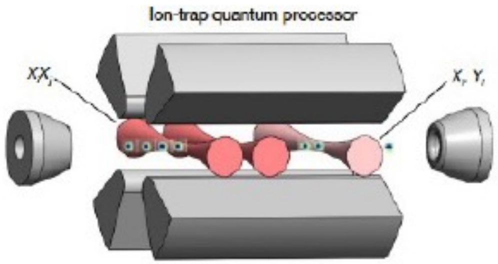
Spain, BSC, Mare Nostrum: **Superconducting; analogue**



France, CEA/GENCI: **Photonic; digital**



Italy, CINECA: **Neutral atoms; analogue**

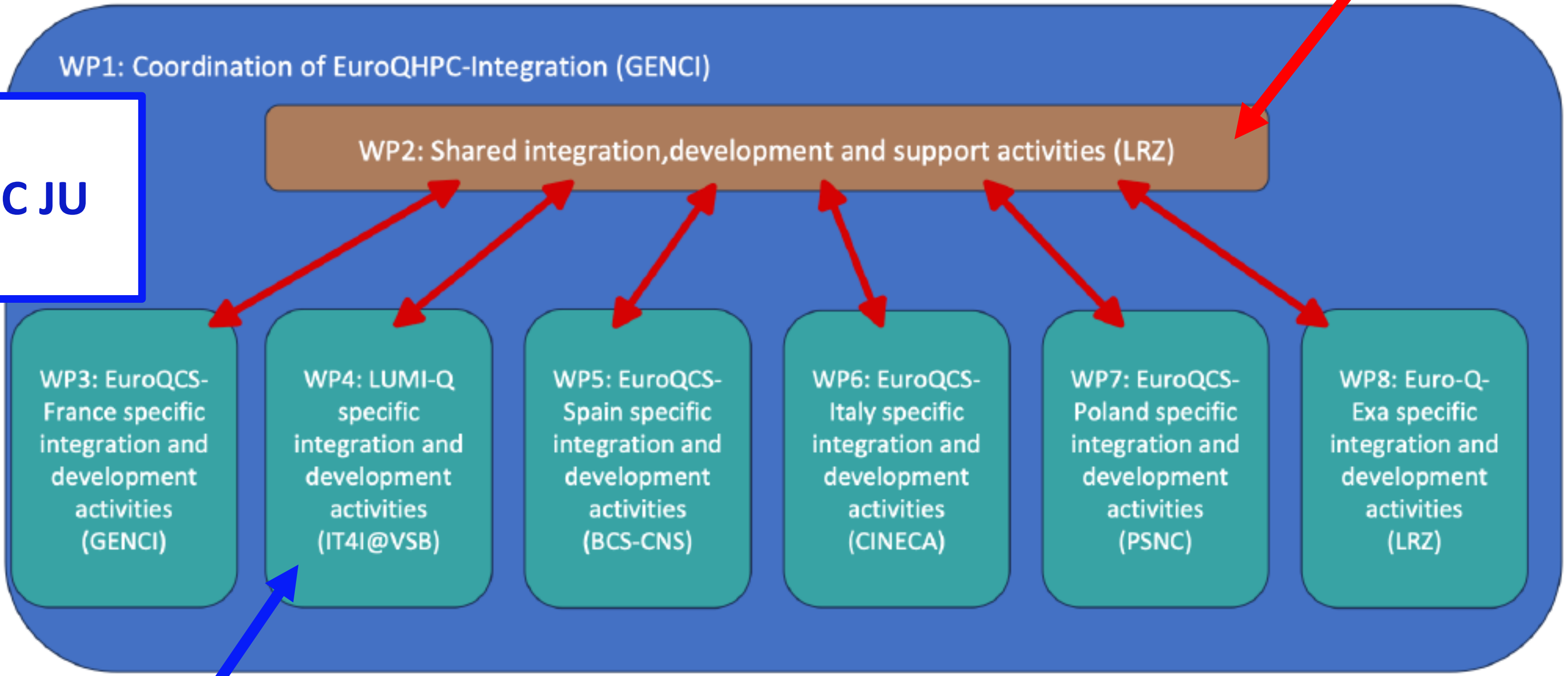


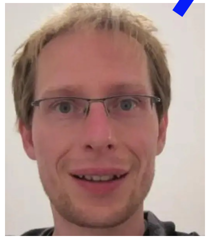
Poland, PSNC: **Ion trap; digital**

EuroQHPC-Integration (2024-2027)(submitted)

WP2, T 2.2: Creation of a repository of shared collection of proof-of-concept applications and benchmarks running on various hybrid systems. CHALMERS

Supported
50% EuroHPC JU
50% VR





WP4, T 4.3: Design and implementation of the Q-scheduler for hybrid quantum-classical asynchronous offloading programming model. CHALMERS/QAL 9000

Competitive Quantum Computing …. What about now?

Google 70q Sycamore (superconducting):
Phase transition in Random Circuit Sampling
arXiv:2304.11119v1
→ Extension of the 2019 Google 53q demonstration of Quantum Supremacy
→ **Demo of Quantum Supremacy** (well beyond the memory storage of the Frontier exascale HPC; 10^{24} Flops (1 year) for classical Tensor Networks)

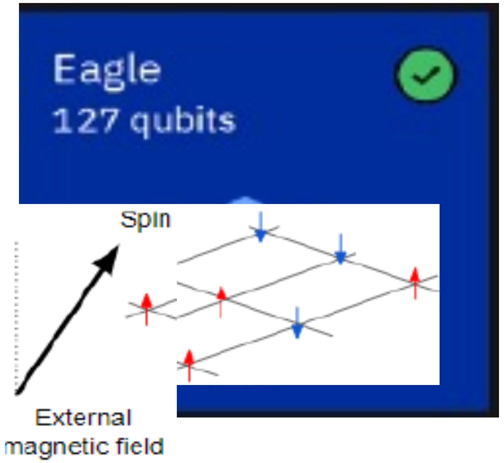
IBM 127q Eagle (superconducting):
Evidence for the utility of quantum computing before fault tolerance
Kim et al. *Nature* **618**, 500–506 (2023).

→ scalable **quantum error mitigation (QEM)** **(ZNE, zero-noise extrapolation)** for noisy quantum circuits produces **competitive expectation values** for measurable quantities.

Evidence for the utility of quantum computing before fault tolerance

Kim et al. *Nature* **618**, 500–506 (2023).

Digital-analog simulation of average magnetization of a **2-dimensional transverse-field Ising model (TFIM) with 127-spins** programmed on a **127 qubit Eagle processor**:



This experiment is **impossible by brute-force HPC simulation for memory reasons** and indicates emerging **Quantum Advantage of scale (but not time).**

Nevertheless, soon after appeared the following paper **classically reproducing the 127q IBM result**.
Efficient tensor network simulation of IBM's Eagle kicked Ising experiment,
Joseph Tindall, Matthew Fishman, E. Miles Stoudenmire, and Dries Sels, arXiv: 2306.14887

So, we are now waiting for the 433 Osprey to show what it can do ….. ☺ with lots of error mitigation – which is an NP-hard problem ….. ☹

→ In the near term, **Quantum Advantage** may take the form of NISQ devices emulating interesting physical systems intractable by HPC supercomputers – "Quantum wind tunnel experiments".

USTC, Hefei, China, 66q Zuchongzhi-2 (superconducting):

→Extended in 2022 the 2019 Google 53q demonstration of Quantum Supremacy

→ Now online with cloud access, adding control interfaces of 110 coupled qubits, allowing users to manipulate 176 quantum bits.

RIKEN RQC-Fujitsu, Japan, 64q (superconducting):

- Platform leverages new 64 qubit superconducting quantum computer to accelerate R&D for quantum chemistry calculations and quantum financial algorithms. Includes one of the world's largest 40 qubit quantum computer simulators developed by Fujitsu.

NOTE: to "accelerate R&D for quantum chemistry calculations and quantum financial algorithms" is standard hype use to sell quantum computers. To be really useful (i.e. show decisive Quantum Advantage) they must wait for QEC.

The Future of competitive Quantum Computing ….

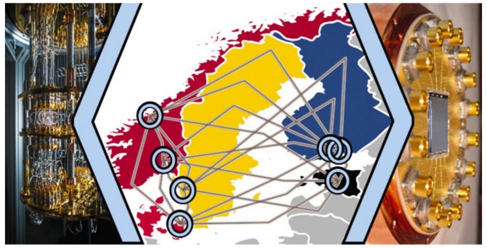
Needed: 1000+ perfect qubits with infinite coherence time to compute for seconds, minutes, hours, days …

Now: NISQ (Noisy Intermediate-Scale Quantum) devices:
>> 1 millisecond coherence (quantum computing) time
→ Entangle max 20 qubits with high probability **(Quantinuum ion trap!!)**

For **quantum error correction (QEC)**, prepare for a 10-20 years marathon ….

For **quantum error mitigation (QEM)**, prepare for 5+ years of intense exploration ….

Thanks for your attention!



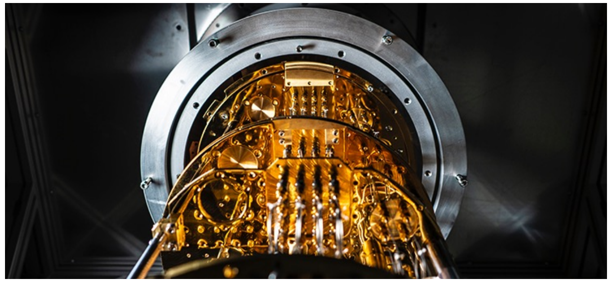
Suggested further reading:

List of quantum processors - Wikipidia
https://en.wikipedia.org/wiki/List_of_quantum_processors

Quantum information processing with superconducting circuits: a perspective
G. Wendin; https://arxiv.org/abs/2302.04558

Quantum computer scales up by mitigating errors
Göran Wendin, Jonas Bylander, Nature 618, 462 (2023).

Coherent manipulation of a spin qubit
Göran Wendin, Vitaly Shumeiko, Science 373, 390 (2021)



The OpenSuperQ project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820363.