Advanced Parallel School 2022
Quantum Computing – Day 5
Quantum Computing @ CINECA

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18 Feb 2022

CINECA QUANTUM COMPUTING LAB

CINECA Overview

CINECA: Italian HPC center

Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**Supercomputer Fugaku** - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,630,848	442,010.0	537,212.0	29,899
14	**Marconi-100** - IBM Power System AC922, IBM POWER9 16C 3GHz, Nvidia Volta V100, Dual-rail Mellanox EDR Infiniband, IBM CINECA Italy	347,776	21,640.0	29,354.0	1,476

List of the 500 most powerful supercomputers in the world

CINECA Overview

CINECA: Italian HPC center

Leonardo: Cineca pre-exascale supercomputer

Coming soon. Will be in the **top five most powerful supercomputers in the world**

CINECA Overview

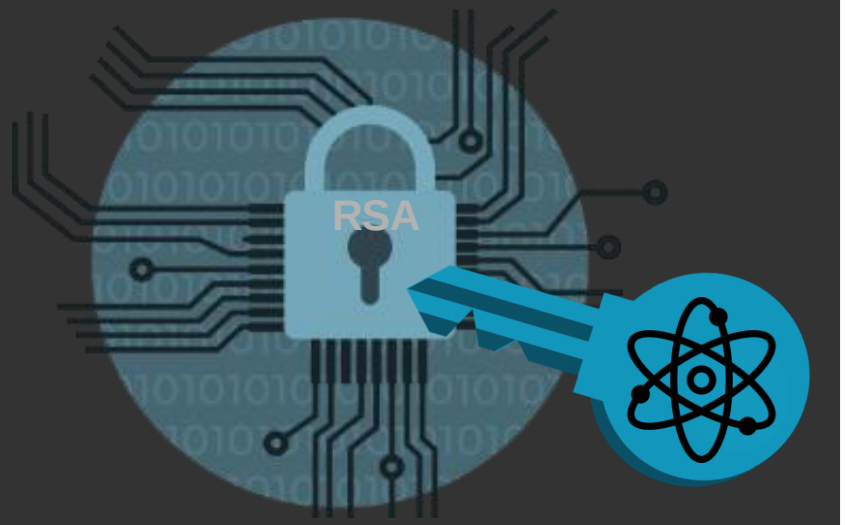
- **Today Access to:**
  - **D-Wave Quantum Annealer**
  - **Pasqal Neutral Atoms**
- **Future:**
  - **Soon others..**
  - **On-site?**

Old School Quantum Algorithms: Overview

Cryptography

Shor's Algorithm

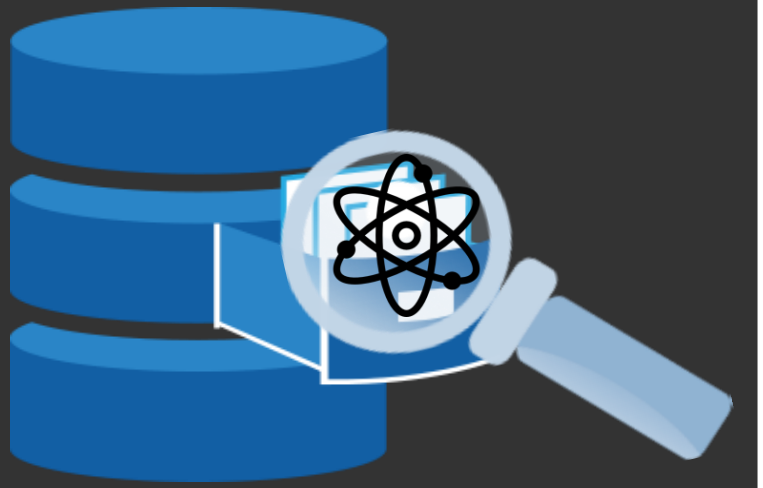
Exponential Speedup



Optimization

Grover's Algorithm

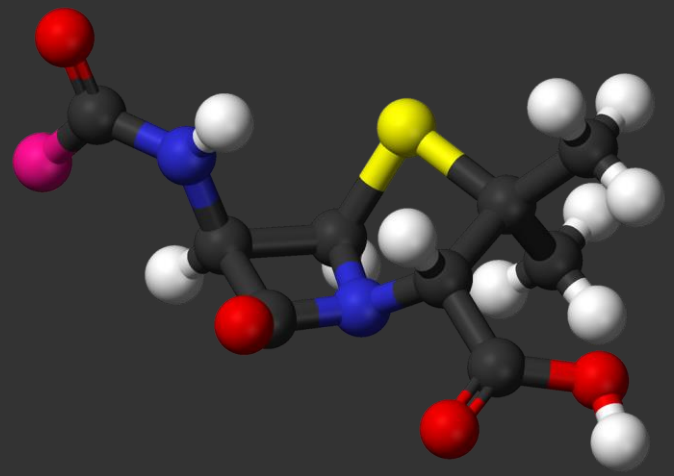
Quadratic Speedup



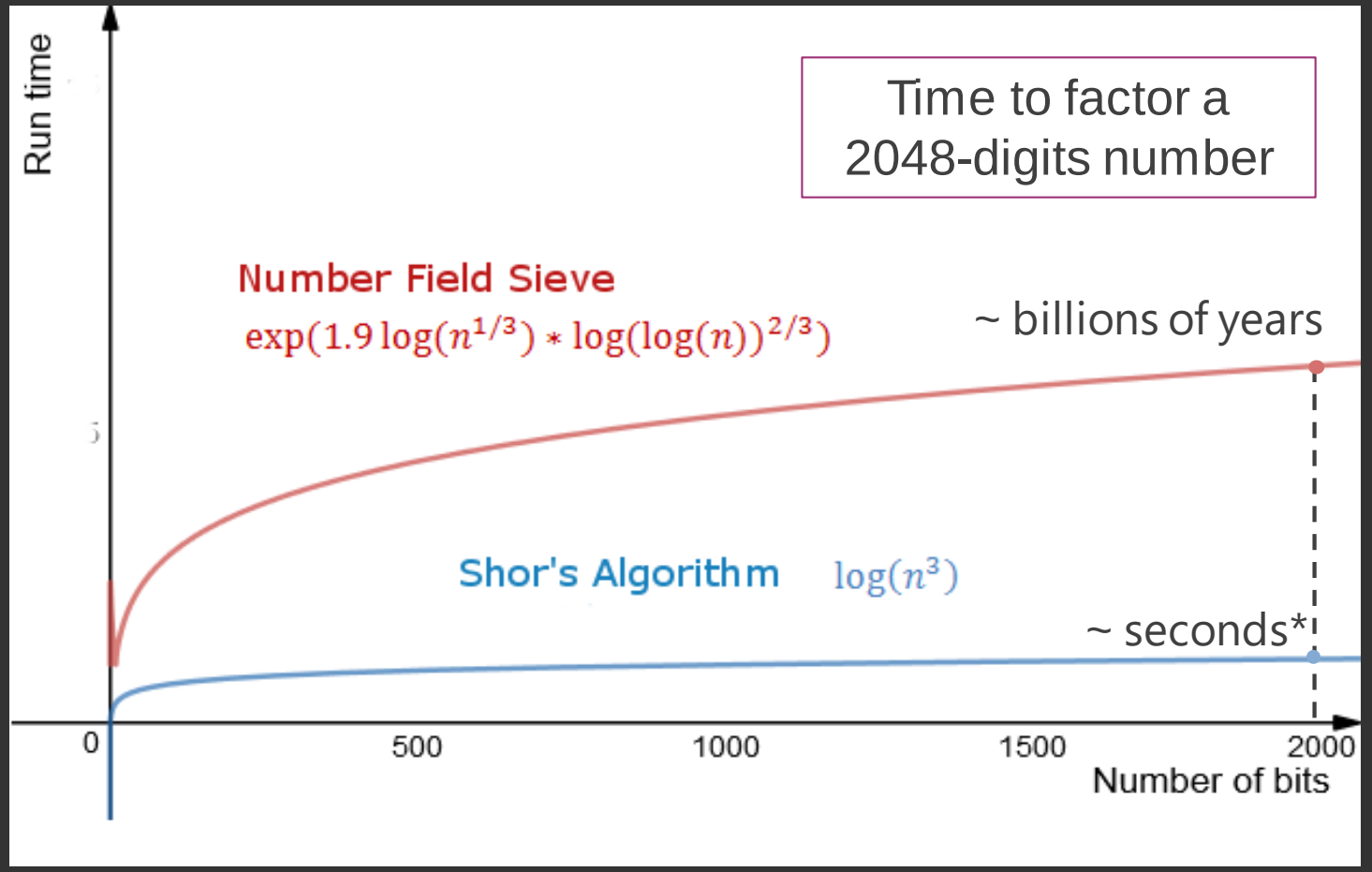
Chemistry

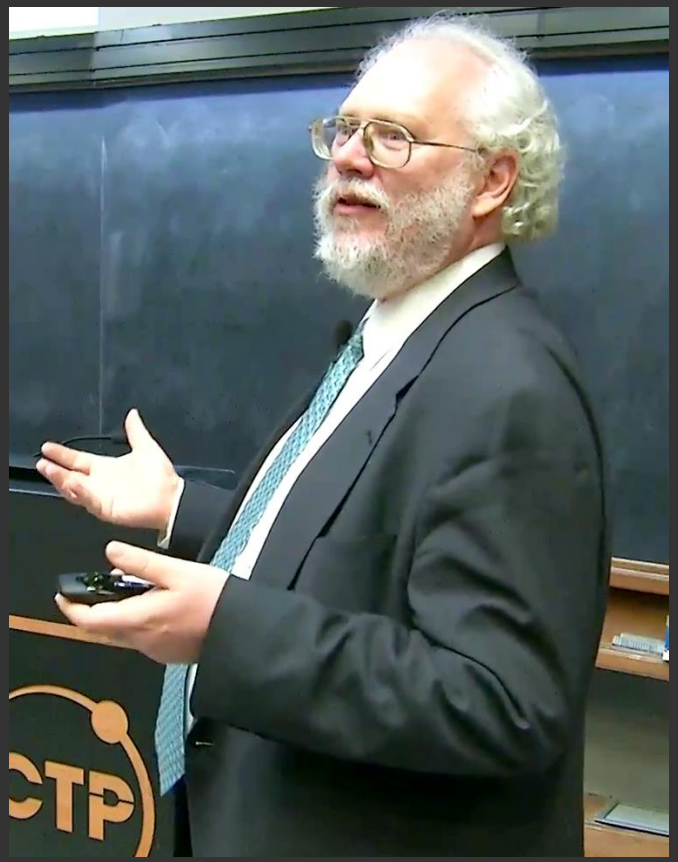
Hamiltonian Simualtion

Exponential Speedup



Old School Quantum Algorithms: Shor's algorithm (1994)





* Assuming we have a fault-tolerant quantum computer capable of executing Shor's algorithm by applying gates at the speed of current quantum computers based on superconducting circuits

Old School Quantum Algorithms: Error Correction

Cryptography

Shor's Algorithm

Exponential Speedup

Optimization

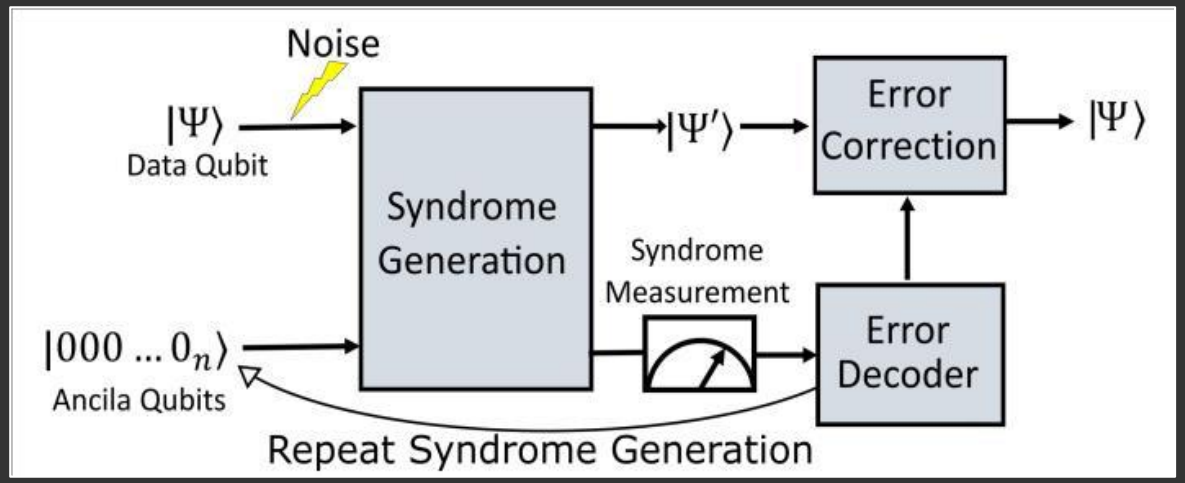
Grover's Algorithm

Quadratic Speedup

Chemistry

Hamiltonian Simualtion

Exponential Speedup



- Require **error corrected** quantum computers with about **1 million or 100 thousands of qubits**
- Will be availabe in **10-20 years**

CINECA QUANTUM COMPUTING LAB

The NISQ Era

NISQ = Noisy Intermediate-Scale Quantum

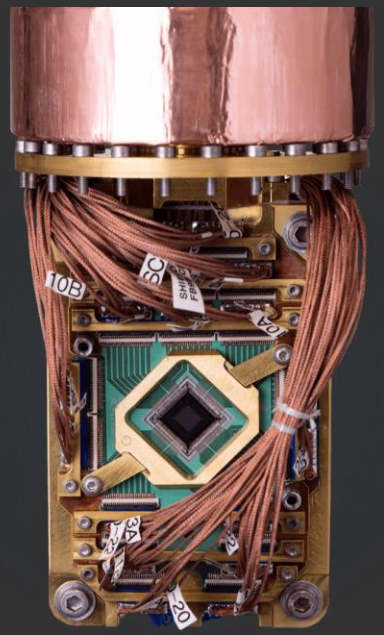
Intermediate-Scale Quantum computers with no error correction

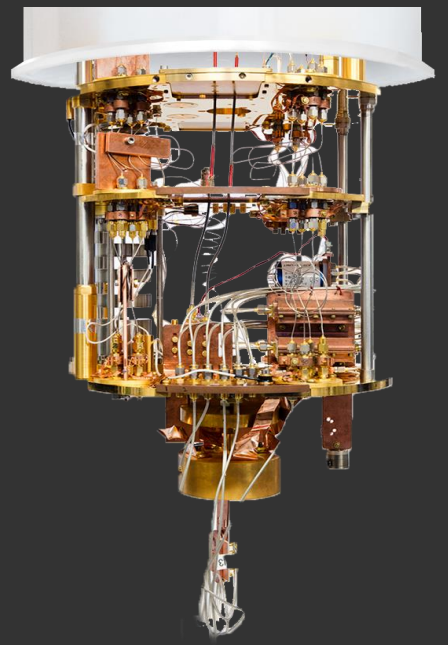
The NISQ Era

NISQ = Noisy Intermediate-Scale Quantum

Intermediate-Scale Quantum computers with no error correction

1. Quantum Annealers





2. Circuit Quantum Computers

The NISQ Era

NISQ = Noisy Intermediate-Scale Quantum

Intermediate-Scale Quantum computers with no error correction

The scientific community believes that NISQ technology could **outperform** traditional classical computers for **specific applications**

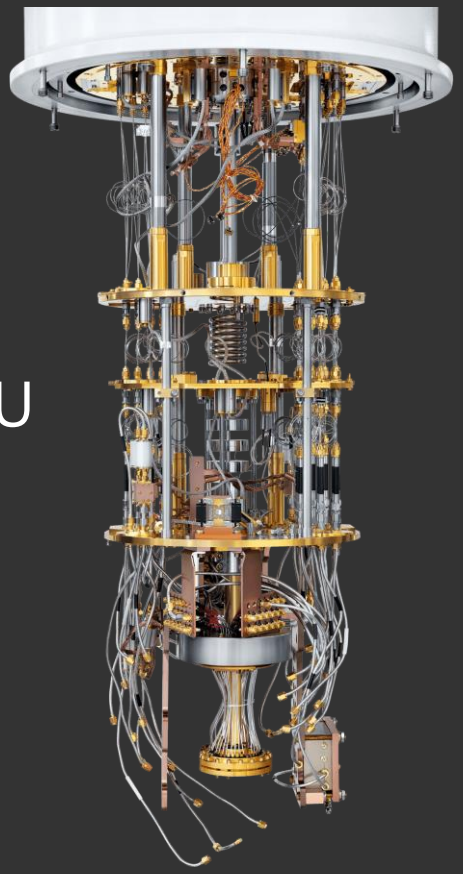
- Speed up
- Better quality solutions
- Lower energy consumption

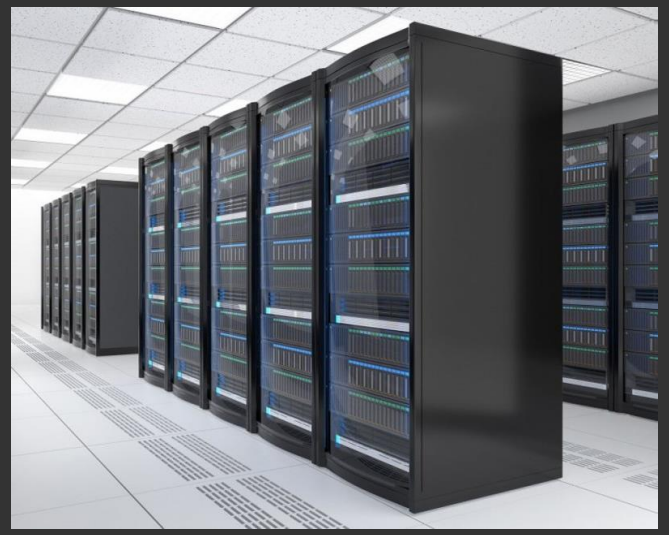
- Quantum Chemistry
- Quantum Optimization
- Quantum AI/Machine Learning

Cineca Quantum Computing Lab: Vision

Quantum Computing will always be Hybrid

QPU





HPC

Cineca Quantum Computing Lab: Vision

Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

Hybrid workflows: development of problem oriented hybrid QPU-HPC algorithms

Scheduling hybrid resources: ensure a task is run with the resources it needs and decide when and how to allocate QPU-HPC resources

Real-world applications: chemistry, optimization, machine learning, simulations, etc.

CINECA QUANTUM COMPUTING LAB

Cineca Quantum Computing Lab: Emulators

Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

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Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

Usage:

- Development and verification of Quantum Algorithms
- Benchmarking
- Study Noise
- Assess hardware constraint
- Co-design of quantum hardware
- …

Cineca Quantum Computing Lab: Emulators

Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

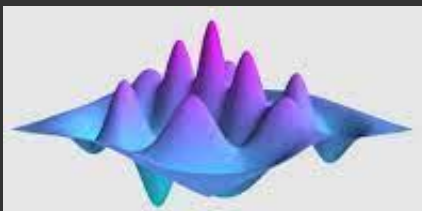
State-vector emulators

- Single node Multi-threading using OpenMP to achieve state of the art emulation of quantum circuits.

Qiskit

Cirq

- Working on a multithread/multi-node implementation



QuTiP

Quantum Toolbox in Python

Cineca Quantum Computing Lab: Emulators

Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

State-vector emulators

- Single node Multi-threading using OpenMP to achieve state of the art emulation of quantum circuits.

NVIDIA CuQuantum Testing …

- Working on a multithread/multi-node implementation

QuTiP
Quantum Toolbox in Python

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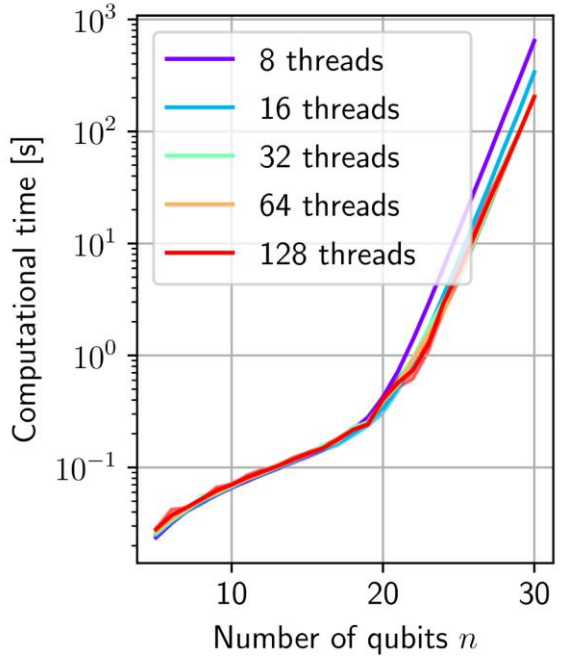
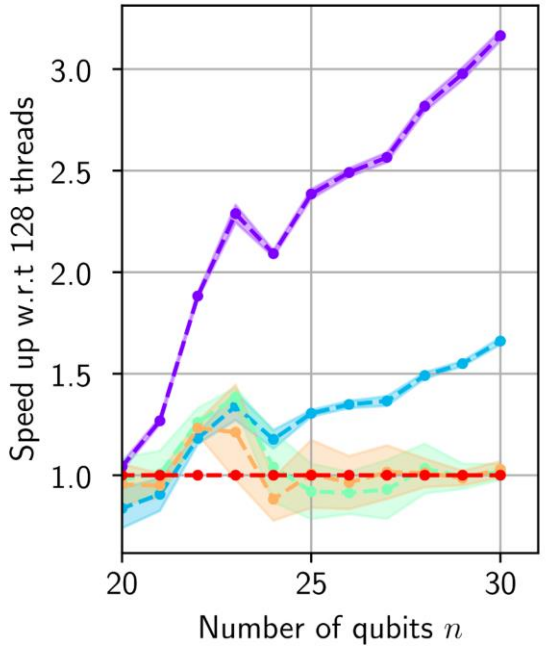
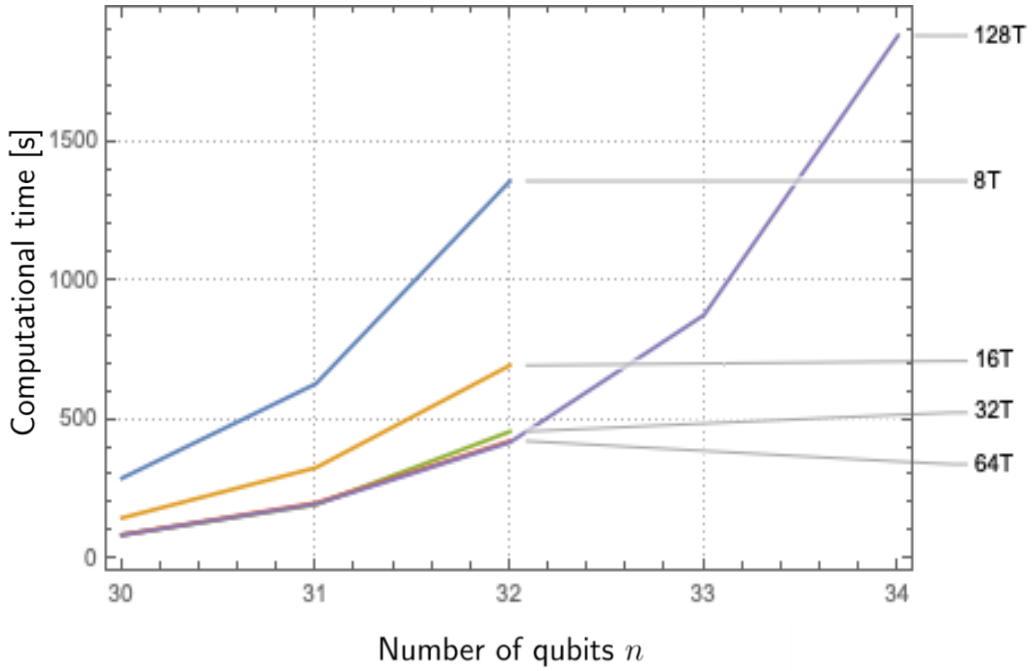
State-vector emulators







CINECA QUANTUM COMPUTING LAB

Cineca Quantum Computing Lab: Emulators

Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

Tensor Network emulator

- Single node MPS simulator developed in fortran QCOMPS.
- Python interface: qiskit and strawberry fields
- Working on a parellized implementation

UNIVERSITÀ DEGLI STUDI DI PADOVA

QCOMPS

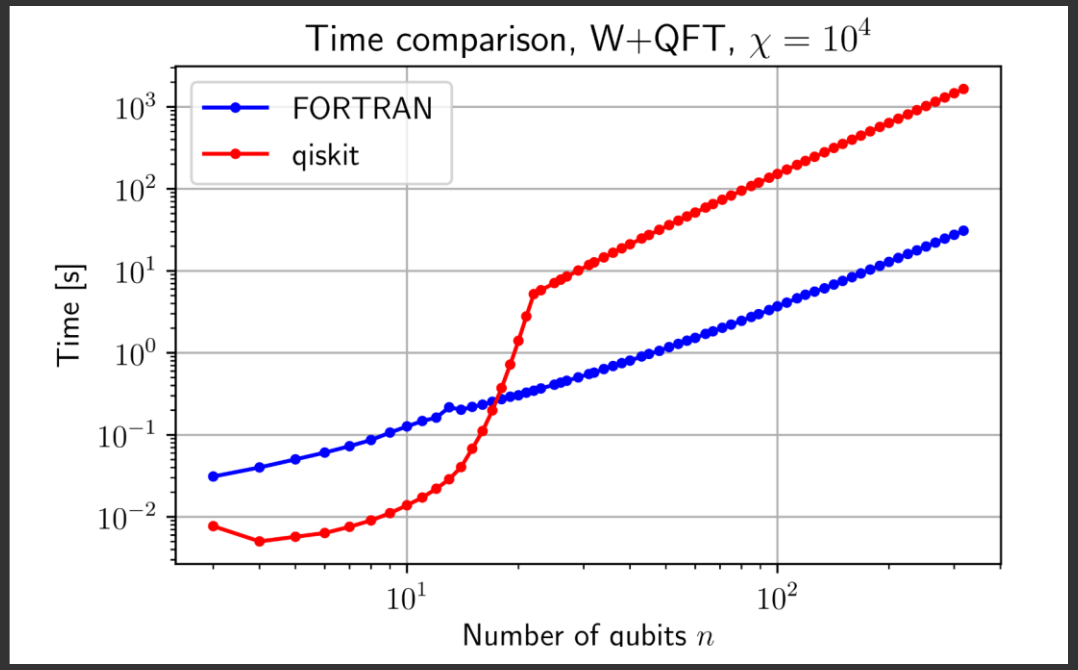
Qiskit

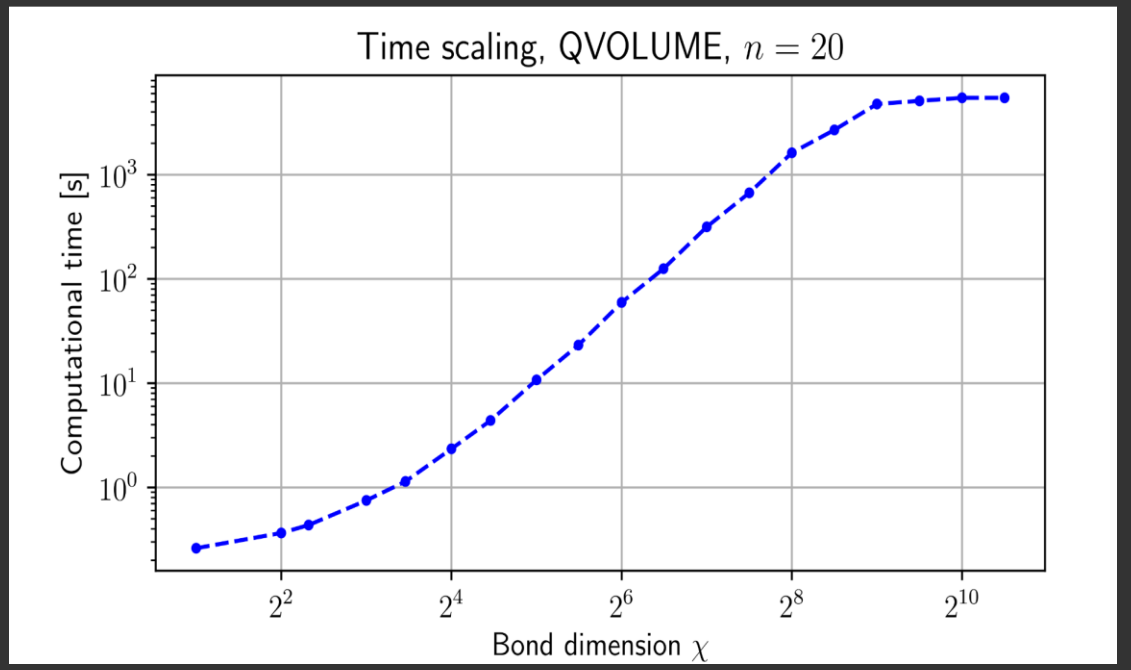
XANADU STRAWBERRY FIELDS

Cineca Quantum Computing Lab: Emulators

Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

Tensor Network MPS emulator





CINECA QUANTUM COMPUTING LAB

Cineca Quantum Computing Lab: Emulators

Emulators: develop/test HPC ready software for simulating quantum systems and quantum computers

Simulated Quantum Annealing

- D-Wave neal library for simulated annealing

- SQAOD Collections of solvers/annealers for simulated quantum annealing on CPU and CUDA(NVIDIA GPU).

Cineca Quantum Computing Lab: Hybrid workflows

Hybrid workflows: development of problem oriented hybrid QPU-HPC algorithms

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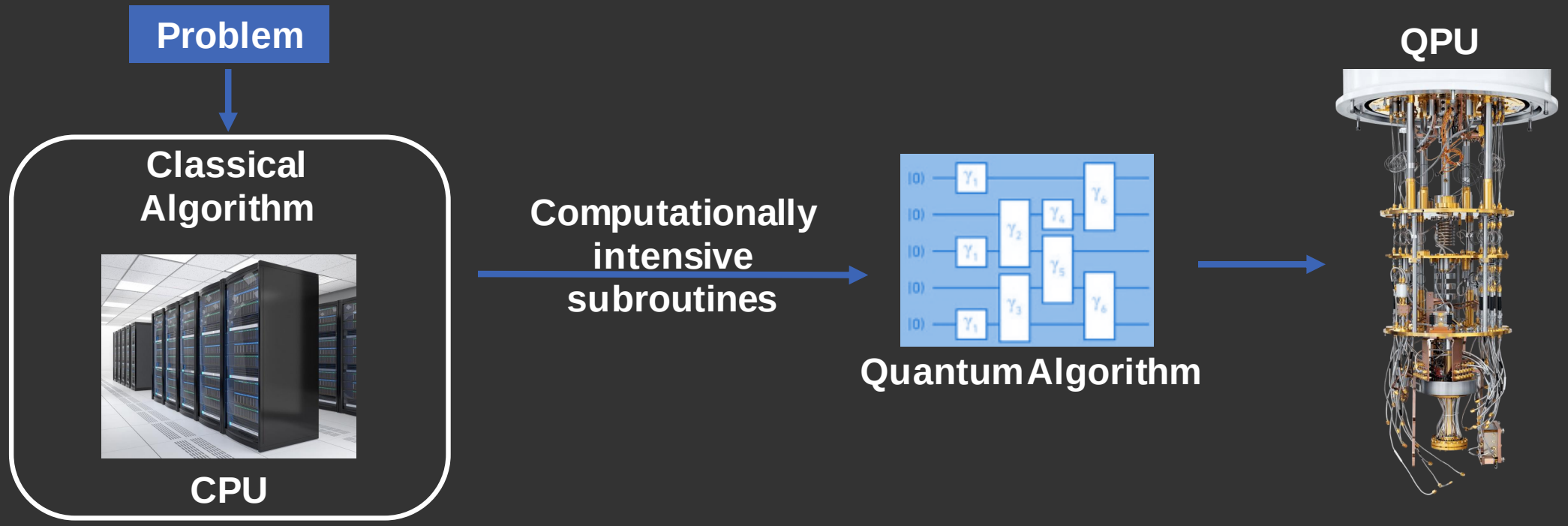
Hybrid workflows: development of problem oriented hybrid QPU-HPC algorithms

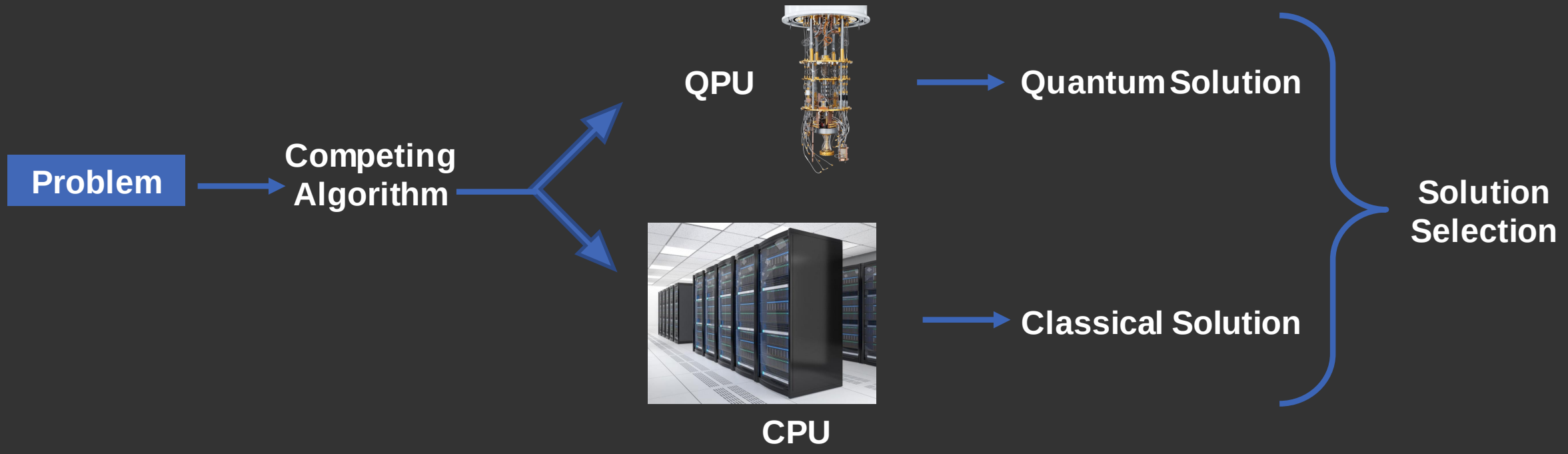
1. QPU - enhanced computation



Cineca Quantum Computing Lab: Hybrid workflows

Hybrid workflows: development of problem oriented hybrid QPU-HPC algorithms

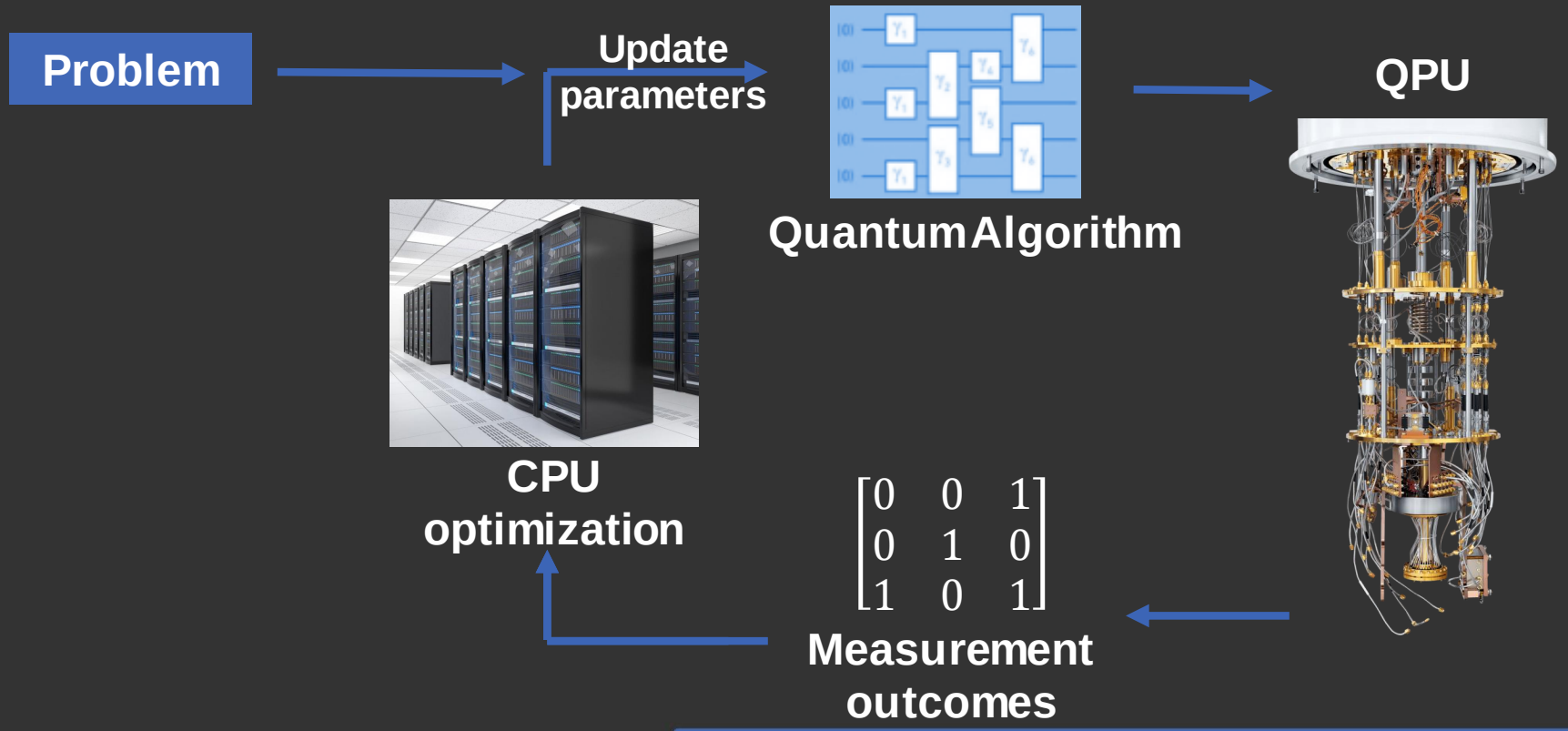
2. Competing CPU-QPU



Cineca Quantum Computing Lab: Hybrid workflows

Hybrid workflows: development of problem oriented hybrid QPU-HPC algorithms

3. Iterative Hybrid algorithm



Cineca Quantum Computing Lab: Scheduling

Scheduling hybrid resources: ensure a task is run with the resources it needs and decide when and how to allocate QPU-HPC resources

Cineca Quantum Computing Lab: Scheduling

Scheduling hybrid resources: ensure a task is run with the resources it needs and decide when and how to allocate QPU-HPC resources

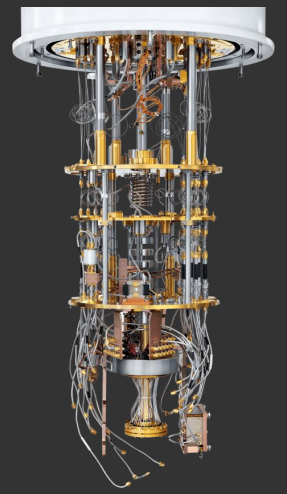
Today

Quantum Circuit

every iteration

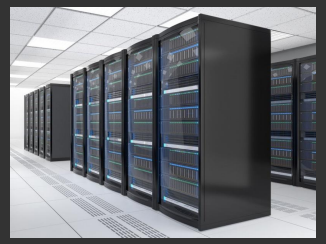
QPU Hardware Queue

QPU



$$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

Classical Parameters



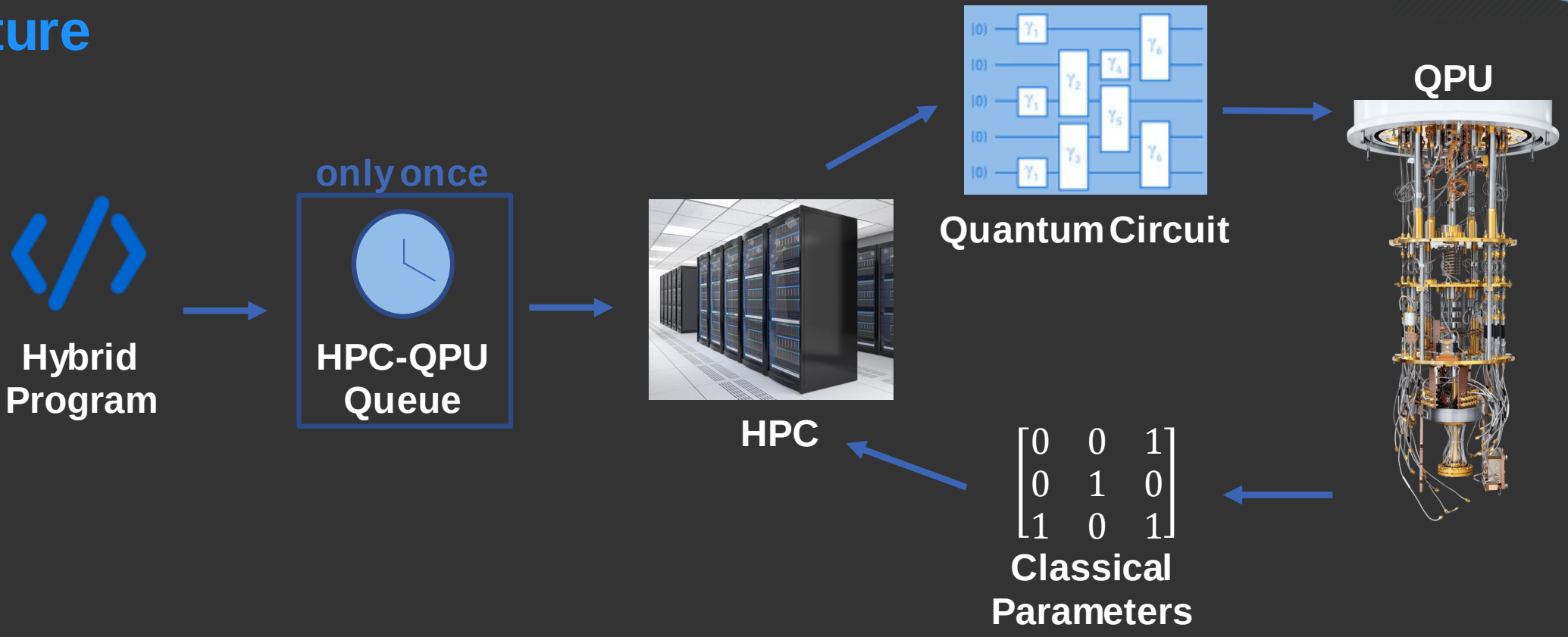
HPC

CINECA QUANTUM COMPUTING LAB

Cineca Quantum Computing Lab: Scheduling

Scheduling hybrid resources: ensure a task is run with the resources it needs and decide when and how to allocate QPU-HPC resources

Future



Cineca Quantum Computing Lab: Applications

Real-world applications: chemistry, optimization, machine learning, simulations, etc.

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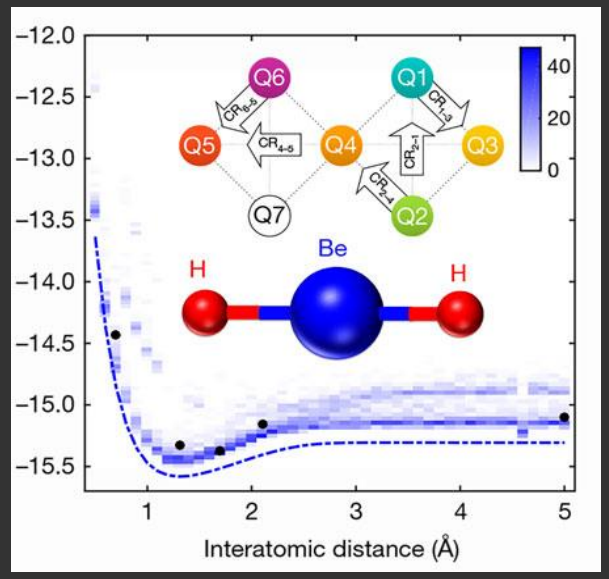
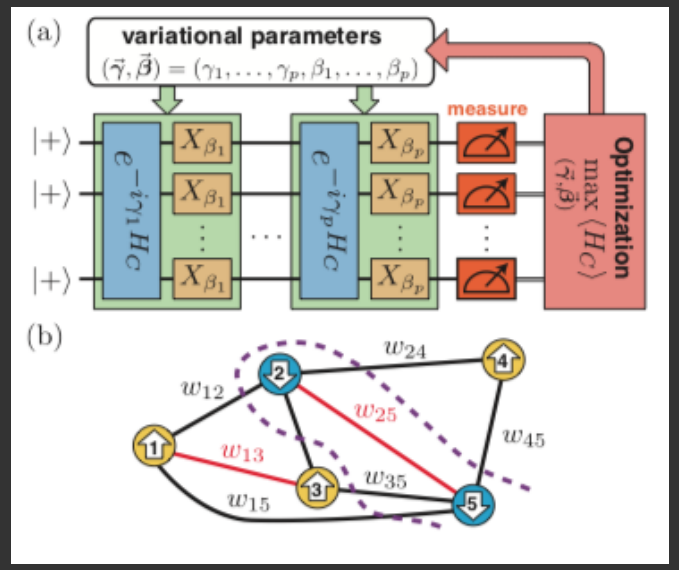
Gate model QC

VQE



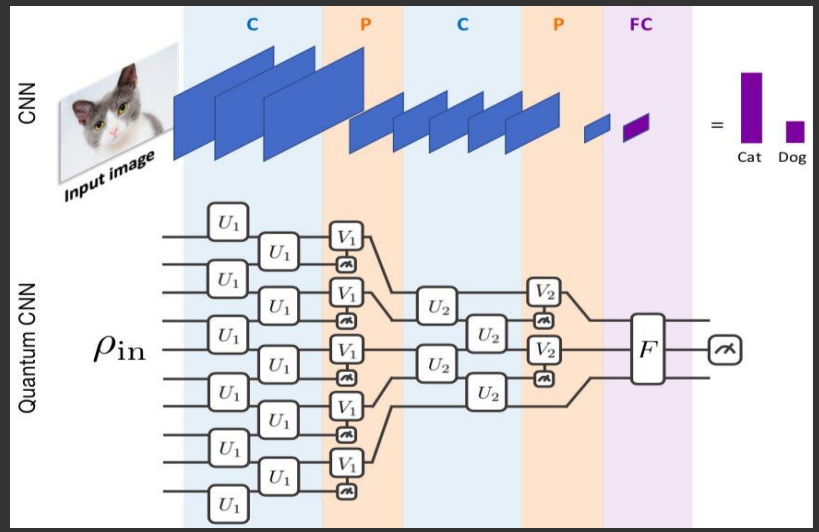
Quantum Chemistry

QAOA



Quantum Optimization

QNN



Quantum Machine Learning

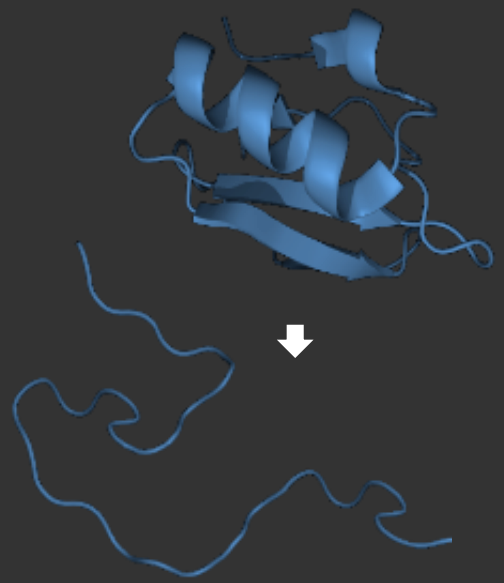
CINECA QUANTUM COMPUTING LAB

Cineca Quantum Computing Lab: Applications

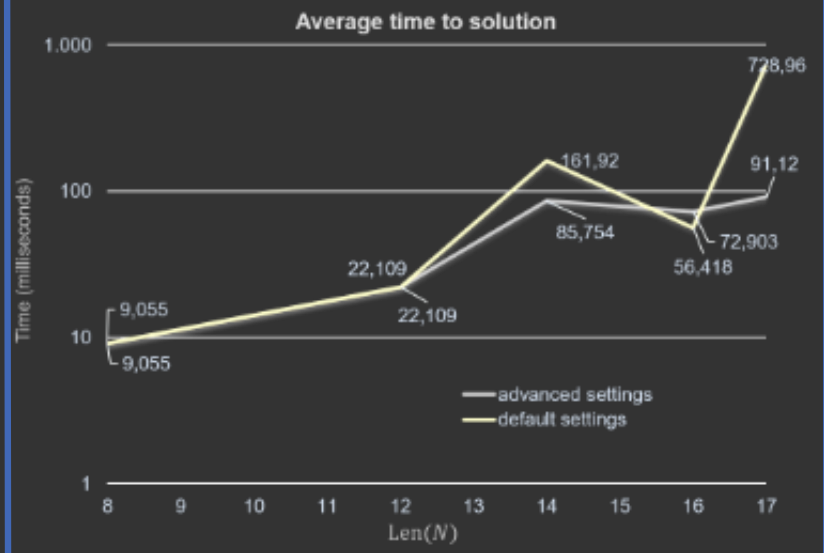
Real-world applications: chemistry, optimization, machine learning, simulations, etc.

Quantum Annealing

Molecular Unfolding



Factorization



System of Eqn.s solver

$$AX = \begin{pmatrix} D_1 & B_1^T & & & & \\ B_1 & D_2 & B_2^T & & & \\ & \ddots & \ddots & \ddots & & \\ & & B_{N-2} & D_{N-1} & B_{N-1}^T & \\ & & & B_{N-1} & D_N & \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_{N-1} \\ X_N \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_{N-1} \\ F_N \end{pmatrix}$$

CINECA QUANTUM COMPUTING LAB

Cineca Quantum Computing Lab: Applications

Real-world applications: chemistry, optimization, machine learning, simulations, etc.

QUANTUM ADVANTAGE IN THE NISQ ERA?

Quantum Computing @ CINECA

CINECA Quantum Computing Lab:

- Collaborate with Universities, Industries and QC startups
- Internship programs, Courses and Conference (HPCQC)

QUANTUM COMPUTING LAB

https://www.quantumcomputinglab.cineca.it

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