Pasqal

Quantum Korea | 2024

June 27, 2024

Towards industry-relevant (quantum) applications on Pasqal QPUs

A. Andrea Gentile, Head of ML Quantum Models

Pasqal Defining the quantum reality

PASQAL: from the lab to an integrated Product Ecosystem

Pasqal

>40+

CLIENTS & PARTNERS

Multiple QPUs sold via EU HPCQS framework, activities in more than 10 countries, and engagements with top cloud distributors

→10k

QUBITS

Over 1000 qubits demonstrated, concrete path to 10,000

55+

PATENTS & APPLICATIONS

800+ publications

230+

EMPLOYEES

18 nationalities

FULL-STACK

QUANTUM HARDWARE & SOFTWARE TODAY

Aiming for Practical Quantum Advantage

PASQAL's Global Presence

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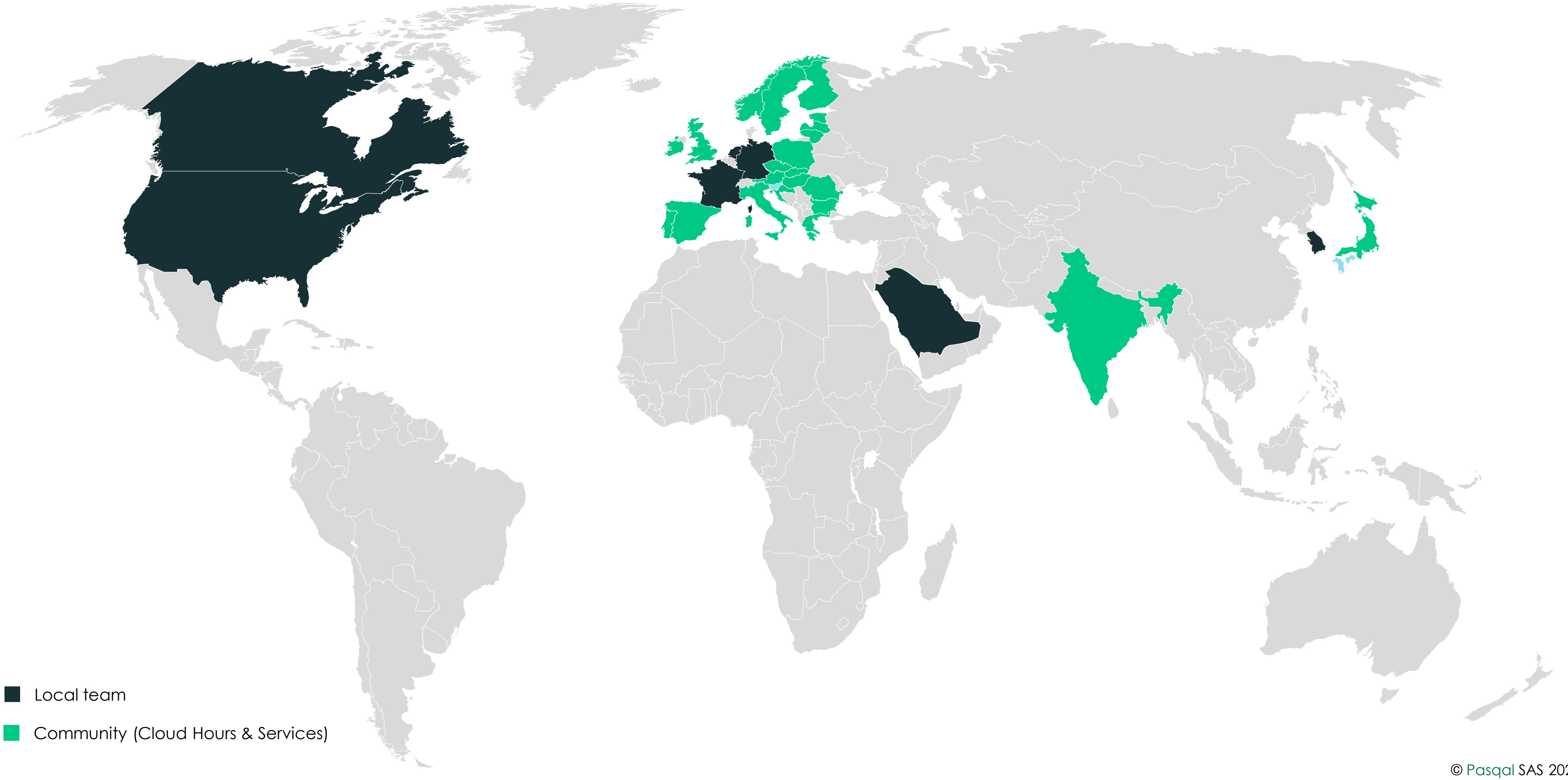

Neutral Atom QPUs can implement Algorithms with High Number of Equivalent Gates

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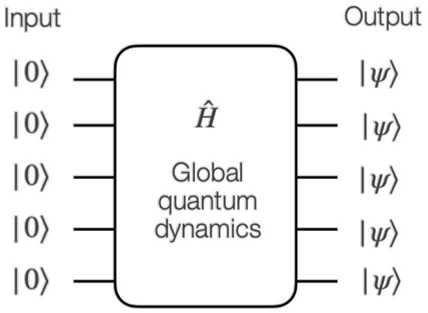
Analog Control

Programming a Hamiltonian sequence

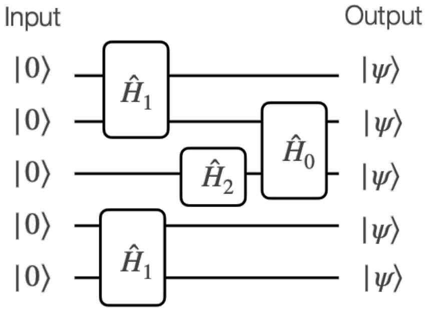
The Hamiltonian faithfully describes the dynamics of a physical quantum system or a reformulation of an operational case. Parameters can be tuned continuously.



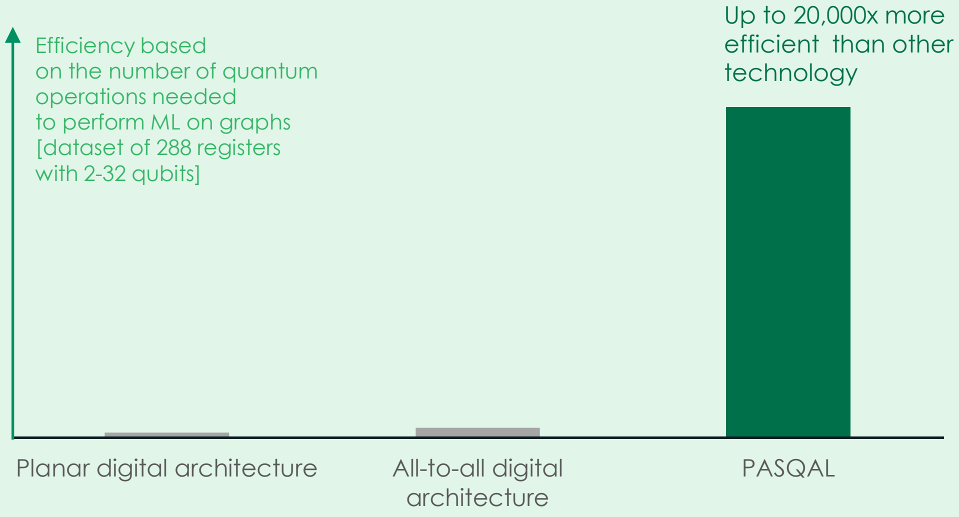
Digital Control

Programming a quantum circuit with digital quantum gates

Elementary operations are discrete digital quantum gates, that can act either on individual qubits, or on several qubits at the same time.



Due to reconfigurability, PASQAL'S QPU needs 10,000x to 20,000x less operations than other QPUs to perform graph ML algorithms[1].



[1] Albrecht, et al., Phys. Rev. A 107, 042615 (2023)

Combining Hardware & Software

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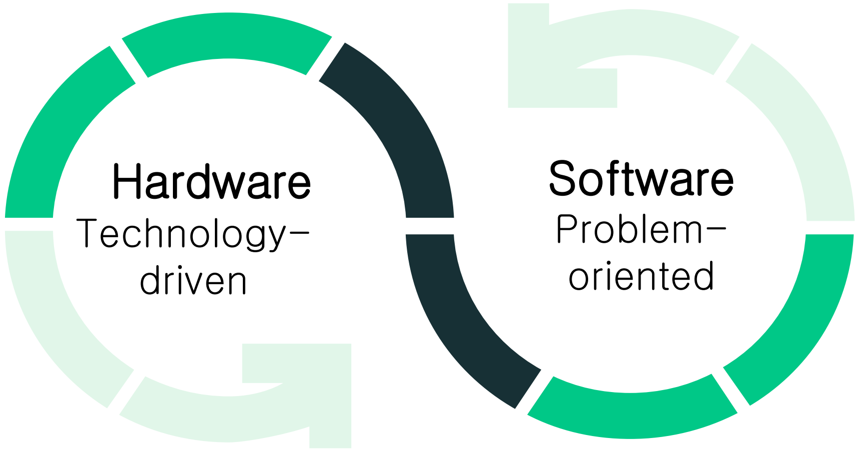

Co-developing hardware and software

Quantum Simulation

- Spin model dynamics (Ising/XY). In 2021, IOGS/CNRS lab implemented quantum Ising model beyond what could be simulated classically [1].
- Chemistry & Material Science Applications

Graph Machine Learning

- HW-native Quantum Evolution Kernel (QEK) [2].
- Extensions to state-of-art graph ML models (*graph transformers, shortest path*, …)

Optimization

- Graph-based optimization problems (*MIS, MaxCut*, …)
- Quantum Extremal Learning (QEL) Combinatorial optimization

Differential Equations

- Differentiable Quantum Circuit (DQC) proposal [3].
- Many extensions including *stochastic* differential equations.

[1] Scholl, et al., Nature volume 595, pages 233–238 (2021)
[2] Henry, et al., Phys. Rev. A 104, 032416 (2021)
[3] Kyriienko, et al., Phys. Rev. A 103, 052416 (2021)

Developing an open-source SW community

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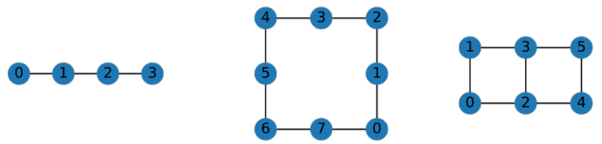
QADENCE

A library for Digital-Analog circuit design

- Automatic Differentiability via PyTorch integration.
- Parametric quantum programs with an intuitive symbolic system
- A simple interface to work with neutral-atom qubits using arbitrary registers topologies.



PULSER

Design and simulate pulse sequences for neutral atoms QPUs

- Programmable atomic arrays
- Control over relevant physical parameters
- Simulation with noise and errors

and more...

- State-vector emulators interfaceable with Qadence and Pulser (PyQ, QuTip)
- Tensor-network-based emulator upcoming (Q4 2024)
- Algorithmic libraries upcoming (2025)

Quantum Age today: industry-relevant use cases

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PASQAL develops quantum solutions in collaboration with several clients and partners. Among others:

	Fluid Dynamics	Material Deformation	Satellite Mission plan	Weather Modelling
Example partners:	LG	BMW GROUP	THALES	BASF
	Battery Modelling	Fuell cell Modelling	Process optimization	Quantum Chemistry
Example partners:	northvolt	Fraunhofer	posco	Panasonic

... And many others!

Solving Differential Equations

Problem Introduction

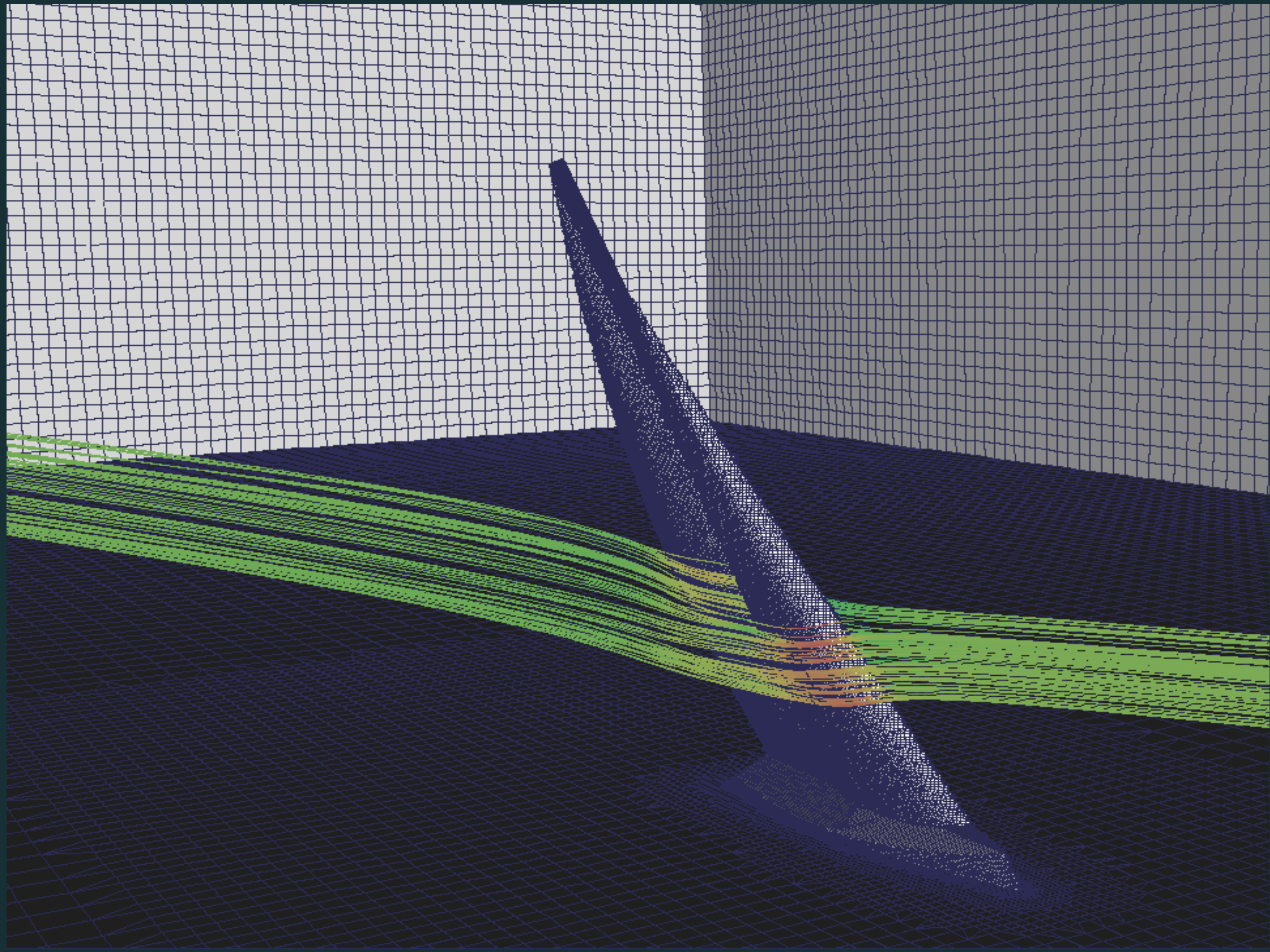
Solve (sets of partial) differential equations modelling physical phenomena or socio-economic processes

Goal

Surpass the limitations of state-of-art approaches and address instances which require unfeasible amount of classical computing power

In collaboration with:

LG



The limitations of grid-mesh based methods

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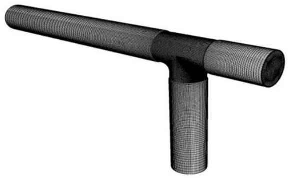
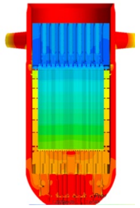
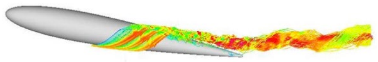
When modelling exemplary physical systems

Thermal fatigue **in T-junction**, Eulerian approach	**Golf ball** aerodynamics at DNS accuracy	**Nuclear fuel assembly** at LES accuracy	**Aerospace** modelling at DNS accuracy



~mins	~hours	~weeks	intractable

Time (on > 10^3 cores)

~GB	~100s GB	~10s TB	unfeasible

Memory

(Quantum) Scientific Machine Learning

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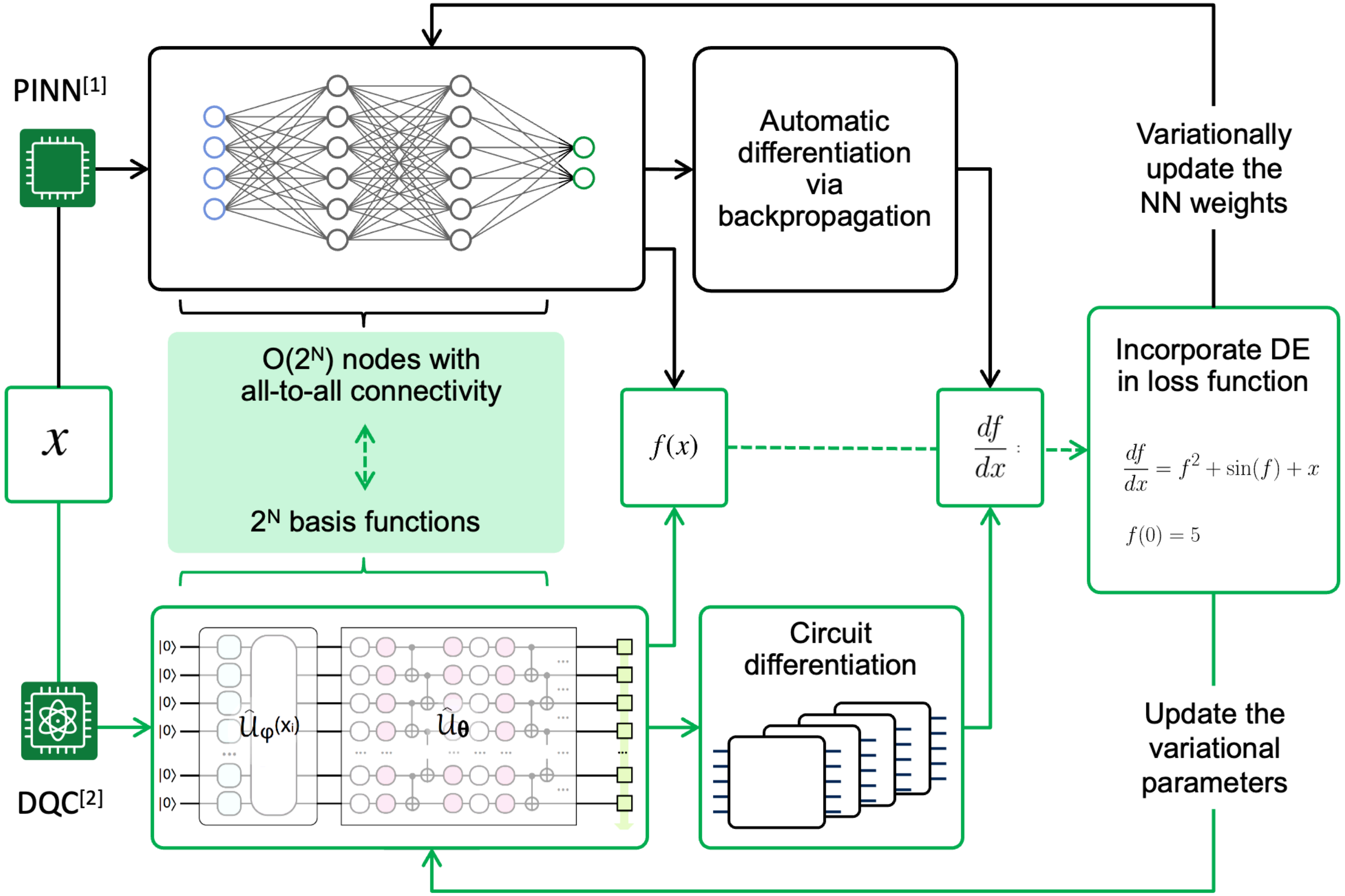
Methodology

- Physics-Informed Neural Networks: a ML-based approach to solve differential equations.
- A neural network acts as a function approximator, optimized by minimizing the residual of the differential equation.
- Highly-expressive classical NNs require an exponentially large number of nodes with high connectivity.
- **Differentiable Quantum Circuits (DQC)** [1] give access to highly-expressive function approximators with much fewer qubits



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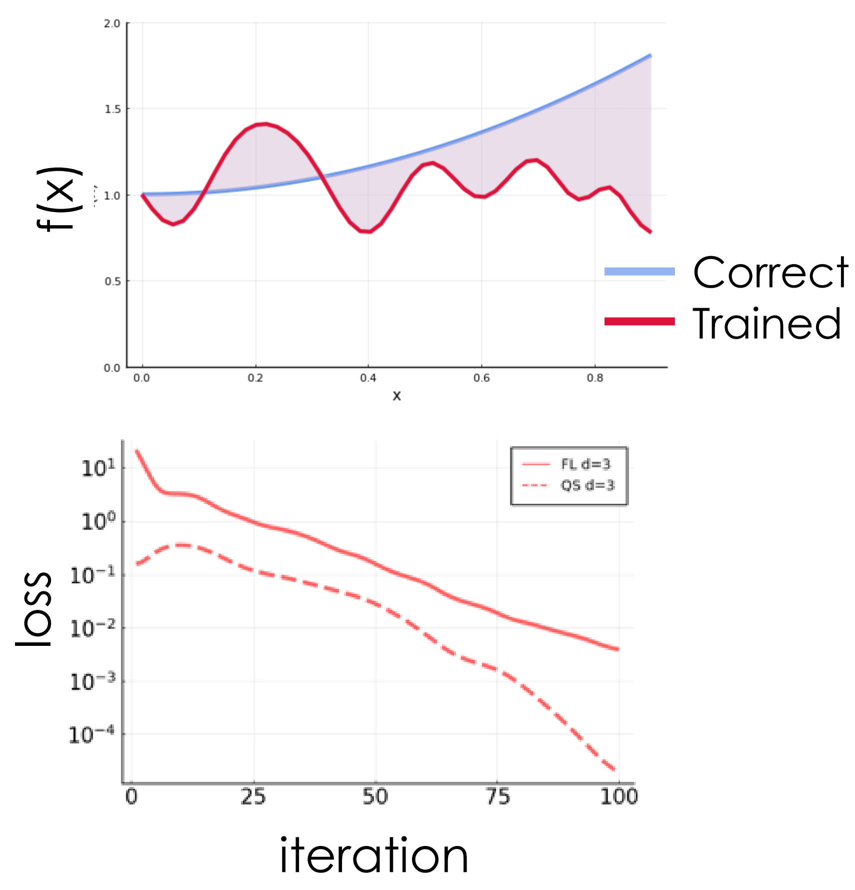

[1] Kyriienko et al., Phys. Rev. A 103, 052416 (2021)

Computational Fluid Dynamics (CFD)

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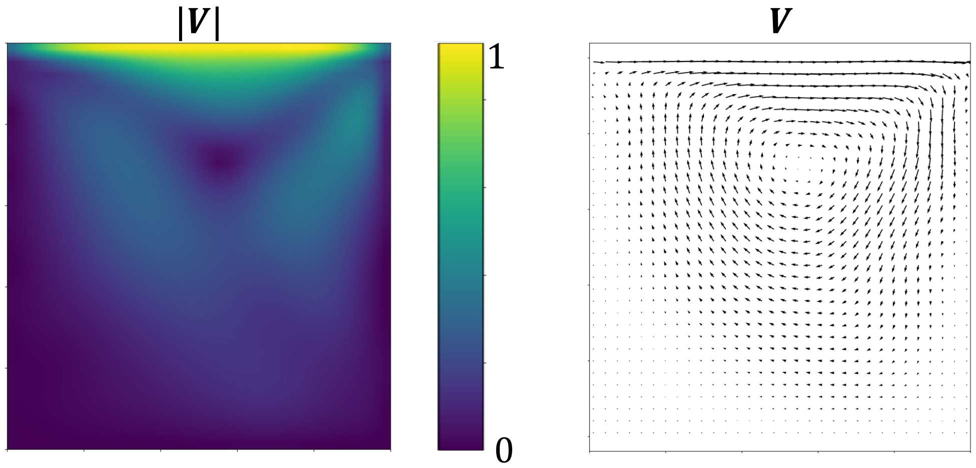
Problem Layout

- CFD solutions can pose severe challenges for mesh-based (e.g. FEM) solvers, when the "Reynold number" Re describes turbulent regimes
- We test DQC by solving for the fluid velocity $\boldsymbol{V}$ in steady-state $(\partial \cdot / \partial t = 0)$ incompressible Navier-Stokes eq.:

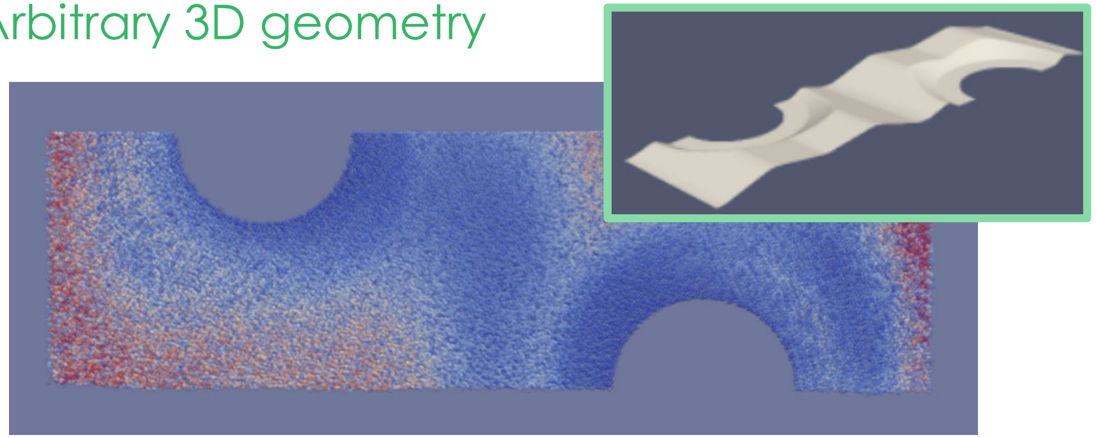
$$\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V} \cdot \nabla)\boldsymbol{V} = -\nabla p + \frac{1}{Re}\nabla^2 \boldsymbol{V}$$

- We use DQC with $O(10)$ qubits to solve paradigmatic lid-driven geometries up to $Re \sim 500$ as well as complex geometries
- We achieve good agreement with FEM benchmarks

Lid-driven cavity



Arbitrary 3D geometry



Industrial Process optimization

Problem Introduction

Producing H_2 from ammonia cracking

Goal

Minimize power consumption and hazardous emissions while maximizing production

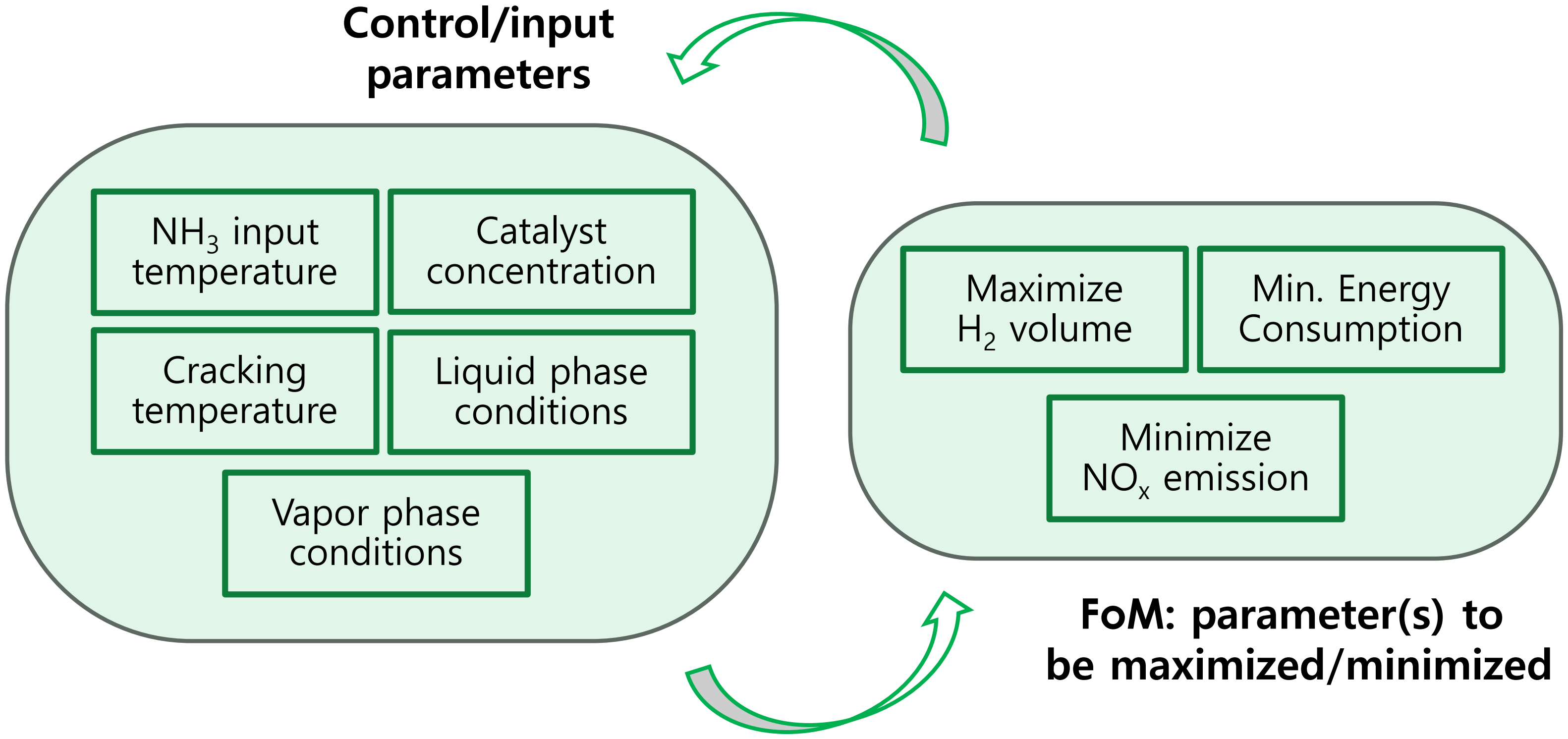
In collaboration with:

posco

Process optimization of a chemical plant

Problem setting

- Some key Figures of Merit (FoM) are controlled by tuning a finite set of process parameters
- Maximising the FoMs predicted by a (here, unknown) model is an extremization process that can involve continuous or discrete parameters
- Pasqal's Quantum Extremal Learning (QEL) is ideally suited to target this problem



Quantum Extremal Learning (QEL)

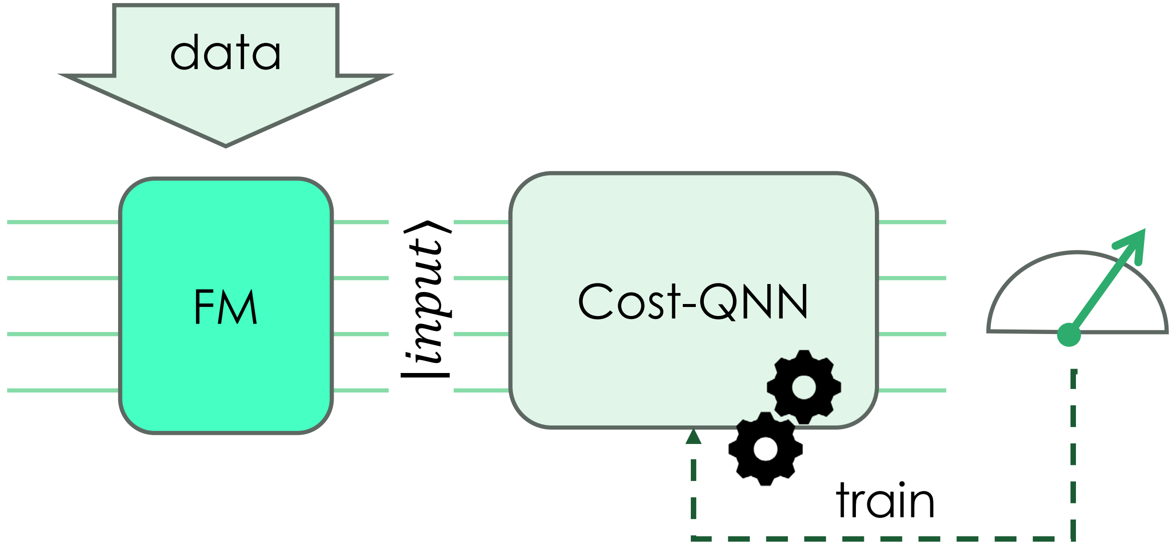
Methodology

QEL [1] addresses the challenge of not only modelling the data but finding the input to a hidden function that extremizes the function output, without having direct access to said function, but only to partial input-output data

Why? this approach becomes use-full when we are looking for a high dimensional extremal point

QEL works in two main steps:

- **Train QNN**: a parametric quantum circuit (cost-QNN) is variationally trained to model data input-output relationships by reducing a loss



[1] Varsamopoulos et al., arXiv:2205.02807 (2022).

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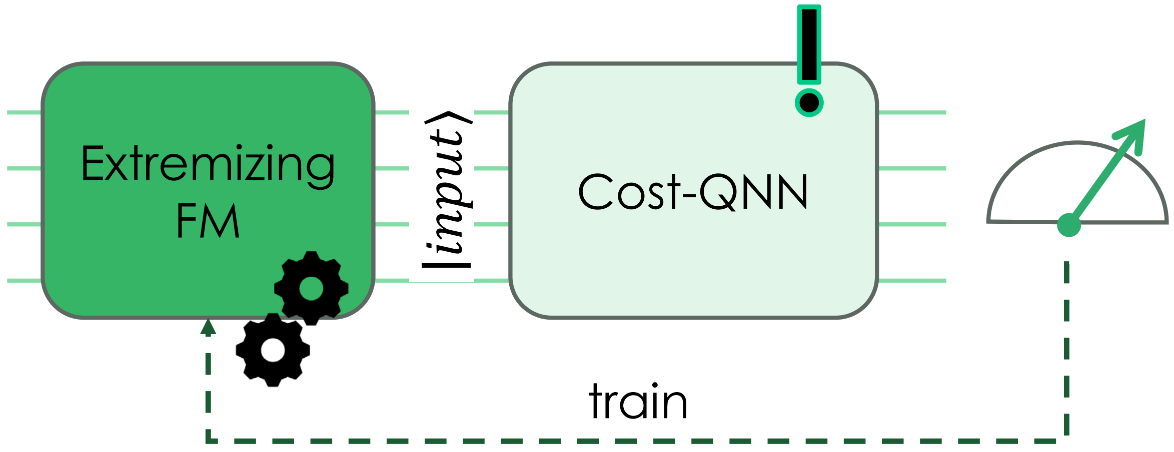
QEL works in steps:

- **Find extremal point**: a trainable Extremising Feature Map, encoding input data, is analytically differentiated to find the extremizing coordinate



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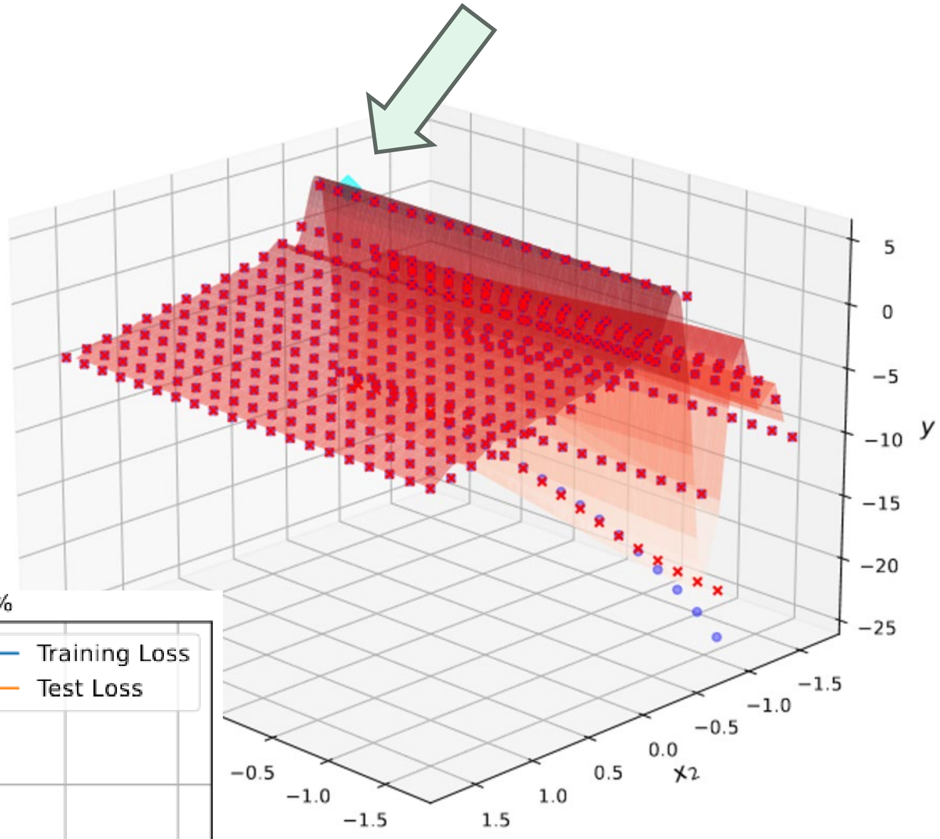
Process optimization of a chemical plant

QEL in action

- Optimization instance with 2 independent control parameters
- Analysis with a 6-qubit, depth-10 cost-QNN
- Training adopted: 320 pts
- We checked the generalization capabilities of the model by performing the Testing on: 80 pts



Mission planning for Satellites

Quantum computing for earth observation

In collaboration with:

GENCI
Le calcul intensif au service de la connaissance

THALES
Building a future we can all trust

esa
European Space Agency

Combinatorial optimization for satellites

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Problem Introduction

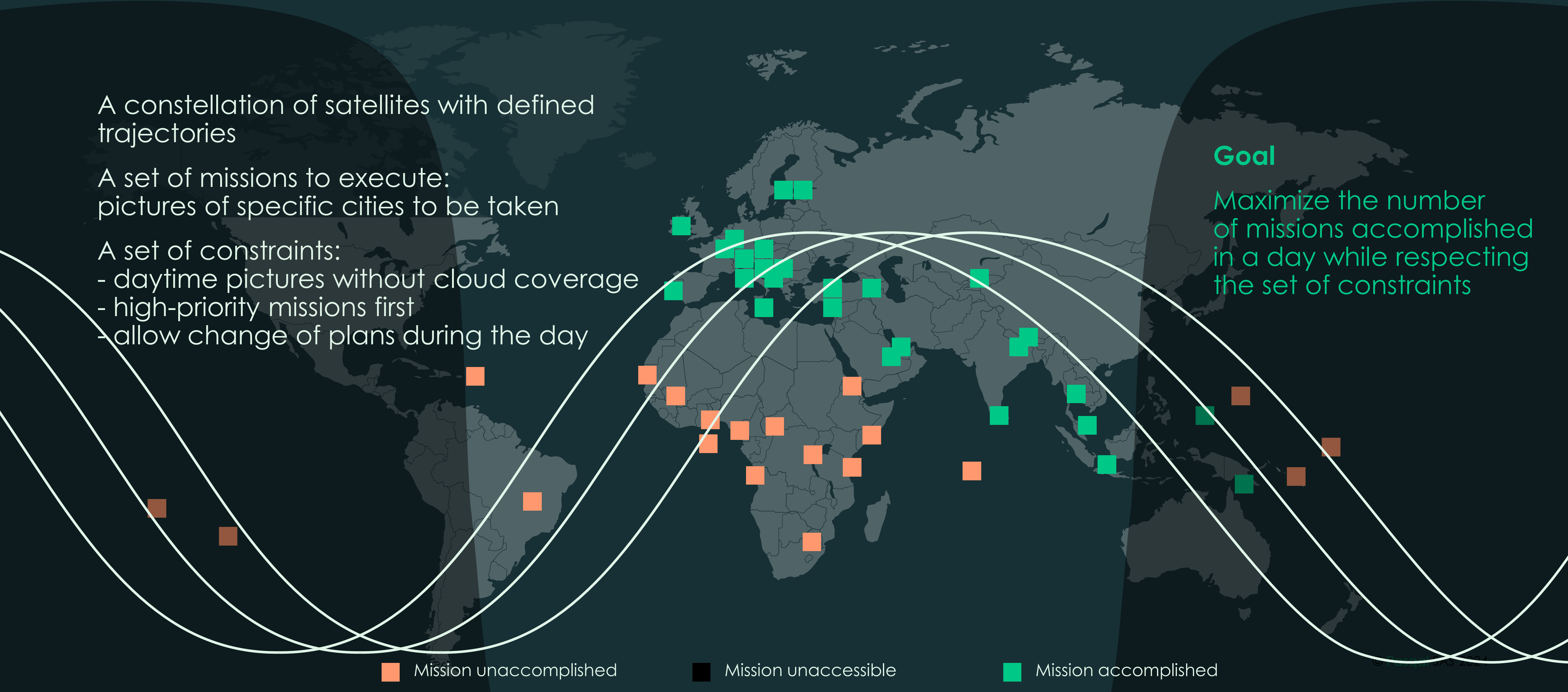
A constellation of satellites with defined trajectories

A set of missions to execute:
pictures of specific cities to be taken

A set of constraints:
- daytime pictures without cloud coverage
- high-priority missions first
- allow change of plans during the day

Goal

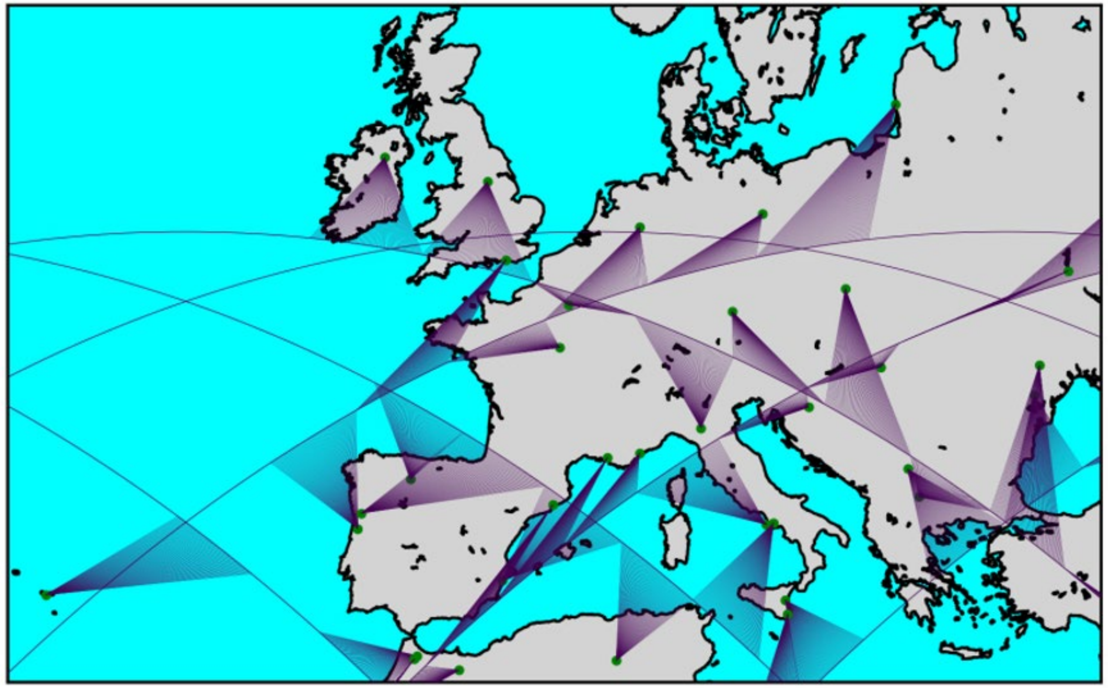
Maximize the number of missions accomplished in a day while respecting the set of constraints



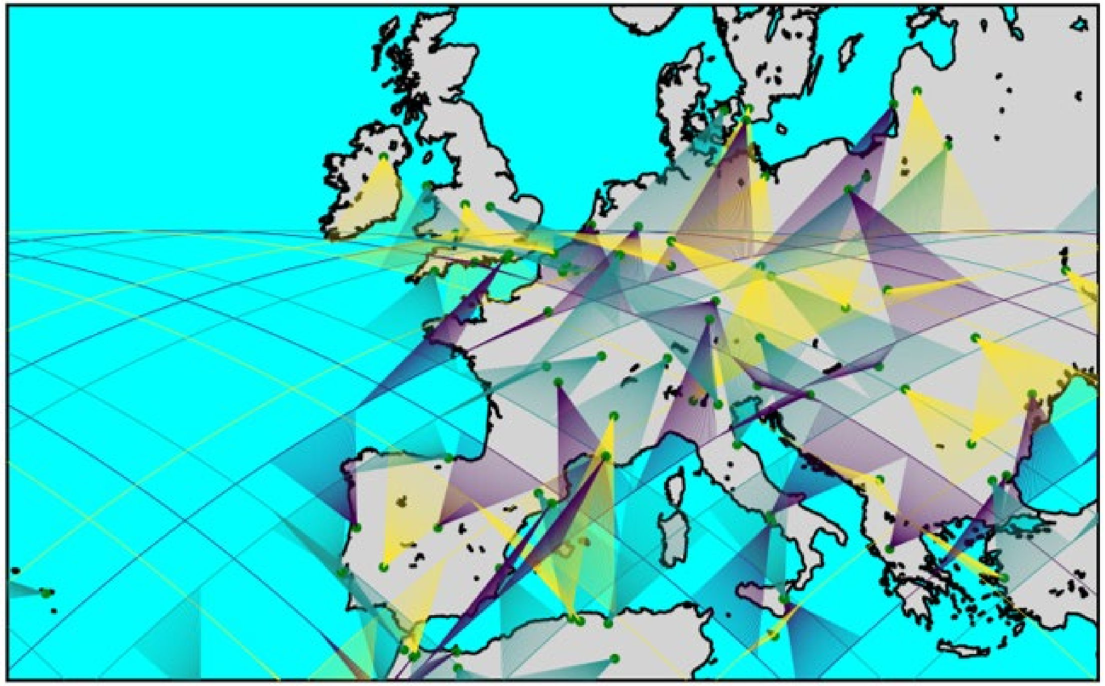
Extending the problem to multiple satellites requires better performing solutions

Problem Introduction

1 satellite



3 satellites



Encoding the problem in a Graph Structure

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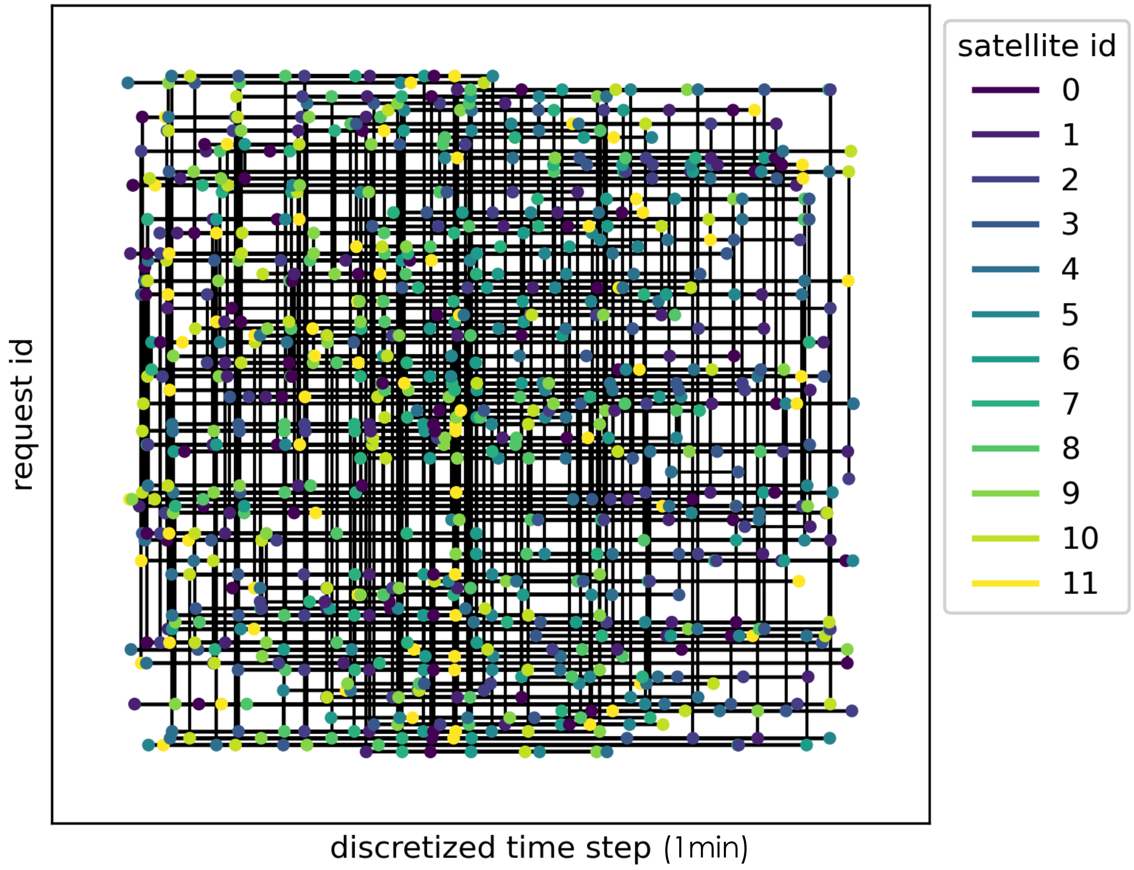
- Nodes are equivalent to mission slots
- Colors represent unique satellites of the constellation
- Edges are equivalent to incompatibilities of constrains
    1. Each request performed only once
    2. No overlapping time slots per satellite
- To retrieve the solution we apply a Maximum Independent Set graph methodology [1,2]

Visiting capitals with 12 shifted ISS



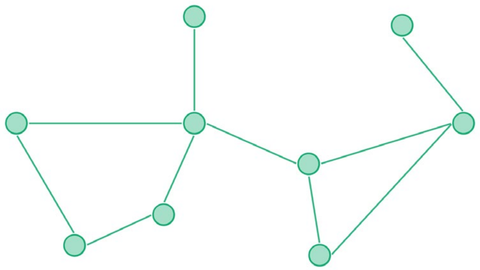
[1] D. Eddy et al. (2021)
[2] S. Ebadi et al. (2022)

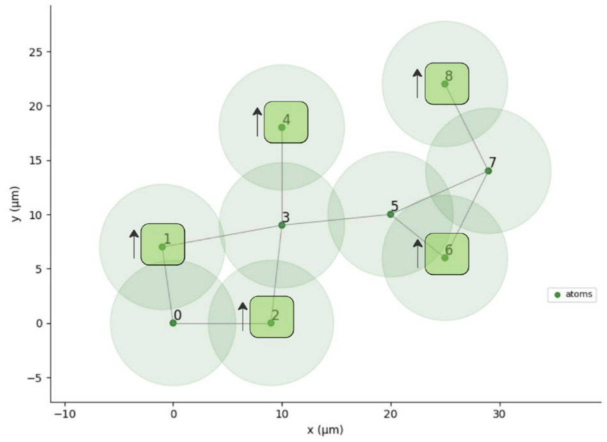
Solving the MIS on PASQAL QPUs

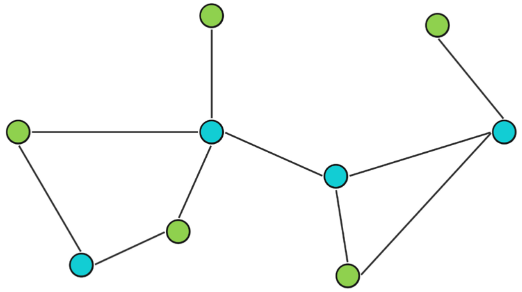
Maximum Independent Set (MIS) is a well-suited problem for Rydberg atoms

Graph-structured problems are
natively addressable
with neutral atoms !

- Atoms’ positions and mutual distances **encode directly** the target graph.
- Rydberg dynamics can be leveraged to naturally encode the **constraints** and solution to the MIS problem for **unit-disk graphs**.



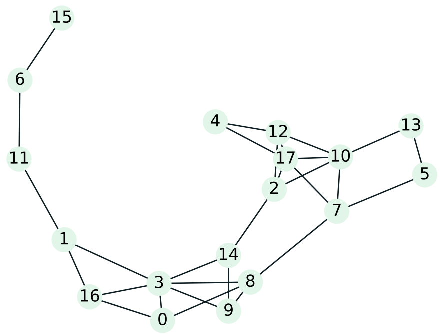




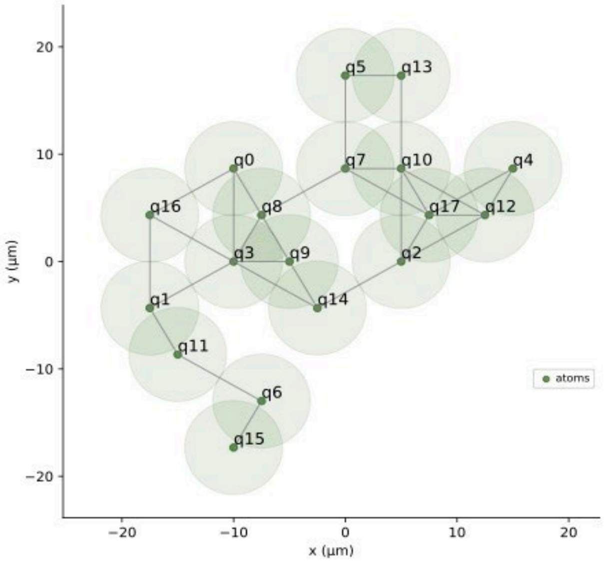
Adiabatic state preparation of MIS configurations

Maximum Independent Set (MIS) is a well-suited problem for Rydberg atoms

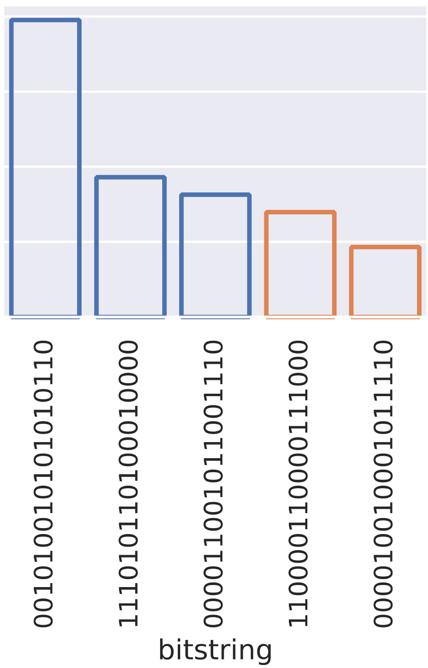
Original Graph



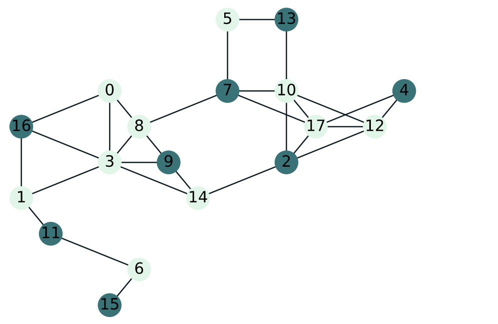
Embedding State preparation



Result Distribution



Maximum Independent Set



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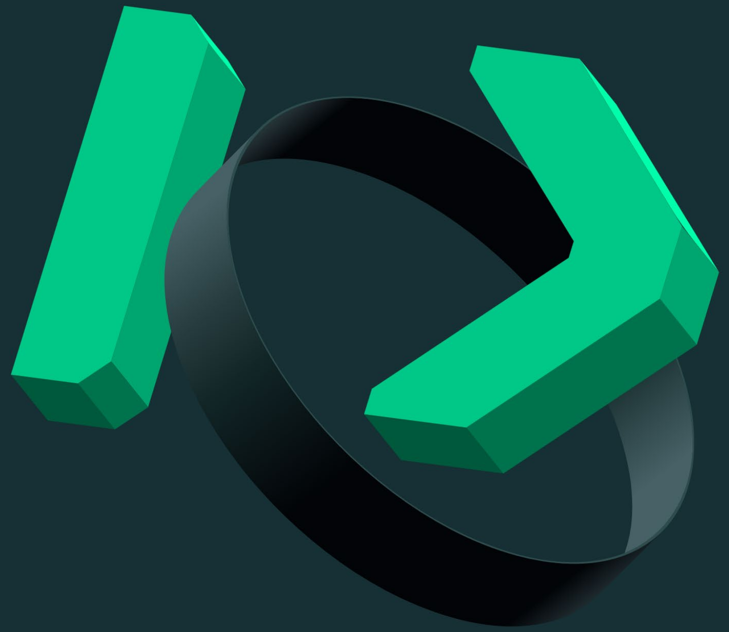
Perspectives

- Quantum solutions to real-world industrial problems,
- Implementations on real QPUs, today.
- We can customize or extend existing solutions to other problems with industrial relevance.



Towards industry-relevant applications on

Pasqal

QPUs

Thank you for your attention