Pasqal Defining the quantum reality

Ensuring relevance of benchmarks for Quantum Computing

Louis-Paul Henry

TQCI, Reims, 2024

Pasqal

Agenda

Our approach to Quantum Computing

- Pasqal & Neutral-atom QPU

Accounting for different paradigms

- From NA-QPUs to graphs
- From Q. Simulation to Analog QC
- Hybrid

Building relevant benchmarks

- Choosing the right metrics
- Example 1 : Column Generation (Optimization)
- Example 2 : Quantum Kernel (Machine Learning)

Conclusion

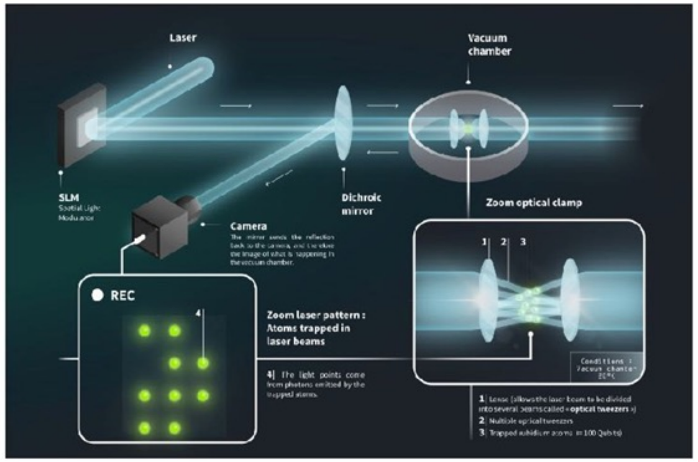
Pasqal Defining the quantum reality

Our approach to Quantum Computing

Pasqal

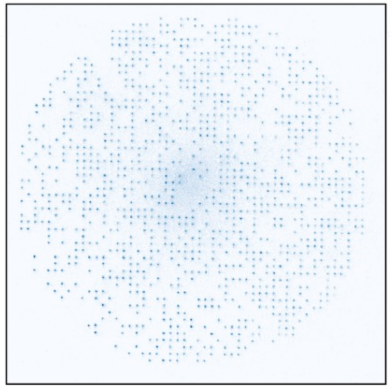
Pasqal

- Founded in 2019
- 200+ scientists & engineers
- Building neutral-atom QPUs



- Full stack : from HW to applications

- 1 industrialized QPU on the cloud
- 2 to be installed in HPC centers
- More on the way
- Electrical consumption of 4 washing machines

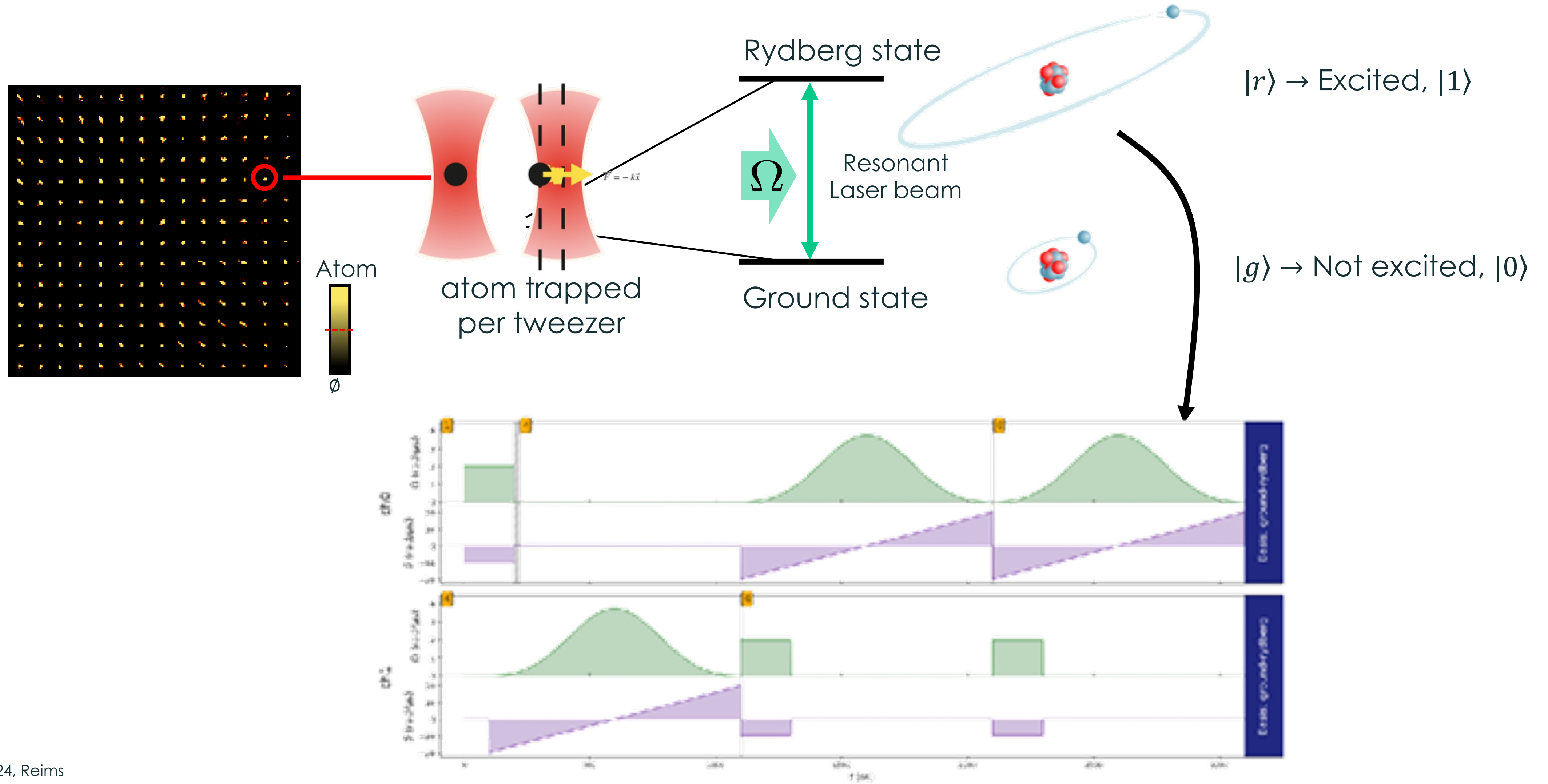


arXiv:2405.19503

- 2 devices dedicated fo R&D
  - Larger qubit number
  - FTQC program

Neutral atom QPU in a nutshell

Pasqal



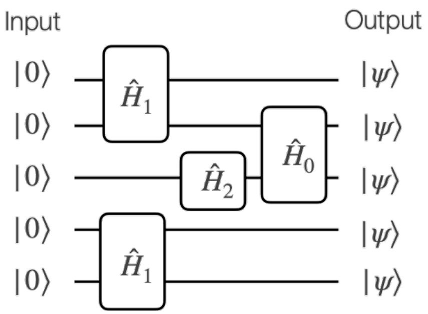
Modes of operation

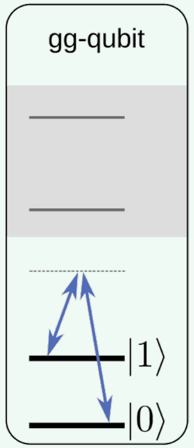
Pasqal

Gate-based

Programming a quantum circuit with quantum gates

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





$|g\rangle \equiv |0\rangle$ $\quad |g'\rangle \equiv |1\rangle$

+ Extremely long lifetimes (msec – sec)
– Weakly interacting: requires intermediate $|r\rangle$ state

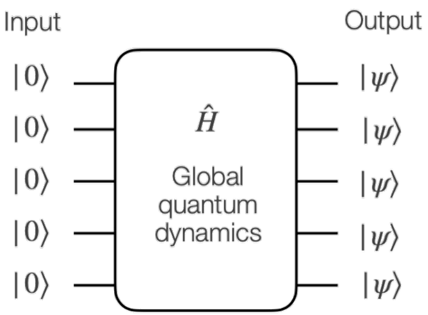
⇨ 1- and 2-qubit gates

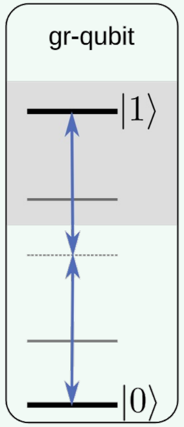
Isenhower (2010), Müller (2014), Maller (2015), Kaufman (2015), …

Analog

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.





$|g\rangle \equiv |0\rangle$ $\quad |r\rangle \equiv |1\rangle$

+ Simple, few laser fields
+ Easier to prepare
+ Easier to measure
– Limited by lifetime of Rydberg state ($\sim 100\mu s$)

⇨ Ising model

Bernien (2017), Lienard (2018, Guardado-Sanchez (2018), …

02

Accounting for different paradigms

From gates to analog and hybrid

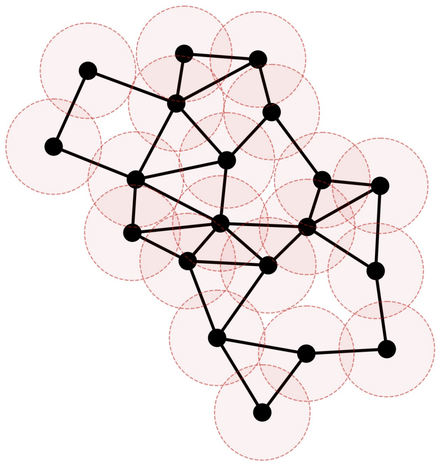
From Neutral atom QPU to graphs

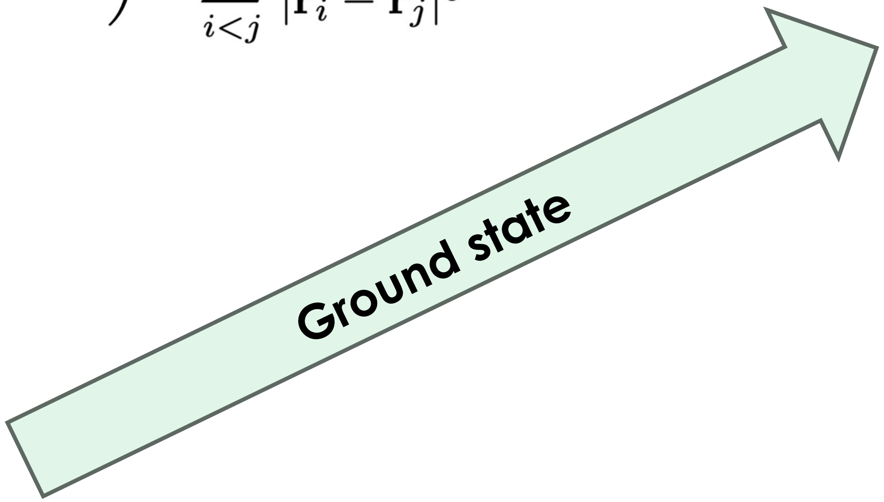
Pasqal

Hamiltonian

$$\hat{\mathcal{H}}(t) = \hbar \sum_{i=1}^{N} \left(\frac{\Omega(t)}{2} \hat{\sigma}_i^x - \delta(t)\, \hat{n}_i \right) + \sum_{i<j} \frac{C_6}{|\mathbf{r}_i - \mathbf{r}_j|^6} \hat{n}_i \hat{n}_j$$

Unit disk graph



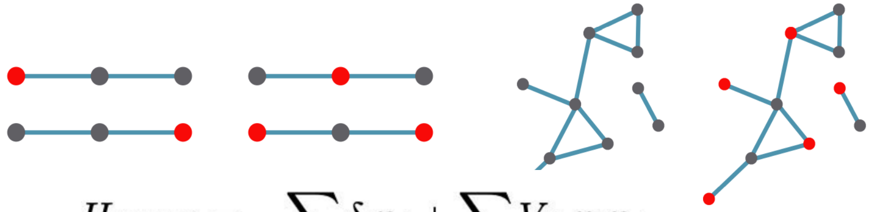


Graphs

Maximum Independent Set(s)

Let $\mathcal{G} = (V, E)$ be a graph.

$S \subset V$ is an independent set if $\forall v, w \in S,\ (v, w) \notin E$.



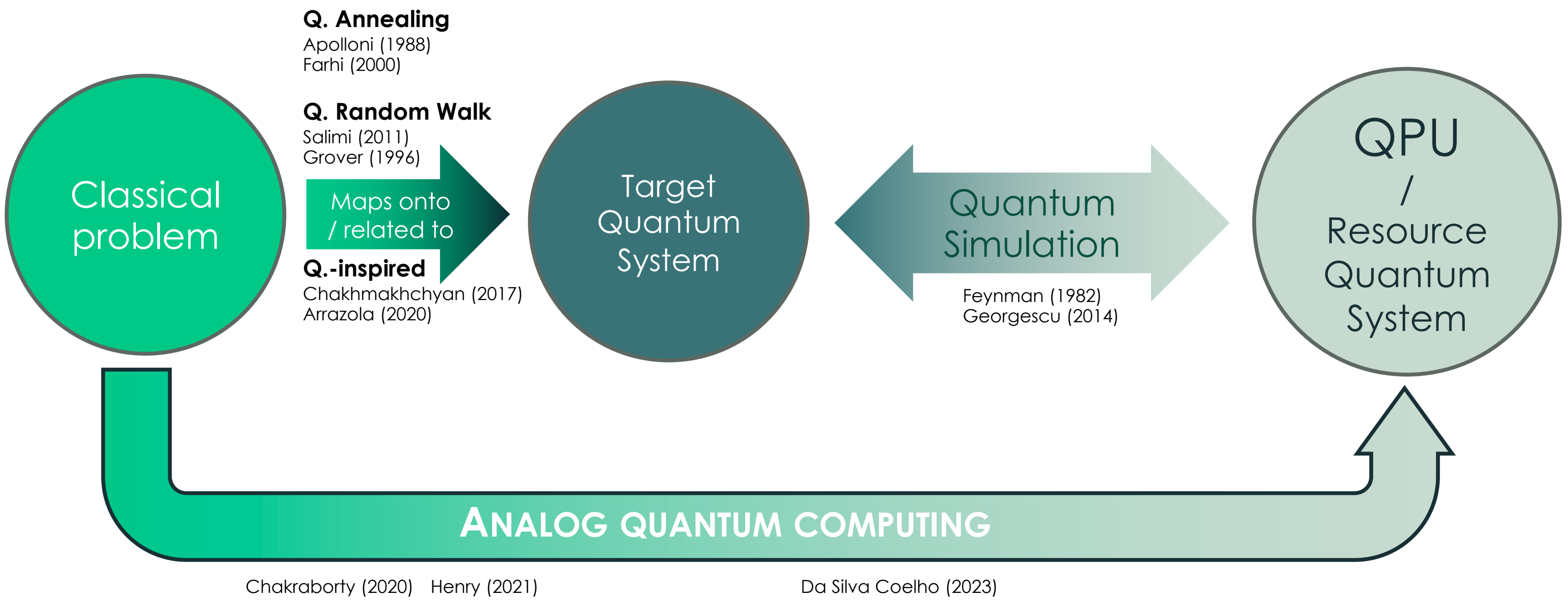
$$H_{\text{MWIS}} = -\sum_{i} \delta_i n_i + \sum_{i<j} V_{ij}\, n_i n_j$$

**Optimization problem
with a wide range of applications**

Graph-structured problems are natively addressable with neutral atoms!

From Quantum Simulation to analog QC

Pasqal



Analog vs gate-based

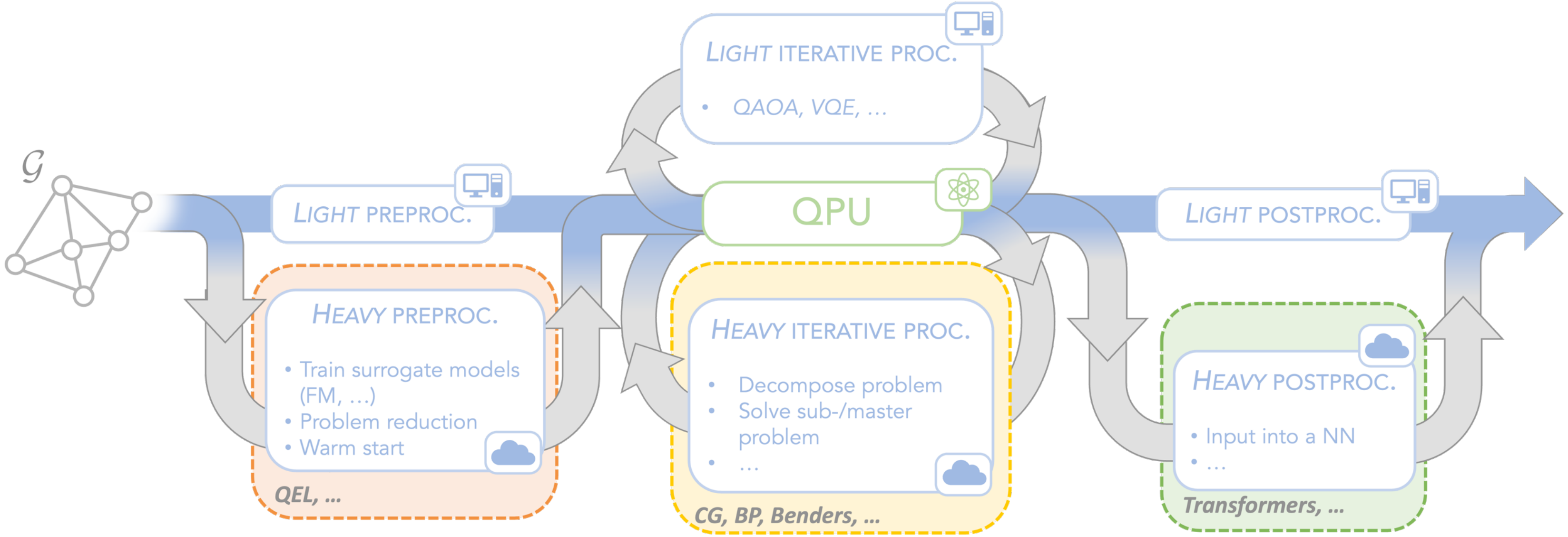
- Not a short-term « esatz », but a different paradigm
  - *Some similar algorithms*
  - *New ones*
- Interactions are always on
  - *Quick development of correlation/entanglement*
  - *No need of Trotterization*
  - *Undesired cross-talk*
- Programed through continuous control
  - *Lot of freedom*
  - *No clear framework yet*

Hybrid algorithms

Pasqal

What do we mean by « hybrid »?

Heavily rely on classical processing (Might derive from a fully classical framework, replacing specific éléments)`



- *Examples*

  Optimization (Column Generation, Branch & Bond, …)
  Graph Machine Learning (Transformers, …)

How do you compare ?

- Classical and quantum costs can be similar :
  - *How do you take into account the cost of the classical part?*
  - *What do you compare the quantum elements to?*
- What metric is the most relevant?
  - *➜ Application-driven metrics*
- *(existing classical ones, Q-score, …)*

arXiv:2403.11931

Pasqal Defining the quantum reality

03

Building relevant benchmarks

To better fit users needs and help development

Choosing the right metrics

Pasqal

How one compares Classical and Quantum

- Determining the scaling of an algorithm
  - Classical complexity theory
    - *Nb. of operations, memory usage*
  - Quantum complexity theory
    - *Nb. of gates, circuit depths, Nb. of qubits*
- Advantages of this approach
  - Provides nice theoretical arguments
  - Compatible with classical complexity theory
- Issues with this
  - No clear framework for Q. sim. and analog QC
  - Often restricted to "worst-case scenario" scaling, or to certain types of instances

What one wants to measure *in practice*

- *Most* Q. algorithms aim at finding a *bitstring* :

$$\boldsymbol{b} = b_0, b_1, \dots, b_{N-1} \in \{0,1\}^N$$

sampled with probability $p_{\boldsymbol{b}}$ from the final state

- In practice, one repeats n times the same preparation and measurement

$$\{\boldsymbol{b}_1, \dots, \boldsymbol{b}_n\}$$

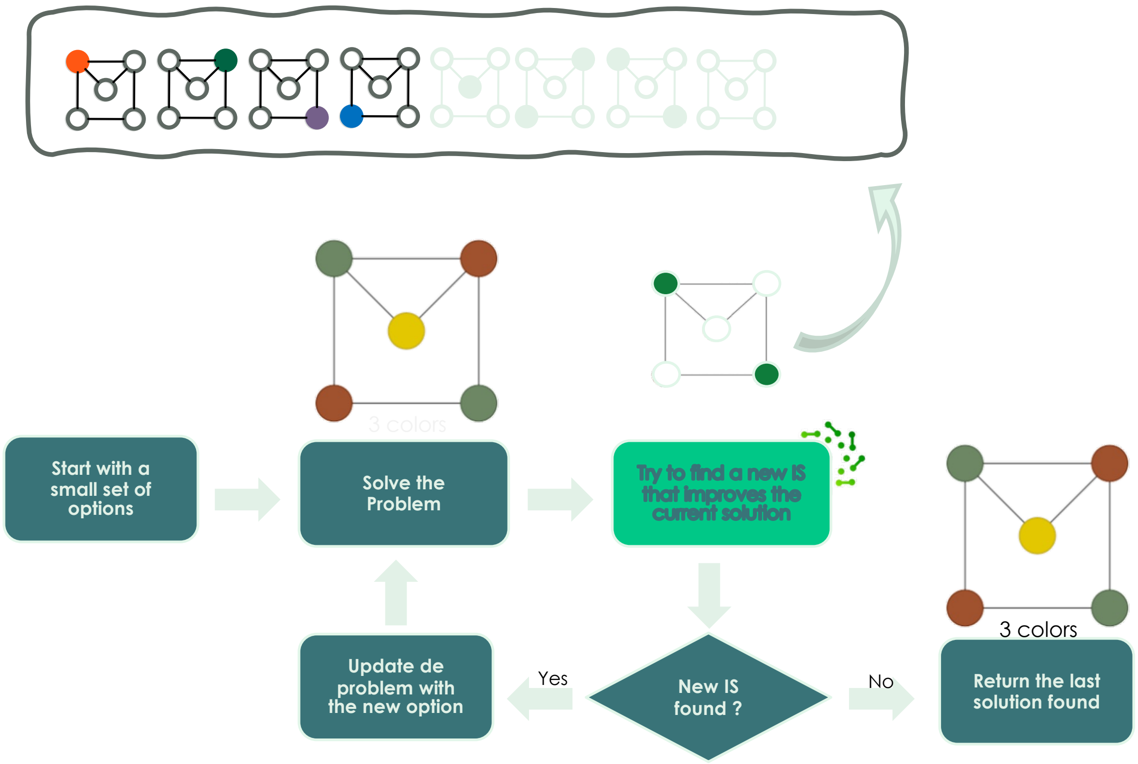
- For applications, *users* are rather interested in
  - **Time to solution (TTS)** $TTS \sim p_{\boldsymbol{b}}^{-1}$
  - **Quality of solutions** $\min_i f(\boldsymbol{b}_i)$
  - **Computation cost/Energy consumption**
- Classical solvers rely *a lot* on heuristics and are tailored to specific problems

➜Application-specific benchmarks and metrics

Example 1 : Column generation (optimization)

Pasqal

Algorithm

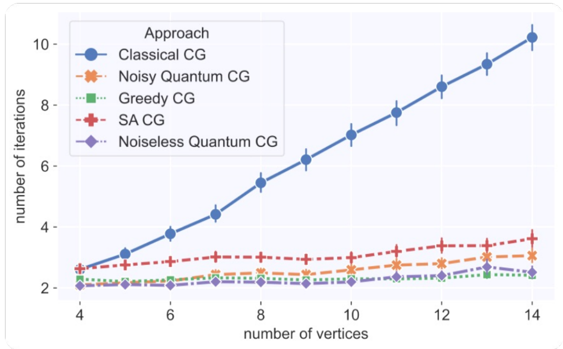


Done on classical (super) computers

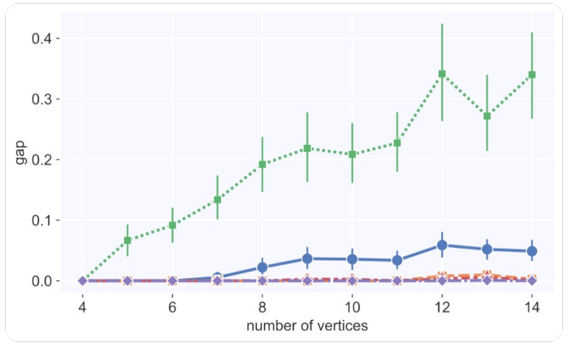
Done on QPUs

Results

Number of iterations generating new options



Distance from the global optimal solution



- Our hybrid quantum-classical method has the best overall performance
- It can find better options than state-of-the-art heuristics : up to 80% less colours
- It is faster than fully classical methods : up to 6 times faster than the exact classical framework

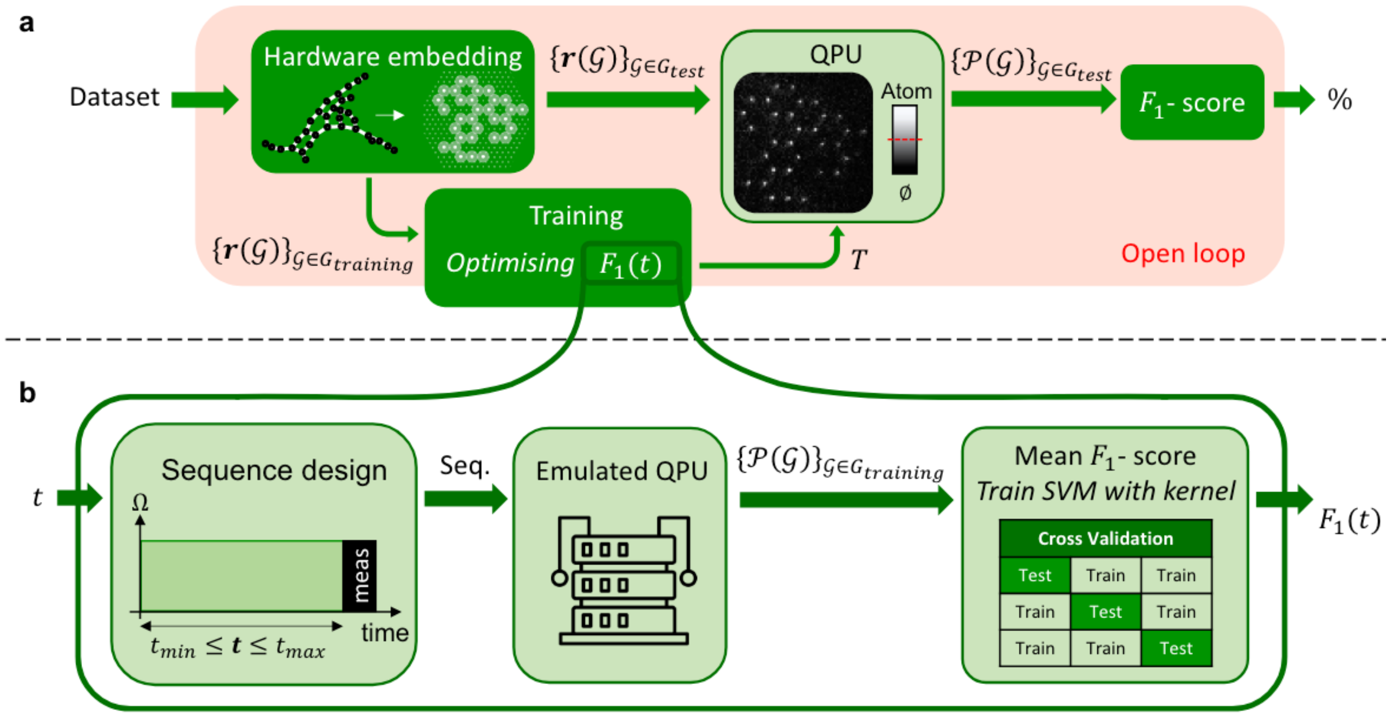
arXiv:2301.02637

Example 2 : Graph Kernel (Machine Learning)

Pasqal

Experiment on Pasqal hardware:

- Dataset: PTC-FM
- 286 molecules of sizes ranging from 2 to 32 nodes
- Classification task



Kernel	F_1-score (%)
QEK	60.4 ± 5.1
QEK (size-compensated)	45.1 ± 3.7
SVM-ϑ	58.2 ± 5.5
Size	56.7 ± 5.6
Graphlet Sampling	56.9 ± 5.0
Random Walk	55.1 ± 6.9
Shortest Path	49.8 ± 6.0

PRA **107** 042615 (2023)

Conclusion

Implementing benchmarks

Pasqal

A wide variety of applications

Quantum applications are extremely diverse

- *Different HW technologies*
- *Different QC paradigms :*
  - *Gate-based, analog, annealers…*
- *Different use of QPUs :*
  - *Variational, hybrid…*

This diversity might stay beyond near-term

- *Low-level benchmarks have limited interest*

⇒ Application benchmarks!

Defining Application benchmarks

- Content
  - Relevant and diverse datasets
  - Useful metrics (applicable to various plateforms and approaches)
  - Keep up with the classical SotA
  - HW specific as well as HW independant
- How to do this ?

⇒ Work with classical experts and with end users!

Implementing benchmarks

Pasqal

Technology
PASQAL & affiliated ecosystem

	2022 - 2023	2024 - 2025	2026 - 2027	2028+
HARDWARE PLATFORM				
Max qubits	200	1,000	10,000	
Addressability	Z add	Z+X add; Addressable 1Q and 2Q gates	Addressable 1Q and 2Q gates	
Base repetition rate	1 Hz	3 Hz	10 Hz	100 Hz
FTQC Program		Atom shuttling; Ultra High-Fidelity Gates	Scalable logical qubits architecture	
HARDWARE ACCELERATED LIBRARIES				
Quantum Matter & Quantum AI	Algorithm Blueprint	Algorithm Development	Production	Production

Products

	2022 - 2023	2024 - 2025	2024 - 2025	2026 - 2027	2026 - 2027	2028+
QUANTUM PROCESSORS						
Generation	**Orion Alpha** ~3M gates	**Orion Beta** ~5M gates On premise delivery	**Orion Gamma** ~10M gates On premise delivery	**Vela** ~40M gates	**Pegasus** ~200M gates	**Centaurus FTQC QPU** 128+ Logical qubits 200M+ gates
Total hours of QPU for users	500	5-10,000	20-30,000	60-70,000	200-250,000	500-550,000
Factories	France	Canada	Factory 3			
COMMUNITY						
Platform		Learn	Interact	Collaborate		
Open-source Software Stack	Pulser	Qadence	Solvers & Emulators	Solvers & Emulators		

Pasqal Defining the quantum reality

Thank you!