Jeudi 10 Février 2022

Quantum Computing

Etat de l'art et perspectives

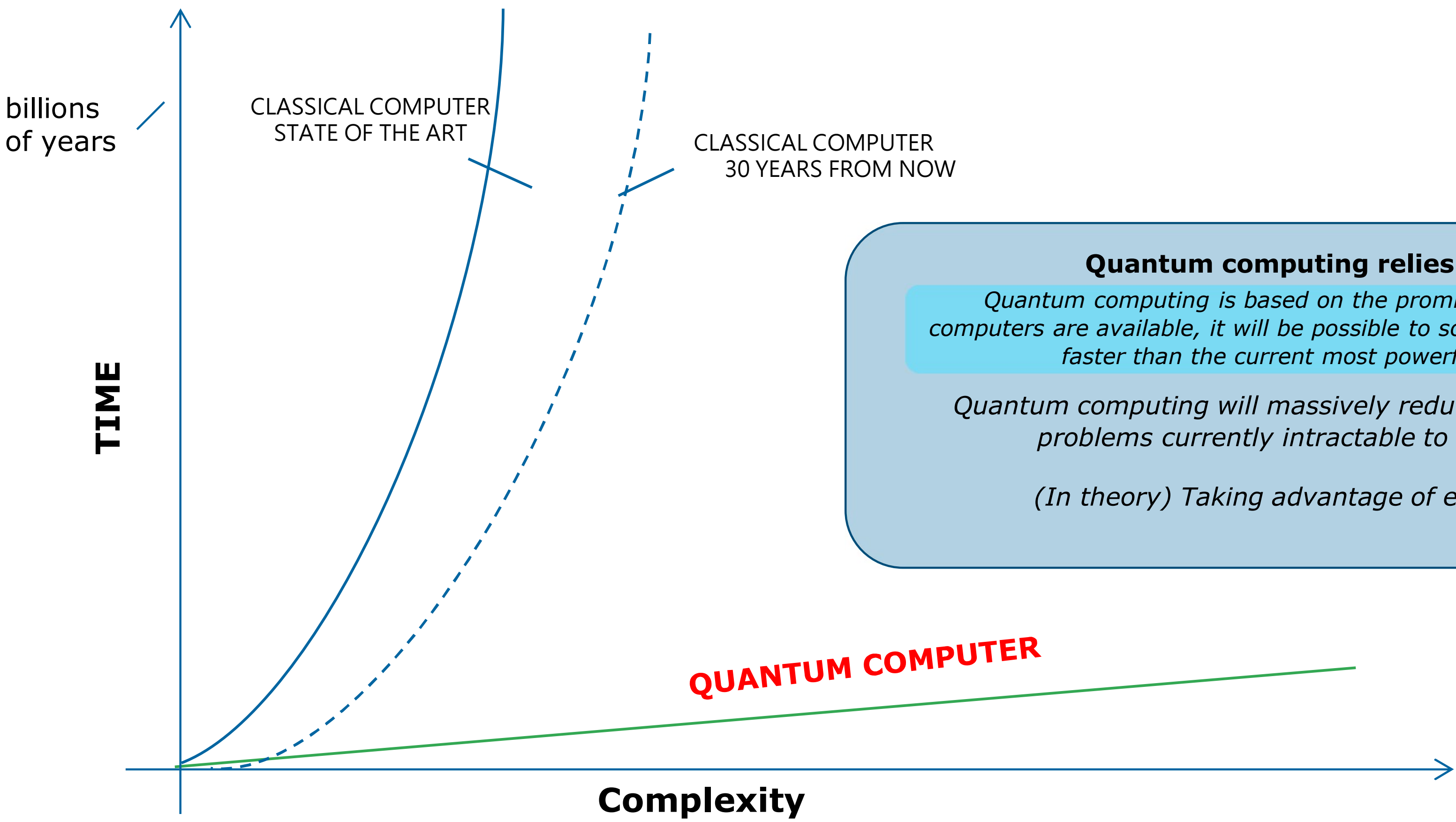
Journée Informatique

Olivier Hess
ATOS Quantum Computing
olivier.hess@atos.net

Agenda

- Introduction à l’informatique quantique
- Etat de l’art des développements
- Les principaux domaines d’applications

Classical computing software limitations



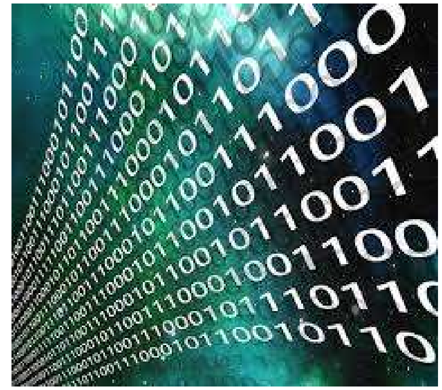
Quantum computing relies on one promise:

Quantum computing is based on the promise that, when quantum computers are available, it will be possible to solve some complex problems faster than the current most powerful HPC systems.

Quantum computing will massively reduce the complexity of some problems currently intractable to classical computers

(In theory) Taking advantage of exponential growth : 2^n

Classical Information …. ☺



bit 1	bit 2	bit 3	bit 4
0	1	1	0

- Each bit is in a definite state : 0 or 1
- Reading a bit does not change the state
- You can copy a bit
- All of the information of a bit is stored in that bit
- bits do not interact

0 0

0 1

1 0

1 1

0 0 0

0 0 1

…

1 1 1

0 0 0 0

…

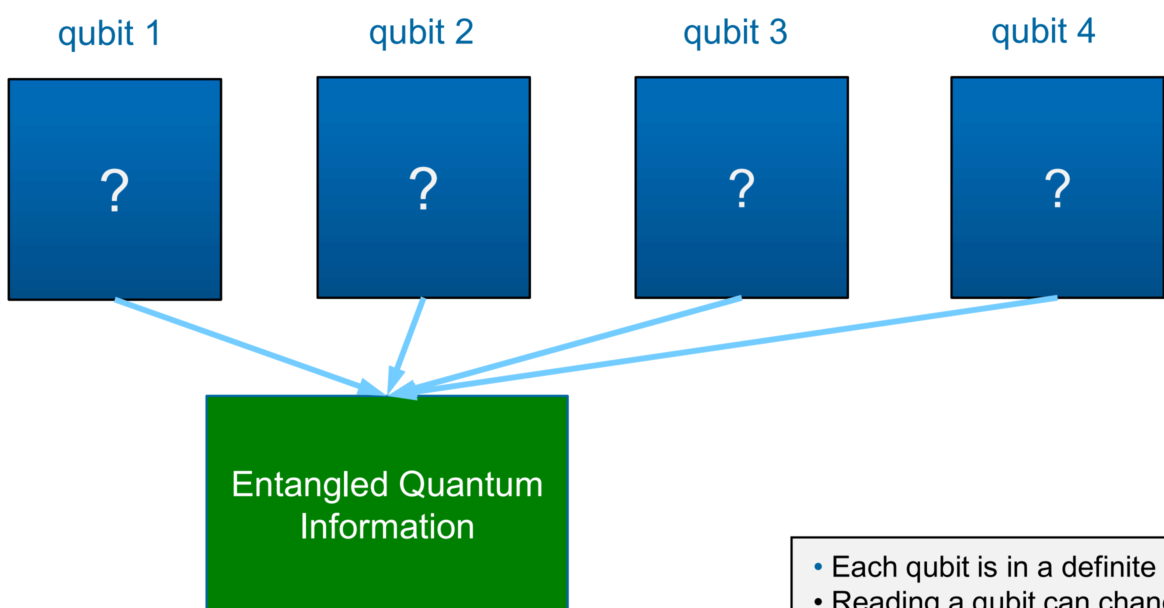
1 1 1 1

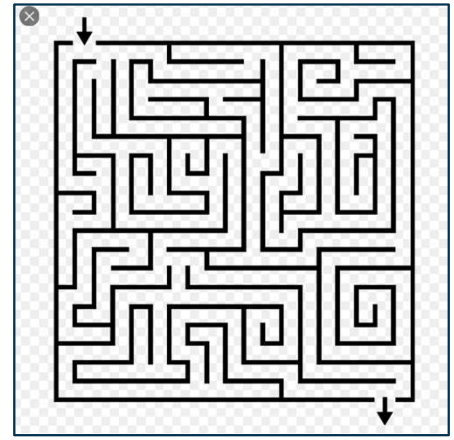
…

011100110

….

Quantum Information …
The very basic principles ☺





- Superposition
- Entanglement

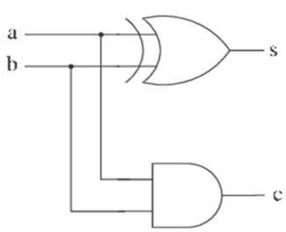
- Each qubit is in a definite state |0> or |1> or can be in superposition state
- Reading a qubit can change the state
- You cannot copy a qubit state (no cloning)
- Information can be stored in correlations of qubits

What is quantum computing?

Classical computing: *the world as we know it*	Quantum computing: *a new paradigm*

Classical computing: *the world as we know it*

classical bits or “bits”: **1|0**



Boolean gates
Boolean circuit

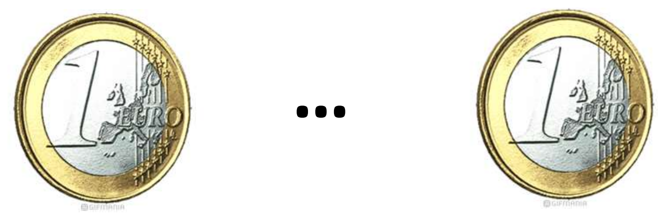
Serial logic

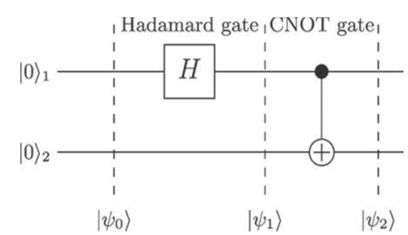
Ψ_n = 0000…000|0000…001|…|1111…111

Information: **n bits → n bit values**

Quantum computing: *a new paradigm*

quantum bits or “qubits”: **a.|1>+b.|0>**





Quantum gates
Quantum circuit

Parallel logic

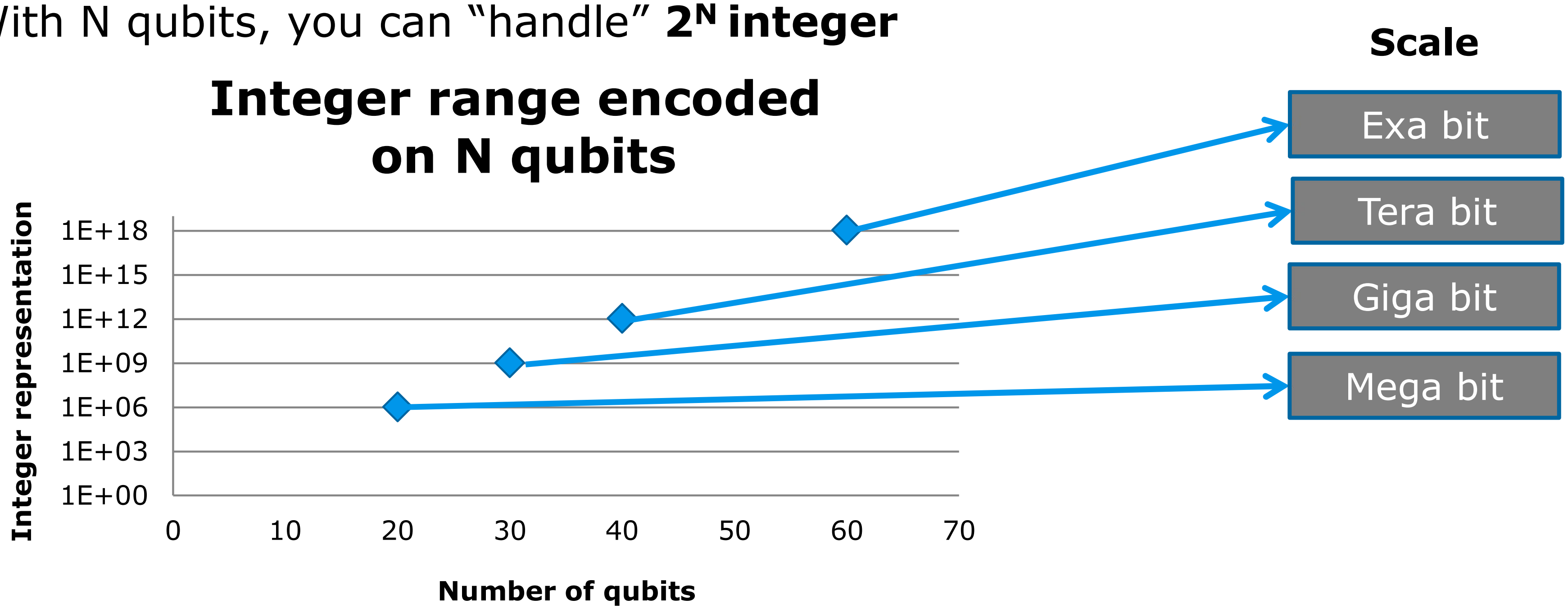
$|\Psi_n\rangle = a_1\,|0000...000\rangle + a_2\,|0000...001\rangle + \dots + a_{2^n}\,|1111...111\rangle$

Information: **2^n states → 2^n amplitudes!**

Quantum Physics properties

- States superposition & quantum measurement

- With N qubits, you can “handle” **2^N integer**



2^{200} **more basis states than there are atoms in the observable universe :** ☺
1606938044258990275541962092341162602522202993782792835301376

Existing Technologies to design a qubit

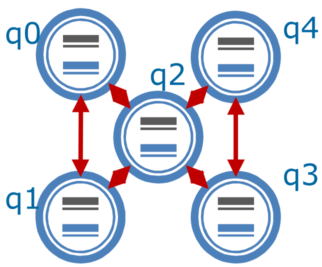
Quantum Annealing	Super-conducting	Trapped ions	Topological qubits	Photons	Silicon qubits	Misc.
D-Wave The Quantum Computing Company	IBM	IONQ	Microsoft	Hewlett Packard Enterprise	intel	QDTI Quantum Diamond Technologies
Limited to optimization algorithms	intel	AQT	NOKIA	XANADU	cea	PASQAL
	Google	universität innsbruck	QuTech	University of Oxford	NOKIA	
	rigetti	Honeywell		ORCA Computing	NTT	
	QCI					
	OQC					
	QuTech					
	UCSB					
	IQM					

Quantum computing in the physical world

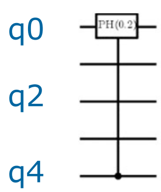
Counting hurdles…

Hardware constraints

Limited connectivity



how to run such a gate:



Limited expressivity

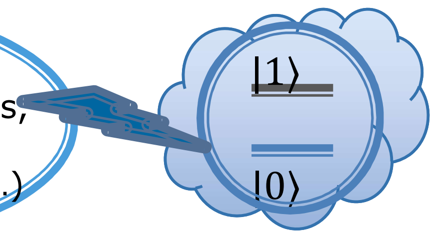
"only CNOT gates"

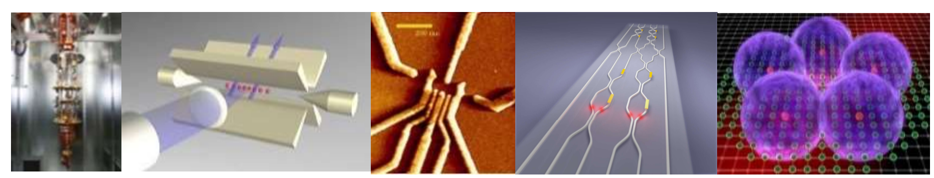
insert swaps, rewrite as combination of native gates…

Larger gate counts

Quantum decoherence

Outside world
(electro-magnetic fields,
other energy levels,
unwanted couplings, …)





Shorter time window

This information is essential to assess the quality of the final result

Quantum Computing : Where we are

1981: **First basic model** of a quantum computer
R. Feynman

1994: **Quantum algorithm development** to factorize large numbers. *P. Shor*

2016: IBM Quantum Network

2017: Atos introduced **Quantum Learning Machine**

~ 2023: **Physical qubits**
NISQ devices era (Noisy Intermediate-Scale Quantum)
- Quantum accelerator industrialization

2035+: **Logical qubits**
- *FTQC (Fault Tolerant Quantum Computers)*

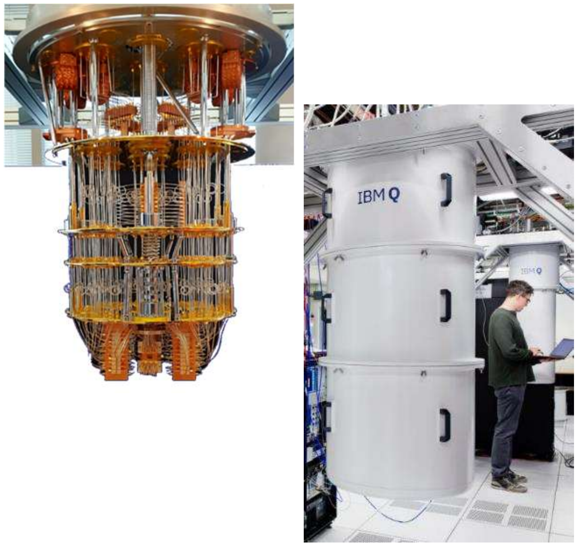
Discovery phase | **NISQ Era** *(Noisy Intermediate-Scale Quantum)* | FTQC era

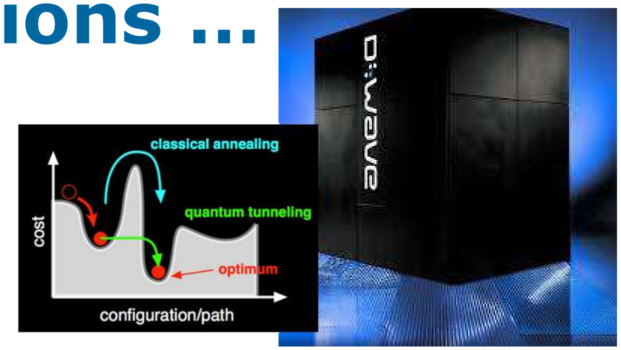
Today
- **NISQ HW prototypes** (IBM, Google, Rigetti, Honeywell, DWave …)
- **Learning Systems (Atos QLM)**

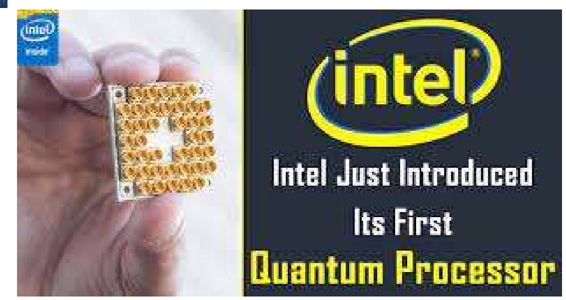
… and for (many) other reasons increasing the number of qubits and keeping the "quantum effects" (or coherence) is a key challenge:
➔ **NISQ Era** ("Noisy Intermediate Scale Computing")

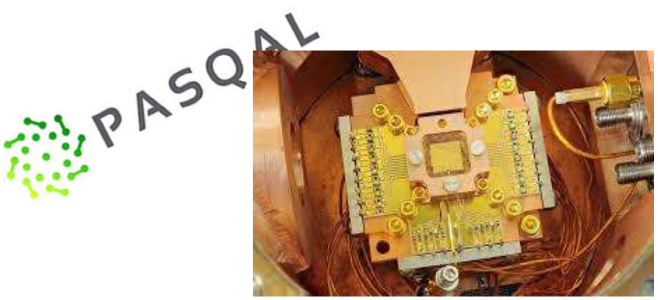
… **and as a consequence far from demonstrating a "Quantum Advantage"**

Existing (NISQ) solutions …

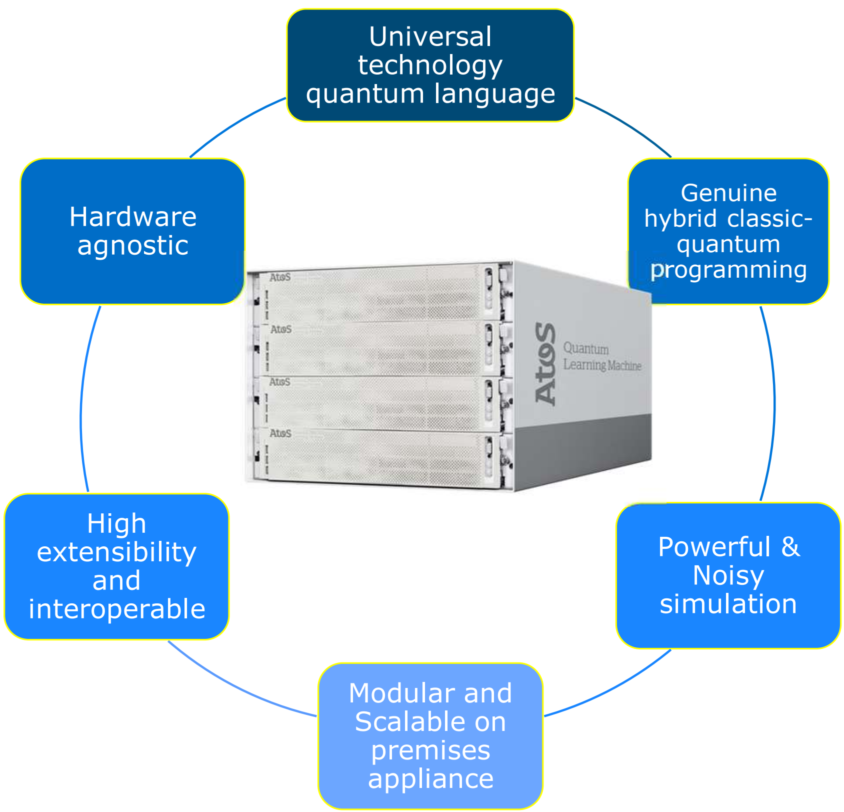


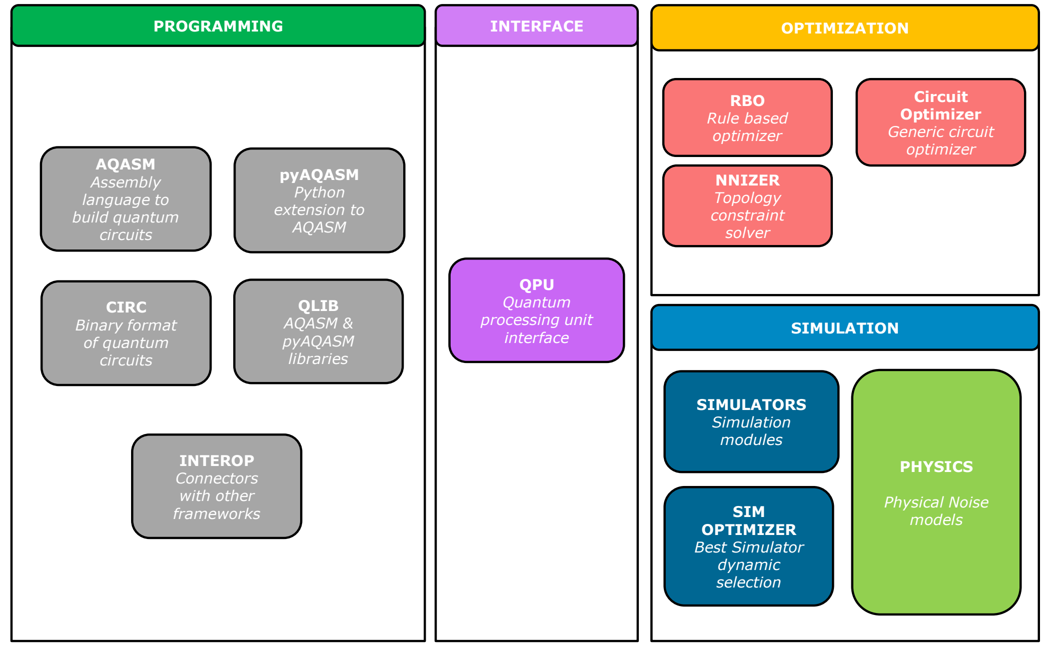






The Atos Quantum Learning Machine (QLM)





Our solutions:

- **Identify** use cases in your production
- **Design and test** their quantum version
- **Educate** your teams
- Provide a **hardware-agnostic** high performance quantum simulator

Atos Quantum Simulator : Universal gateway to quantum technologies

2 myQLM

Universal programming environment

Desktop solution

- Freeware
- Entry-level simulation
- Open-source plugins
- Scalability: ~20 qubits

Interoperability

Proprietary programming frameworks

1 Atos Quantum Learning Machine

On-Premise solution

- Advanced simulation
  - Noise modelling
  - Quantum Gates
  - Quantum annealing
- Multi-tenancy
- Scalability: 40 qubits
- Performance
  - Optional GPU acceleration

Universal front-end for quantum technologies

Any Quantum Computing hardware

- Superconducting
- Trapped ions
- Rydberg atoms
- ...

3 QC Expert Services

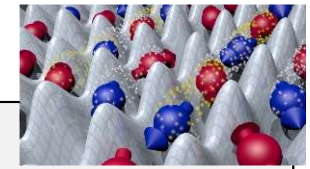
- Product Training
- Atos Quantum Academy
- Consulting Services

Quantum Computing

- Hardware approach

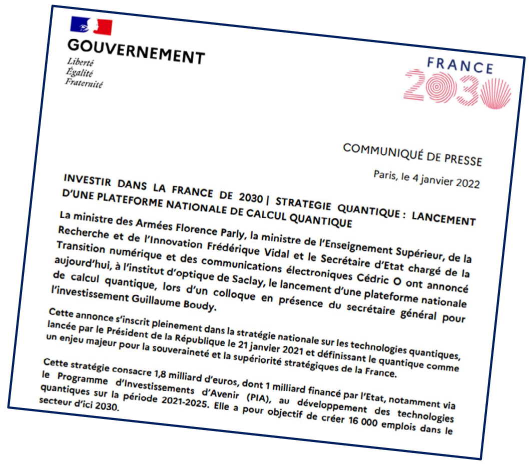
- Pros
  - Real Quantum speedup
- Cons
  - Heavy environmental constraints
  - Technology uncertainty
  - Probabilistic output makes it hard to develop algorithms

- Simulator approach



- Pros
  - Speeds up the quantum algorithm development phase
  - Possibility to allow quantum algorithms development without quantum hardware constraints
  - Assessing different hardwares/environments for an algorithm of interest
- Cons
  - No Quantum speedup

The road to quantum-accelerated HPC


GOUVERNEMENT
Liberté
Égalité
Fraternité

FRANCE 2030

COMMUNIQUÉ DE PRESSE

Paris, le 4 janvier 2022

INVESTIR DANS LA FRANCE DE 2030 | STRATEGIE QUANTIQUE : LANCEMENT D'UNE PLATEFORME NATIONALE DE CALCUL QUANTIQUE

La ministre des Armées Florence Parly, la ministre de l'Enseignement Supérieur, de la Recherche et de l'Innovation Frédérique Vidal et le Secrétaire d'Etat chargé de la Transition numérique et des communications électroniques Cédric O ont annoncé aujourd'hui, à l'institut d'optique de Saclay, le lancement d'une plateforme nationale de calcul quantique, lors d'un colloque en présence du secrétaire général pour l'investissement Guillaume Boudy.

Cette annonce s'inscrit pleinement dans la stratégie nationale sur les technologies quantiques, lancée par le Président de la République le 21 janvier 2021 et définissant le quantique comme un enjeu majeur pour la souveraineté et la supériorité stratégiques de la France.

Cette stratégie consacre 1,8 milliard d'euros, dont 1 milliard financé par l'Etat, notamment via le Programme d'Investissements d'Avenir (PIA), au développement des technologies quantiques sur la période 2021-2025. Elle a pour objectif de créer 16 000 emplois dans le secteur d'ici 2030.

2016
- Launch of the **Atos Quantum Program**

2017
- Launch of the **Atos QLM** (up to QLM40)
- Installation of the first Atos QLM at Oak Ridge National Laboratory

2018
- **Noisy Simulation** in the Atos QLM

2019
- myQLM
- Qlu> QLM User Club

2020
- **Atos QLM E**[nhanced]
- **S**imulated **Q**uantum **A**nnealing

2021
- **Q-score**
- **myQLM Power Access**

2022
- **QPU maker** offer

2023
- Atos' **NISQ** accelerator

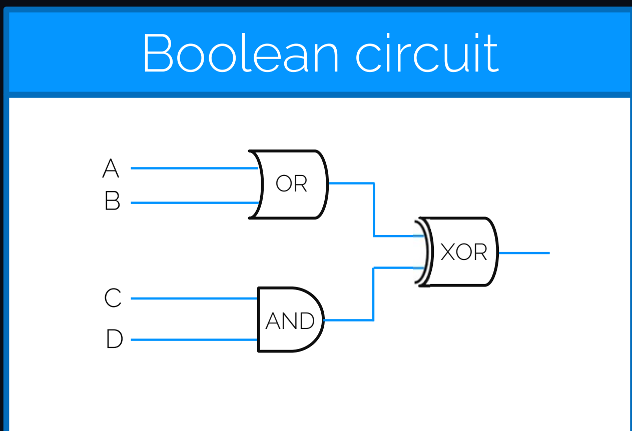
2024
- Application-specific solutions

2025
- Quantum-Accelerated **HPC**

2. Programming Tools

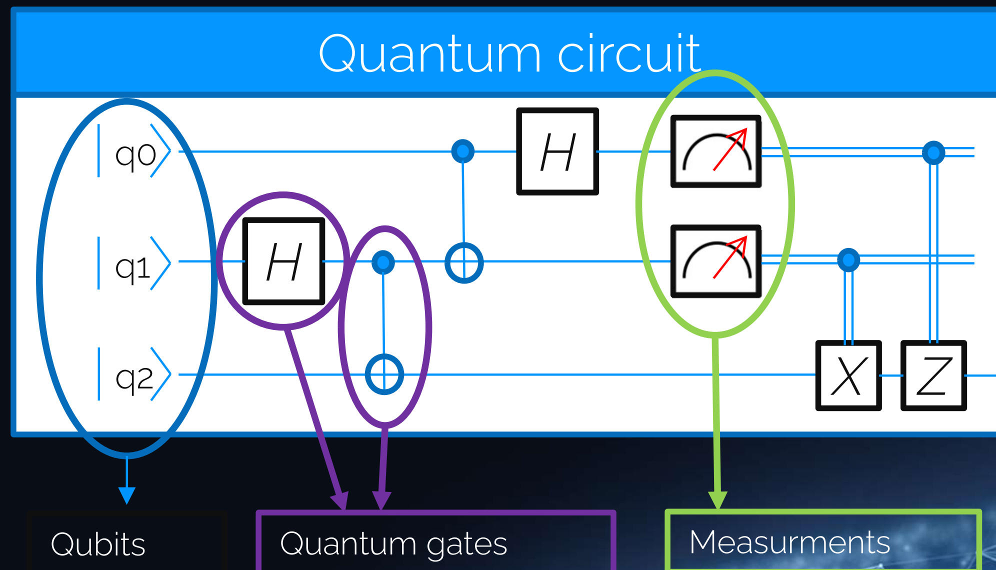
Quantum Computing

Classical and quantum circuits



Output:

CD \ AB	00	01	10	11
00	0	1	1	1
01	0	1	1	1
10	0	1	1	1
11	1	0	0	0



Output:

Atos

Writing your first circuit

A few notions: standard gates

Operator	Gate(s)		Matrix
Pauli-X (X)	X	⊕	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$

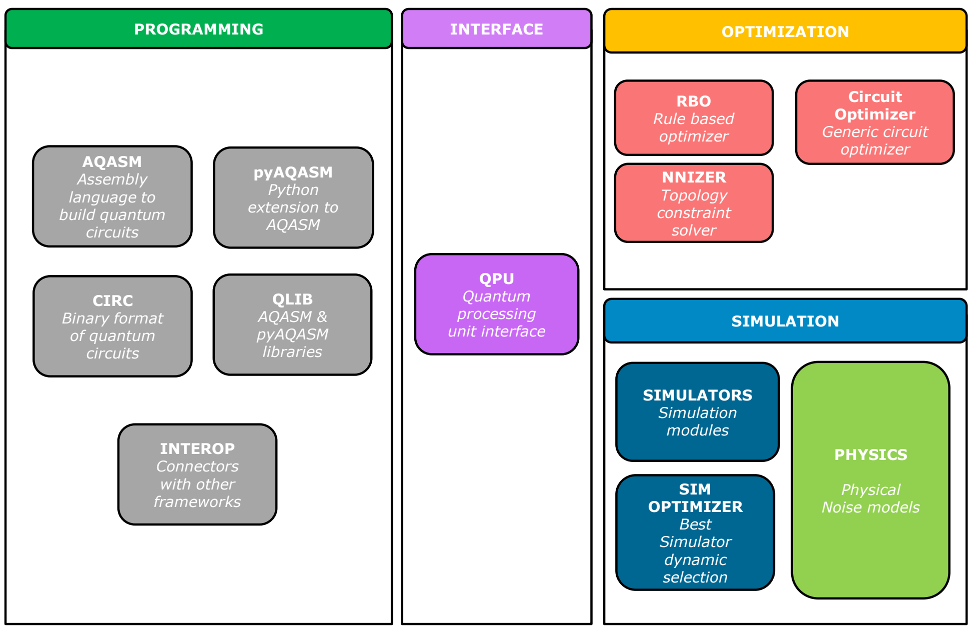
Operator	Gate(s)		Matrix
Controlled Not (CNOT, CX)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)			$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

For non-standard gates, **abstract gates** could be defined by a matrix or a routine

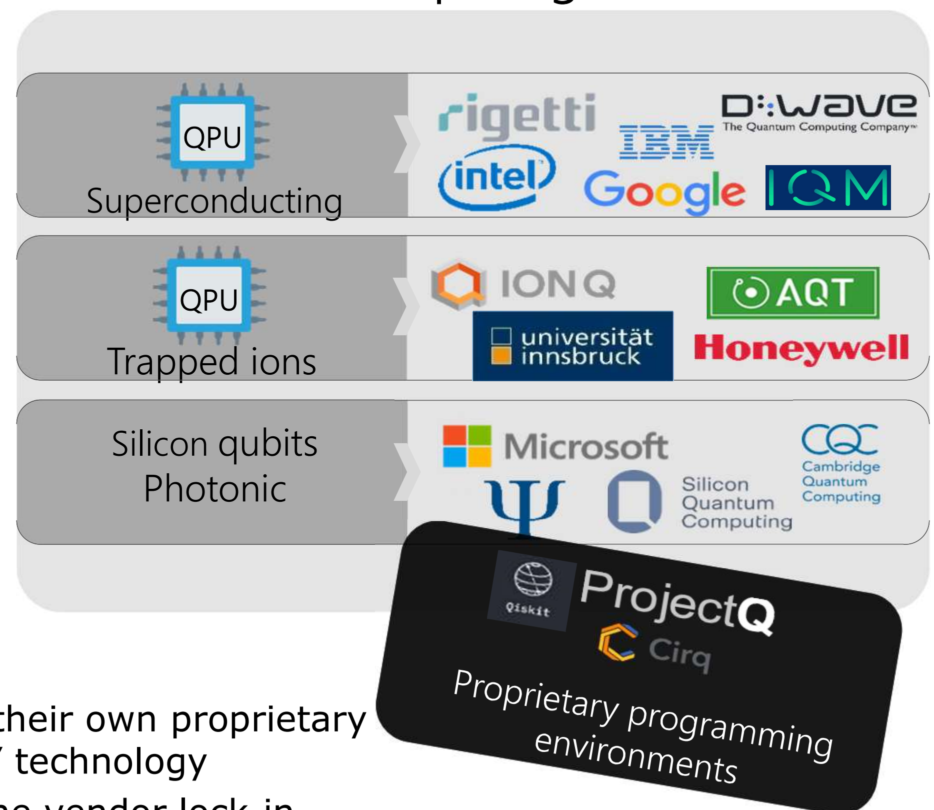
$$XX[\theta] = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 0 & 0 & -ie^{i\theta} \\ 0 & 1 & -i & 0 \\ 0 & -i & 1 & 0 \\ -ie^{-i} & 0 & 0 & 1 \end{pmatrix}$$

Quantum Computing Programming environment

Atos QLM Environment



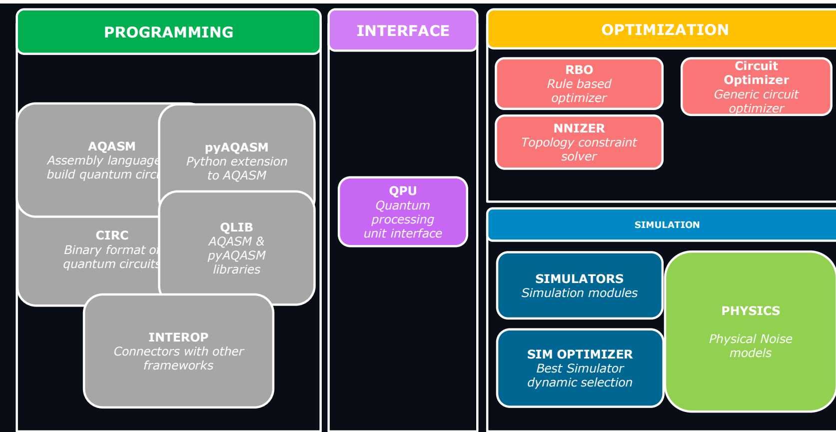
Quantum Computing Hardware



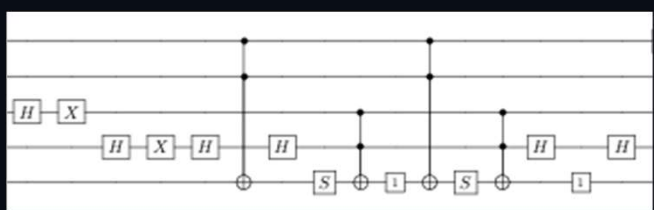
- Quantum computing hardware manufacturers have created their own proprietary programming software and standards, based on their qubits' technology
- Atos offers a universal programming environment to avoid the vendor lock-in

Atos Quantum Learning Machine

A full set of capabilites



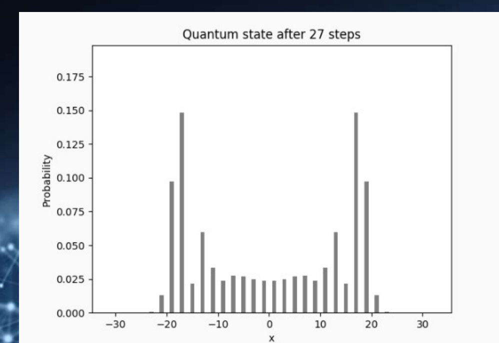
Quantum Programs



Simulation

Linear Algebra
Feynman
Matrix Product States
Stabilizers
Noisy simulation

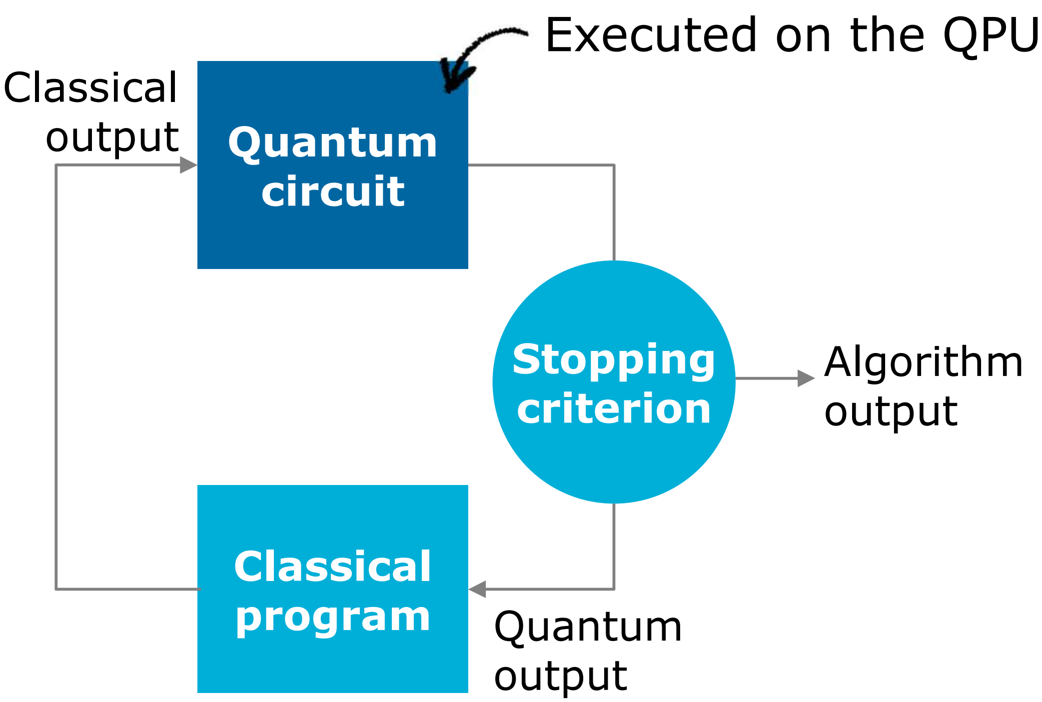
Quantum Results



All probabilities Distribution

Atos

One common approach
variational algorithms



- ▶ A variational algorithm is a hybrid quantum-classical algorithm
  - A classical optimizer is used to minimize a problem-specific cost function provided by a quantum circuit
- ▶ Many applications
  - Quantum Approximate Optimization Algorithm
  - Variational Quantum Eigensolver/ Variational Imaginary Time Evolution
  - Variational Quantum Factoring
  - Variational Quantum Classifier
  - …
- ▶ Well suited for NISQ processors

myQLM : Atos environment to start Programming

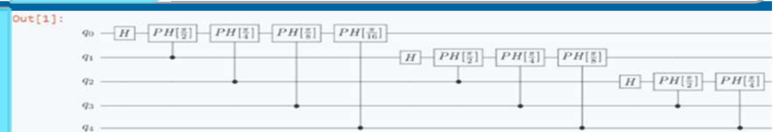
Available for FREE @ https://atos.net/myqlm

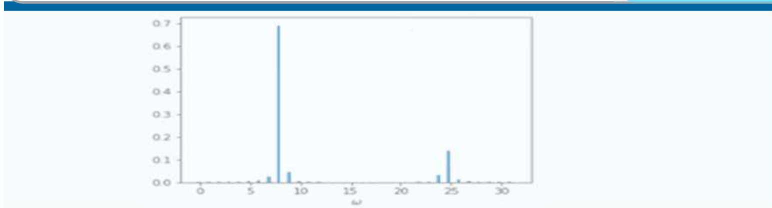
- **Scientists**: You are currently using the Atos QLM and you want to prepare your code and run them on your laptop?
- **Students**: You want to start programming Quantum algorithms using the same framework as your professors?
- **Tech enthusiasts**: You want to discover Quantum programming using an accessible user-friendly environment?

In [1]:
```
from qat.lang.AQASM import Program
from qat.lang.AQASM.qftarith import QFT
from qat.lang.AQASM.oracles import StatePreparation
from demo_init import prepare_ft_signal
```

1 Write your code in AQASM or PyAQASM

2 Visualize your quantum circuits

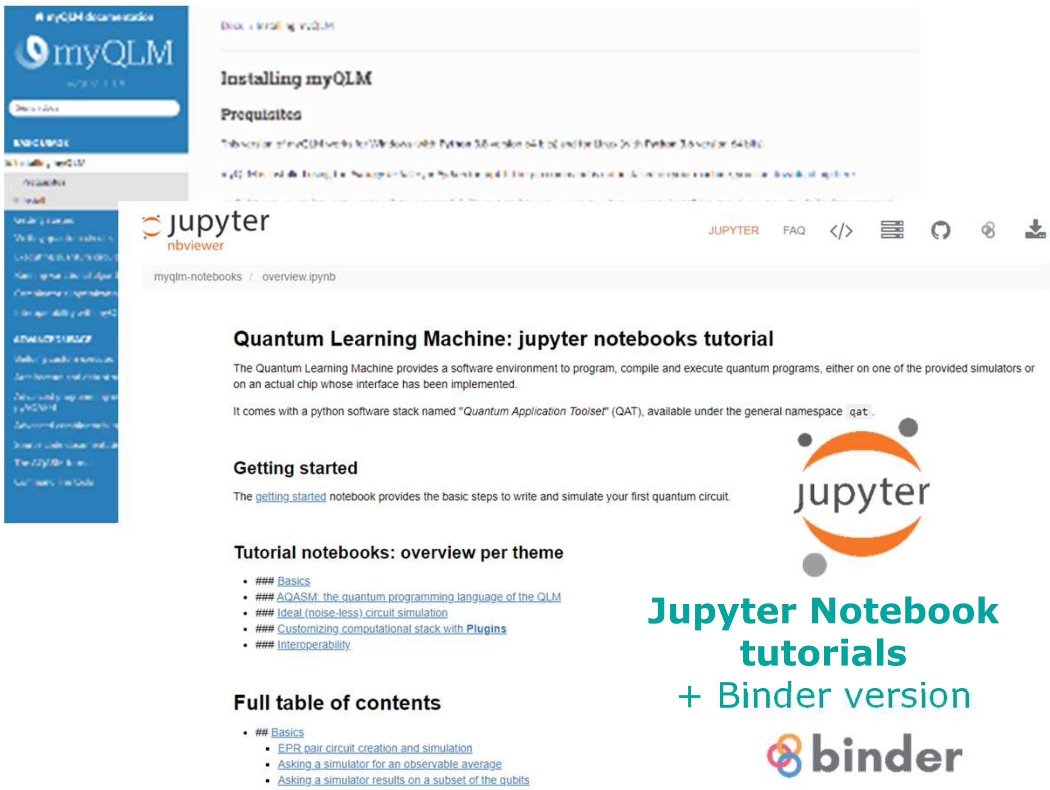




3 Simulate them on your laptop or on a real QLM

myQLM ecosystem

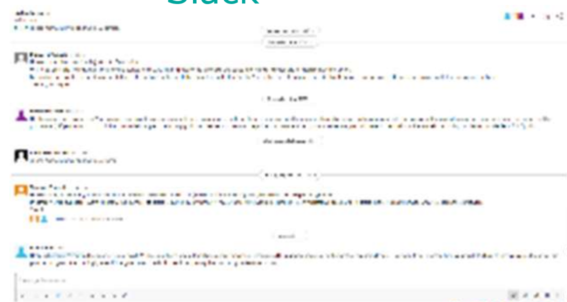
Hosted
Documentation



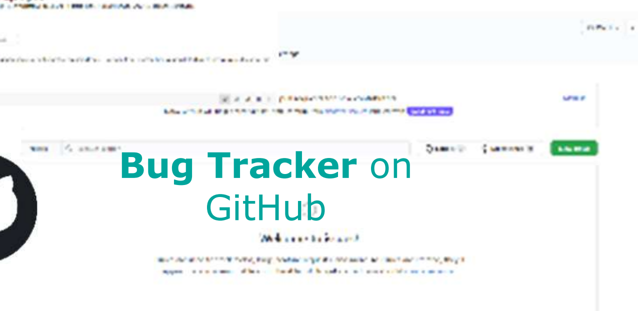
Jupyter Notebook tutorials
+ Binder version

Community Forum on Slack

www.atos.net/myqlm



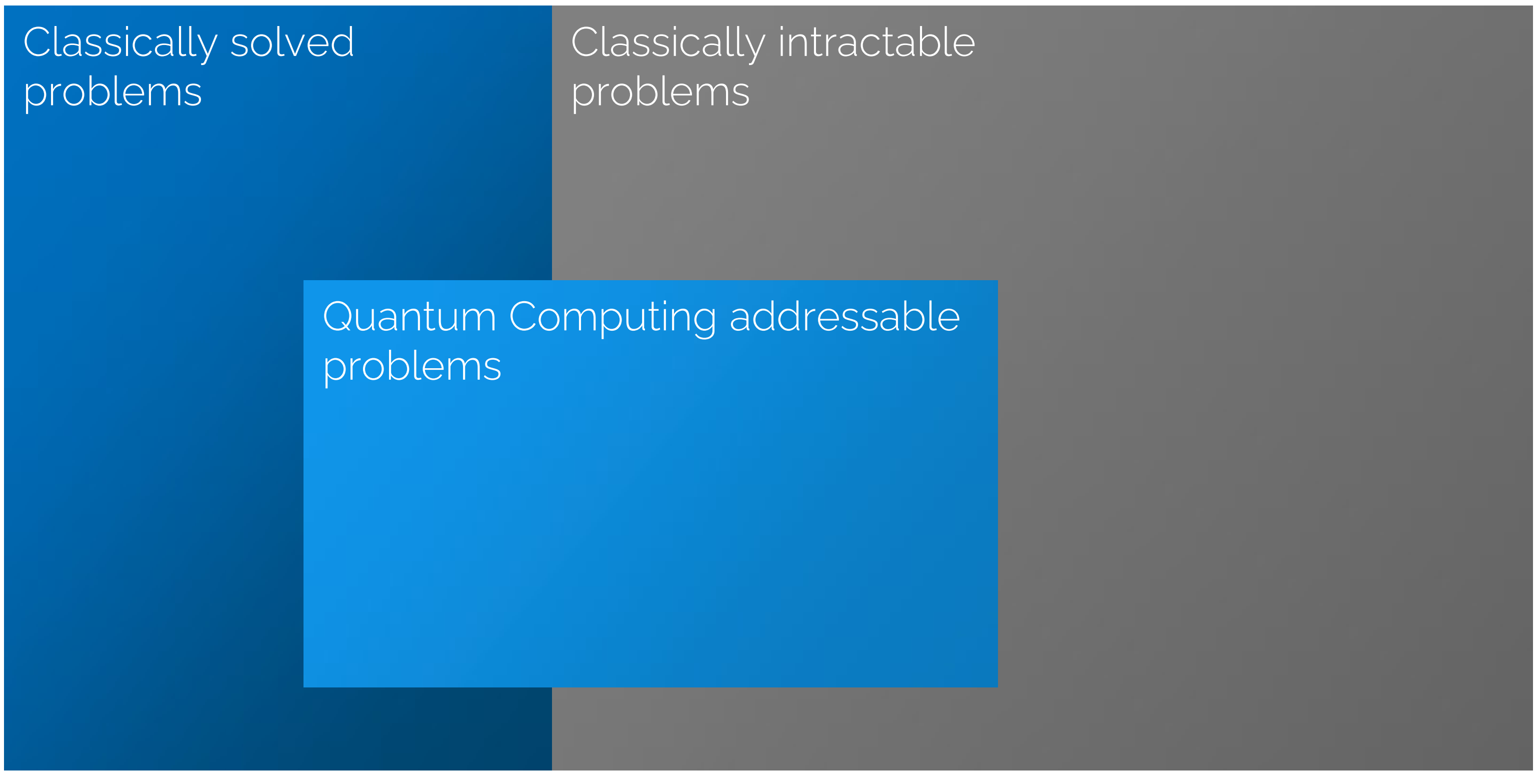
Bug Tracker on GitHub



www.github.com/myQLM/myqlm-contrib

2. What Would You Want A Quantum Computer For?

Why quantum computing?



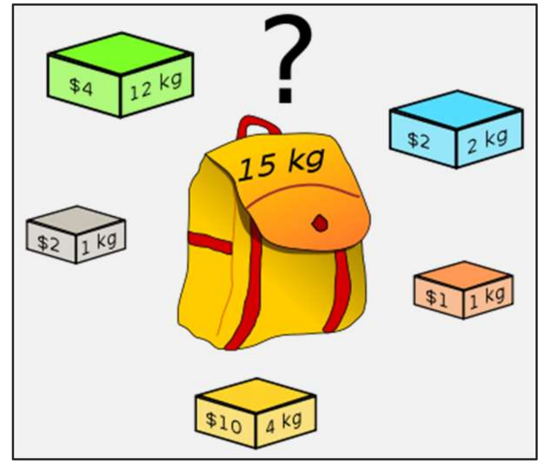
There are many important hard problems (intractable)

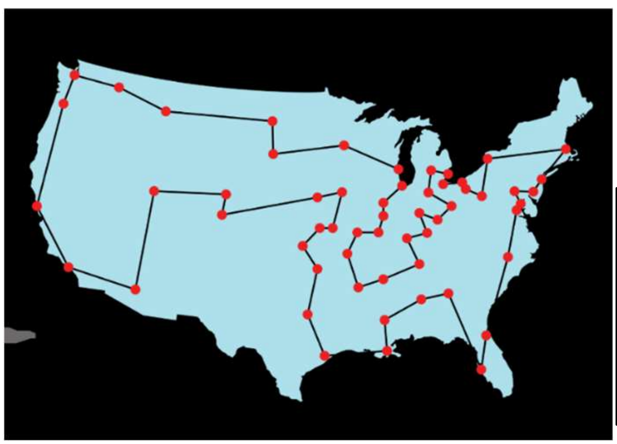
10 Tables and 10 invitees per Table
10 ! = 3.26 million of combinations

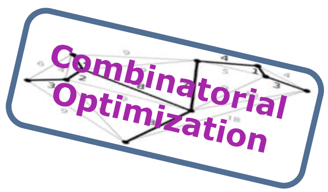
12 Tables and 12 invitees per Table
12 ! = 479 million of possibilities

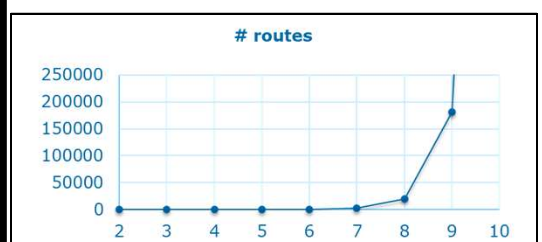
…

50 ! = 30 414 093 201 713 378 043 612 608 166 064 768 844 377 641 568 960 512 000 000 000 000

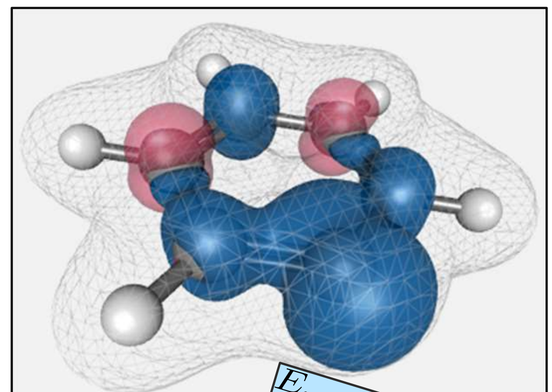






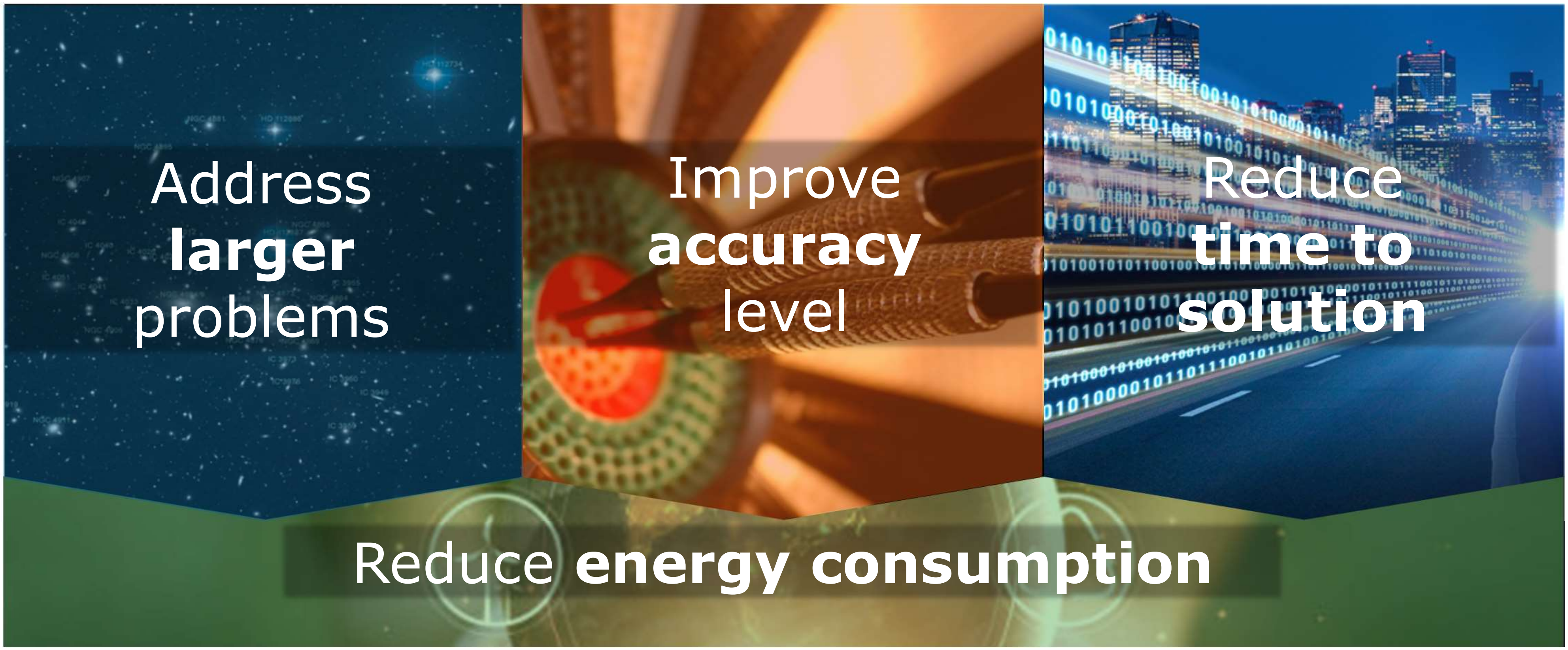


15 Cities will require **15 !** combinations (approx. ***10^{12}***)



$$E_{min} = \min_{\theta} \langle \psi(\theta) | H | \psi(\theta) \rangle$$

The promises of Quantum Computing



Quantum Computing applications

Numerous cross-industry impacts

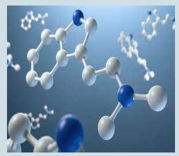
Manufacturing

- Autonomous vehicle
- Logistics
- Supply chain
- Software validation
- Batteries
- Polymers

Public Sector & Defense

- Neural networks
- Process optimization
- Cryptanalysis
- Material science
- Nanotechnologies

Chemistry & material Science



- Materials science
- NanoTech.
- Batteries
- Polymers
- Catalysts, enzyme design
- Molecular modeling
- Protein folding
- Drug discovery

Financial Services & Insurance

- Fraud detection
- Trading strategies
- Market simulation
- Portfolio optimization
- Risk assessment
- Cryptocurrency

Telecom, Media & Technology

- Personalized content
- 5G antenna location
- Chip layout optimization
- Post-quantum cryptography

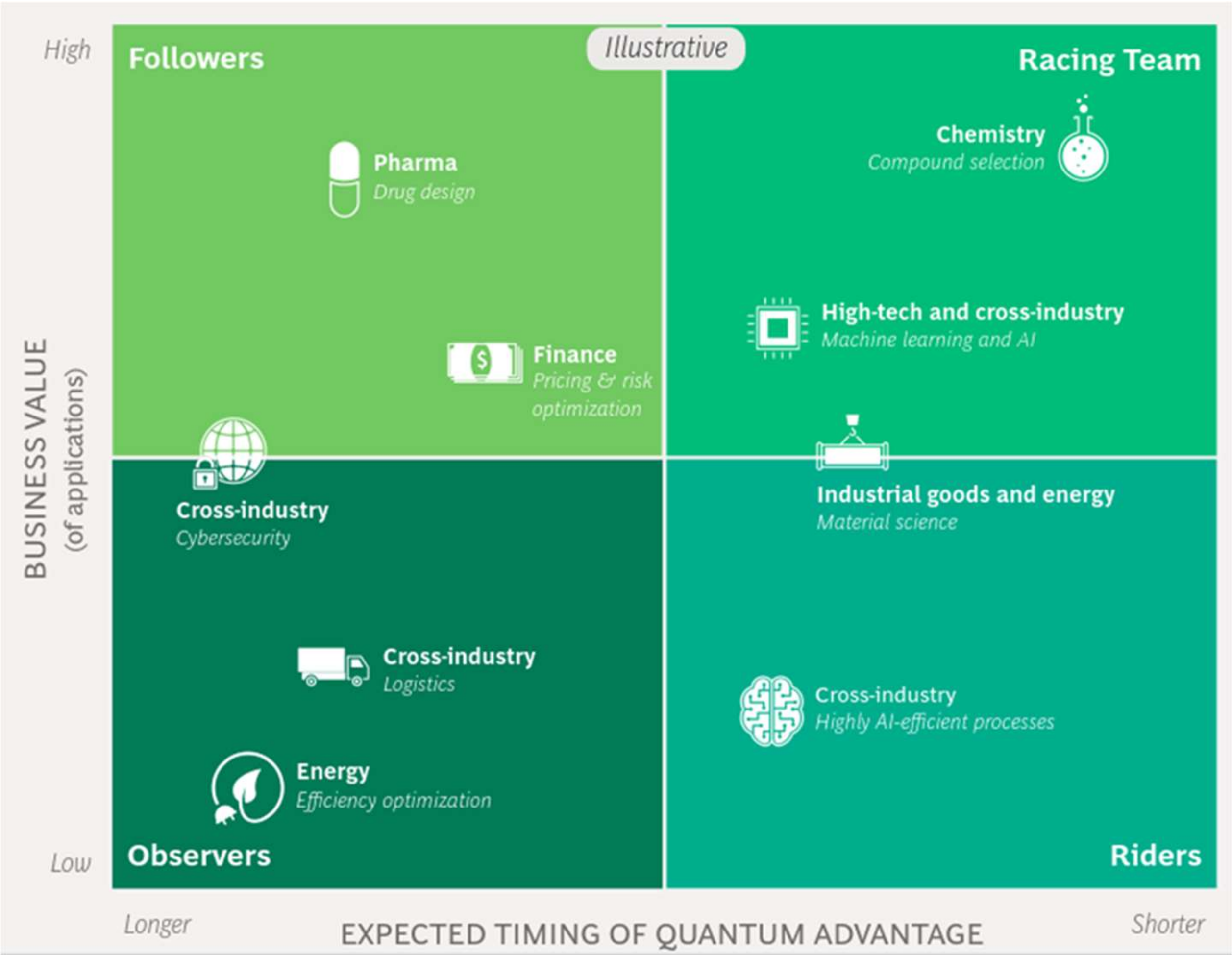
Resources & Services

- Smart grids
- Flight scheduling
- Oil well optimization
- Yield management
- Cybersecurity
- Carbon dioxide capture

Health & Life Sciences

- Genomics
- Virtual screening
- Protein folding
- Drug discovery
- Personalized medicine

Expected timing of Quantum Advantage



Source: BCG analysis

Chemistry

One of today's most active application areas!

Goal

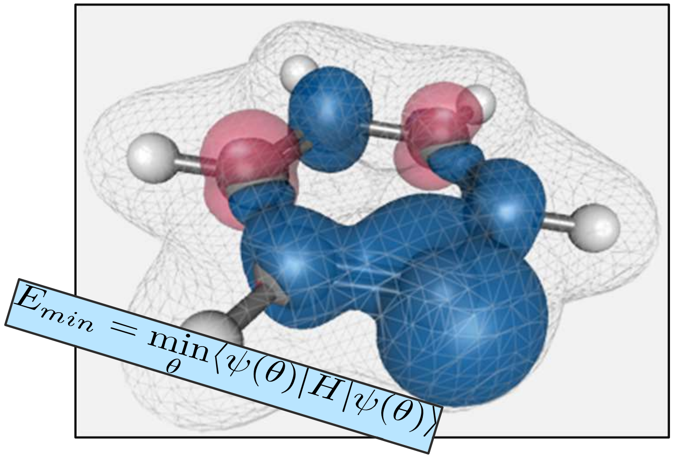
- Compute the exact energy of large molecules
  - This is intractable today
  - Cost: 2 qubits per orbital even without error correction!

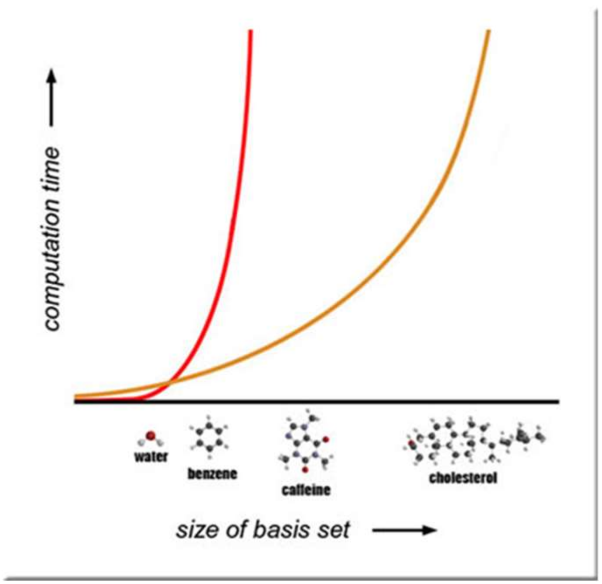
Star algorithms

- Variational Quantum Algorithms (VQE and derivatives)

Impact

- New discovery and energy savings in synthesis for fertilizers, lubricants, …





Quantum Computing for Finance

Quantum Machine Learning

Data classification
- Credit scoring
- Fraud detection

Regression analysis
- Financial supply chain management

Neural Network training
- Market prediction
- Credit risk analysis

Principal Component Analysis
- Portfolio optimization

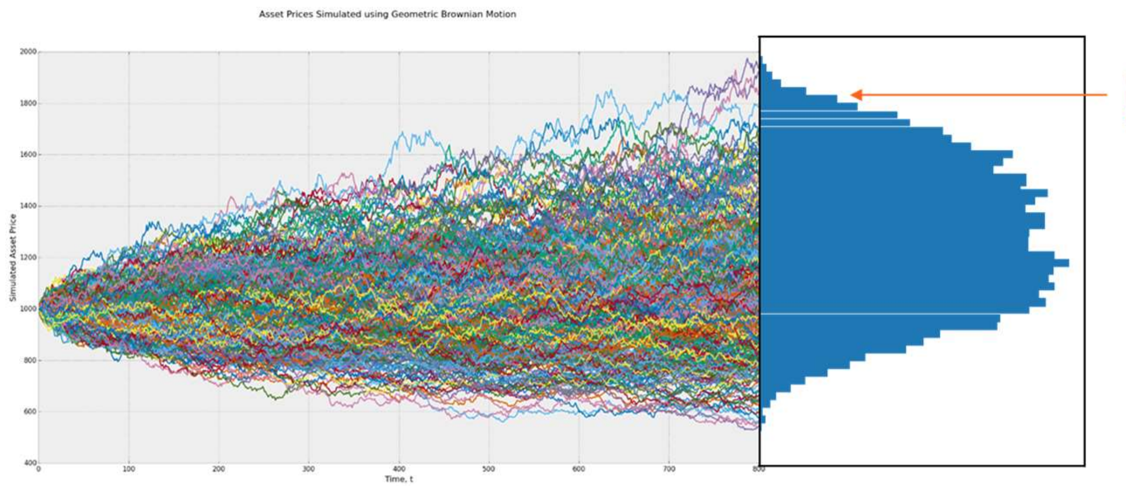
STAR ALGORITHMS

- Quantum Principal Component Analysis (PCA)
- Quantum Support Vector Machines (SVM)
- Harrow-Hassidim-Lloyd (HHL) algorithm
- Variational Quantum Linear Solver (VQLS)

Quantum Computing for Finance

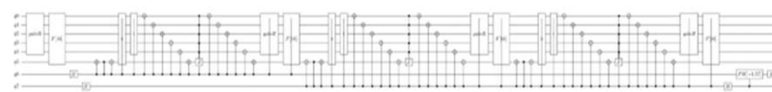
Stochastic Modeling

- Financial **risk assessment**
- Pricing of financial derivatives (**option pricing**)
  - **Black**-**Scholes** equation can be **derived** from the **Schrödinger** equation



$$\sigma_{t+1}^2 = \omega + \alpha R_t^2 + \gamma I_t R_t^2 + \beta \sigma_t^2$$

$$I = 1\ if\ (R_t^2 < 0), otherwise\ I = 0$$



STAR ALGORITHMS	
	▶ Quantum Amplitude Estimation (QAE) ▶ Quantum Monte Carlo (QMC) ▶ Quantum Random Walk

Oil Prospection

Goal

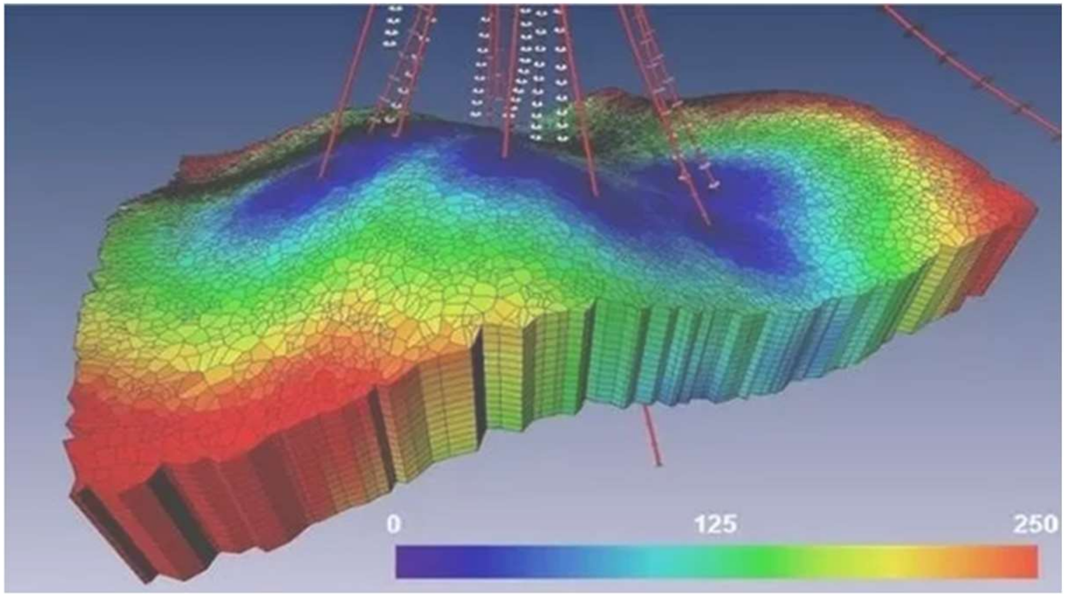
- Solve Partial Differential Equations with an exponential speed-up

Star algorithms

- HHL, the matrix inversion algorithm

Impact

- Unprecedented performance and accuracy for
- Oil well optimization
- Seismic simulation



From a disruptive innovation to a commercial success

ICHEC Irish Centre for High-End Computing

Hartree Centre Science & Technology Facilities Council

World Wide Technology

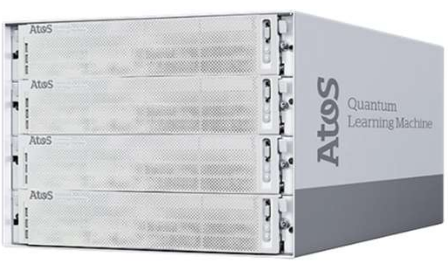
CSC

BMW GROUP

Argonne NATIONAL LABORATORY

Stanford University

OAK RIDGE National Laboratory



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Atos Quantum

Empowering international research on Quantum Computing

Quantum Applications

Quantum Algorithms

Next Generation Architectures

Quantum Computing
Why investing now?

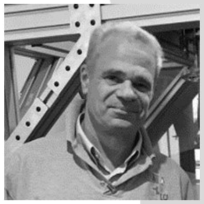
Quantum computing is an opportunity, now available for businesses…

Quantum Computing: when QPUs are available, organizations with the greatest expertise may get an order-of-magnitude edge

Investing in **Quantum Computing** is urgent

- Access existing commercial quantum **simulation** capabilities,
- Test newly available hardware **platforms**, and software **applications**,
- Develop new algorithms
- Resources are scarced
- Develop **your own IP**

Merci



Olivier HESS
Quantum Computing France
M+ 33 6 76757902
olivier.hess@atos.net