March 20, 2024 | EuroHPC Summit 2024

Quantum Computing @ Fraunhofer: One Stop Solution for Research and Industry

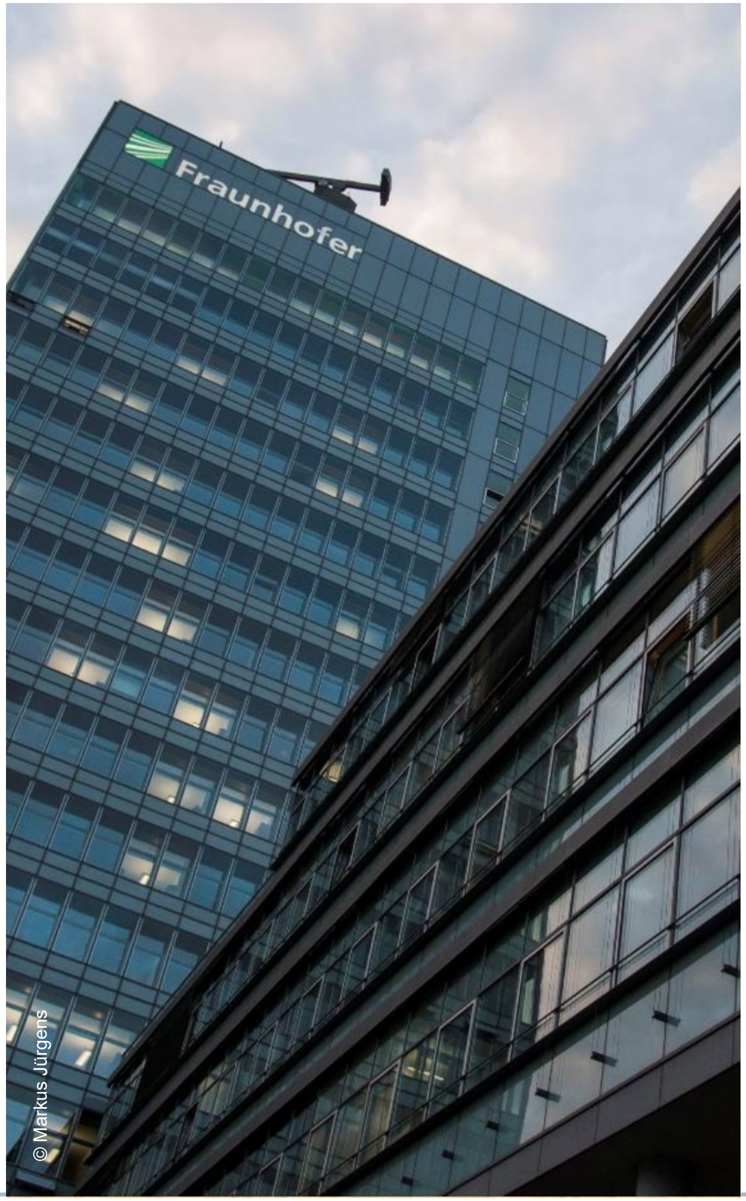
Dr. Hannah Venzl

The Fraunhofer-Gesellschaft
The leading applied research organization

The Fraunhofer-Gesellschaft, based in Germany, is the world's leading applied research organization. By prioritizing key technologies for the future and commercializing its findings in business and industry, it plays a major role in the innovation process.

A trailblazer and trendsetter in innovative developments and research excellence, it is helping shape our society and our future.

Founded in 1949, the Fraunhofer-Gesellschaft currently operates 76 institutes and research units throughout Germany. More than 30,000 employees, predominantly scientists and engineers, work with an annual research budget of roughly 3 billion euros, 2.6 billion euros of which is designated as contract research.



The Fraunhofer-Gesellschaft

At a glance

Applied research focusing on key future-relevant technologies and the commercialization of findings in business and industry. A trailblazer and trendsetter in innovative developments.

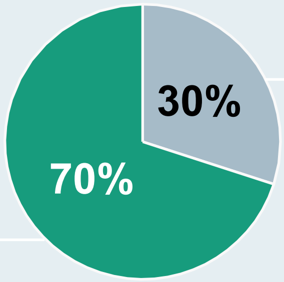
> 30,000 employees

76 institutes and research units

€ 3.0 billion business volume
€ 2.6 billion contract research

Base funding from Germany's federal and state governments

Industrial contracts and publicly-funded research projects

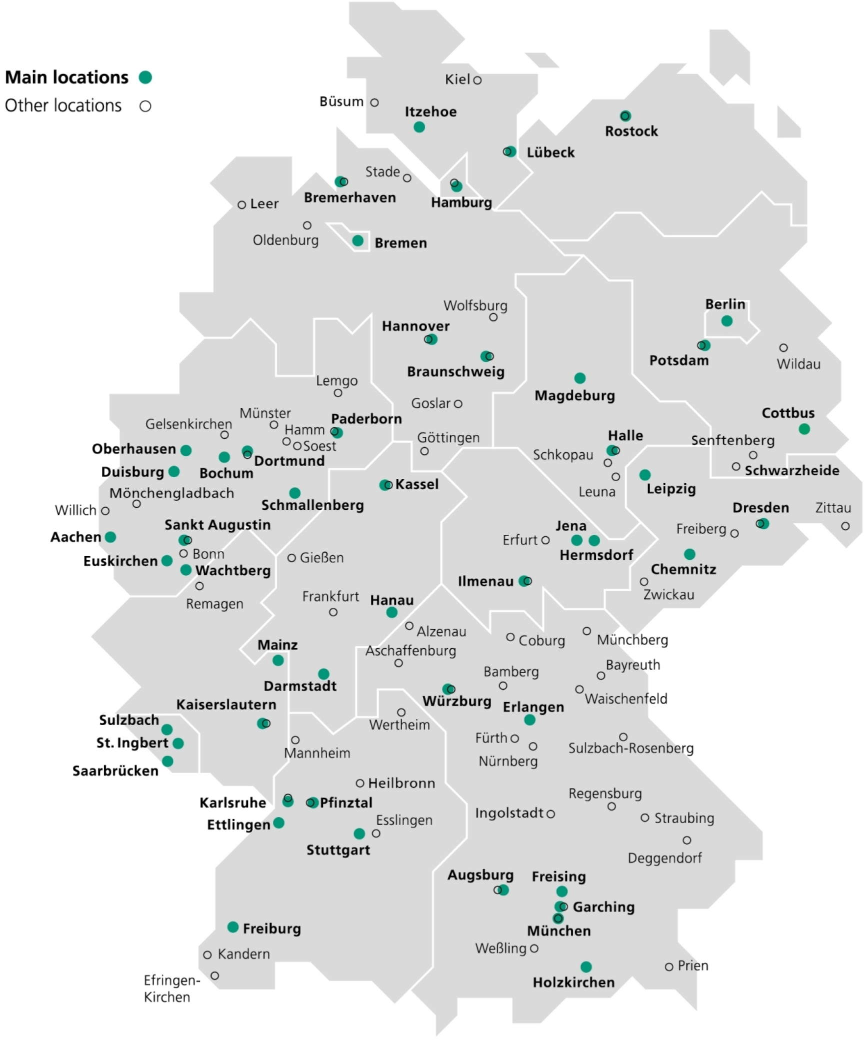


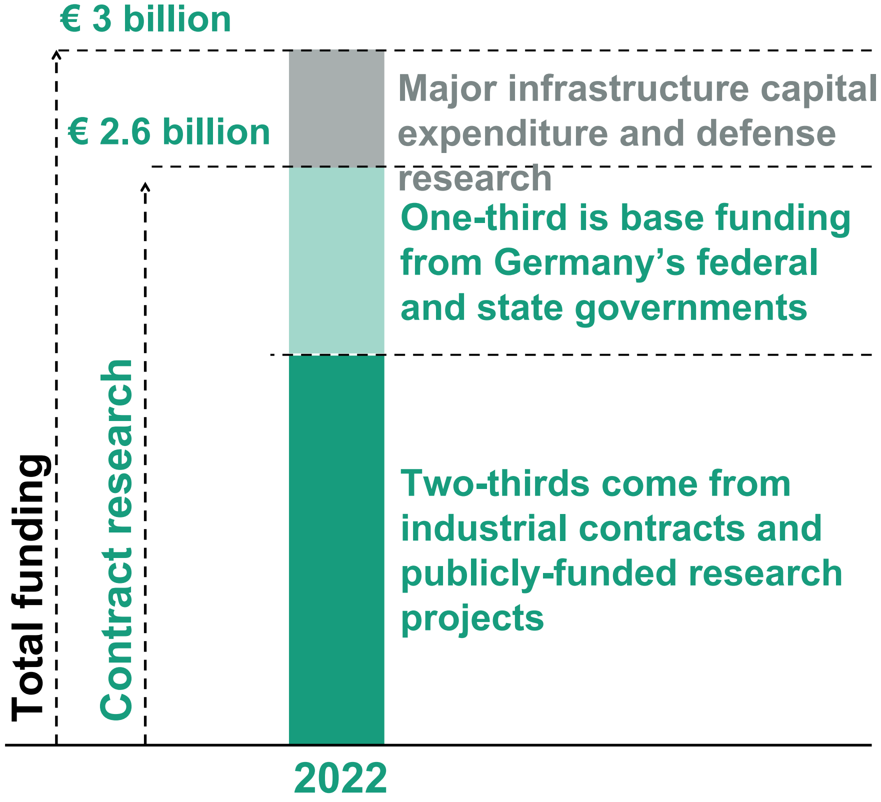
 © Fraunhofer Public

Fraunhofer

The Fraunhofer-Gesellschaft

At a glance



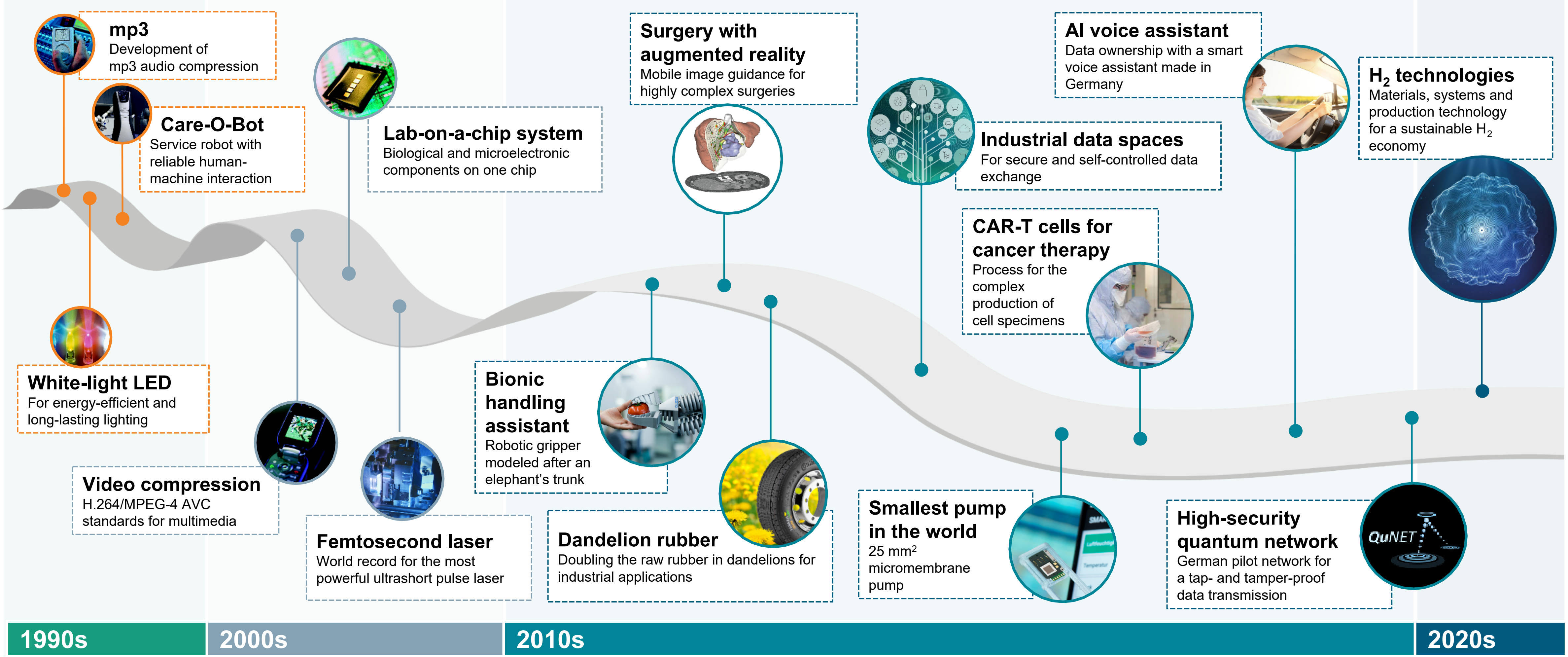


© Fraunhofer

Public

Fraunhofer

Fraunhofer Research
Highlights



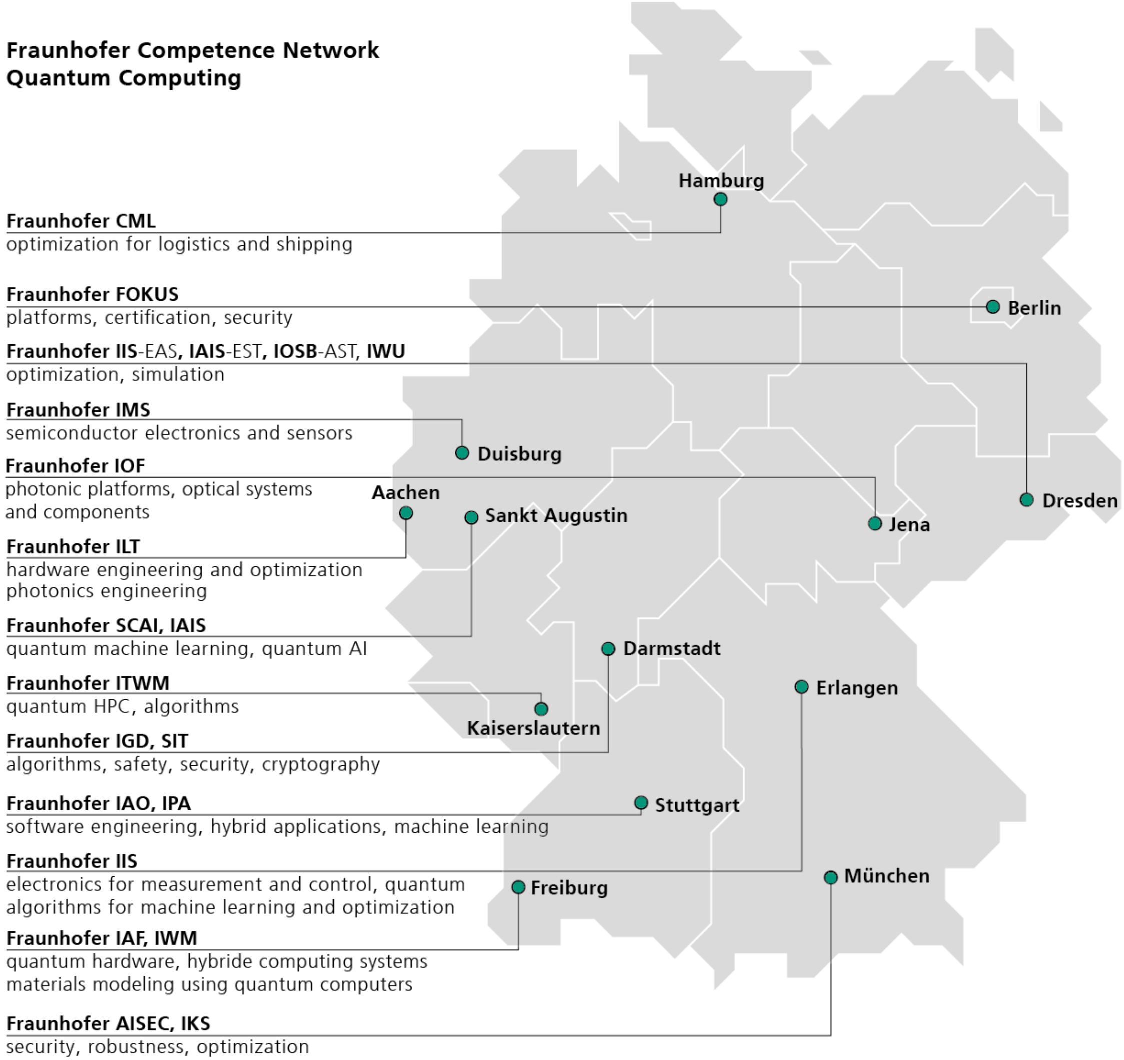
 © Fraunhofer Public Fraunhofer

Fraunhofer Competence Network Quantum Computing

One Stop Solution for Research and Industry

- 9 regional Competence Centers, consisting of Fraunhofer Institutes, each with its own research focus
- 19 participating Fraunhofer Institutes
- Strategic development by Board of Directors and Industry Advisory Board
- Wide range of fields of application: logistics, chemical and pharmaceutical industry, finance and energy sector, materials science, IT security technologies and much more
- Multi-level training and education program

Speaker: Prof. Manfred Hauswirth (FOKUS)
Deputy: Prof. Anita Schöbel (ITWM), Prof. Rüdiger Quay (IAF)

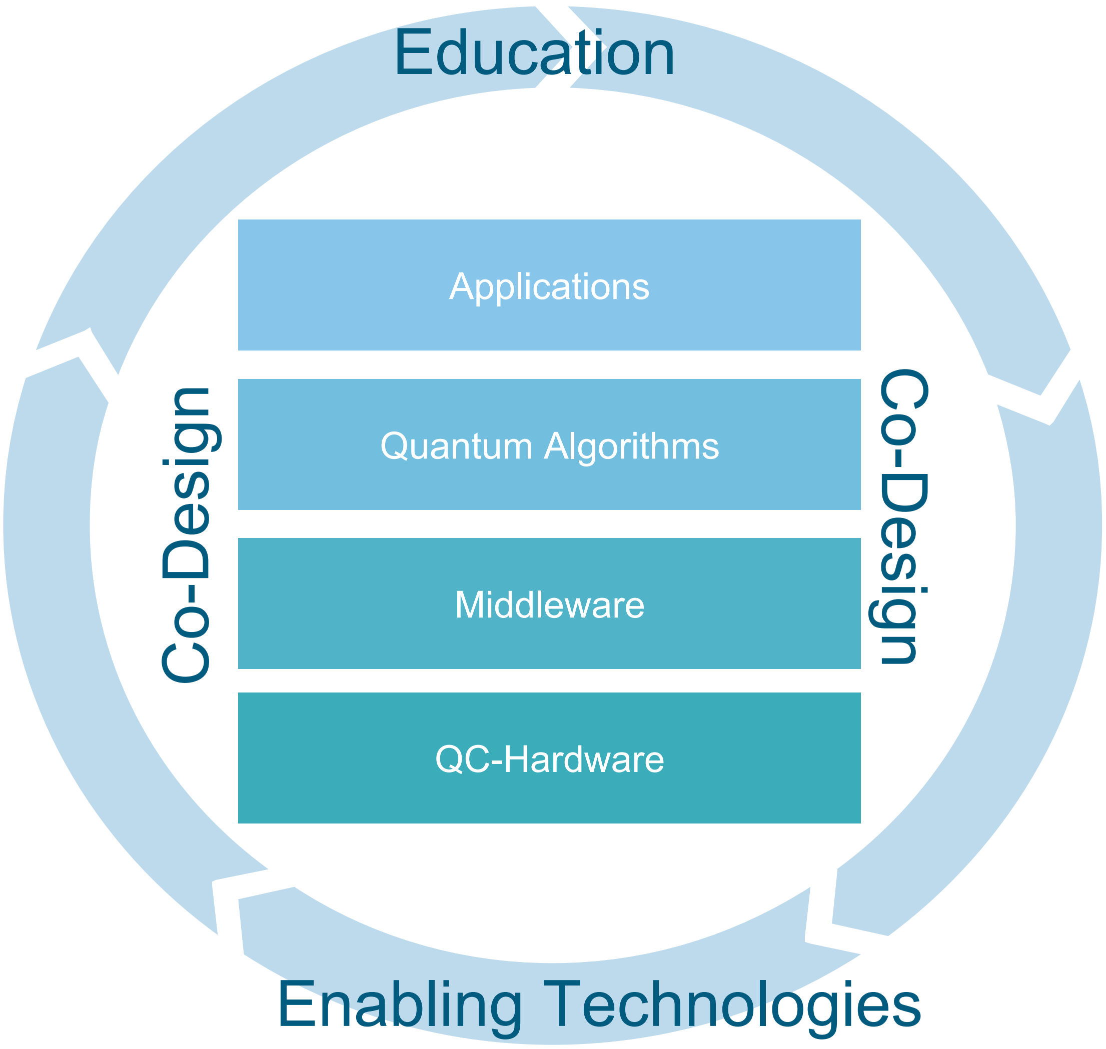


Fraunhofer

Fraunhofer Competence Network Quantum Computing

One Stop Solution for Research and Industry

- 9 regional Competence Centers, consisting of Fraunhofer Institutes, each with its own research focus
- 19 participating Fraunhofer Institutes
- Strategic development by Board of Directors and Industry Advisory Board
- Wide range of fields of application:
  logistics, chemical and pharmaceutical industry, finance and energy sector, materials science, IT security technologies and much more
- Multi-level training and education program



Speaker: Prof. Manfred Hauswirth (FOKUS)
Deputy: Prof. Anita Schöbel (ITWM), Prof. Rüdiger Quay (IAF)

Fraunhofer

Quantum Computing at Fraunhofer

Doing, Mission and Aims

Fraunhofer

Fraunhofer is the strong and competent partner for the industry (contract research, joint research projects)

Fraunhofer is building a strong German and European Quantum Computing Ecosystem

Fraunhofer is Enabler and Gatekeeper for the German industry and R&D landscape: We gave partners exclusive access to an IBM Quantum Computing research platform (02/2020-02/2024)

Fraunhofer researchers are working on standardization and benchmarking (collaboration with various QC hardware providers)

Investigating the potentials of Quantum Computing

Enabling the German and European industry to establish new business models and to open up markets

Quantum Computing at Fraunhofer

Why quantum computing? Promising fields of application

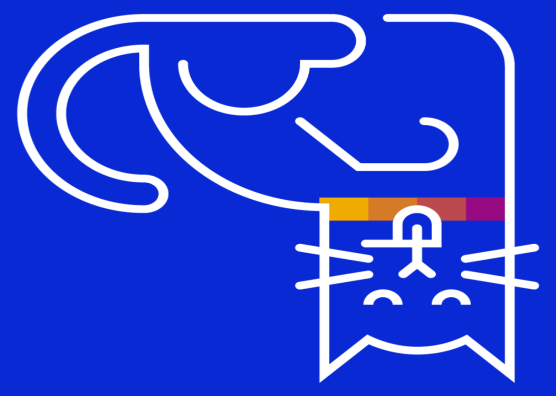
Simulation	Development of **pharmaceuticals**, vehicle **batteries**...
Optimization	Optimization of **route planning**, **risk analysis**...
AI	Improvement of **fraud detection**...
IT security	Protection of **telecommunication links**, **RSA cryptography**, information transfer via **QKD**…
Networks	Establishment of a **quantum internet**...
Energy	Distribution and control of e-mobility **charging stations**, **wind** farms, **hydrogen** pipelines...
Logistics	Optimal **route planning**, **traffic** & **smart city** simulations
Production	**Topology optimization** of components, **material simulation**, optimization of **production chains**…
Financial sector	**Portfolio** and **risk models**…
Engineering	**(Material) simulations** …

Contact

Dr. Hannah Venzl
Fraunhofer Competence Network Quantum Computing

Hannah.venzl@zv.fraunhofer.de
www.quantencomputing.fraunhofer.de/en

Quantum Computing: what is it?

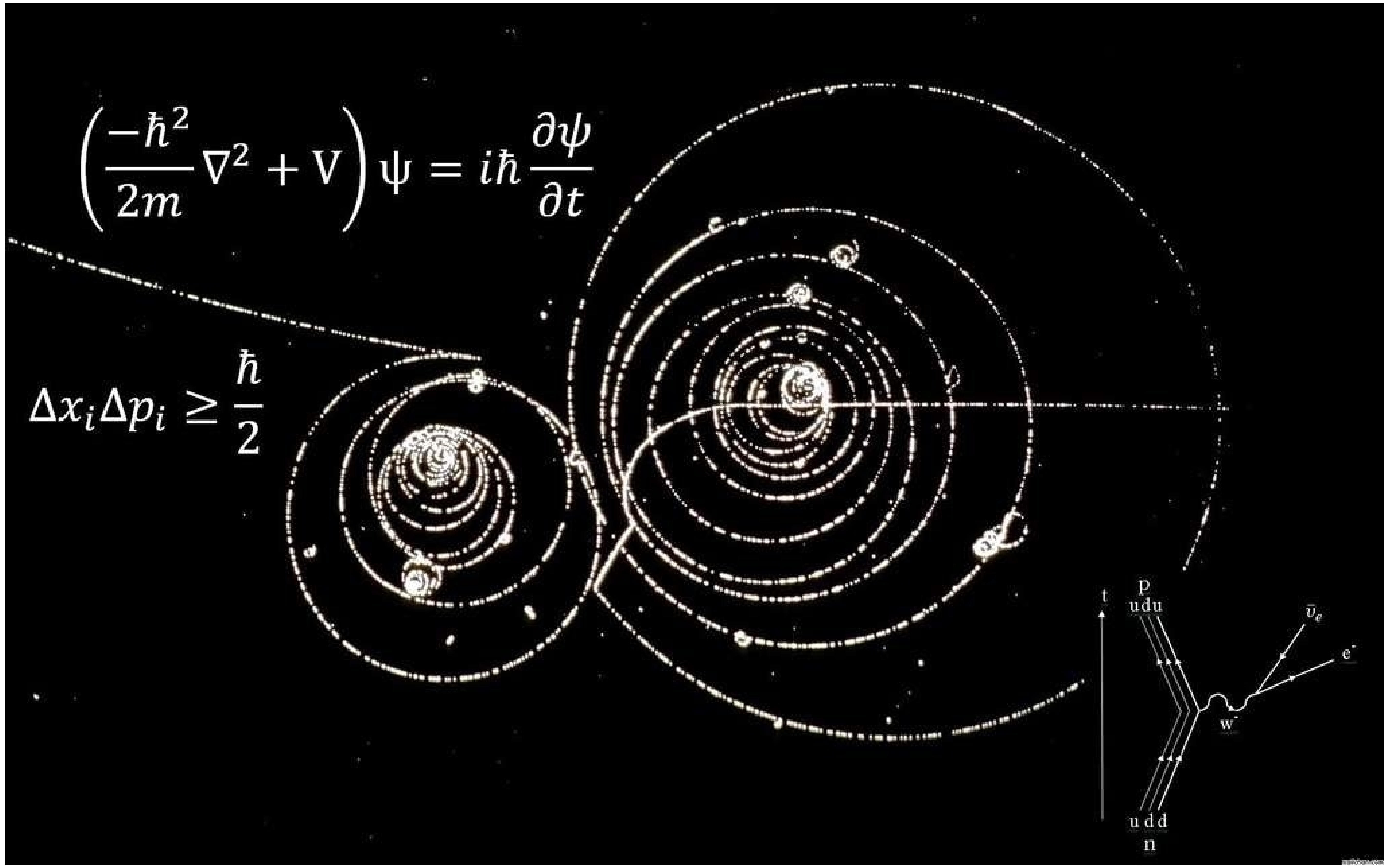
$|\psi\rangle = \frac{1}{\sqrt{2}}\Big(|$  $\rangle + |$  $\rangle \Big)$

Laure Le Bars

Quantum technologies

- **Quantum 1.0**: transistors, laser, atomic clocks are using quantum technologies

- **Quantum 2.0**: new range of applications:
  - Sensors, metrology, imaging
  - Communication
  - Simulators
  - Computers



Small survival guide for a quantum world

Wave-particle duality

- Sub-atomic objects (photon, electron, etc) behave as waves or as particles

Indeterminism

- As a consequence, we talk about probability. Or in other words, if we know one property precisely (e.g. position), another property is undetermined (e.g. speed)

measurement

- When measuring, it collapses the quantum state ; as a consequence, It is impossible to create an identical copy of an arbitrary unknown quantum state (this is the **no-cloning** principle)

Superposition:

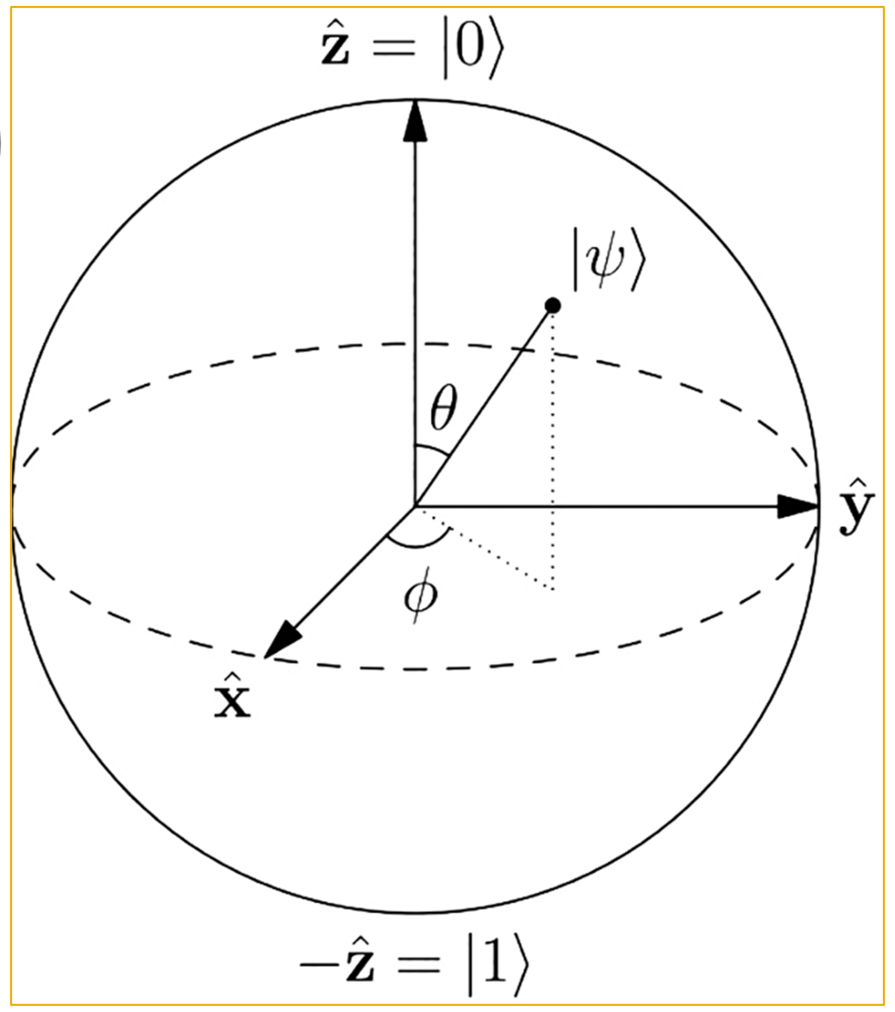
- Quantum particles can be in more than 1 quantum state at the same time

Entanglement

- States of entangled quantum particles are correlated without any signal exchange, even if far from each other; entangled particles behave as 1 particle

Quantum bits (qubit)

- quantum information unit, equivalent to classical bit
- But can represent 2 states at the same time, |0> and |1> with certain probabilities
- A state can be written α|0> + β|1> , with complex numbers α β where $|\alpha|^2+|\beta|^2 = 1$
- States can also be written like this: | ↑> or $\begin{pmatrix}1\\0\end{pmatrix}$ and | ↓> or $\begin{pmatrix}0\\1\end{pmatrix}$
- Quantum states can be defined with 2 angles θ and ϕ on a Bloch sphere (see figure)

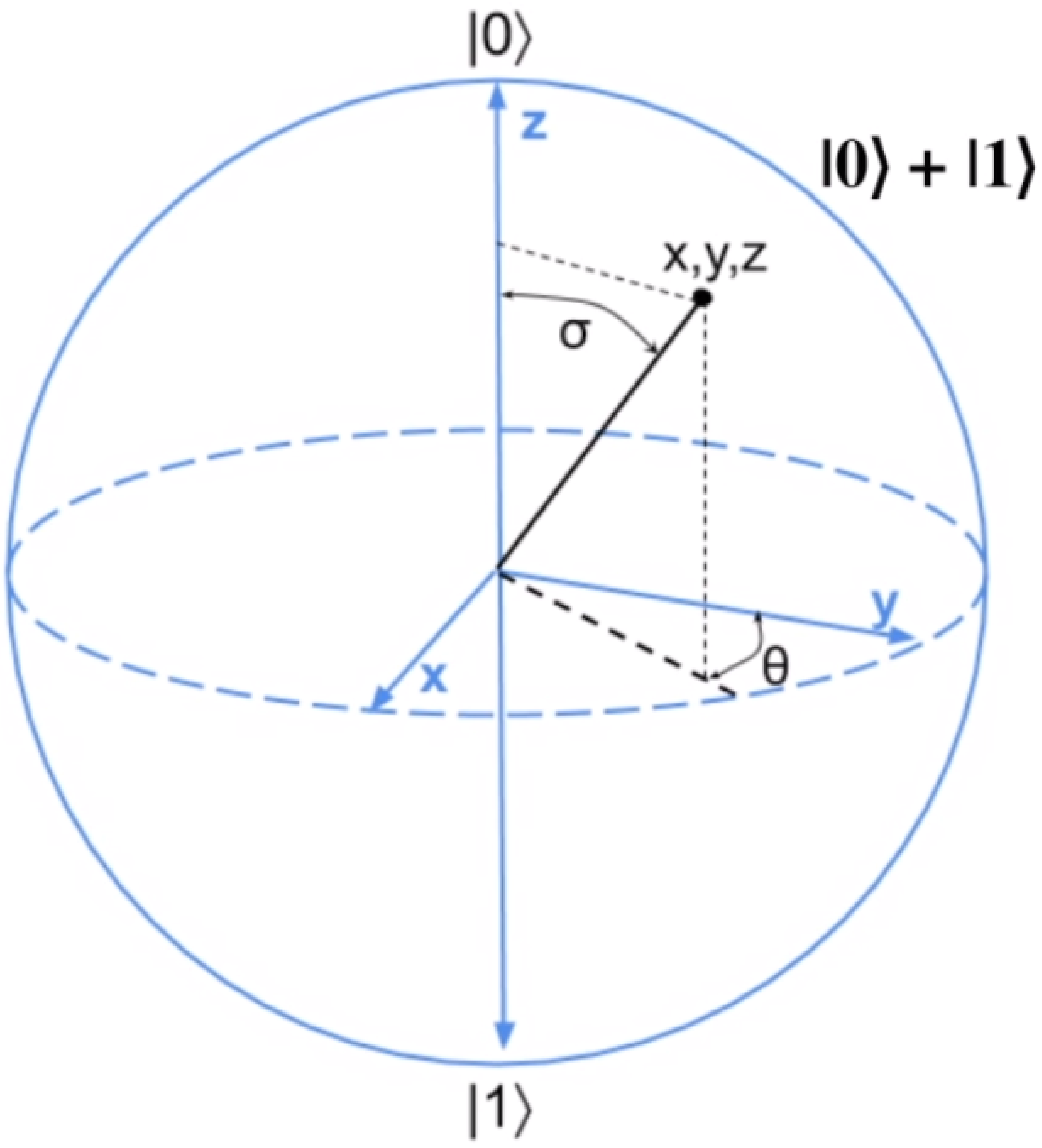


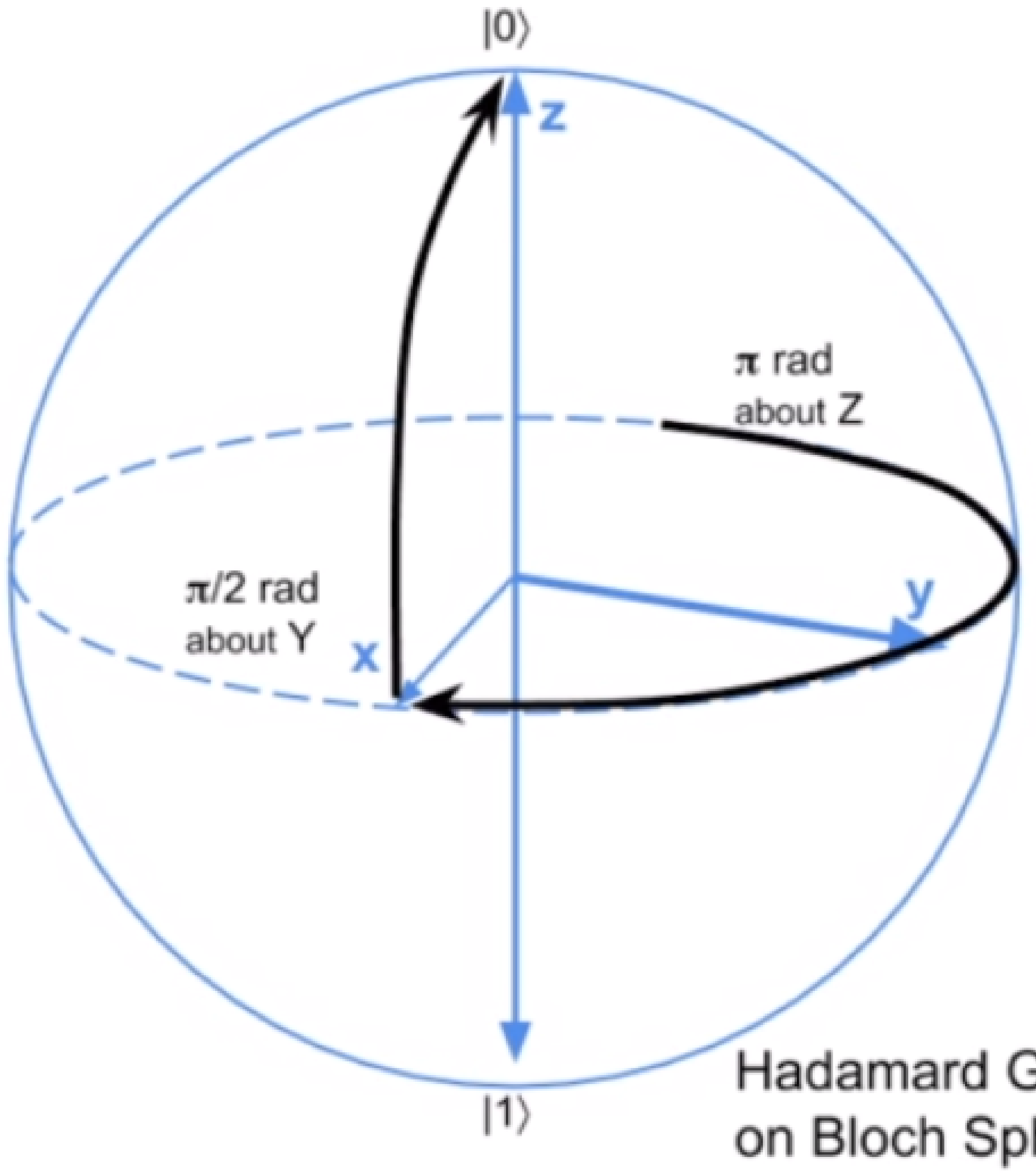
- Superposition of states:
  - α|00> + β|10> + γ|01> + δ |11> :
  - 2 qubits will have 4 states (2^2), etc… n qubits 2^n states

Qubits and gates

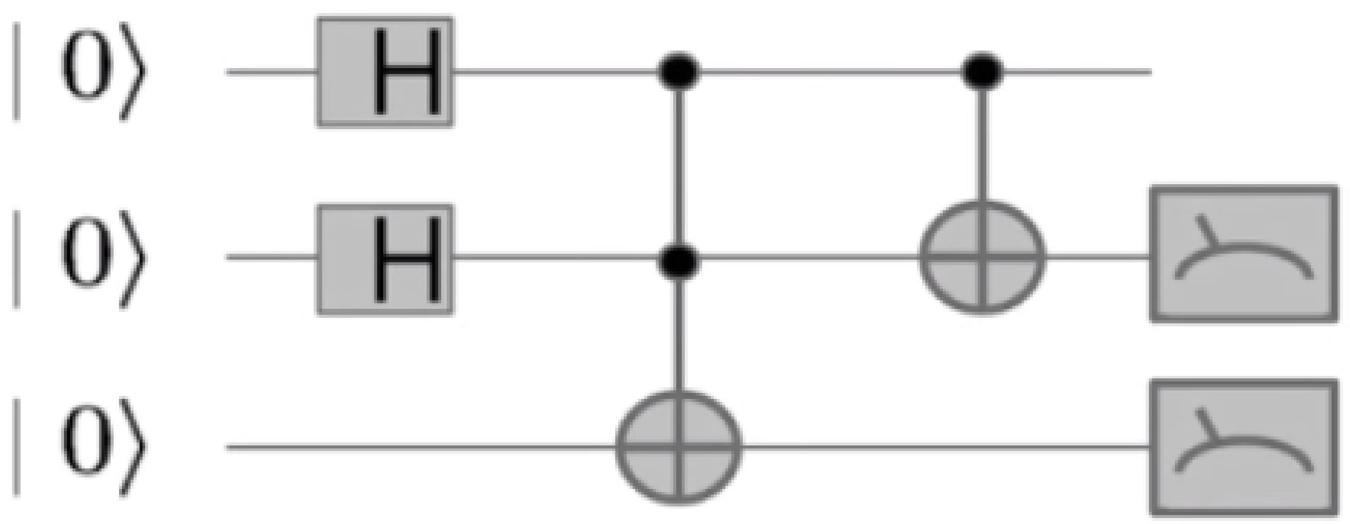
Quantum Bits: Qubits and Gates

Superposition and Entanglement





Hadamard Gate Operation on Bloch Sphere



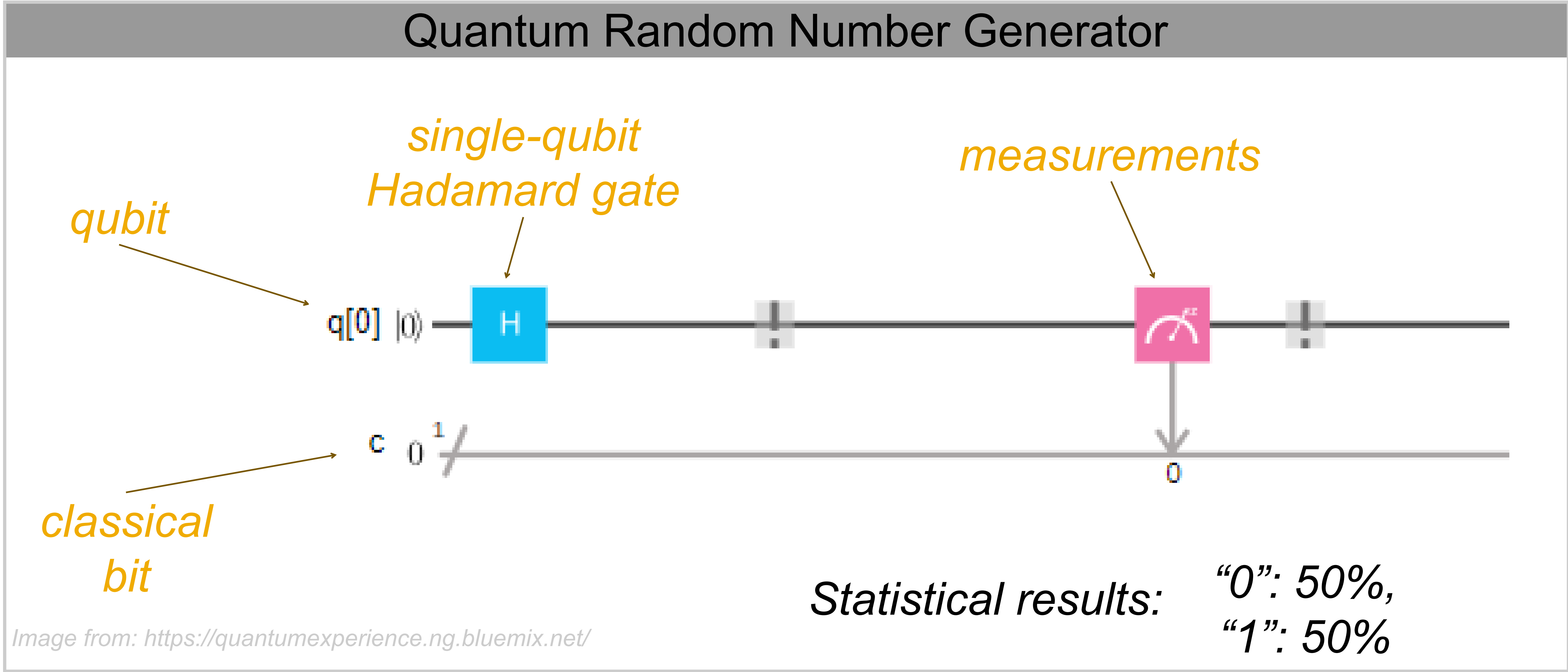
Quantum algorithms

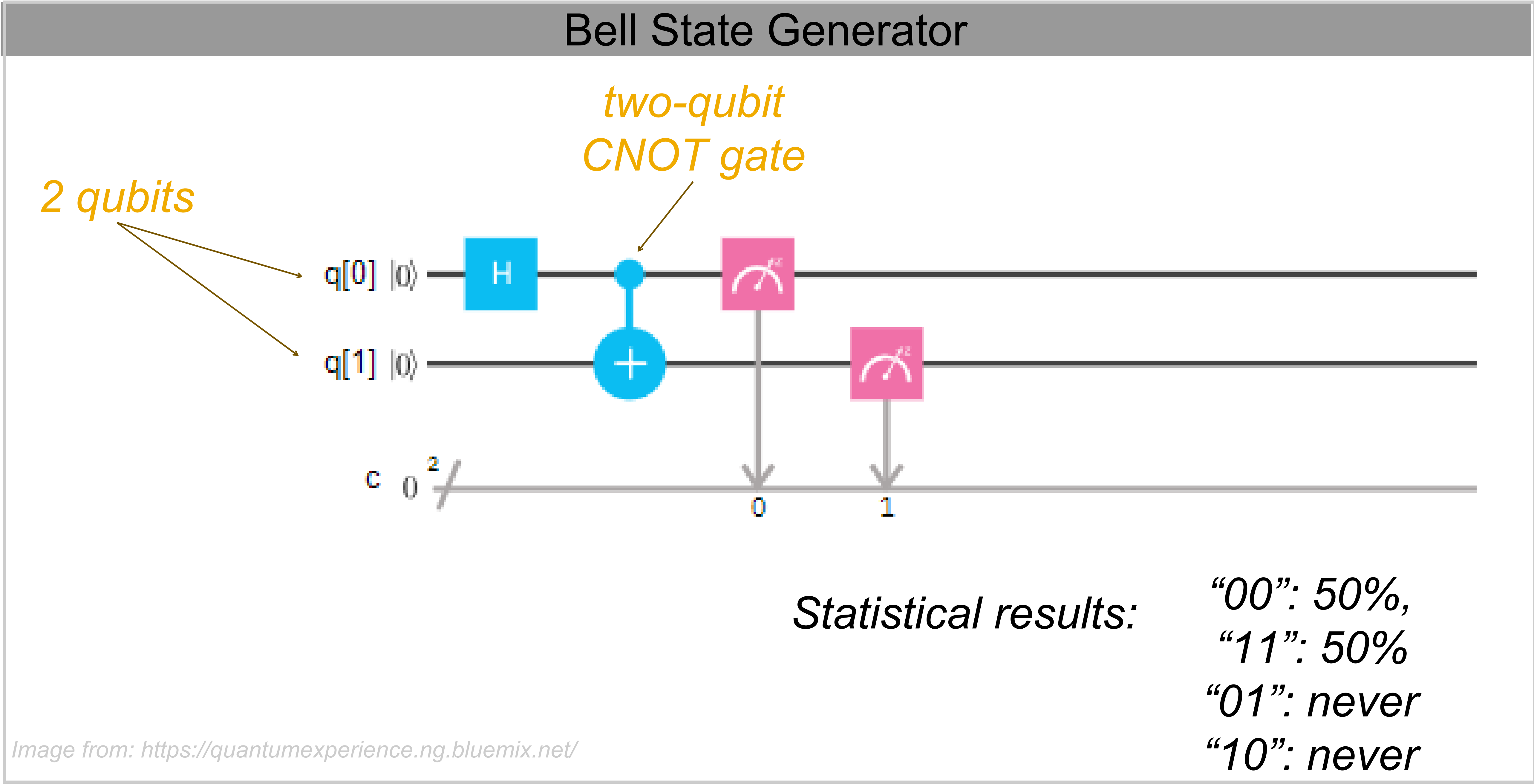
- **Algorithm** = a sequence
  of states and transitions between states such as NOT, AND, OR

- **Quantum Algorithm** =

a sequence of quantum states stored in qubits & transitions called gates such as Hadamard and CNOT

- **Quantum Algorithm** ≈ Classical Algorithm, except use of
  - Quantum states instead of binary states and
  - Quantum gates instead of binary operations *(for quantum circuits and gate-based quantum computer architecture)*



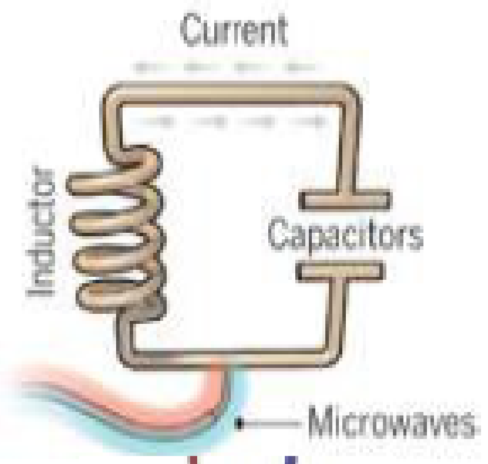


Quantum algorithms : examples

- **Shor's algorithm: integer factorization** (1994)
  - with classical computer, when number size increases, time grows exponentially
  - with Shor's algorithm on quantum computer, time grows much slower
  - in other words, Shor's algorithm is exponentially quicker than classical computer
- **Grover's algorithm: database search** (1996)
  - Quadratic speedup
- **Harrow, Hassidim, Lloyd** (2008)
  - Quantum Machin Learning
- **Several use cases in optimization and Artificial Intelligence / Machine Learning**
- **And many more… ... But perfect qubits don't exist yet**
- **Error corrections codes and 'logical' qubits**

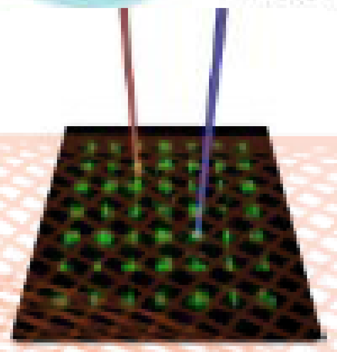
Quantum Computing in the EU Now

Superconducting



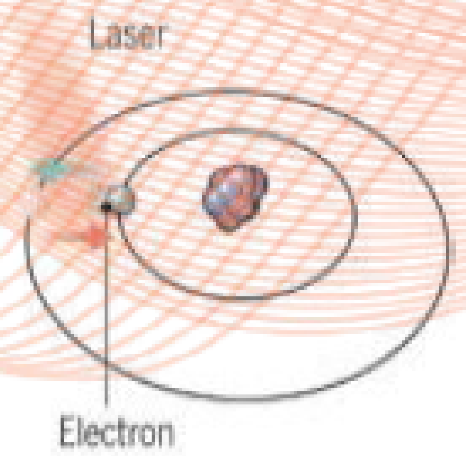
IQM QuTech
QILIMANJARO
ALICE & BOB

Neutral Atoms



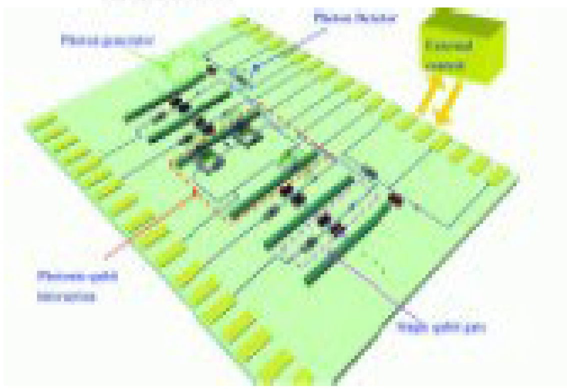
PASQAL
planqc

Trapped Ions



AQT eleQtron
JÜLICH Forschungszentrum

Photonics (PICs)

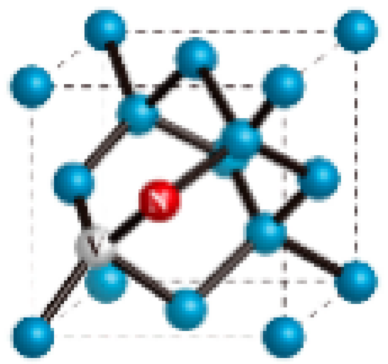


QUIX QUANTUM QUANDELA

Spins /Quantum Dots

SemiQon QuTech
siquance imec

NV Centers



XEED SaxonQ

OpenSuperQPlus

EuRyQa PASQuanS2

MILLENION QUANTUM

Projects starting in early 2024

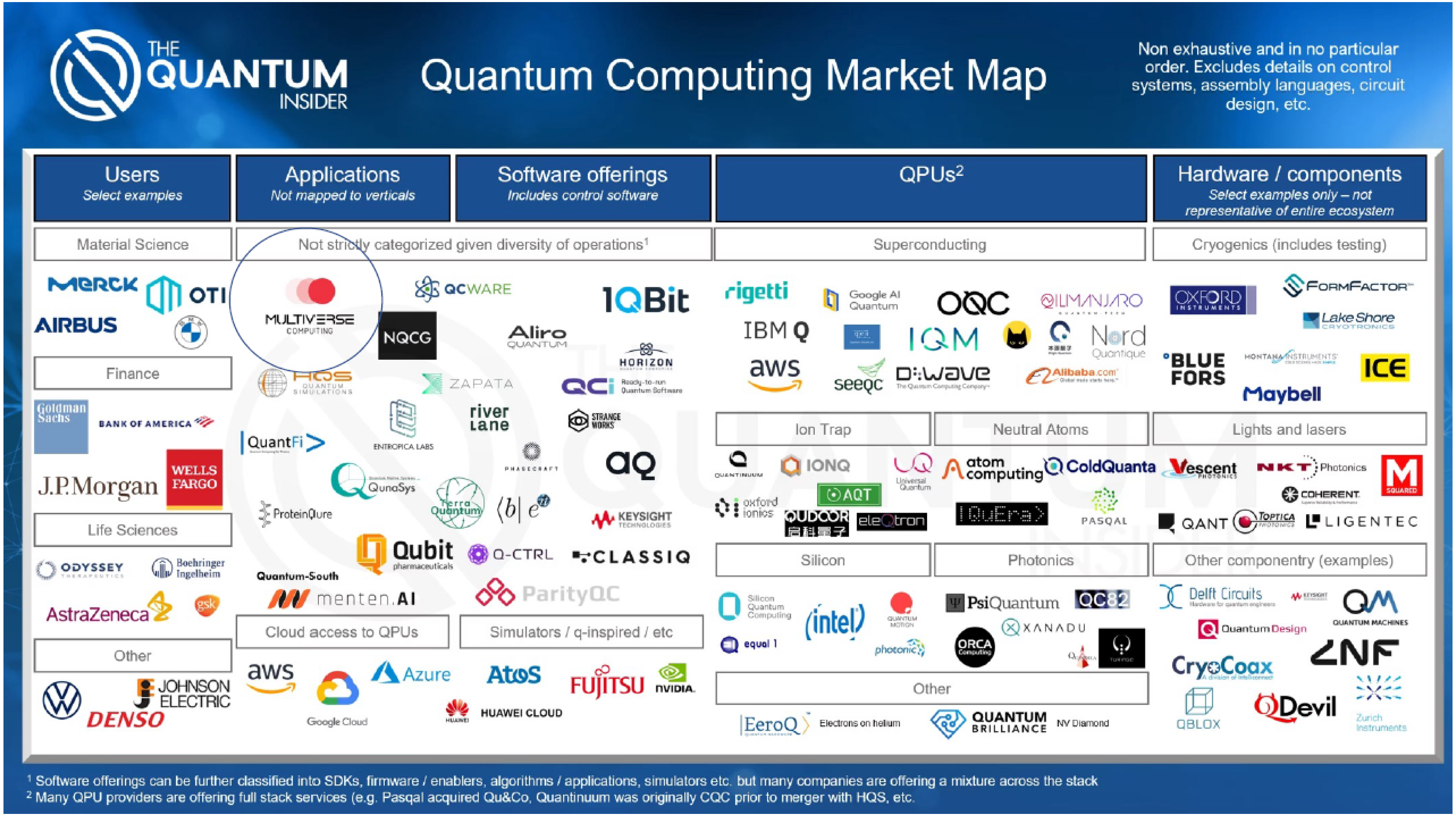
QLSI IGNITE

New FPA in 2024

Projects starting in early 2024

European Commission

Quantum computing market map

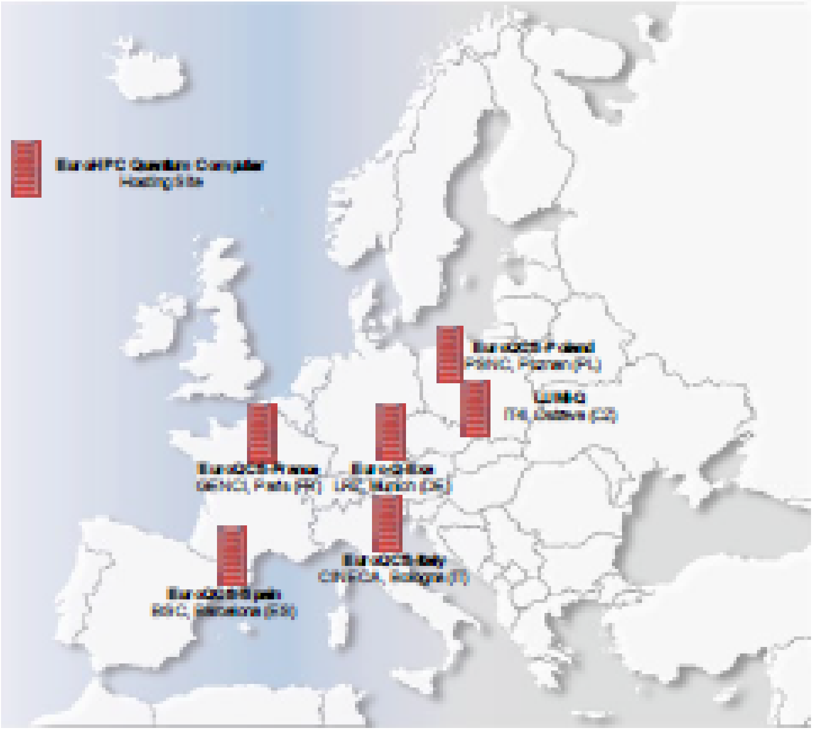


EuroHPC EuroQCS

EuroHPC Joint Undertaking

Interfacing Quantum Computers with HPC

⟨HPC|QS⟩



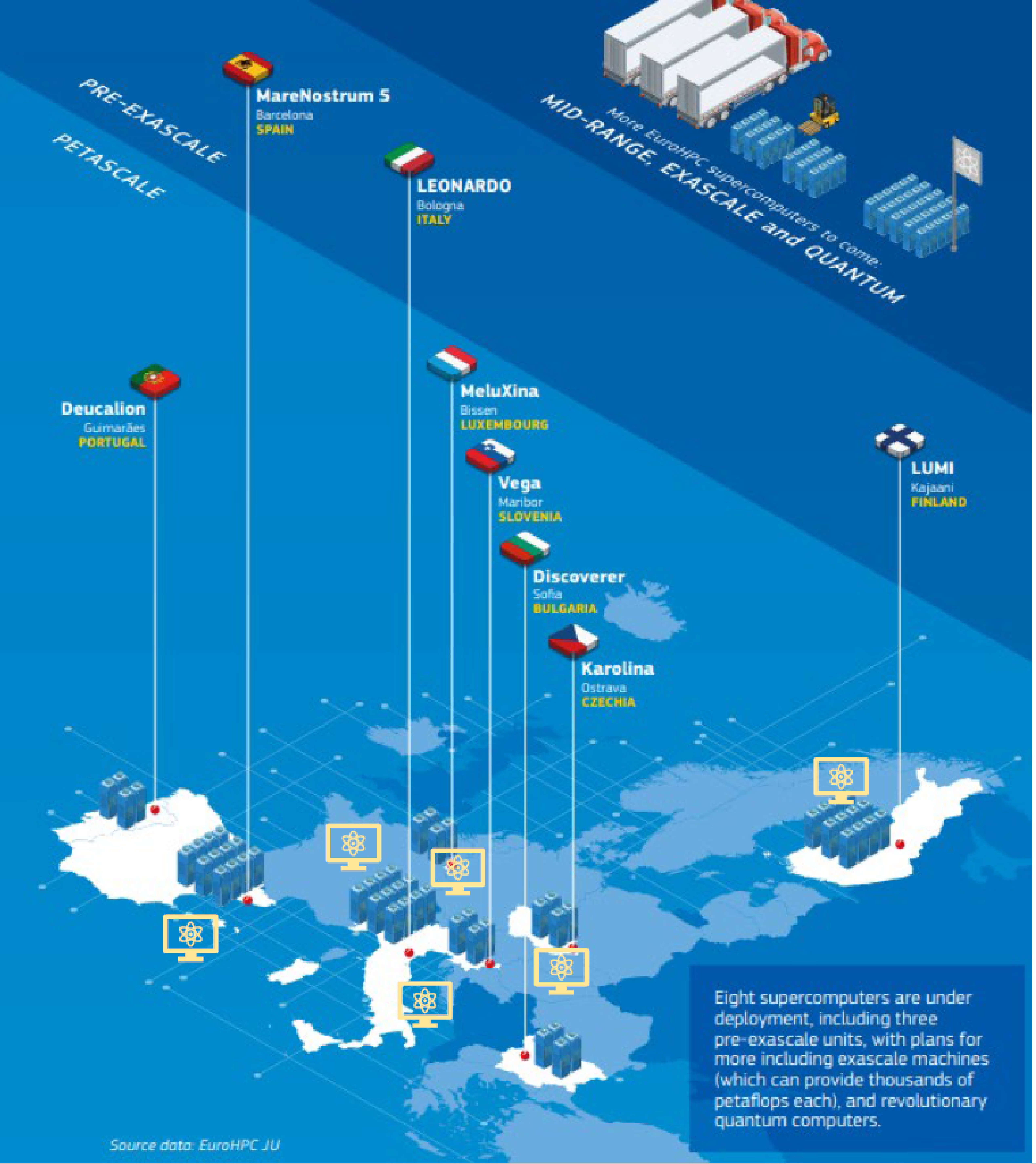
	2019 & 2020	2021	2022	2023	2024	2025	2026	2027
HPC Infrastructure	pre-exascale + petascale HPC systems	Several petascale, pre-exascale systems and exascale HPC systems				exascale and post-exascale HPC systems		
Quantum Infrastructure	**quantum simulators** interfacing with HPC systems	1st generation of **quantum computers** + **quantum simulators** interfacing with HPC systems				2nd generation of **quantum computers** + **quantum simulators**		

Hardware connection between classical supercomputers and quantum computers → **Use the quantum computer as an accelerator for the supercomputer** → **Develop a software platform for seamless programming of the hybrid system** → **Test and validate hybridisation in key applications** →

Priority use cases

- **Climate modelling**
- **New materials (batteries)**
- **Drug simulation**

European Commission



Deployment of 6 Quantum Computers

- **6 hosting sites**
  - Czechia, France, Germany, Italy, Poland, Spain
- **4 different platforms**
  - Trapped ions, Superconducting, Photonics, Rydberg atoms
- **New call 2023-24** (31 march)
  - At least 2 new hosts

[Call to host new quantum computers - European Commission (europa.eu)]

European Commission

European Quantum Industry Consortium (QuIC)

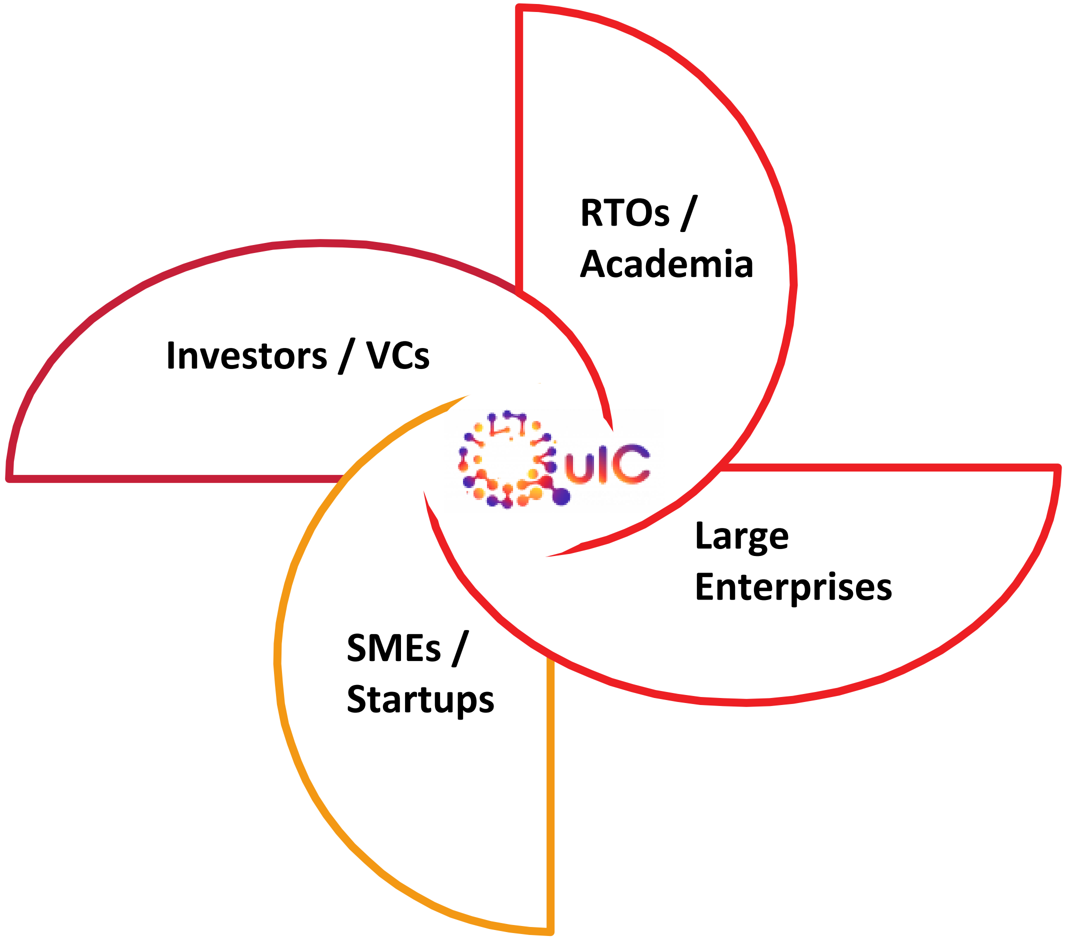
Europe’s Largest Quantum Industry Association

QuIC at a glance

Our **HISTORY**: Non-profit association established in 2021 by several key business actors – large enterprises, SMEs, startups, investors – from across Europe.

Our **MISSION**: grow and strengthen the quantum technology industry, and position Europe as a global leader of the sector.

Our **METHOD**: serve as a collaboration hub between researchers, industry leaders, investors and end-users.



QuIC

European Quantum Industry Consortium

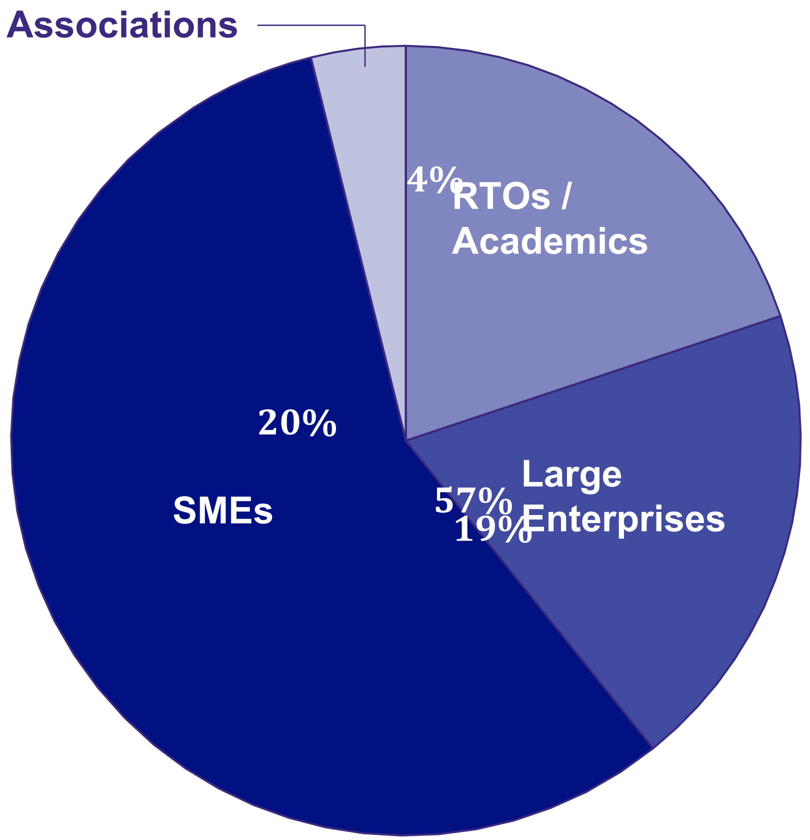
181 members – all from European countries

144 members from 18 EU Member States

37 members from other European nations

QuIC Membership

Member type	Full	Associate	Total
Large Enterprises	25	10	35
SMEs	75	28	103
Academics/ RTOs		36	36
Associations		7	7
Total	**100**	**81**	**181**



(Members as of 23rd February 2024)

QuIC Work Groups & Expert Groups

Expert Group – QUANTUM COMPUTING & SIMULATION

Expert Group – QUANTUM COMMUNICA-TION

Expert Group – QUANTUM SENSING & METROLOGY

Expert Group – ENABLING TECHNOLOGIES

WG - MTU: MARKET TRENDS & USE CASES

WG - SIR: STRATEGIC INDUSTRY ROADMAP

WG - MTI: MARKET & TECHNOLOGY INTELLIGENCE

WG - IPT: INTELLECTUAL PROPERTY & TRADE

WG - ST: STANDARDS

WG - EDU: EDUCATION

WG - ECO: QT ECOSYSTEM

WG - SF: SME & FUNDING

WG - NC: NATIONAL CHAPTERS

QuIC,s international leadership

International Council of Quantum Industry Associations

Proud Founding member of **ICQIA**.

Fellow international members:

- QED-C (USA)
- QIC (Canada)
- Q-STAR (Japan)

Trusted partner of the European Commission

QuIC supports the European Commission in its **bilateral international dialogues** with partners.

- United States of America
- Japan
- South Korea
- India

Quantum Standardisation

QuIC acts as a bridge between its many Members and the international quantum standardisation committees:

- JTC-22 (Europe)
- JTC-3 (worldwide)

QuIC Strategic Industry Roadmap (SIR)

European Quantum Industry Consortium

Quantum Computing & Simulation

Quantum Communications

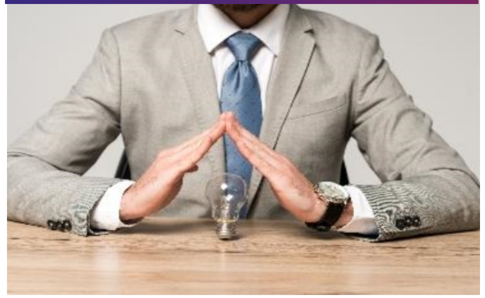
Quantum Sensing & Metrology

Enabling Technologies

Education & Skills

Standards

IP & Trade



Growth & Funding

Industrial Applications

Strategic Industry Roadmap – Shared with European Commission and governments across Europe to inform quantum policies across the continent.

QuIC supporting EU initiatives

Partner in project QUCATS, which coordinates and supports the **European Quantum Flagship**.

Member of the **Strategic Advisory Board** to the European Commission on quantum technologies.

Private Member of the **EuroHPC Joint Undertaking** (JU) governing board.

Member of the **Research & Innovation Advisory Group** (RIAG) to the EuroHPC JU.

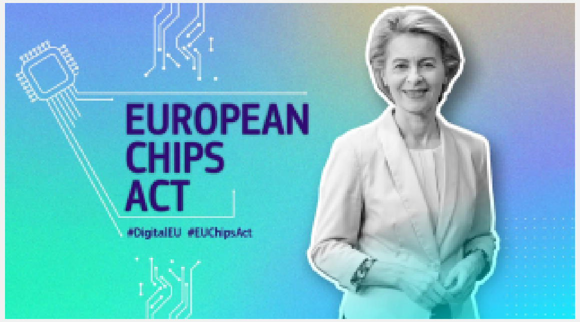
Contributor to the EIB's **Quantum Finance Lab**.

Member of the EIC Scaling Club to support tech scale-ups in Europe.

QuIC supporting EU initiatives

European & Global Standardisation:

- Among select entities in EU High-Level Forum on Standardisation
- Contributor to the EU's rolling plan for ICT Standardisation.
- Links to JTC-22 & JTC-3.



Support of **EU Chips Act** on quantum:

- MoU with AENEAS, large industry association for electronic components and systems.
- Links with Chips JU board.

QuIC Membership Benefits

A two-day **global quantum gathering** hosted and organized by QuIC. Day 1 features a business expo and Day 2, an insightful plenary day. The event brings together business leaders, quantum solution providers, researchers and policymakers from around the world.

Information sessions on the **latest global developments** in connection with the quantum industry, **available for QuIC Members only**. Recent topics include export control regulations, global standardization efforts, and deep dives on critical enabling technologies.

Matchmaking Sessions designed to help **QuIC Members find each other and form project consortia** for public funding calls. Sessions are **also organized with partner associations**, such as AENEAS (electronic components and systems community) in the context of the EU Chips Act. These are an exclusive benefit of QuIC membership.

Q-Expo

11 – 12 June 2024
KIT Royal Tropical Institute, Amsterdam, NL

Q-Expo: Bringing the global quantum industry to Europe

Day 1: The Exhibition & Day 2: Plenary Day

- Simplified and standardised Booth Concept. Highest flexibility for exhibitors and equal conditions for every exhibitor. Simple price structure. Easy for SMEs.
- "Everyone is welcome" to join the exhibition. Favour end-users and government reps as attendees. Investors also to be included. General public as spots remain.
- 3 Pillar System – "3 in 1 Event" – highest flexibility for participants

Key Benefits for QuIC Members & external Participants

- Draw governments (w/ support from QDNL) to meet and engage with industry.
- No-cost entry: attract end-users and investors.
- Easy format for QuIC members to promote their tech & solutions.
- Many Networking Opportunities over 2 days:
  - Coffee Breaks, Lunch Breaks and Social Dinner
  - Social Activities (incl. Quantum Meets Week)

Q-Expo: an event unlike any other.

European Quantum Industry Consortium

Thank you!

www.euroquic.org

More Information about Q-Expo

Camille de Valk, EuroHPC, March 20th 2024

Quantum computing *industrial applications*

How to create a path to quantum advantage

Capgemini

What's State of the Art?

FRONTIER

1.6 quintillion calculations per second

9,472 AMD 64-core CPU's (total >600k cores)

37,888 Radeon Instinct MI250X GPUs
12.8 TiB/s bandwidth

What can it do?

Weather forecasting

Aerodynamics simulation

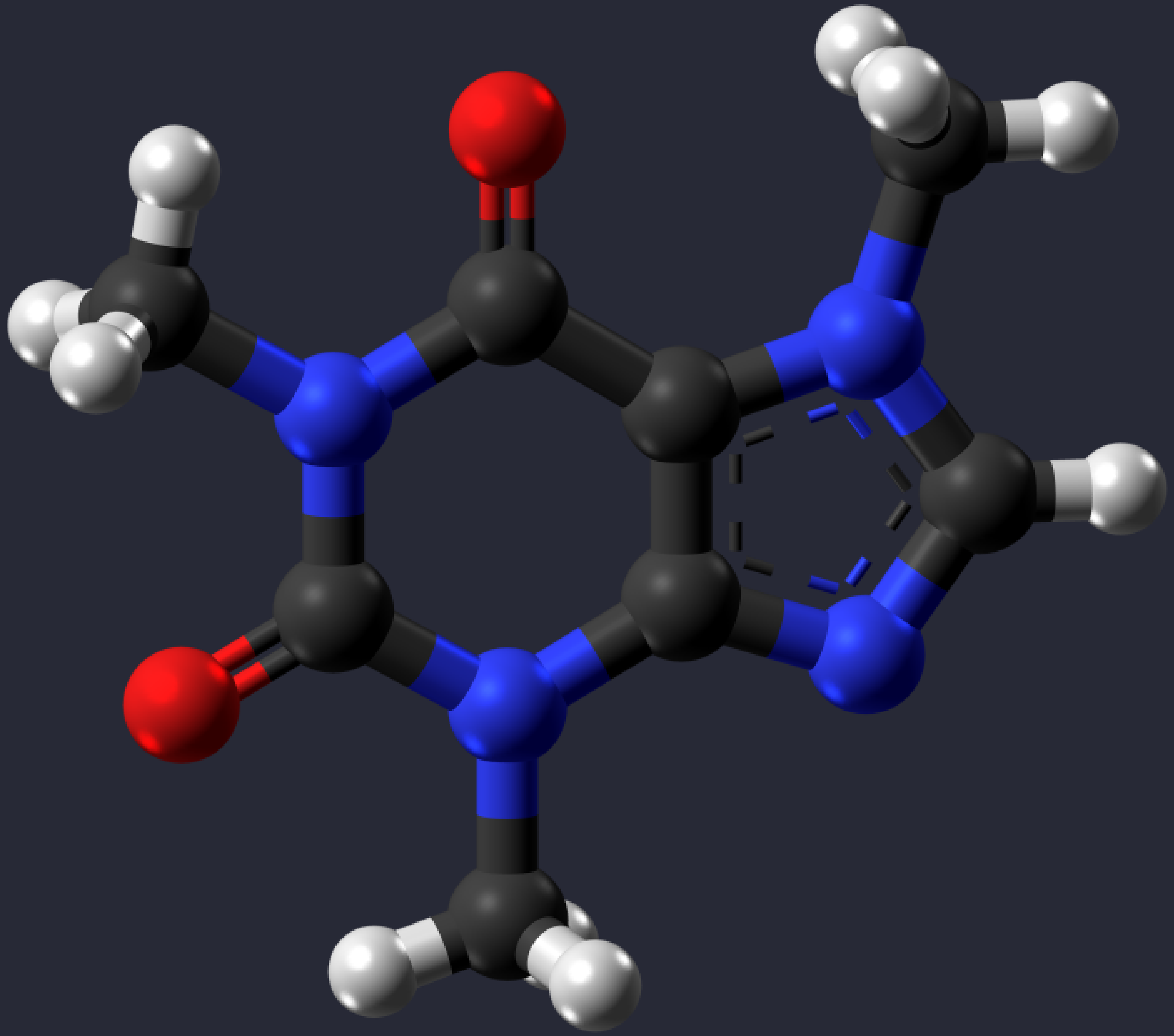
Machine learning tasks

Nuclear test simulations

What can it *not* do?

Company Confidential © Capgemini 2024. All rights reserved |

What can it *not* do?



Simulating Caffeine

10^{48} bits for energy configuration

That's terra terra terra terra

Company Confidential © Capgemini 2024. All rights reserved |

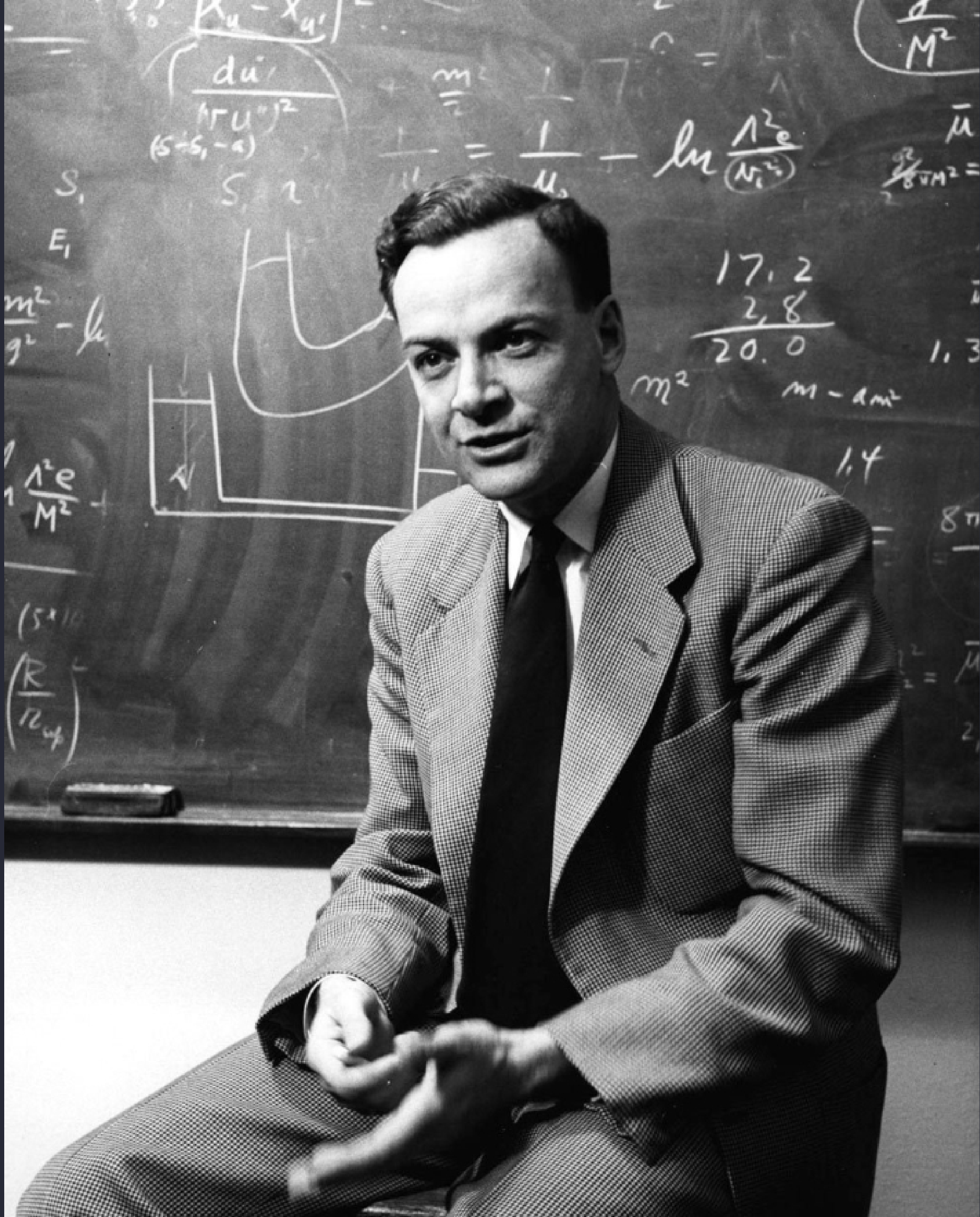
What can it *not* do?

Find a catalyser for nitrogen fixation

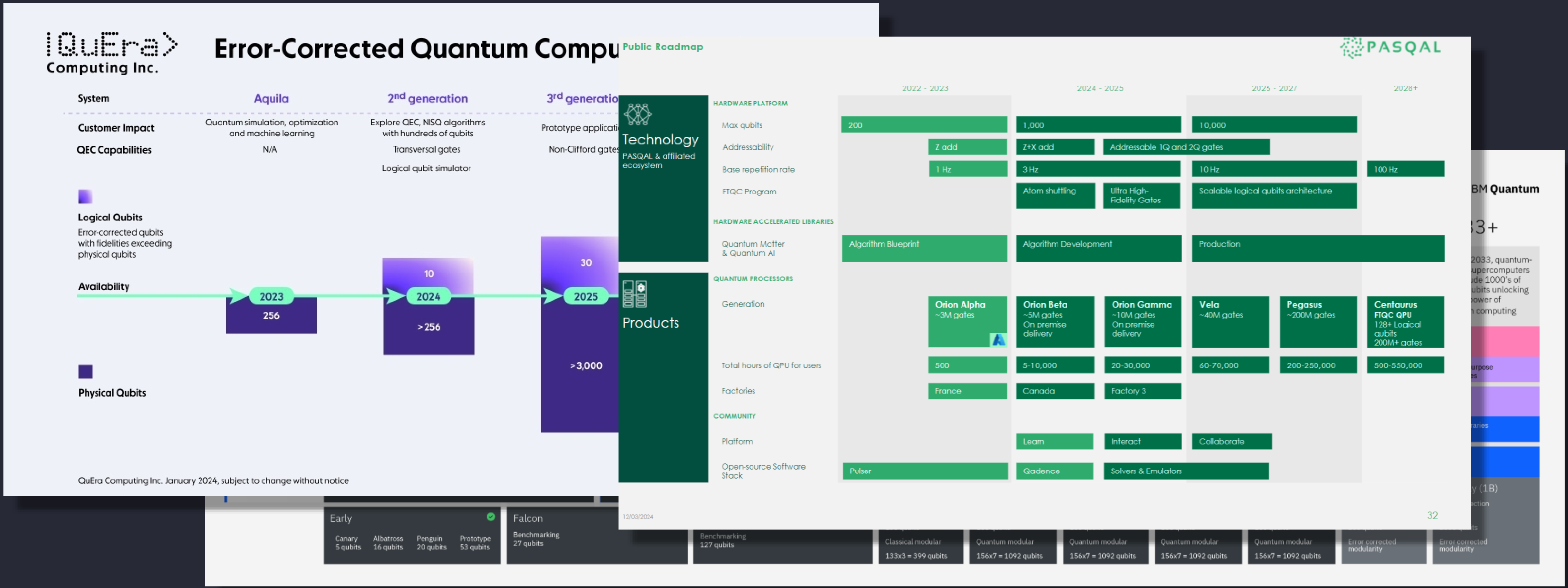
What can it *not* do?

Accurately predict extreme weather events

"… nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly, it's a wonderful problem because it doesn't look so easy"



We could soon see a quantum computer...



...WHICH CAN BE USED FOR COMMERCIAL APPLICATIONS

Company Confidential © Capgemini 2024. All rights reserved |

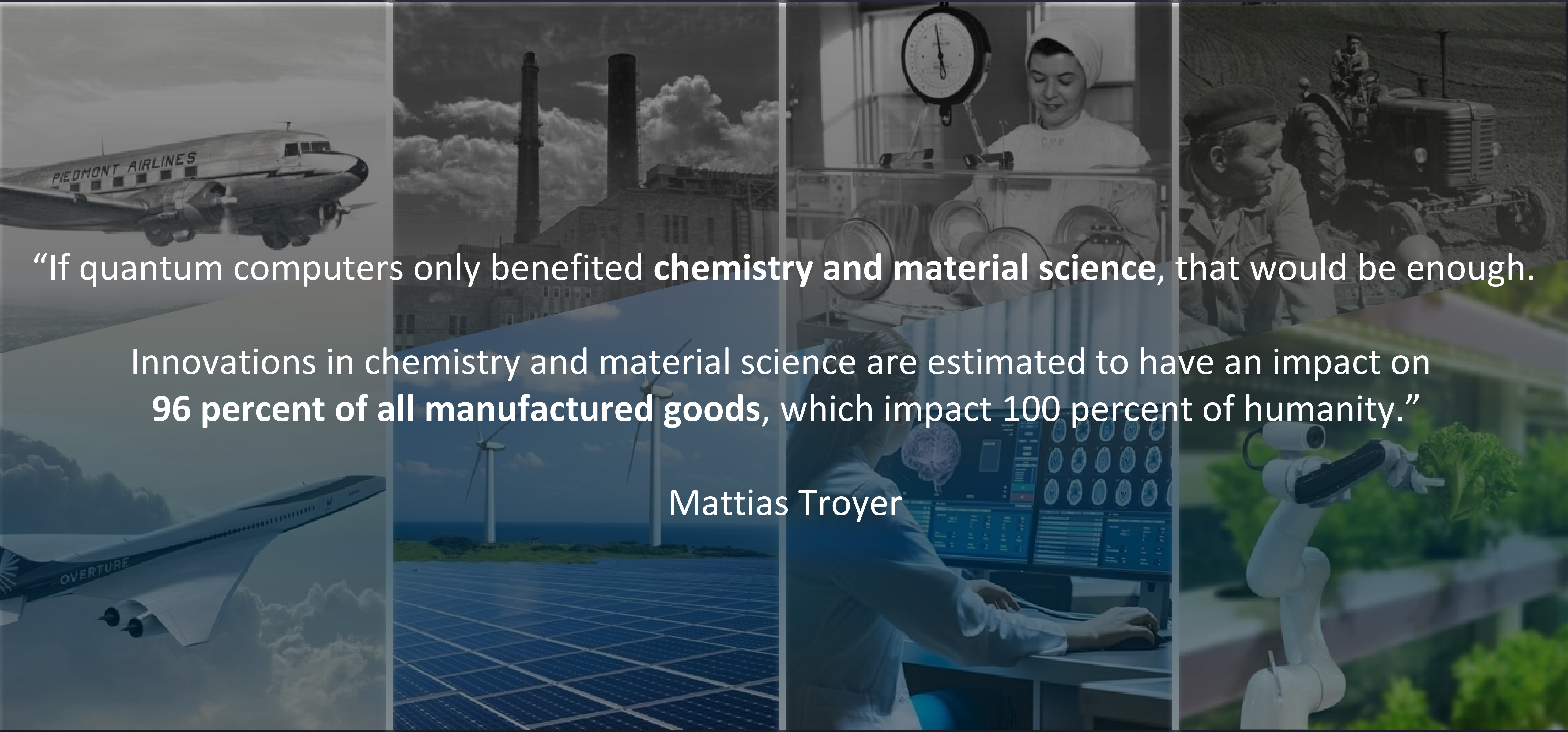
What would you do with such a QC?

Quantum computing to simulate reality?

No.

Capgemini

QUANTUM CHEMISTRY IS STILL OUR BEST SHOT



"If quantum computers only benefited **chemistry and material science**, that would be enough.

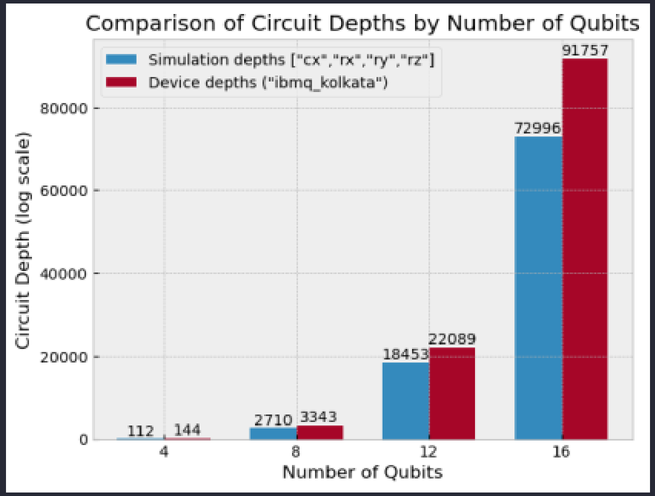
Innovations in chemistry and material science are estimated to have an impact on **96 percent of all manufactured goods**, which impact 100 percent of humanity."

Mattias Troyer

Company Confidential © Capgemini 2024. All rights reserved |

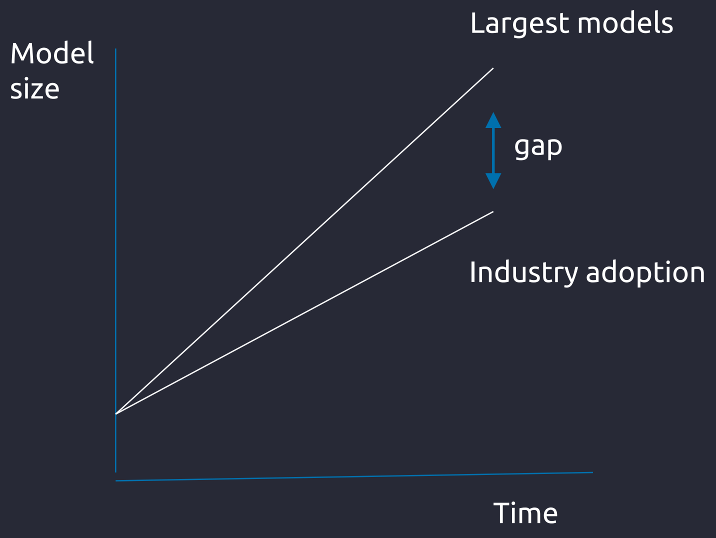
BUT IT'S STILL FAR FROM EASY

Still very deep circuits



Properties of interest are impossible or too expensive to calculate analytically

Even then, is there a business case, and are organisations ready?

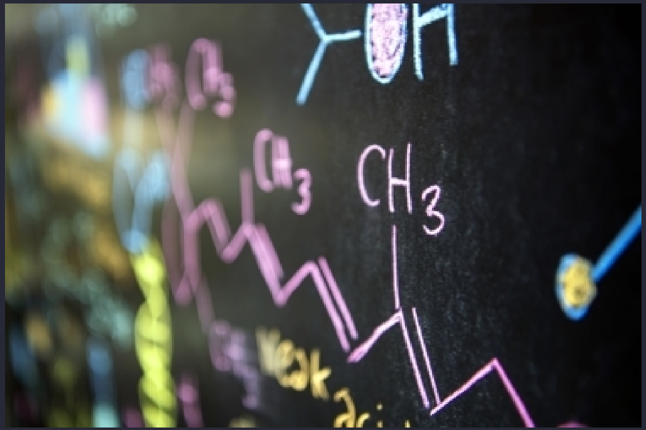


Company Confidential © Capgemini 2024. All rights reserved |

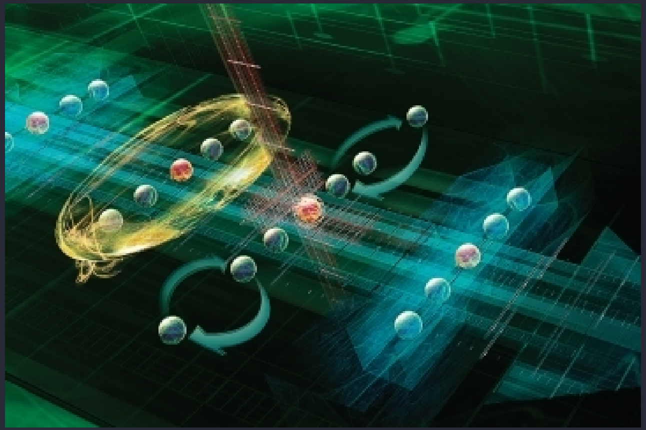
To make it work, we need an end-to-end approach

Specifying the
business case

Specifying the
use case



Specifying the
hardware implementation

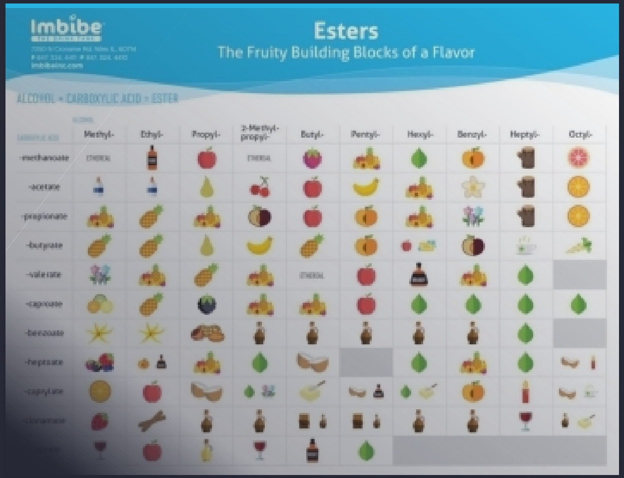


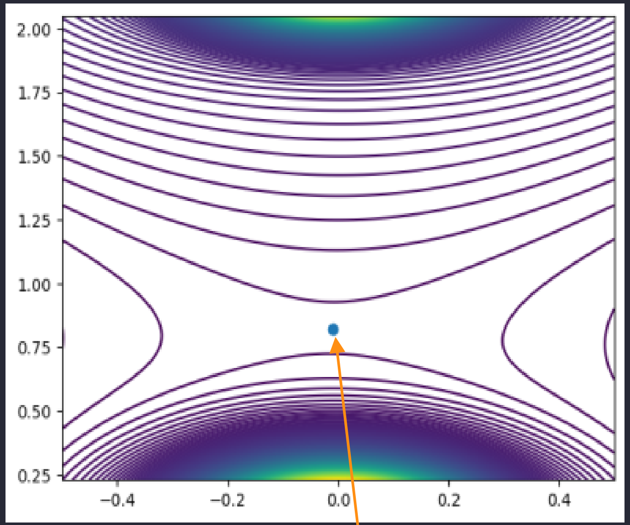
Company Confidential © Capgemini 2024. All rights reserved |

Predicting *biodegradability*

Capgemini

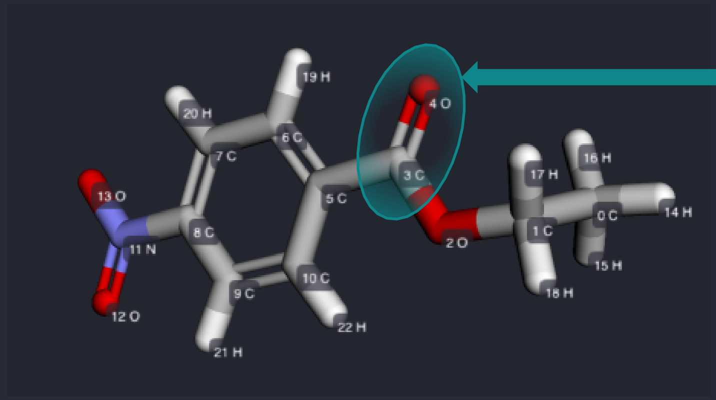
Predicting ester degradation

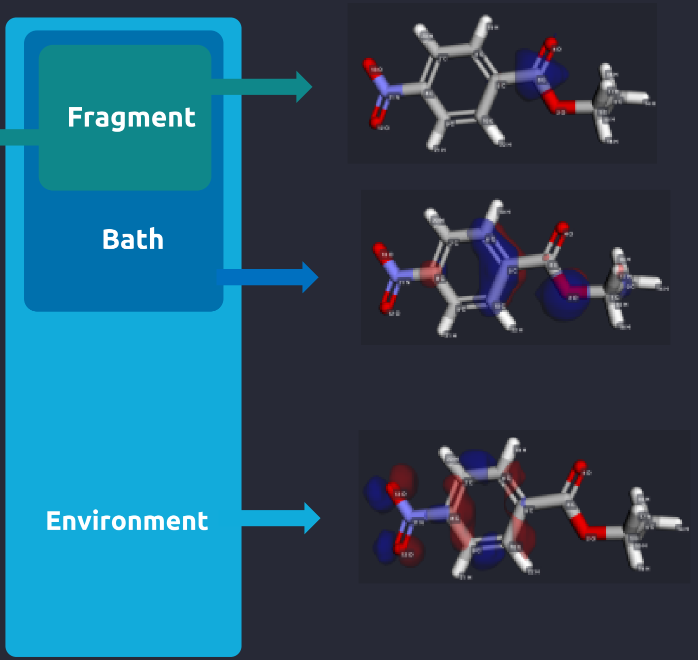




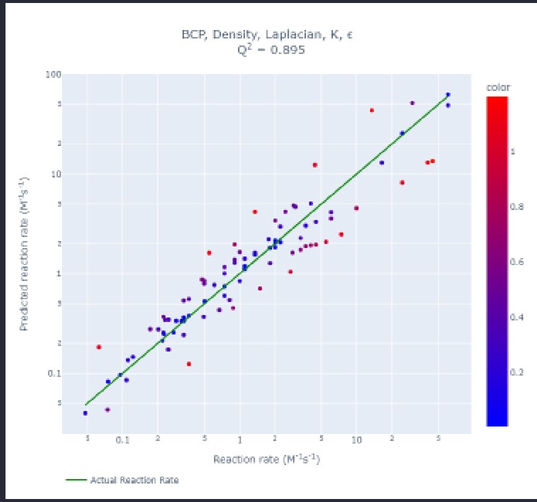
Promethium

features derived from electronic structure, such as bond critical points





$$H = \sum_{rs}^{F+B} h^{\mathrm{eff}}_{rs} \hat{a}_r^\dagger \hat{a}_s + \sum_{pqrs}^{F+B} (pq|rs) \hat{a}_p^\dagger \hat{a}_r^\dagger \hat{a}_s \hat{a}_q - \mu \sum_{r}^{F} \hat{a}_r^\dagger \hat{a}_r$$



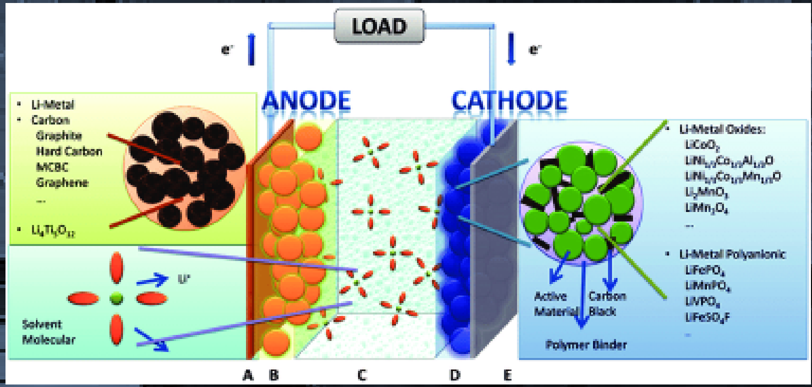
.. can be predictive for hydrolysis rate

Company Confidential © Capgemini 2024. All rights reserved |

Optimising
batteries

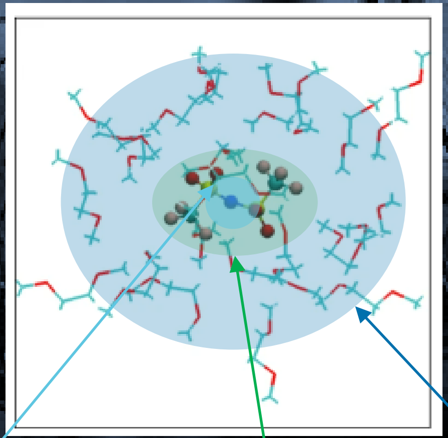
Capgemini

Q-ACES: Advancing chemical energy storage with quantum



UK Research and Innovation

Simulation of electrolyte chemistry

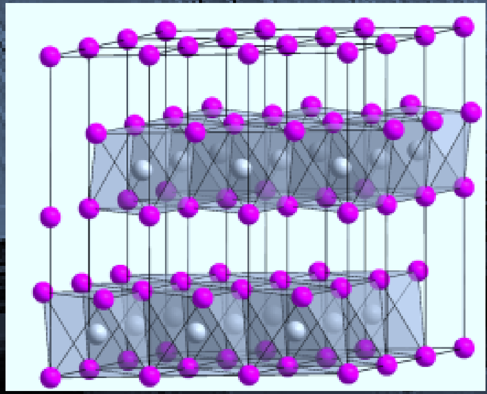


Core simulated on quantum computer

Embedded in approximate semi empirical quantum environment

Solvation model with molecular dynamics

Simulation of electrodes and interfaces

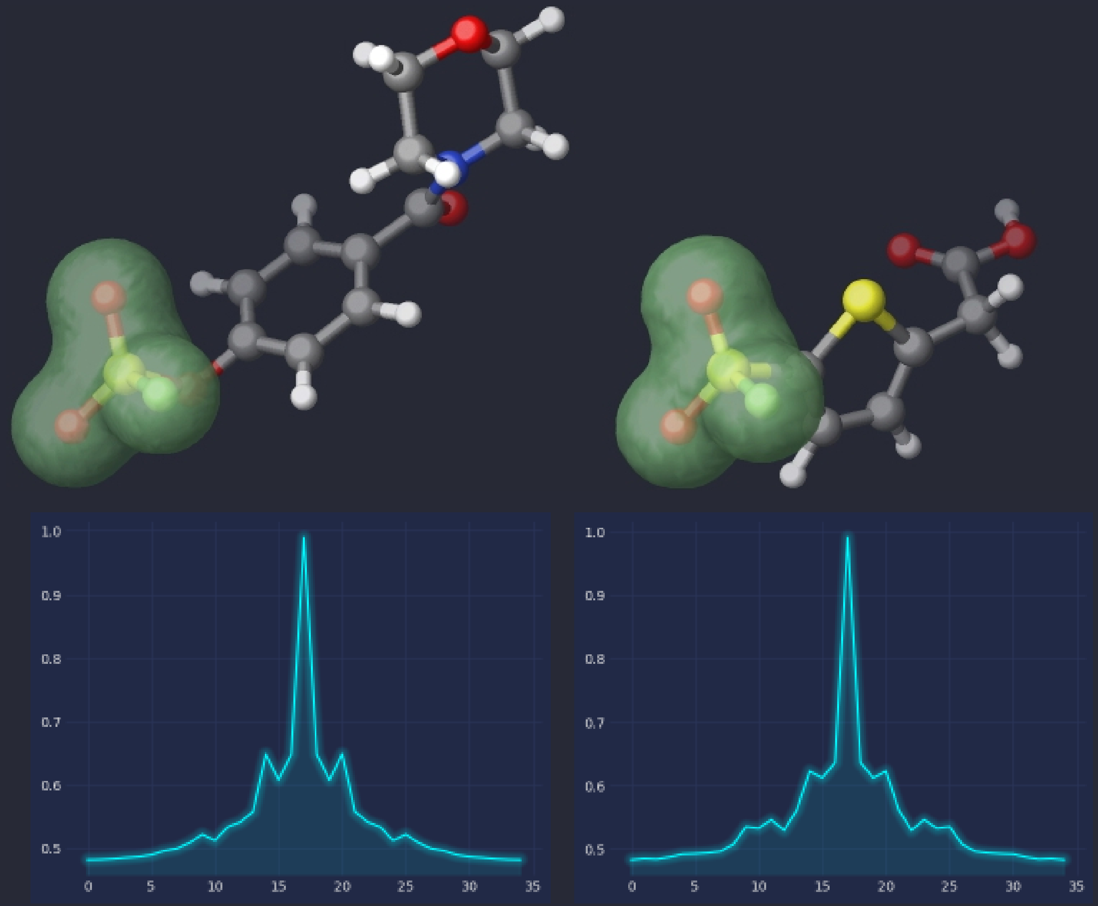


Finding *new drugs*

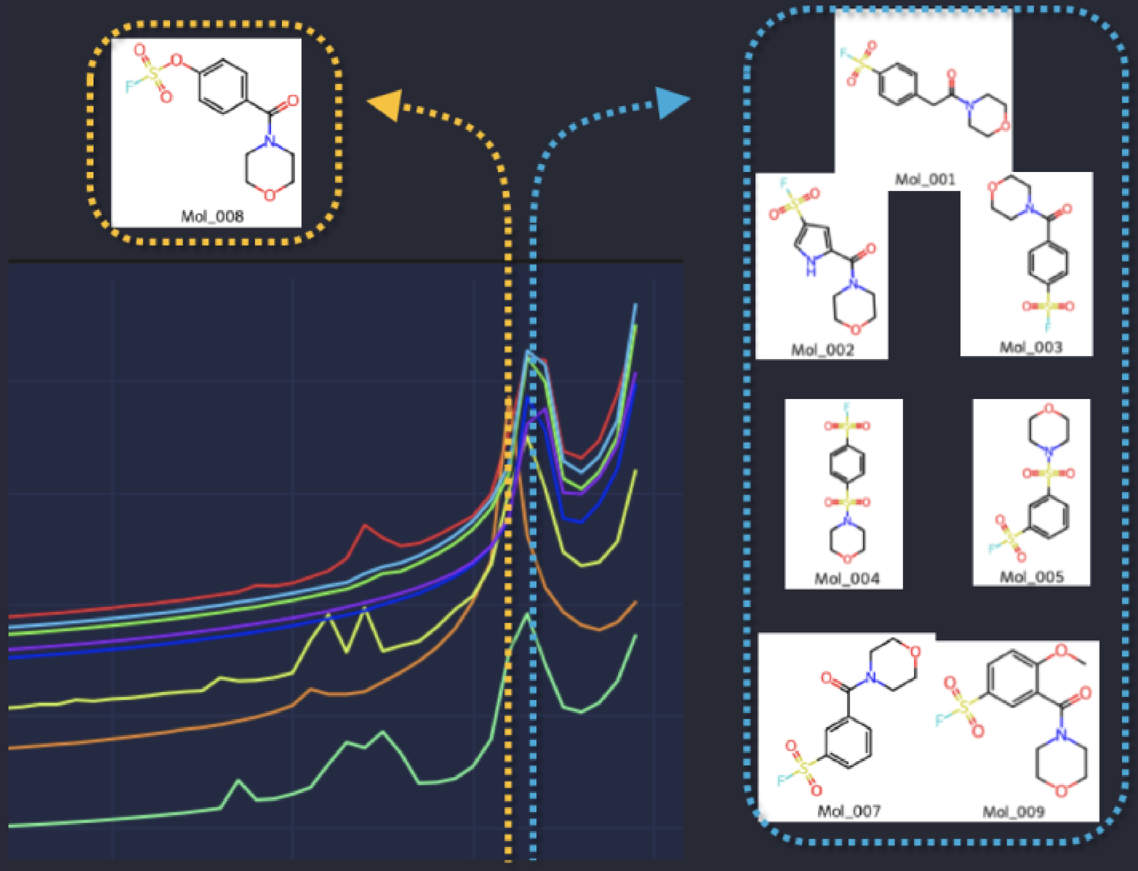
Capgemini

Predicting reactivity of covalent drugs

OBTAINING DYNAMICAL FEATURES



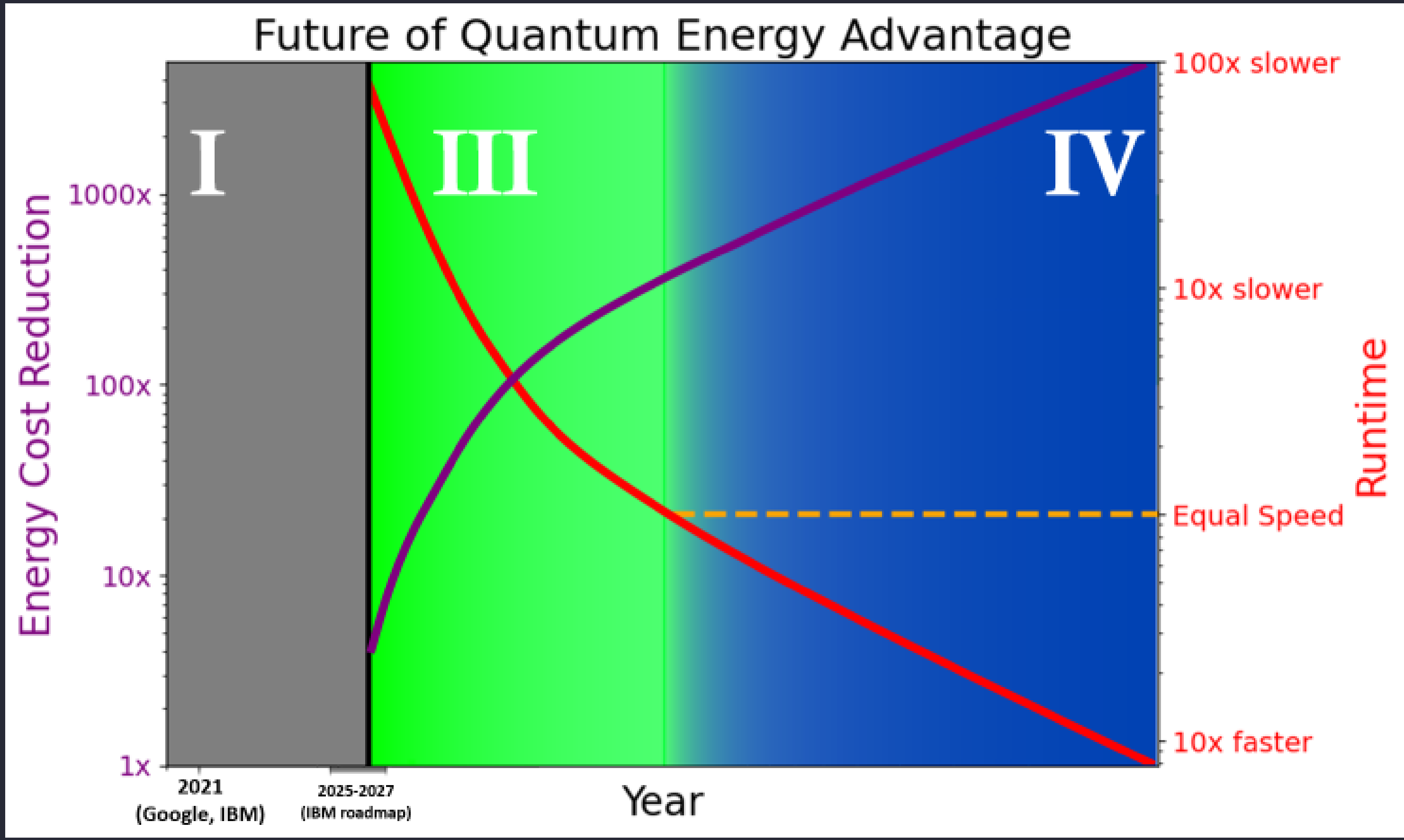
.. AND CORRELATING THEM WITH STRUCTURES



Company Confidential © Capgemini 2024. All rights reserved |

Quantum energy advantage?

Don't forget other advantages than speed-up



EQUALITY brings together leading research groups, SMEs, and prominent industrial players to develop **quantum algorithms** for **real problems** running on **real quantum hardware.**

AIRBUS

Capgemini

DA VINCI LABS

Fraunhofer ENAS

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center

Inria

Universiteit Leiden The Netherlands

PASQAL

The consortium has been awarded in the highly competitive Horizon Europe funding programme, and the partners will receive a cumulative €6M grant from the European Commission from 2022 to 2025.

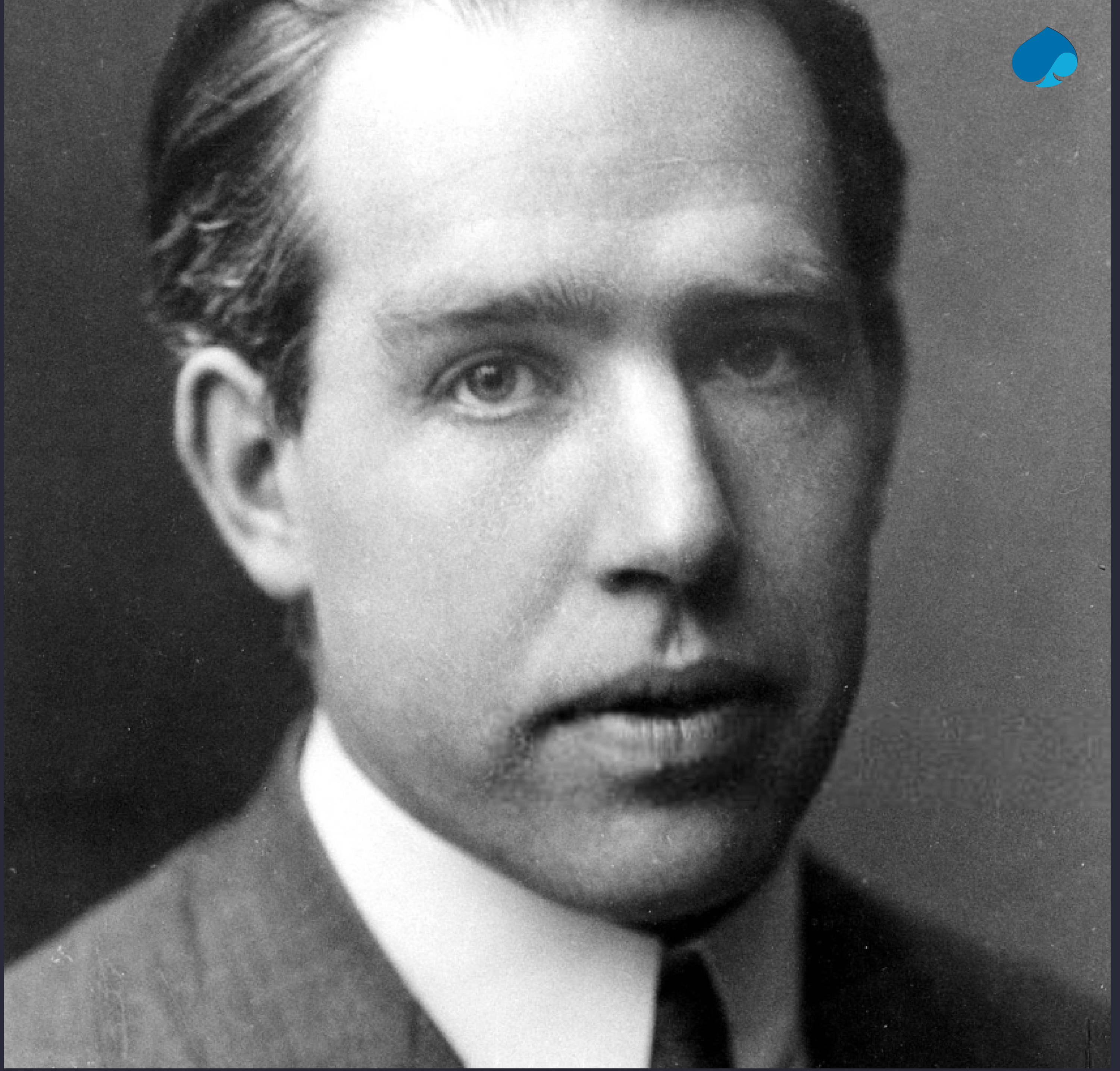
Funded by the European Union under Grant Agreement 101080142

Funded by the European Union

Any questions?

"Those who are not shocked when they first come across quantum theory, cannot possibly have understood it"

- Niels Bohr, 1952



ANTWERP

Exploring novel directions for Quantum Computation

Yasser Omar

PQI – Portuguese Quantum Institute & IST, ULisbon

Exploring novel directions for Quantum Computation

Yasser Omar

contact.yasser@pqi.pt

PQI – Portuguese Quantum Institute

DM, Instituto Superior Técnico, Universidade de Lisboa

Physics of Information and Quantum Technologies Group, CeFEMA

Academia das Ciências de Lisboa

PORTUGUESE QUANTUM INSTITUTE

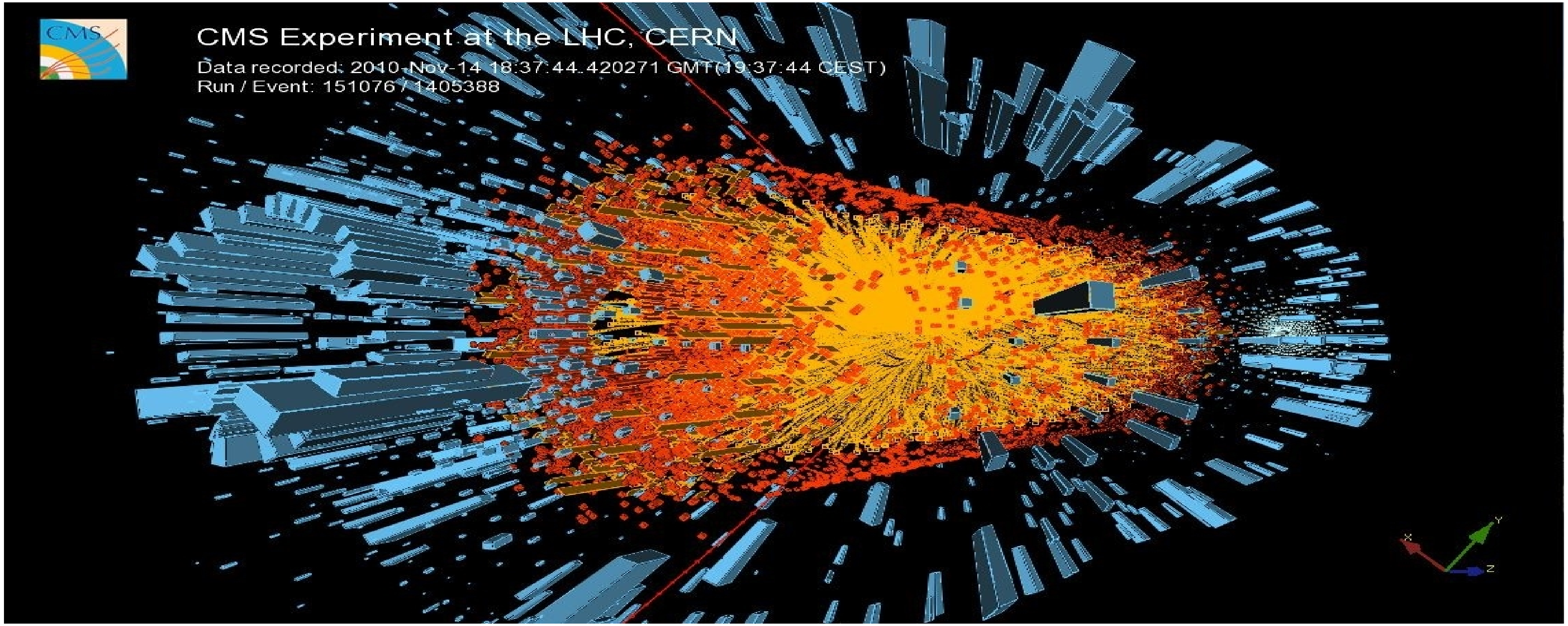
TÉCNICO LISBOA

CeFEMA
Center of Physics and Engineering of Advanced Materials

ACADEMIA DAS CIÊNCIAS DE LISBOA

I. High-Energy Physics

Quantum Computation for High-Energy Physics



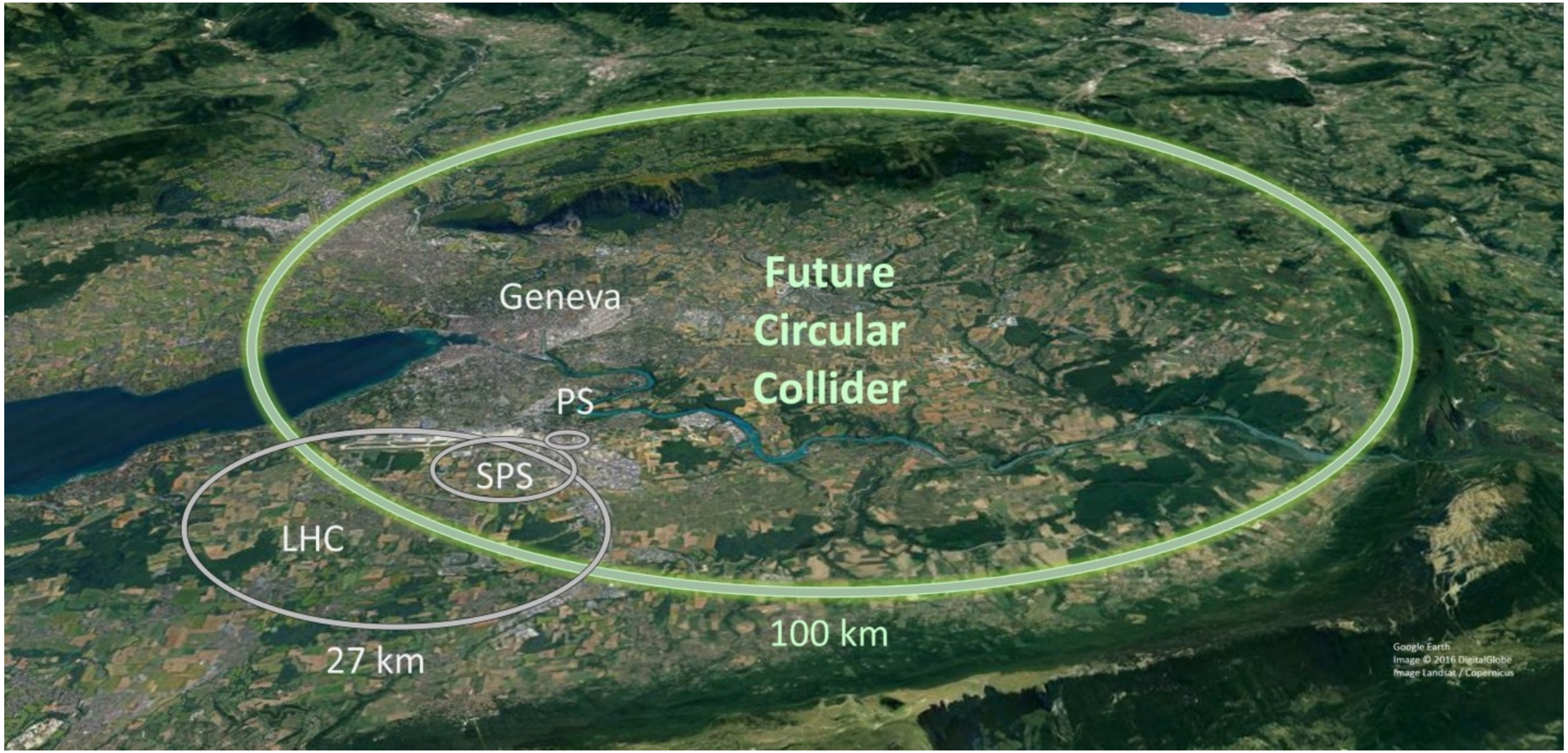
QuantHEP

QuantHEP – Quantum Computing Solutions for High-Energy Physics

QuantERA project, 2020-2023

QUANTERA

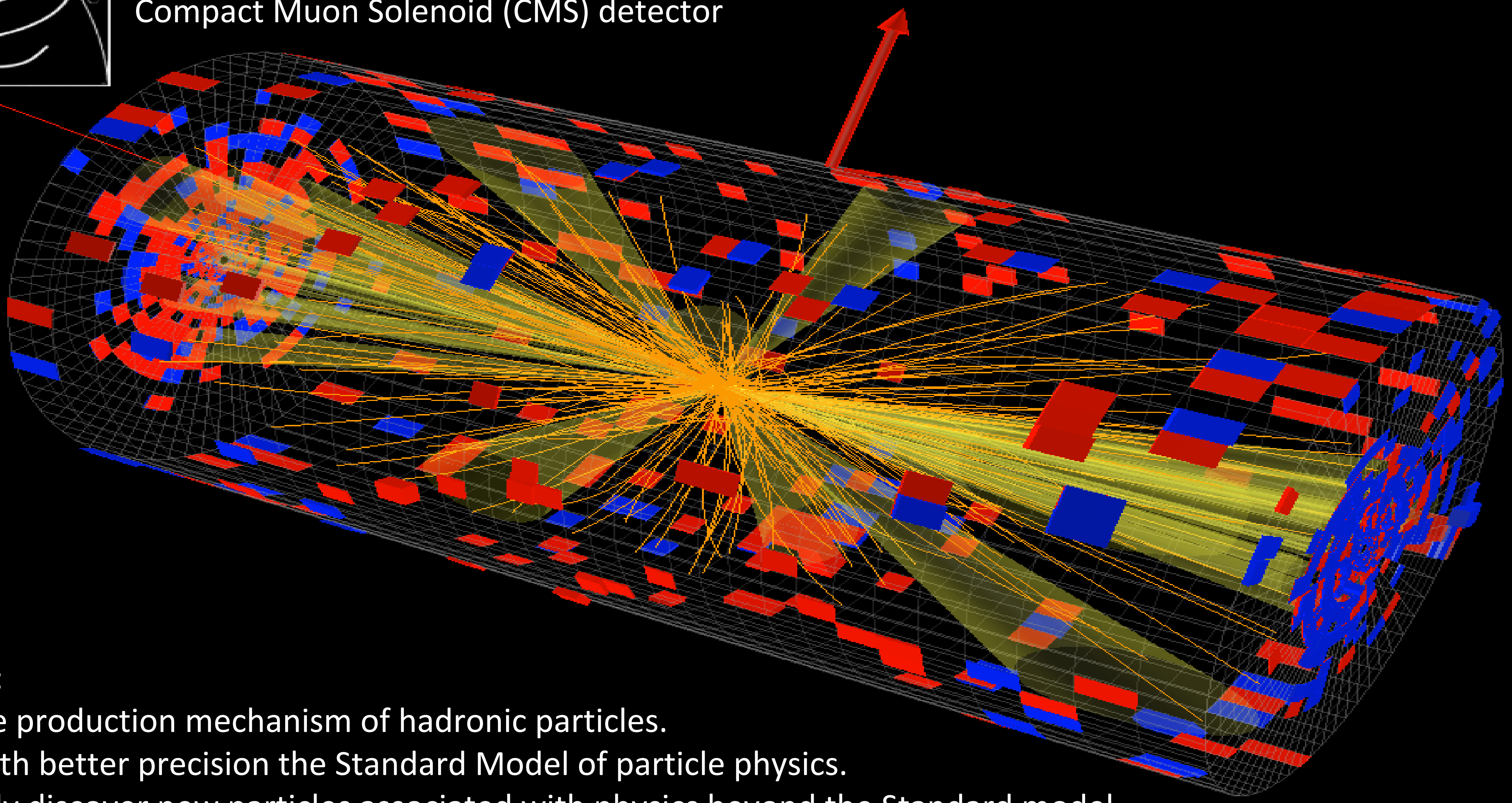
Colliding particles to understand Nature



Proton-proton collisions at the Large Hadron Collider (LHC) at CERN now.
Future: High-Luminosity LHC (HL-LHC) in 2027, Future Circular Collider (FCC)?

CMS Experiment at LHC, CERN
Data recorded: Thu Apr 5 01:18:00 2012 CEST
Run/Event: 190389 / 107592030
Lumi section: 138

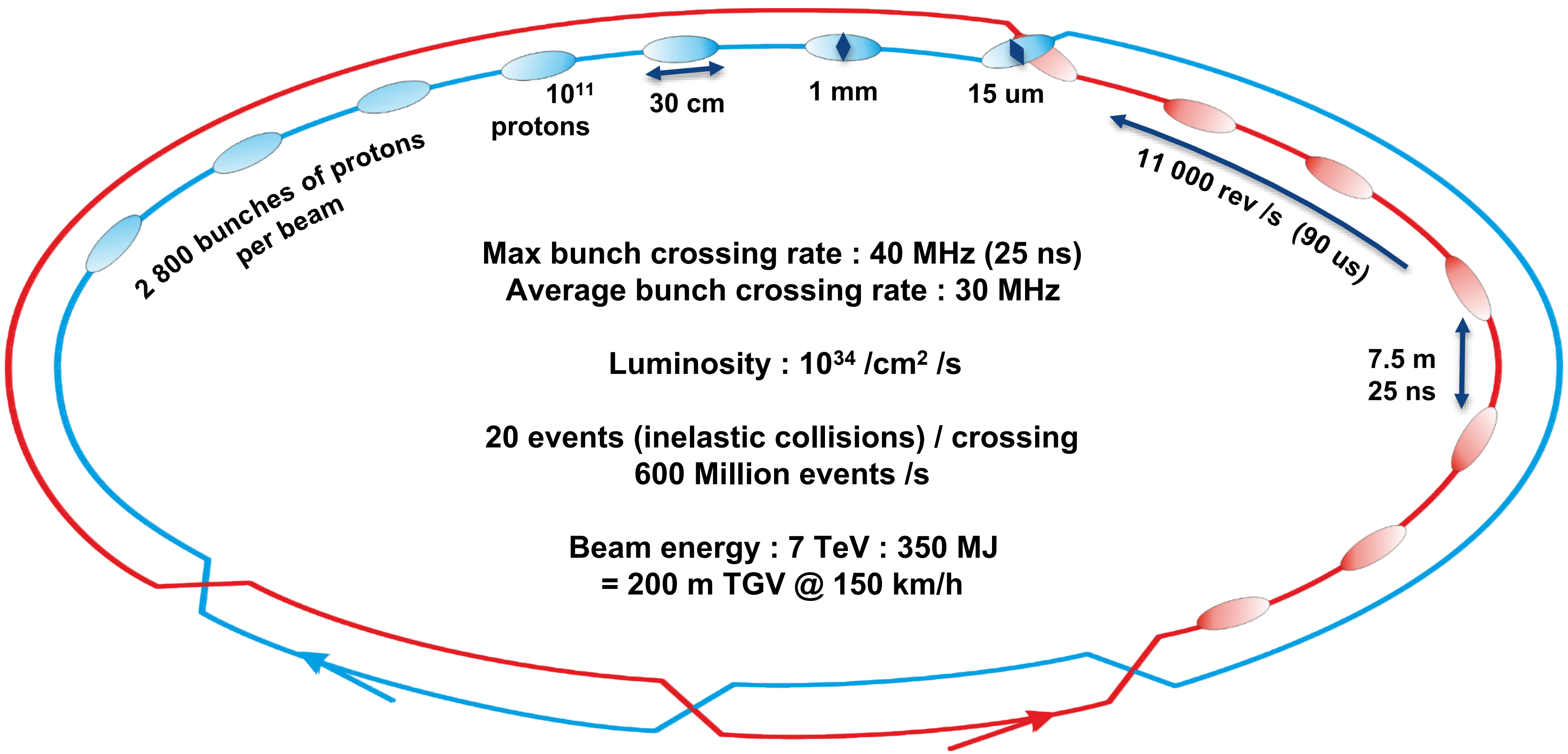
Compact Muon Solenoid (CMS) detector



Collisions to:

- unveil the production mechanism of hadronic particles.
- to test with better precision the Standard Model of particle physics.
- to possibly discover new particles associated with physics beyond the Standard model.

Colliding 10^{11} protons every 25 ns at LHC



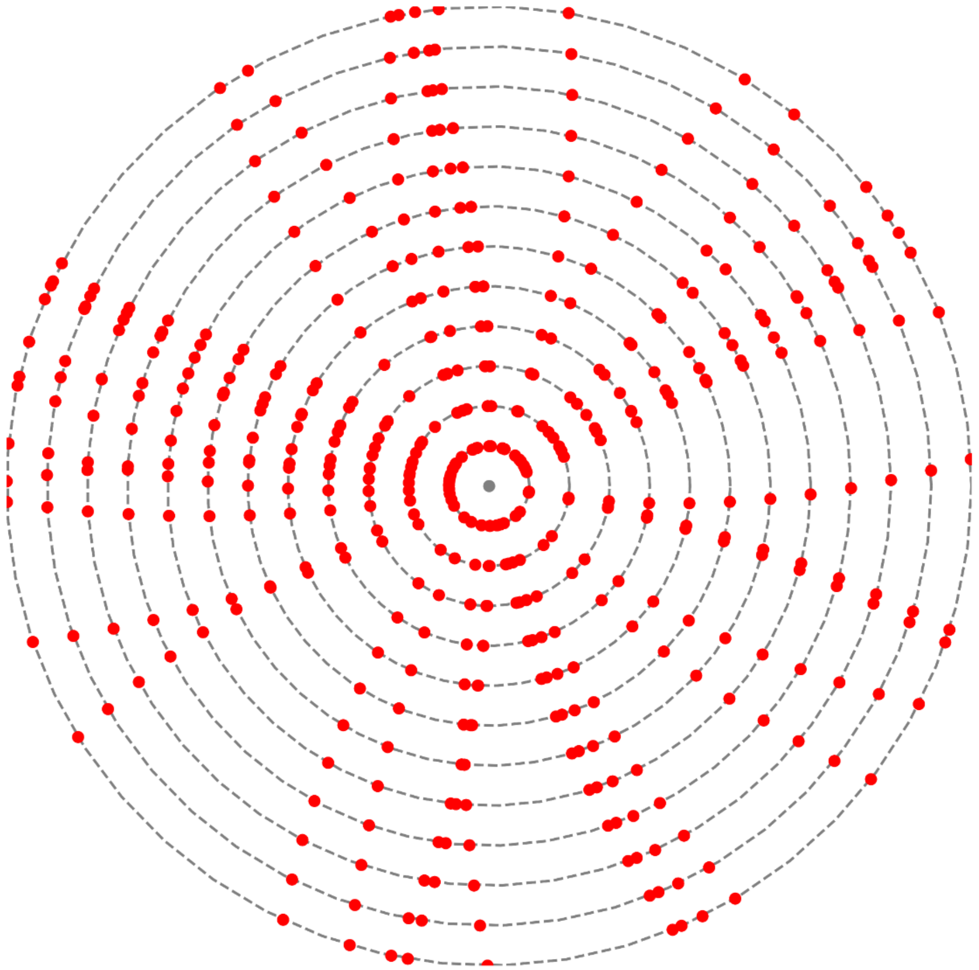
Precision measurements and search for rare events require statistical precision.

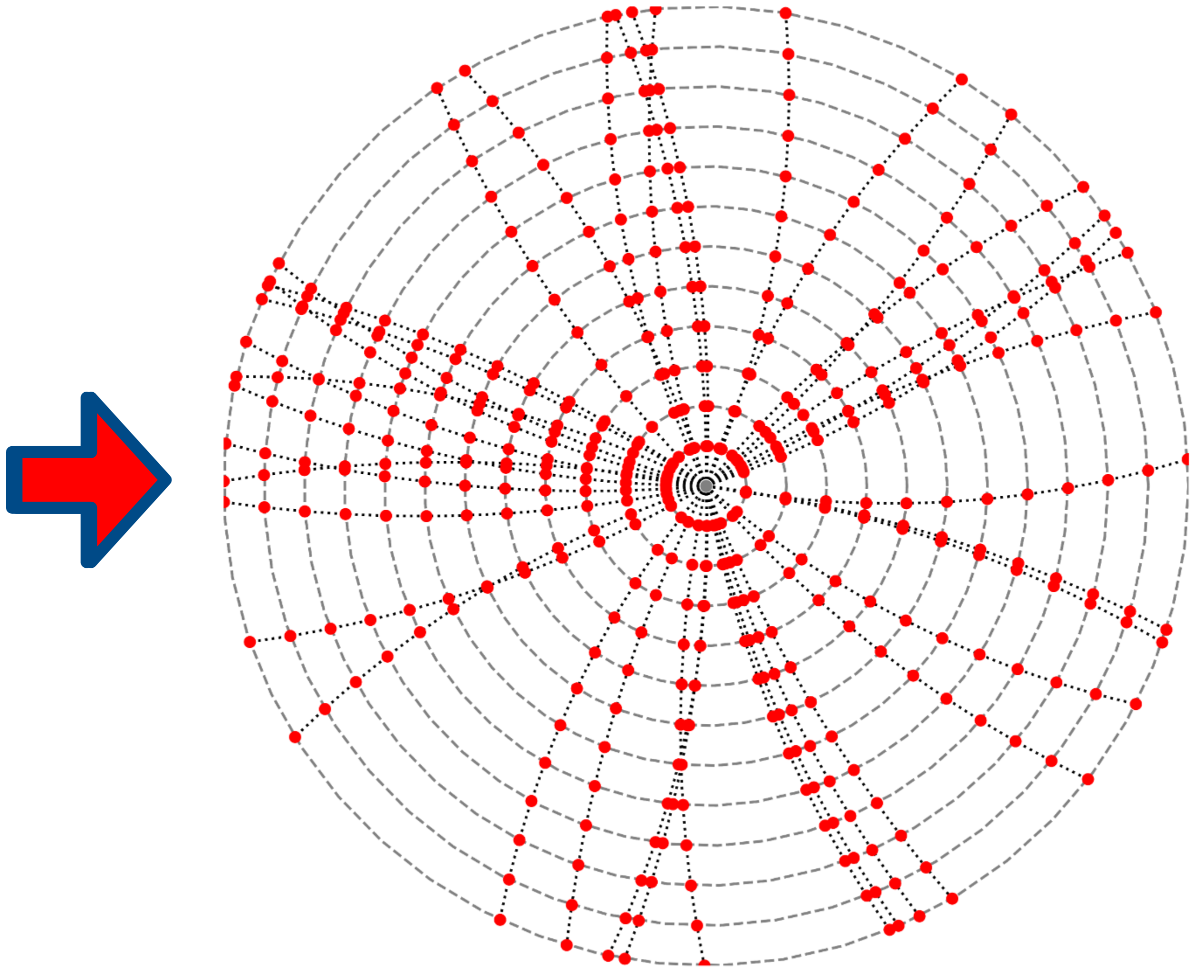
The LHC beam is constituted by 2800 *bunches* separated by a time interval of 25 ns.

The detected tracks are helicoidal in the magnetic field of the detector (if field uniform).

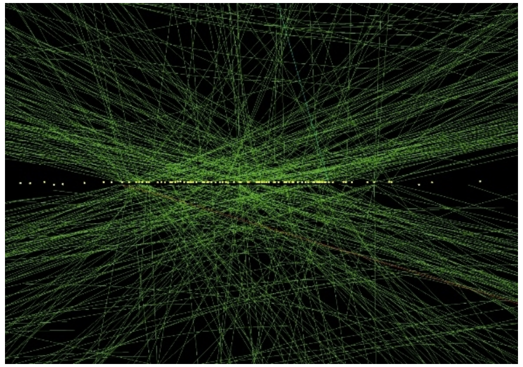
Detector: 3D picture every 25 ns, i.e. 40×10^6 pictures/s. But only 10^3/s are recorded, 100 Tb/s.

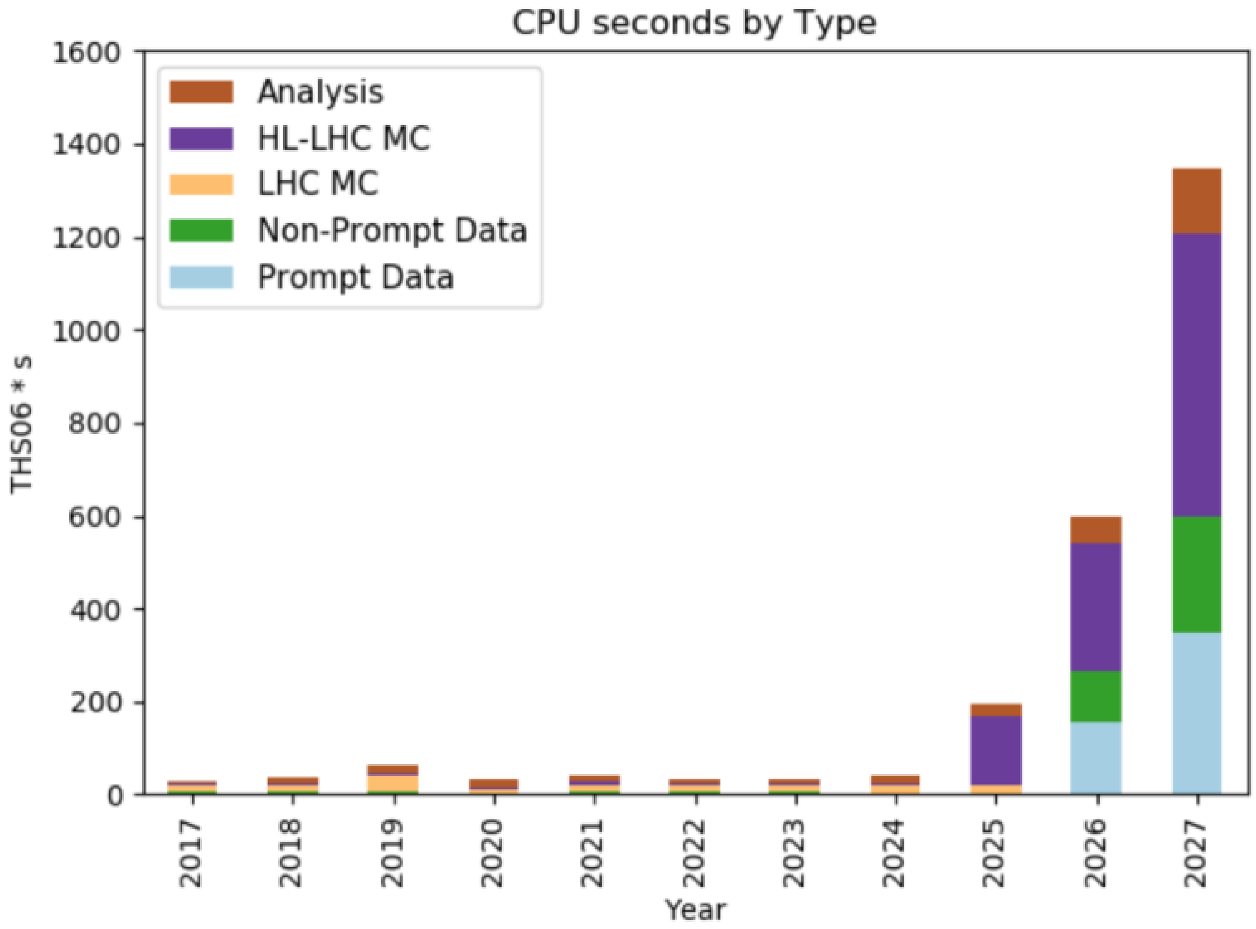
The Tracking Problem

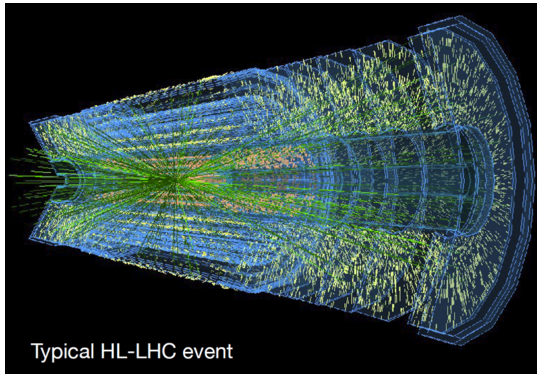




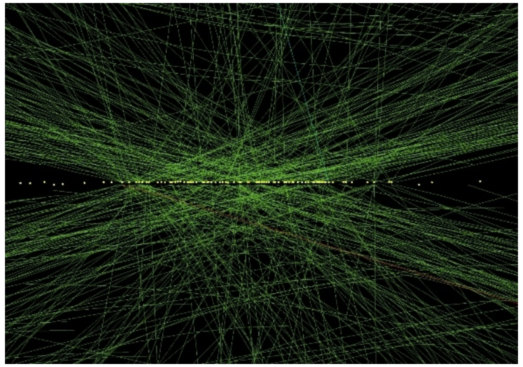
Tracking: a challenging computational problem

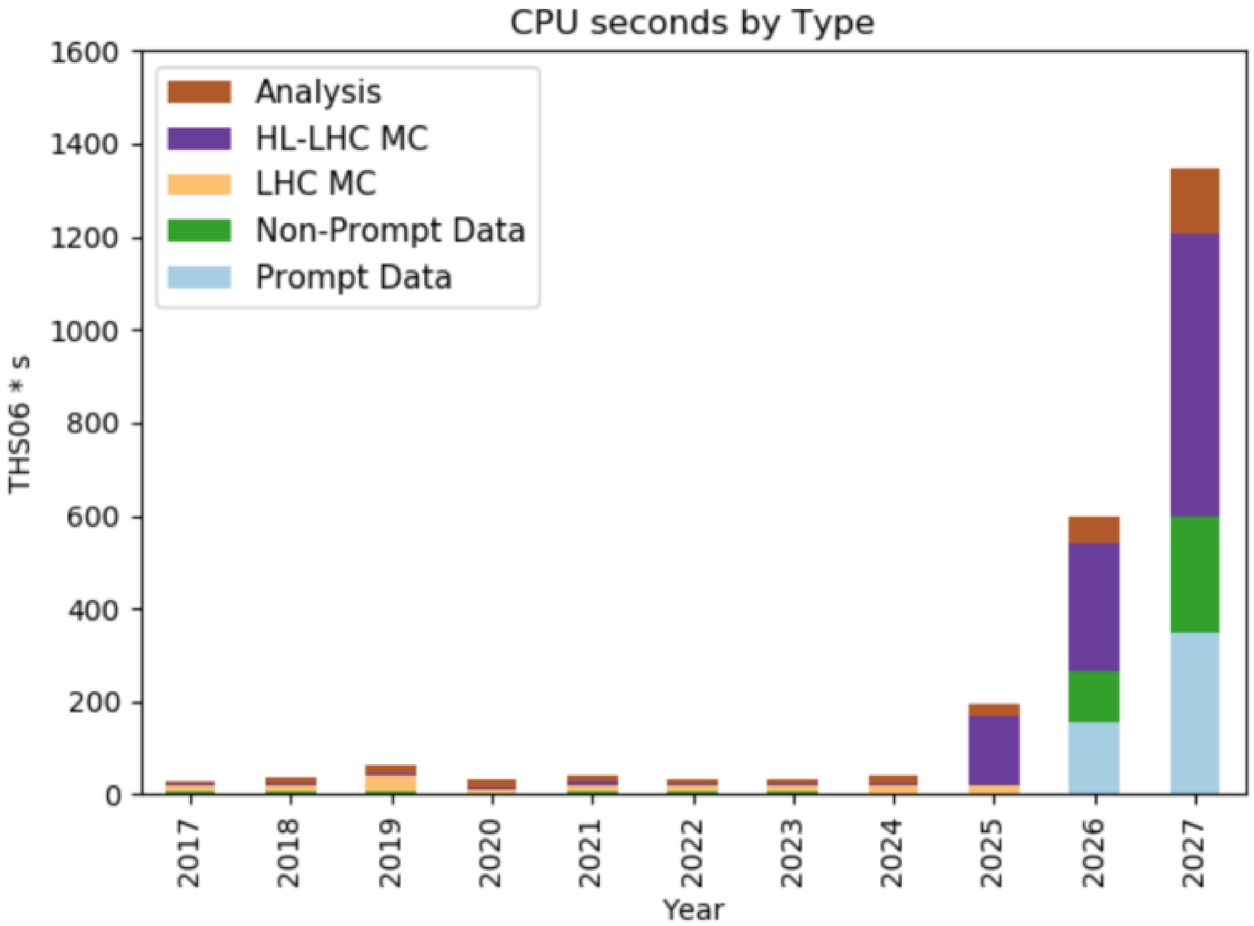


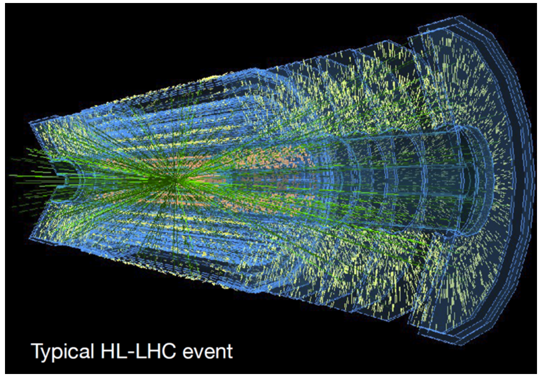




Tracking: a challenging computational problem







If computational performance does not meet the increasing demand, in HL-LHC or in the 100 TeV potential FCC, an immense amount of data will have to be discarded, significantly reducing the chances of observing rare events!

First proven quantum speedup for a HEP problem

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Highlights Recent Accepted Collections Authors Referees Search Press About Editorial Team

Quantum speedup for track reconstruction in particle accelerators

D. Magano, A. Kumar, M. Kālis, A. Locāns, A. Glos, S. Pratapsi, G. Quinta, M. Dimitrijevs, A. Rivošs, P. Bargassa, J. Seixas, A. Ambainis, and Y. Omar

Phys. Rev. D **105**, 076012 – Published 19 April 2022

13

More

Article | References | Citing Articles (3) | PDF | HTML | Export Citation

Given *n* particles/tracks:

Track Cleaning: $O(n^6) \rightarrow O(n^3 \log n)$ Our classical improvement, by complexity analysis!

Track Finding: $O(n^4) \rightarrow O(n^{3.5})$ Quantum speedup.

Jet Clustering

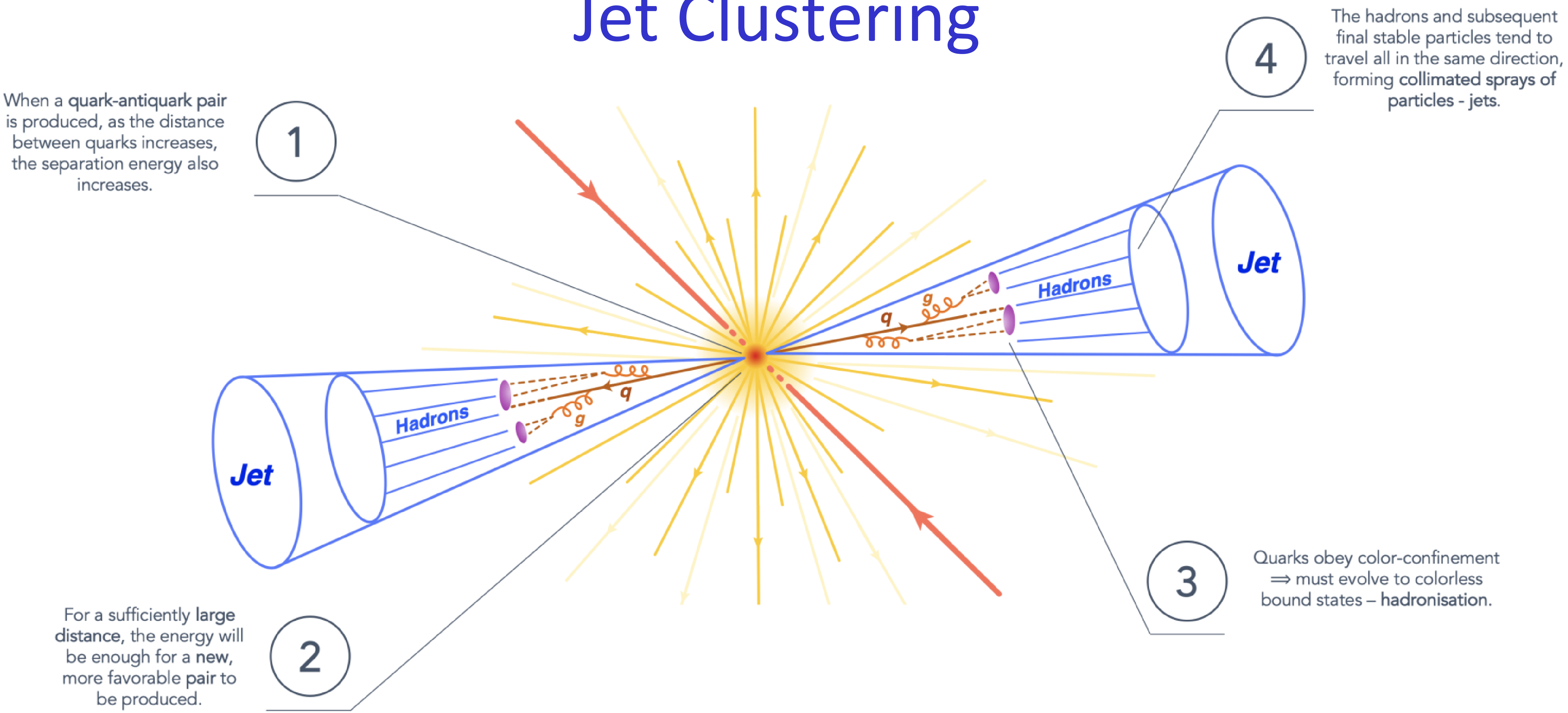


Figure 1. Example of a Dijet event (*e.g.* from an e^+e^- collision), where a quark-antiquark pair is produced, later giving origin to colorless bound states through hadronisation, and resulting in two back-to-back jets.

Physics Letters B 843 (2023) 138000

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Adiabatic quantum algorithm for multijet clustering in high energy physics

Diogo Pires [a], Yasser Omar [a,b], João Seixas [a,c,*]

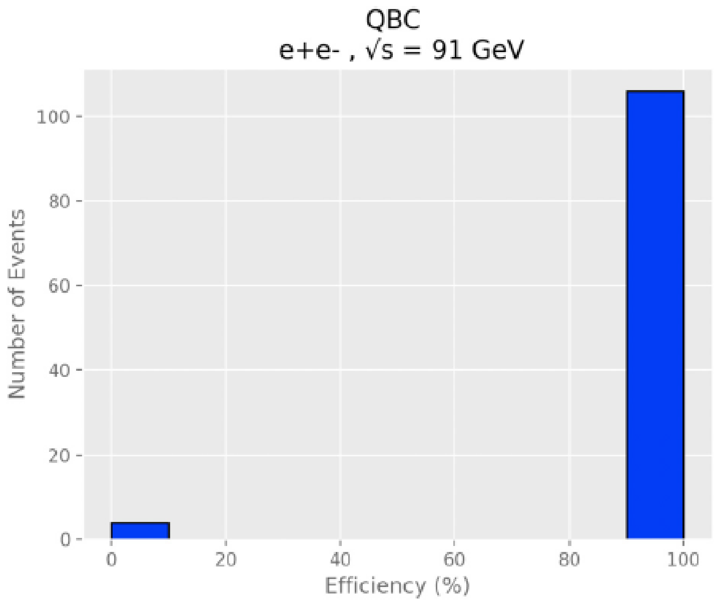


Fig. 1. Histogram of the obtained efficiency for the proposed quantum binary clustering algorithm, ϵ_{QBC}.

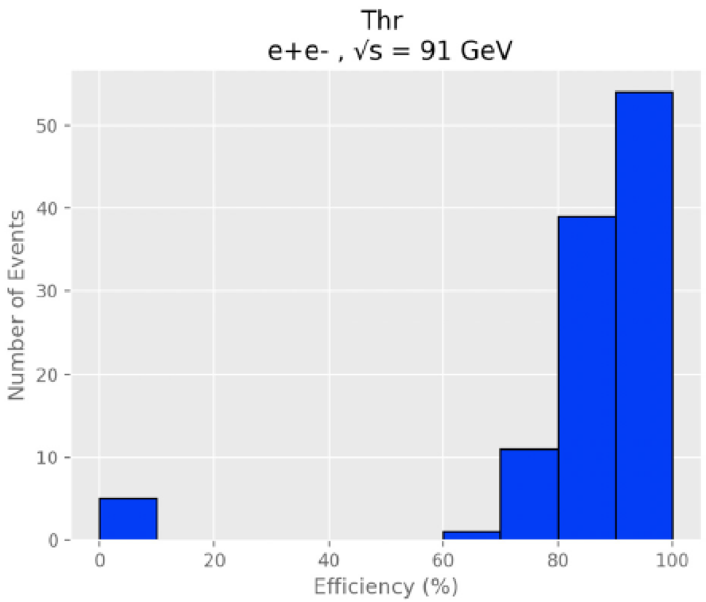


Fig. 2. Histogram of the obtained efficiency for the Thrust-based algorithm by Wei et al. [3], ϵ_{Thr}.

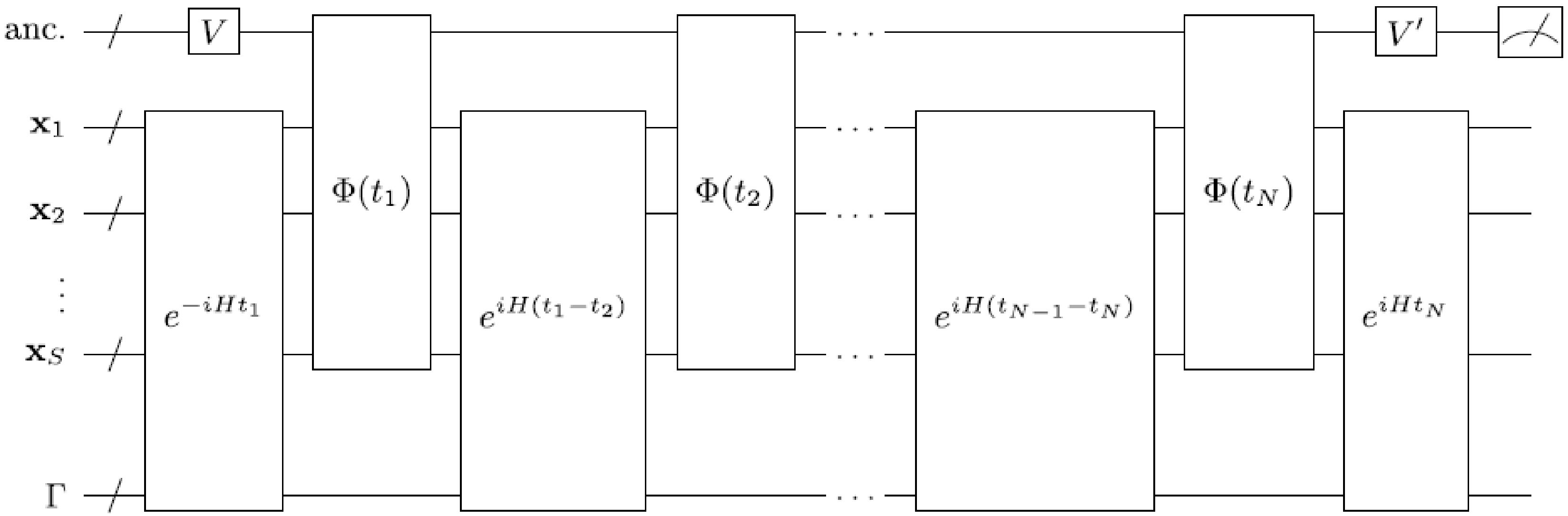
arXiv > quant-ph > arXiv:2305.07692

Quantum Physics

[Submitted on 12 May 2023 (v1), last revised 14 Nov 2023 (this version, v2)]

Towards Quantum Simulation of Bound States Scattering

Matteo Turco, Gonçalo M. Quinta, João Seixas, Yasser Omar

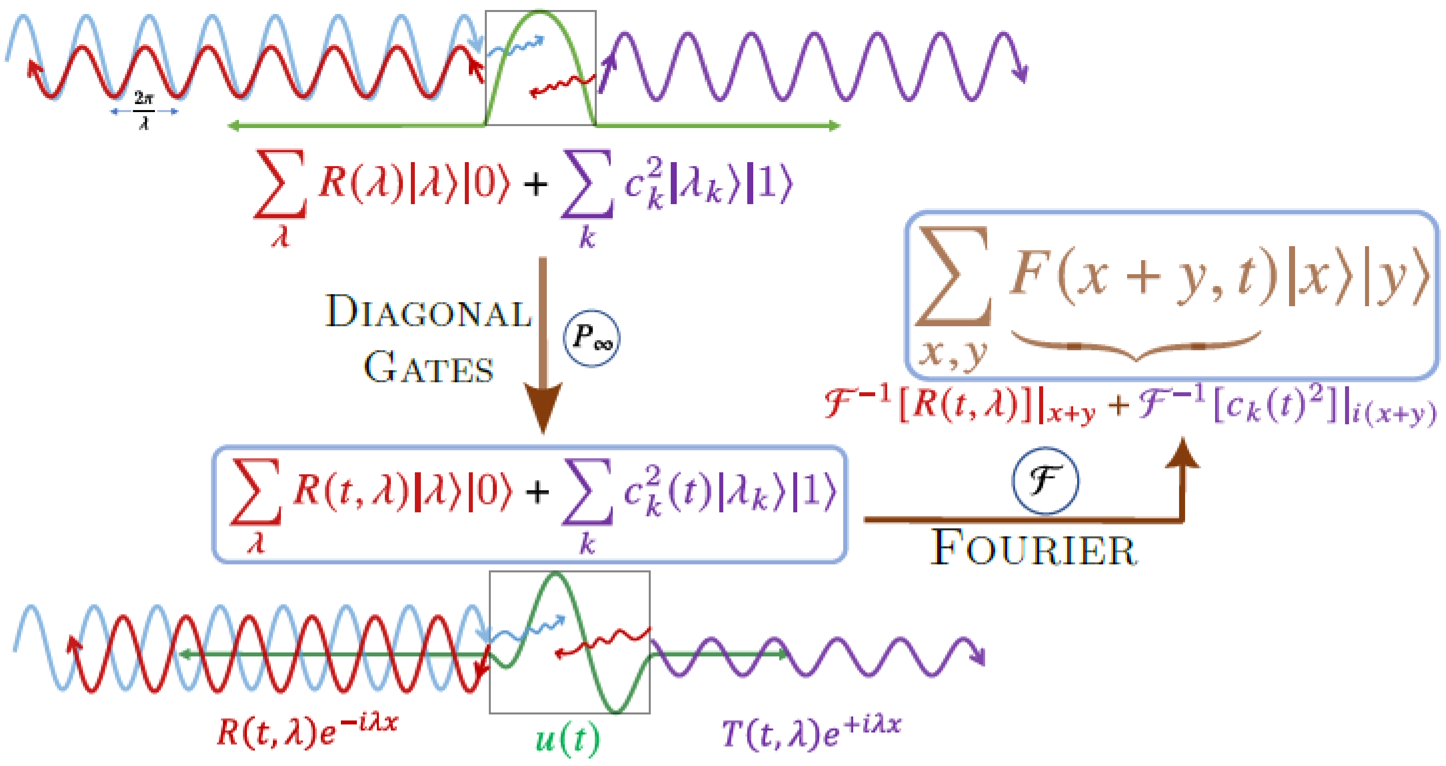


Preparation of composite particles: an important novelty in the context of q. sim. of scattering.

Accepted for publication in PRX Quantum (2024).

II. Plasma Physics

Quantum Algorithm for Korteweg–de Vries Equation



Joint work with D. Cruz, A. Kumar, N. F. Loureiro.

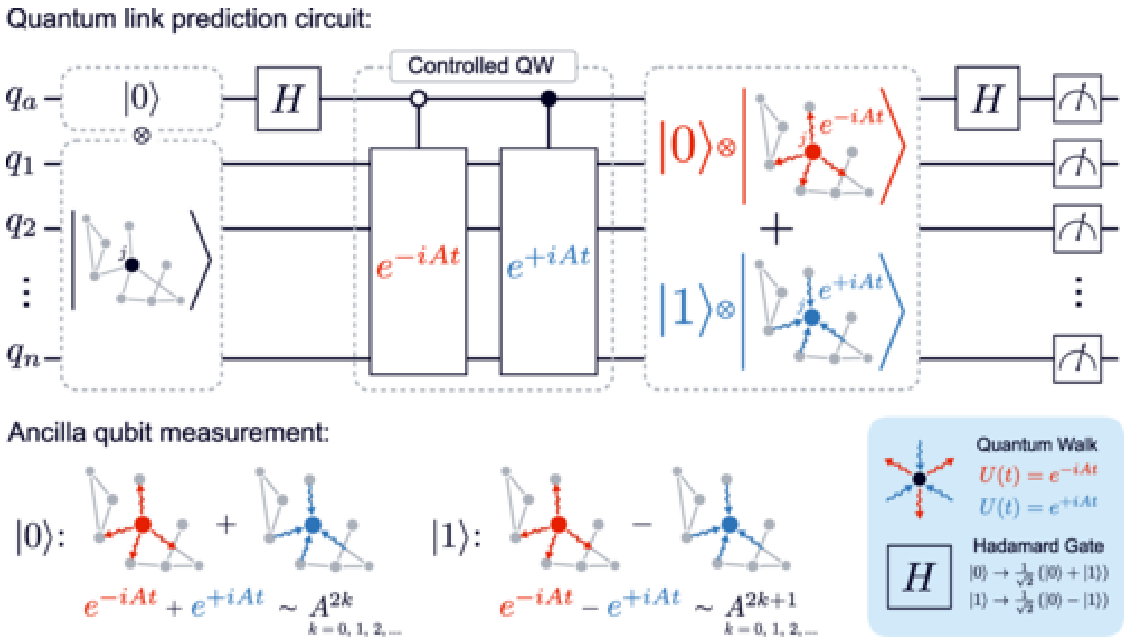
To appear soon!

III. Complex Networks

PHYSICAL REVIEW A
covering atomic, molecular, and optical physics and quantum information

Quantum link prediction in complex networks

João P. Moutinho, André Melo, Bruno Coutinho, István A. Kovács, and Yasser Omar
Phys. Rev. A **107**, 032605 – Published 10 March 2023



Potential speed-up afforded by quantum walks.

IV. Networking QPUs

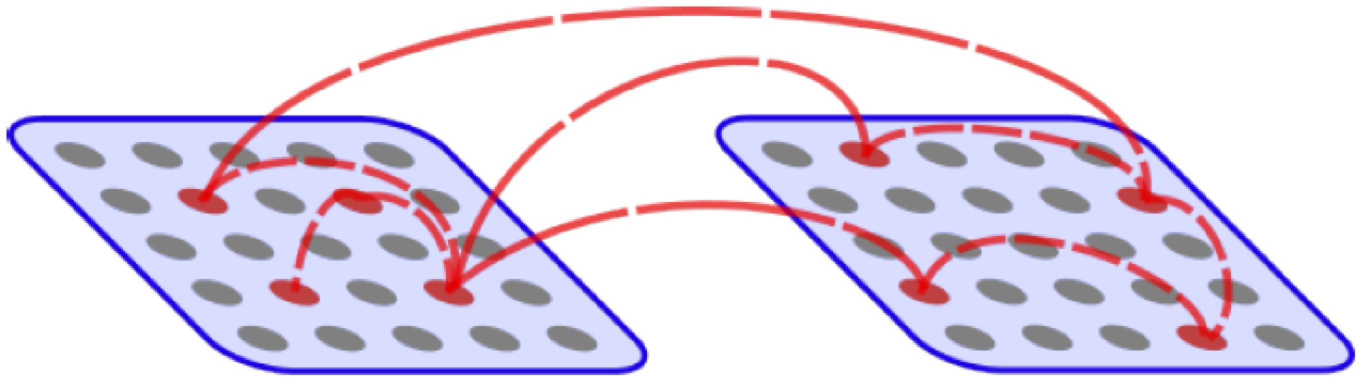
arXiv > quant-ph > arXiv:2212.02465

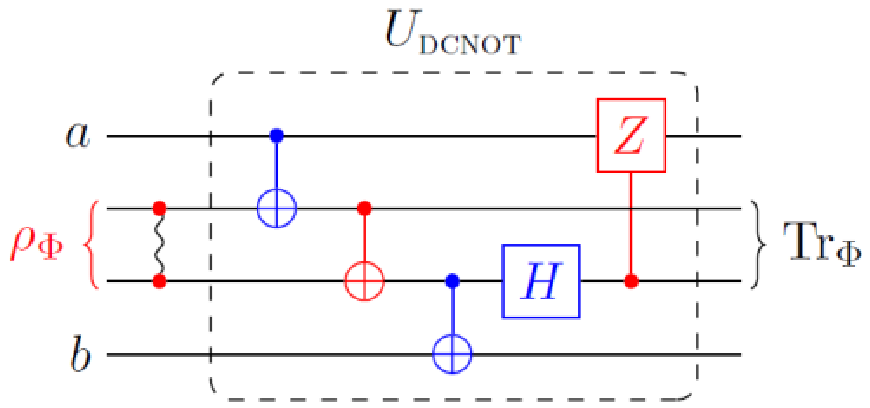
Quantum Physics

[Submitted on 5 Dec 2022]

A path towards distributed quantum annealing

Raúl Santos, Lorenzo Buffoni, Yasser Omar





Non-local couplings to enhance connectivity inside, as well as between, processors.

V. Hybrid Quantum-Classical Computing

Hybridising Quantum and Classical Computing

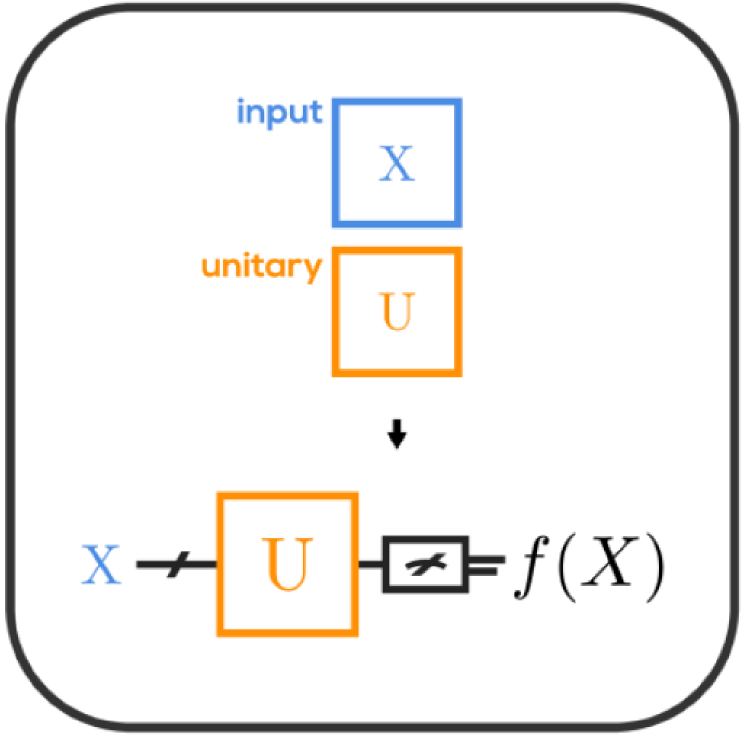
1. How to develop hybrid quantum-classical algorithms?
2. Why?
   - Because quantum processors are limited?
   - Because classical supercomputers are limited?
3. For which applications?
4. How do hybrid algorithms perform?
5. How to implement them?

Hybridising Quantum and Classical Computing

1. **How to develop hybrid quantum-classical algorithms?**
2. Why?
   - Because quantum processors are limited?
   - Because classical supercomputers are limited?
3. For which applications?
4. **How do hybrid algorithms perform?**
5. How to implement them?

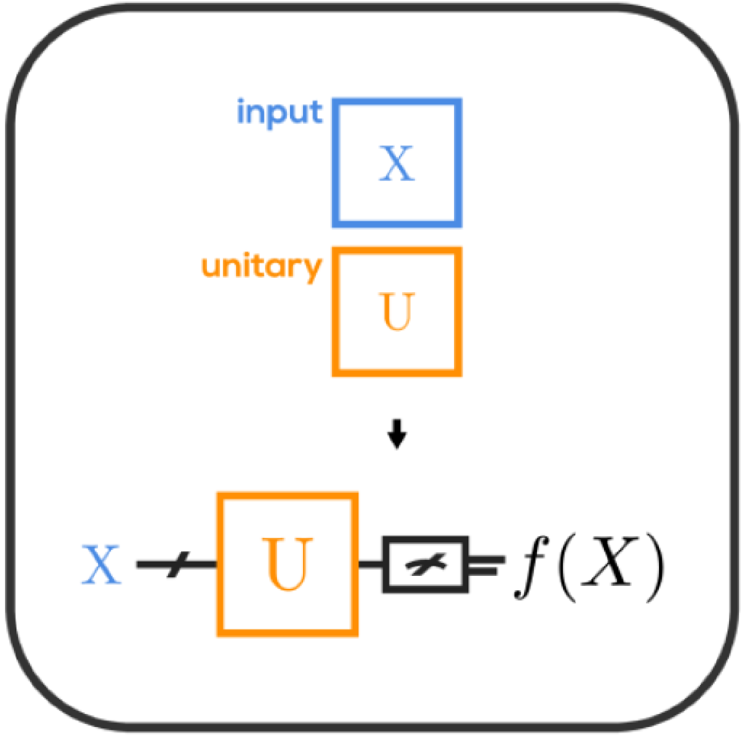
Two methods to break down a quantum algorithm

Quantum query algorithm:



Two methods to break down a quantum algorithm

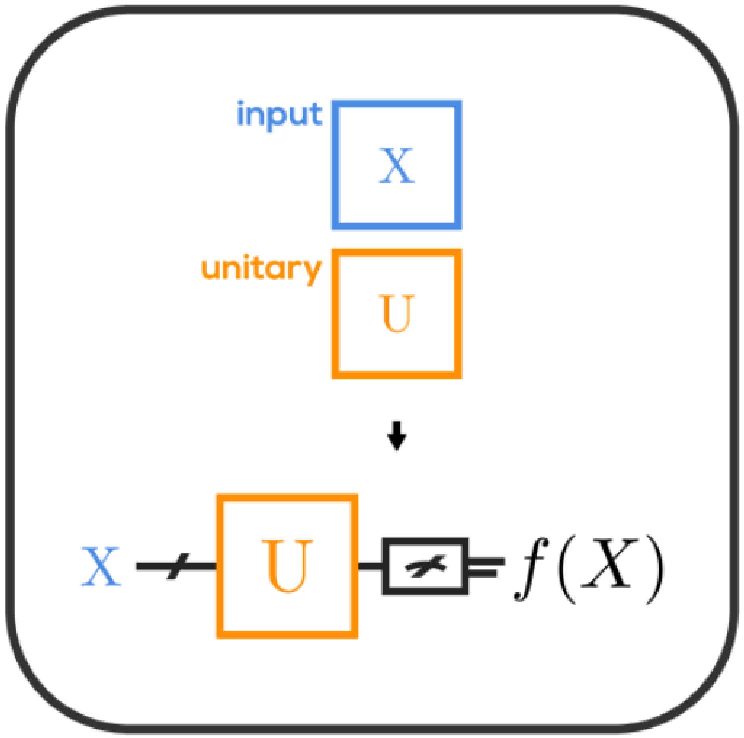
Quantum query algorithm:



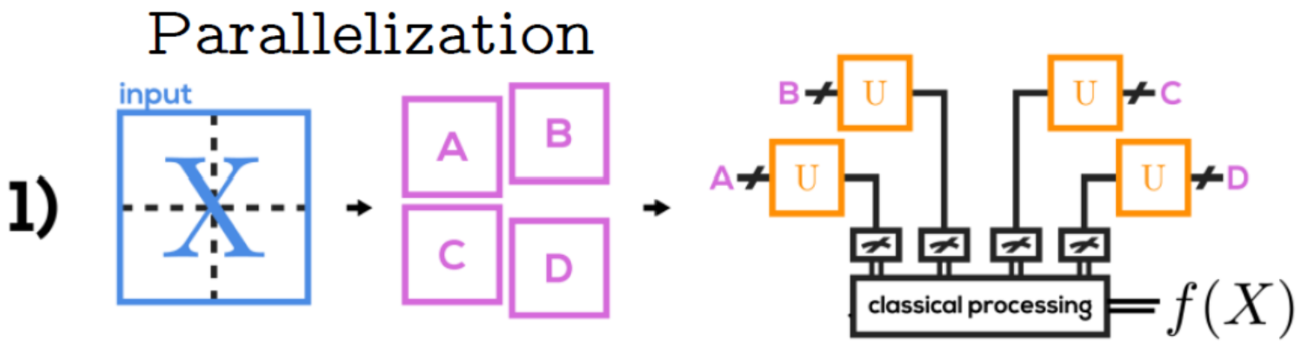
Oh no! Requires large circuit depth:
many coherent quantum queries!

Two methods to break down a quantum algorithm

Quantum query algorithm:



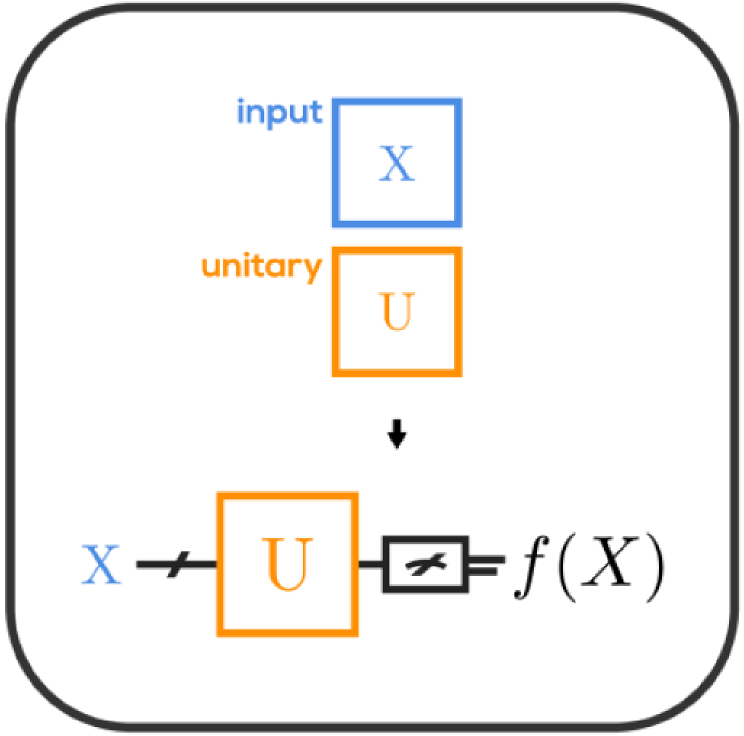
Oh no! Requires large circuit depth: many coherent quantum queries!



Partitions the input into smaller sub-problems

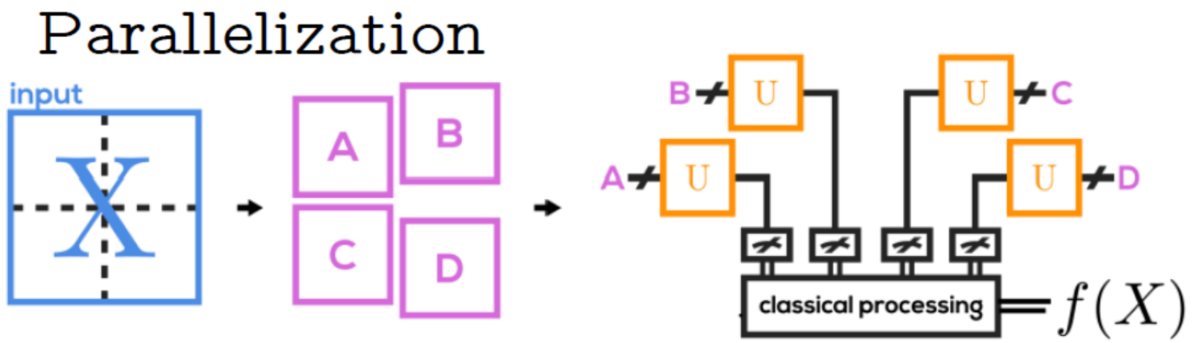
Two methods to break down a quantum algorithm

Quantum query algorithm:



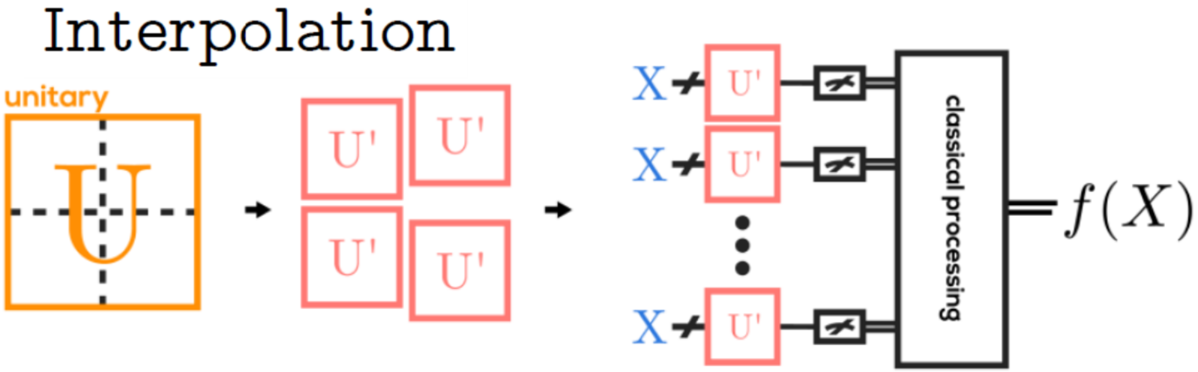
Oh no! Requires large circuit depth: many coherent quantum queries!

1)



Partitions the input into smaller sub-problems

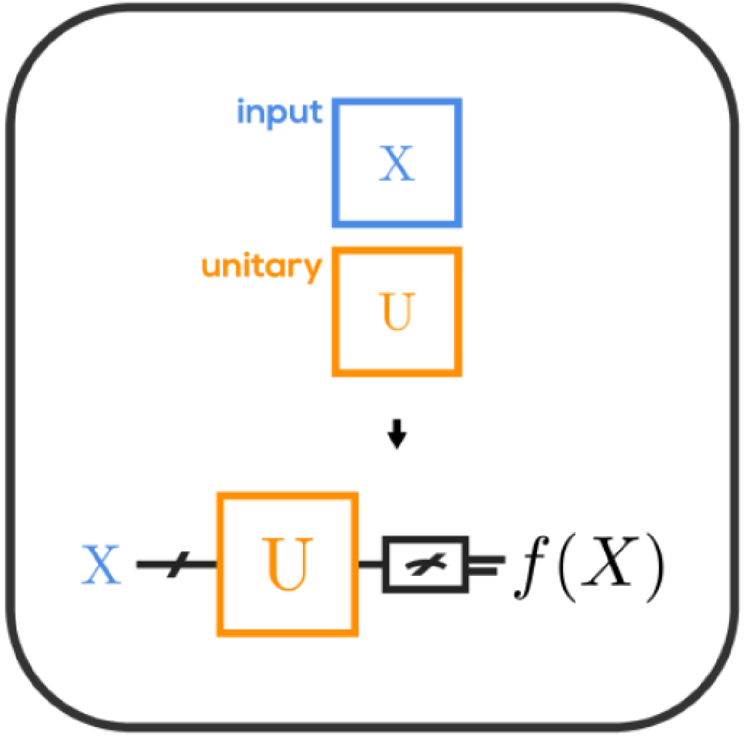
2)



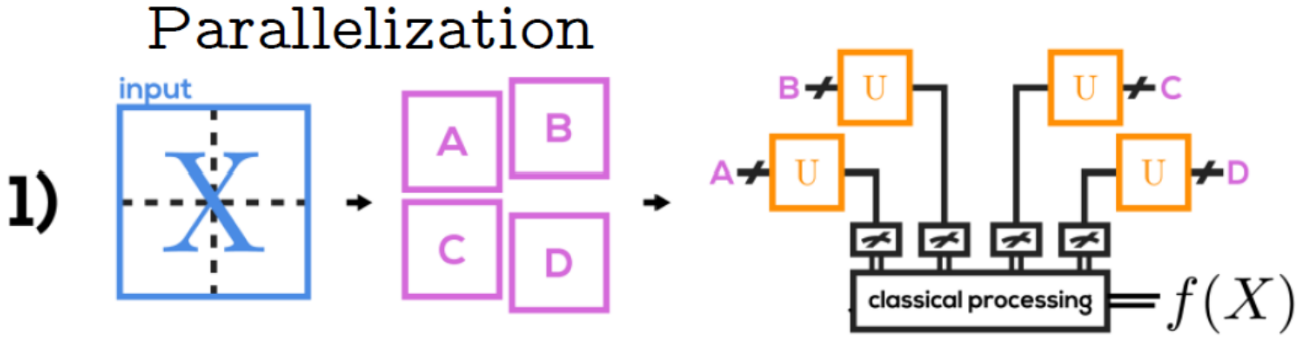
Repetitions of some U' that requires individually less coherent queries, but that collectively yields the same information as a single run of U.

Two methods to break down a quantum algorithm

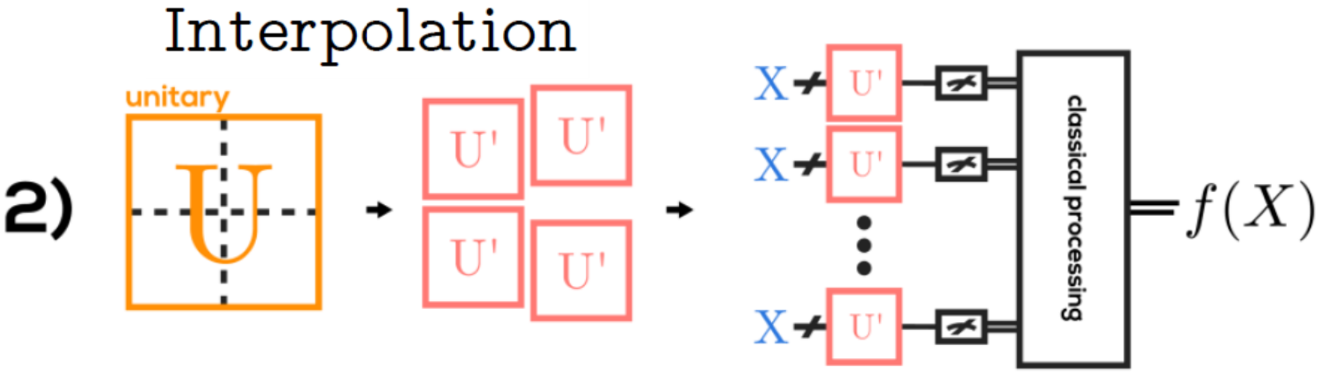
Quantum query algorithm:



Oh no! Requires large circuit depth: many coherent quantum queries!



Partitions the input into smaller sub-problems



Repetitions of some U' that requires individually less coherent queries, but that collectively yields the same information as a single run of U.

M. Murça, D. Magano, Y. Omar, **Making the cut: two methods for breaking down a quantum algorithm**, Physical Review A **109**, 022412 (2024).

PHYSICAL REVIEW A
covering atomic, molecular, and optical physics and quantum information

Two methods for breaking down a quantum algorithm

Miguel Murça, Duarte Magano, and Yasser Omar
Phys. Rev. A **109**, 022412 – Published 9 February 2024

ABSTRACT

Despite the promise that fault-tolerant quantum computers can efficiently solve classically intractable problems, it remains a major challenge to find quantum algorithms that may reach computational advantage in the present era of noisy, small-scale quantum hardware. Thus, there is a substantial ongoing effort to create new quantum algorithms (or adapt existing ones) to accommodate depth and space restrictions. By adopting a hybrid query perspective, we identify and characterize two methods of breaking down quantum algorithms into rounds of lower (query) depth, designating these approaches as "parallelization" and "interpolation." To the best of our knowledge, these had not been explicitly identified and compared side by side, although one can find instances of them in the literature. We apply them to two problems with known quantum speedup: calculating the k-threshold function and computing a NAND tree. We show that for the first problem parallelization offers the best performance, while for the second interpolation is the better choice. This illustrates that no approach is strictly better than the other, and that there is more than one good way to break down a quantum algorithm into a hybrid quantum-classical algorithm.

HQCC

Hybrid Quantum Classical Computation

Hybrid quantum-classical computing combines the power of quantum and classical processors to compute faster. This is of particular relevance in the current Noisy Intermediate-Scale Quantum (NISQ) computing era, when quantum processors are still very limited. Moreover, hybrid computing bears the strongest potential for reaching a practical quantum advantage, as it will take a long time before fault-tolerant quantum computers completely replace classical machines, if ever. For these reasons, hybrid quantum-classical architectures have taken center stage in the recent heuristic exploration of the potential of quantum computers. A rigorous framework is, however, painfully lacking to date. The goal of project HQCC is to put this important field onto solid theoretical footing.

We aim to address the fundamental questions about the power of hybrid computation:

– What problems are more amenable to the hybrid quantum-classical approach?
– With what algorithms can we solve them?
– What data structures and encodings perform better under this approach?
– Can we classify how hard these problems are in this context, namely can we define hybrid quantum-classical computational complexity classes?

Valsts izglītības attīstības aģentūra · DFG Deutsche Forschungsgemeinschaft · Nemzeti Kutatási, Fejlesztési és Innovációs Hivatal · FCT

Call topic

Quantum Phenomena and Resources

Start date

May 2022

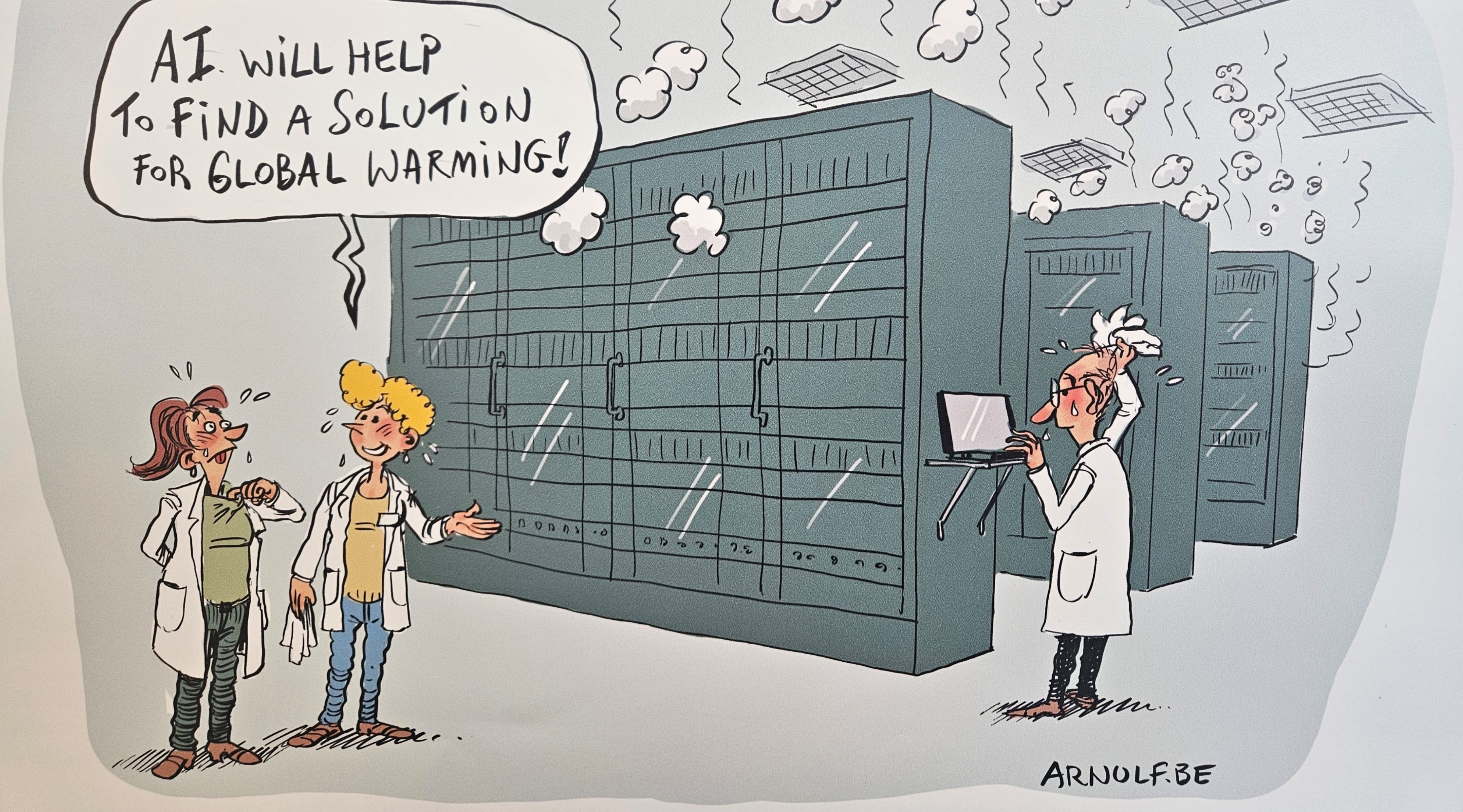
Duration

36 months

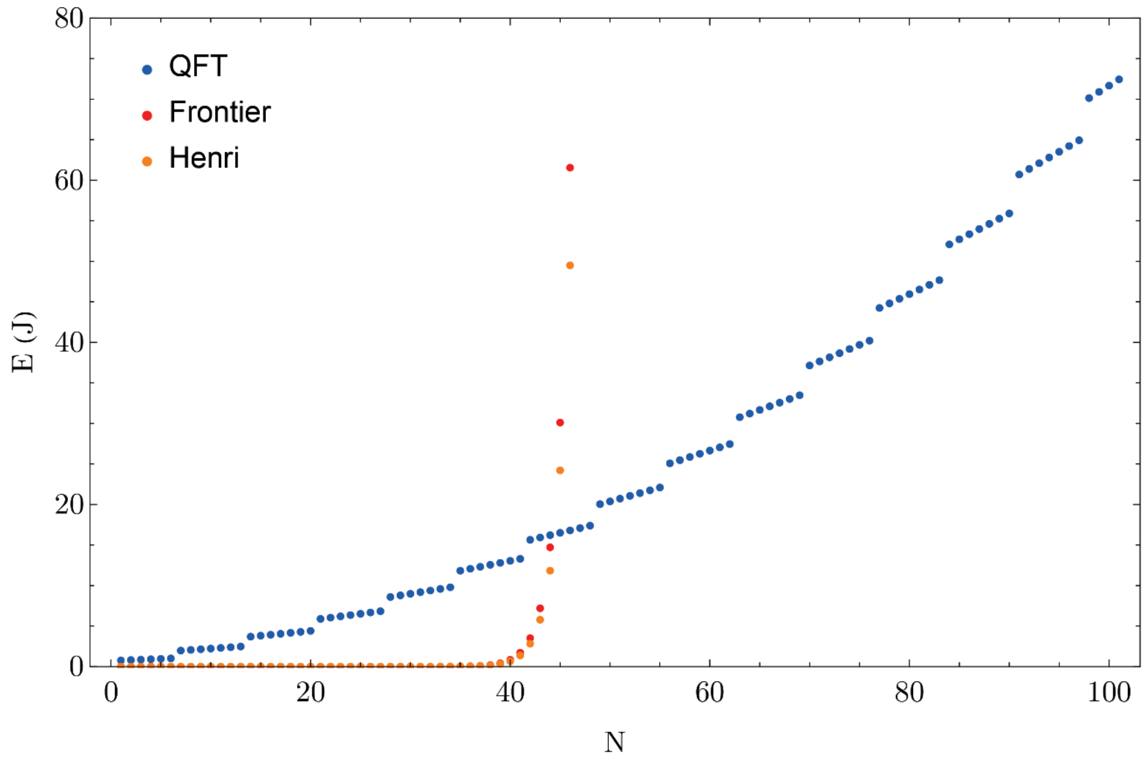
Funding support

€ 728 414

VI. Energetics of Quantum Computation


AI WILL HELP TO FIND A SOLUTION FOR GLOBAL WARMING!
ARNOLF.BE

Energetics of Fourier Transform on Trapped-ions QC



Estimated energy cost *E(J)* for increasing input size *N* of implementing the Quantum Fourier Transform on a trapped-ion quantum computer vs. the discrete Fourier Transform on the supercomputers Frontier and Henri.

F. Góis, M. Pezzutto, Y. Omar,
Energetics of Quantum Fourier Transform on a Trapped-ions Quantum Processor,
to appear soon.

Energetics of Quantum Computation

Additional results:

- *Quantum dynamics for energetic advantage in a charge-based classical full-adder*, PRX Energy **2**, 033002 (2023).
  Patent PT116602A (2023).

- *Classical Half-Adder using Trapped-ion Quantum Bits: Toward Energy-efficient Computation*, Applied Physics Letters **123**, 154003 (2023).

- *Low-Dissipation Data Bus via Coherent Quantum Dynamics*, Physical Review B 108, 075405 (2023).

Summary

Exploring novel directions for Quantum Computation:

1. High-Energy Physics
2. Plasma Physics
3. Network Problems
4. Networking Quantum Processors
5. Hybrid Quantum-Classical Computing
6. Energetics of Quantum Computation

PORTUGUESE QUANTUM INSTITUTE

TÉCNICO LISBOA

EQSI.org

PQC
PORTUGUESE QUANTUM INSTITUTE
QMATH
QuSoft Research Center for Quantum Software
Technical University of Munich TUM
Quantum Computing at the University of Latvia

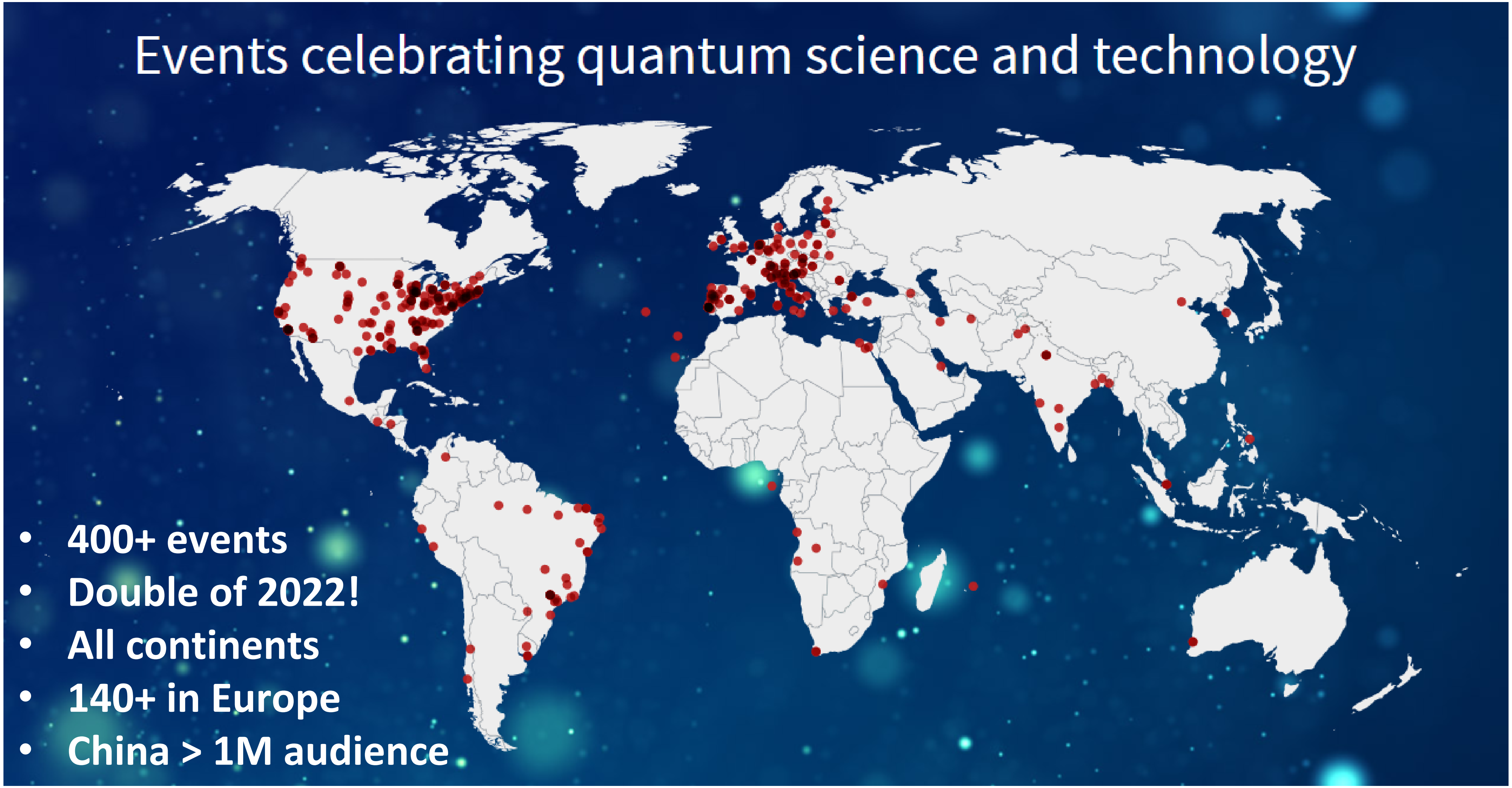
Join the 2024 edition of the World Quantum Day!

worldquantumday.org

@WorldQuantumDay

WORLD QUANTUM DAY APRIL 14

World Quantum Day 2023: some numbers and examples



worldquantumday.org

@WorldQuantumDay

For more information, see below, or write to me: *contact.yasser@pqi.pt*

worldquantumday.org **@WorldQuantumDay**

EQTC, 18-20 November 2024, Lisbon, Portugal

European Quantum Technologies Conference

EQTC.eu

PORTUGUESE QUANTUM INSTITUTE

QUANTUM FLAGSHIP

Physics of Information & Quantum Technologies Group

We gratefully acknowledge the support from:

John Templeton Foundation

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

MARIE CURIE ACTIONS

"la Caixa" Foundation

cost

European Science Foundation

SEVENTH FRAMEWORK PROGRAMME

HORIZON 2020

QUANTUM FLAGSHIP

QUANTERA

Summary

Exploring novel directions for Quantum Computation:

1. High-Energy Physics
2. Plasma Physics
3. Network Problems
4. Networking Quantum Processors
5. Hybrid Quantum-Classical Computing
6. Energetics of Quantum Computation

PORTUGUESE QUANTUM INSTITUTE

TÉCNICO LISBOA

Exploring novel directions for Quantum Computation

Yasser Omar

contact.yasser@pqi.pt

PQI – Portuguese Quantum Institute

DM, Instituto Superior Técnico, Universidade de Lisboa

Physics of Information and Quantum Technologies Group, CeFEMA

Academia das Ciências de Lisboa

PORTUGUESE QUANTUM INSTITUTE

TÉCNICO LISBOA

CeFEMA
Center of Physics and Engineering of Advanced Materials

ACADEMIA DAS CIÊNCIAS DE LISBOA