

QUAI4EO

*Quantum computing for Earth
Observation and Particle Physics*



QUANTUM
TECHNOLOGY
INITIATIVE

Sofia Vallecorsa

CERN IT

June 27th, 2022

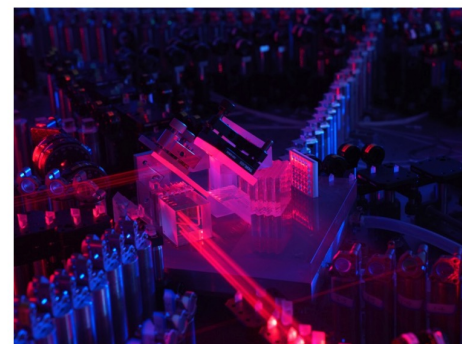
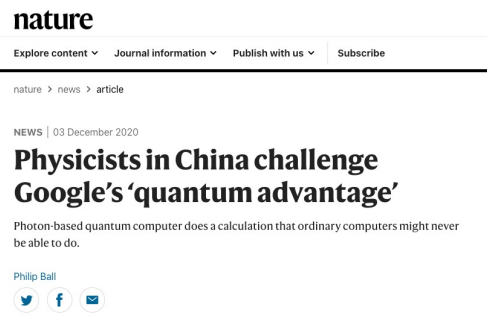
Quantum Computing: Hype and Potential

2019: Google



<https://www.nature.com/articles/s41586-019-1666-5>

2020: Hefei National Lab



This photonic computer performed in 200 seconds a calculation that on an ordinary supercomputer would take 2.5 billion years to complete. Credit: Hansen Zhong

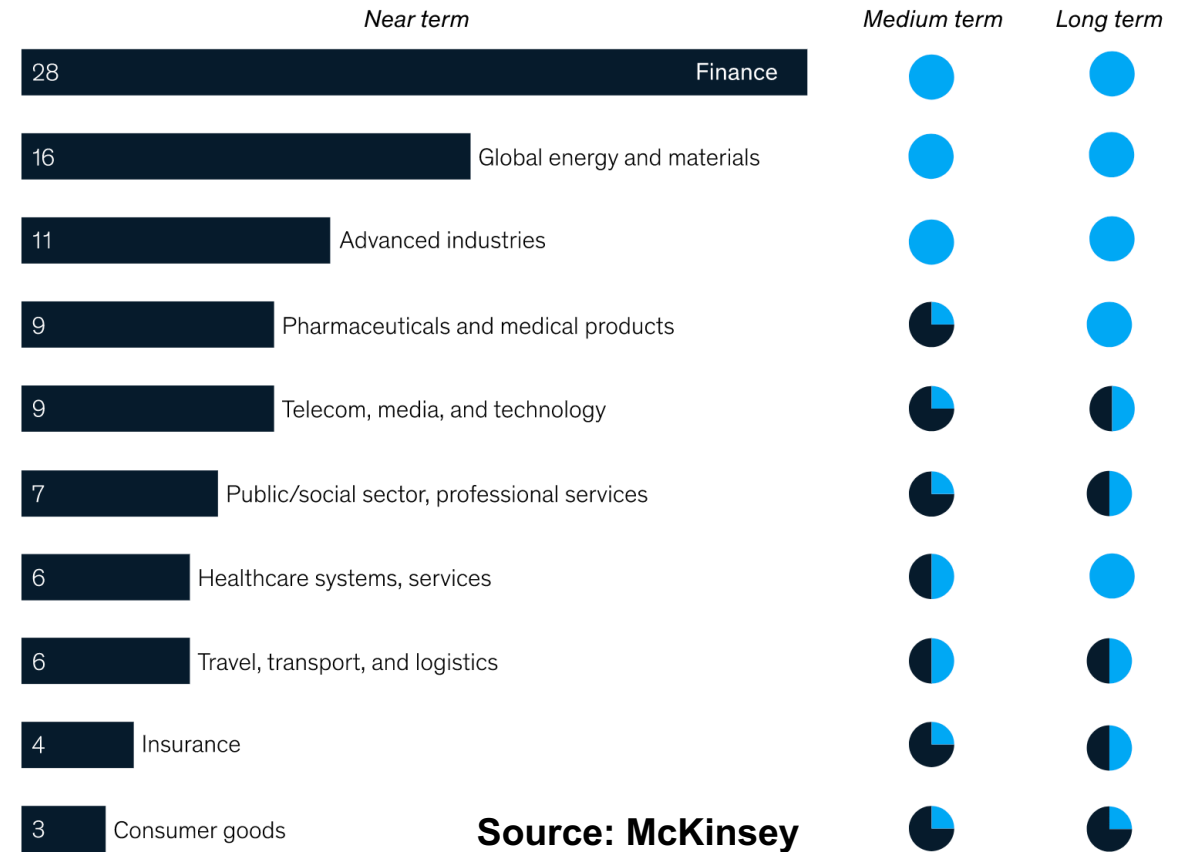
<https://www.nature.com/articles/d41586-020-03434-7>

Who could create value with quantum computing?

Distribution of quantum-computing use cases, 2019, %

Estimated value at stake¹

● High ● Medium ● Low



Source: McKinsey

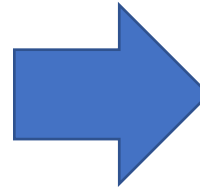
QC use cases in different sectors: the situation in 2019 with the estimated **medium** (2025) and **long** (2035) term impact.

Algorithms & Applications

Quantum effects (superposition entanglement, no-cloning theorem, ...)
improve and accelerate complex algorithms

- Efficient **sampling, searches** and **optimization**
- Linear algebra, matrices and machine learning
- New algorithms/methods for **cryptography** and **communication**

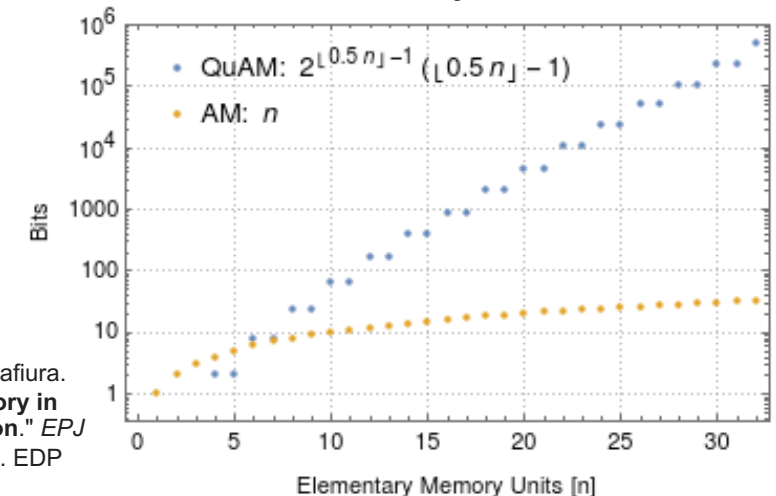
Challenge is re-thinking algorithms design and define fair benchmarking and comparison to classical algorithms



Many potential applications in High Energy Physics:

- Monte Carlo and Event Generation
- Quantum Simulation
- Pattern Recognition
- QML

Ex.: Exponential data compression with a Quantum Associative memory

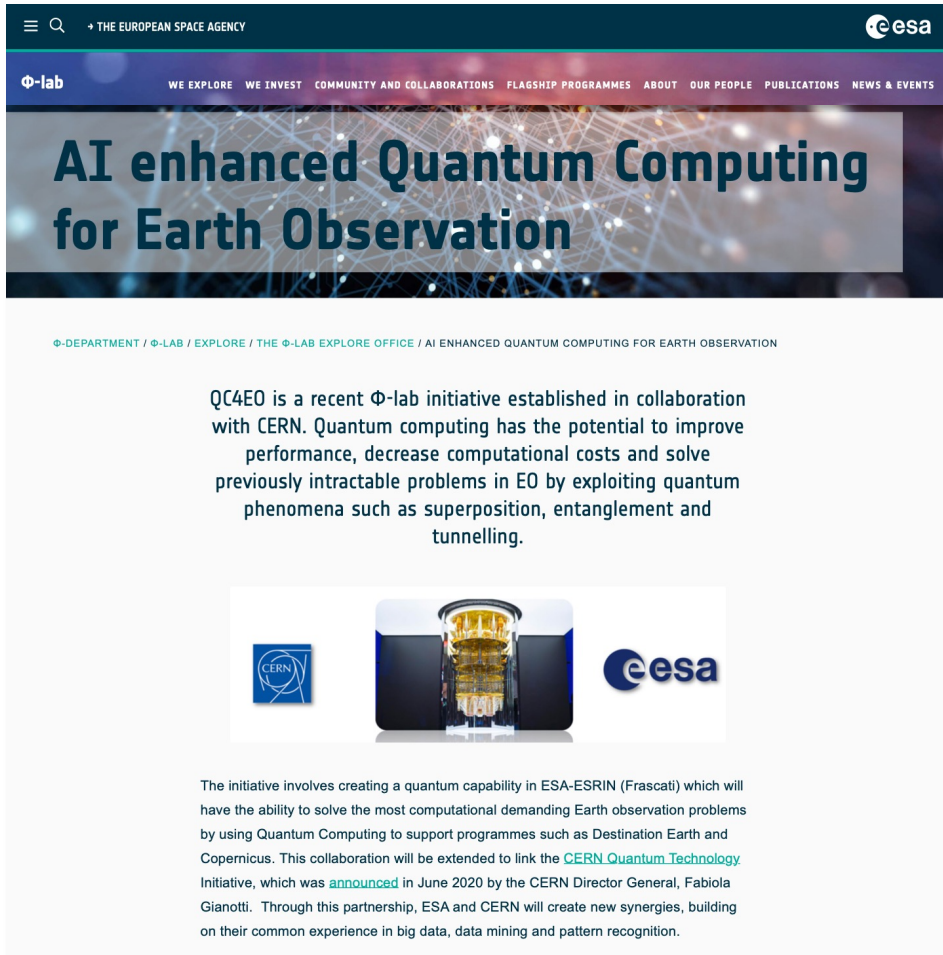



Shapoval, Iliya, and Paolo Calafiura. "Quantum associative memory in HEP track pattern recognition." *EPJ Web of Conferences*. Vol. 214. EDP Sciences, 2019

The ESA-CERN Cooperation Agreement

- ESA and CERN have in place a Collaboration Agreement since 2014 to explore common technologies and interests, such as hardware radiation hardening for particle detectors and spacecraft instruments
- Experiments like CLOUD are bridging the communities
- Cold Atom Technologies (CAT) are proposed as promising solutions for the Voyage 2050 programme
- **A collaboration on Artificial Intelligence and Quantum Computing has started in 2020**
- An initial programme of co-funded PhD-level research is in place since January 2021

The ESA-CERN Joint Announcement at Phi-Week 2020




☰ THE EUROPEAN SPACE AGENCY 

Φ-lab WE EXPLORE WE INVEST COMMUNITY AND COLLABORATIONS FLAGSHIP PROGRAMMES ABOUT OUR PEOPLE PUBLICATIONS NEWS & EVENTS

AI enhanced Quantum Computing for Earth Observation

Φ-DEPARTMENT / Φ-LAB / EXPLORE / THE Φ-LAB EXPLORE OFFICE / AI ENHANCED QUANTUM COMPUTING FOR EARTH OBSERVATION

QC4EO is a recent Φ-lab initiative established in collaboration with CERN. Quantum computing has the potential to improve performance, decrease computational costs and solve previously intractable problems in EO by exploiting quantum phenomena such as superposition, entanglement and tunnelling.



The initiative involves creating a quantum capability in ESA-ESRIN (Frascati) which will have the ability to solve the most computational demanding Earth observation problems by using Quantum Computing to support programmes such as Destination Earth and Copernicus. This collaboration will be extended to link the [CERN Quantum Technology Initiative](#), which was [announced](#) in June 2020 by the CERN Director General, Fabiola Gianotti. Through this partnership, ESA and CERN will create new synergies, building on their common experience in big data, data mining and pattern recognition.



Special announcement

Exploring the next frontiers of disruptive innovation



AI-enhanced Quantum Computing for EO

ESA UNCLASSIFIED – For Official Use



→ THE EUROPEAN SPACE AGENCY

Challenges and Opportunities in Earth Observation

- **Destination Earth**

- High precision digital model of the Earth
- Model, monitor and simulate natural phenomena and related human activities

- **Weather forecast and analysis**

- **Climate changes**

- **Natural disaster prediction / reaction**

Applications heavily relying on modelling complex dynamic systems regulated by (linear and non-linear) differential equations in high-dimensional spaces



QUAI4EO – QC Research

- Understand which EO applications can profit from quantum algorithms
 - Choose **representative use cases**
 - Understand **challenges and limitations** (on NISQ and fault tolerant hardware)
 - **Optimize** quantum algorithms
- **Quantum Machine Learning** algorithms are a primary candidate for investigation
 - Increasing use of ML in many computing and data analysis flows
 - Can be built as **hybrid models** where quantum computers act as accelerators
 - **Efficient data handling is a challenge**

QML for image analysis

- First PhD project started in January 2021
- CERN – ESA – EPFL

Quantum CNN for multi-class classification

Su Yeon Chang

[CERN openlab, EPFL]

Bertrand Le Saux [ESA phi-lab], Sofia Vallecorsa, Michele Grossi [CERN openlab]

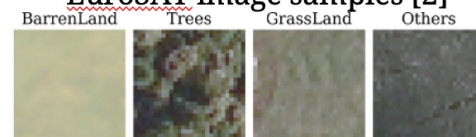
14. April 2022

Challenge

- Large dimension of input data → How to reduce its dimension ?
- Choice of quantum embedding method → How to embed data into quantum circuit?
- Architecture of quantum circuit → How to construct **Quantum Convolutional NN**?
- Noise of current quantum devices → How to train while mitigating the errors?



EuroSAT image samples [2]

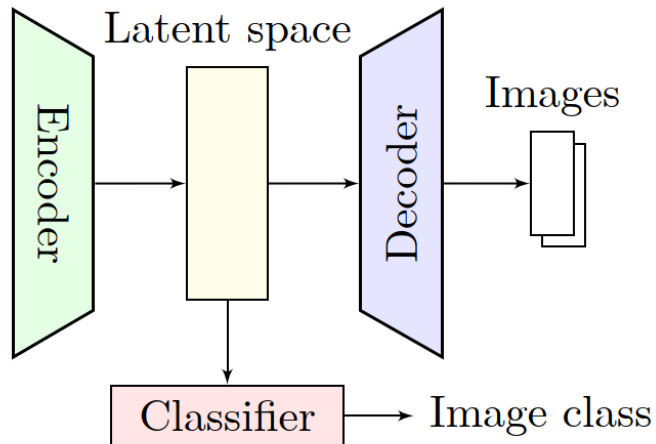
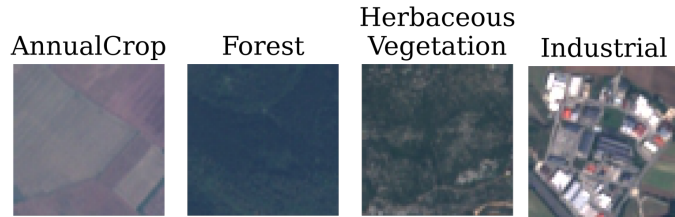


SAT4 image samples [3]



Hybrid multi-class classification

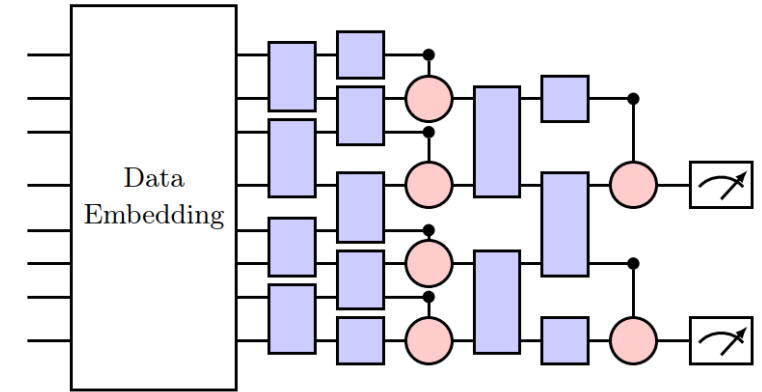
- Hybrid classical-quantum qCNN for multi-class classification (EuroSAT dataset for land cover classification from Sentinel-2)



Chang, Su Yeon et al., "Multi-class classification with hybrid classical-quantum CNN", IGARRS2022

27.06.22

- Quantum analogue of CNN¹
- Convolutional filters & pooling layers
- Modified : Different parameters for each filters



5 Hur, T., Kim, L., & Park, D.K., (2021). Quantum convolutional neural network for classical data classification.

Classical classifier

		EuroSAT				
True labels	Annual Crop	0.94	0.021	0.023	0.018	1.0 0.8 0.6 0.4 0.2 -0.0
	Herb. Forest	0	0.99	0.01	0	
	Herb. Vegetation	0.055	0.055	0.77	0.12	
	Industrial	0.002	0	0.0099	0.99	
Predicted labels		Annual Crop	Forest	Herb. Vegetation	Industrial	

Quantum classifier

		EuroSAT				
True labels	Annual Crop	0.9	0.023	0.076	0.0033	1.0 0.8 0.6 0.4 0.2 -0.0
	Herb. Forest	0.0017	0.97	0.025	0	
	Herb. Vegetation	0.021	0.032	0.91	0.037	
	Industrial	0.008	0.018	0.024	0.95	
Predicted labels		Annual Crop	Forest	Herb. Vegetation	Industrial	

QML for time series and sequences

- PhD project started in June 2022
- CERN – ESA – U. of Leiden

Challenges:

- **Efficiently map the state of a dynamic system to a Hilbert space where the time evolution is a linear operator?**
 - Can we derive properties of the dynamical system?
 - Can the quantum circuit learn from data, i.e. time series generated by the dynamical system ?
 - For which dynamical systems and which tasks would there be an advantage over classical model?

Broadening the scope: QC4EO Joint Project

- **Larger collaboration** creates **synergies** between disciplines like **High Energy Physics, Numerical Weather Prediction and Simulation**
- Developing relevant EO use cases demonstrating QC4EO advantages in the medium (<5 years) to long term (<20 years) to the EO field
- Defining a strategic objectives in a White Paper

