Bringing the power of Quantum Computing to Earth Observation

Bertrand Le Saux

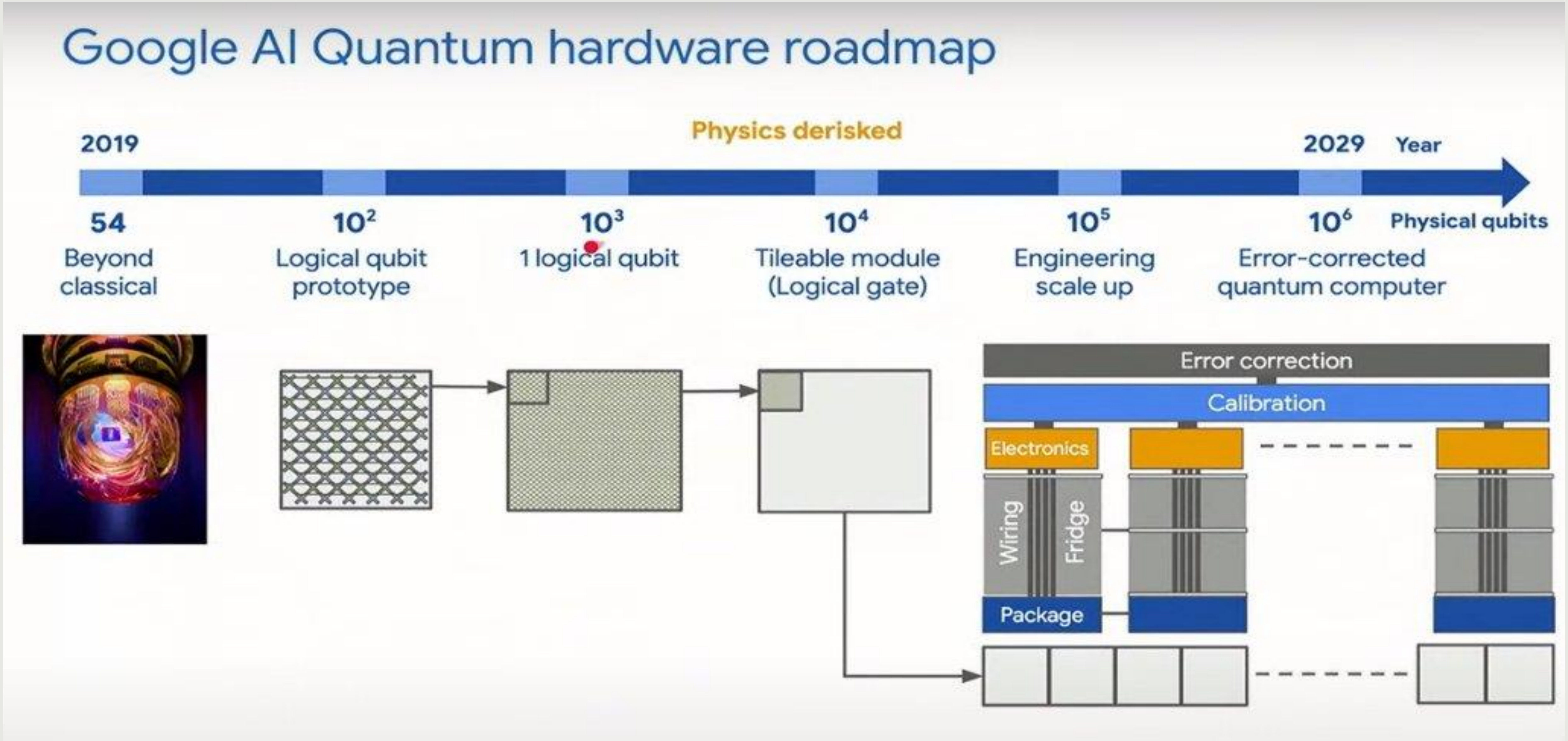
ESA EOP-S Φ-lab

01/06/2023

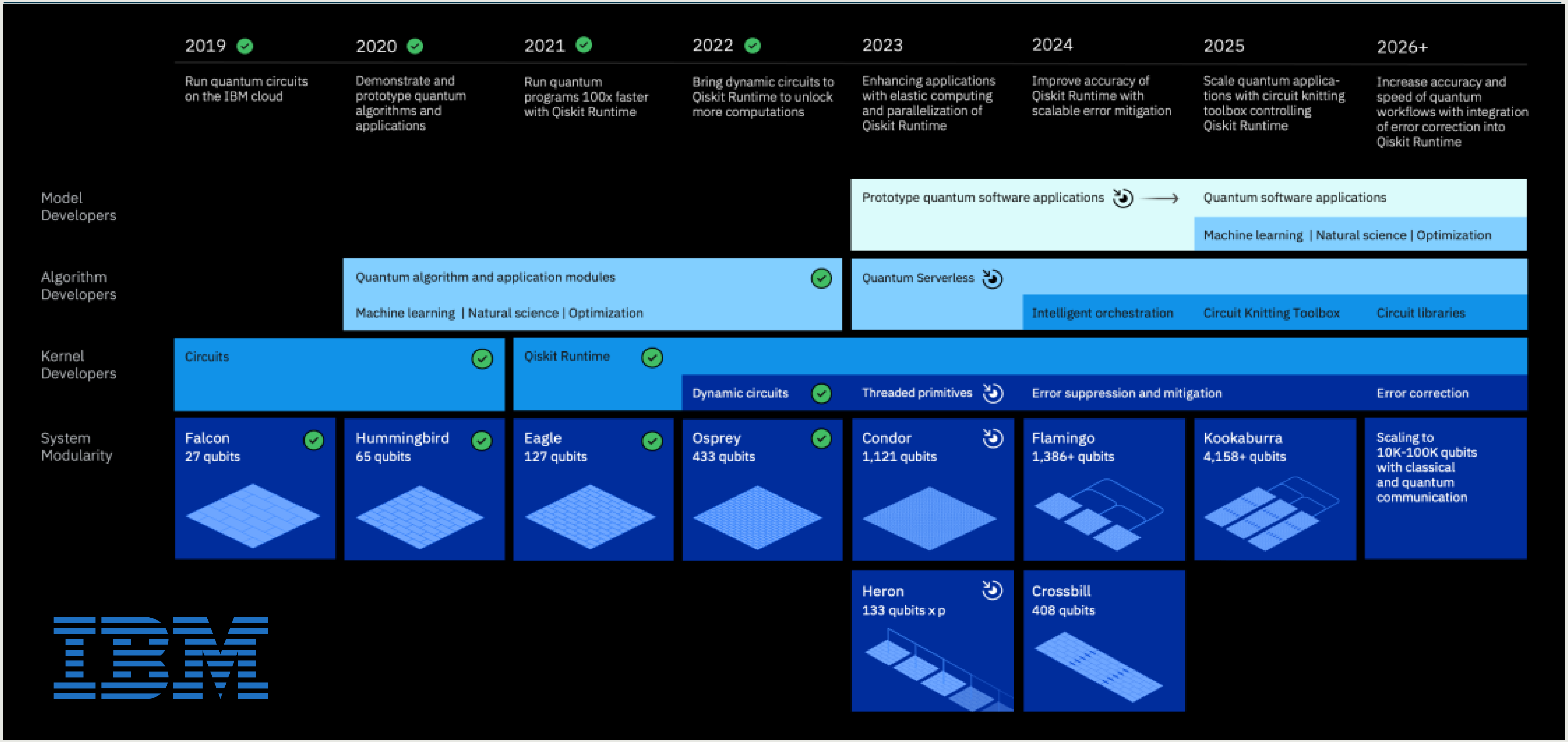
Quantum Computing Trends in 2023

Time magazine
February 2023 issue

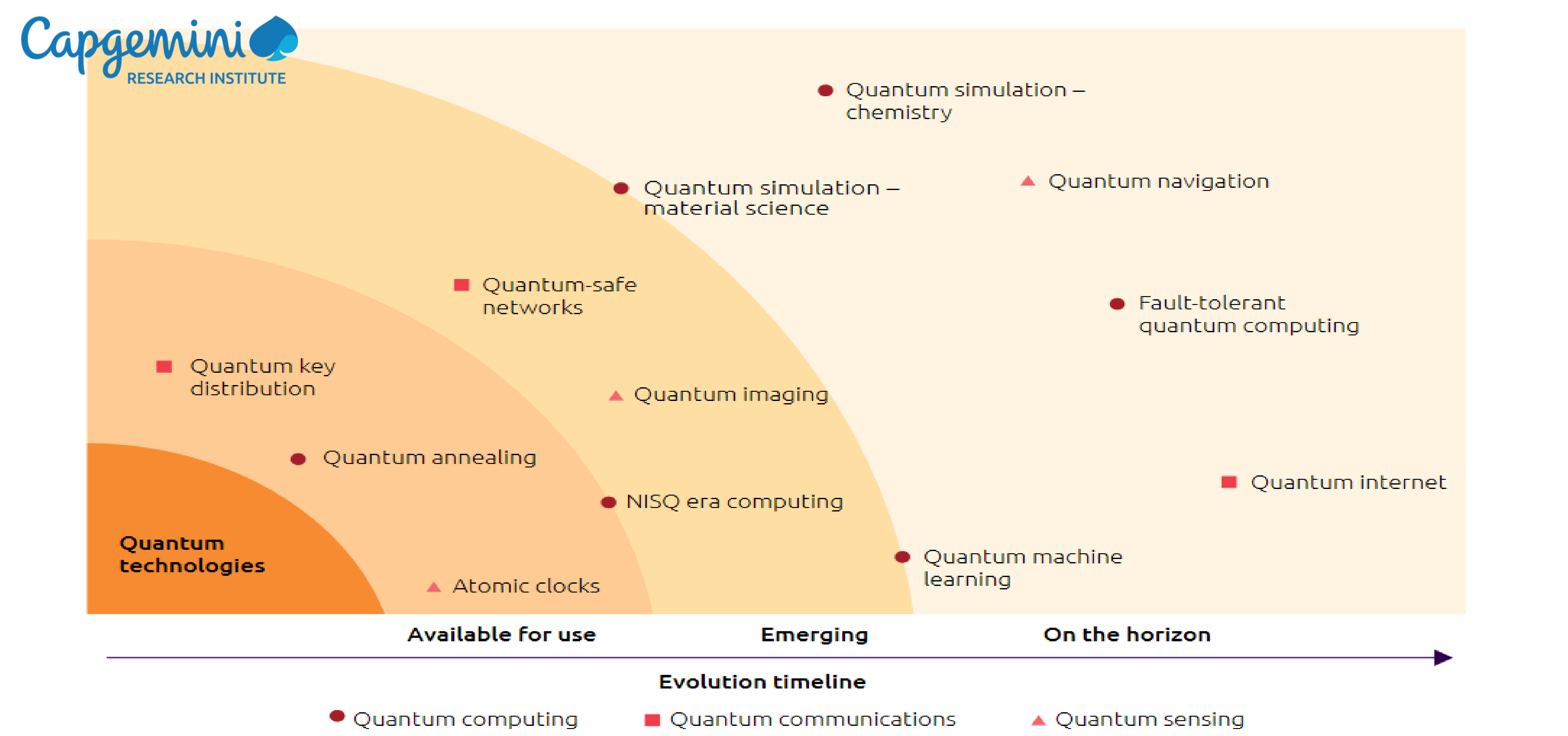
Quantum Computing Trends in 2023



Quantum Computing Trends in 2023



Quantum Computing Trends in 2023



Three directions

1. Roadmap definition (QC4EO studies)

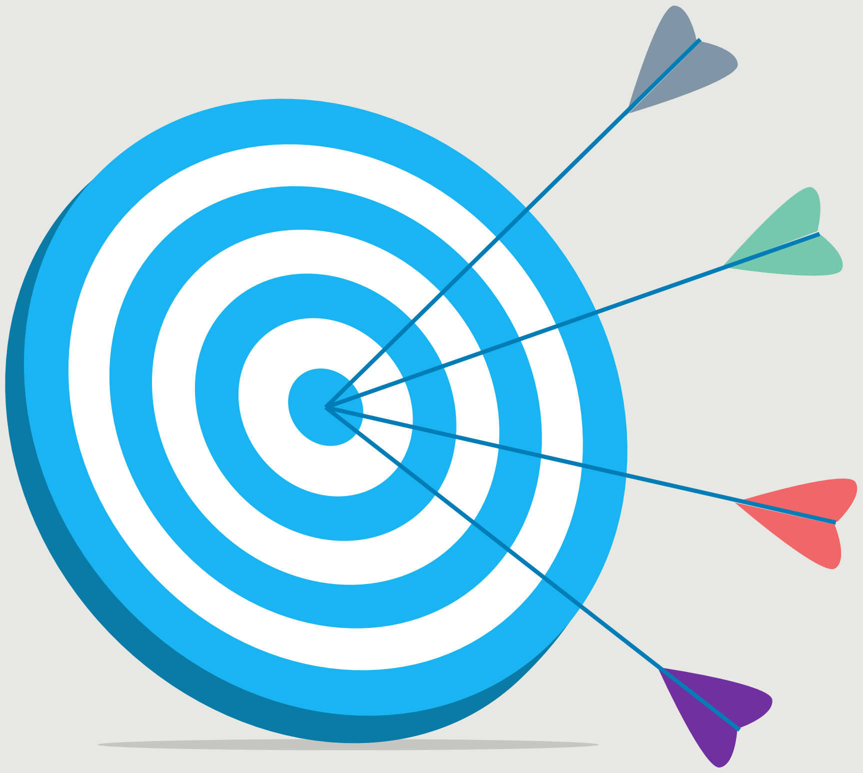
2. QML and QC Exploratory activities

3. QC4EO Network

Roadmap definition: QC4EO Studies

QC4EO Studies

2 projects during Q1 / Q2 2023 following ESA AO/1-11125/22/I-DT QUANTUM COMPUTING FOR EARTH OBSERVATION STUDY (QC4EO STUDY)



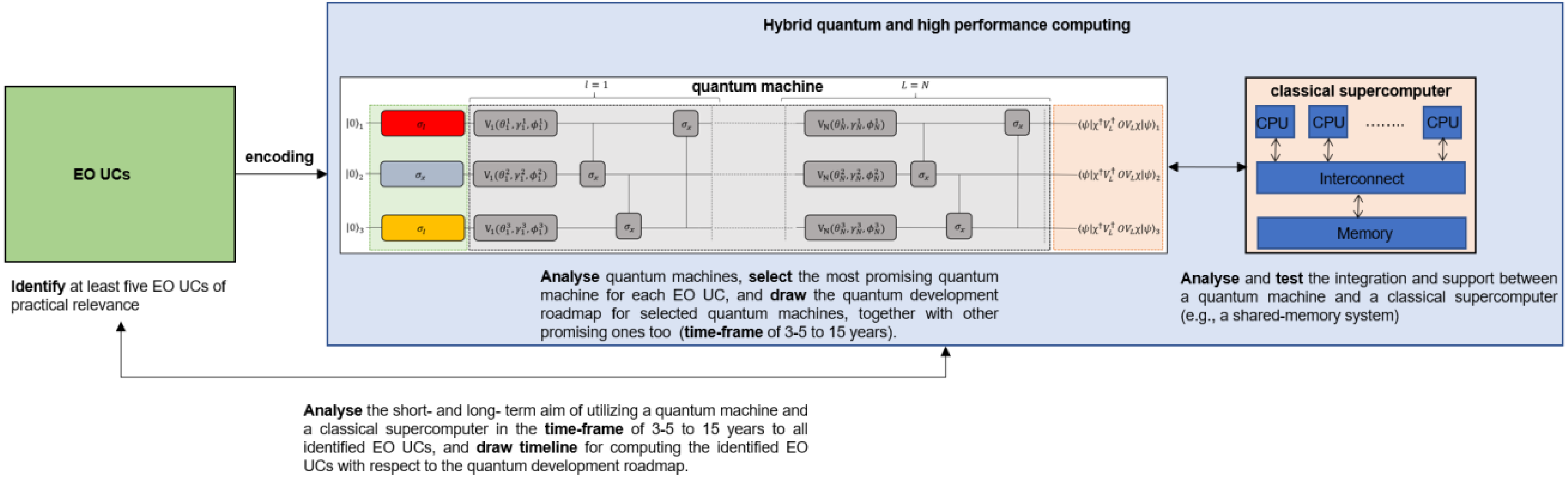
Objectives:

- ***Identify use cases relevant to the Earth Observation domain****, for which QC is expected to dramatically enhance computational performances with respect to traditional methods.*
- ***Provide options for QC or hybrid machine architectures*** *required to solve the identified QC4EO use cases, with the relevant sizing, e.g. in term of Qubits.*
- *Perform a* ***maturity and forecast assessment of the QC machine industry roadmaps****; and*
- ***Derive a credible QC4EO timeline of use cases*** *that could take advantage of a QC approach*

ESA Contract No. 4000140122/22/I-DT

Quantum Advantage for EO (QA4EO) project overview

- Identify hard Earth observation use cases (EO UCs) for quantum computers (e.g., quantum machines) or a hybrid approach
- Analyse quantum machines according to their number of qubits, errors, and so on
- Draw the roadmap of quantum computers



Quantum Advantage for Earth Observation

Project duration: **4 months (February to May 2023)**

Prime-contractor: **DLR**

Sub-contractors: **VTT, CSC, SYDERAL, ETOS, Jagiellonian University**

Use-cases:

I. Variational quantum algorithms for EO Image processing

II. Climate adaptation digital twin hpc+qc workflow

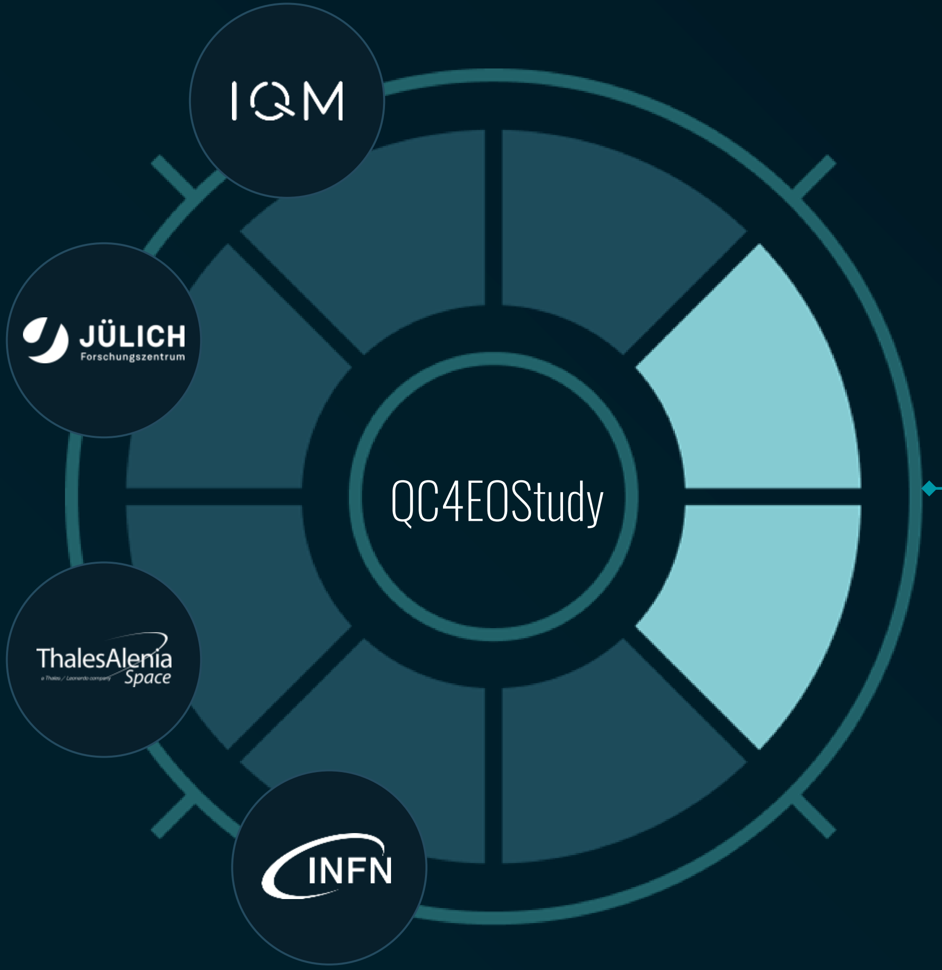
III. Earth land cover understanding

IV. Feature selection for environmental monitoring hyperspectral imagery

V. Uncertainty quantification for remotely-sensed datasets

Quantum

COMPUTING FOR EARTH OBSERVATION



Can QC offer advantages to EO applications within a medium to long timeframe (between the next 3-5 to 15 years)? What hardware developments are necessary to achieve this quantum advantage?

- OPTIMAL SOLUTIONS
- BETTER MODELLING
- SPEED-UP
- ENERGY EFFICIENCY

Potential quantum advantages

QC4EO Studies

Quantum Computing for Earth Observation

Project duration: **5 months (March to August 2023)**
Prime-contractor: **ForschungsZentrum Jülich (FZJ)**
Sub-contractors: **TASF, TASI, INFN, IQM**

High-level list of identified use-cases:

Scenario n° 1 – Phase Unwrapping problem for interferometric SAR applications
Scenario n° 2 – Quantum Fourier Transform for SAR raw dara processing
Scenario n° 3 – Satellite Image Time Series Classification
Scenario n° 4 – Optical Agile Satellites Mission Planning
Scenario n° 5 – Multiple-view Geometry on optical images
Scenario n° 6 – Digital beamforming
Scenario n° 7 – Quantum algorithms for SAR raw data compression
Scenario n° 8 – Quantum algorithms for SAR image segmentation

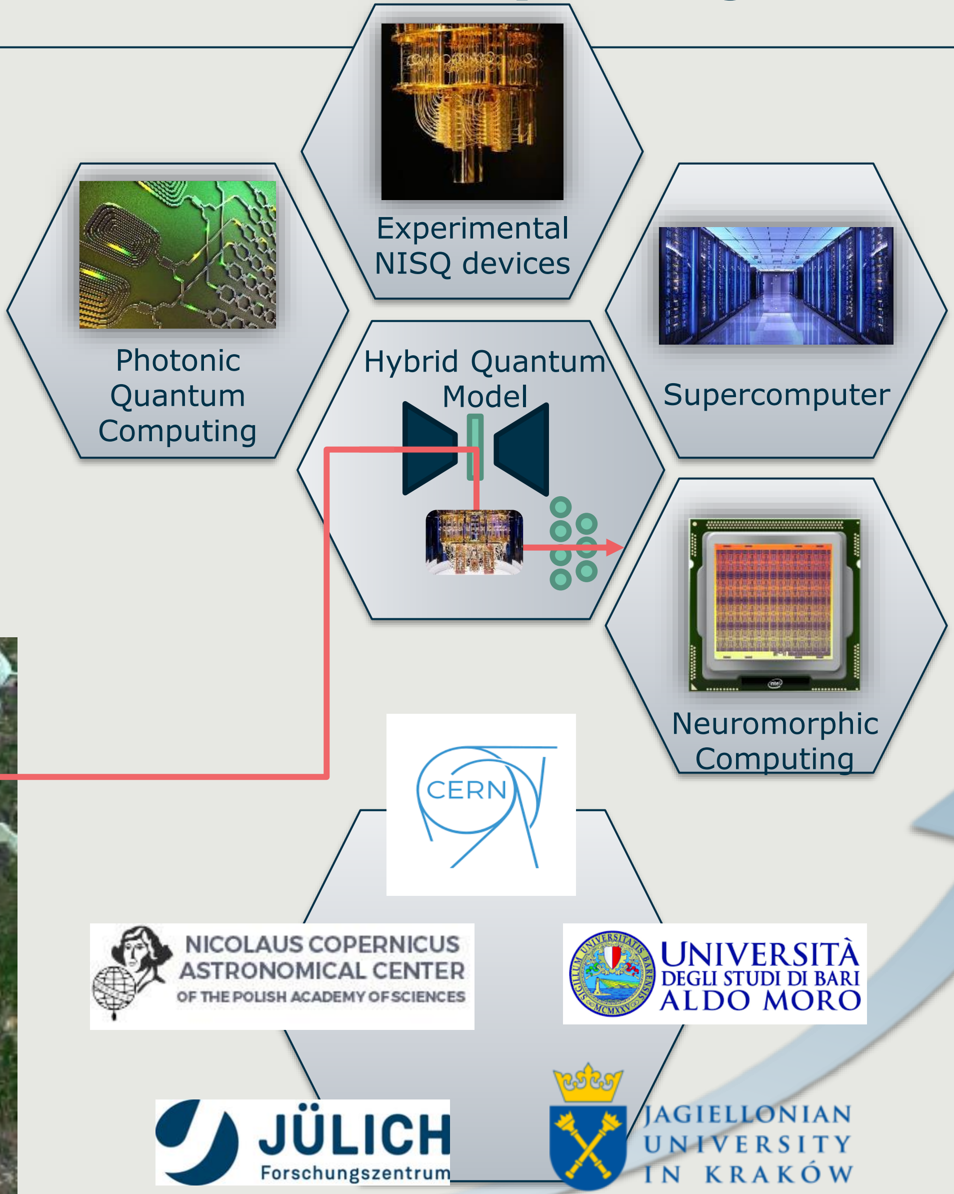
Exploratory activities

Exploratory activities in QML and Quantum Computing

Explore the potential of Quantum Machine Learning for Earth Observation use cases

Devise hybrid quantum classical AI models in high performance computing environments

Build a strong community of experts in both Quantum Computing and Earth Observation



Exploratory activities in QML and Quantum Computing

➢ **Hybrid Classical Quantum Networks** (Quantum Convnets, Quantum GANs, Recurrent nets)

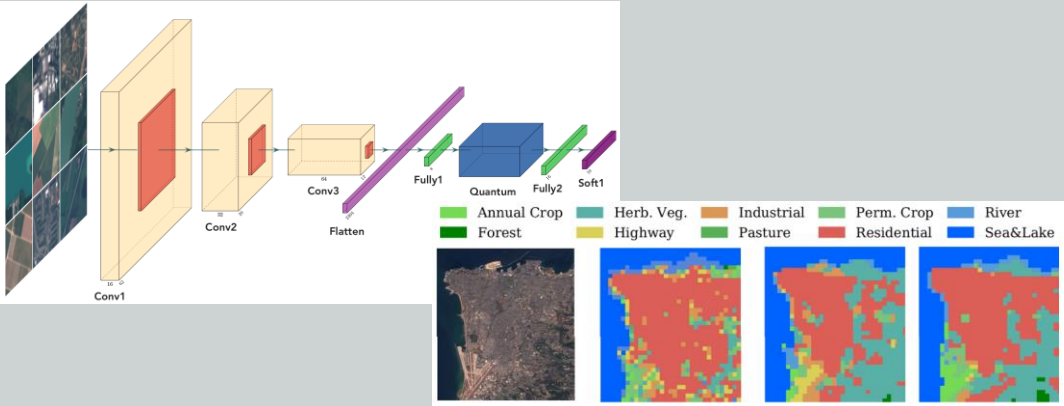
Case Study 1: Hybrid QCNN for EO classification

Use-case: EO image classification for land-use and land-cover.

Approach: Hybrid Quantum Classical CNNs enrich standard conv nets with a quantum layer!

Findings:

- ➢ Successful Proof of concept, with slightly better performances than comparable CNNs thanks to entanglement.



Sebastianelli et al. "On Circuit-based Hybrid Quantum Neural Networks for Remote Sensing Imagery Classification", IEEE JSTARS (15) 2021

UNIVERSITÀ DEGLI STUDI DEL SANNIO Benevento

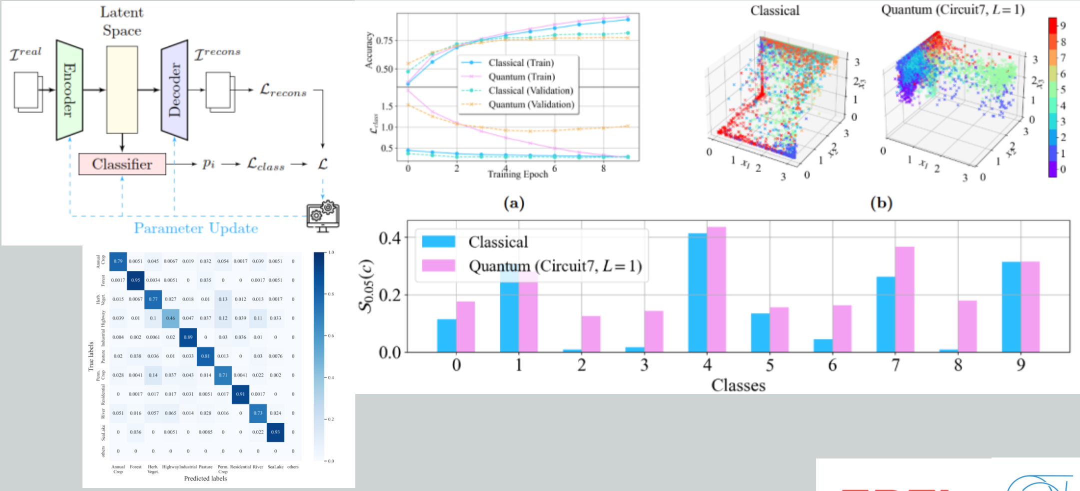
Case Study 2: Hybrid QCNN Expressivity

Use-case: EO image classification

Approach: Hybrid models with latent space embedding

Findings:

- ➢ Investigation of Quantum Ansätze: better expressivity with circuits with two-qubit SU 4 state
- ➢ End-to-end Proof of Concept for EO image classification with SOTA performances



Chang et al., "Quantum Conv Circuits for EO image classif.", IGARSS 2022

EPFL CERN

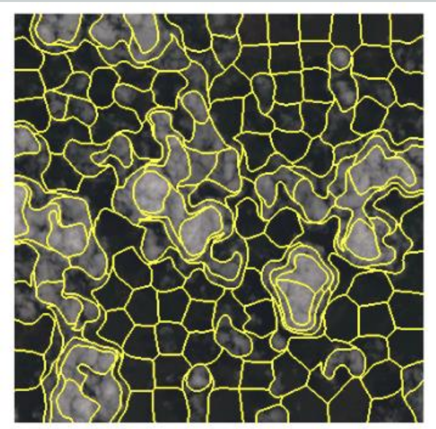
Exploratory activities in QML and Quantum Computing

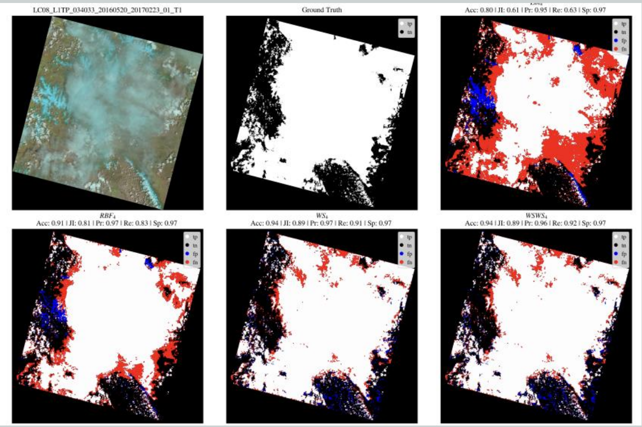
- Exploring **Quantum Kernels** (e.g. Projected Quantum Features, SVMs…)

Case Study 3: Circuit-based Quantum SVM

Use case: cloud detection in multispectral EO images.
Approach: Hybrid Support Vector Machines (SVMs) with **gate-based quantum kernels**.

Findings:
- End-to-end pipeline to embed and process EO data with small NISQ circuits.
- Successful Proof of Concept, with results on par with standard SVM thanks to Quantum Kernel Target Alignment.





Miroszewski, A., Mielczarek, J., Czelusta, G., Szczepanek, F., Grabowski, B., Le Saux, B., & Nalepa, J. (2023). Detecting Clouds in Multispectral Satellite Images Using Quantum-Kernel Support Vector Machines. arXiv preprint arXiv:2302.08270.

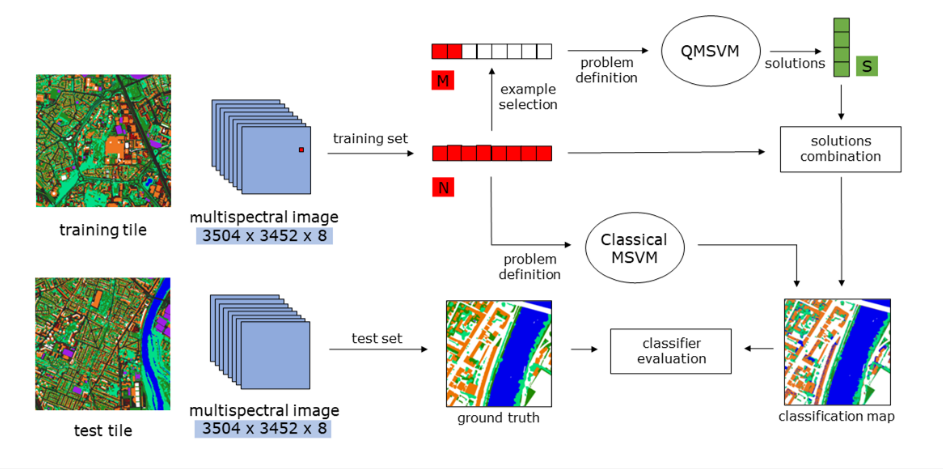
JAGIELLONIAN UNIVERSITY IN KRAKÓW

KP LABS

Case Study 4: Annealing-based Quantum SVM

Use case: Classification of multispectral EO data.
Approach: Hybrid Support Vector Machines (SVMs) with **Julich SC Quantum Annealer**.

Findings:
- Advantage Annealer operates only a limited number of samples for Q optimization…
- …. But execution times increase linearly!



Delilbasic, A., Le Saux, B., Riedel, M., Michielsen, K., & Cavallaro, G. (2023). A Single-Step Multiclass SVM based on Quantum Annealing for Remote Sensing Data Classification. arXiv preprint arXiv:2303.11705.

JÜLICH Forschungszentrum

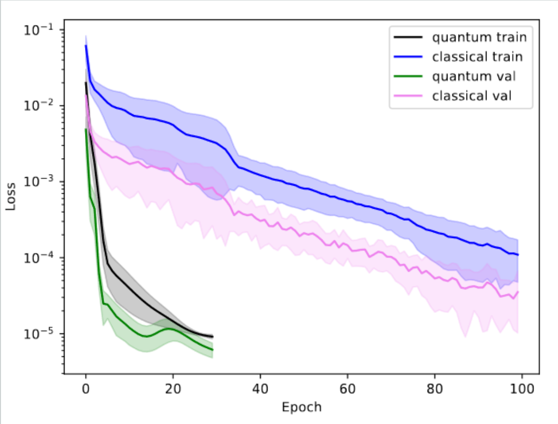
Exploratory activities in QML and Quantum Computing

➢ **Hybrid Classical Quantum Networks** (Quantum Convnets, Quantum GANs, Recurrent nets)

Case Study 5: Continuous-variable QC RNNs

Use case: Earth Systems observation and prediction.
Approach: Recurrent Neural Networks for time-series on Continuous-Variable QC.

Findings:
- Promises of faster training convergence
- For a small number of trainable parameters, it can achieve lower losses than its classical counterpart.



Siemaszko, McDermott, Buracsewski, Le Saux & Stobinska "Rapid training or recurrent quantum neural networks", **QTML 2022 / Qu Mach. Intell. 2023**

UNIVERSITY OF WARSAW

Case Study 6: Quantum Generative AI

Use case: Generative modelling and synthesis of images.
Approach: Quantum Generative Adversarial Networks (QGANS) : Quantum Generator + Classical Discriminator.

Findings:
- Trick #1: Latent space embedding by pretrained autoencoder
- Trick #2: Continuous, Style-based quantum GAN
- Successful image generation for varied image types
- Faster and better performances (in terms of distribution mapping) with less parameters

Chang et al., to appear

Hybrid Quantum-Classical Neural Networks

Su Yeon Chang [CERN, EPFL]

23/05/2022

Motivation and objectives

- **Quantum Machine Learning (QML)**
- Intersection between Machine Learning (ML) and Quantum Computing (QC)
- Potential to improve the existing ML techniques
- Can be efficiently simulated on the real quantum hardware
- Increasing studies on application of QML on Earth Observation (EO) images

PhD Objective : Implement quantum generative models to reproduce EO images

Challenges

1. **Scale EO data** for current quantum simulators → Dimensionality reduction techniques

2. Transfer classical data to quantum & quantum data to classical
→ How to **interpret the quantum circuit output** into classical data?

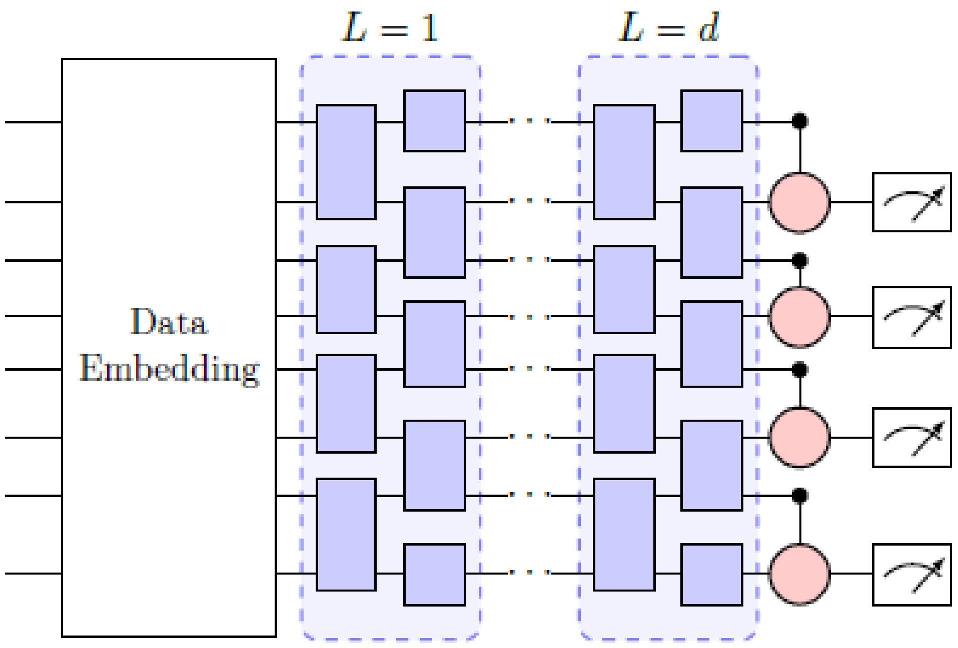
3. Find the **quantum circuit architecture** which is the most trainable, efficient and accurate
→ Hardware Efficient Ansatz (HEA), Quantum Convolutional Neural Networks (QCNN), Alternating Layered Ansatz (ALT), etc…

3. Possibility of **quantum advantage**
→ Quantum advantages expected in case the training is classically intractable
→ Can quantum generative model learn hidden image properties that classical ML cannot?

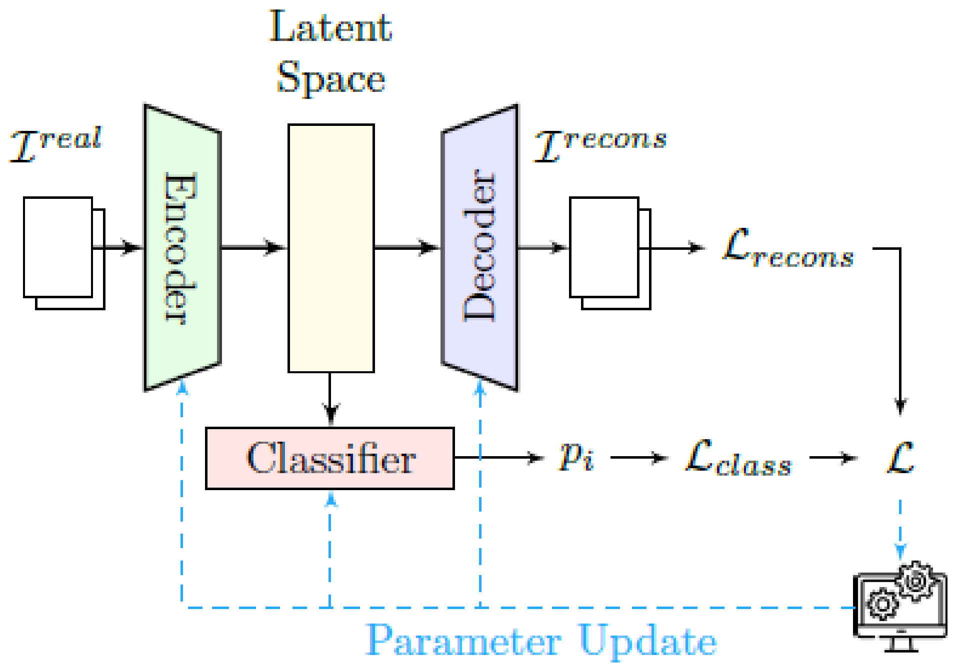
5. Trainability on **real quantum hardware**
→ Aim to run quantum circuit on different quantum devices, e.g. superconducting chips (IBMQ), Ion trap (IONQ)

Multi-task hybrid model for image classification

- Work presented in Quantum Information Processing 2023 conference
- **Hybrid classical-quantum model** for image reconstruction and classification
- Classical autoencoder for dimensionality reduction & image reconstruction
- Quantum classifier for feature classification



(a)

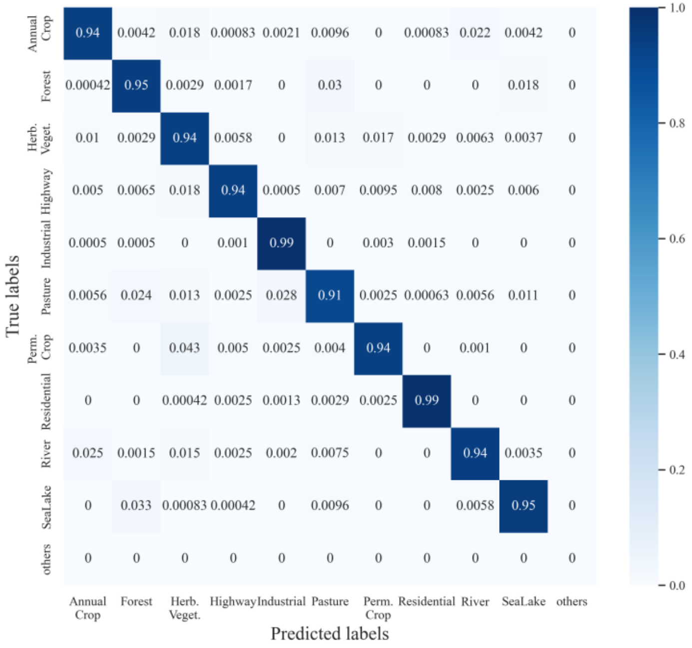


(b)

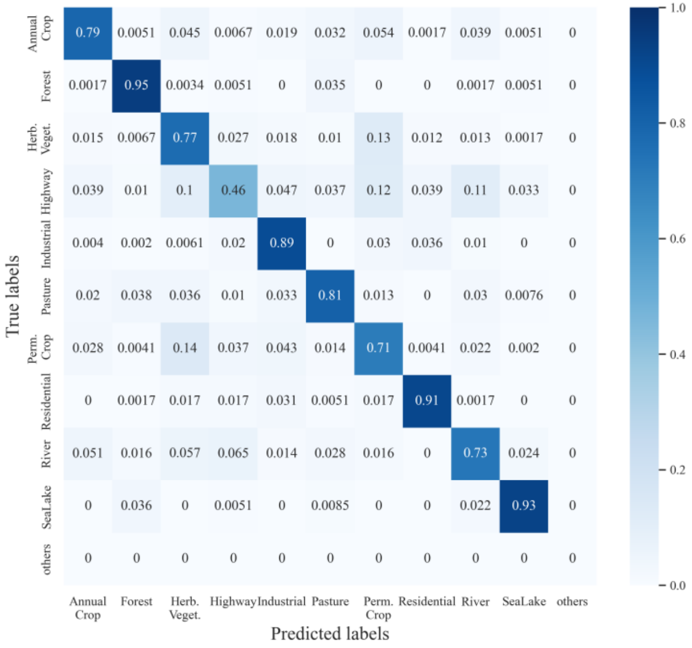
Multi-task hybrid model for image classification

- Successful classification for EuroSAT dataset (10 classes)
- Challenge : Cannot observe quantum advantage with current model

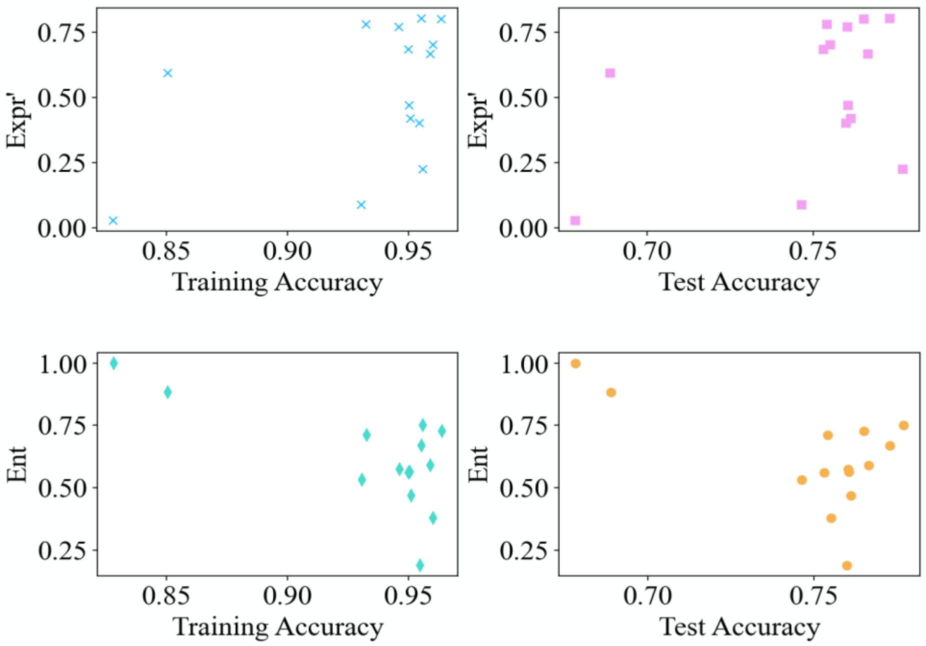
→ Investigate latent feature arrangement to understand the limitation



Train set



Test set

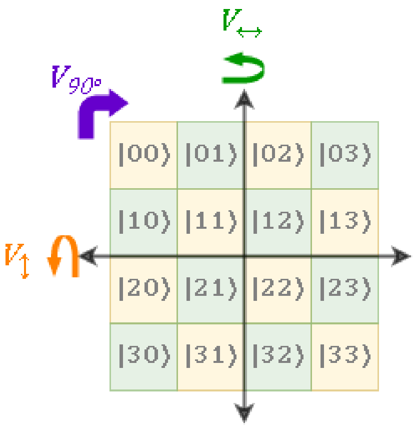


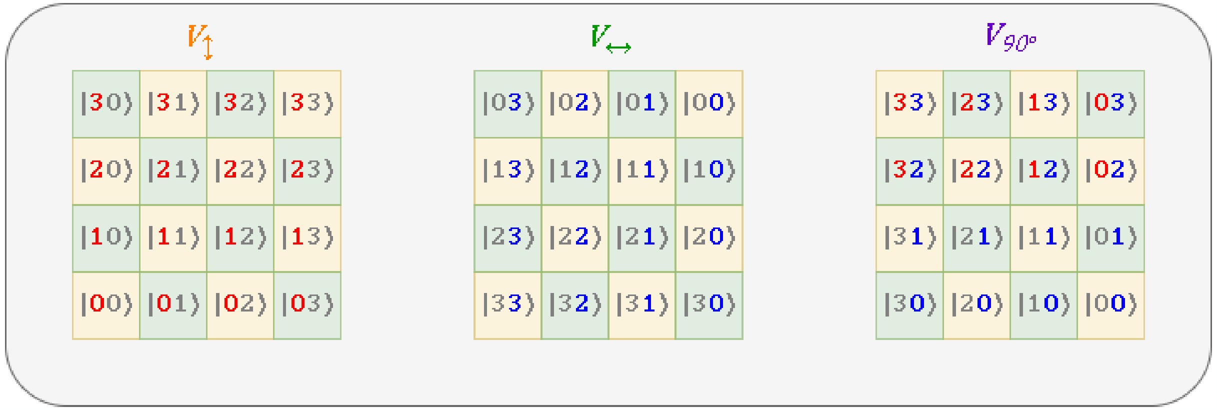
Study correlation between PQCircuit architecture & classification accuracy

- **Pearson Correlation Coefficient** calculated for Expressibility /Entanglement capability v.s. Accuracy
- Higher Expressivity → Higher Accuracy
- Higher Entanglement → Lower Accuracy

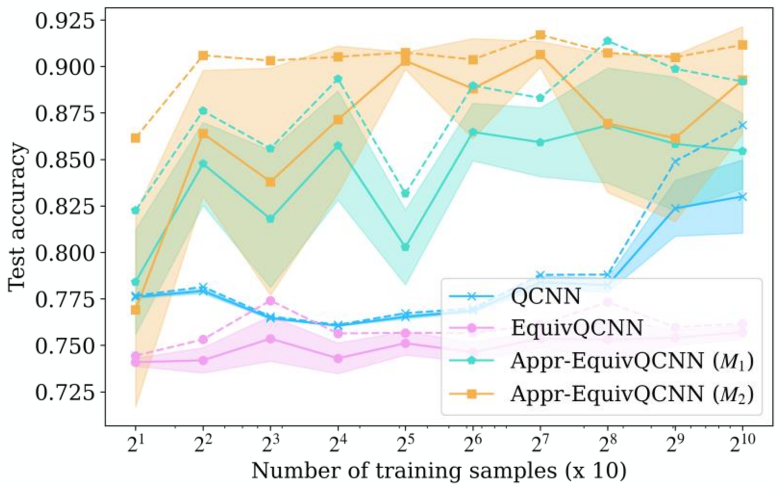
Equivariant Quantum CNN

- Work submitted to IEEE Quantum Week 2023
- Construct an equivariant quantum CNN for image classification under rotation & reflection symmetry
- Better generalization power compared to the non-equivariant model
- **Challenge** : Extend the application to larger RGB datasets

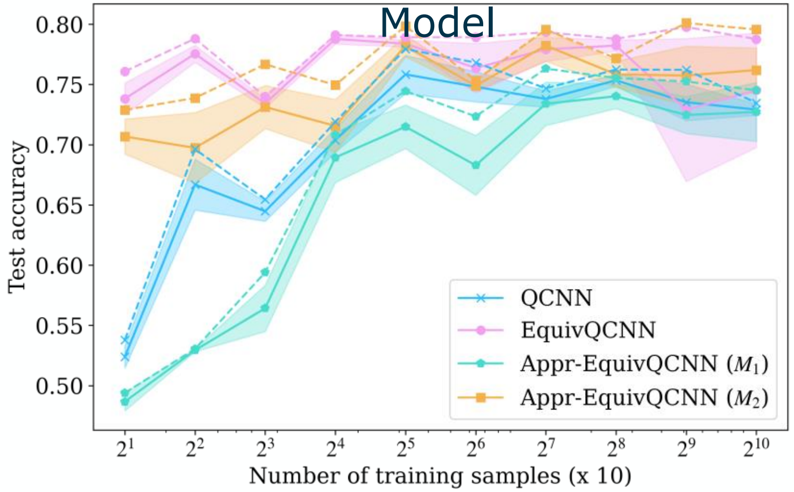




MNIST Image classification (digits 4,5)



Phase classification for Ising Model

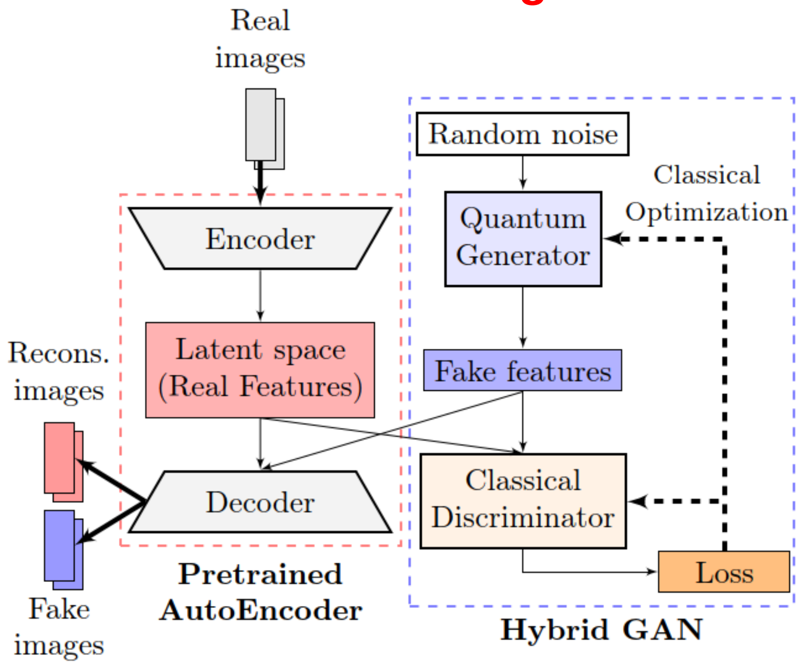


Style-based quantum GAN for image generation

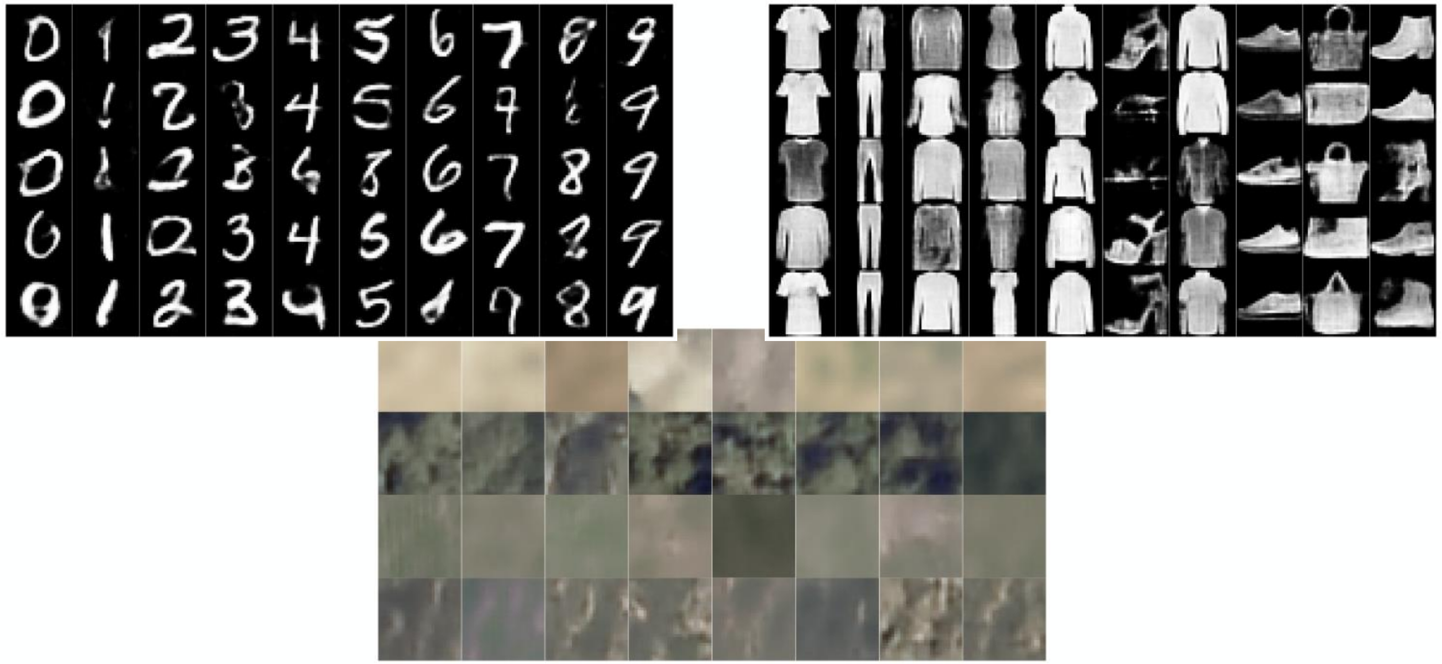
- Quantum Generative Adversarial Networks : **Quantum Generator + Classical Discriminator**

→ Hybrid approach allows to scale up the model for realistic use cases

- Features extracted from images via a **pretrained autoencoder** used as GAN training set
- Generated features passed back to the autoencoder to reconstruct images
- **Successful GAN training with MNIST, FashionMNIST and SAT4 dataset**



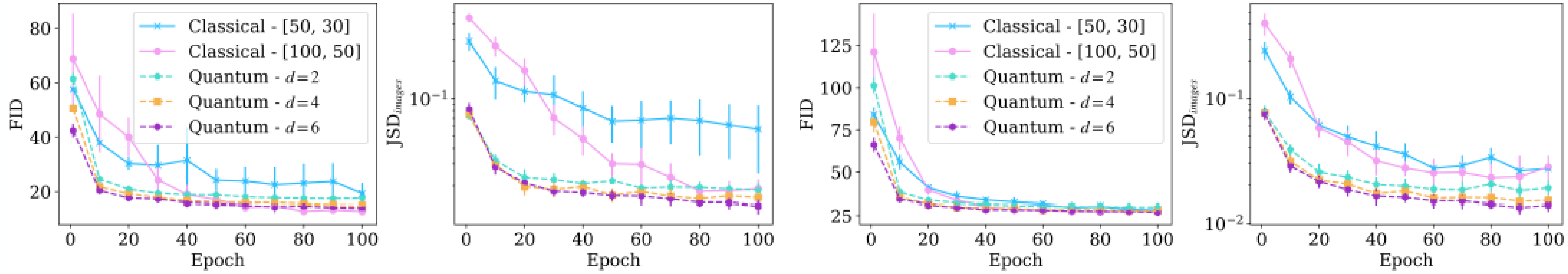
Training schema of hybrid GAN model with pretrained autoencoder



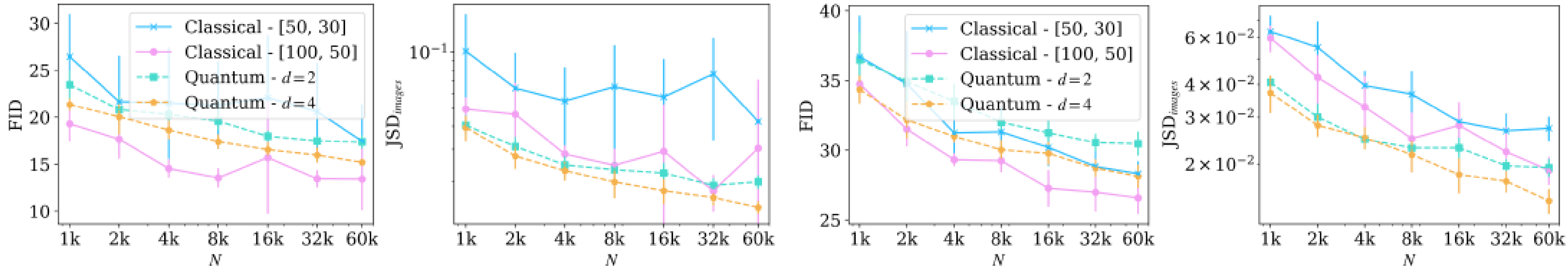
Samples generated with quantum GAN

Style-based quantum GAN for image generation

- **Faster convergence** using similar number of parameters
- **Better generalization** power with less number of training samples



(a) MNIST (b) FashionMNIST



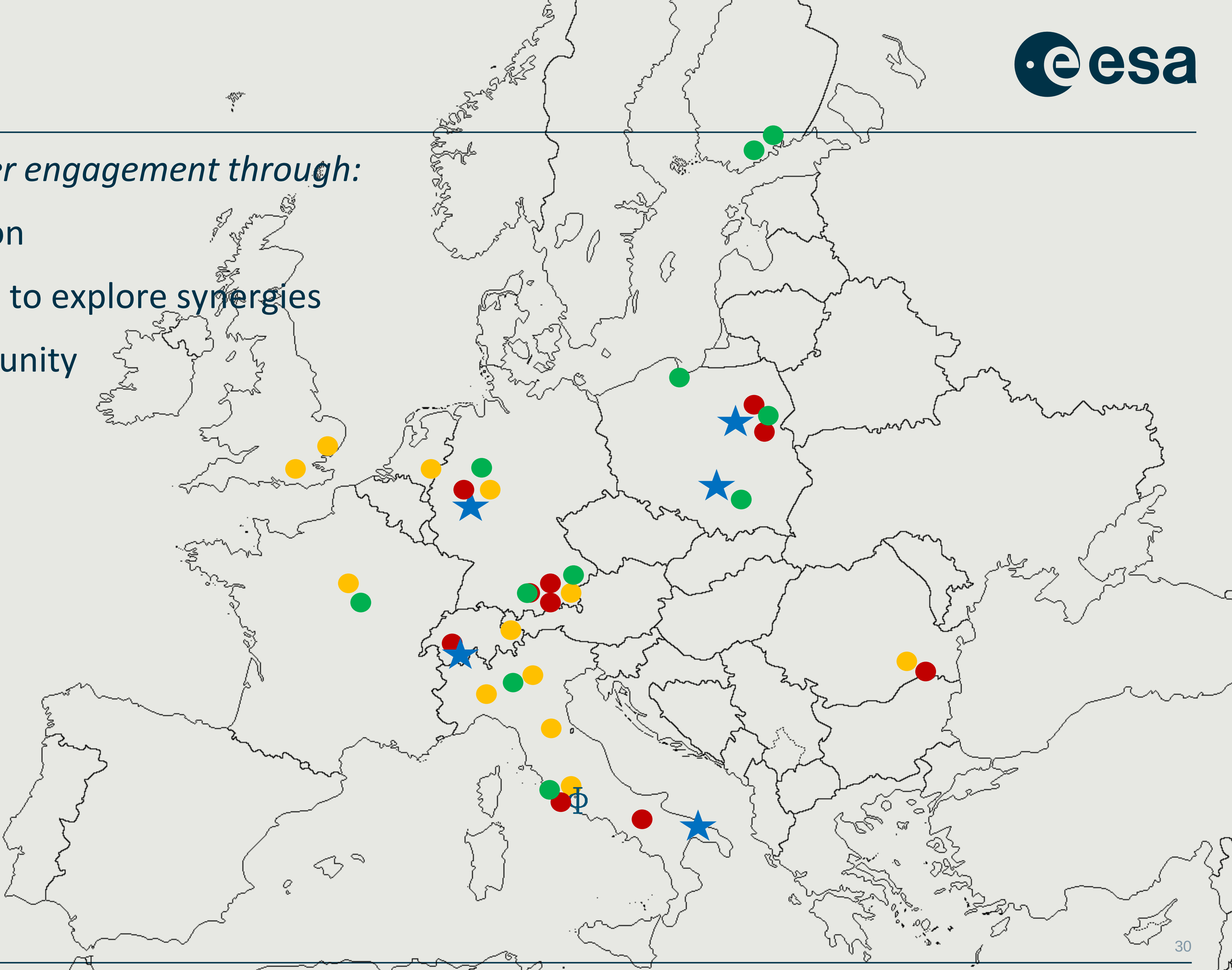
(a) MNIST (b) FashionMNIST

QC4EO Network

QC4EO Network

Community building and stakeholder engagement through:

- Workshop and event organisation
- Consult QC and EO communities to explore synergies
- Support emerging QCxEO community



- ● QC4EO Study
- ★ Co-funded research
- ● Partners / visitors
- ● Community / events

QC4EO Network: workshops and events

- 2019 Workshop on Quantum Processing: from Quantum Computing to Earth Observation in Rome,
  https://philab.phi.esa.int/workshop-quantum-for-earth-observation/
- 2021 ESA-Ellis Workshop on Quantum Algorithms and Machine Learning for EO applications,
  https://ellisqphml.github.io/ellisphilab2021
- 2021 Φ-week QC4EO session in Frascati,
  https://phiweek.esa.int
- 2021 ESA 5th Quantum Conference Quantum Computing session,
  https://atpi.eventsair.com/5th-quantum-technology-conference/
- 2022 Living Planet Symposium, Agora Session on "Future of Computing for FutureEO"
- 2022 QTML 2022 Industry Panel
- 2023 ESA 6th Quantum Conference Quantum Computing session,
  https://nikal.eventsair.com/6th-quantum-technology-conference

QC4EO Network: organisations

Stakeholder engagement

- AI-enhanced Quantum Computing for EO: Joint initiative between CERN and ESA-EOP
- QC4EO JP: Consultation with CERN, DLR, TU Munich, LRZ, Ellis, etc…
- Companies: IBM, Quantinuum, Quandela, Thales, Xanadu, etc.

Community events and thematic initiatives

- IEEE GRSS High-performance and Disruptive Computing (HDCRS) Summer School, May 2022, 2023
  https://www.hdc-rs.com
- CINECA **Introduction to Quantum Computing School** June 2023
- Quantum Open Software Foundation mentoring https://qosf.org/
- Quantum Climate initiative https://q4climate.github.io/

Publications

- IEEE JSTARS Special Issue on “Quantum resources for Earth Observation” → 2021 / 2022
  Ed. M. Datcu (DLR), J. Le Moigne (NASA), B. Le Saux (ESA) → *https://ieeexplore.ieee.org*

QC4EO Network: visiting researchers

esa

Senior visiting researchers:

Mihai Datcu

(Politehnica Uni of Bucharest)

Gabriele Cavallaro

(Forschungszentrum Jülich)

Piotr Gawron

(CAMK / Polish Acad of Sciences)

Early-career researchers:

Michal Siemaszko

(PhD, Univ. Warsaw)

Alice Barthe

(PhD, CERN / Leiden Uni)

Andrea Ceschini

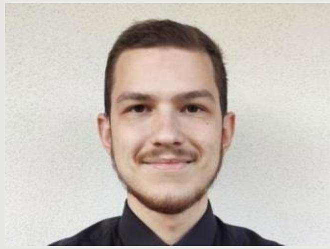
(PhD, La Sapienza)

Francesca de Falco

(MSc., La Sapienza)

Francesco Mauro

(PhD, Uni. Sannio)



Amer Delilbasic

(PhD, Uni of Iceland / FZ Jülich)

- **We are welcoming visiting researchers from academia and industry!**
- **Spend short stays or residencies at the Φ-lab to mingle with EO, AI, and QC experts!**
- **Let's get in touch!**

Conclusions

ESA Φ-lab's Initiative on Quantum Computing for Earth Observation (QC4EO)

General perspectives:

- *Increase the **mutual awareness** of the needs and capabilities of the **Quantum Computing** and **Earth Observation** communities*
- *Create new **synergies**, building on shared experience in **AI**, optimisation, and **high-performance computing***
- *Prepare the ground for the opportunities that will be presented when the quantum community will be able to produce hardware and software for applied problems*

ESA Φ-lab's Initiative on Quantum Computing for Earth Observation (QC4EO)

Practical perspectives:

- *Look for **practical applications and use-cases**, enabled by increased quantum volume*
- *Understand the **advantages** (faster, better, etc.?) brought by QC with **exploratory activities***
- ***Design hybrid computing** frameworks including traditional CPU, GPU, HPC and new paradigms such as quantum and neuromorphic computing for optimal problem solving*

Bringing the power of Quantum Computing to Earth Observation

- *Follow us: https://www.esa.int/ / https://philab.esa.int/*
- *Join ESA Φ-lab@ESRIN: https://jobs.esa.int/*
- *Contact: alessandro.sebastianelli@esa.int, bertrand.le.saux@esa.int*

SAVE THE DATE!
6th ESA Quantum Technology Conference | 19 – 21 September 2023 | Matera, Italy