Bringing the power of Quantum Computing to Earth Observation

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ESA ESRIN Φ-lab

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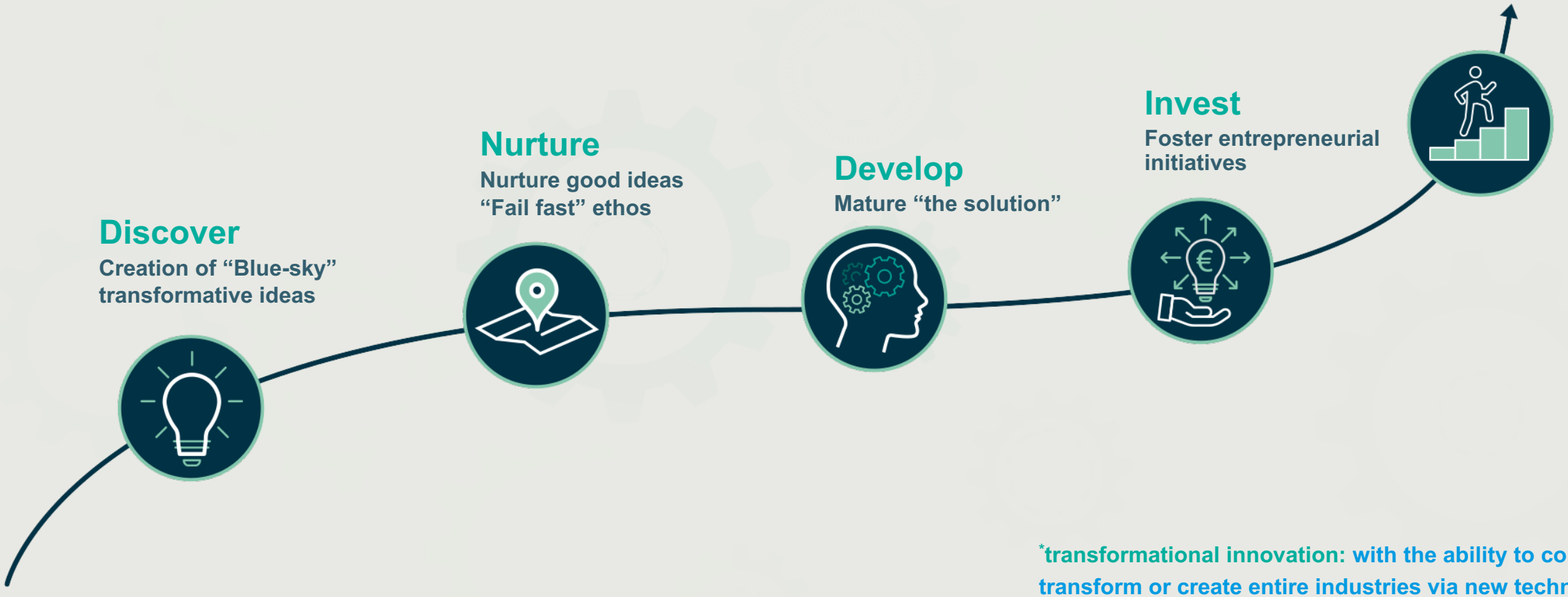
The ESA Φ-lab@ESRIN

Accelerate the future of Earth Observation via transformational innovation* strengthening Europe's world-leading competitiveness



*transformational innovation: with the ability to completely transform or create entire industries via new technologies

The ESA Φ-lab@ESRIN Offices

Φ-lab Explore Office

Explore the innovation universe
and connect EO sensor revolution
with the digital revolution

Φ-lab Invest Office

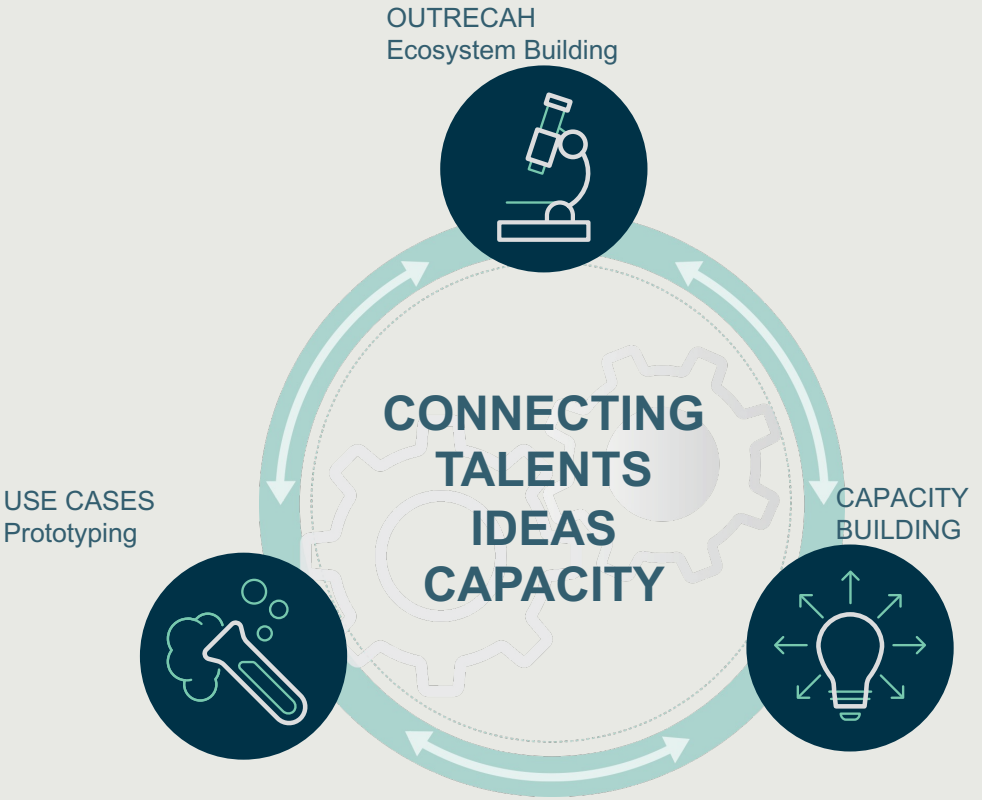
Stimulate competitiveness growth
fostering entrepreneurial initiatives
By Investment actions from
ESA MSs and the investors market

The ESA Φ-lab@ESRIN Explore office

We work on

Φ-lab Explore innovation cycle is

- Focus on a meaningful problem
- Connect expert partners
- Enable solutions developing capacity
- Experiment “fail and recover fast” on use cases



Today's talk

1. Roadmap definition (QC4EO study)

2. QML and QC Exploratory activities

3. QC4EO Network

1. Roadmap definition (QC4EO Study)

Why Quantum Computing for Earth observation?

High-level challenges

- Strategic vision, with long term application – 15/20 years
  - Seize the potential of QC as a transformative tech
  - Benefit from and contribute to the huge, global effort around HPC and QC

- Identify potential use-cases among EO applications

  From signal / image / data processing to weather forecast, climate change monitoring, sustainable development goals, green energy, distributed computing…
- **Prepare workforce and develop the agency architecture to exploit HPC / QC**
- Experiment with EO data and modular HPC to inspire creativity and unlock innovation
- Develop a **network of experts** and talents aware of specificities of both fields

Defining a QC4EO Roadmap

Practical challenges

- Are there any problems that quantum computing could solve more efficiently?
- What kind of advantage can be expected:

  speed-up, optimal solutions, better modelling, energy efficiency ?

1. How could Quantum Computing (QC) bring a “quantum advantage” to Earth Observation (EO) Science & Applications?
2. What are the "relevant" EO problems that could be solved by QC “faster” or “better” than any known classical algorithm on the best classical computer?
3. What kind of “hybrid” computing paradigm would be needed to deliver such quantum advantage?
4. By when would it become possible?

QC4EO Study ITT and contract

- Invitation to tender run in 2022 → https://doing-business.sso.esa.int/
- Selected consortium to be announced soon!
- Study will contribute to define ESA EOP roadmap on QC/HPC
- 2023 the contract will start

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 in the short and longer term.*
- ***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*

2. Exploratory activities in QML and Quantum Computing

Exploratory activities in QML and Quantum Computing

Investigating QML with EO data (~ multispectral images, time-series) = **general purpose QML**

➢ Many challenges!

- Challenge 1: All data is big wrt. NISQ devices → How to compress/reduce it for quantum processing?
- Challenge 2: How to transfer classical data to quantum?
- Challenge 3: How to define efficient hybrid architectures / circuits ?
- Challenge 4: How to make the most of the various hardware architectures ?

Through currently 2 main axis of research:

✓ **Quantum Kernels (Projected Quantum Features, SVMs…)**

✓ **Hybrid Classical Quantum Networks (Quantum Convnets, Recurrent nets)**

Exploratory activities in QML and Quantum Computing

Past/ongoing projects:

- 2021: QML (Quantum Neural Networks) for Classification of EO data, with **University of Sannio (IT)**

- 2022-2023: QML for Classification of EO data (spectral info, change detection), with **CAMK (PL)**
- 2021-2024: Generative Modelling of EO data for classification and synthesis, with **CERN (CH)**
- 2022-2025: Hybrid Supercomputing-Quantum processing of EO data, with **FZ Julich (DE)**

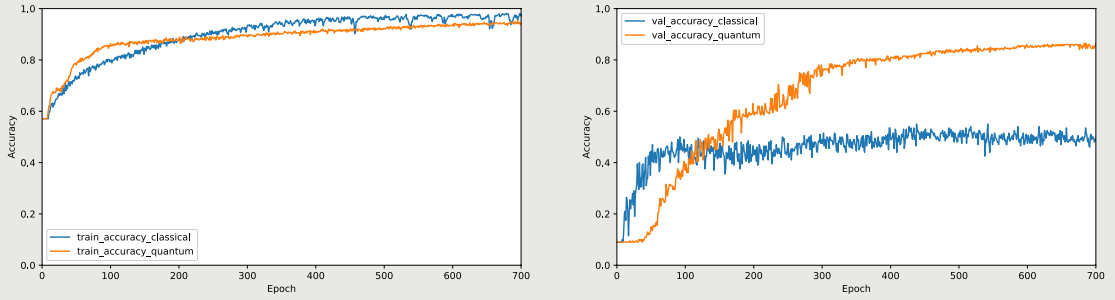
Starting projects:

- 2022-2024: QML (Quantum Kernels) for Classification of EO data, with **Jiagellonian Univ. (PL)**
- 2022-2025: QML (Reservoir computing) for Time Series Processing, with **CERN (CH)**
- 2022-2025: Quantum Computing for Ground Motion Measurements, with **Uni Bari (IT)**

Quantum Kernels

- Exploring Quantum Circuits as kernel functions (e.g. Projected Quantum Features, SVMs…)

Classification of multispectral EO data encoded by projected quantum kernel (PQK) method : Training and validation accuracy of feedforward neural network with and without access to quantum features

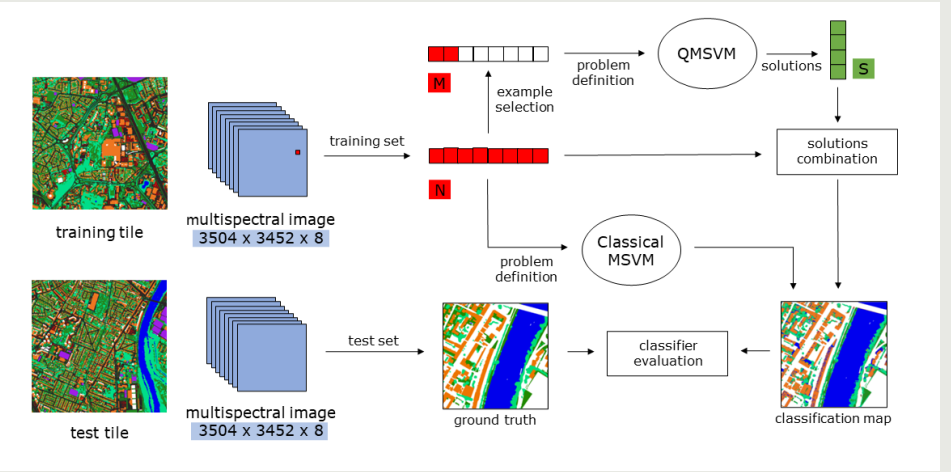


Gupta, Beseda & Gawron, “How QC-friendly multispectral data can be?”, IGARSS 2022

NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

Classification of multispectral EO data by quantum SVMs on Julich SC Quantum Annealer

- Limited number of samples for Q optimization
- But execution times increase linearly



Delilbasic, Cavallaro, Le Saux, Riedel & Michielsen, “Multiclass SVM with Quantum Annealing”, ECML-PKDD QML ws 2022

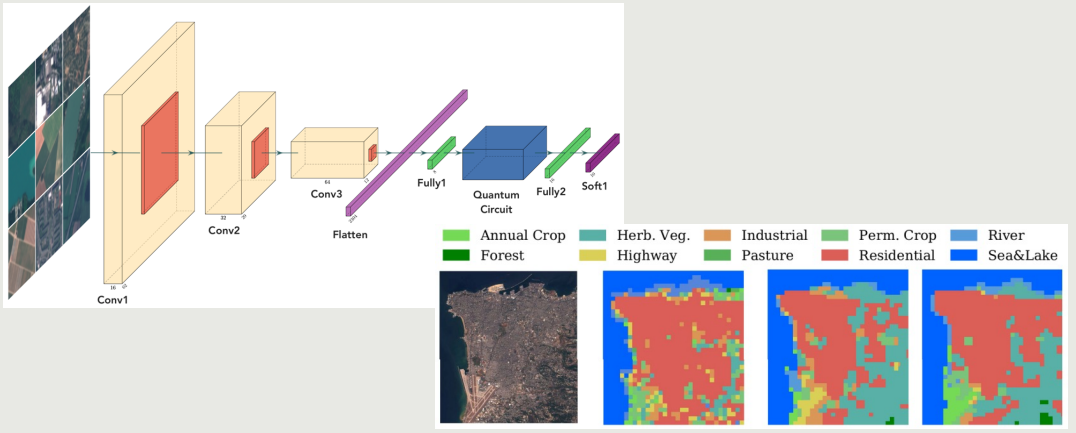
JÜLICH Forschungszentrum

Hybrid Classical Quantum Networks

- Hybrid Classical Quantum Networks (Quantum Convnets, Quantum GANs, Recurrent nets)

Circuit-based Hybrid Quantum Neural Networks for Remote Sensing Imagery Classification:

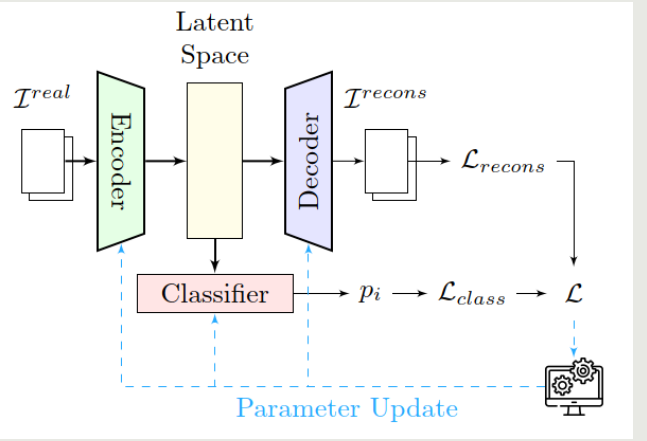
- Hybrid Network with quantum circuit as a layer: QCNN is able to overpass the classical counterpart.

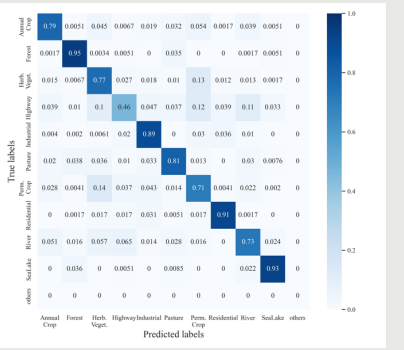


Sebastianelli et al. "On Circuit-based Hybrid Quantum Neural Networks for Remote Sensing Imagery Classification", IEEE JSTARS (15) 2021

Hybrid model : End-to-end trained Classical Autoencoder + Quantum Classifier. :

- EO image classification with SOTA performances





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

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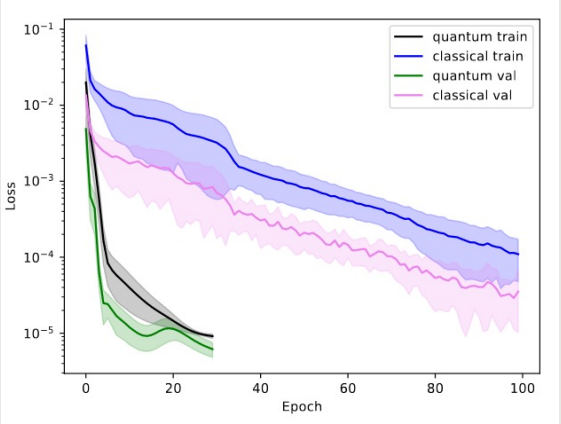
EPFL CERN

Hybrid Classical Quantum Networks

- Hybrid Classical Quantum Networks (Quantum Convnets, Quantum GANs, Recurrent nets)

Recurrent Neural Networks for time-series on Continuous-Variable QC:

- Promises of faster training convergence

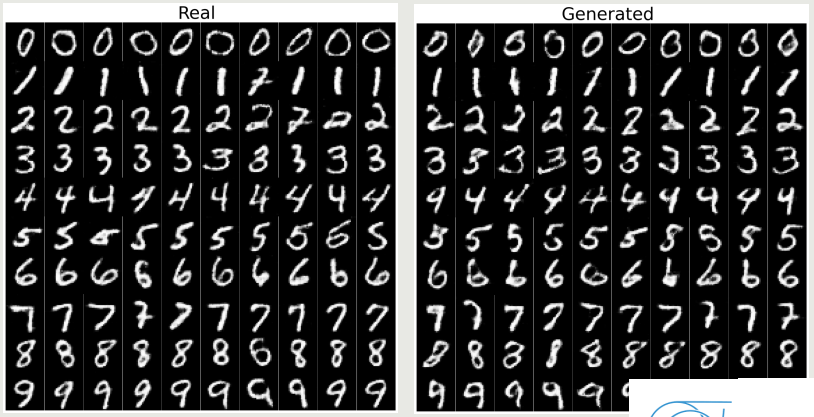


Siemaszko, McDermott, Buracsewski, Le Saux & Stobinska “Rapid training or recurrent quantum neural networks”, **QTML 2022**

UNIVERSITY OF WARSAW

Quantum Generative Adversarial Networks : Quantum Generator + Classical Discriminator

- 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** dataset → Plan to apply on EO image generation



Chang et al., to appear

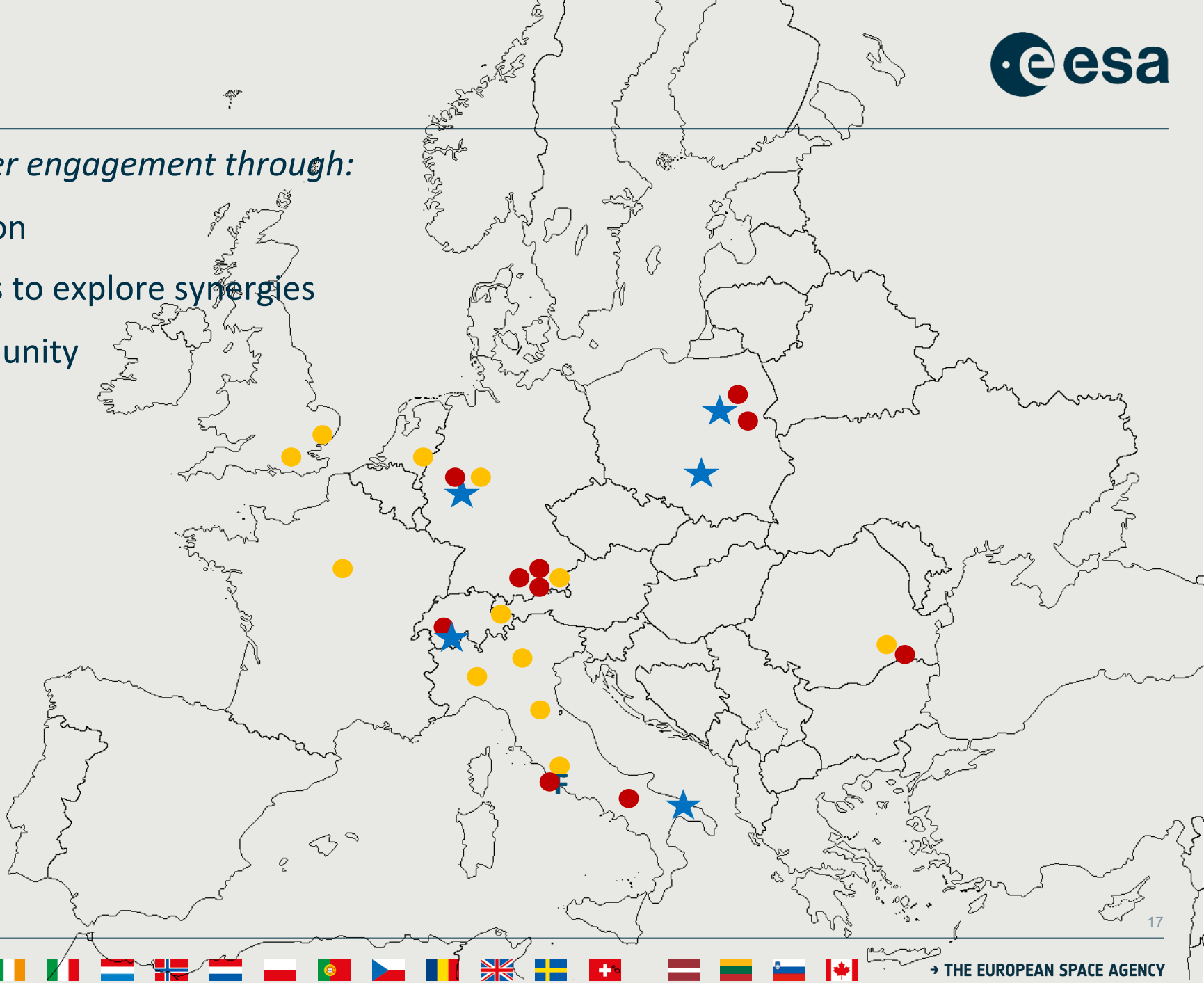
CERN EPFL

3. 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



★ 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”

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…

Community events and thematic initiatives

- IEEE GRSS High-performance and Disruptive Computing (HDCRS) Summer School
  https://www.hdc-rs.com → Once again in May-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" → Open until Dec.2022!
  Ed. M. Datcu (DLR), J. Le Moigne (NASA), B. Le Saux (ESA) → *https://ieeexplore.ieee.org*

QC4EO Network: visiting researchers

Senior visiting researchers:

- 2021: Mihai Datcu (DLR / Politehnica University of Bucharest)
- 2022: Gabriele Cavallaro (Forschungszentrum Jülich)
- 2022: Piotr Gawron (Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences)

Early-career researchers:

- 2022: Michal Siemaszko (PhD Student Univ. Warsaw – Magdalena Stobinska group)
- 2022: Alice Barthe (PhD Student CERN / Leiden University – Vedran Djunko group)
- 2022: Andrea Ceschini (PhD Student La Sapienza University – Massimo Panella group)

- **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!**

Conclusion

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, data mining and optimisation*
- *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**, as quantum volume is likely to increase*
- *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*

Make Space for Europe

- *Follow us: https://www.esa.int/ / https://philab.esa.int/*
- *Join ESA Φ-lab@ESRIN: https://jobs.esa.int/*

  → Internal Research Fellow (postdoc) for AI4EO, QC4EO early 2023, etc.

- *Contact: alessandro.sebastianelli@esa.int, bertrand.le.saux@esa.int*