Φ-lab

Bringing the power of Quantum Computing to Earth Observation

ESA Φ-lab

Climate Action, Sustainability and Science Department

Directorate of Earth Observation Programmes

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European Space Agency

The ESA Φ-lab – What ?

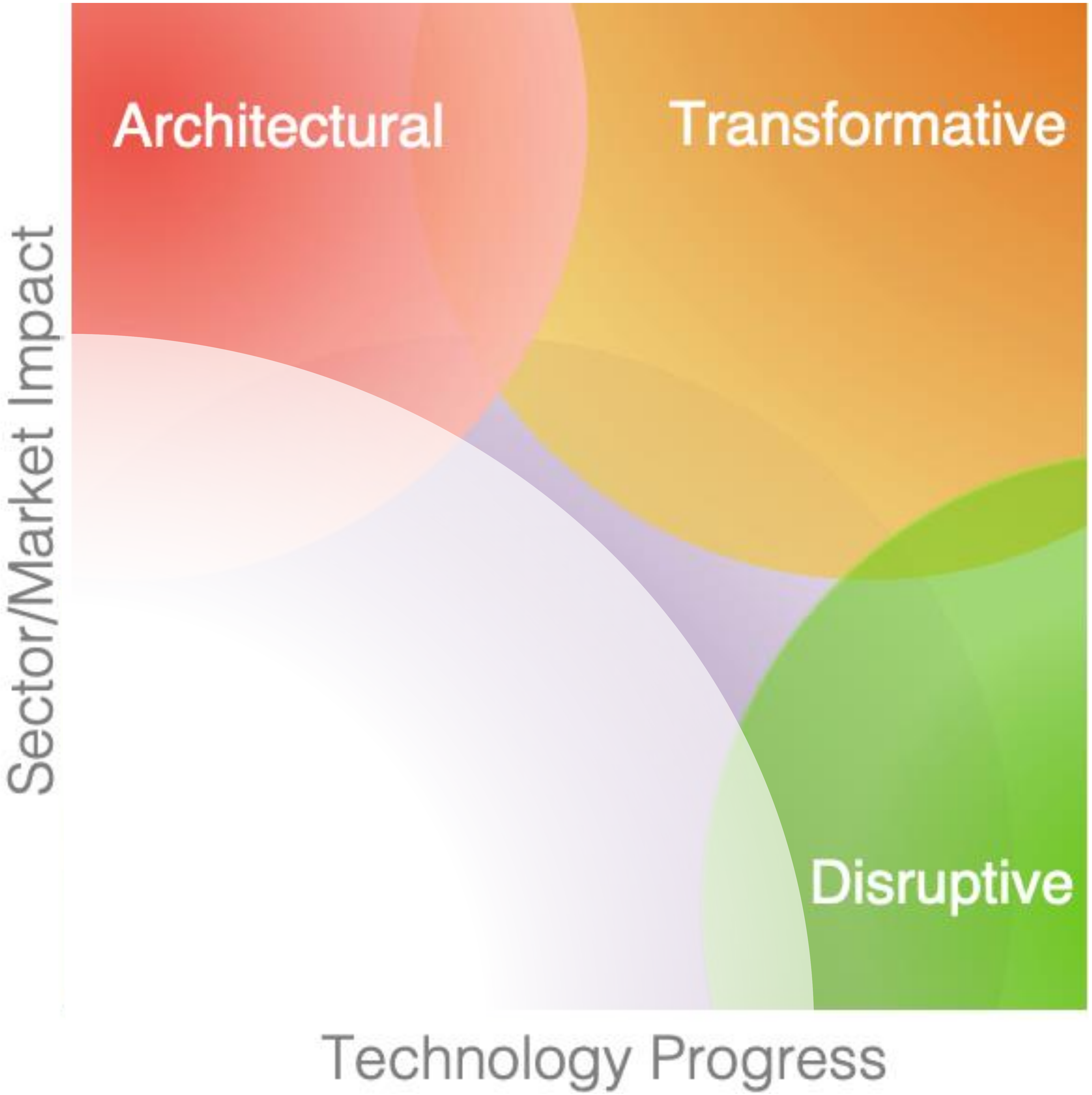
Φ-lab
innovate and apply
under-one-roof

Accelerate the future of Earth Observation via transformative/disruptive innovation*

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

Innovation comes in multiple flavors

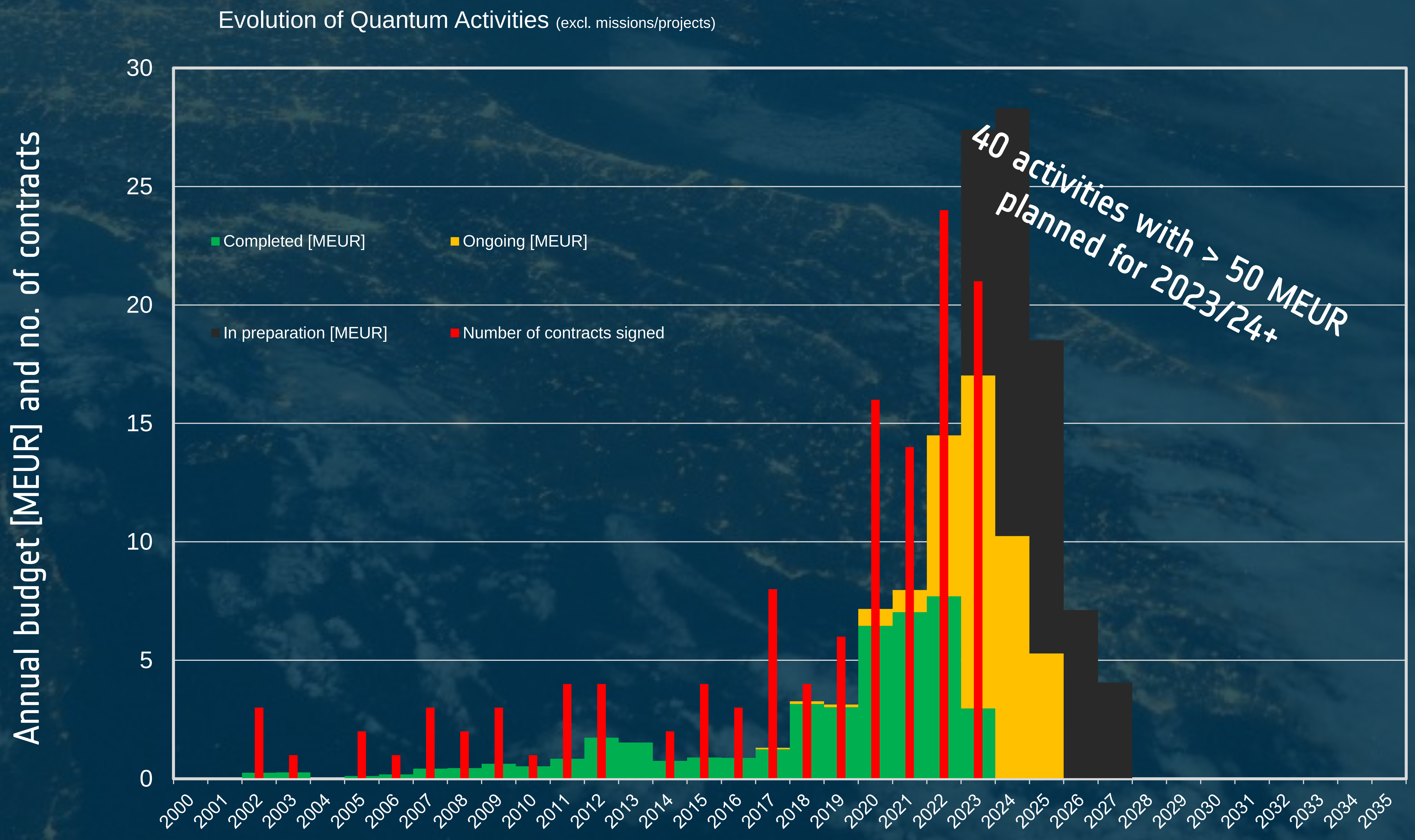
Transformative innovation delivers unique competitive advantage



ESA Quantum Technology Cross Cutting Initiative

QT-CCI coordinates the content of ESA Quantum Technology Activities

- QT established as ESA priority in 2021
- 10 ESA directorates, 50+ people
- Collaborating with industry & academia
- ESA White Paper: Goals for space-based QT



QT-CCI: Technical Topics

Quantum Communication
- Quantum key distribution and (non-QKD) quantum internet applications

Atomic Frequency Standards
- Atomic clocks, optical clocks, time & frequency transfer, optical frequency combs / for science or applications

Cold Atom Interferometers
- Cold atom interferometers for science or applications

Post Quantum Cryptography
- Space qualified quantum computing resistant algorithms, hardware and security concepts

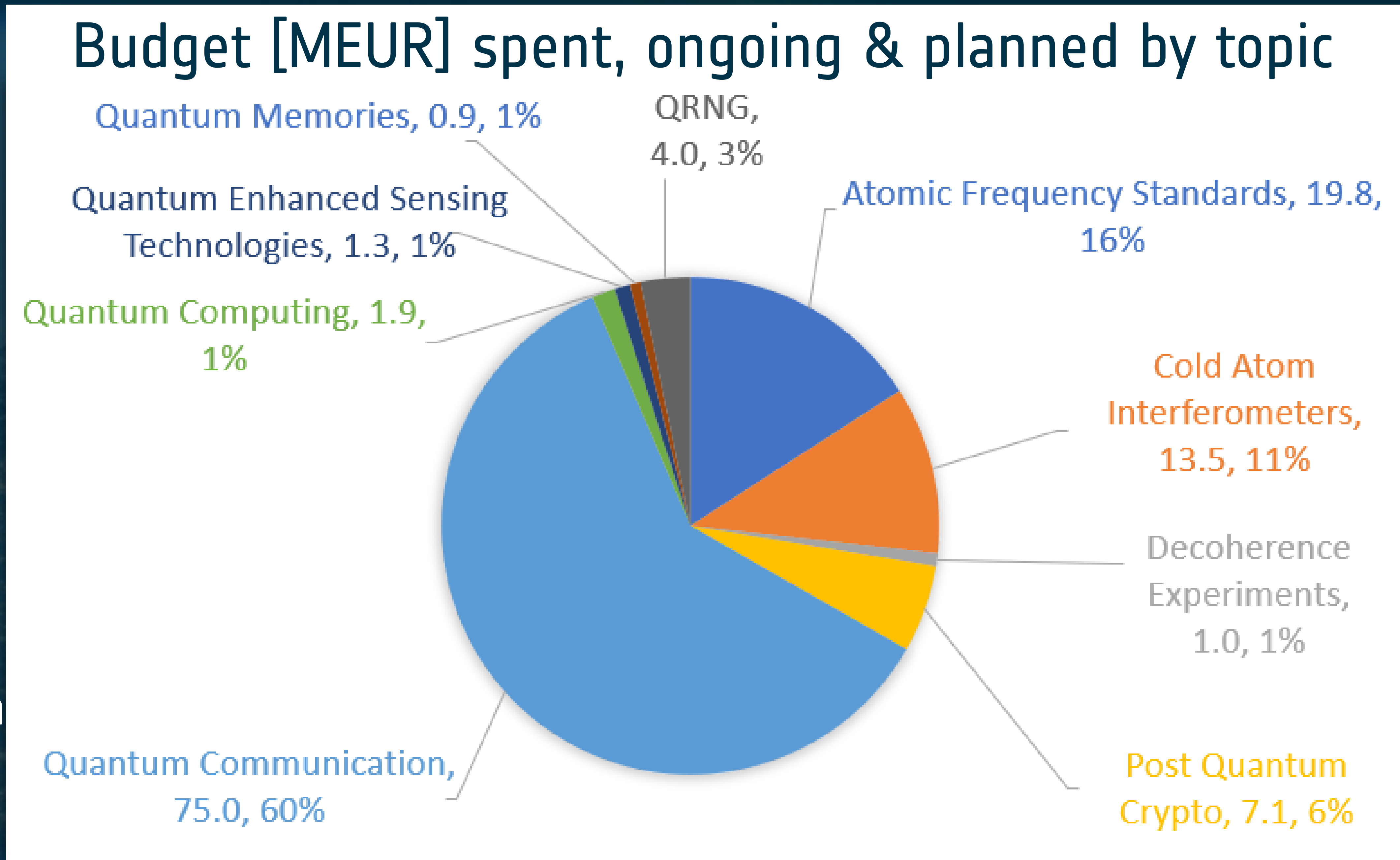
Quantum Random Number Generators
- Space suitable RNGs for quantum or classical security applications based on quantum effects

Decoherence Experiments
- Decoherence experiments probing quantum gravity of macroscopic quantum mechanics

Quantum Computing
- Quantum computing algorithms for space applications (earth observation data processing, orbit optimizations, etc.)

Quantum Memories
- Understanding and developing quantum memories for space-based science experiments or applications

Quantum Enhanced Sensing Techniques
- Quantum based magnetometers, Q-LIDAR, Q-RADAR, Q-Imaging



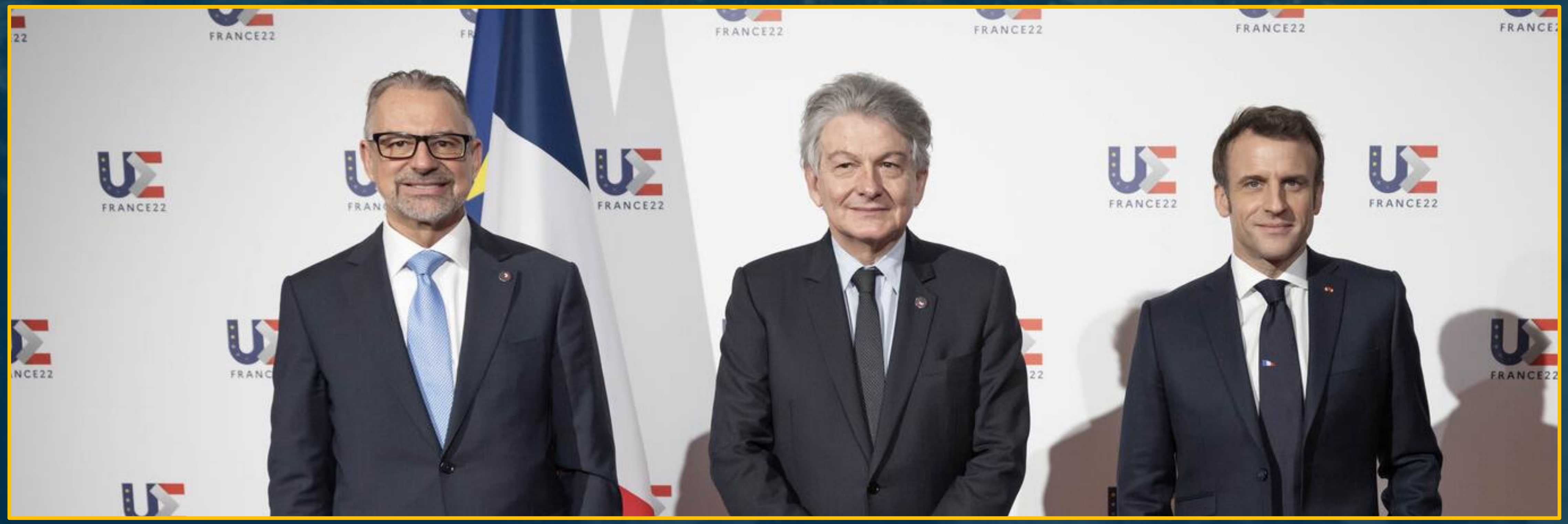
Highlights of the past 12 months

14 April 2023: Juice launches to Jupiter with quantum sensor MAGSCA

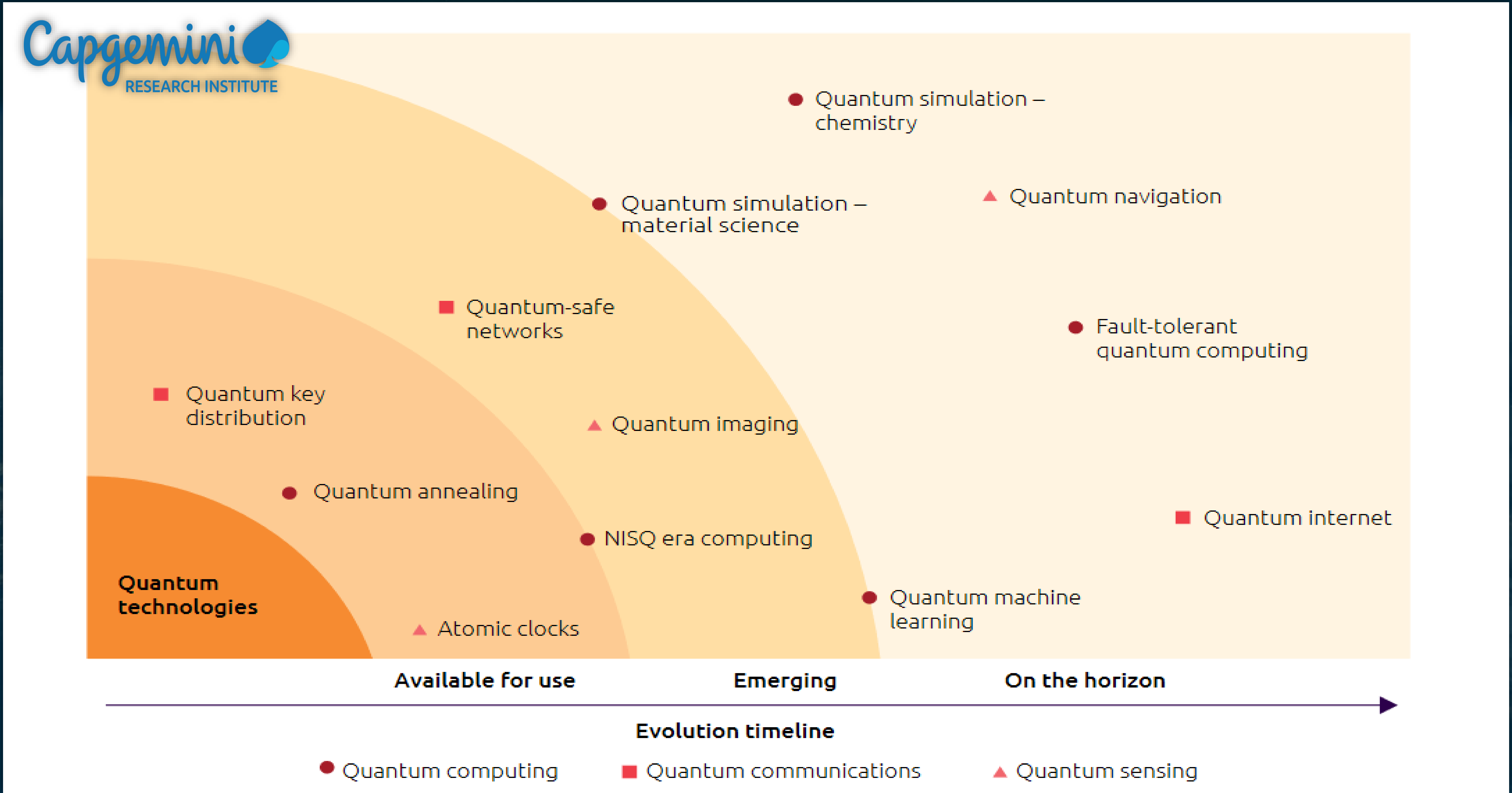
MAGSCA measures the absolute strength of the magnetic field. The quantum effect is generated by specifically modulated laser light interfering with rubidium atoms in the glass cell of the sensor. This measurement is free from calibration errors because the effect is based on fundamental physical constants. Consequently, MAGSCA can calibrate the two other sensors of J-MAG instrument, allowing them to fully characterise the magnetic field

SAGA Phase B1 Studies

Two competitive industry studies and technology developments defining the QKD space segment for the EC led EuroQCI. SAGA will be the space segment of the EC governmental QKD service



Quantum Trends in 2023



Quantum Computing Trends in 2023

2019	2020	2021	2022	2023	2024	2025	2026+
Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime

Model Developers

- Prototype quantum software applications → Quantum software applications
  - Machine learning | Natural science | Optimization

Algorithm Developers

- Quantum algorithm and application modules
  - Machine learning | Natural science | Optimization
- Quantum Serverless
  - Intelligent orchestration
  - Circuit Knitting Toolbox
  - Circuit libraries

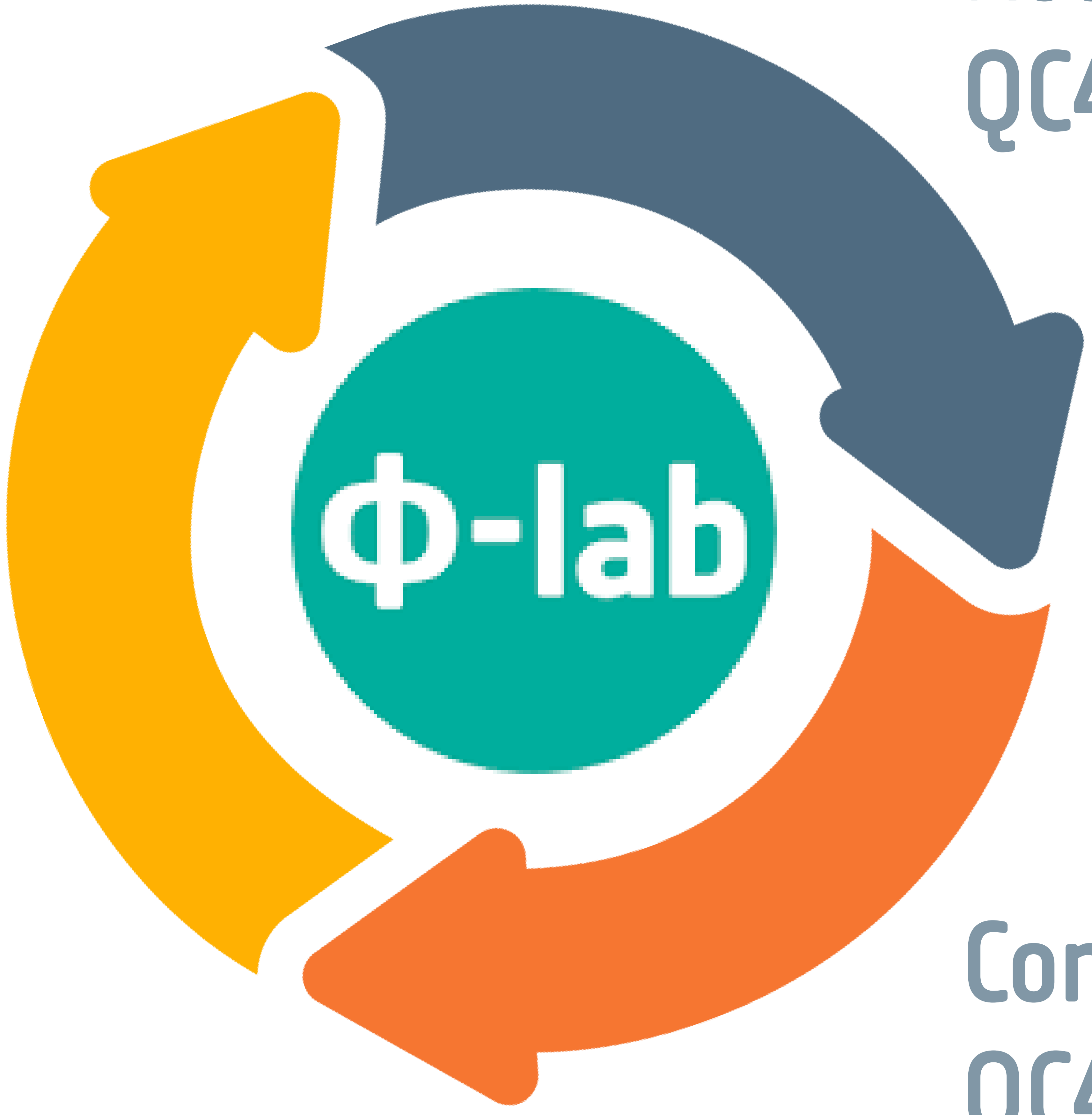
Kernel Developers

- Circuits
- Qiskit Runtime
  - Dynamic circuits
  - Threaded primitives
  - Error suppression and mitigation
  - Error correction

System Modularity

- Falcon: 27 qubits
- Hummingbird: 65 qubits
- Eagle: 127 qubits
- Osprey: 433 qubits
- Condor: 1,121 qubits
- Flamingo: 1,386+ qubits
- Kookaburra: 4,158+ qubits
- Scaling to 10K-100K qubits with classical and quantum communication
- Heron: 133 qubits x p
- Crossbill: 408 qubits

ESA QC4EO initiative the Three pillars



Roadmap definition
QC4EO studies

QC and QML
Exploratory activities

Community building
QC4EO Network

QC4EO fundamental question

Will QC bring a real advantage in Earth Observation applications within next 5-15 years and how?

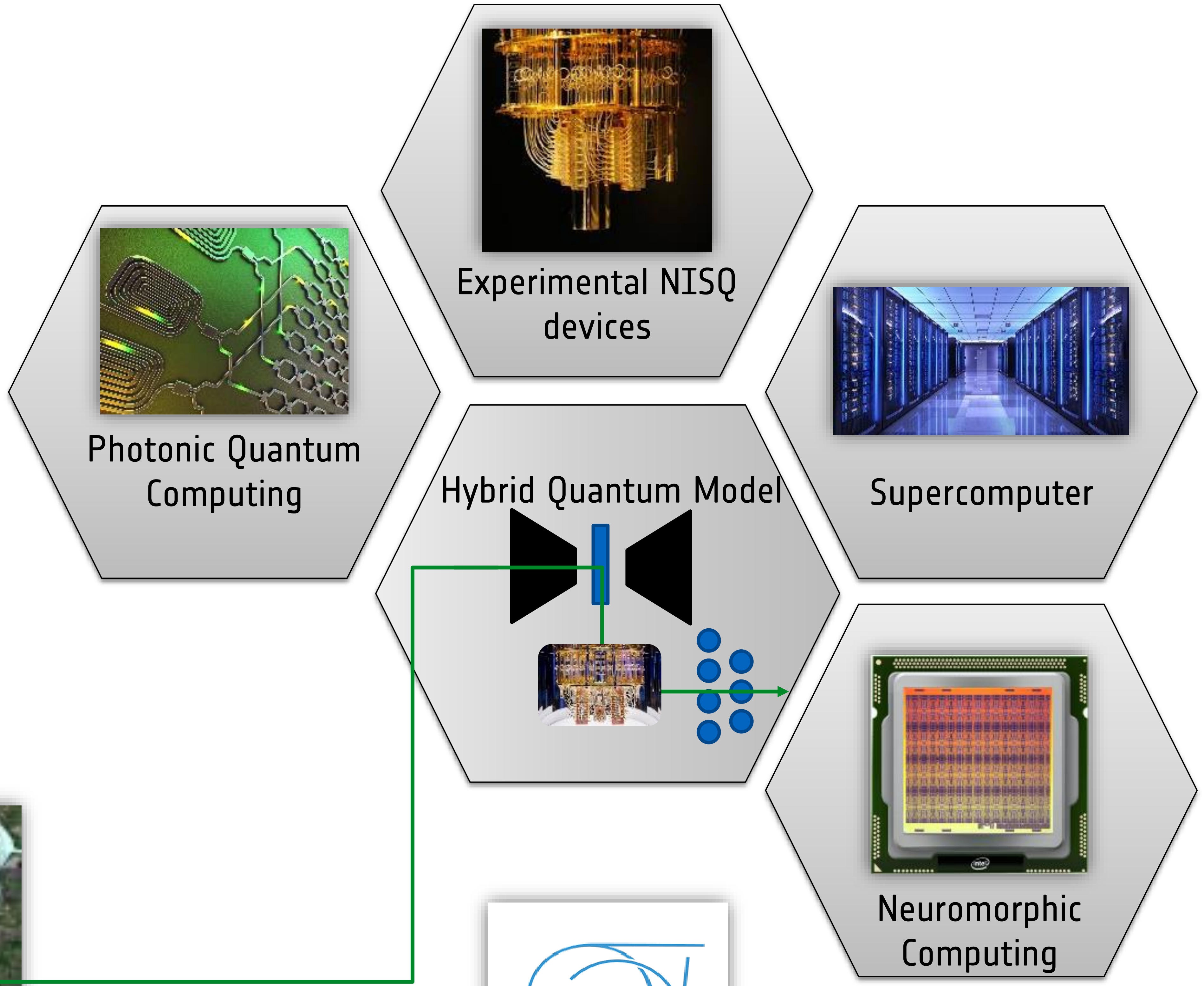
- QC promises to revolutionize several industrial sectors that will benefit from a substantial cost reduction in terms of time and energy consumption
- EO area is rich in computationally hard problems for in space and on ground use cases

- ESA QC4EO goals are to :

1. identify relevant EO use cases that can significantly benefit from QC
2. define the HW and Information Theory implementation requirements (roadmap)
3. estimate when this benefits will be delivered for a real size problem

Exploratory activities in QC and QML

- Explore QC models and computational paradigms
- Explore the potential of Quantum Machine Learning for Earth Observation use cases
- Devise hybrid quantum AI models in HPC environments
- Build a strong community of experts in both Quantum Computing and Earth Observation



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JAGIELLONIAN UNIVERSITY IN KRAKÓW

Exploratory activities in QML and Quantum Computing

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

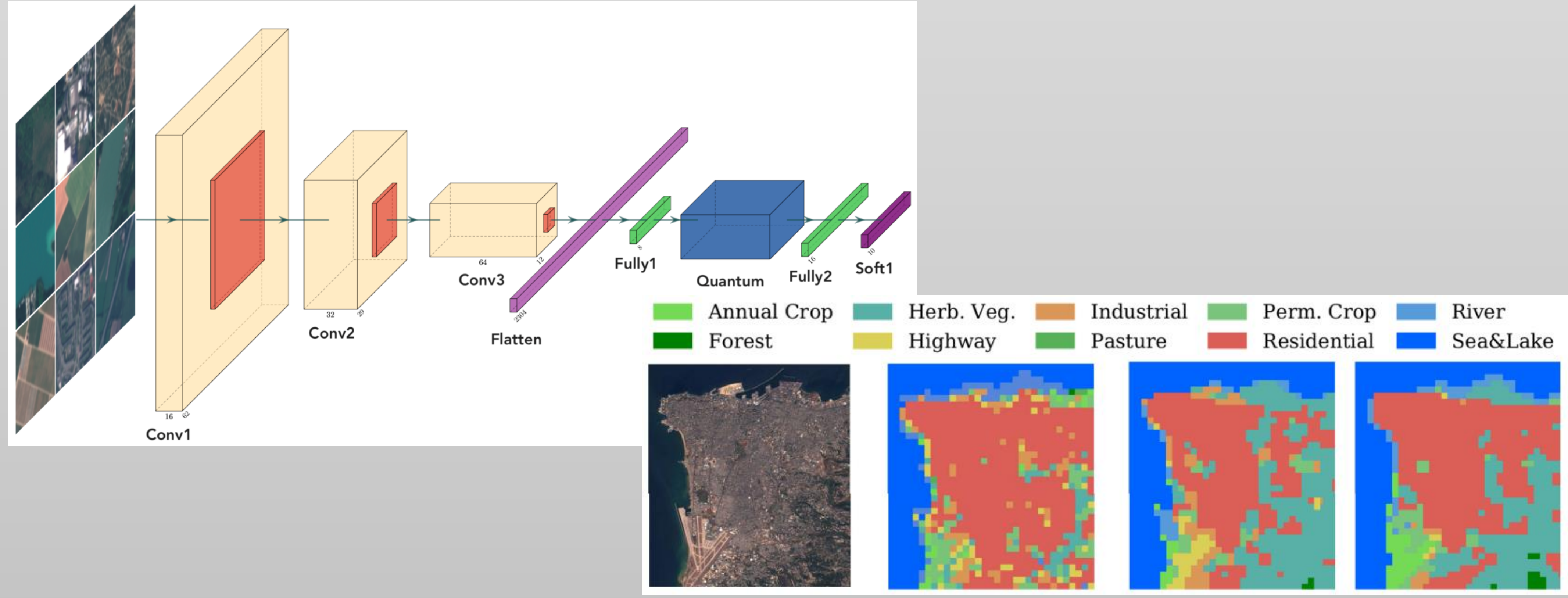
Case Study 1: Hybrid QCNN for EO classification

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

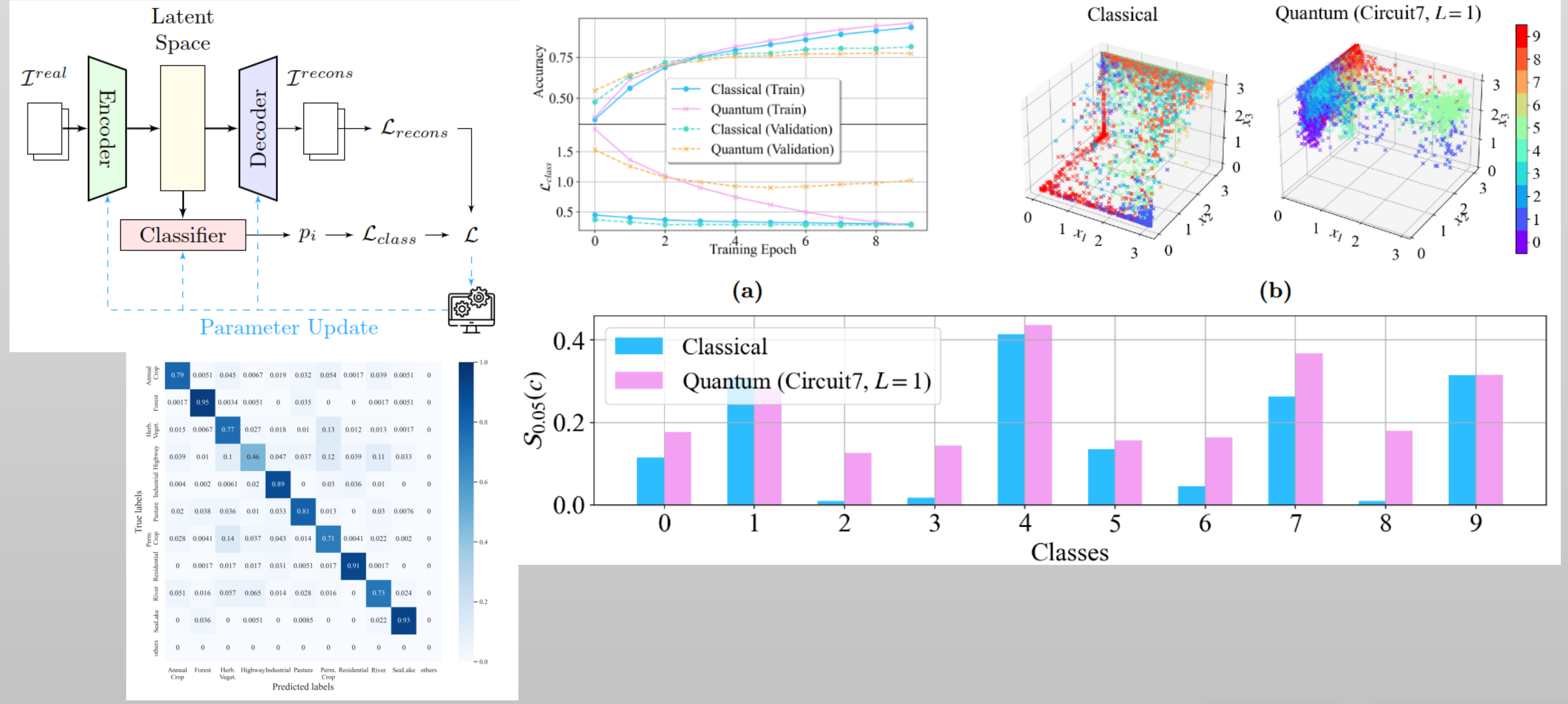
Use-case: EO image classification

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

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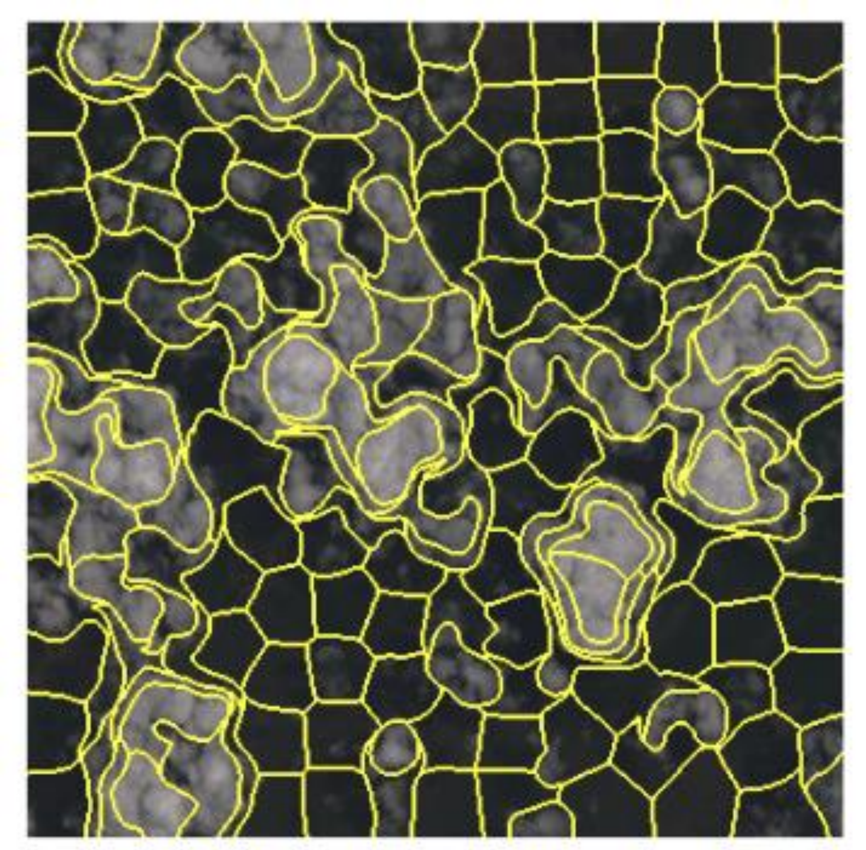
Exploratory activities in QML and Quantum Computing

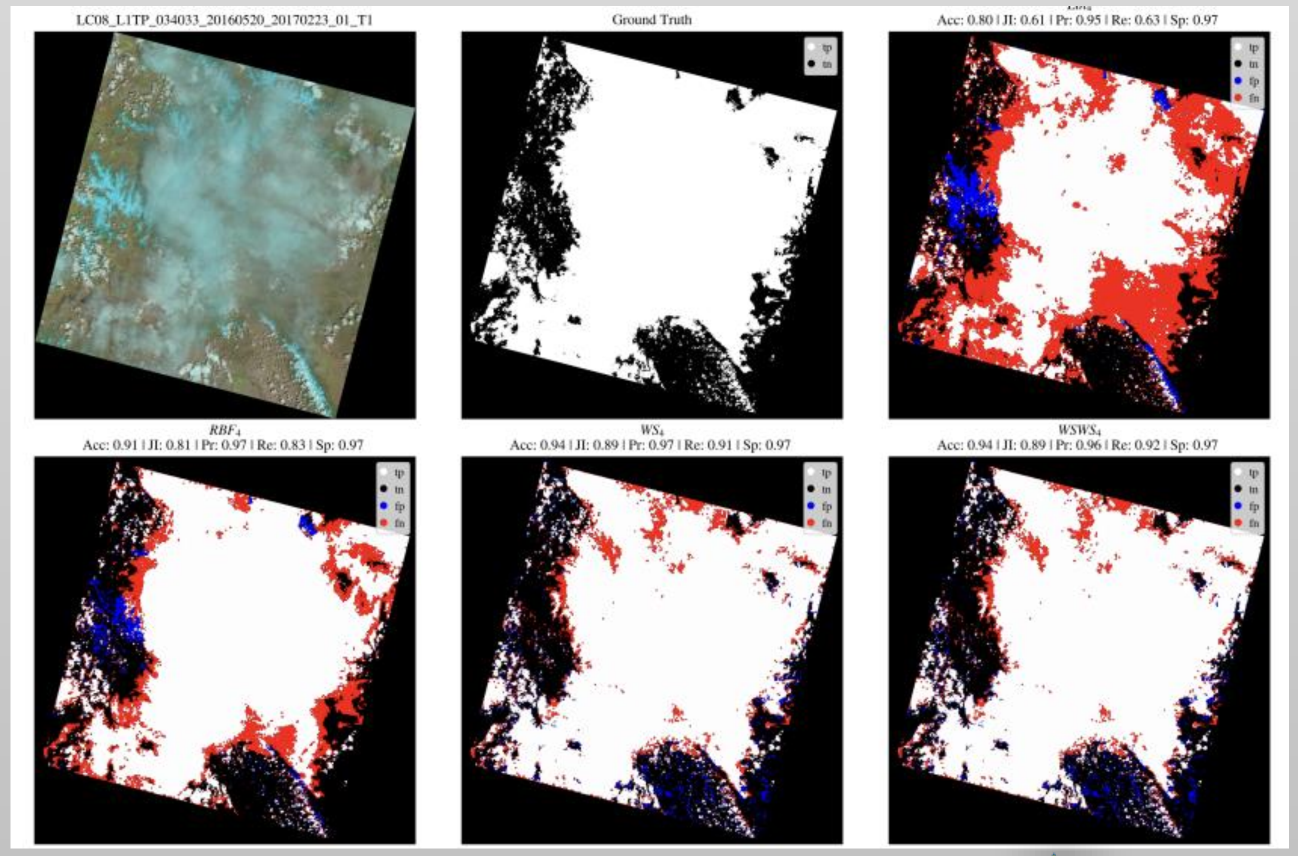
➢ Exploring Quantum Kernels (e.g. Projected Quantum Features, SVMs…)

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.

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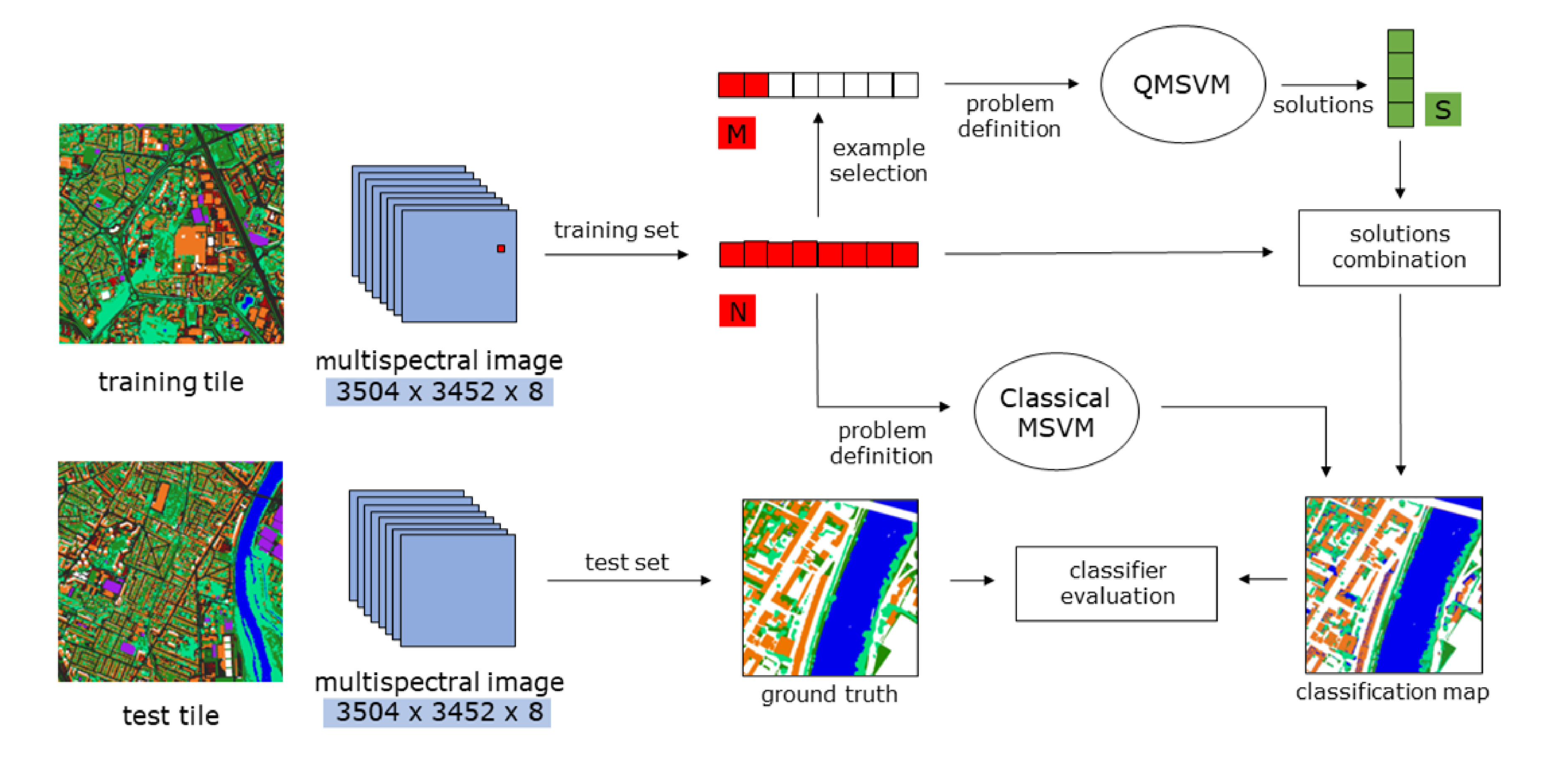
Case Study 4: Annealing-based Quantum SVM
Use case: Classification of multispectral EO data.
Approach: Hybrid Support Vector Machines (SVMs) with **Julich SC Quantum Annealer**.

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.

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Exploratory activities in QML and Quantum Computing

Quantum Generative AI

Case Study 5: Quantum Diffusion Models

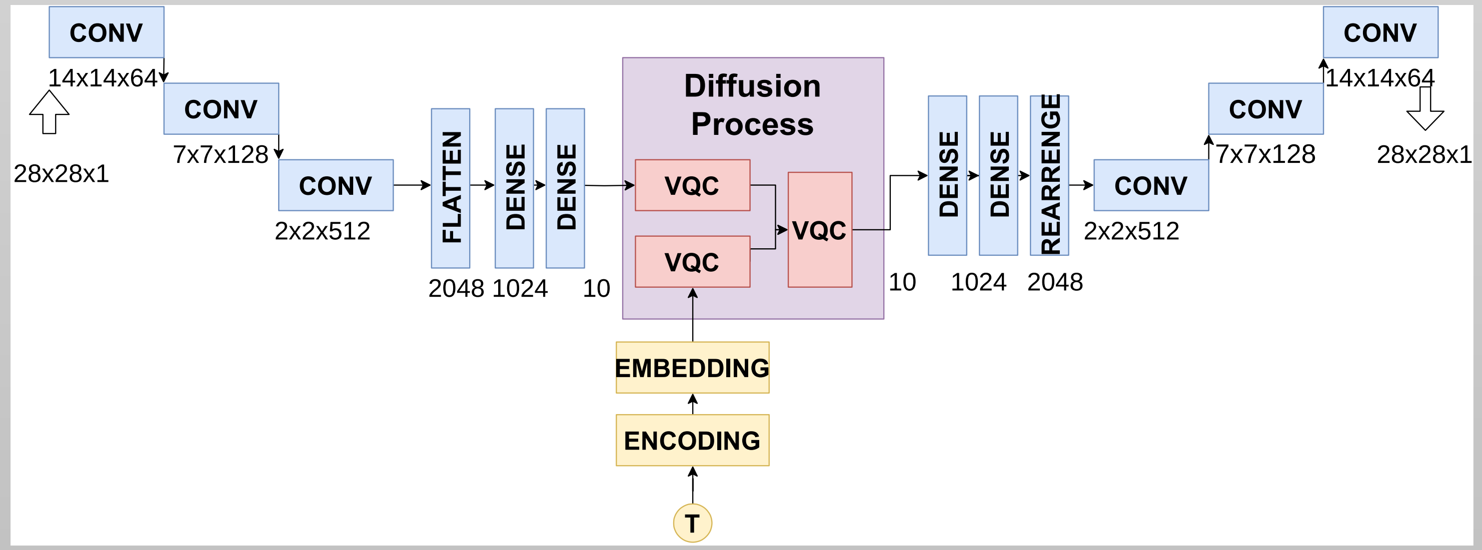
Use case: Generative modelling and synthesis of images.

Approach:

1. Hybrid Quantum ResNet for denoising in a standard diffusion ,
2. then Latent Quantum Diffusion: images are encoded in latent space, to run the diffusion process in a fully quantum approach.

Findings:

- Proof of concept of Latent Quantum Diffusion Models, with results on par with "exotic" approaches e.g., spiking NNs
- Latent Quantum Diffusion circuit allows a significantly lower number of parameters.



Quantum (Params = 360)
FID = 91.3434
KID = 0.0713 ± 0.0018
IS = 3.6518± 0.1045

Di Falco et al., QTML 2023

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Case Study 6: Quantum GANs

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

Exploring the generalisation power of Quantum Networks

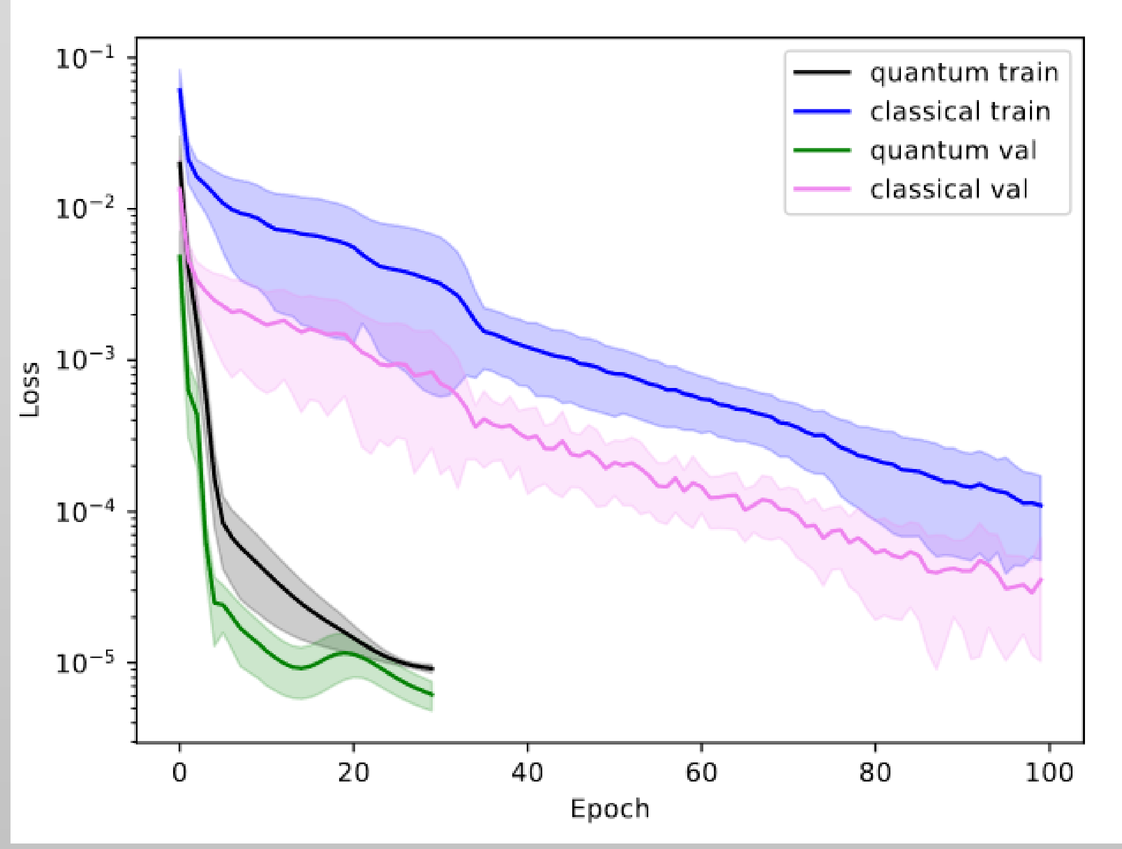
Case Study 7: Continuous-variable QC RNNs

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

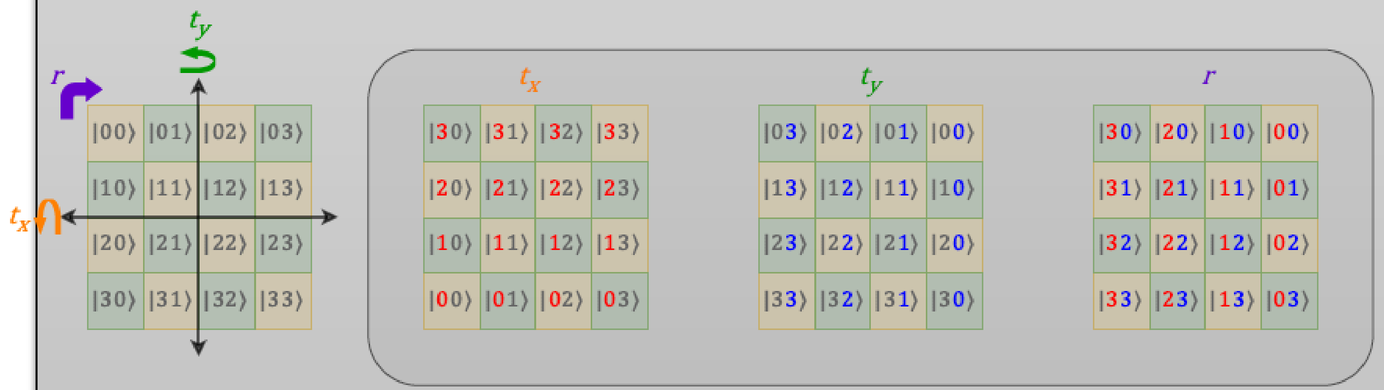
Case Study 8: Quantum Equivariant NN

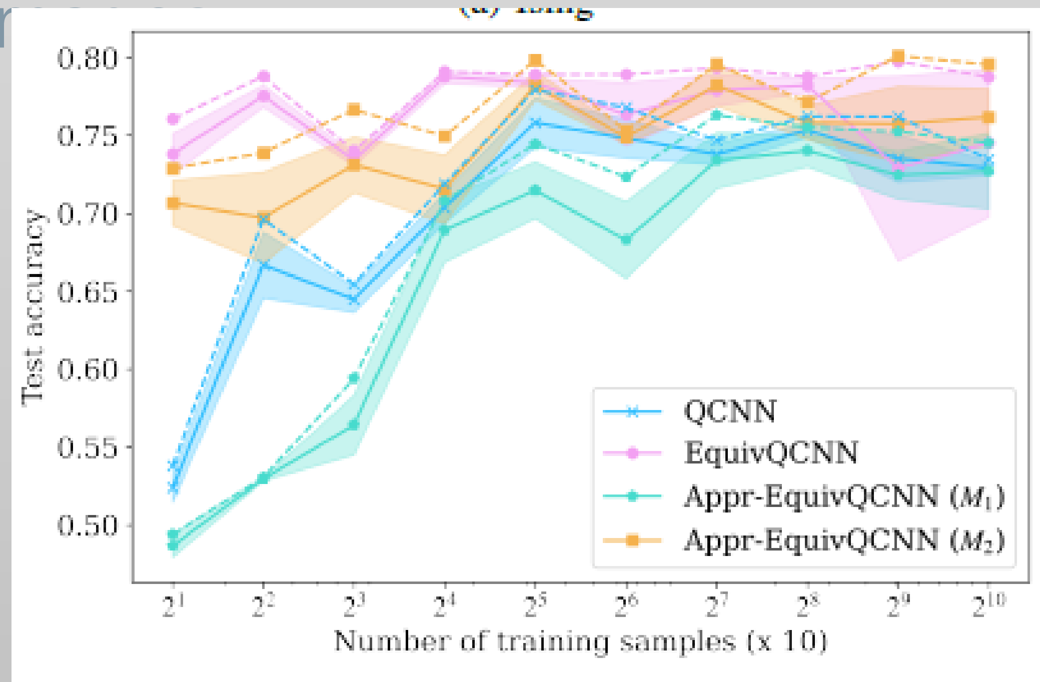
Use case: Data and image classification.

Approach: .design Quantum Neural Nets equivariant with respect to the underlying symmetry of the data to force inductive bias of the model.

Findings:

- Equivariance for planar wallpaper symmetry group p4m (reflections, 90d rotations)
- Equivariant design increases generalization power, in particular, while using only a small number of training samples
- Approximately- equivariant QNNs (with added noise) perform better on symmetric i





(b) Extended MNIST

Chang et al., IEEE Quantum Week 2023

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Exploratory activities in QML and Quantum Computing

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ESA Φ-lab @ QTML'2023:

- **Geometric QML:** Embedded equivariance leads to better generalisation with few samples

  Chang et al., Approximately Equivariant Quantum Neural Network for p4m Group Symmetries in Images, IEEE Quantum Week 2023, QTML 2023

- **Quantum Generative AI:** Quantum layers in hybrid networks improve generation scores!

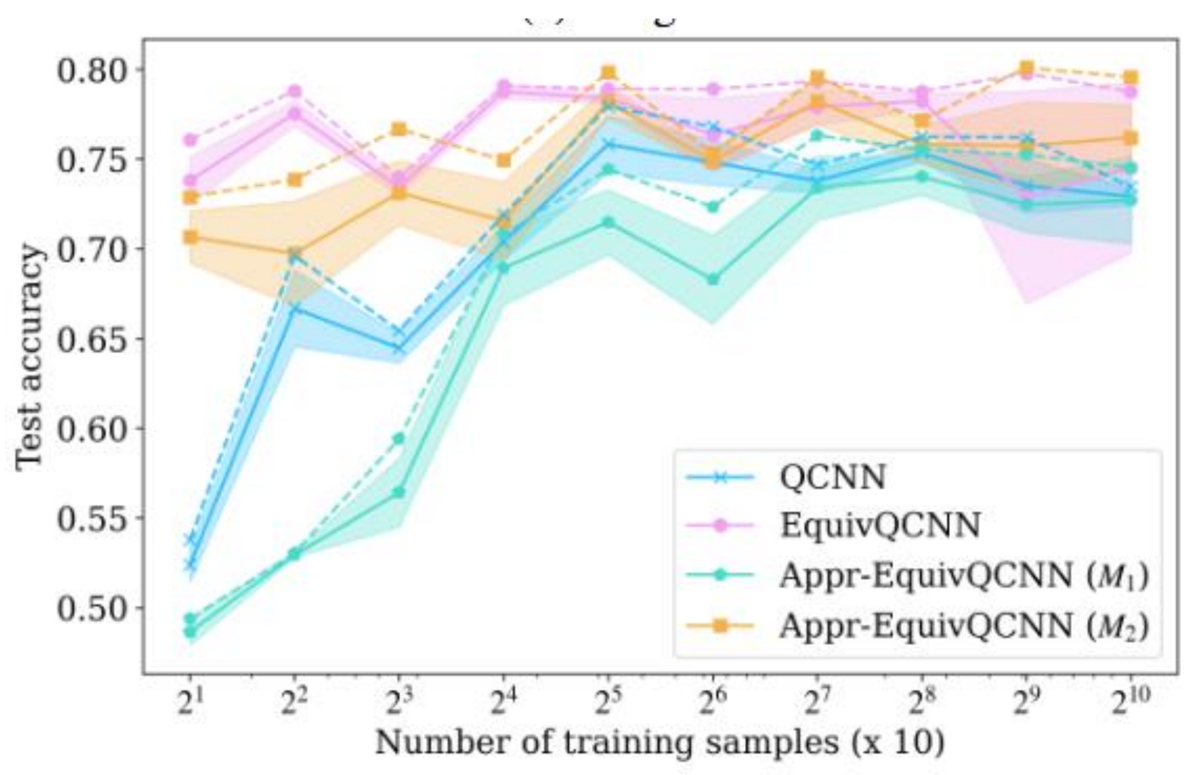
  De Falco et al., Towards Quantum Diffusion Models, QTML 2023

- **QNN Optimisation:** visualisation of optimisation landscapes as a tool to avoid vanishing gradients

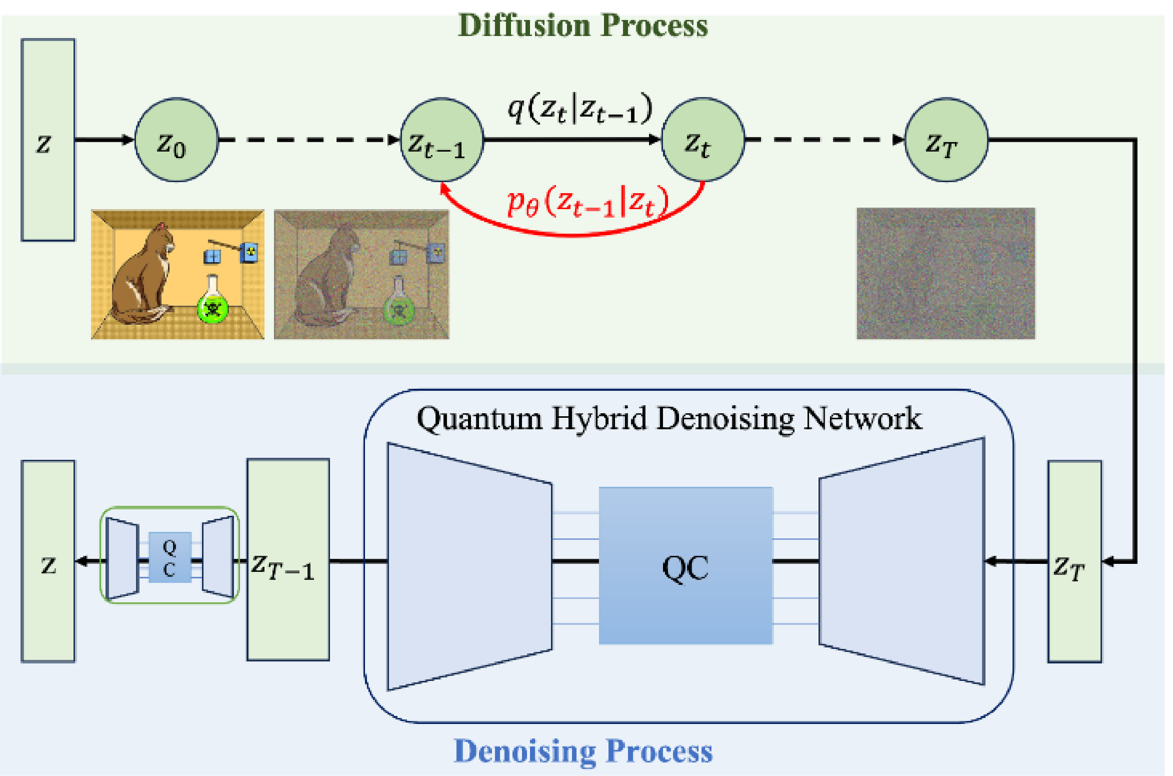
  Mair et al., Towards Strategies to Avoid Barren Plateaus, QTML 2023

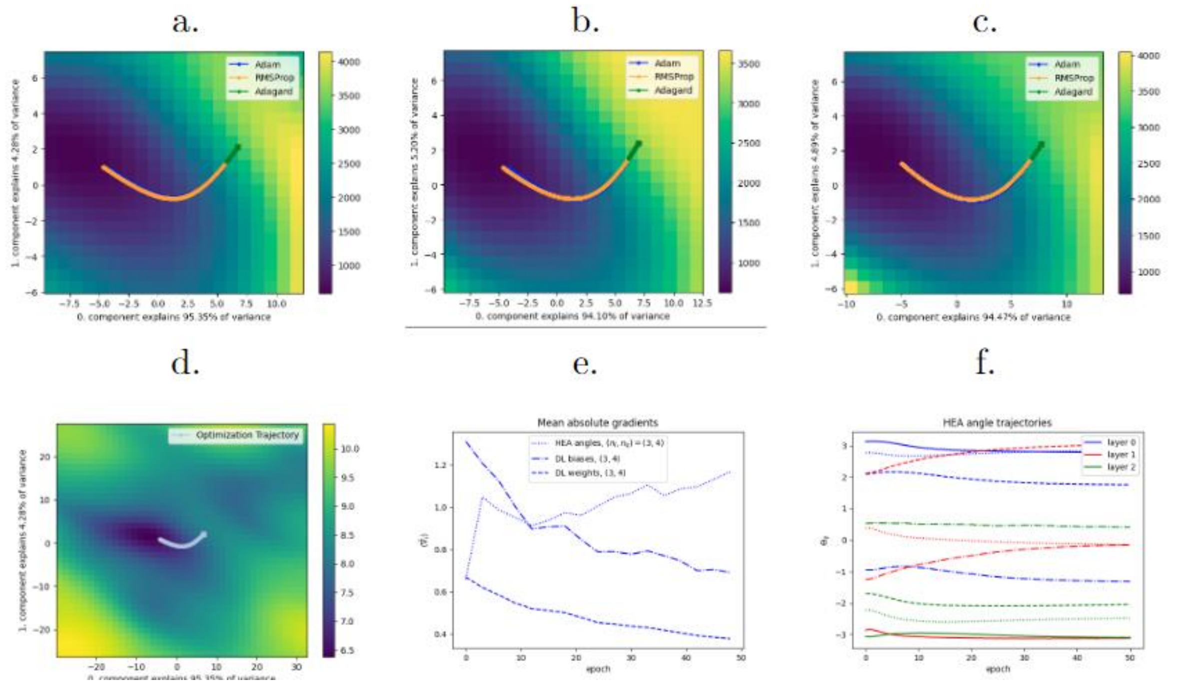
- **A Single-Step Multiclass SVM based on Quantum Annealing for Remote Sensing Data Classification:** quantum annealing for image classification

  Delilbasic et al., A Single-Step Multiclass SVM based on Quantum Annealing for Remote Sensing Data Classification, QTML 2023



(b) Extended MNIST





QC4EO studies : some Use Cases

MISSION PLANNING for EO CONSTELLATIONS ACQUISITIONS

LARGE CONSTELLATION DESIGN

EM SIMULATIONS FOR ANTENNA DESIGN OPTIMIZATION

SAR ANTENNA DESIGN OPTIMIZATION

RADAR DIGITAL BEAMFORMING

SAR RAW DATA PROCESSING

PHASE UNWRAPPING

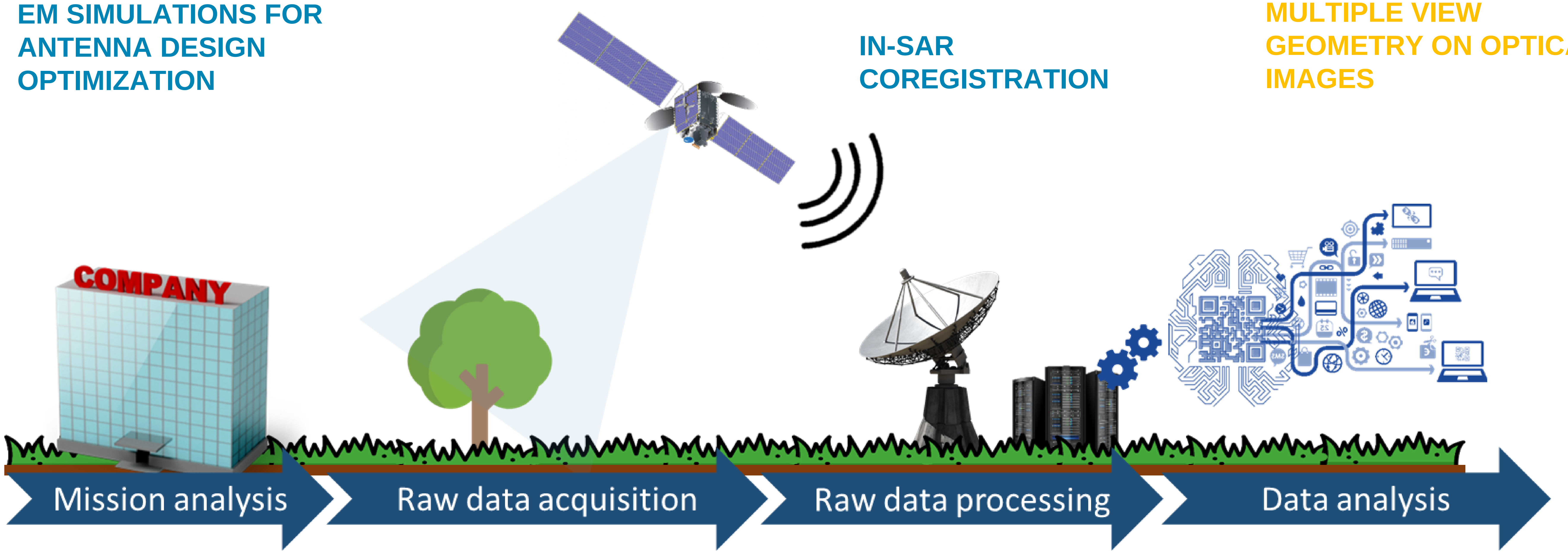
IN-SAR COREGISTRATION

OPTICAL AND RADAR DATA FUSION

SAR IMAGE SEGMENTATION

IMAGE CLASSIFICATION

MULTIPLE VIEW GEOMETRY ON OPTICAL IMAGES



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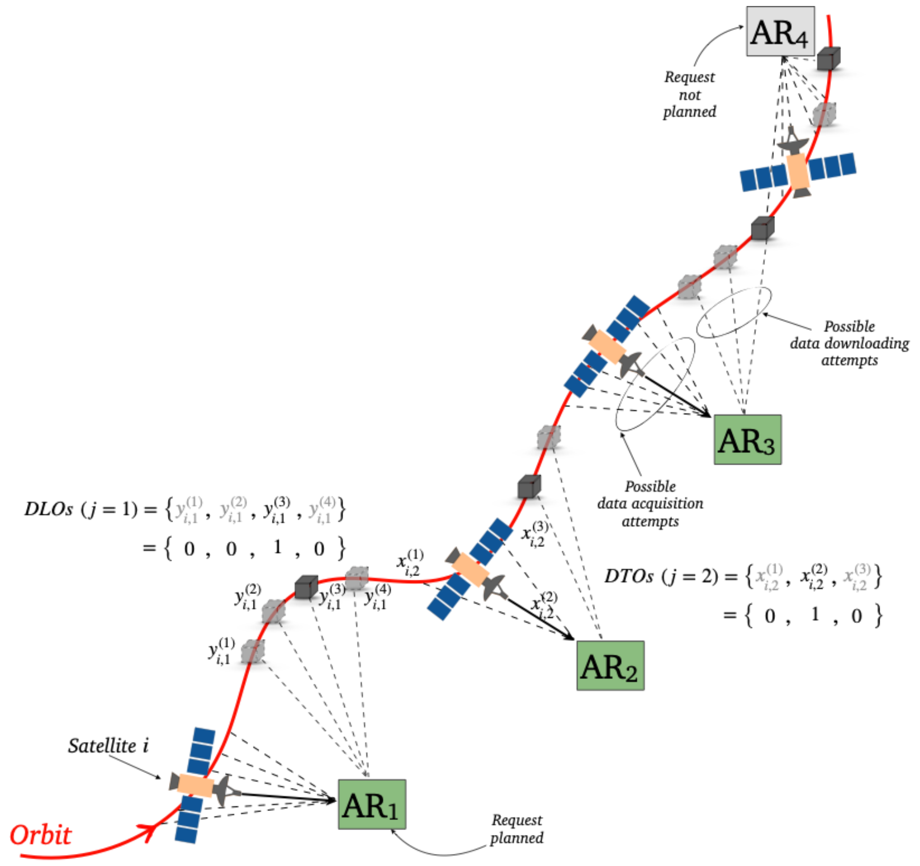
Mission Planning



Description: optimal scheduling of satellite observations for a given list of user requests

Motivations: trend of large constellations, useful for both optical and radar images

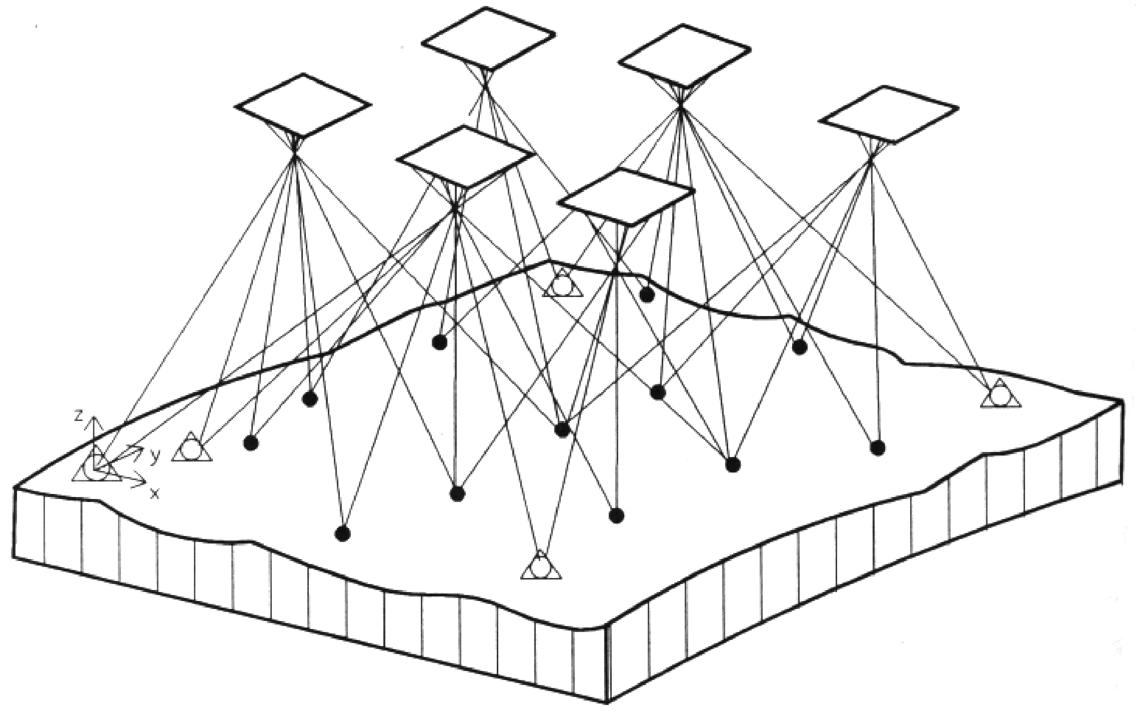
Mission step: raw data acquisition

Sizing: research space scales a 2^N, with N > 100

Classical solutions: Genetic algorithms, simulated annealing

Bottlenecks: Quality of the solution for large constellations and time horizons > few days

Multiple-view Geometry on optical images



Description: acquisition of different views of same the area of interest: images may be rotated or translated, the illumination or scale may differ from one image to another

Motivations: change analysis, terrain reconstruction, enhancing applications like target detection

Mission step: raw data acquisition

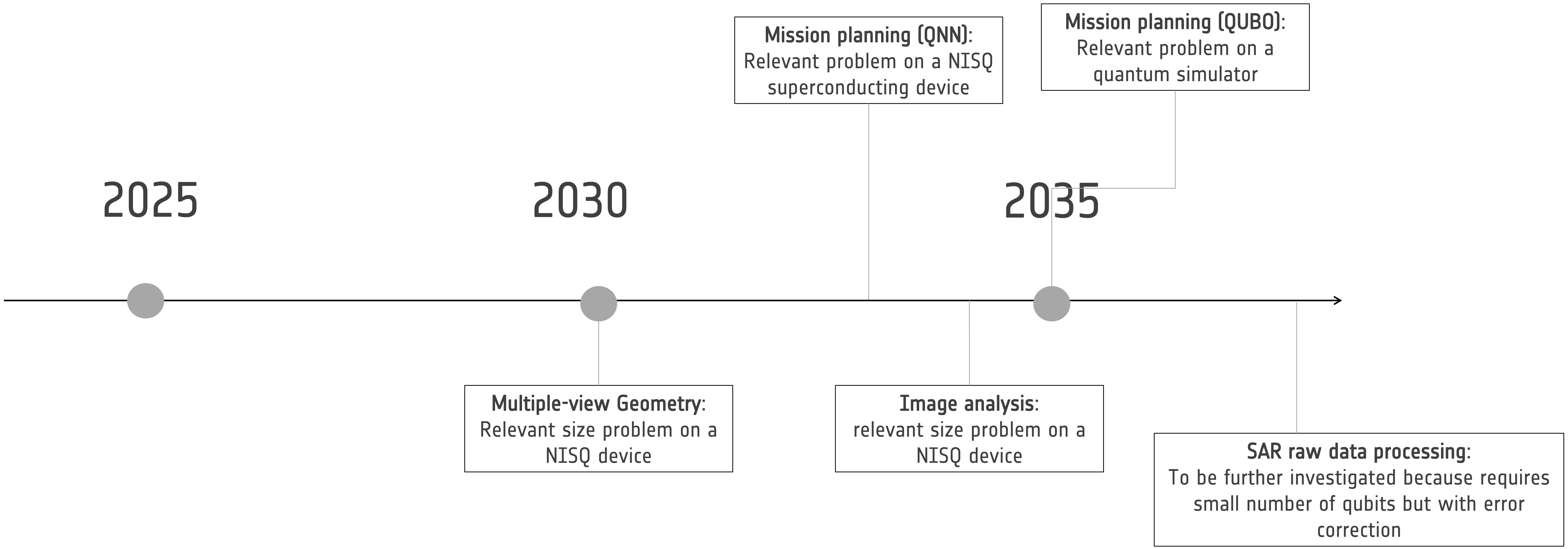
Sizing: 30000 x 30000 x 4 images (VHR)

Classical solutions: computer vision algorithms for keypoint extractions and alignments

Bottlenecks: Not solvable as one large optimization

Estimating a QC4EO TIMELINE

Comparing the industrial roadmaps of QC machines with the expected size of these use cases we can estimate a timeline for the use cases



For all UCs, resolving ful size problems with Error Correction is envisioned to happen beyond the time horizon of this study (>15 y)

QC4EO Studies' outcome

2 projects in 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 enhance computational performances w.r.t. 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;
- Derive a credible **QC4EO timeline of use cases** that could take advantage of a QC approach

Potential use-cases in EO definitions and roadmaps available on by end of 2023 :

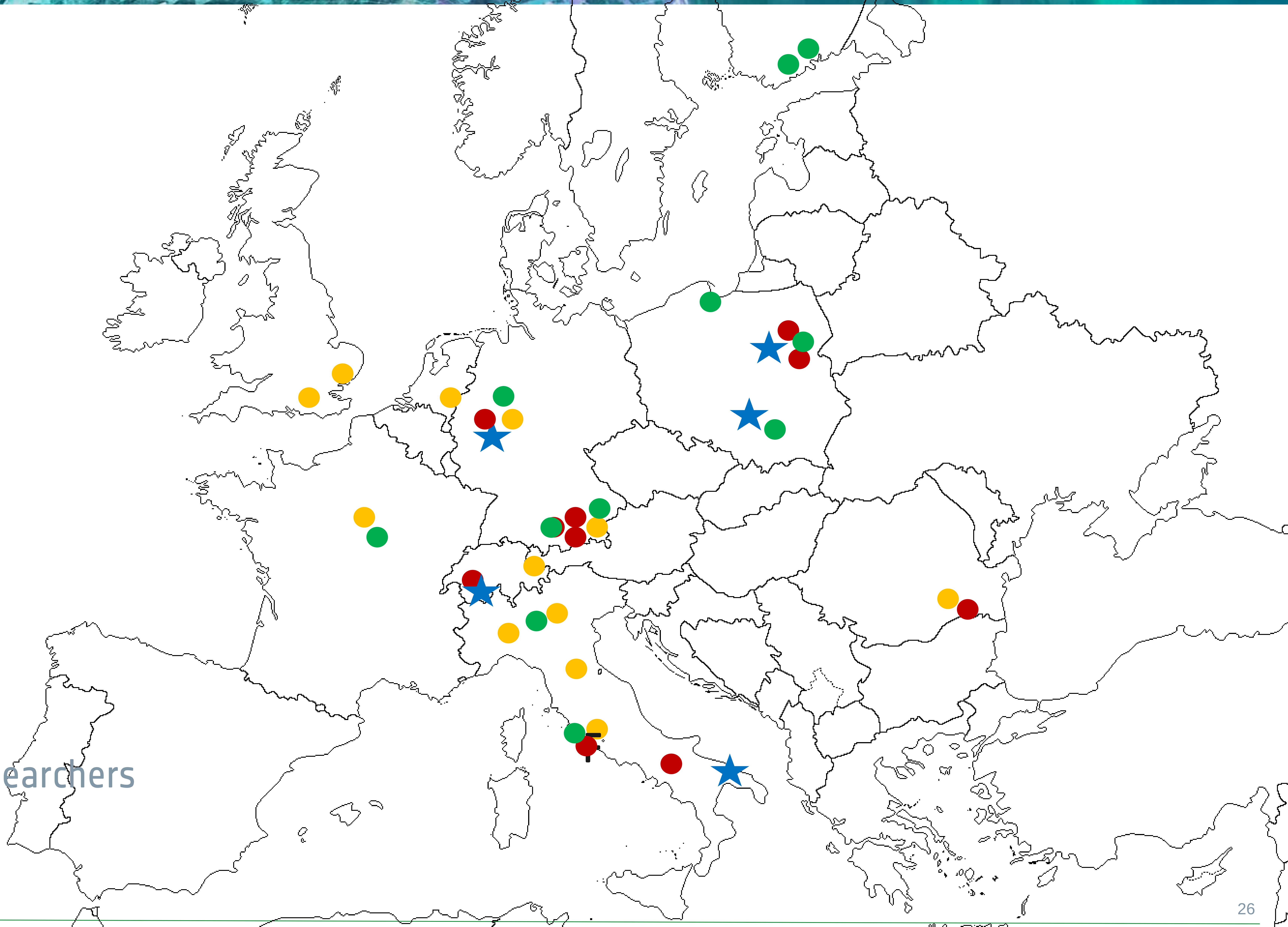
https://eo4society.esa.int/projects/qc4eo-study/

https://eo4society.esa.int/projects/qa4eo-study/

QC4EO Community Network

Community building and stakeholder engagement through:

- Foster centres of excellence
- Workshop and event organisation
- Consult QC and EO communities to explore synergies

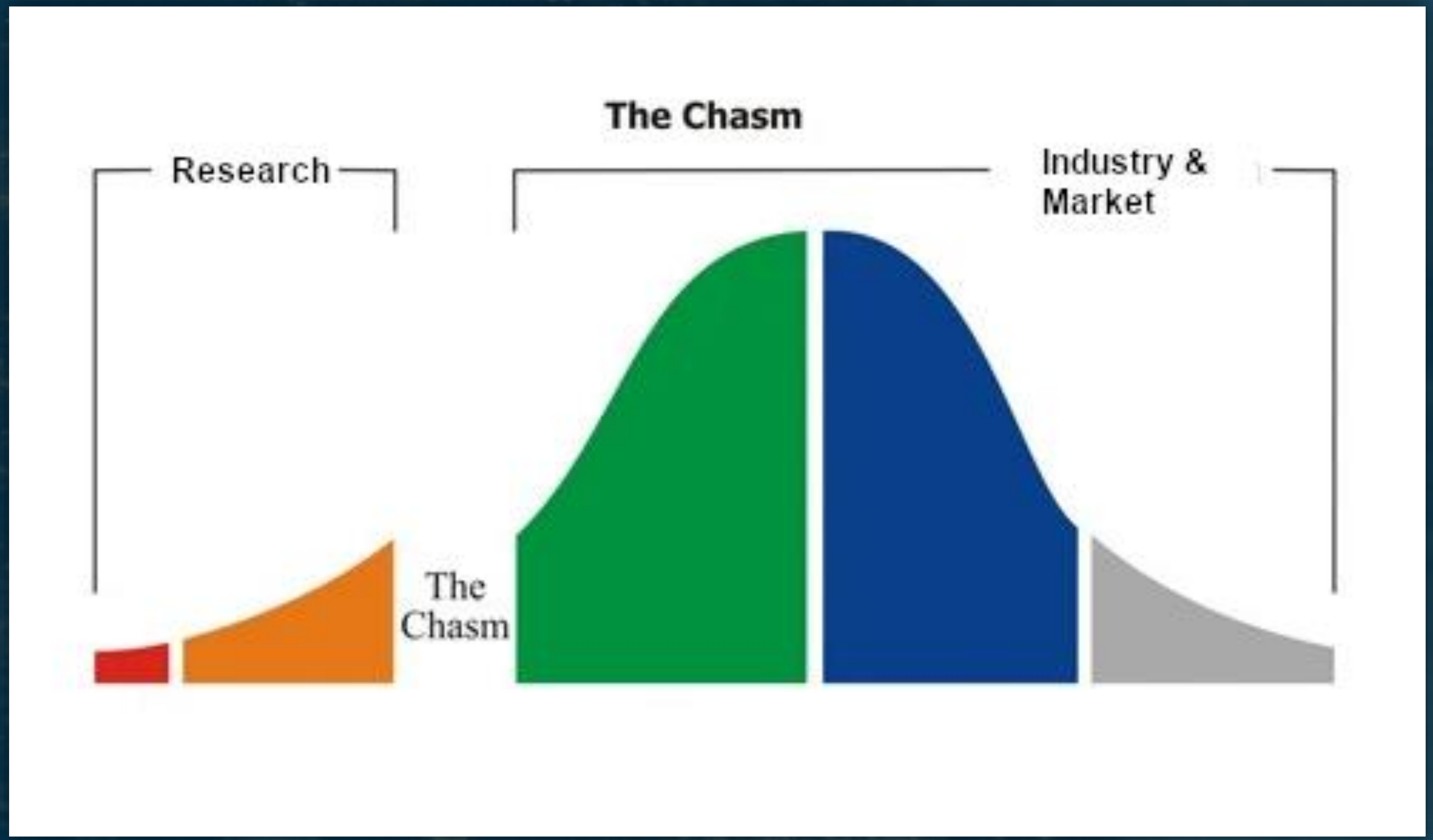


- ● QC4EO Study members
- ★ ESA Co-funded research
- ● ESA Φ-lab partners / visiting researchers
- ● Other Community / events

Conclusions

Act now to shape the future of QC4EO

- **Generic, and industry perspective:**
  - Develop industry relevant use-cases and benchmark QC hardware & algorithms
  - Foster end-user uptake and market creation



- **Specific ESA EO perspective**
  - Build a QC4EO ecosystem with mutual benefits
  - Prepare hybrid computing frameworks including traditional CPU, GPU, Quantum PU within modular HPC environments

ESA QC4EO initiative

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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!

Contact:

- Bertrand.Le.Saux@esa.int