USC-C WG Quantum Computing

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For the Quantum Computing workgrup @ USC-C: Andrea Bulgarelli, Carlo Burigana, Luca Cappelli, Vincenzo Cardone, Stefano Cavuoti, Farida Farsian, Irene Graziotti, Massimo Meneghetti, Giuseppe Murante, Nicolò Parmiggiani, Giuseppe Riccio, Alessandro Rizzo, Roberto Scaramella, Giuseppe Sarracino, Francesco Schillirò, Vincenzo Testa, Tiziana Trombetti

USC-C General Assembly, Trieste
March 10, 2026

INAF Quantum Computing Workgroup

- INAF contributed to **Spoke 10 (Quantum Computing) of the ICSC, Italian Research Center on High Performance Computing, Big Data and Quantum Computing**

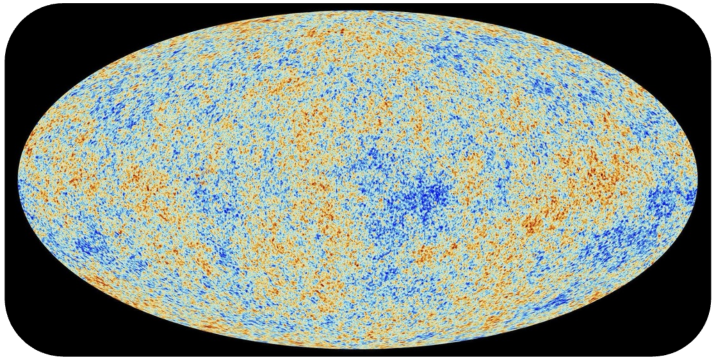
- Now we establish a Thematic Group **Quantum Computing** of **INAF-USC-C**

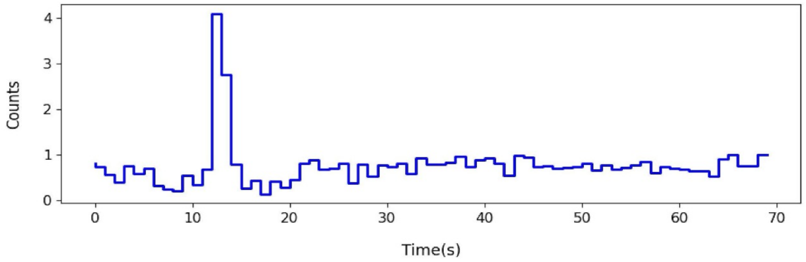
- **Goal: Developing and benchmarking Quantum Algorithms to tackle computational challenges in Astrophysics and Cosmology.**

- Current **Noisy Intermediate-Scale Quantum (NISQ)** devices lack error correction, limiting circuit depth (coherence time) and connectivity.

- We are developing algorithms using **simulators** to be ready for real hardware.

- **We are looking for collaborations to have access to real hardware**





Contribution to USC-C QC WG

Goal: Developing and benchmarking Quantum Algorithms algorithms to tackle computational challenges in Astrophysics and Cosmology.

INAF Bologna:

- Andrea Bulgarelli
- Nicolò Parmiggiani
- Carlo Burigana
- Massimo Meneghetti
- Tiziana Trombetti

INAF Catania :

- Farida Farsian
- Francesco Schillirò
- Alessandro Rizzo

INAF Napoli:

- Stefano Cavuoti
- Giuseppe Riccio

INAF Roma:

- Roberto Scaramella
- Vincenzo Cardone
- Vincenzo Testa
- Giuseppe Sarracino

INAF Trieste :

- Giuseppe Murante
- Luca Cappelli

INAF Quantum Computing Workgroup/2

- This section

- A. Bulgarelli, R. Scaramella - Quantum Computing activities at INAF
- R. Scaramella – Quantum Computing Intro
- G. Sarracino - Quantum Computing for Optimization and Sampling of Cosmological Functions
- **F. Schillirò - Quantum Sensors for Astrophysics and Space Science**
- F. Farsian - Application of Quantum Fourier Transform in Cosmic Microwave Background Data Analysis
- A. Rizzo - Comparing Classical and Quantum Deep Learning Techniques for Anomaly Detection of Short-Duration Gamma-Ray Signals

- Tomorrow course

Introduction to Quantum Computing

11 Mar 2026, 11:30

1h 30m

San Giusto (Savoia Excelsior Palace)

Training

Speakers

- Farida Farsian (Istituto Nazionale di Astrofisica (INAF))
- Francesco Schilliro' (Istituto Nazionale di Astrofisica (INAF))
- Giuseppe Sarracino (Istituto Nazionale di Astrofisica (INAF))
- Prof. Roberto Scaramella (Istituto Nazionale di Astrofisica (INAF))

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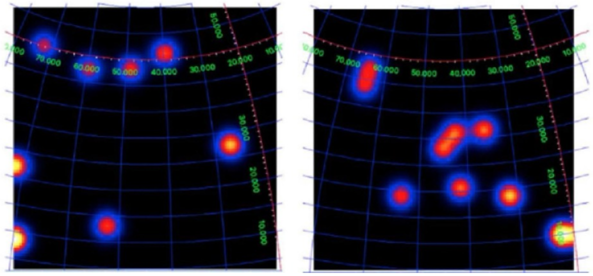
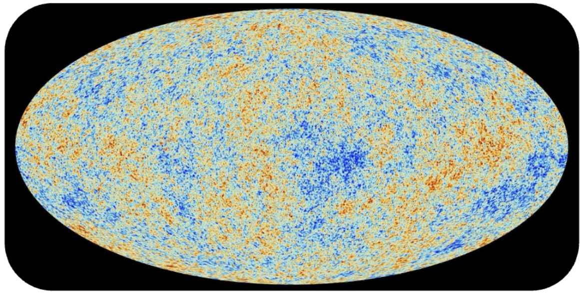
USE CASES

Challenges & Use Cases & Papers

- We applied **Quantum Computing** to several astrophysical and cosmological problems (**Bulgarelli et al. 2026** for a review).

High-Energy Astrophysics	Distinguishing GRB transient signals from background noise and identifying candidate anomalous events in unlabeled datasets via classification and reconstruction techniques. **(Rizzo et al., 2024; Farsian et al., 2024; Rizzo et al., 2025; Farsian et al., 2025; Rizzo et al., 2026)**
Cosmological Parameter Estimation	Estimating the fundamental best-fit values that describe the Universe's composition and evolution using observational datasets. **(Sarracino et al., 2024; Sarracino et al., 2025; Sarracino et al., 2026)**
Cosmic Microwave Background Data Analysis	Replacing classical Fast Fourier Transform with their **Quantum Fourier Transform** counterpart to compute the Cosmic Microwave Backgorund power spectrum and explore scaling advantages at high resolutions. **(Farsian et al., 2025b)**
Dark Matter Simulations	Modeling the non-linear gravitational evolution of Dark Matter fluids by mapping the classical Vlasov-Poisson system into the Schrödinger-Poisson equation. **(Cappelli et al., 2024)**
Large Scale Structure Analysis	Capturing complex connectivity and relational information between dark matter halos to classify cosmic structures beyond classical statistical methods. **(Farsian et al., 2026)**

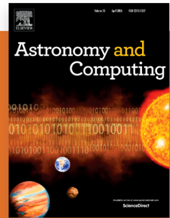




Papers

12 papers, of which 8 refereed

4 papers in the special issue A&C



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Special issue

Advancing Cosmology and Astrophysics through High-Performance Computing and Machine Learning

Last update 1 December 2025

This special issue gathers groundbreaking research from Spoke 3 of the National Center for High-Performance Computing and the SPACE European Center of excellence, focusing on cosmology and astrophysics. It highlights the integration of high-performance computing (HPC) with machine learning, visualization techniques, and advanced data post-processing tools. The issue explores how these methodologies drive innovation in scientific analysis, offering new insights into complex cosmological phenomena. This collection aims to showcase the synergy between fundamental research and cutting-edge computational techniques, setting a benchmark for future interdisciplinary studies.

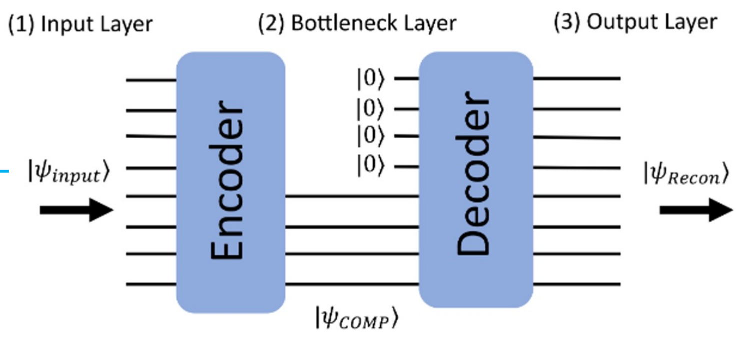
Quantum Models & Architectures

- We implemented and tested several **Quantum Models** and architectures:

High-Energy Astrophysics

Quantum Convolutional Neural Networks: A hybrid model where classical convolutional filters are replaced by a Parameterized Quantum Circuit (PQC) acting as trainable feature extractors within a classical loop.

Quantum Autoencoders: A symmetric structure consisting of a PQC encoder (compressing the input state into a lower-dimensional latent space) and a PQC decoder (reconstructing the original state).



Large Scale Structure Analysis

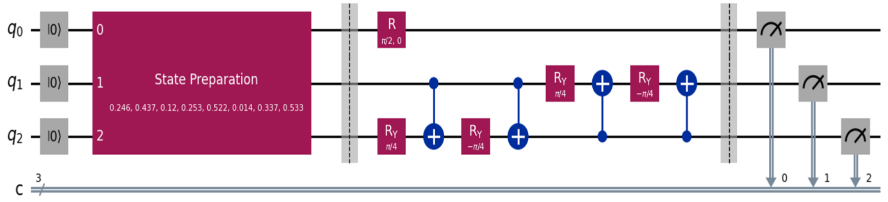
Quantum Graph Neural Networks: Integration of classical Graph Convolutional Networks with a quantum layer designed to capture non-linear correlations and connectivity in graph-structured data.

Quantum Models & Architectures

Cosmological Parameter Estimation

Quantum Genetic Algorithms: An amplitude-encoded algorithm where genetic operations are performed directly on quantum states.

Quantum Markov Chain Monte Carlo: A sampling method that exploits a quantum circuit to propose new steps in the parameter space by deriving shift vectors from the complex components of the resulting statevector.



Cosmic Microwave Background Data Analysis

Quantum Fourier Transform: Quantum analogue of the Fast Fourier Transform, used to process frequency components of the Cosmic Microwave Background power spectrum with potential scaling advantages.

Dark Matter Simulation

Quantum Variational Time Evolution: It uses a PQC ansatz to represent the wavefunction and updates parameters to simulate time evolution.

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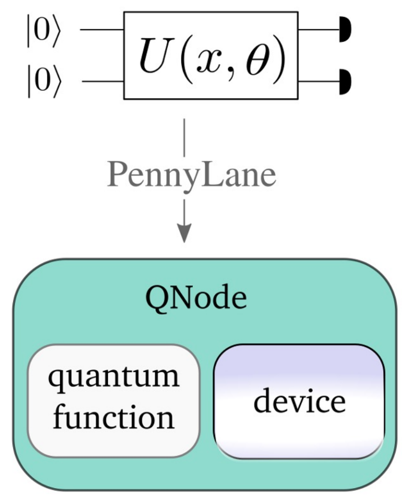
TOOLS

PennyLane Framework

https://pennylane.ai

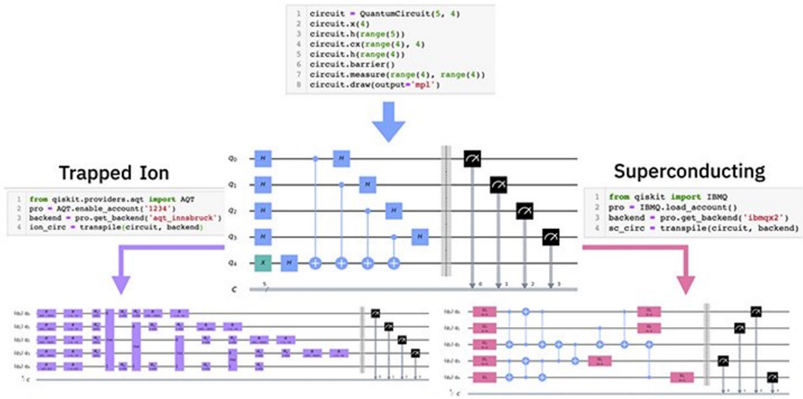
- Most of our works are implemented using two different frameworks: **PennyLane** (Xanadu) and **Qiskit** (IBM Quantum).
- PennyLane is a **cross-platform Python library** for quantum computing, quantum machine learning, and quantum chemistry.
- **Automatic Differentiation**: Integration with classical deep learning libraries (e.g., PyTorch, Tensorflow) to train hybrid models via backpropagation.
- **Hardware Integration**: Allows running the same quantum circuit code on different backends (simulators or real hardware) by simply changing a single line of code.
- **Built-in Tools**: Pre-built templates for variational circuits, embeddings and optimization routines tailored for Quantum Algorithms.



Qiskit Framework

https://www.ibm.com/quantum/qiskit

- **Qiskit** is an open-source, Python-based software stack for quantum computing, originally developed by **IBM Research**.
- It is the primary toolset for building, optimizing, and running quantum workloads on IBM's real quantum processors and classical simulators, accessible via the cloud-based **IBM Quantum Platform**.
- Qiskit operates on a **gate-based paradigm**, where users define ***QuantumCircuit* objects** by initializing quantum and classical registers and applying unitary operators and measurements directly to qubits.
- Qiskit uses a **transpiler** that maps logical circuits to the specific topology of the target backend → Optimized circuits are then executed via primitives like the **Sampler** and the **Estimator.**



Training and collaborations

- **Training activities: High-performance and quantum computing Master, University of Bologna**
- Members of the **Alleanza Quantistica Italiana (AQI)**
- Members of ICSC, National Research Centre for High Performance Computing, Big Data and Quantum Computing, spoke 10
- Many collaborations with Italian universities
- Agreement with UNINSUBRIA is in progress to access to a D-Wave machine (Quantum Annealer)

Conclusions & Future Work

- We applied **Quantum Computing** techniques to many astrophysical tasks: GRB detection, Cosmic Web classification, Dark Matter simulation and cosmological parameters estimation.
- Results are physically **consistent with classical benchmarks**, validating the hybrid quantum-classical approach.

- **Quantum encoding** techniques remains a significant latency factor and the **number of measurements** required for high precision makes quantum solvers slower than optimized classical equivalents.

- Quantum Machine Learning shows promise, especially in:
  - **Parameter Efficiency**: Achieves comparable accuracy with significantly fewer parameters than classical models.
  - **Sample Complexity**: Demonstrates potential advantages with limited training data.

- Most of the presented works were executed on **quantum simulators →** A key future goal is deploying these models on real **NISQ devices** to evaluate their robustness against noise.
- Combining quantum and classical computation is a key near-term strategy, but a practical **quantum speed-up still requires advances in quantum hardware and optimization algorithms**.
- While quantum advantage in these tasks remains a goal for the future, **the continued advancement of both quantum hardware and algorithm design justifies the effort**.
- **<u>We are looking for collaborations to have access to real hardware</u>**
- **<u>If you want to participate to QC USC-C WG you are welcome</u>**