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ICSC
Centro Nazionale di Ricerca in HPC,
Big Data and Quantum Computing

The Application of Quantum Fourier Transform in Cosmic Microwave Background Data Analysis

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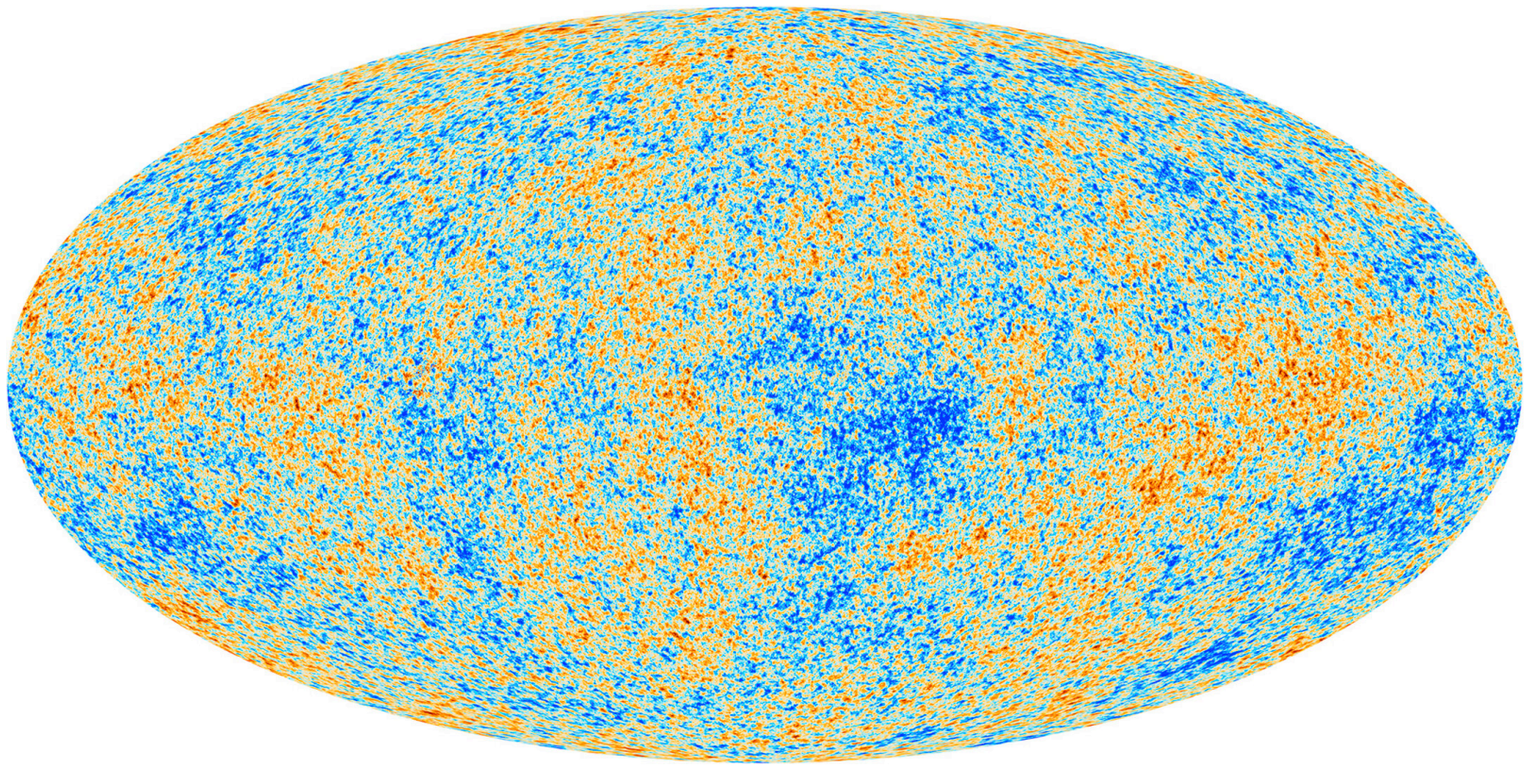
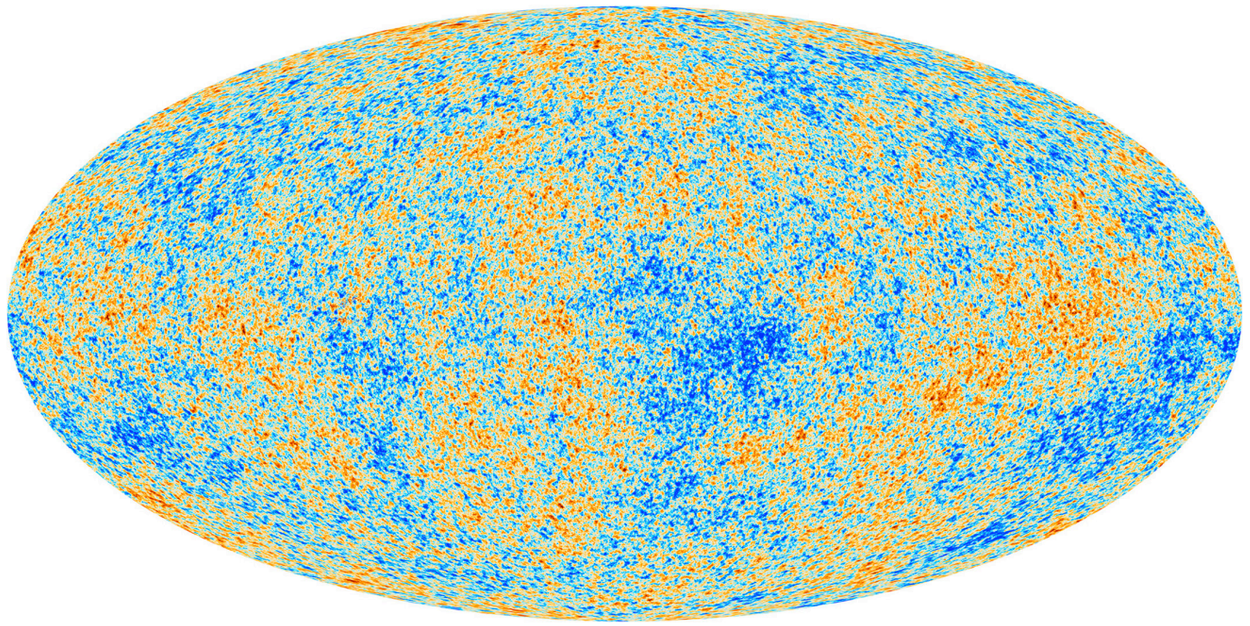
COSMIC MICROWAVE BACKGROUND

- **Relic radiation from recombination (~380,000 yrs post-Big Bang):** Photons decoupled as the universe became transparent; today seen as a ~2.7 K background.
- **Encodes primordial density fluctuations:** Tiny anisotropies ($\Delta T/T \sim 10^{-5}$) reveal the seeds of cosmic structure.
- **Tightly constrains cosmological parameters:** Power spectrum informs H_0, Ω_m, Ω_Λ, Ω_b, and spatial curvature.
- **Supports inflation and early-universe models:** Acoustic peaks and polarization patterns reflect quantum-origin perturbations.



CMB DATA ANALYSIS

- CMB encodes information about **primordial density perturbations**.
- Since the CMB is observed across the entire sky, its fluctuations must be analyzed on a spherical surface using **spherical harmonics**.



- The spherical harmonic decomposition extracts the **power spectrum** (C_ℓ), revealing key cosmological parameters.
- Any inaccuracies in mapping or analysis can introduce biases, affecting constraints on fundamental physics.

$$T(\theta,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

$$a_{\ell m} = \int_0^{2\pi} \int_0^{\pi} T(\theta,\phi) Y^*_{\ell m}(\theta,\phi) \sin\theta \; d\theta \; d\phi$$

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

CMB DATA ANALYSIS AND ITS CHALLENGES

- Handling and processing extensive datasets from numerous detectors.

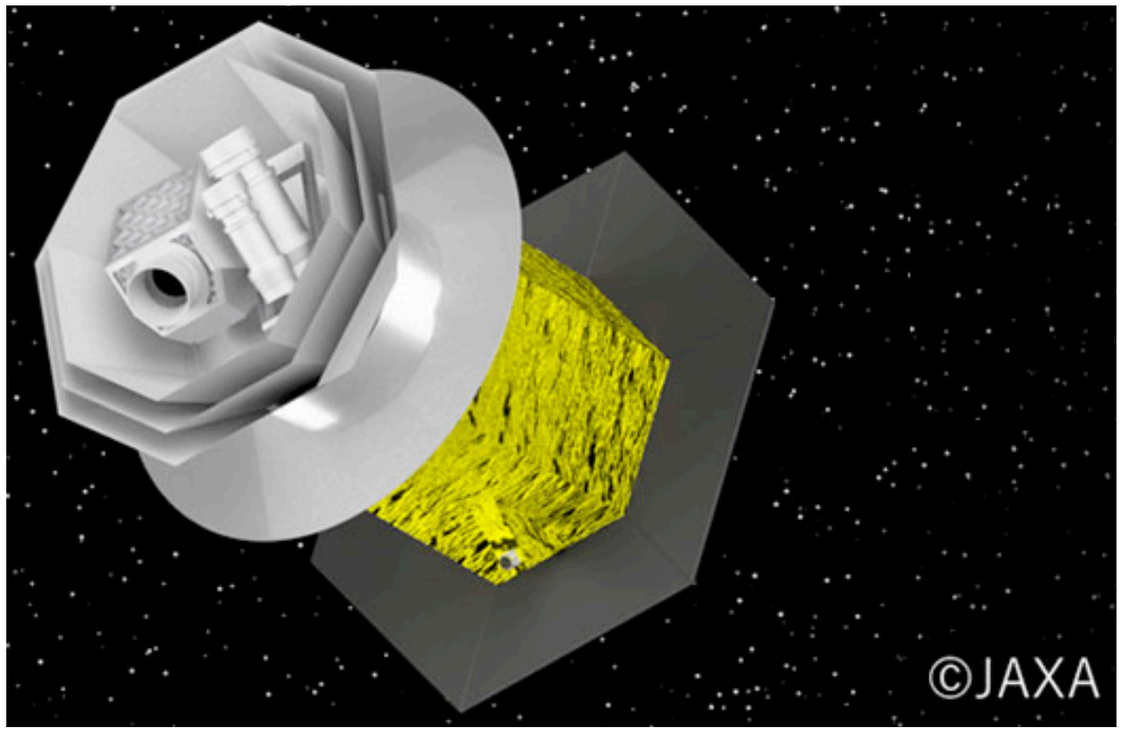
  CMB-S4 Experiment:

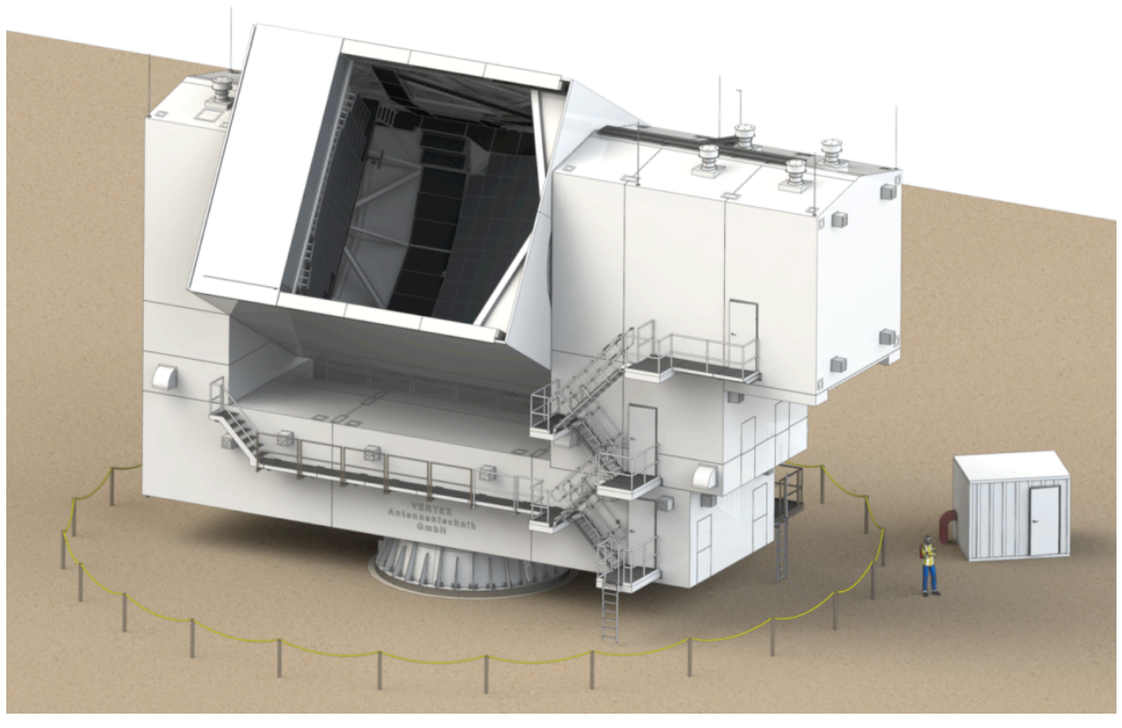
  - Approximately 550,000 bolometers, significantly surpassing previous experiments.

  LiteBIRD Satellite:

  - Over 3,000 bolometers across 15 frequency bands (34–448GHz)

- Accurately distinguishing between cosmic signals and terrestrial or galactic foregrounds.

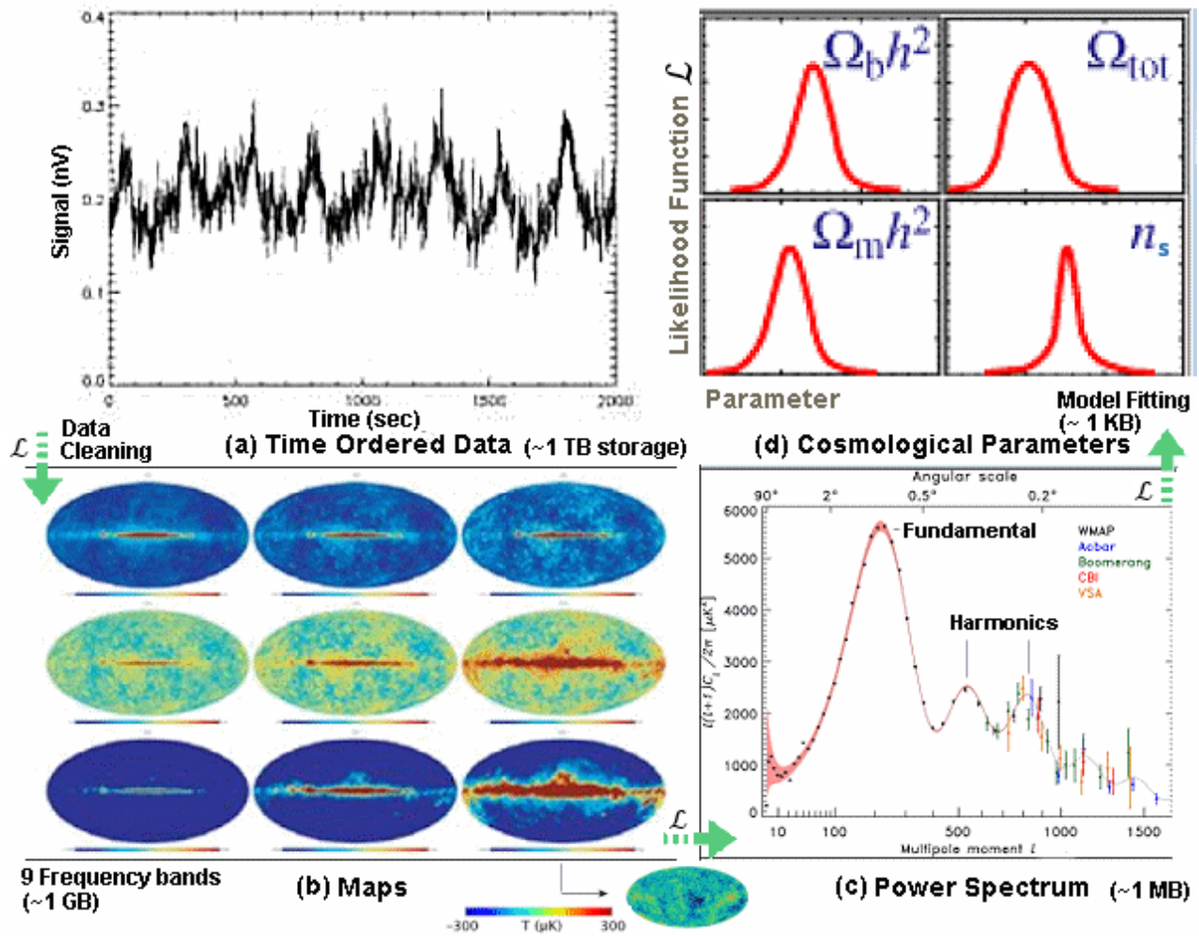




FOURIER TRANSFORM IN CMB DATA ANALYSIS

- **Decomposing Temperature Fluctuations:** The Fourier transform breaks down CMB temperature anisotropies into different spatial scales.

- **Extracting the Power Spectrum:** The Fourier coefficients allow computation of the CMB power spectrum (C_ℓ).



- **Enhancing Statistical Analysis:** Transforming CMB maps into harmonic space simplifies statistical studies, as the anisotropies become nearly uncorrelated.

- **Efficient Data Processing:** Fast algorithms like the Fast Spherical Harmonic Transform (FSHT) enable computationally efficient analysis ($\mathcal{O}(N_{\text{pix}}^{1.5})$) of high-resolution CMB datasets.

QUANTUM FOURIER TRANSFORM

- QFT Overview:

  The QFT is a quantum version of the classical Fourier transform, operating on qubits.

  Transformation: $$|x\rangle = \sum_{j=0}^{N-1} x_j |j\rangle \rightarrow \sum_{k=0}^{N-1} \tilde{x}_k |k\rangle,$$

  Transforms a quantum state |x⟩ into a superposition of phases, similar to how FFT shifts data to frequency components.

  $\tilde{x}_k$ are the Fourier coefficients of the input amplitudes.

  Mathematical Basis:

  For a quantum state |x⟩, QFT applies a sequence of **rotations** and **phase shifts** to encode frequencies.

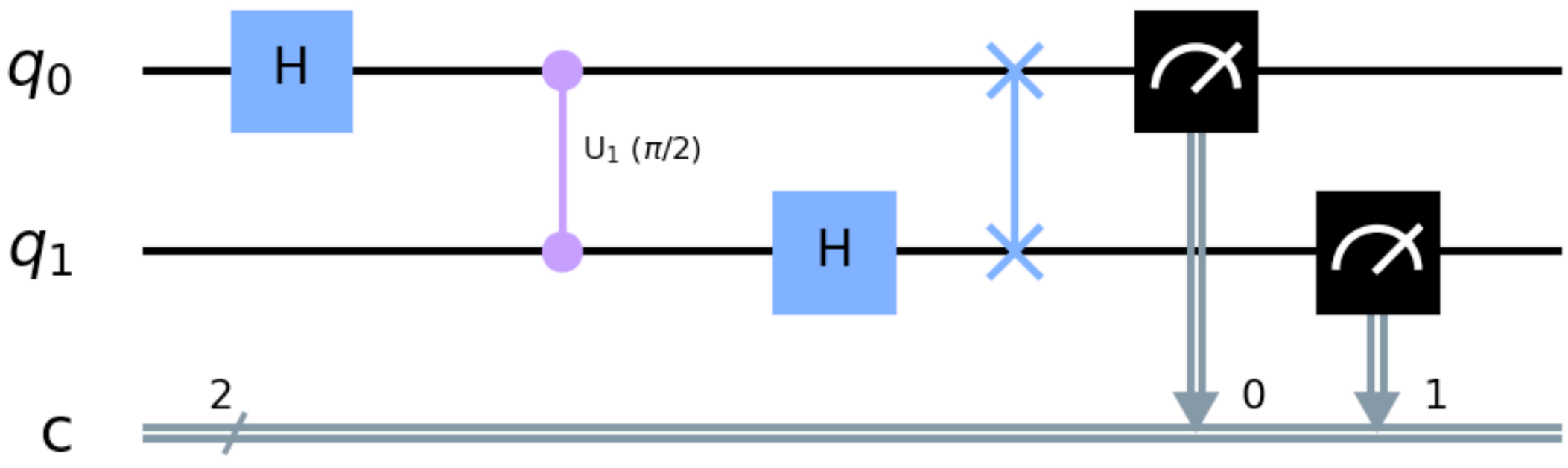
  The transformation is defined by the unitary matrix: $U_{jk} = \frac{1}{\sqrt{N}} e^{2\pi i jk/N}$

Key Difference from FFT:

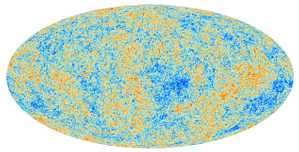
QFT is inherently probabilistic, requiring measurement, while FFT is deterministic.

THEORETICAL ADVANTAGE

- Classical Fourier Transform: $\mathcal{O}(N^2)$ operations for an input of size N
- Fast Fourier Transform (FFT) : $\mathcal{O}(N \log N)$.
- Quantum Fourier transform: $\mathcal{O}(\log^2 N)$ by leverages quantum parallelism



STEPS DOWN TO CHECK THE QFT PERFORMANCE

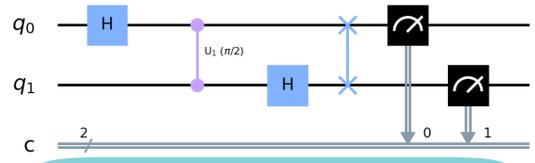


1

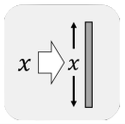
CMB Map Generation: Used *CAMB* to compute power spectra and *healpy* to generate maps.

2

Classical vs. Quantum Decomposition: Applied FFT and QFT in *map2alm* for spherical harmonic analysis.



QFT Implementation: Used *Qiskit* for state preparation, QFT execution, and measurement.



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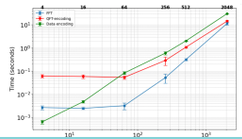
Data Encoding: Adopted amplitude encoding for efficient quantum data representation.

5

Padding Strategy: Used periodic padding to match quantum circuit constraints.

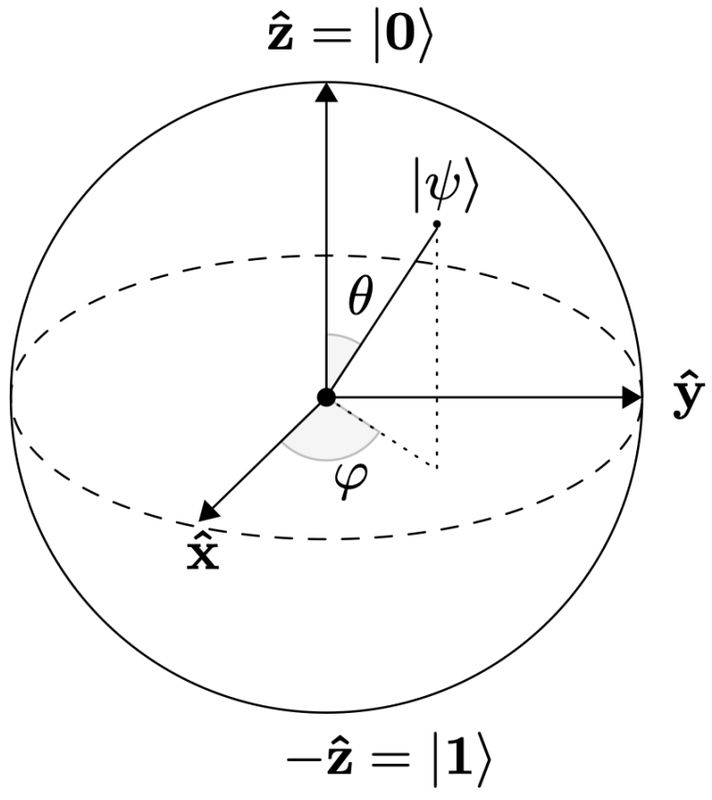


Performance Benchmarking: Compared QFT execution time with classical FFT.

DATA ENCODING METHODS

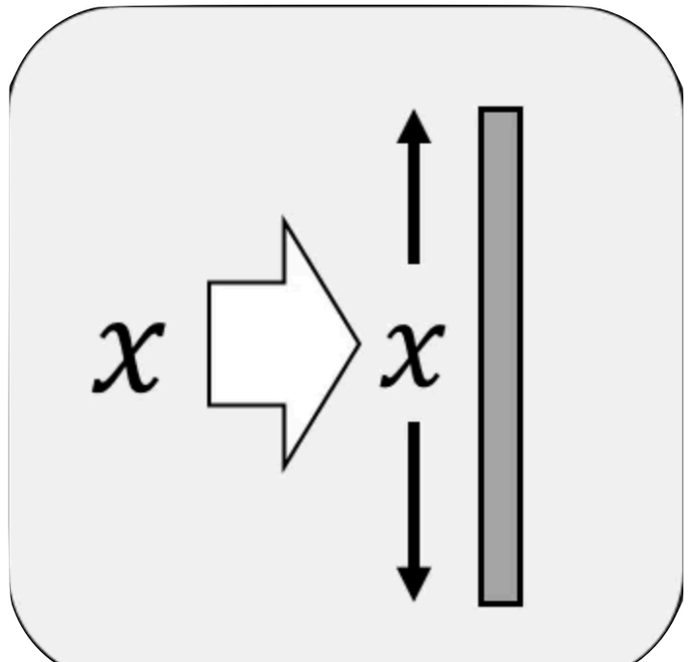
For encoding (embedding), we take a classical data point, *x*, and encode it by applying a set of gate parameters in the quantum circuit. There are different types of encoding the data:

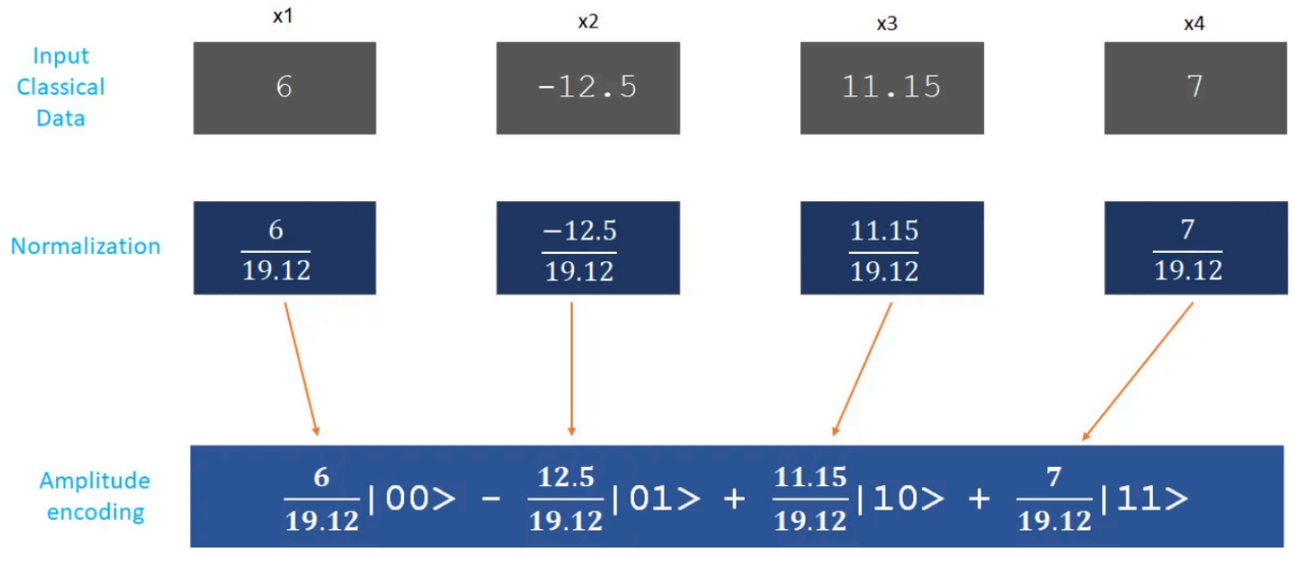
- **Basic encoding**
- **Angle encoding**
- **Amplitude encoding**
- Data Reuploading
- QuAM (Quantum Associated Memory)
- QRAM (Quantum Random Access Memory)
- ...



AMPLITUDE ENCODING

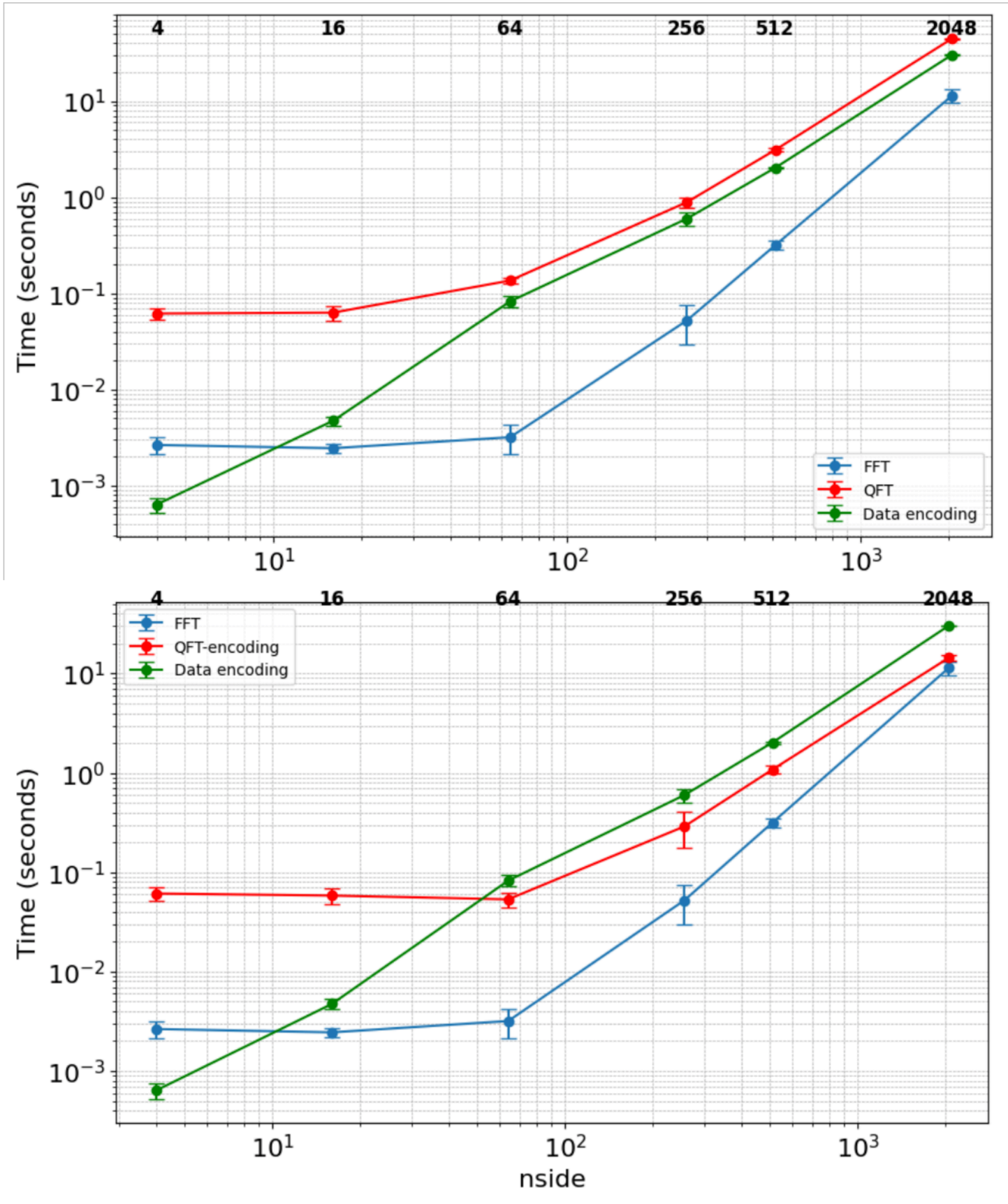
- The data is encoded into the amplitudes of a quantum state.
- This encoding requires **log2 (n) qubits** to represent an n-dimensional data point.





TESTS

- The FFT consistently outperforms the QFT across all tested nside values, with significantly lower computational times.
- The primary slowdown in the quantum approach comes from data encoding, which dominates execution time as nside increases.
- The QFT itself is not the limiting factor; rather, the inefficiencies of amplitude encoding introduce significant computational overhead.



F.Farsian et al, 2025, published in QSW 2025

PRELIMINARY TESTS

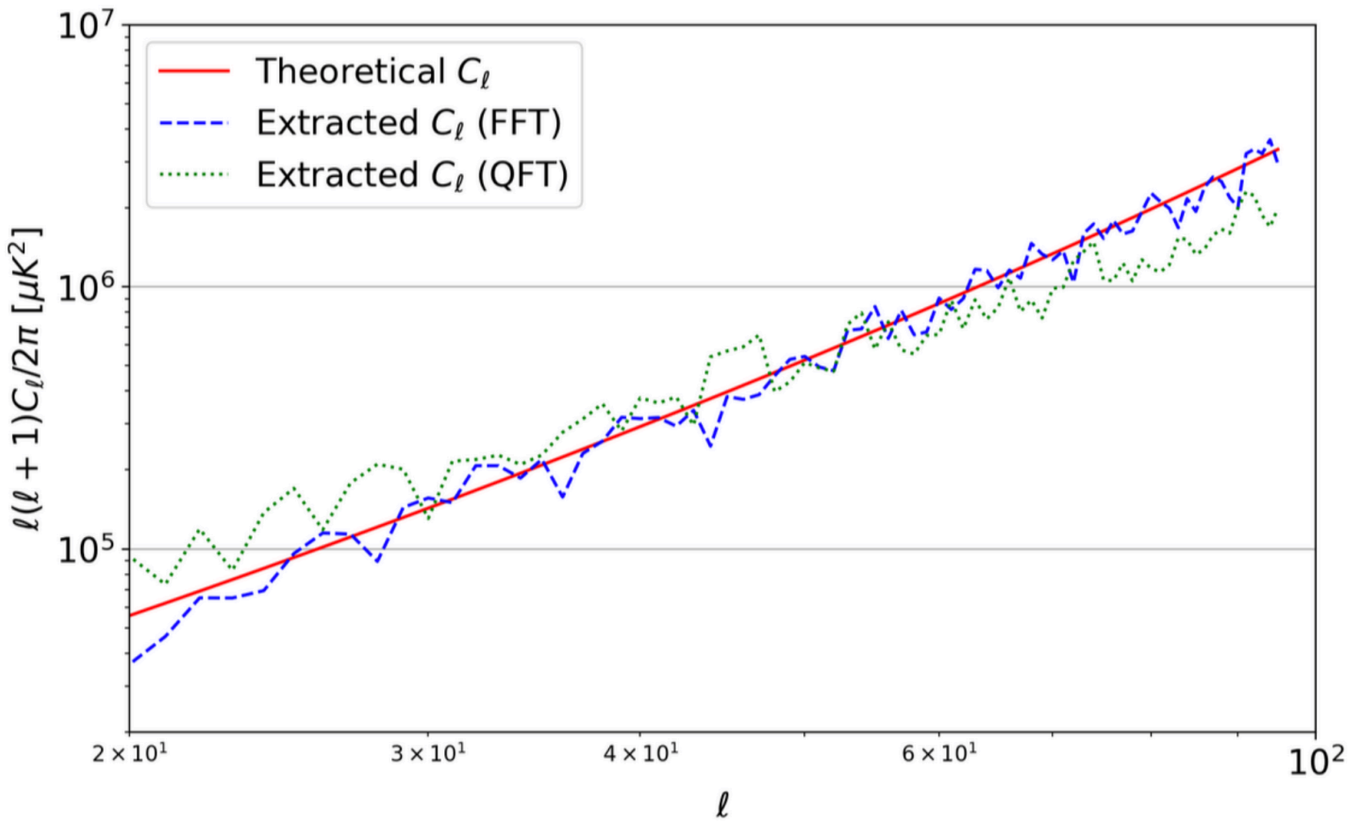
Comparing FFT and QFT Performance

Nside	QFT (simulated)	FFT	Nqubit
2	0.0840	0.0035	6
4	0.0859	0.0036	8
8	0.1178	0.0039	10
256	0.8821	0.1206	20
512	2.795	0.3830	22
1024	11.318	1.2176	24

F.Farsian et al, 2025, accepted in QSW 2025, arXiv:2505.15855

PRELIMINARY TESTS

- Theoretical and extracted CMB power spectra (FFT vs. QFT) show deviations due to numerical errors and resolution constraints ($\mathrm{nside}=32$).
- QFT exhibits increased deviations at low ℓ and reduced power at high ℓ, likely due to quantum algorithm approximations and padding effects.
- QFT-based spherical harmonic decomposition is limited by high memory requirements, restricting analysis beyond $\mathrm{nside}=32$.



F.Farsian et al, 2025, accepted in QSW 2025, arXiv:2505.15855

TAKE HOME MESSAGES

Conclusion

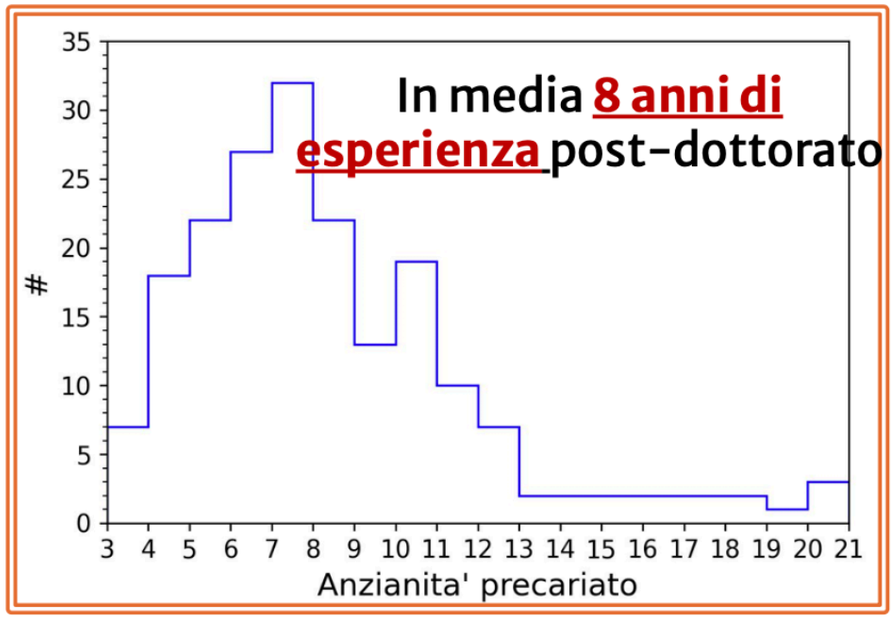
- **QFT is a promising alternative to FFT** in CMB map analysis, with comparable accuracy but limited by current data encoding overhead.
- **Quantum computation time is negligible** compared to the classical-to-quantum encoding step, which is the main performance bottleneck.
- **Efficient encoding methods and hardware improvements** are key to unlocking the full potential of QFT in astrophysical applications.

Future Prospects

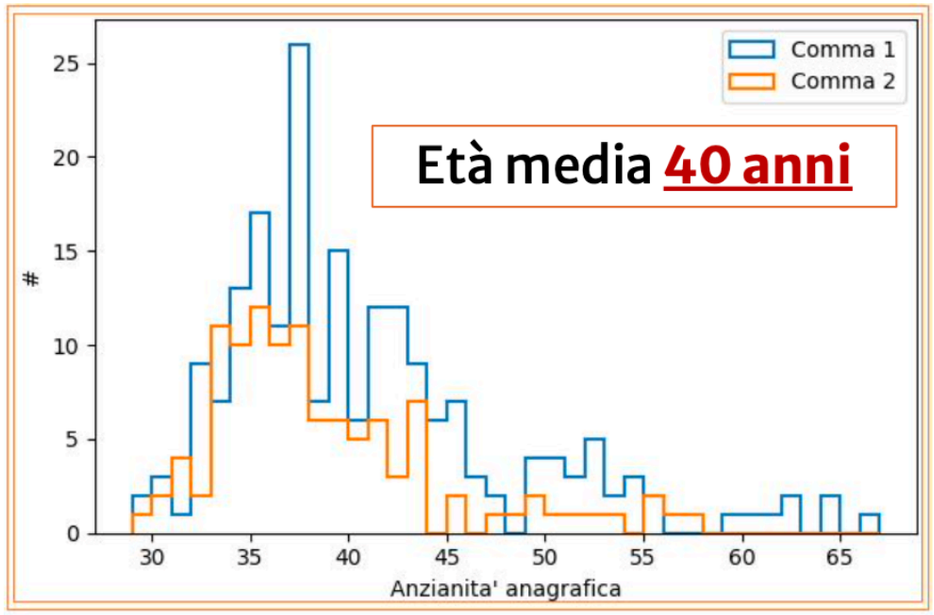
- **Extend to ultra-high resolution maps (nside ≥ 2048)** and test on real quantum hardware to assess scalability and feasibility.
- **Develop a fully quantum pipeline (QFT + inverse QFT)** for CMB map synthesis from power spectra, reducing data input size and enhancing quantum advantage.

La situazione del personale precario in INAF è INSOSTENIBILE!

1.200 Tempo Indeterminato Vs 650 precari: più di 1 precario ogni 2 persone di ruolo



Plot di un campione rappresentativo dei precari INAF al 31/12/2024



Dei 650, 287 possono essere stabilizzati:
173 tramite chiamata diretta (comma 1)
114 tramite concorsi riservati (comma 2)

Entro l'anno, l'attuale situazione determinerà l'esodo di > 100 lavoratori altamente qualificati e il MUR se ne lava le mani

È URGENTE che INAF PROCEDA ORA con le STABILIZZAZIONI TRAMITE MADIA: unica soluzione per questa emergenza

Molti colleghi (972) hanno già firmato, per sostenerci e aggiungere il nome alla lista del QR,
contattaci a retestabilizzandi1.inaf@gmail.com


THANKS FOR YOUR
ATTENTION