QUART&T-Bologna Meeting

13/06/2025

Matteo Franchini

QUANTUM ARCHITECTURES FOR THEORY & TECHNOLOGY

Istituto Nazionale di Fisica Nucleare

Where we are

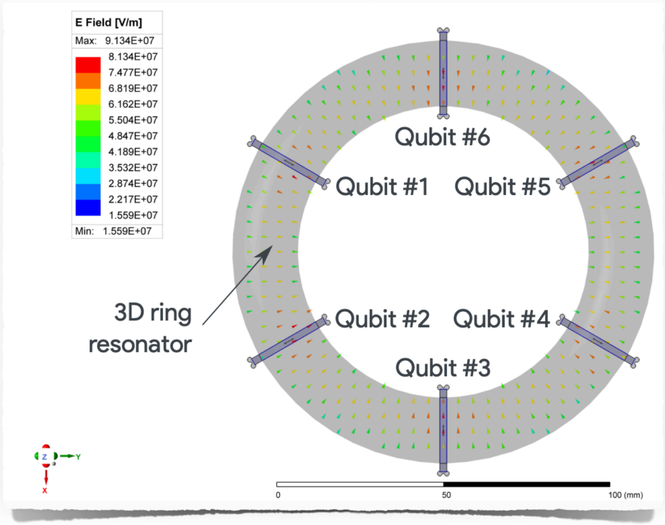
* **21 Feb —>** Kick-off

* **End of March —>** WP2+WP1 meeting discussed first theoretical problem and hamiltonian design
  - Only discussed Quantum Simulation of Collective Neutrino Oscillations by Roggero

* **End of March —>** discussion on how to include Purcel Filters. Strong interest to use them.
  - **May —>** WP2 meeting continues - [Today update by Simona].

* **May —>** test offline on Qibo for RFSoC Board DAQ. We need to understand clear tasks with ours/others board
  - **17 June h 11 —>** meeting Carobene on board limits and applications
  - **Next —>** meeting with Alessio [Frascati] on their needs and status [fast!]
  - **Next —>** contact Ferrara for their board usage [after]

* **Ongoing/Future —>** start studying Quantum ML and its application for QUARTET.
  - **25 June —>** Workshop in Florence with Banchi



Neutrinos oscillations in dense environments

* In **high-density neutrino environments** — such as supernovae, neutron star mergers, or the early universe — neutrino flavor oscillations are significantly affected by neutrino-neutrino interactions.

* Until now, approaches have relied on the mean-field approximation. However, to understand the role of **quantum correlations, such as entanglement**, an exact solution is necessary.

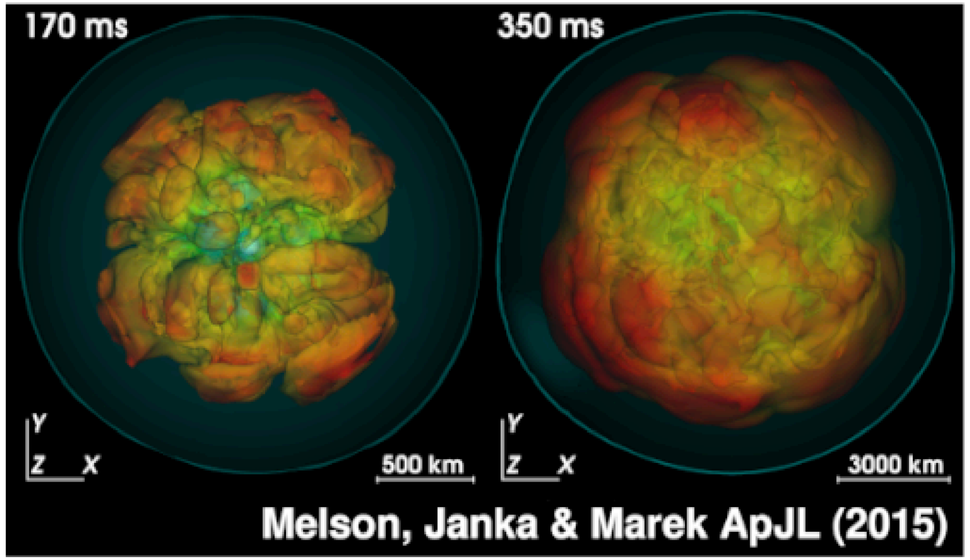
* The Hamiltonian for a two flavors oscillation can be written as:

$$H = \sum_{k=1}^{N} \vec{b} \cdot \vec{\sigma}_k + \sum_{p<q}^{N} J_{pq}\, \vec{\sigma}_p \cdot \vec{\sigma}_q$$

with $\vec{\sigma}_k = (\sigma_k^x, \sigma_k^y, \sigma_k^z)$

* By now with only 2 flavors direct map to spin 1/2 degrees of freedom (qubits) and only one- and two-body interactions ⇒ only O(N2) terms

  - **Issue:** all-to-all interactions are difficult with reduced connectivity



Neutrinos oscillations in dense environments

* **Fully exploit all-to-all interactions** in full analog simulations for simple geometries

* perform **hybrid analog digital simulations** obtaining:
  - useful depth reductions if we could implement

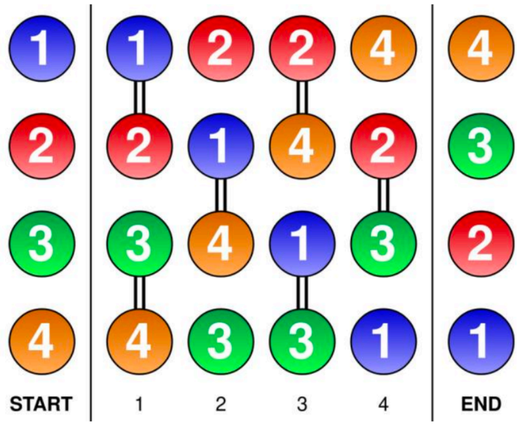
$$U_{really-nice}(\vec{\theta}) = \exp(i \sum_{i,j} \theta_{ij} Z_i Z_j)$$

  - study 3 flavour problem on quTrits

* **Idea:** use the energy repulsion between 20 , $|02\rangle$ and $|11\rangle$ to realize an effective ZZ interaction on the computational subspace;

[Nature 460, 240–244 (2009)]

* Ongoing work on this thread **[more info by Simona]**



Scheme to realize a single time-step simulation. Each double line is formed by $3\binom{N}{2}$ *CNOT +* $15\binom{N}{2}$ *single qubit gates.*

Needs to find other TH tasks for different chip design. Pederiva? Some ideas here in Bologna (Elisa). New master student involved.

RFSoC thoughts

* We have **ZCU111** with working Qibo/Qick: limited in performance (#channels, bandwidth, frequency, …)

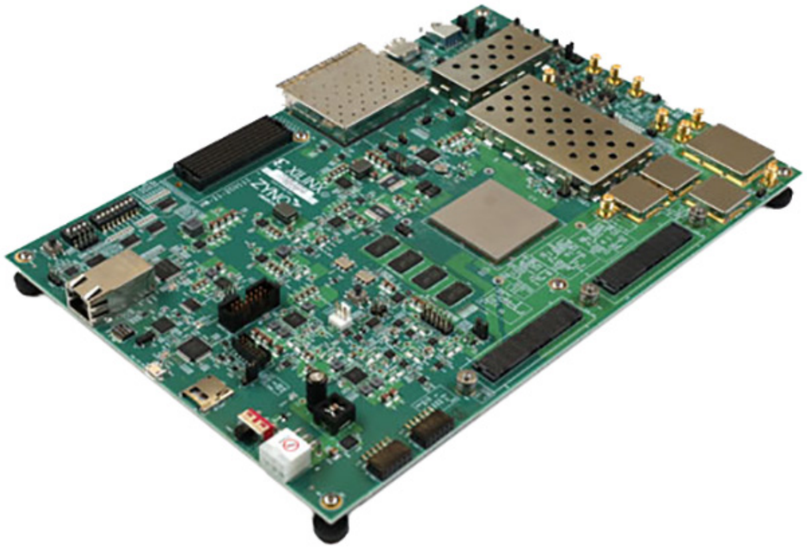
* To **understand exactly** how can be used for qubit measurement in future. Sigle qubit test ok. 2-qubits?

* Trying to **obtain the maximum from our board**, buying VF-100 board to access all ADC/DAC. Purchase ongoing (thanks Franco, Riccardo)

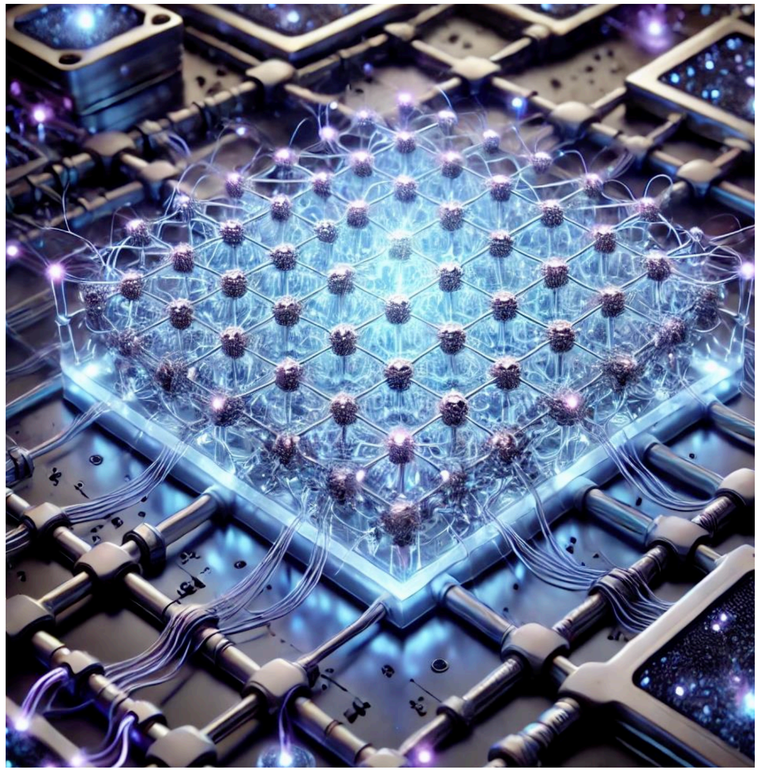
* **More electronics** components needed to make a ~ independent measurement suite
  - RFSoC 4x2 (four 5 GSPS ADCs with 6 GHz RF input bandwidth and two 14-bit, 9.85 GSPS DACs)
  - Mixers RF MM1-0212LS & splitter/combiners

* ***Needs interactions and feedbacks*** from Milano/Frascati/Ferrara

* **Brainstorming!!!**



Quantum ML



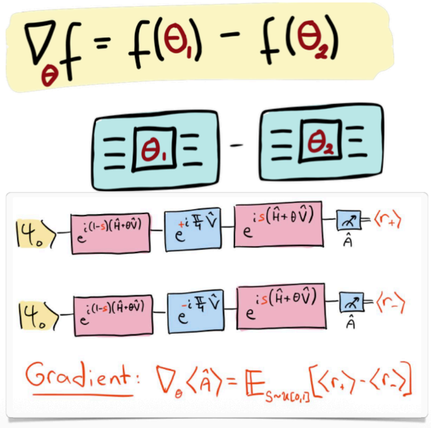
* **Bayesian inference** provides a robust approach to learning models for quantum systems, while preserving physical intuition about the processes involved.

* Neural networks enable the characterisation of complex systems, at the expense of physical intuition.

* Classical optimisation and learning algorithms can improve the performance of quantum sensors.

* Optimize the objective, it is useful to have access to **exact gradients of quantum circuits** with respect to gate parameters

* The strategies to estimate the gradients of measured observables directly from other measurement outcomes will be studied.



Status of purchases for 2025

requests-i_infn_bo_csn5_quartet

Capitolo	Descrizione	Parziali (K-EUR)	
consumo	Consumo generale per materiale RF (connettori, filtri, cavi ecc.)	4.00	
consumo	2 mixer RF MM1-0212LS , 2 splitter/combiner RF ZX10-2-183-S+. per up/down conversion analogica	1.50	
interno	Missioni presso altri laboratori per sessione di lavoro congiunte e misure. Missioni per lavoro congiunto su scheda zcu208 , software e misure sperimentali; test primo prototipo filtro di Purcell in lettura di >=1 qubit	6.00	5000
inventario	Scheda VF-100 (v. allegato) per accedere a tutti i canali ADC/DAC della scheda ZCU111	6.00	800(2000)
licenze-SW	Contributo CNAF per licenza ANSYS - per progettazione elementi 2d quali un filtro di Purcell.	2.50	?
Totale	/	0	

Preventivi 2026 and next

INFN-BO					
Capitolo	**Descrizione**	**1st Y [k€]**	**2nd Y [k€]**	**3rd Y [k€]**	**Total [k€]**
Consumo	Consumo generale RF (filtri, connettori ecc.)	4	6	6	16
Consumo	2 mixer RF MM1-0212LS , 2 splitter/combiner RF	1.5	0	0	2.5
Inventario	Scheda VF-100 per accedere a tutti i canali ADC/DAC della scheda ZCU111 (già presente in sezione)	6	0	0	6
Inventario	Generatore RF TTi (10-6000 MHz) per up/down conversion analogica	0	6	0	6
Licenze-SW	Contributo CNAF per licenza Ansys	2.5	2.5	2.5	7.5
Missioni	Missioni presso altri laboratori per sessione di lavoro congiunte e misure	6	6	6	18
	Total	**20**	**20.5**	**14.5**	**55**

Conclusion

* Work is starting fast!
* Many fronts are opening, we're involved on
  - theoretical side,
  - Chip Design&simulation and Filters,
  - RFSoC DAQ,
  - Quantum ML?
* Schedule bi-weekly meeting to stay in touch (and focused 😁)
* Finalise purchase and meeting with other collaboration units! (Software licences…)
* IQIS 2025 - **Bologna** 8-12 settembre - https://events.unibo.it/iqis-2025/registration

Next Meetings

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