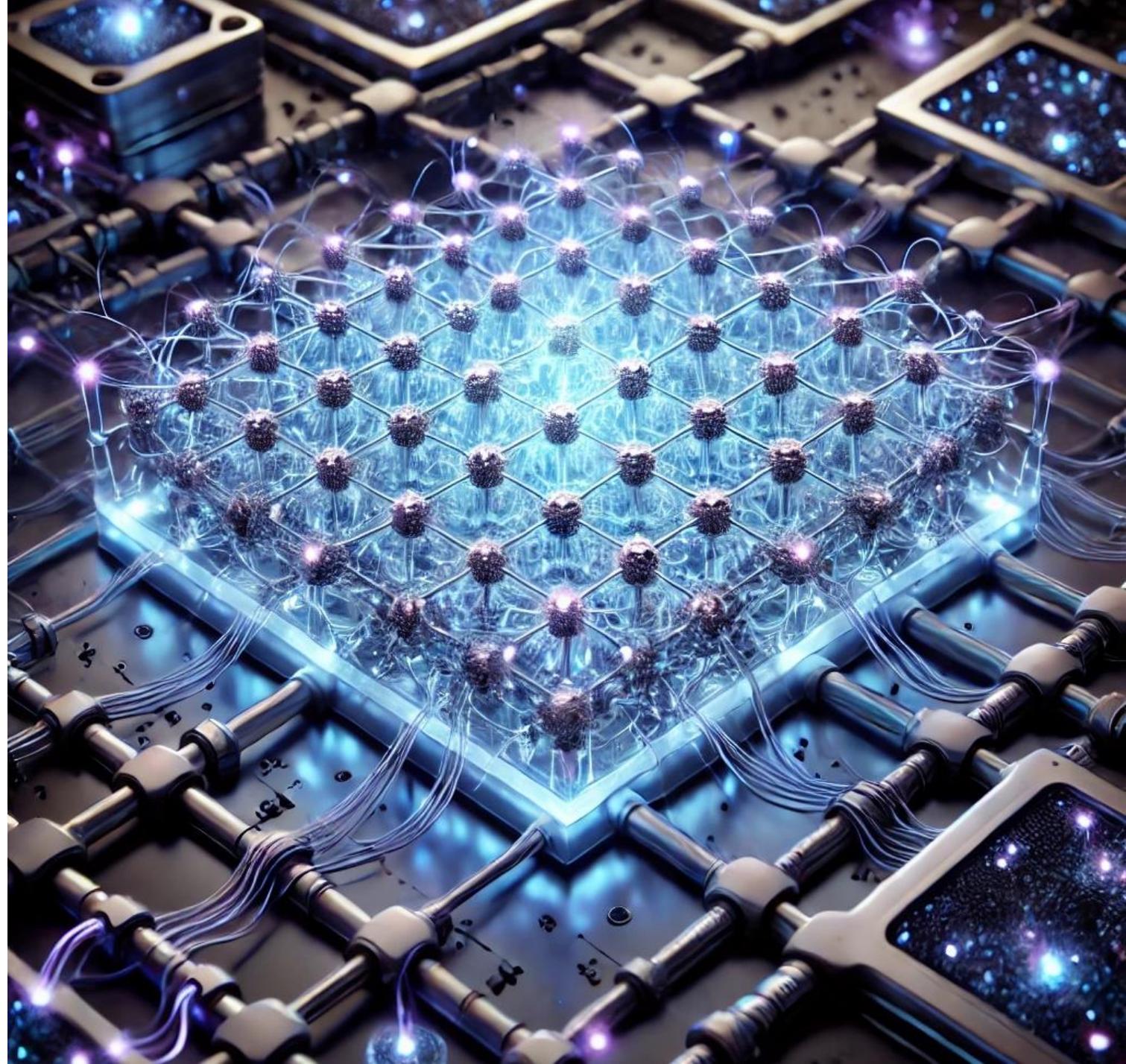# QUART&T WP8: Application for Quantum Sensing and Machine Learning

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WP8: Using the device designed in QUART&T for sensing and machine learning applications

Considering the large range **application of array of qubit with tunable and all-to-all connectivity**, the developed architectures will be also exploited the explore the **application in:**

- quantum sensing (search of light dark matter and dark photons)
- quantum machine learning
- quantum machine learning assisted quantum sensing.

Quantum sensing harnesses the unique properties of quantum mechanics, such as superposition and entanglement, to achieve unparalleled sensitivity in measurements. However, **real-world applications often face challenges due to noise and inefficiencies.** Machine learning offers a powerful tool to address these issues and unlock the full potential of quantum sensing technologies.

One of the goal of the project is to exploit the developed architectures for integrating machine learning with quantum sensing for an improved performance:
1. Optimize the signal-to-noise ratio by means of quantum machine-learning techniques in the 2-qubits device.
2. Extend study to five qubits chip and to the ring-resonator architecture
3. Implement a quantum neural network (QNN) to perform tasks such as pattern recognition, optimization, and data classification with applications in fundamental physics data analysis and quantum sensing.

WP8 Description

In *the first year*, the strategies to estimate the gradients of measured observables directly from other measurement outcomes will be studied. This allow to train and optimize the target observables with simple update rules. Gradient estimation is non-trivial due the the stochastic nature of quantum measurement outcomes, which forbid the application of naive finite difference methods. Different techniques will be adapted to directly get from measurements an unbiased estimator of the gradients with respect to tunable parameters (e.g. control pulse duration).

From *the second year* the aim is to investigate applications in enhancing the success probability of photon counting detection and in the estimation and mitigation of different forms of noise in the device. This will be done first with two-qubit devices and then adapt the techniques to multi-qubit systems with all-to-all connectivity.

Finally, in *the third year* we will consider quantum machine learning application where classical data (e.g. related to fundamental physics problems) are encoded into the control pulses, while the outputs (e.g. whether such input belongs to a certain particle) are estimated from measured observables. The encoding map will be optimized in order to directly extract from quantum measurements the desired data features.

WP8 Tasks

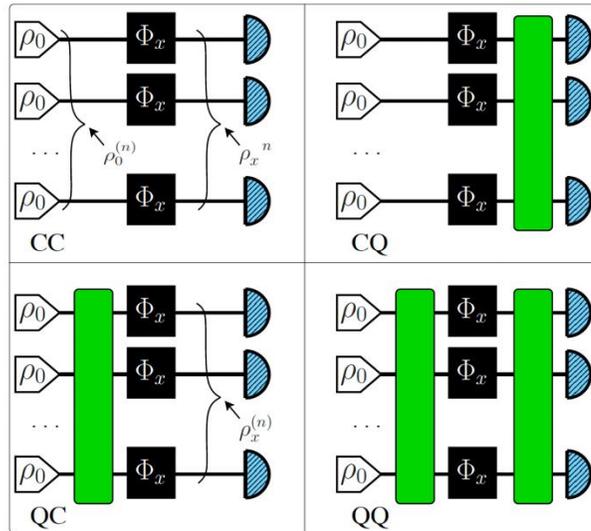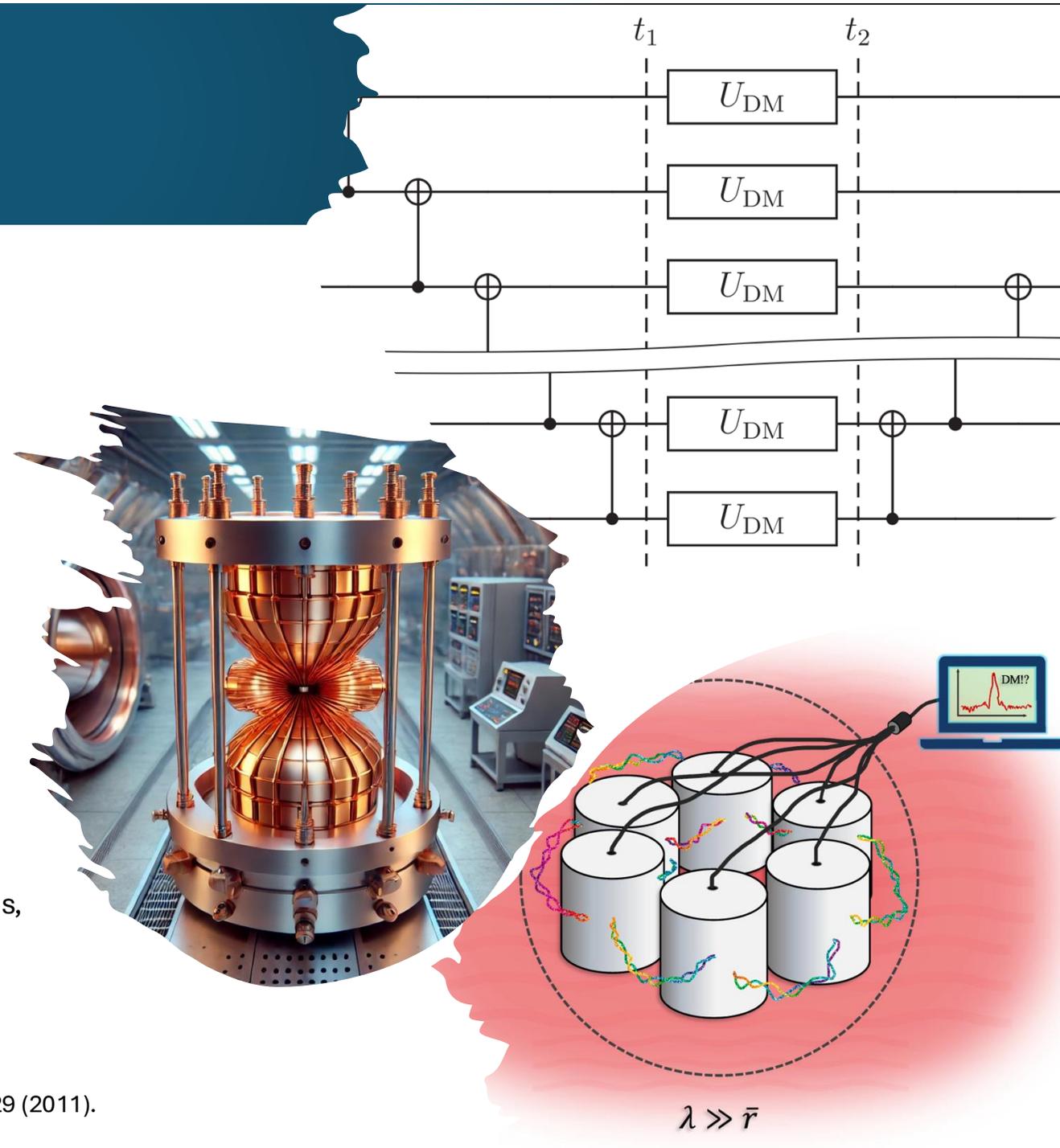| Tasks description |
|---|
| **T8.1**: Defining unbiased gradients of measured observables for QML applications; |
| **T8.2**: Optimization of the photon counter detection efficiency by means of QML techniques; |
| **T8.3**: Application of QML techniques for noise sensing and mitigation ; |
| **T8.4**: Developments of new algorithms for machine learning high-energy physics data ; |
| **Deliverables** |
| **D8.1**: Protocol for stochastic gradient estimation. |
| **D8.2**: Software package for QML applications. |
| **Milestones** |
| **M8.1**: Definition of strategies for stochastic gradient estimation (M12); |
| **M8.2**: Test of an optimized 2-qubits photon counter (M24); |
| **M8.3**: Application of the multi-qubit device for machine learning with fundamental physics data (M36). |

Quantum Sensing

Input probe

Measurement

Entangling

The next generation detector will incorporate numerous qubits and cavities, aiming to minimize dark counts and enhance sensitivity to extremely faint coherent signals.

Giovannetti Lloyd Maccone Quantum Metrology PRL 96 010401 (2006)

Giovannetti Lloyd Maccone Advances in quantum metrology. Nature Photon 5, 222–229 (2011).

$\lambda \gg \bar{r}$

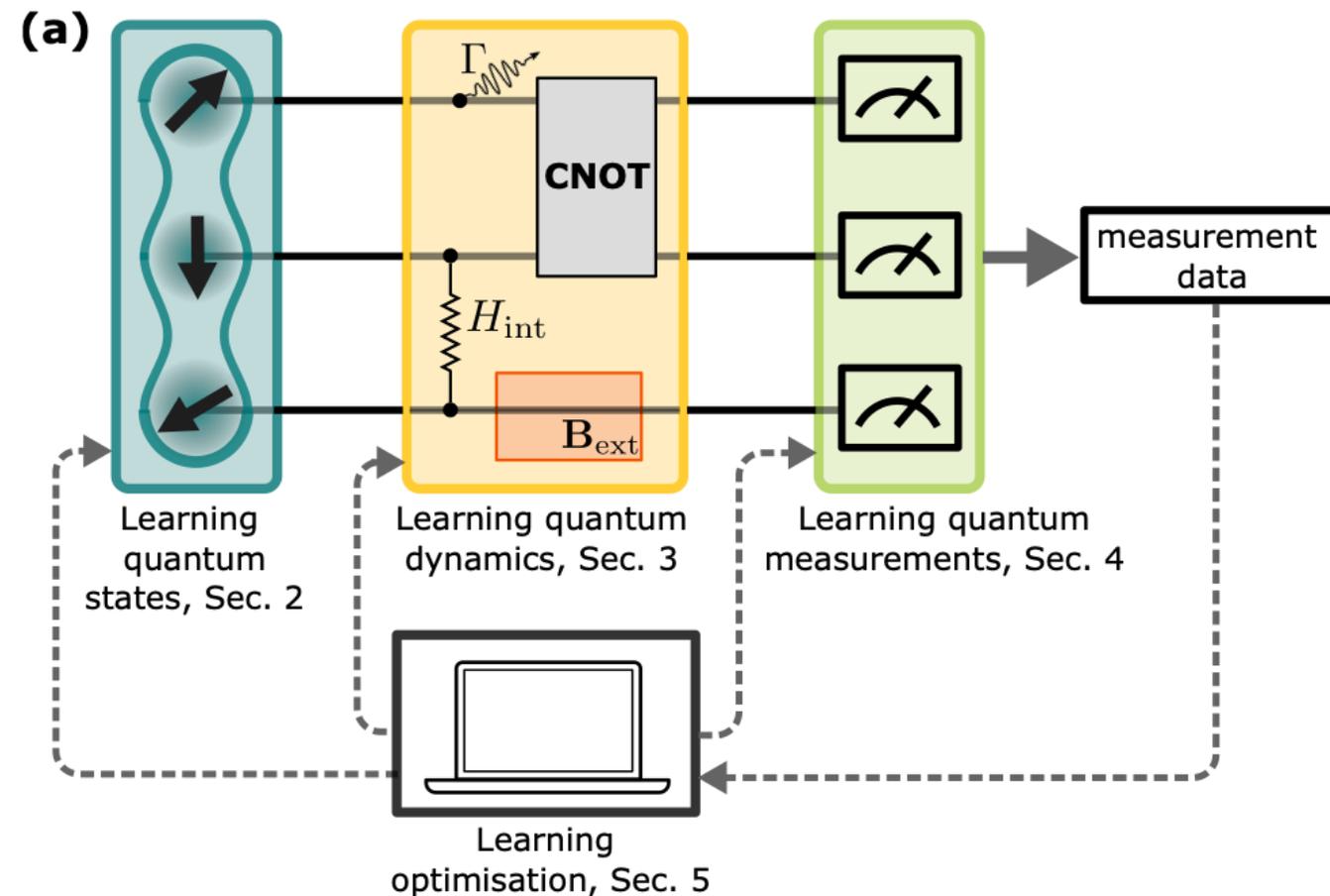# Quantum Machine Learning

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.

Adaptive approaches, that select the next measurement based on knowledge acquired earlier in the estimation, can speed up the characterisation process.

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

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

Challenges: qubits+oscillators systems

Parameter Shift Rule / Hadamard test for   gates
K Mitarai et al. - Physical Review A, 2018
M Schuld et al. - Physical Review A, 2019
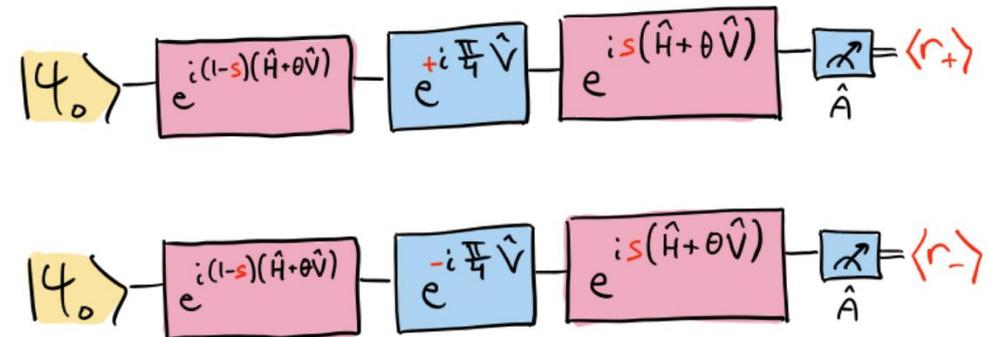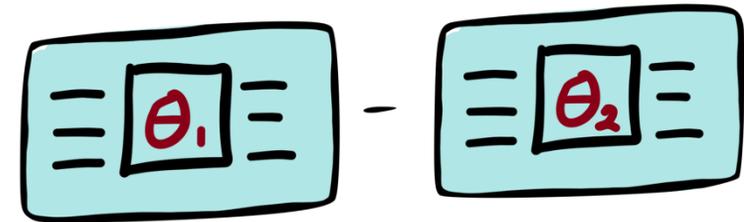
Stochastic PSR for general Hamiltonian evolution
L Banchi, GE Crooks, Quantum 5, 386 (2021)

Continuous variable systems / GBS distribution
N Killoran, et al. Phys. Rev. Research (2019)
L Banchi et al., Phys. Rev. A 102, 012417 (2020)

$$\nabla_\theta f = f(\theta_1) - f(\theta_2)$$

$$\text{Gradient: } \nabla_\theta \langle \hat{A} \rangle = \mathbb{E}_{s \sim u[0,1]} \left[\langle r_+ \rangle - \langle r_- \rangle \right]$$