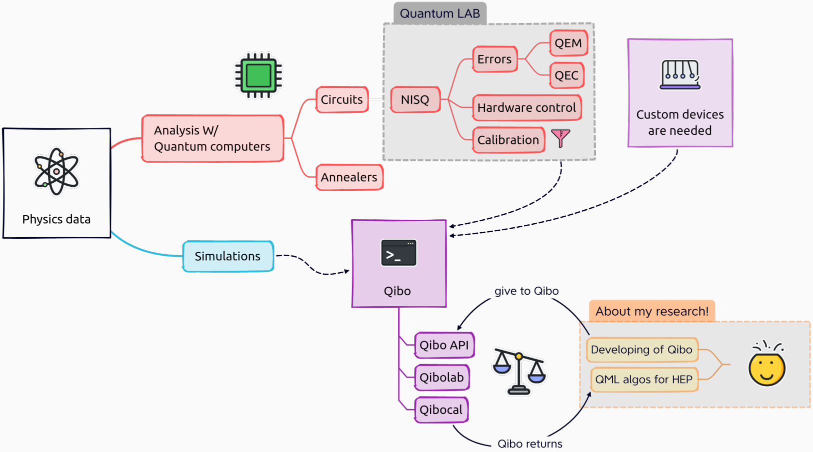
Towards a full-stack quantum operating system

Quantum simulation, control and calibration using `qibo`

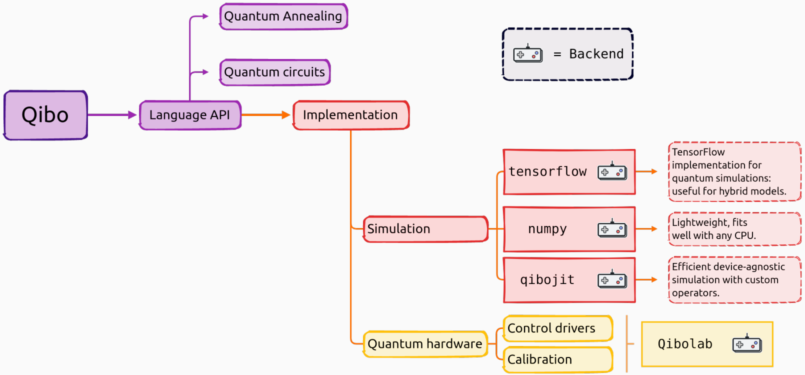
Matteo Robbiati

10 May 2023

Working in the NISQ era



What is `qibo`?



arXiv:2009.01845: *"Qibo: a framework for quantum simulation with hardware acceleration."*

More about `qibojit`

- We do state vector simulation, which solves:

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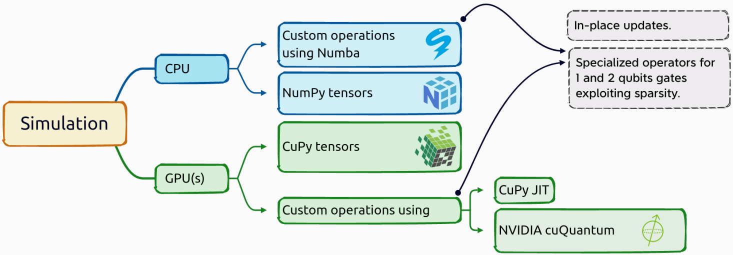
- For this reason we built `qibojit` (recommended if $N_{qubits \geq 20}$):



arXiv:2203.08826: *"Quantum simulation with just-in-time compilation."*

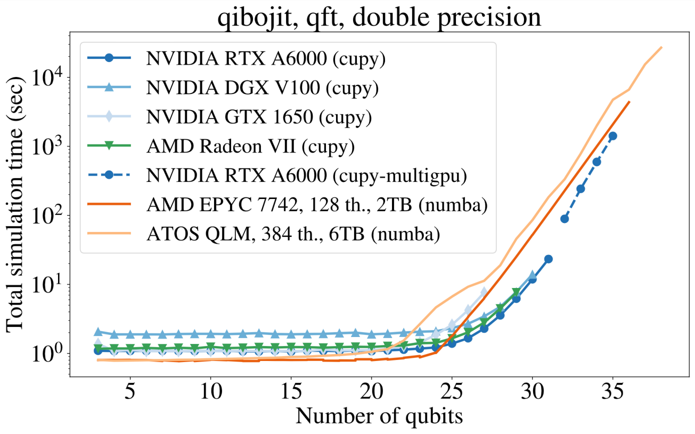


Figure 1: Quantum Fourier Transform execution with `qibojit` backend for growing number of qubits.

More about quantum annealing with `qibo`

- An `AdiabaticEvolution` model is provided, which implements:

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- If `solver=="exp"`, we use the evolutionary operator[1]:

$$|\psi(\tau = j\mathrm{d}t)\rangle = \overleftarrow{\prod_j} U_j \, |\psi(\tau = 0)\rangle \tag{3}$$

[1] Translated into a circuit form using the Trotter decomposition.

Adiabatic evolution on `qibo` backends

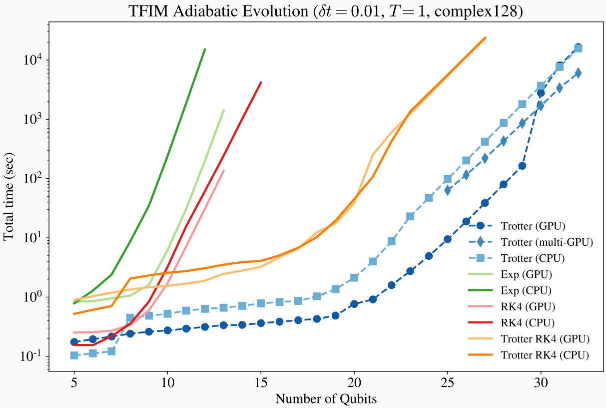
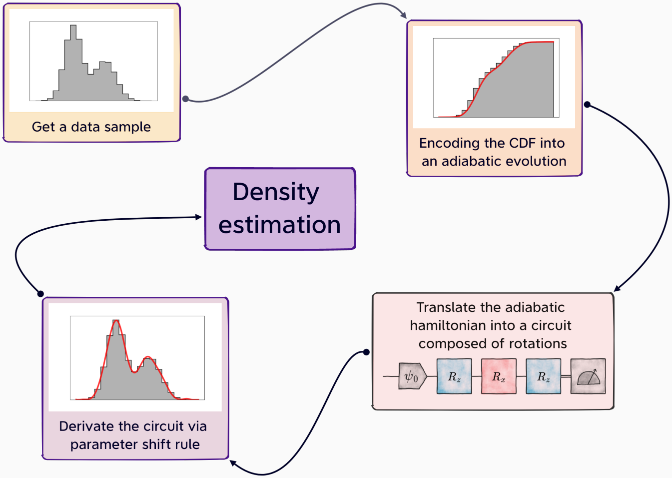


Figure 2: Adiabatic evolution execution with growing number of qubits and different solvers.

A full-stack QML algorithm

The theoretical idea



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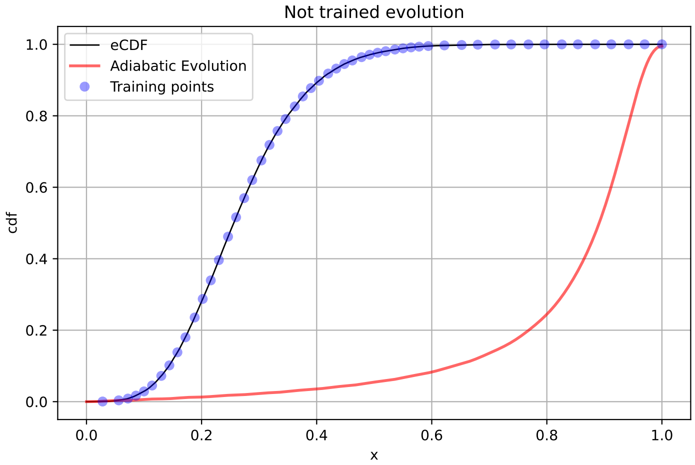
arXiv:2303.11346: *"Determining probability density functions with adiabatic quantum computing."*

A toy example with `nqubits=1` - starting point

- `nparams=20`, `dt=0.1`, `final_time=50` , `target_loss=None`



A toy example - until $J_{\mathrm{MSE}} = 10^{-1}$

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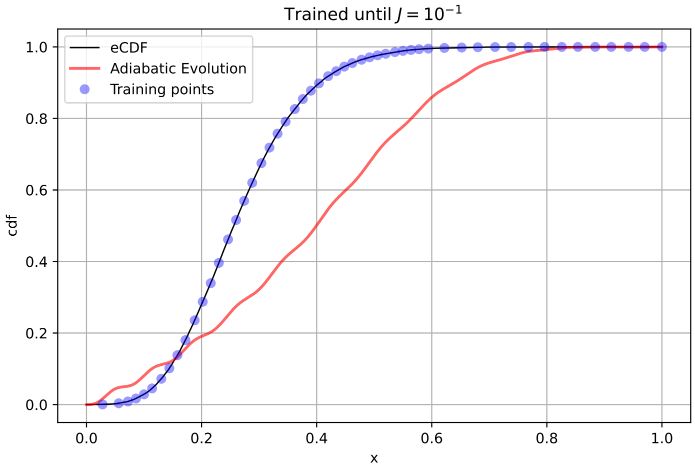
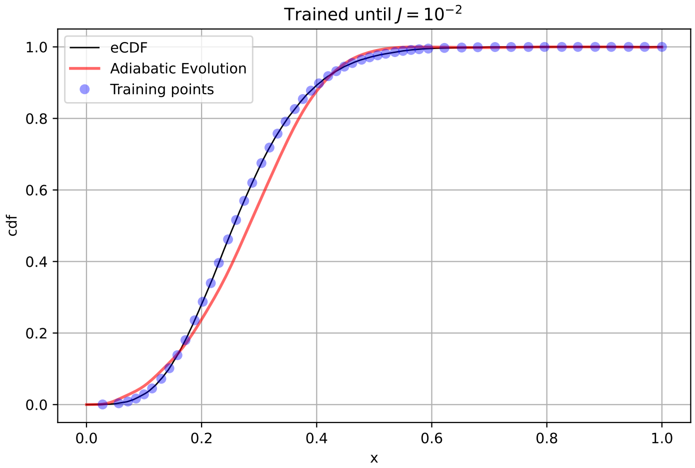


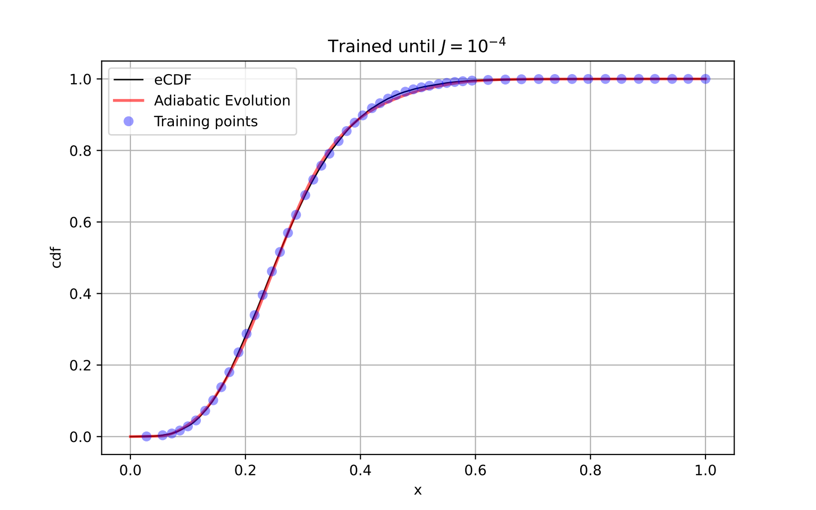
A toy example - until $J_{\text{MSE}} = 10^{-2}$

- `nparams=20`, `dt=0.1`, `final_time=50` , `target_loss=1e-2`



A toy example - ending at $J_{\mathrm{MSE}} = 10^{-4}$

- `nparams=20`, `dt=0.1`, `final_time=50` , `target_loss=1e-4`



SIMULATION: from $\{H_{\mathrm{ad}}\}$ to a circuit and derivate!

- Firstly, we did some calculations and approximations in order to:

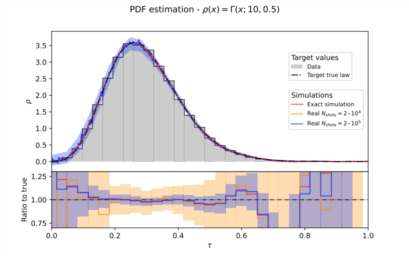
1. translate the Hamiltonians' sequence into a single unitary:

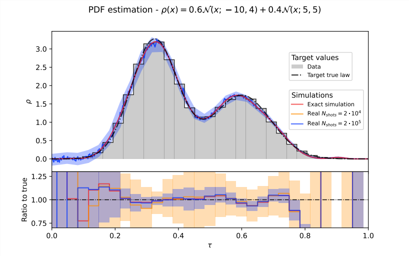
$$\prod_{j=1}^{n} e^{-iH_j \mathrm{d}t} \to \mathcal{U}(t);$$

2. translate this unitary in a sequence of rotational gates:

$$\mathcal{U}(t) = R_z(\theta_1)R_x(\theta_2)R_z(\theta_3) \qquad \text{with } \theta_i \equiv \theta_i(t).$$

- Then, we derivate the expected values using parameter shift rule and chain rule.





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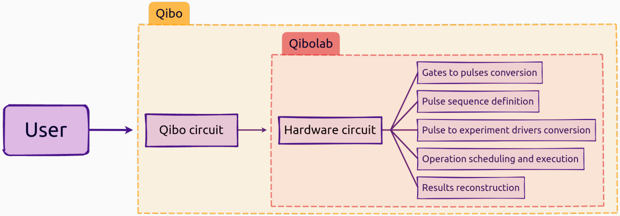

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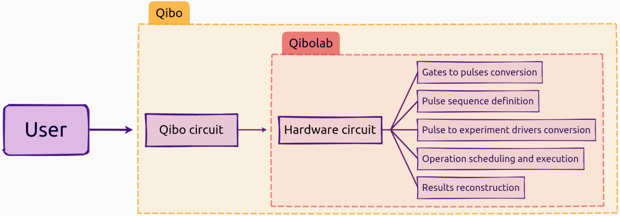

- Some labs are already using qibo:

INFN Istituto Nazionale di Fisica Nucleare

TII Technology Innovation Institute

CQT

BSC

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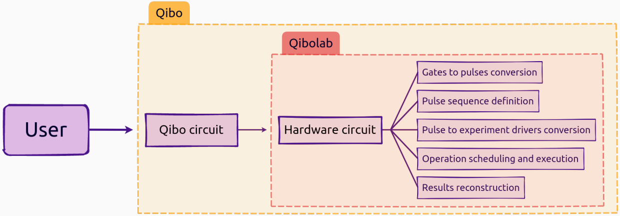

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arXiv:2202.07017: *"An open-source modular framework for quantum computing."*
arXiv:2112.02933: *"ICARUS-Q: Integrated Control and Readout Unit for Scalable Quantum Processors"*

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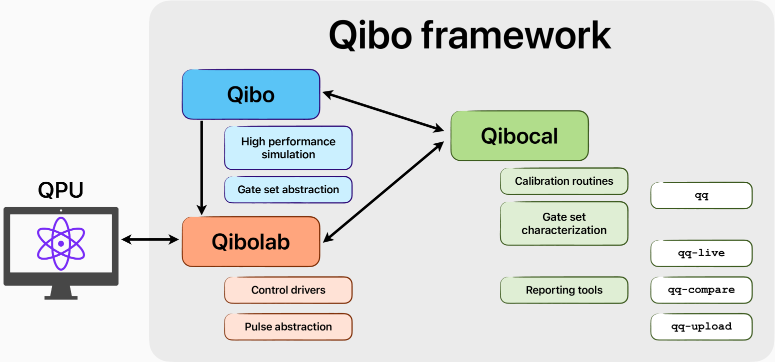
- For this reason, `qibocal` was born: a module for quantum calibration and verification.



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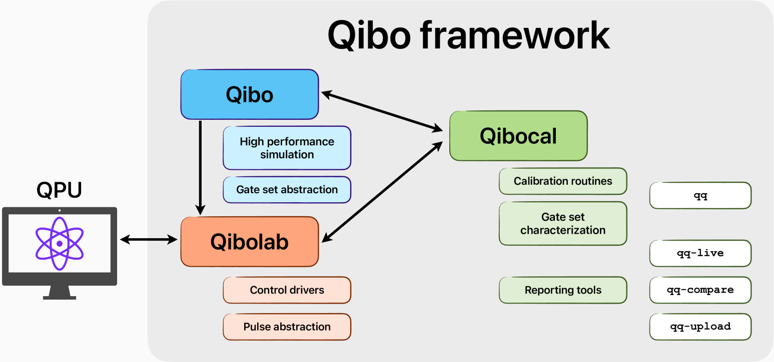


arXiv:2303.10397: *"Towards an open-source framework to perform quantum calibration and characterization."*

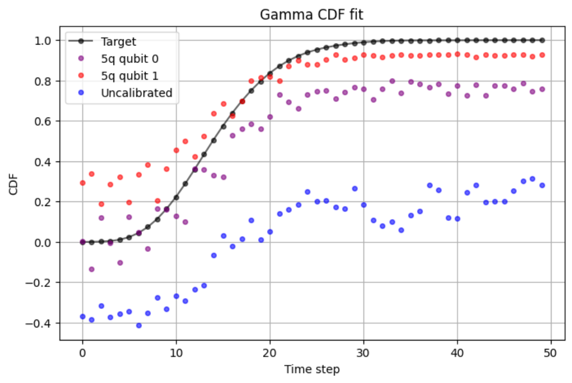
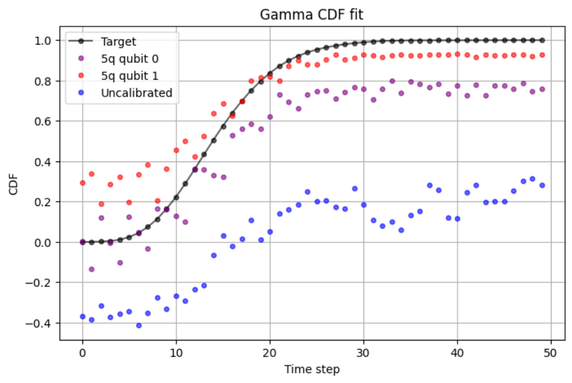


Figure 3: Different qubits requires different calibration and leads to different results.

The importance of `qibocal`



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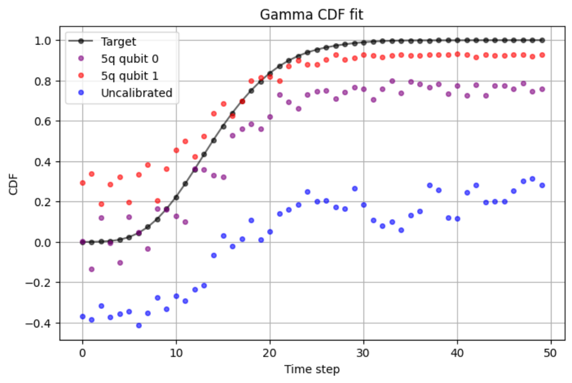

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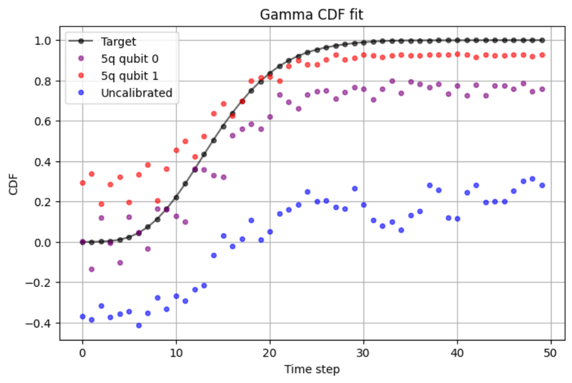

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- Open questions:
  - what if the entire training is performed on a NISQ device? *are the results self-resistent to the noise?*
  - what needed for improving results on the hardware?

☝: **what if we train on hardware?**

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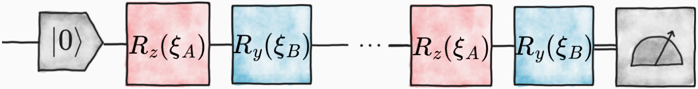

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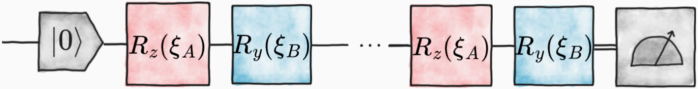

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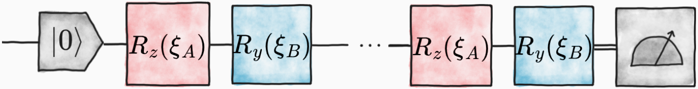

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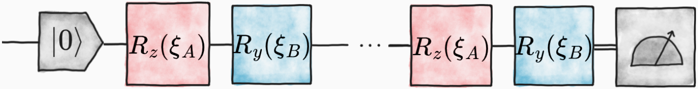

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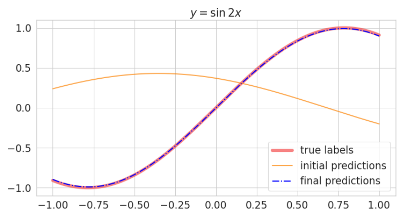
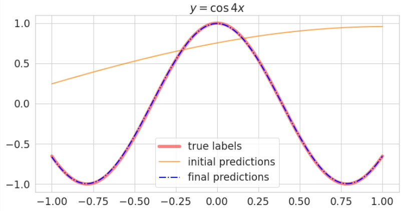
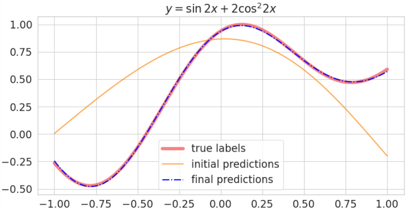
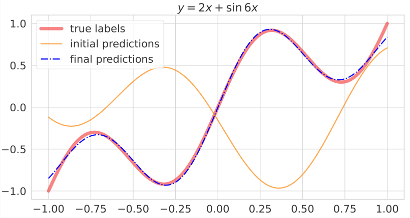
arXiv:2210.10787: *"A quantum analytical Adam descent through parameter shift rule using Qibo."*

Simulation results









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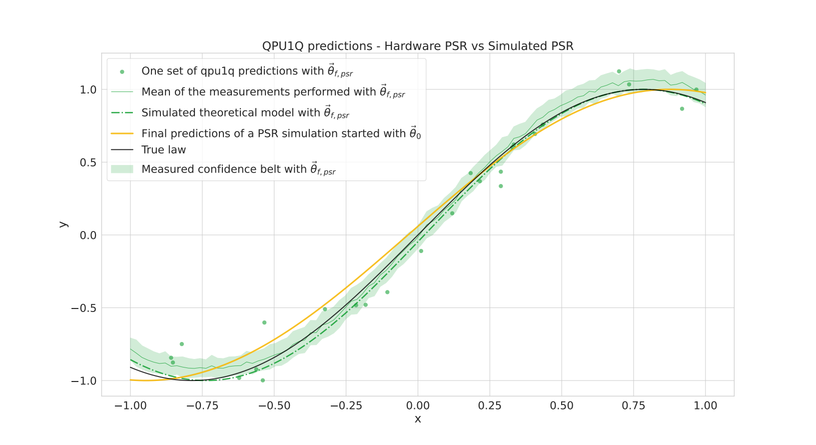


Figure 5: Batch Gradient Descent on the hardware. Gradients are evaluated via Parameter-Shift Rule.

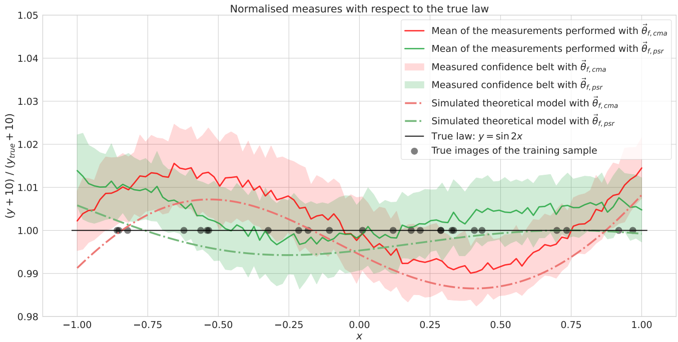


Figure 6: Normalised results of the SGD (green line) compared with true law and a genetic optimizer (red line).

Run on the hardware

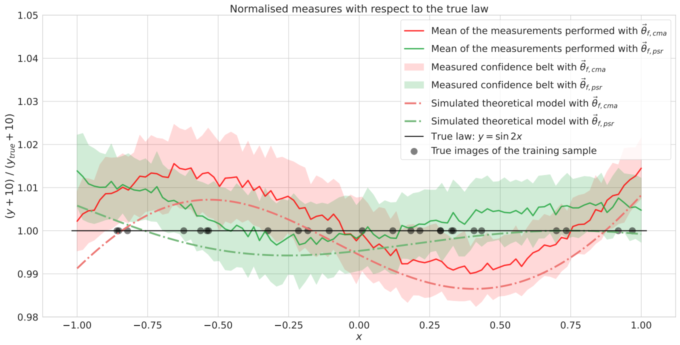
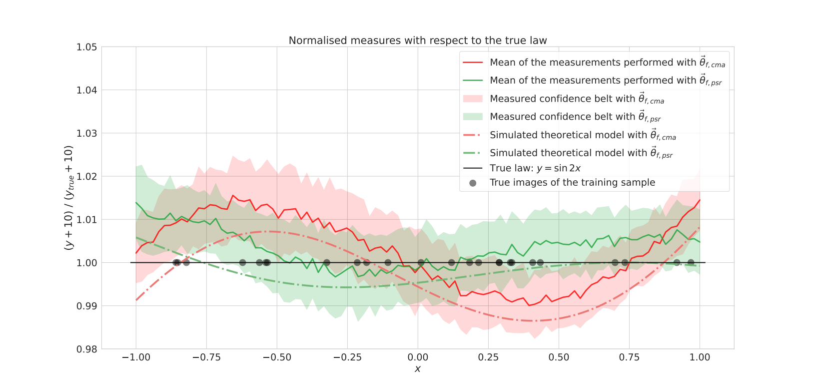


Figure 6: Normalised results of the SGD (green line) compared with true law and a genetic optimizer (red line).

- the full-stack framework works! comparable with a genetic algorithm;



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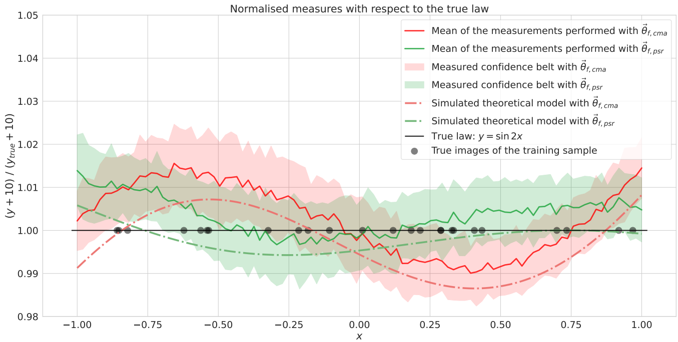

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- the full-stack framework works! comparable with a genetic algorithm;
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- no mitigation: have been the errors absorbed into the optimization?

✌: how to get noise resistance?

- We want to reproduce the u quark PDF fit of *Pérez-Salinas et al*.

[2] We used Zero Noise Extrapolation (ZNE) and Clifford Data Regresssion (CDR).

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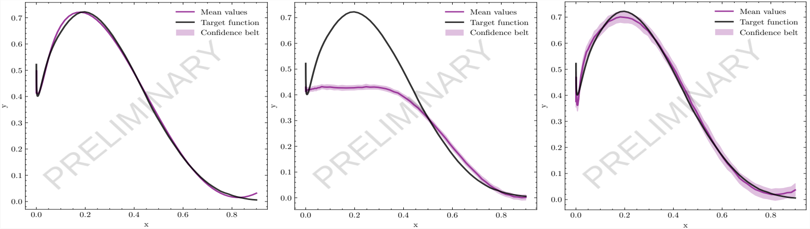

Figure 7: PDF fit performed with different levels of noisy simulation. From left to right, exact simulation, noisy simulation, noisy simulation applying error mitigation to the predictions.

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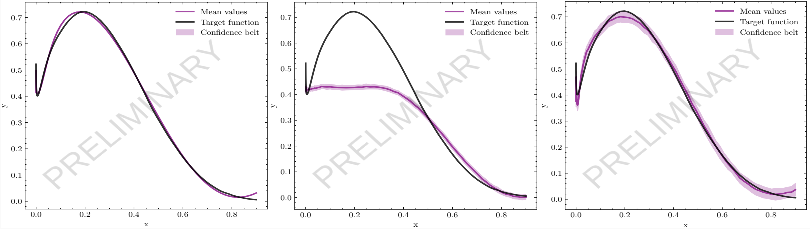

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- Run on the hardware upcoming!

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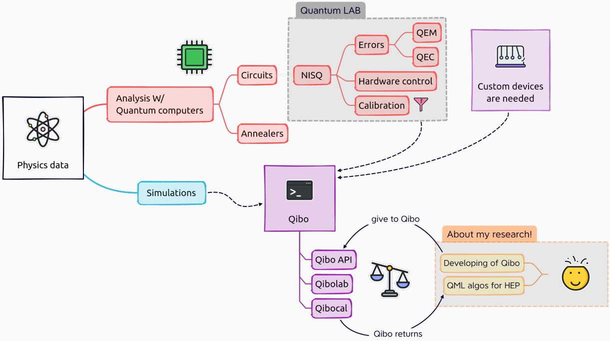

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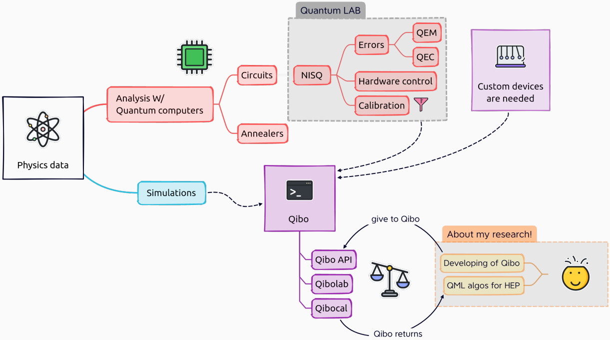

- code is open-source here: feel free to make your own contribution!
- Have a look to our documentation.