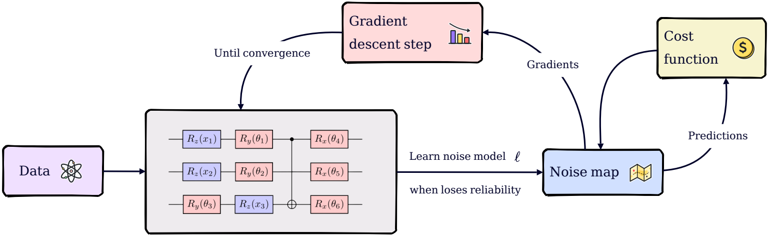
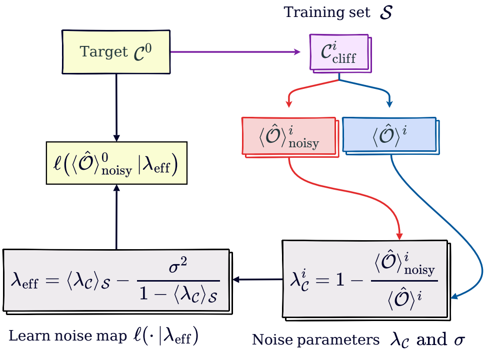
RTQEM pipeline

We define a Real-Time Quantum Error Mitigation (RTQEM) procedure.



1. consider a Variational Quantum Algorithm trained with gradient descent;
2. learn the noise map ℓ every time is needed over the procedure;
3. use ℓ to clean up both predictions and gradients.

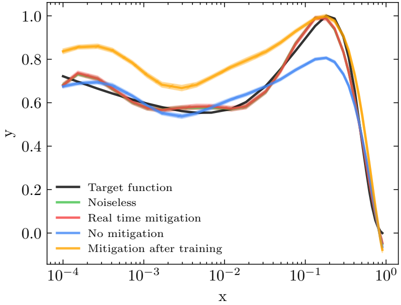
We use the Importance Clifford Sampling (ICS) procedure to learn the noise map ℓ.

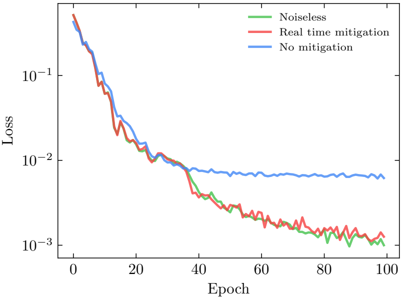


1. sample a training set of Clifford circuits $\mathcal{S}$ on top of a target $\mathcal{C}^0$;
2. process them so that their expectation values on Pauli strings is $+1$ or -1;
3. extract mitigation parameter $\lambda_{\rm eff}$ comparing $\langle\hat{\mathcal{O}}\rangle_{\rm noisy}$ and $\langle\hat{\mathcal{O}}\rangle$;
4. build $\ell \equiv \ell(\cdot|\lambda_{\rm eff})$ following the Phenomenological-Error-Model Inspired (PEMI) protocol.

One dimensional HEP target: the u-quark PDF

Parameter	N_{train}	N_{params}	N_{shots}	$\mathrm{MSE}^{\mathrm{rtqem}}_{\mathrm{best}}$	$\mathrm{MSE}^{\mathrm{unmit}}_{\mathrm{best}}$	Noise
Value	30	16	10^4	$1.1 \cdot 10^{-3}$	$6.1 \cdot 10^{-3}$	local Pauli



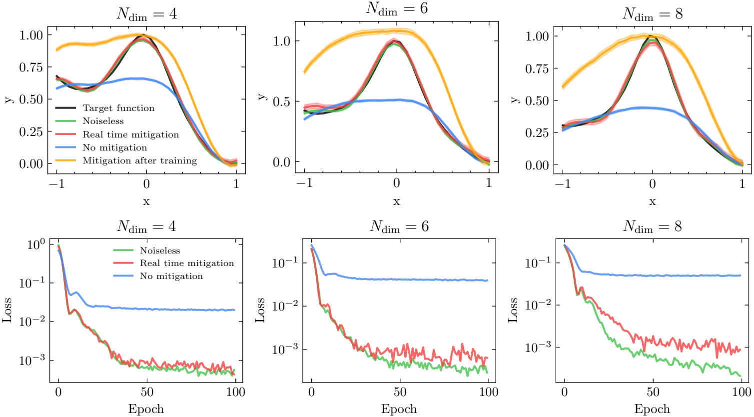


1. thanks to the RTQEM procedure, we reach a good minimum of the cost function;
2. the QEM is not effective is applied to a corrupted scenario (orange curve).

Multidimensional target

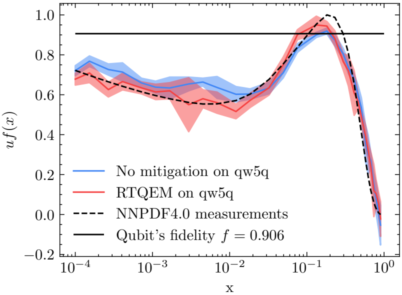
We tackle a multi-dimensional target computing predictions as expected value of a $Z^{\otimes N_{\rm dim}}$ after executing an $N_{\rm dim}$ circuit.

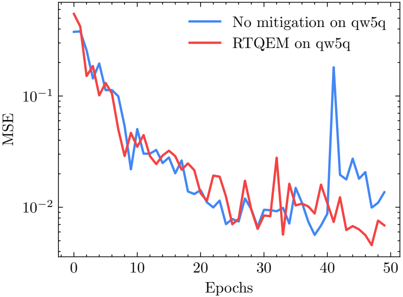
Job ID	$N_{\rm train}$	$N_{\rm params}$	$N_{\rm shots}$	$\mathrm{MSE}^{\rm rtqem}_{\rm best}$	$\mathrm{MSE}^{\rm unmit}_{\rm best}$	Noise
$N_{\rm dim} = 4$	30	48	10^4	$4.4 \cdot 10^{-4}$	$1.9 \cdot 10^{-2}$	local Pauli
$N_{\rm dim} = 6$	30	72	10^4	$4.1 \cdot 10^{-4}$	$3.8 \cdot 10^{-2}$	local Pauli
$N_{\rm dim} = 8$	30	96	10^4	$5.6 \cdot 10^{-4}$	$4.8 \cdot 10^{-2}$	local Pauli



RTQEM on a superconducting qubit

Parameter	$N_{\rm train}$	$N_{\rm params}$	$N_{\rm shots}$	$\text{MSE}^{\rm rtqem}_{\rm best}$	$\text{MSE}^{\rm unmit}_{\rm best}$	Noise
Value	15	16	500	0.0042	0.0055	real noise



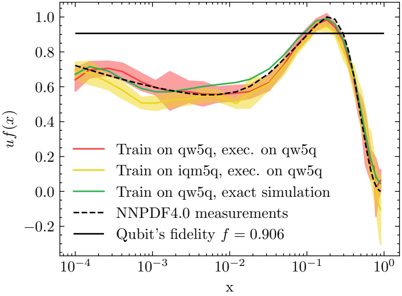


RTQEM allows exceeding the natural bound imposed by noise.

Can RTQEM generalise?

We perform a longer training on two different devices (and noises!) using the same initial conditions of the previous slide but $N_{\text{epochs}} = 100$.

- `iqm5q` by IQM controlled using Zurich Instruments;
- `qw5q` by QuantWare controlled using Qblox.



Train.	Epochs	Pred.	Config.	MSE
qw5q	50	qw5q	noisy	0.0055
qw5q	50	qw5q	RTQEM	0.0042
qw5q	100	qw5q	RTQEM	0.0013
iqm5q	100	qw5q	RTQEM	0.0037
qw5q	100	sim	RTQEM	0.0016

All the hardware results are obtained deploying the $\boldsymbol{\theta}_{\text{best}}$ on `qw5q`.