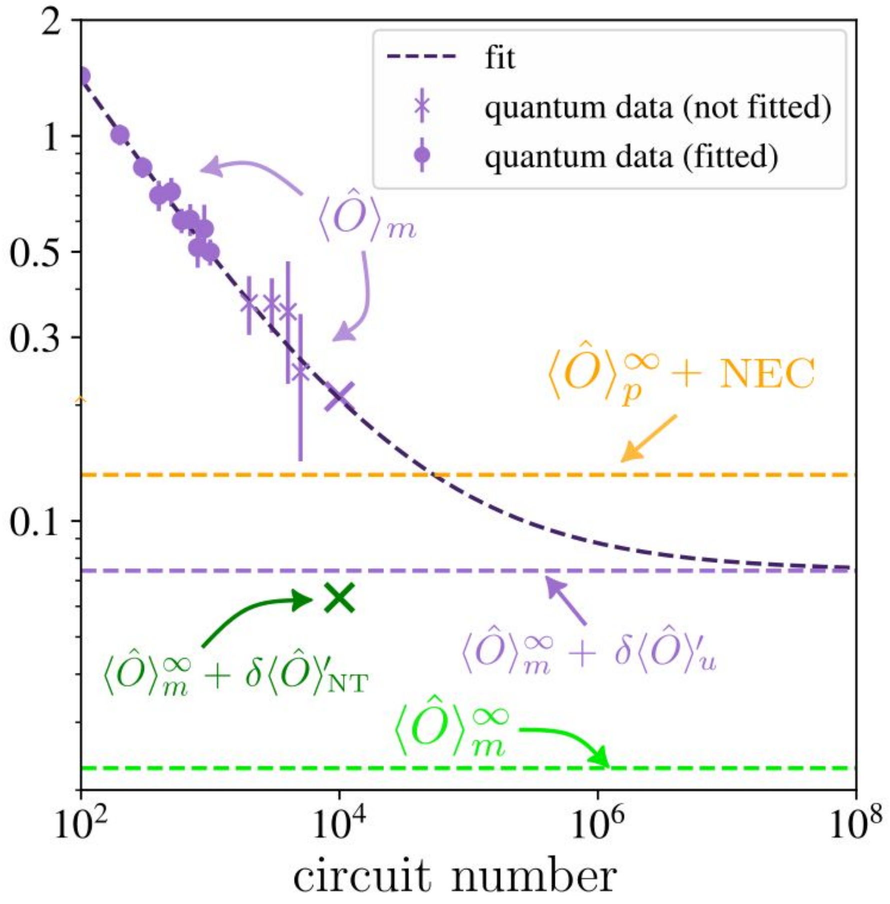
Kyrylo Snizhko
CEA Grenoble

Error mitigation by noise tailoring



"Quantum trajectories" program
03.02.2025, ICTS Bengaluru, India

FRANCE HYBRID HPCQUANTUM INITIATIVE
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Trajectories in Ukrainian embroidery

Image source:
https://ukrvyshyvka.com.ua/

Song "Two colors"

Red is love
Black is sorrow

https://youtu.be/yewhS0v0KxA?si=GHcVT8J7iQo2tQ5N

Noise in quantum computers is detrimental

Mitigating crosstalk errors by randomized compiling: Simulation of the BCS model on a superconducting quantum computer

Hugo Perrin,[1,*,†] Thibault Scoquart,[1,*,‡] Alexander Shnirman,[1,2] Jörg Schmalian,[1,2] and Kyrylo Snizhko[3]
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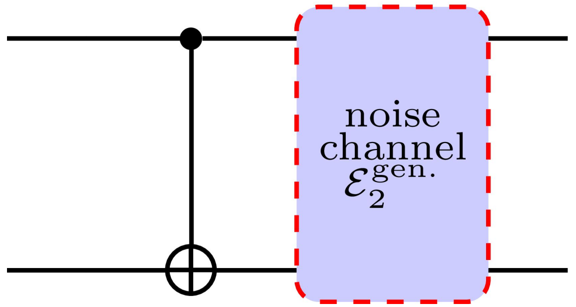
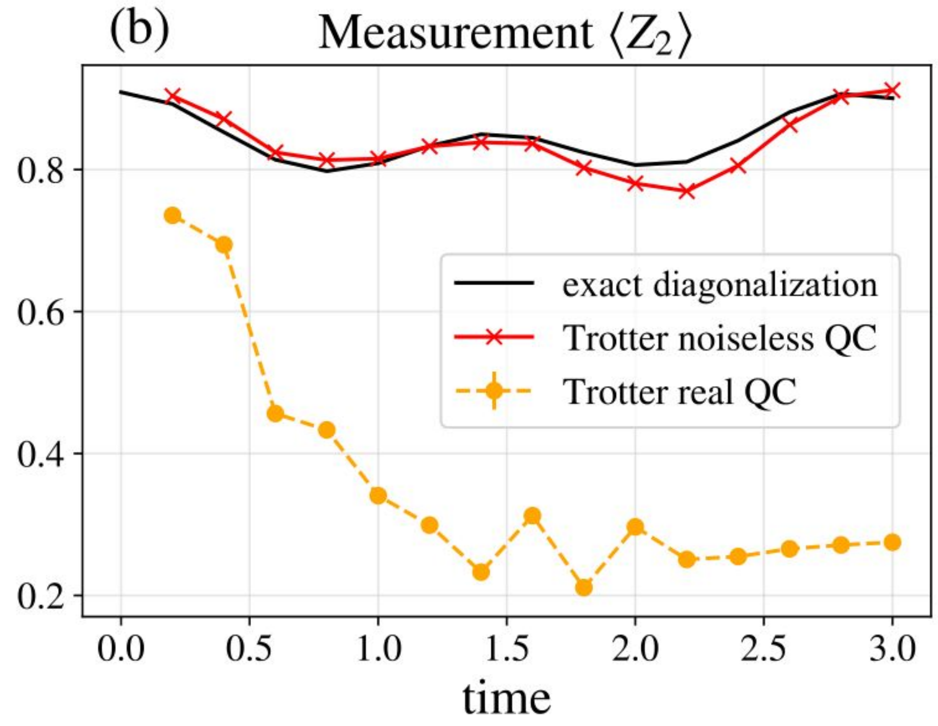
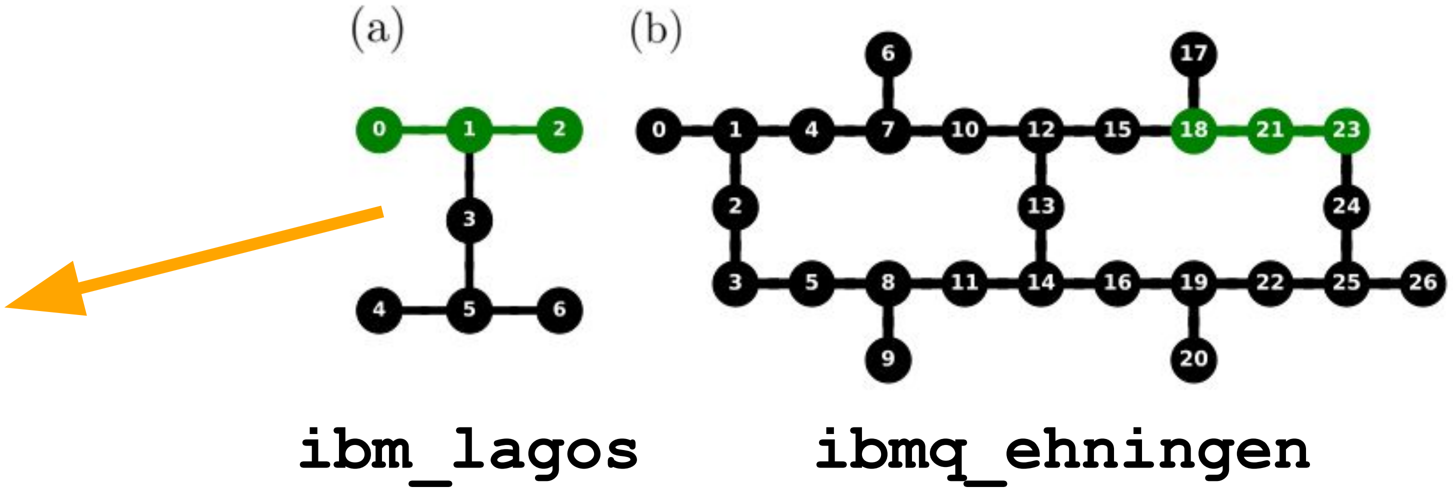
[2]*Karlsruher Institut für Technologie, Institut für Quantenmaterialien und Technologien, IQMT, 76021 Karlsruhe, Germany*
[3]*Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France*

PRResearch **6**, 013142 (2024)



$$\hat{H}_{\rm BCS} = -\sum_{j=0}^{L-1}(\epsilon_j - \frac{g}{2})\sigma_j^z - \frac{g}{2}\sum_{\substack{i,j=0\\ i<j}}^{L-1}\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right)$$



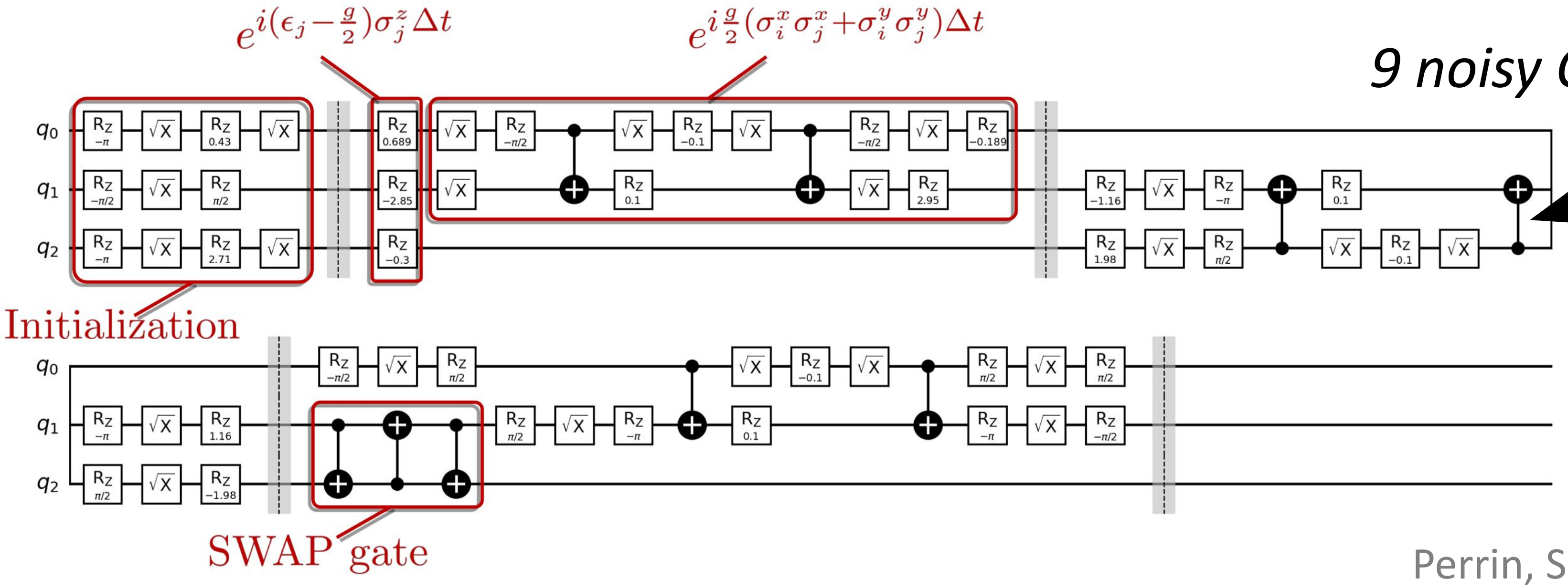


Simulating quench dynamics in the BCS model

$$\hat{H}_{\rm BCS} = -\sum_{j=0}^{L-1}(\epsilon_j - \frac{g}{2})\sigma_j^z - \frac{g}{2}\sum_{\substack{i,j=0\\ i<j}}^{L-1}\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right)$$

$L = 3$ qubits/Cooper pairs

$$\hat{U}_{\rm BCS}(\Delta t) \simeq \prod_j e^{i(e_j - \frac{g}{2})\sigma_j^z \Delta t}\prod_{i<j} e^{i\frac{g}{2}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y)\Delta t}$$

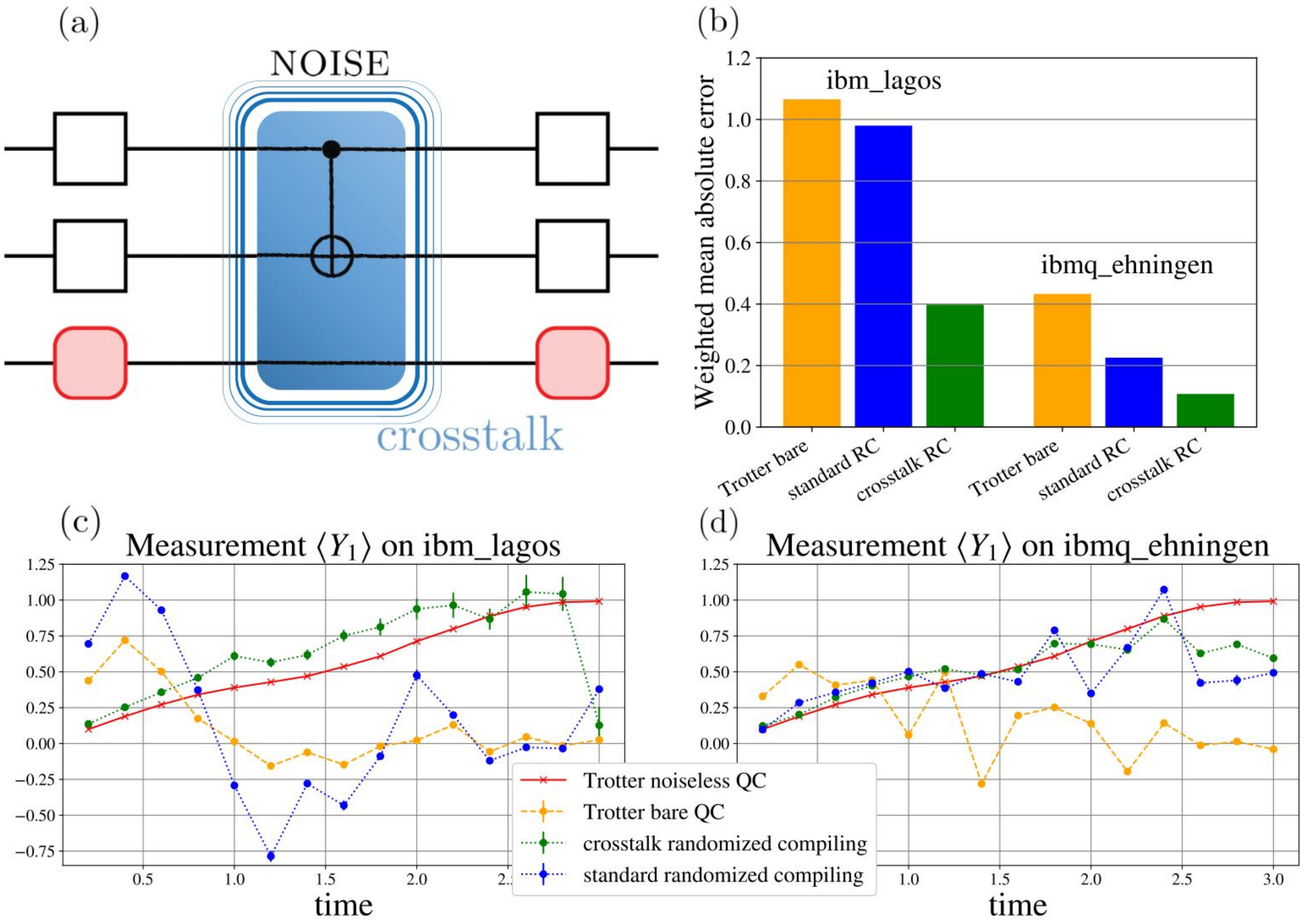


9 noisy CNOT gates per Trotter step

99% accurate CNOTs
⇒ 1% error per CNOT
⇒ 9% error per Trotter step
⇒ **expect complete noise after ~11 steps**

Perrin, Scoquart, …, KS PRResearch **6**, 013142

Mitigating the noise and seeing the crosstalk



⇐ expect complete noise after ~11 steps

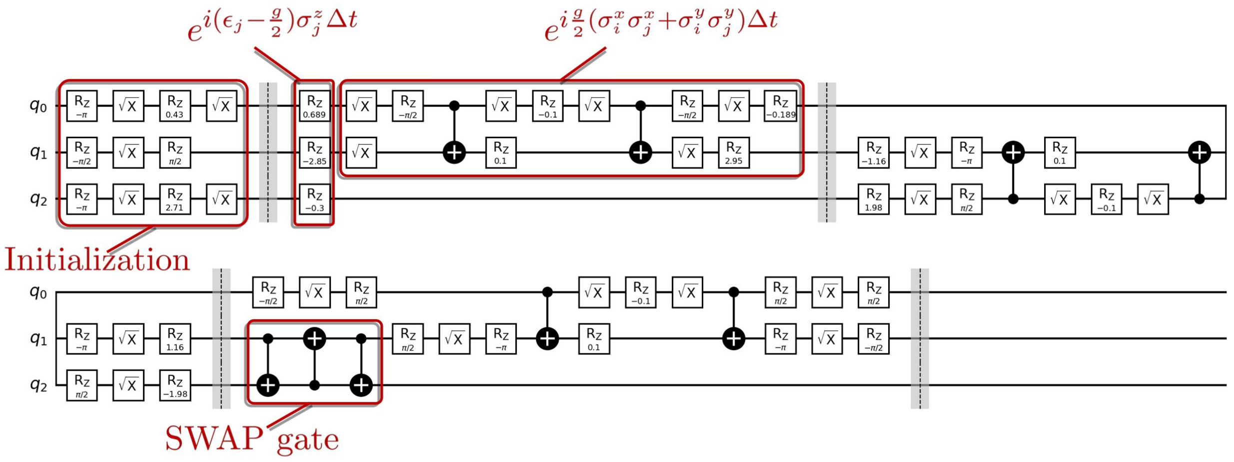
Perrin, Scoquart, …, KS PRResearch **6**, 013142

Mitigation: noise estimation circuit (NEC)

Example: Assume N-qubit, **global** depolarizing noise:

$$\mathcal{E}_n^{\text{glob.}}(\rho) = (1-\lambda_{\text{glob.}})\rho + \lambda_{\text{glob.}}\frac{\mathbb{I}}{2^N} \longrightarrow \langle \mathcal{O} \rangle_{\text{noisy}} = (1-\lambda_{\text{glob.}})^{n_{\text{CNOT}}} \langle \mathcal{O} \rangle_{\text{noiseless}}$$

Multiplicative error removed by running **circuits with only the CNOT skeleton:**



Urbanek et al., PRL **127**, 270502 (2021)

Mitigation: noise estimation circuit (NEC)

Example: Assume N-qubit, **global** depolarizing noise:

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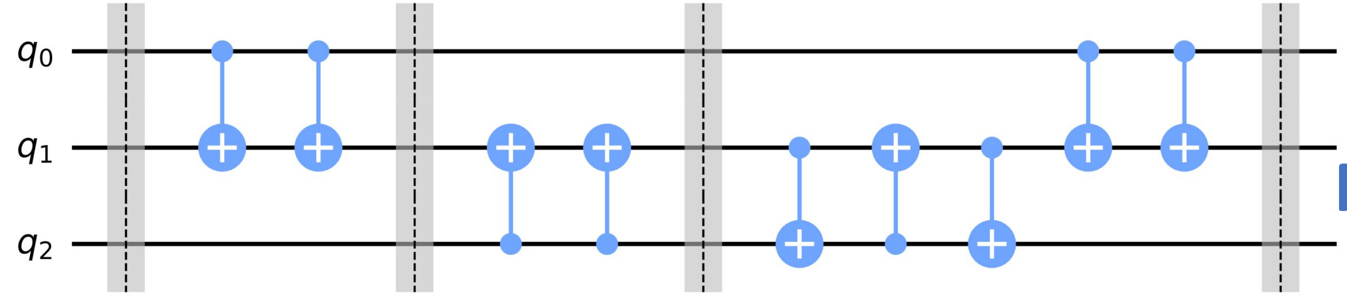


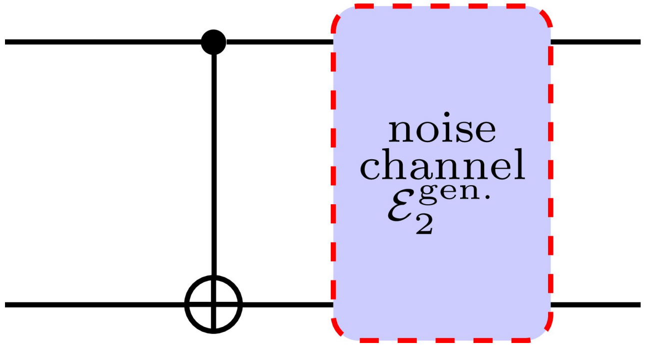
Noise estimation circuit
=
Trotter step circuit without single qubit gates

$$\langle\hat{O}\rangle_{\text{mitigated}} = \frac{\langle\hat{O}\rangle_{\text{measured}}}{\mathcal{F}_{\text{NEC}}} \sim \frac{\langle\hat{O}\rangle_{\text{measured}}}{\langle 1\rangle_{\text{measured}}}$$

Urbanek et al., PRL **127**, 270502 (2021)

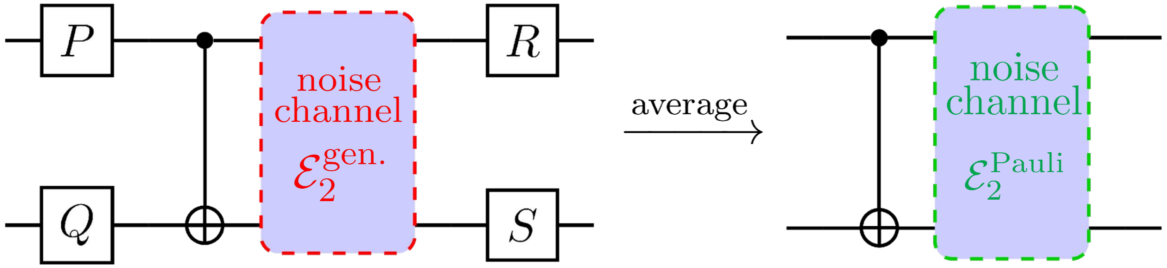
Simplifying the noise structure: randomized compiling (RC)

- General noise:



$$\mathcal{E}_2^{\text{gen.}}(\rho) = \sum_{i,j,k,l=0}^{3} p_{ijkl} (\sigma^i \otimes \sigma^j).\rho.(\sigma^k \otimes \sigma^l)$$

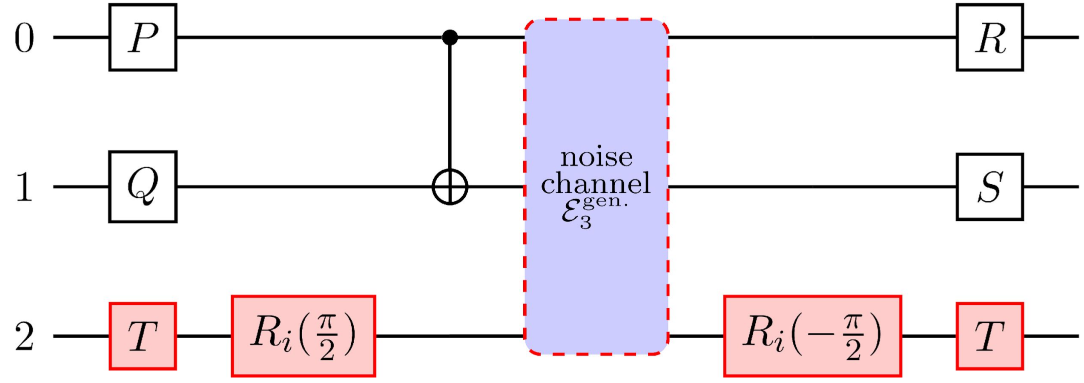
- Randomized compiling to get Pauli noise



$$\mathcal{E}_2^{\text{pauli}}(\rho) = \sum_{i,j=0}^{3} p_{ij} (\sigma^i \otimes \sigma^j).\rho.(\sigma^i \otimes \sigma^j)$$

Kern et al., Eur. Phys. J. D **32**, 153 (2005)
Wallman, Emerson, PRA **94**, 052325 (2016)
Hashim et al., PRX **11**, 041039 (2021)

Crosstalk!

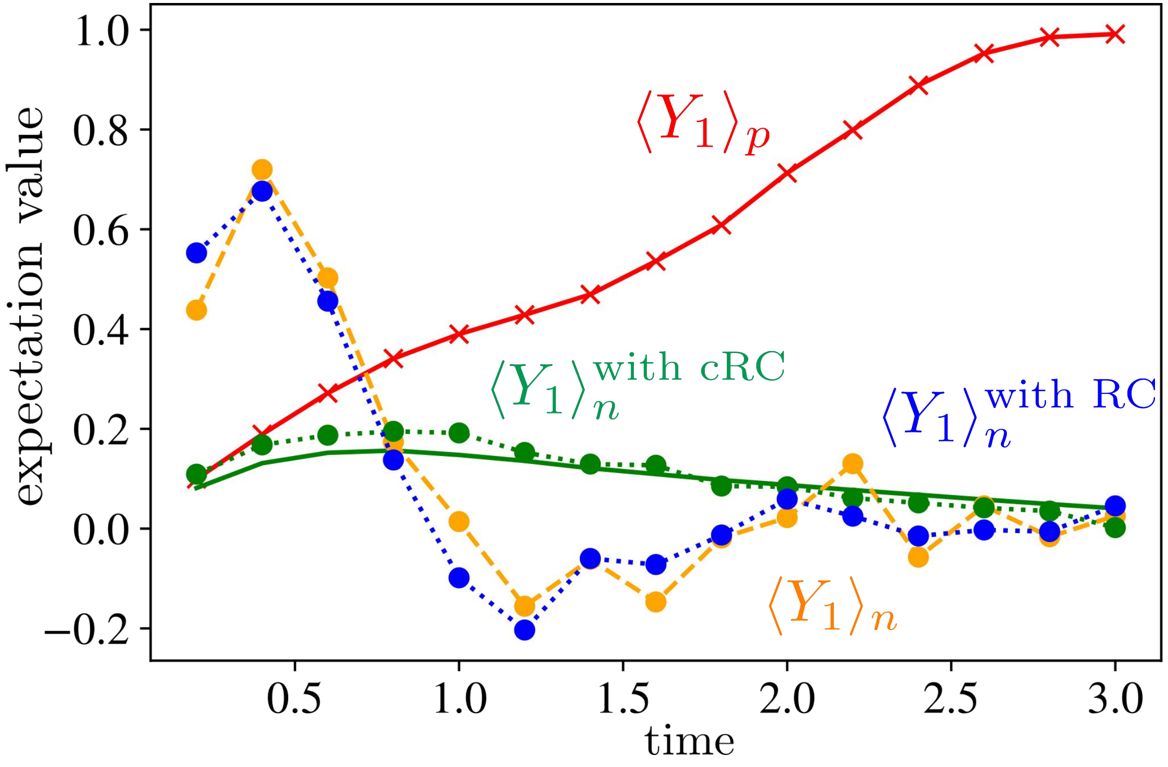


Crosstalk RC (cRC) average

$$\mathcal{E}_1^{\text{dep.}}(\rho) = \left(1-\lambda'\right)\rho + \lambda'\frac{\mathbb{I}_2}{2}$$

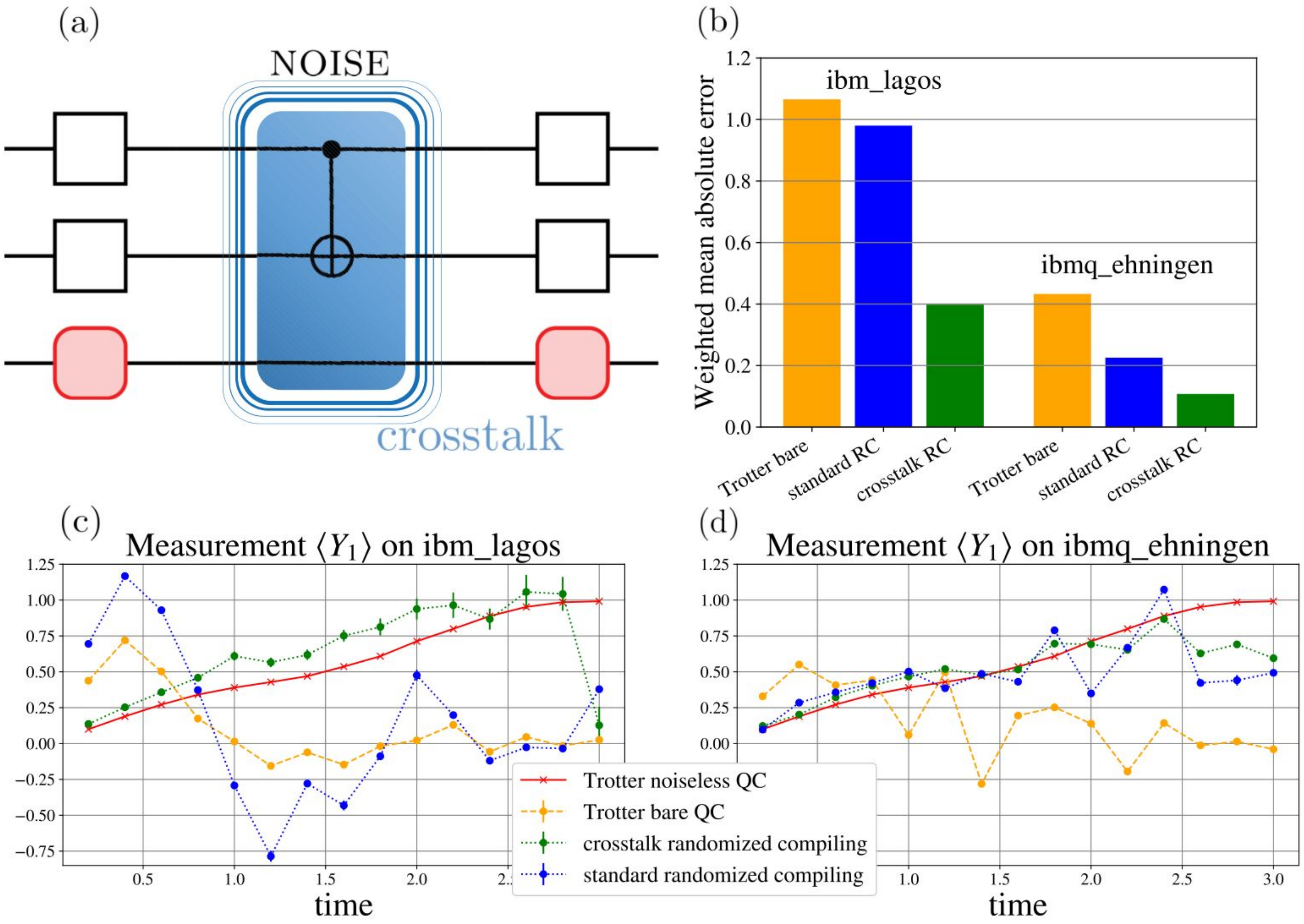
Yields **depolarizing noise** on the **neighbouring qubit !**

RC (no NEC):



Perrin, Scoquart, …, KS PRResearch **6**, 013142

RC + NEC = improved results + error characterization



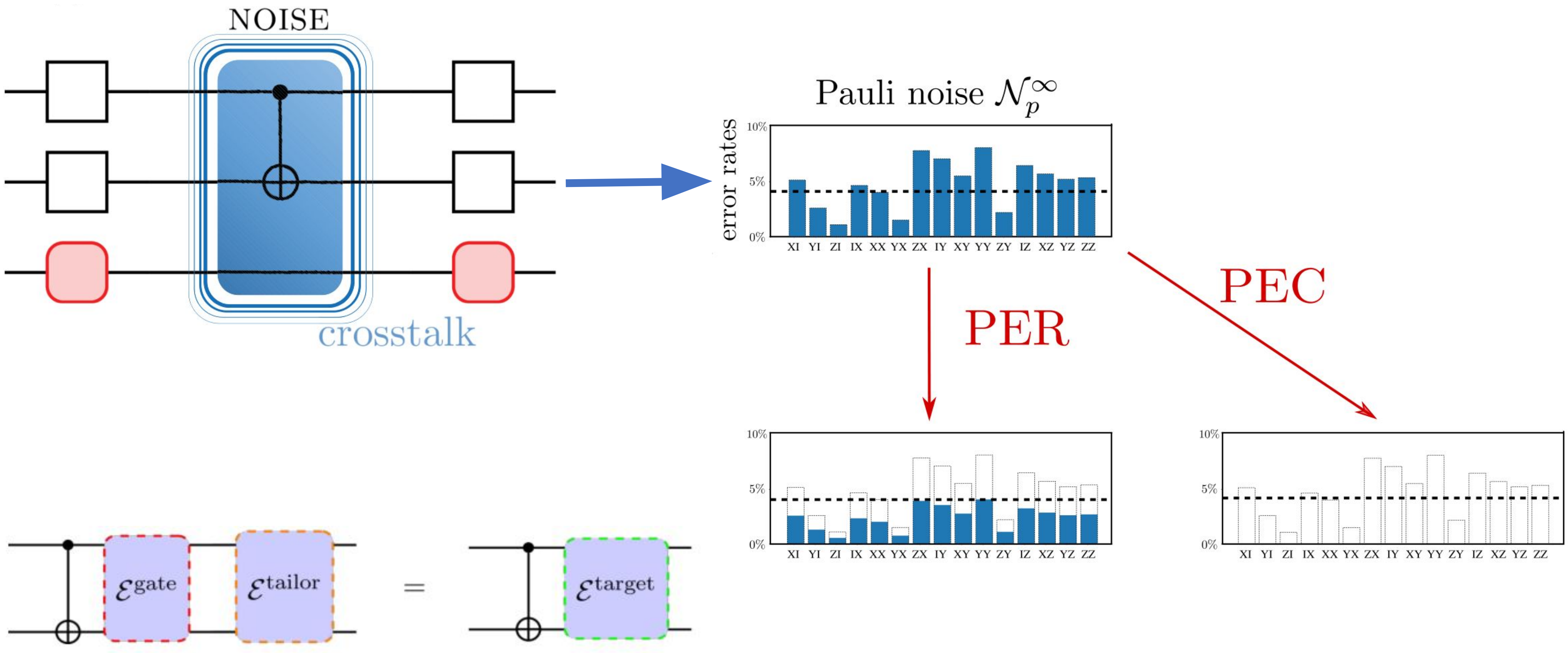
NEC requires global **depolarizing** noise

$$\mathcal{E}_n^{\text{glob.}}(\rho) = (1 - \lambda_{\text{glob.}})\rho + \lambda_{\text{glob.}} \frac{\mathbb{I}}{2^N}$$

⇐ NEC used for all curves

Perrin, Scoquart, …, KS PRResearch **6**, 013142

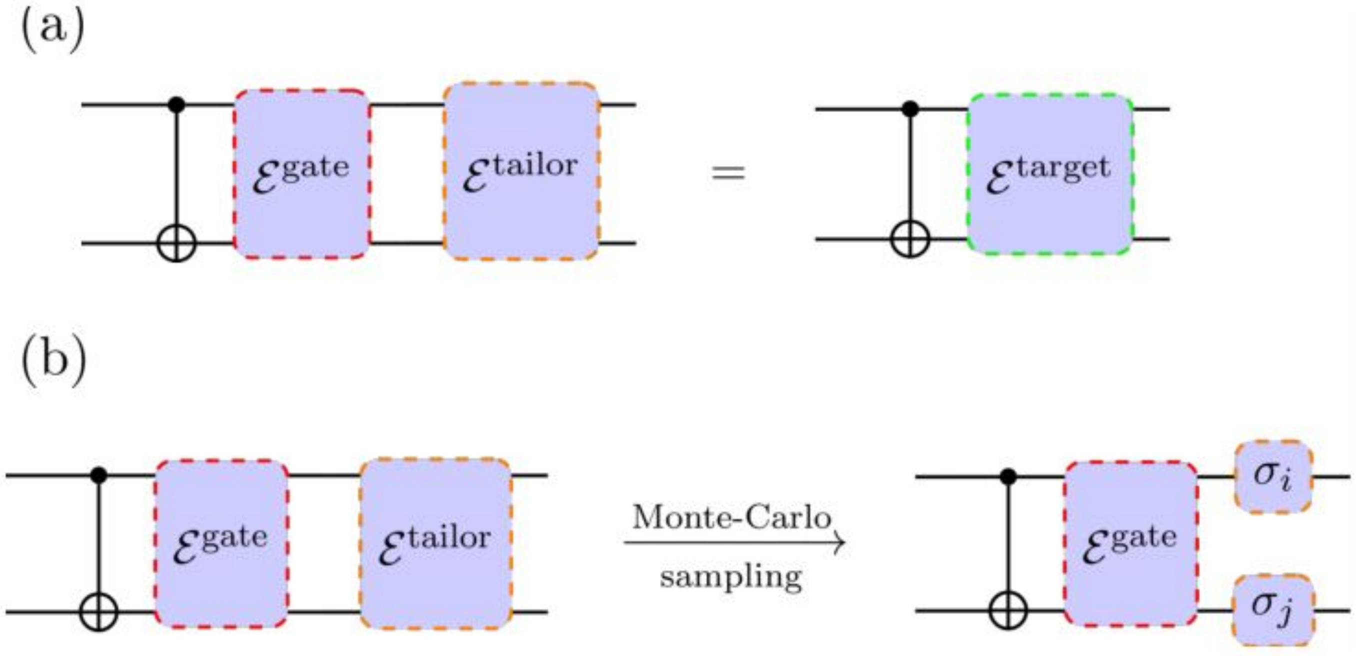
Probabilistic error cancellation (PEC) reduction (PER)



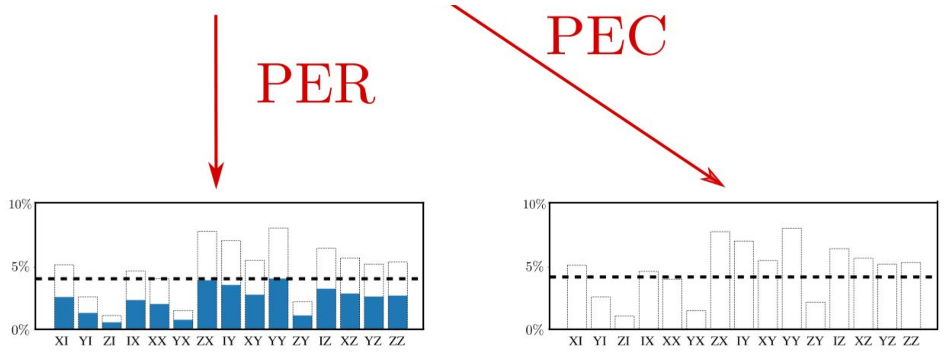
Temme, Bravyi, Gambetta, PRL **119**, 180509 (2017)

Berg, Minev, Kandala, Temme, Nature Physics **19**, 1116 (2023)

How do PEC and PER work?



Sample σ_i, σ_j → Get target noise channel



Temme, Bravyi, Gambetta, PRL **119**, 180509 (2017)
Berg, Minev, Kandala, Temme, Nature Physics **19**, 1116 (2023)

Noise channel representations

χ-matrix representation:

$$\rho \to \mathcal{E}(\rho) = \sum_{a,b} \chi_{ab} P_a \rho P_b$$

with n-qubit Pauli matrices $P_a \in \{I, X, Y, Z\}^{\otimes n_{\text{qubits}}}$

Pauli noise: $\chi_{ab} = p_a \delta_{ab}, \sum_a p_a = 1$

Pauli transfer-matrix (PTM) representation:

$$\rho = \rho_a P_a \qquad \left(\text{or } \rho_a = \frac{1}{2^{n_{\text{qubits}}}} \mathrm{Tr}(P_a \rho)\right)$$

$$\{\rho_a\} \to \left\{ \sum_b E_{ab} \rho_b \right\}$$

PTM: $E_{ab} = \frac{1}{2^{n_{\text{qubits}}}} \mathrm{Tr}\big(P_a \mathcal{E}(P_b)\big)$

Pauli noise: $E_{ab} = f_a \delta_{ab}$

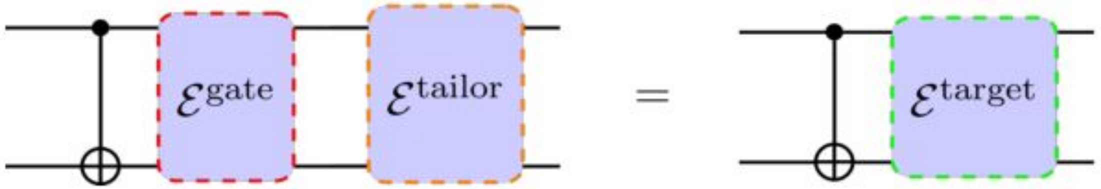
Connection (Walsh-Hadamard transform):

$$p_a = \frac{1}{4^{n_{\text{qubits}}}} \sum_b (-1)^{\langle P_a, P_b \rangle_{\text{sp}}} f_b$$

Symplectic inner product:

$$\langle P_a, P_b \rangle_{\text{sp}} = \begin{cases} 0, & \text{if } P_a P_b = +P_b P_a \\ 1, & \text{if } P_a P_b = -P_b P_a \end{cases}$$

How do PEC and PER work?

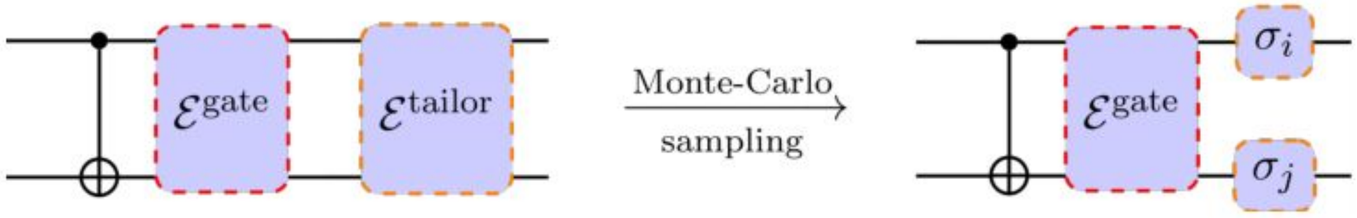


$$E^{\text{target}} = E^{\text{tailor}} \times E^{\text{gate}}$$

$$\Rightarrow E^{\text{tailor}} = E^{\text{target}} \times (E^{\text{gate}})^{-1} = f_a^{\text{tailor}} \delta_{ab}$$

$$p_a^{\text{tailor}} = \frac{1}{4^{n_{\text{qubits}}}} \sum_b (-1)^{\langle P_a, P_b \rangle_{\text{sp}}} f_b^{\text{tailor}}$$

$$\mathcal{E}(\rho) = \sum_a p_a^{\text{tailor}} P_a \rho P_a$$

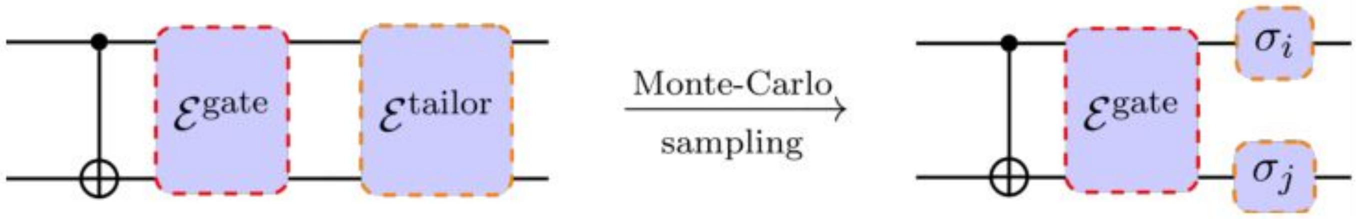


Create trajectories by hand!

Temme, Bravyi, Gambetta, PRL **119**, 180509 (2017)
Berg, Minev, Kandala, Temme, Nature Physics **19**, 1116 (2023)

How do PEC and PER work?

$$p_a^{\text{tailor}} = \frac{1}{4^{n_{\text{qubits}}}} \sum_b (-1)^{\langle P_a, P_b \rangle_{\text{sp}}} f_b^{\text{tailor}} \qquad \mathcal{E}(\rho) = \sum_a p_a^{\text{tailor}} P_a \rho P_a$$



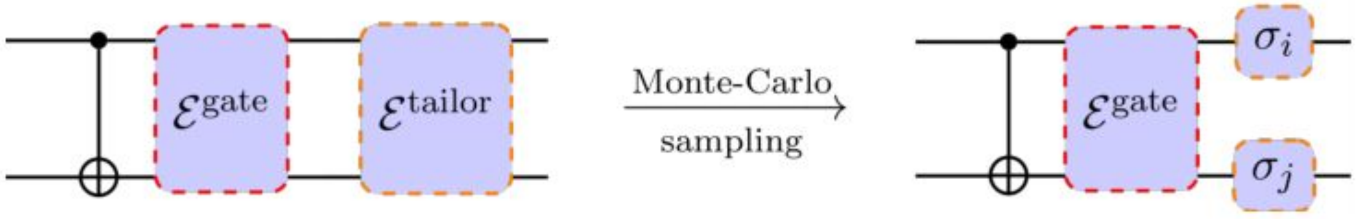
Problem: p_a^{tailor} can be negative

Temme, Bravyi, Gambetta, PRL **119**, 180509 (2017)
Berg, Minev, Kandala, Temme, Nature Physics **19**, 1116 (2023)

How do PEC and PER work?

$$q_a^{\text{tailor}} = \frac{1}{4^{n_{\text{qubits}}}} \sum_b (-1)^{\langle P_a, P_b \rangle_{\text{sp}}} f_b^{\text{tailor}} \qquad \mathcal{E}(\rho) = \sum_a q_a^{\text{tailor}} P_a \rho P_a$$

Sample: $\tilde{p}_a^{\text{tailor}} = \frac{|q_a^{\text{tailor}}|}{\gamma}, \quad \gamma = \sum_a |q_a^{\text{tailor}}| > 1$



Take the sign q_a^{tailor} into account when calculating the Monte-Carlo average

Multiply the average by $\gamma^{n_{\text{CNOT}}}$

⇒ exponentially costly to keep a fixed error bar (sign problem)

Temme, Bravyi, Gambetta, PRL **119**, 180509 (2017)
Berg, Minev, Kandala, Temme, Nature Physics **19**, 1116 (2023)

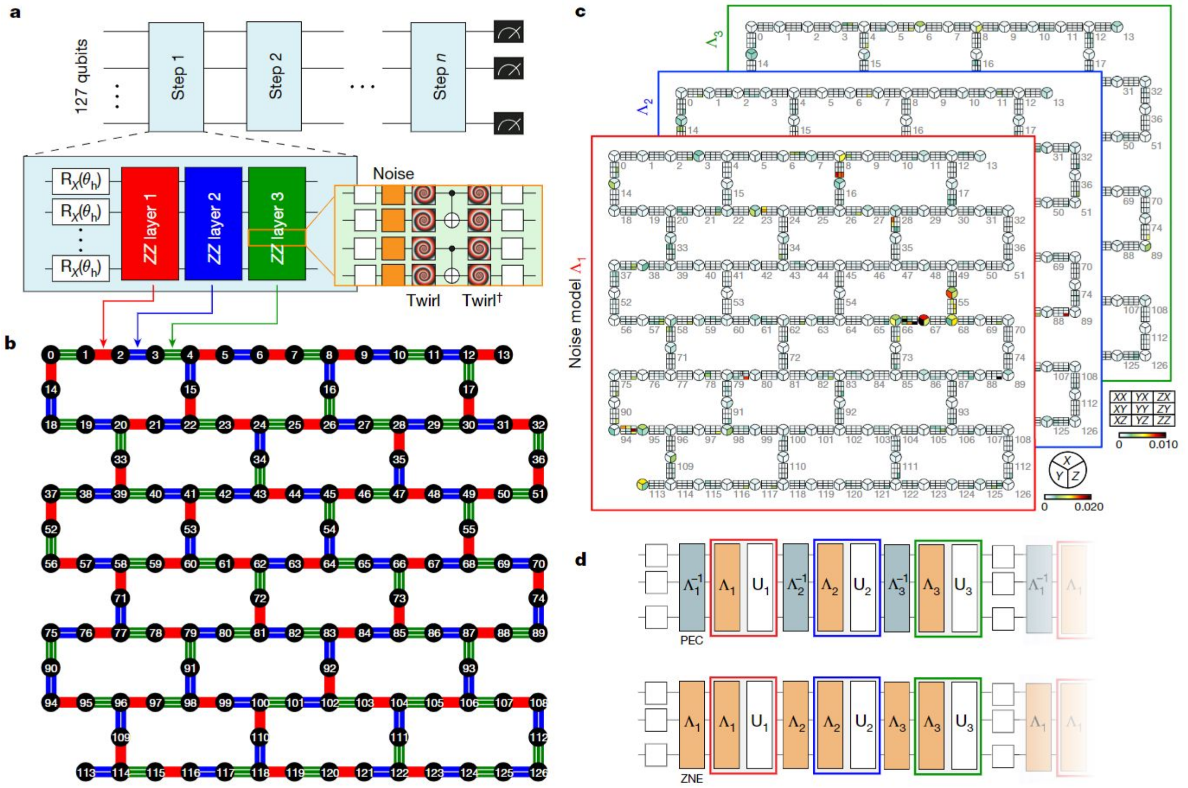
How do PEC and PER work?

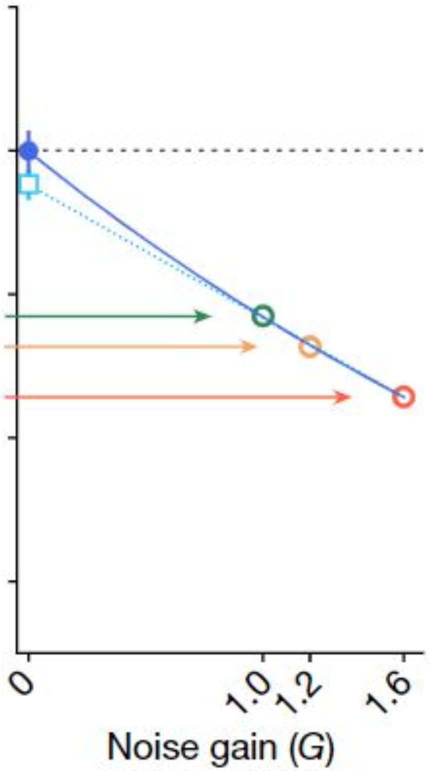
Multiply the average by $\gamma^{n_{\mathrm{CNOT}}}$

$\Rightarrow$ **exponentially costly when reducing noise**

Possible solution: increase noise (avoid quasiprobability distributions!)

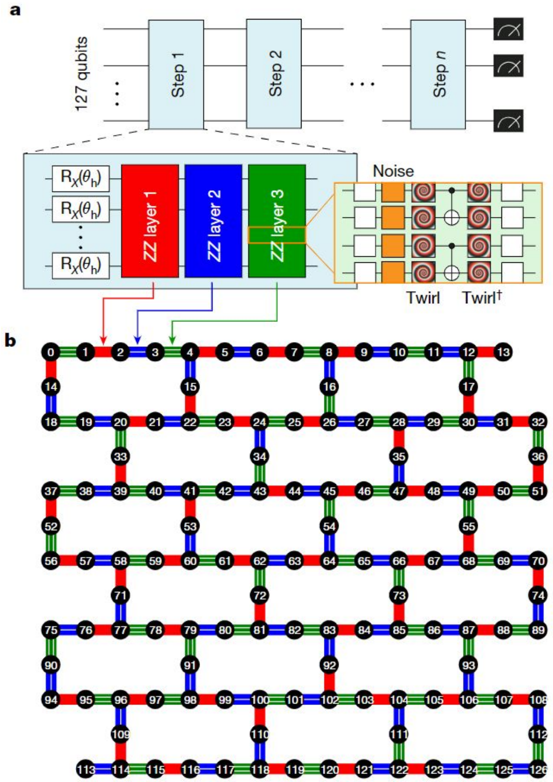
E.g., IBM “quantum utility” experiment:





Kim et al., Nature **618**, 500 (2023)

Quantum utility?



Kim et al., Nature **618**, 500 (2023)

SIGBOVIK 2024 proceedings, page 199

Quantum Disadvantage

Or, simulating IBM's 'quantum utility' experiment with a Commodore 64

Anonymous
quantum.disadvantage@proton.me
https://quantum-disadvantage.co.uk

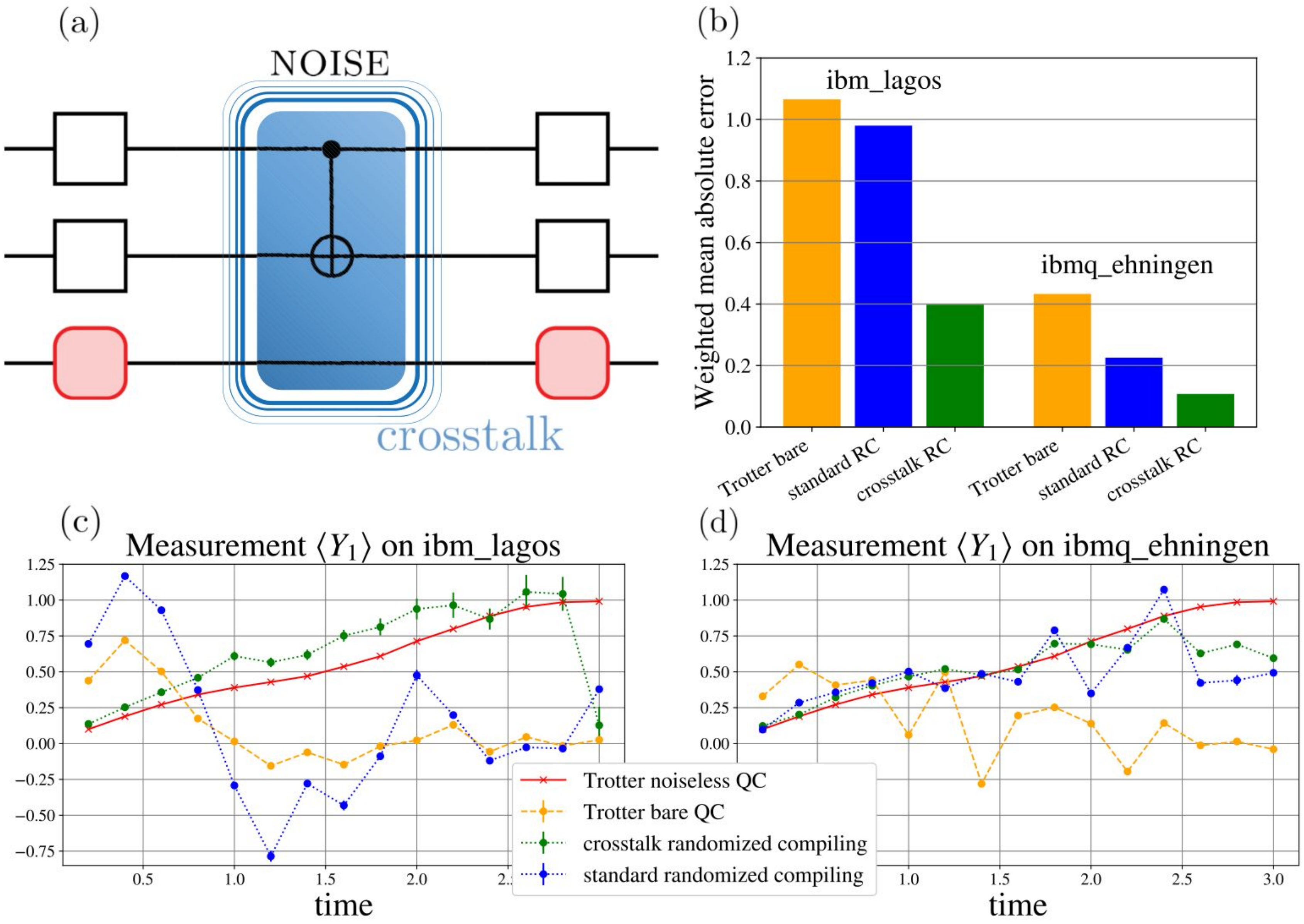
March 29, 2024

Abstract

measuring expectation values of a Trotterized Ising model on their 127-qubit
m that their results were unlikely to be replicable on a classical computer. In the
implement a classical simulation of the same experiment using a Commodore
)ulwich Quantum. Our simulation requires less than 15kB of memory and
ime per data point. To accomplish this we use a variant of the sparse Pauli
d by Begušić and Chan. We show that aggressive truncation combined with
ibitive (for a C64) memory cost of storing the truncated Pauli basis in SPD,
tch the error-mitigated results obtained from the quantum device.

Figure 2: The experimental setup – a Commodore 64 is connected to a monitor through a composite video to HDMI converter, with the code cartridge inserted into the expansion port.

RC + NEC = improved results + error characterization



NEC requires global **depolarizing** noise

$$\mathcal{E}_n^{\text{glob.}}(\rho) = (1-\lambda_{\text{glob.}})\rho + \lambda_{\text{glob.}}\frac{\mathbb{I}}{2^N}$$

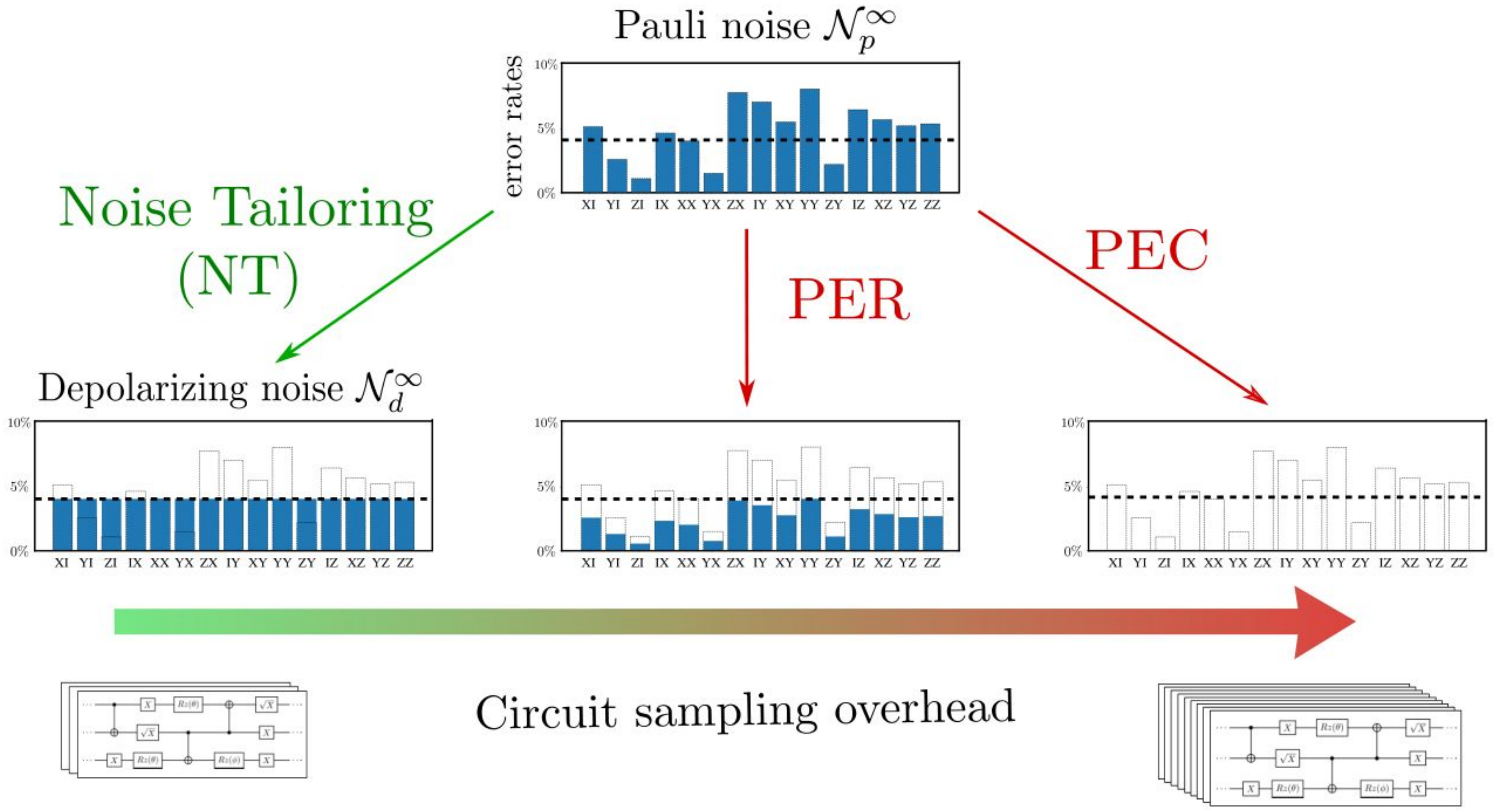
⇐ **NEC used for all curves**

Perrin, Scoquart, …, KS PRResearch **6**, 013142

Why not change the noise shape?

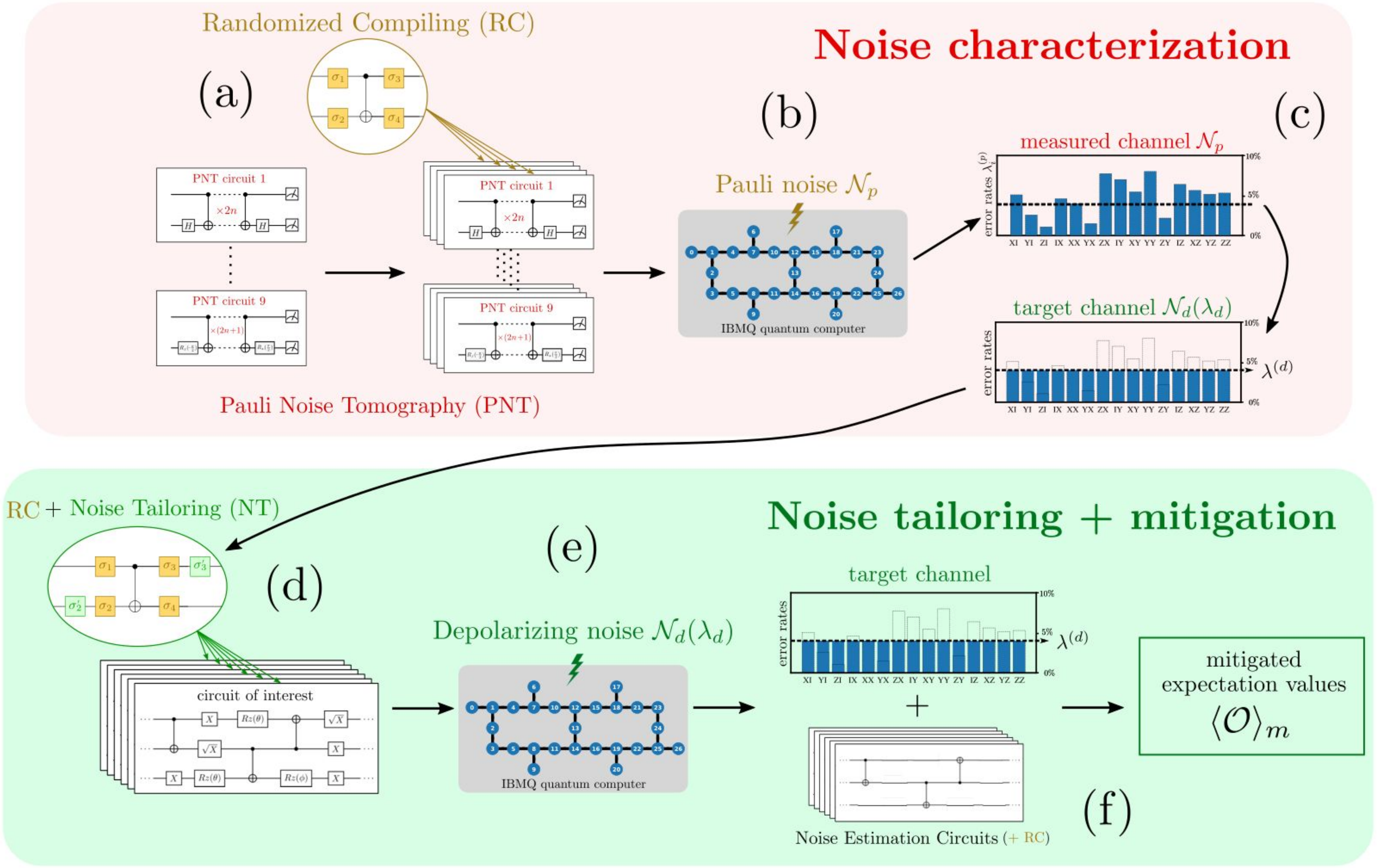
NEC requires global **depolarizing** noise

$$\mathcal{E}_n^{\text{glob.}}(\rho) = (1 - \lambda_{\text{glob.}})\rho + \lambda_{\text{glob.}} \frac{\mathbb{I}}{2^N}$$



Perrin, Scoquart, KS unpublished

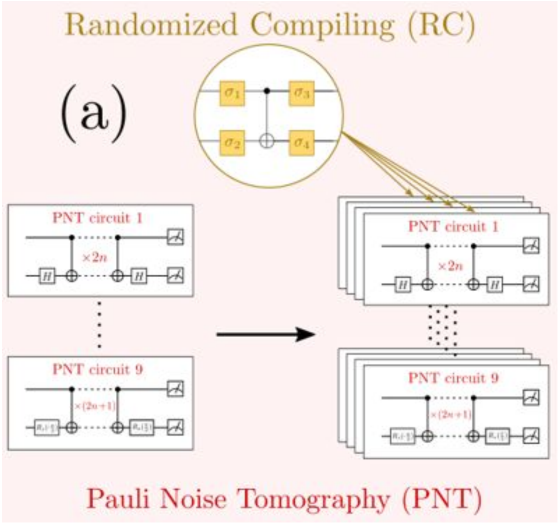
Noise tailoring (NT) protocol

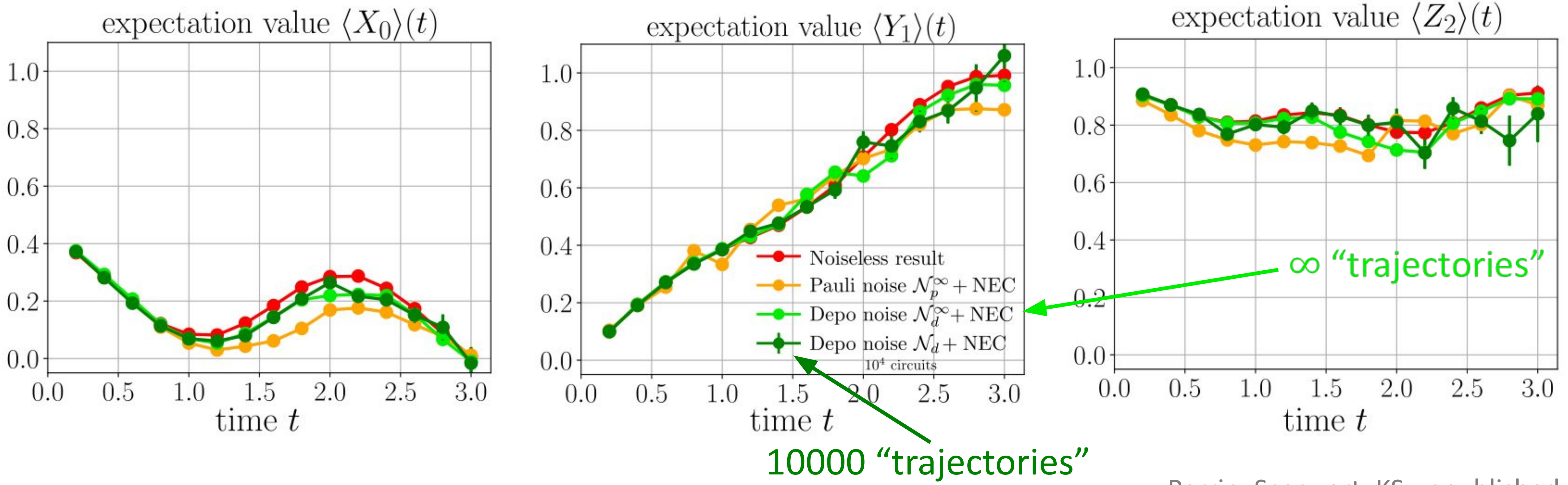


Perrin, Scoquart, KS unpublished

Classical simulations of NT

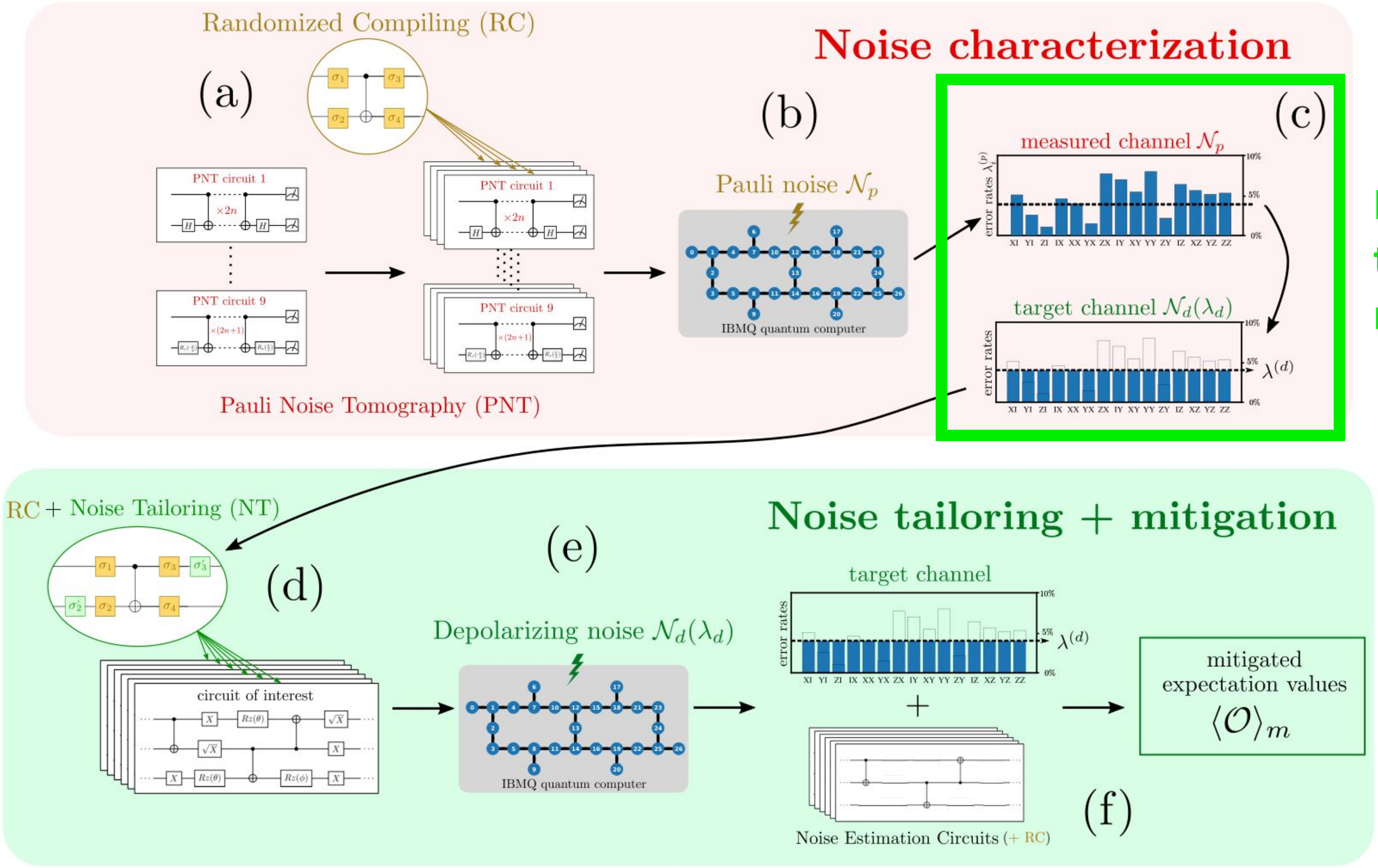
Noise extracted from actual
IBM quantum computer (**`ibm_hanoi`**, 27 qubits)





Perrin, Scoquart, KS unpublished

Noise tailoring (NT) protocol



How to choose the target noise?

Perrin, Scoquart, KS unpublished

Choosing the target noise

Our target: depolarizing noise.

$$\mathcal{N}_d^{\infty}(\rho) = (1 - 15\lambda_d)\rho + \lambda_d \sum_{i=1}^{15} \sigma_i^{2-\text{qubit}} \rho \sigma_i^{2-\text{qubit}}$$

Reason: NEC mitigation

$$\langle \hat{O} \rangle_{\text{mitigated}} = \frac{\langle \hat{O} \rangle_{\text{measured}}}{\mathcal{F}_{\text{NEC}}} \sim \frac{\langle \hat{O} \rangle_{\text{measured}}}{\langle 1 \rangle_{\text{measured}}}$$

The effect of finite circuit («trajectory») sampling:

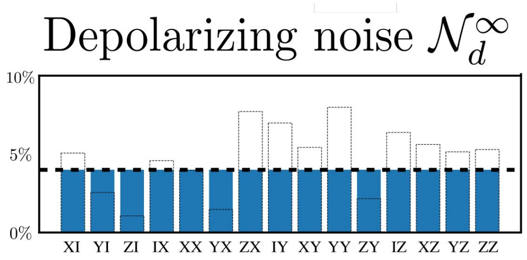
$$\langle \hat{O} \rangle_{\text{mitigated}} = \langle \hat{O} \rangle_{\text{mitigated}}^{\infty} + \frac{\gamma^{n_{\text{CNOT}}}}{\mathcal{F}_{\text{NEC}}} [\text{Sampling errors}]$$

Choose λ_d to minimize $\frac{\gamma^{n_{\text{CNOT}}}}{\mathcal{F}_{NEC}}$

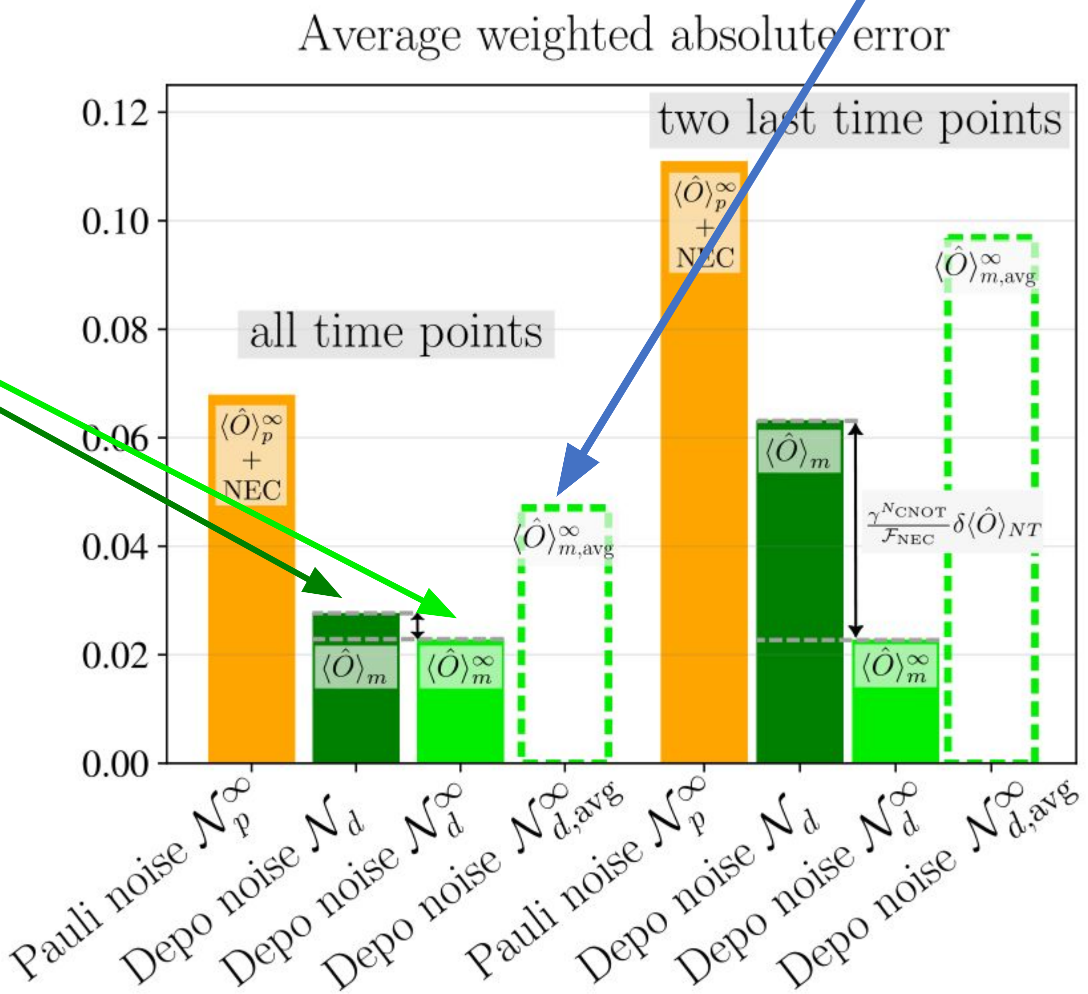
Perrin, Scoquart, KS unpublished

Classical simulations of NT

Choose average λ_d

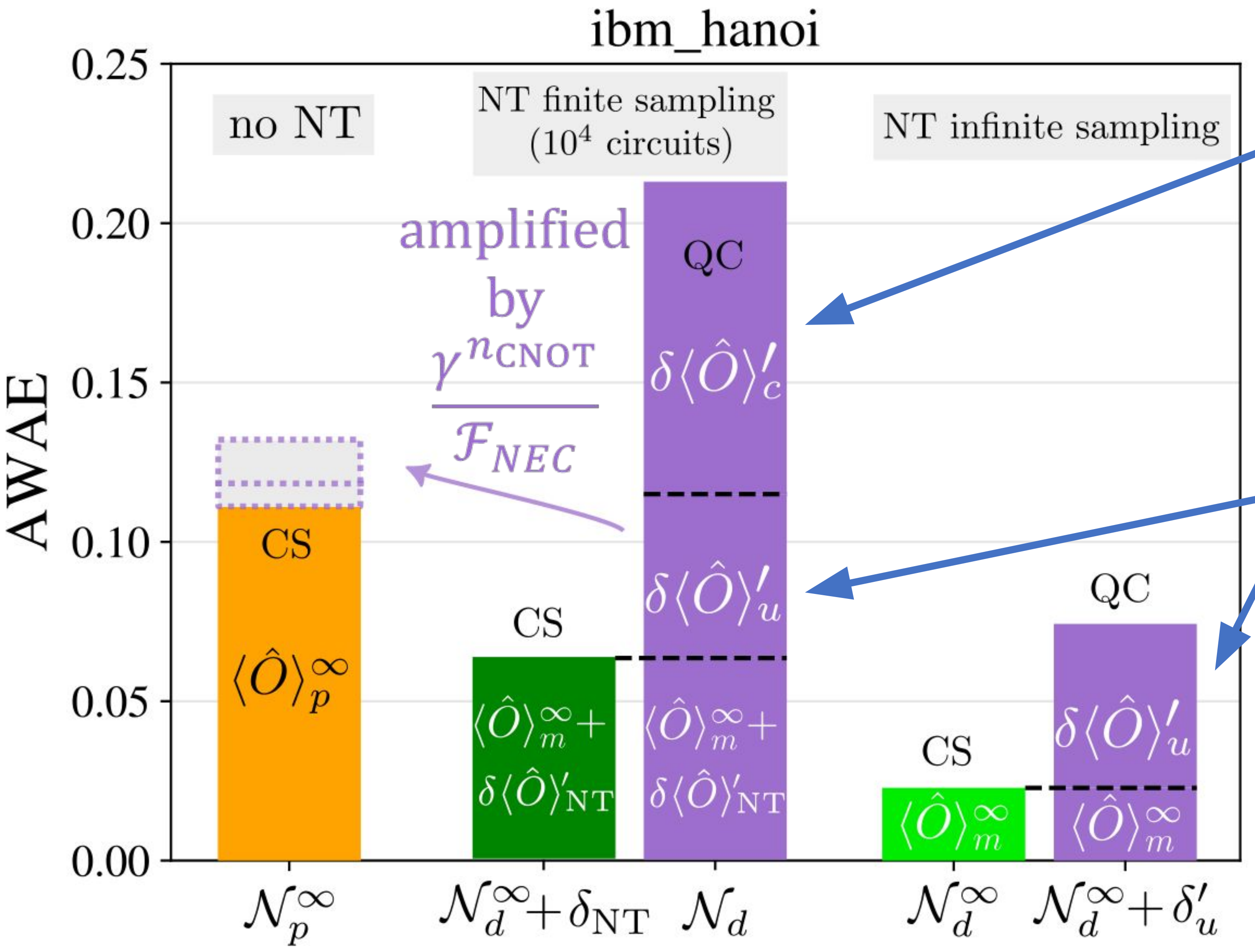


Choose λ_d to minimize $\frac{\gamma^{n_{\mathrm{CNOT}}}}{\mathcal{F}_{NEC}}$



Perrin, Scoquart, KS unpublished

NT on an actual quantum computer

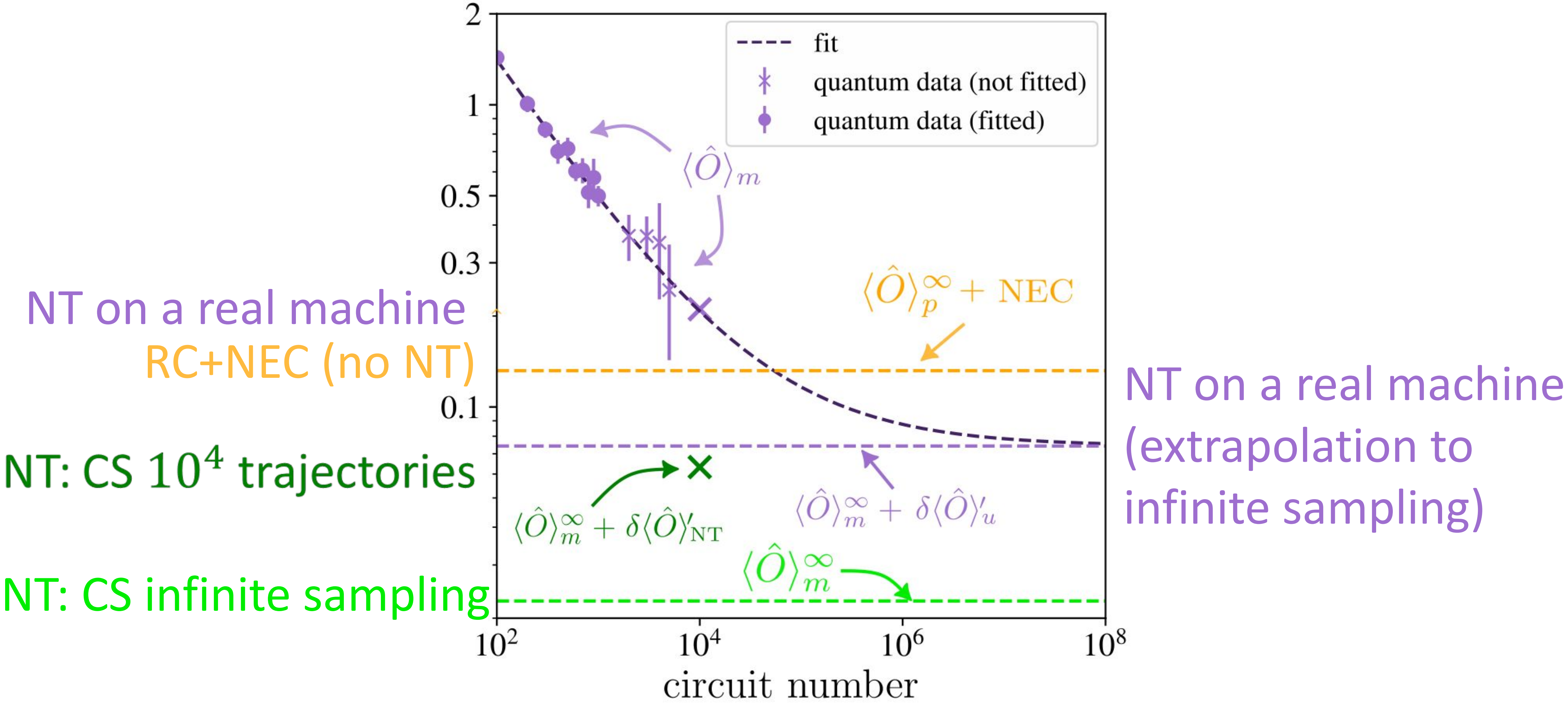


Coherent errors (RC undersampling)

Non-Markovian errors
(time correlations, leakage etc.)
and single-qubit errors

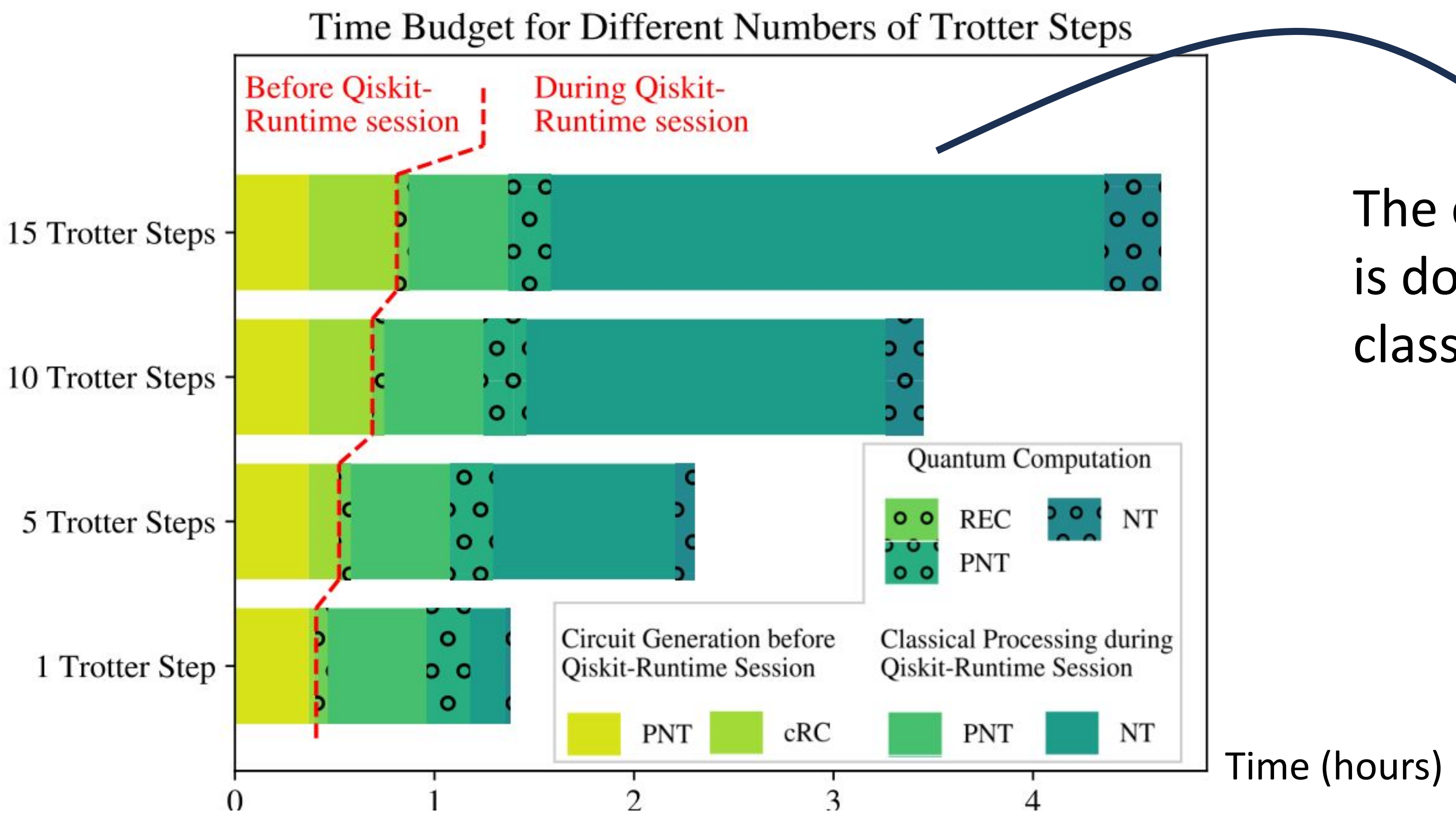
Perrin, Scoquart, KS unpublished

What could we expect on an actual quantum computer?



Perrin, Scoquart, KS unpublished

Cost of increasing sampling?



The computation time
is dominated by
classical generation of trajectories

(Can be much improved with adjusting the way of storing circuits?)

Note: noise evolves in time: need to be fast enough

Perrin, Scoquart, KS unpublished

Trajectories in Ukrainian life

Oleksandra Gulla-Sekretareva, the founder of

Medicine for Ukraine

https://www.hopp.bio/medicine4ukraine

Decision: study math before doing biology

2018 — Bachelor's degree in math

2019–2020 — plays violin in an orchestra
does an internship in biochemistry
prepares for Master's in biology

"Measurement": exam failed

fails entrance exam for Master's in biology

2021 — succeeds in the exam;
starts the Master's in biology (scheduled to finish in 2023)

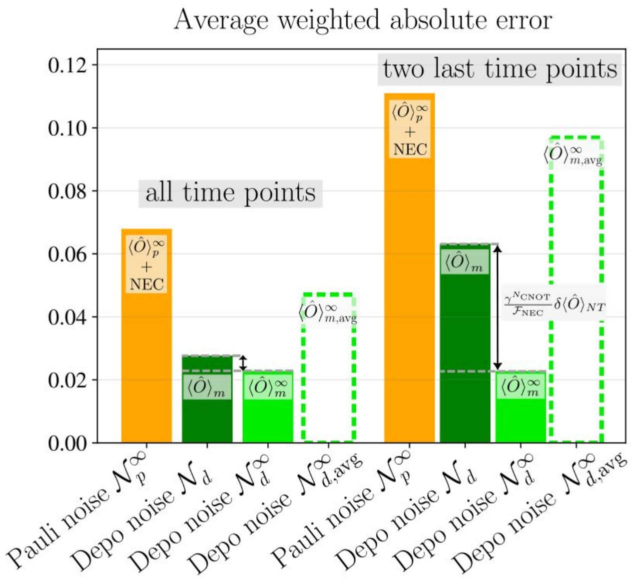
"Measurement": full-scale invasion by Russia

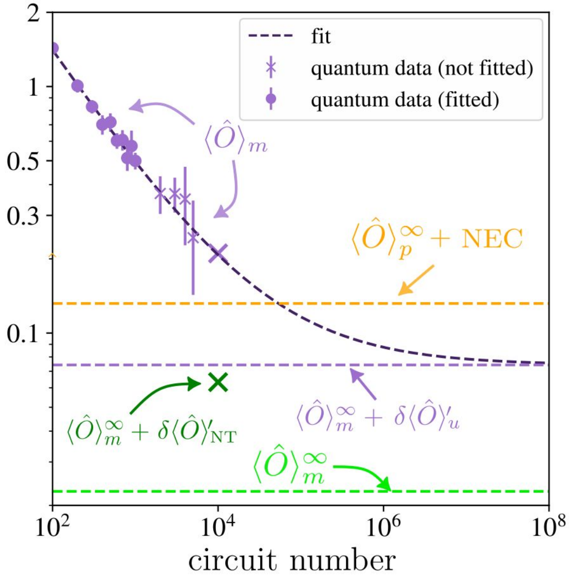
Decision: focus on what's most important now

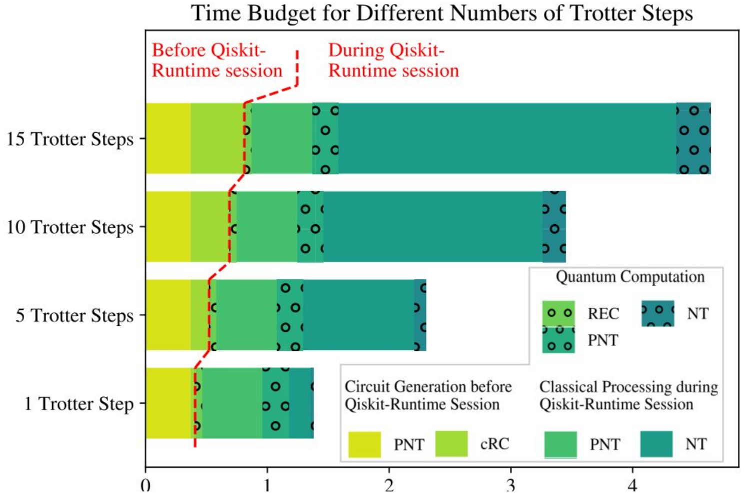
2022 — interrupts her studies;
starts a civil group to provide
Ukrainian military with advanced medical supplies

Conclusions

Noise tailoring: artificial quantum trajectories can help mitigate noise

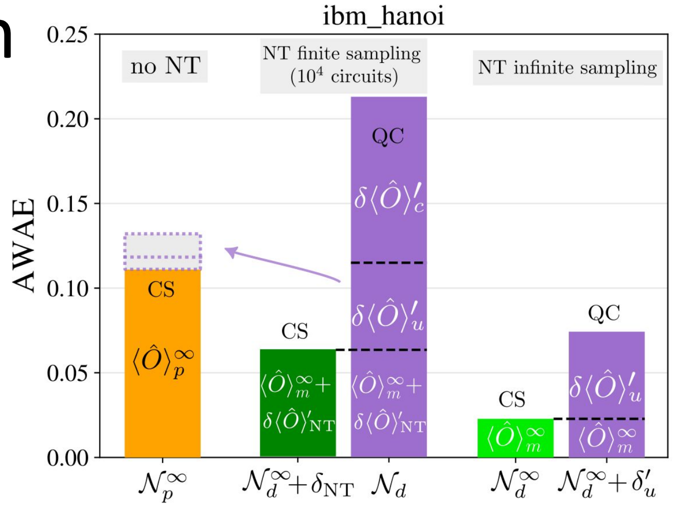






Classical coding improvements needed

Application-based diagnostics of quantum computers



Thank you for attention!

Solution to the portability issue: QLM/Qaptiva

FRANCE HYBRID HPCQUANTUM INITIATIVE

BACQ MetriQs-France

Welcome to Qaptiva Access Portal

QLMaaS-1.9.1

Qaptiva Access is a software solution that extends myQLM to submit Quantum jobs to a Qaptiva Applicance: Qaptiva 800s Plugins and QPUs are available through myQLM.

Install	Get started	Configure

Qaptiva Access client is available on PyPI. This python library can be installed from your terminal using the following command:

```
python3 -m pip install myqlm
```

Useful links

Documentation | Display Notebooks | Download Notebooks

https://qlm35e.neasqc.eu/

Solution to the portability issue: QLM/Qaptiva

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Welcome to Qaptiva Access Portal

QLMaaS-1.9.1

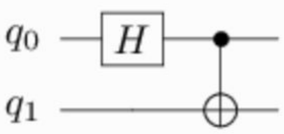
n jobs to a Qaptiva Applicance: Qaptiva 800s

Configure

led from your terminal using the following

Quantum Hello World

The following code snippet creates and simulates a simple Bell pair circuit:



Functional mode   Sequential mode

```
from qat.lang import qrout, H, CNOT

@qrout
def bell_pair():
    H(0)
    CNOT(0, 1)

result = bell_pair().run()

for sample in result:
    print(f"State {sample.state} amplitude {sample.amplitude}")
```

```
State |00> amplitude (0.7071067811865475+0j)
State |11> amplitude (0.7071067811865475+0j)
```

Download Notebooks

https://qlm35e.neasqc.eu/

Solution to the portability issue: QLM/Qaptiva

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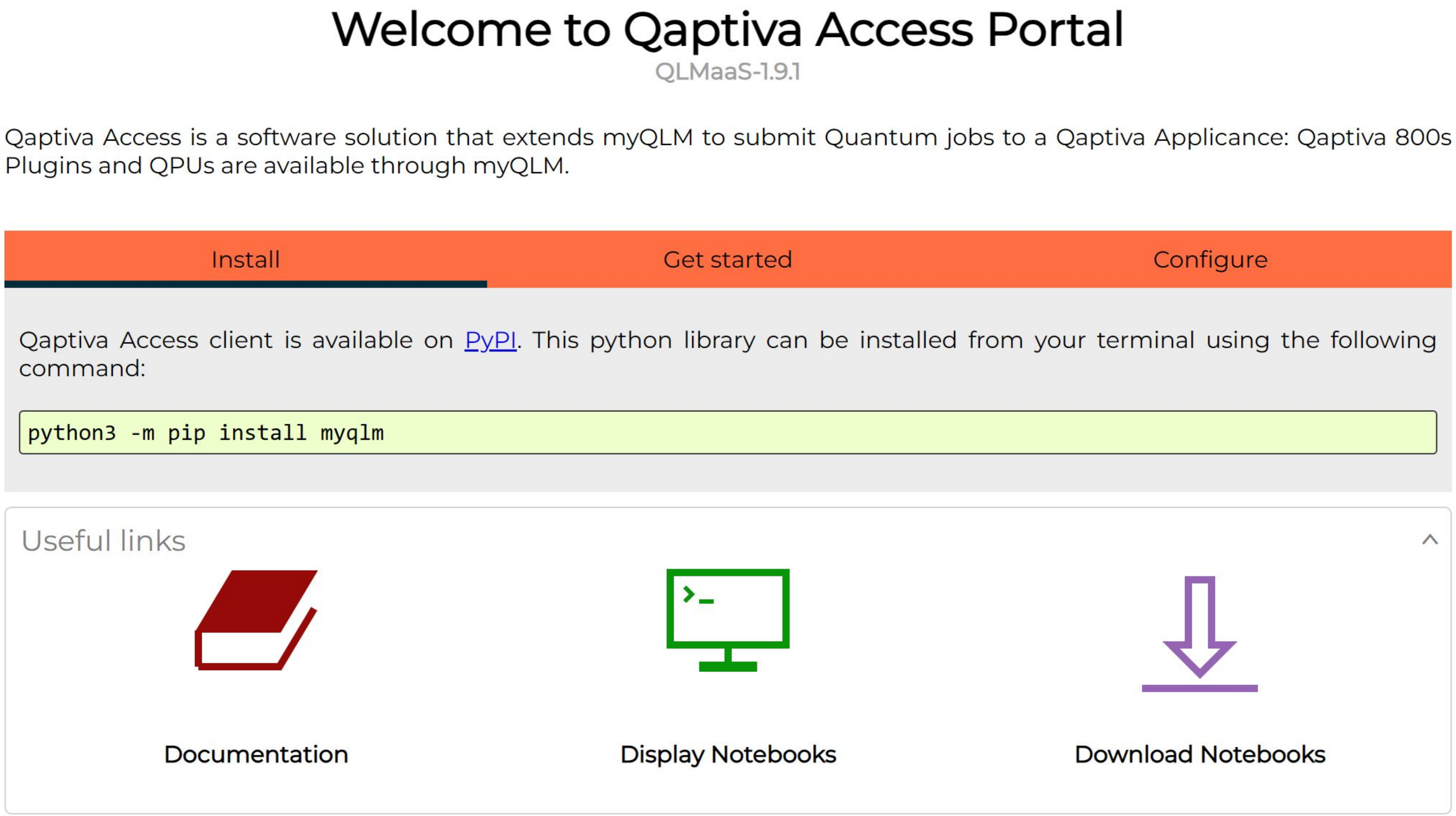

https://qlm35e.neasqc.eu/

Qaptiva (paid) — advanced simulation
+ (in the future) access to quantum hardware

Solution to the portability issue: QLM/Qaptiva

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myQLM documentation

1.9.9

Search docs

Getting started

» Welcome page

myQLM – Quantum Python Package

myQLM is the quantum software stack developed by Eviden, for writing, simulating, optimizing, and executing quantum programs. Through a Python interface, it provides:

- a **powerful semantic** for writing quantum algorithms (gate-based programing, analog programing, or quantum annealing programing)
- a **versatile execution stack** for running quantum jobs, including an easy handling of observables, special tools for carrying NISQ-oriented variational methods (such as VQE, QAOA), an easy API for designing custom plugins (e.g. compilation), as well as for connecting to any Quantum Processing Unit (QPU)
- a **seamless interface** to available quantum processors and major quantum programming frameworks

https://myqlm.github.io/

Solution to the portability issue: QLM/Qaptiva

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myQLM documentation

EVIDEN

» Welcome page

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- ...**amless interface** to available quantum processors and major quantum programming ...neworks

Interoperability

Warning

Interoperability packages are deprecated for Python versions 3.6 and 3.7

This package enables access to other quantum programming environments such as Qiskit, ProjectQ, PyQuil, Cirq ... This package will not automatically install dependency packages because someone who want to interface with Qiskit may not want to interface with Cirq... The desired quantum environment can be cherry-picked using the pip command:

Qiskit | ProjectQ | Cirq | PyQuil | All frameworks

```
pip install myqlm-interop[qiskit_binder]
```

https://myqlm.github.io/

myQLM = my Quantum Learning Machine

myQLM (free) — gate-based programming and noiseless simulation

Lots of examples