Prolonging a discrete time crystal by quantum-classical feedback

Gonzalo Camacho[1], Benedikt Fauseweh[1,2]
[1]German Aerospace Center (DLR), SC-HPC
[2]TU Dortmund, Department of Physics

gonzalo.camacho@dlr.de

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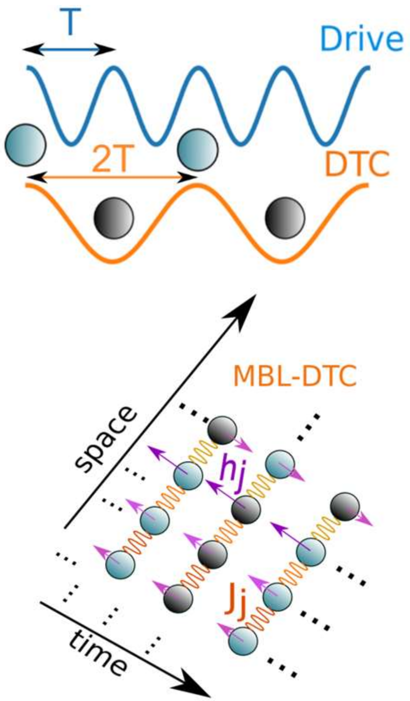
Motivation

☝DTC Concept

F. Wilczek,
Phys. Rev. Lett. 109, 160401 (2012)



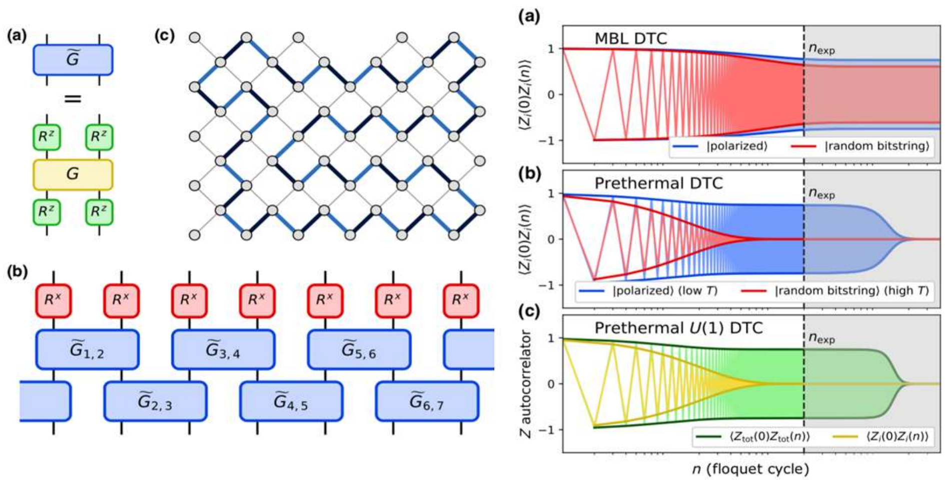
✎Proposal: DTC on a quantum computer

PRX QUANTUM **2,** 030346 (2021)

Featured in Physics

Many-Body Physics in the NISQ Era: Quantum Programming a Discrete Time Crystal

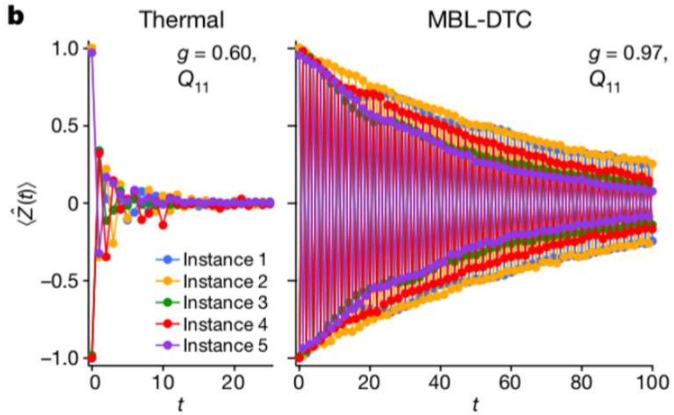
Matteo Ippoliti,[1,*] Kostyantyn Kechedzhi,[2] Roderich Moessner,[3] S.L. Sondhi,[4] and Vedika Khemani[1]



✵ DTC quantum experiment

☑ Realized on NISQ devices

☒ Problem: Decoherence noise



X. Mi et.al. Nature, 601, 531–536 (2022)

Approach

Overcoming noise effects employing in-circuit measurements

Hybrid computation quantum+classical

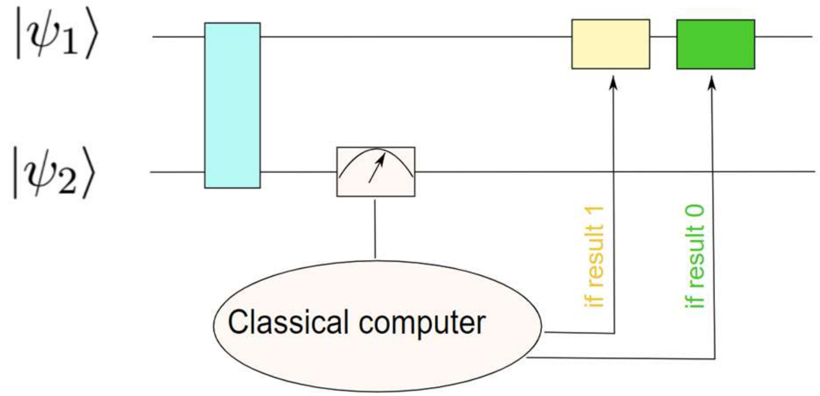
Near-to-classical quantum states → Low entanglement

$|\Psi\rangle$ DTC states

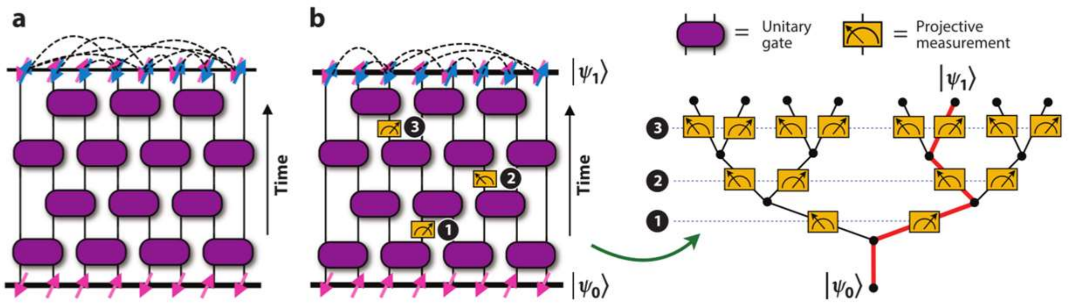
$\cos(n\Omega)|\uparrow\uparrow\downarrow\uparrow\downarrow\rangle + i\sin(n\Omega)|\downarrow\downarrow\uparrow\downarrow\uparrow\rangle$

Employ information on partial measurements to exert action over the state.

Simplest quantum-classical feedback



Context: Monitored quantum circuits (non-unitary operations)



M.P.A. Fisher et.al., Annu. Rev. Condens. Matter Phys. 14, 335-379 (2023)

Model

Floquet unitary

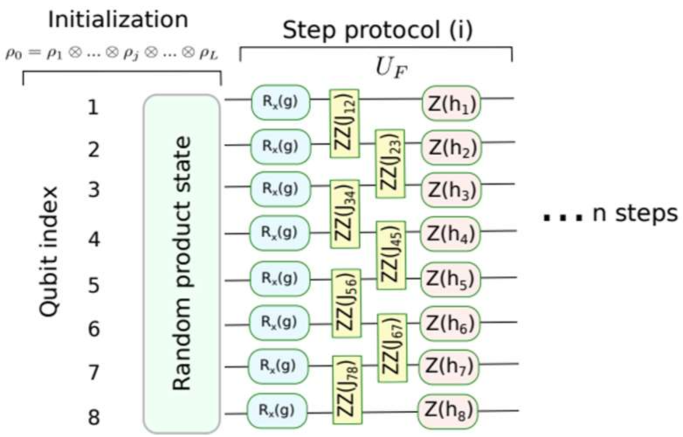
$$U_F = e^{-\mathrm{i}\frac{T}{4}\sum_j \left(J_j \sigma_j^z \sigma_{j+1}^z + 2h_j \sigma_j^z\right)} e^{-\mathrm{i}\frac{\pi g}{2} T \sum_j \sigma_j^x}$$

X. Mi et.al. Nature, 601, 531–536 (2022)

Quantum circuit realization

G.Camacho, B.Fauseweh, arXiv:2309.02151

Unitary U_F



Model

Floquet unitary

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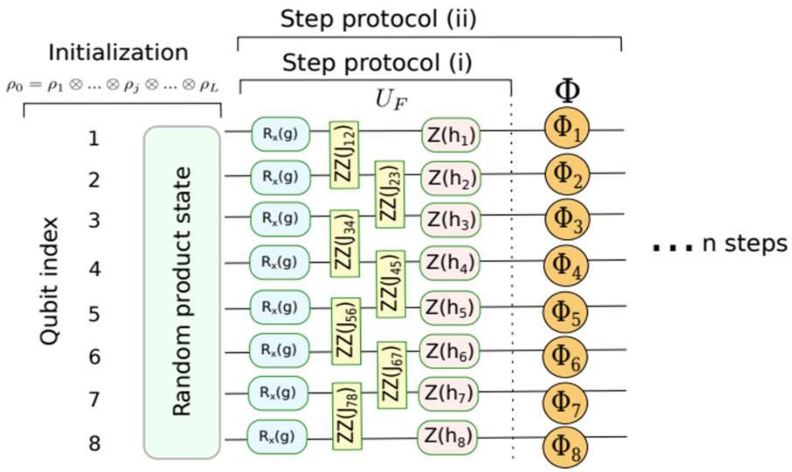


Unitary U_F
Quantum channel Φ

Model

Floquet unitary

$$U_F = e^{-\mathrm{i}\frac{T}{4}\sum_j \left(J_j \sigma_j^z \sigma_{j+1}^z + 2h_j \sigma_j^z\right)} e^{-\mathrm{i}\frac{\pi g}{2} T \sum_j \sigma_j^x}$$

X. Mi et.al. Nature, 601, 531–536 (2022)

Quantum circuit realization

G.Camacho, B.Fauseweh, arXiv:2309.02151

Bit-flip noise model

$$\Phi(\rho) = \sum_{i=0}^{Q-1} K_i \rho K_i^\dagger, \quad \sum_i K_i^\dagger K_i = I$$

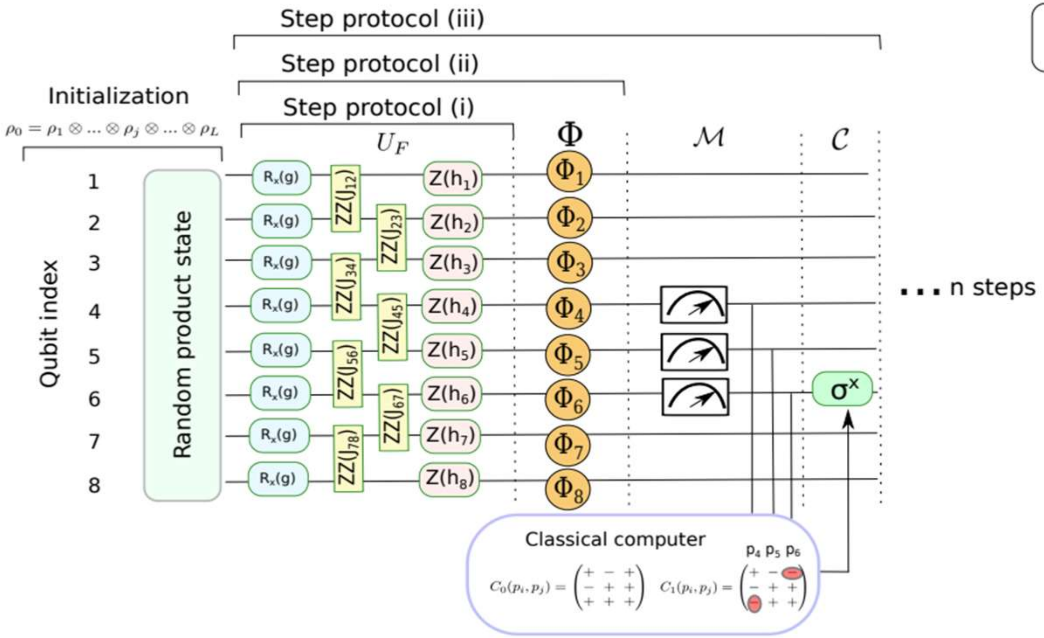
Kraus operators

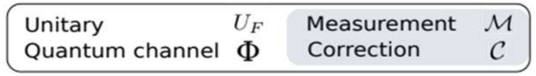
$$K_0 = \sqrt{1-p}I, \;\; K_1 = \sqrt{p}\sigma^x$$

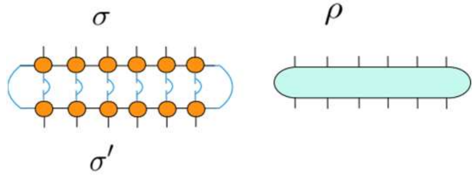
Represent state ρ as Matrix Product Density Operator (MPDO)

F. Verstraete, et.al. Phys. Rev. Lett. 93, 207204 (2004)

A. H. Werner et.al. Phys. Rev. Lett. 116, 237201 (2016)







Protocol (i)	$\rho_n = U_F^n \rho_0 (U_F^\dagger)^n$
Protocol (ii)	$\rho_n = \Phi\left(U_F \rho_{n-1} U_F^\dagger\right)$
Protocol (iii)	$\rho_n = \mathcal{C} \circ \mathcal{M} \circ \Phi\left(U_F \rho_{n-1} U_F^\dagger\right)$

Correction scheme for protocol (iii)

At step "n"...

(1) Measure M adjacent qubits at random location

Set of indices

$$\mathcal{S}^{(n)} = \{x_0^{(n)}, x_0^{(n)} + 1, ..., x_0^{(n)} + M - 1\}$$

(2) Store result into classical register (bits)

$$\vec{\sigma}_n(\mathcal{S}^{(n)})\Big|\sigma_j \in \{+1, -1\}$$

Initialization values

$$\vec{\sigma}_0(\mathcal{S}^{(n)})$$

(3) Compute classical correlations for that specific domain wall

$$\begin{aligned} C_n(i,j) &= \vec{\sigma}_n^T \otimes \vec{\sigma}_n \quad i,j \in \mathcal{S}^{(n)} \\ C_0(i,j) &= \vec{\sigma}_0^T \otimes \vec{\sigma}_0 \end{aligned}$$

Comparison matrix

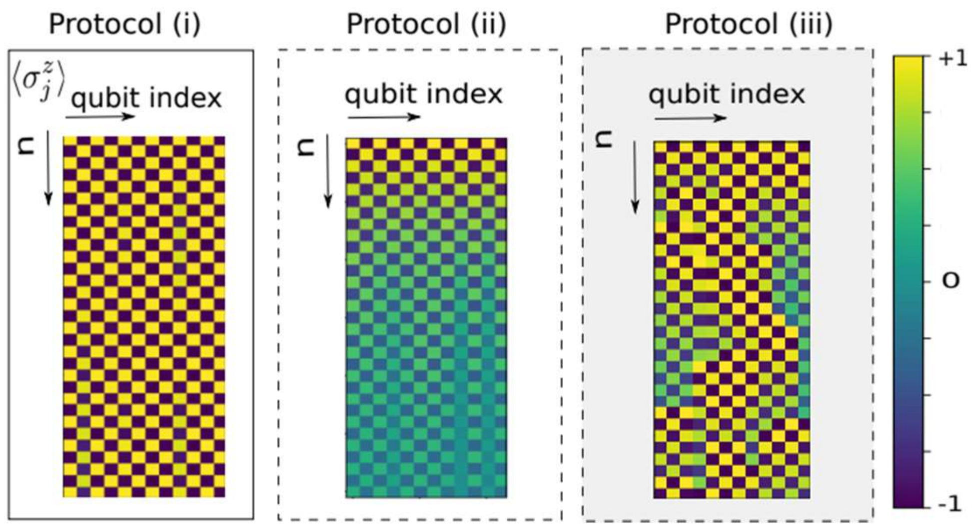
$$\delta_{ij}(n) = \text{int}\left(\frac{1}{2}(\text{J}_{ij} - C_0(i,j) * C_n(i,j))\right)$$

(4) Identify index *i*(*n*) and correct

$$i(n) = \max\left(\sum_j \delta_{ij}(n)\right)$$

...continue to step n+1

Protocol instances



Key remarks for DTC correction

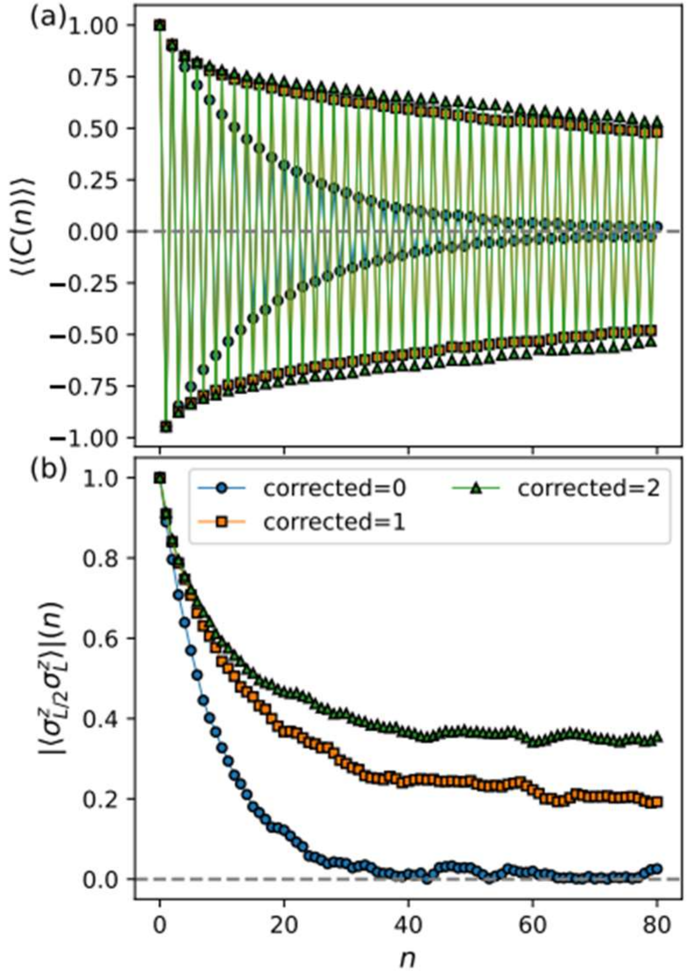
- ☑ T-periodic scheme
- ☑ Local regions correction
- ☑ Error qubit identification improves with number of qubits

Results

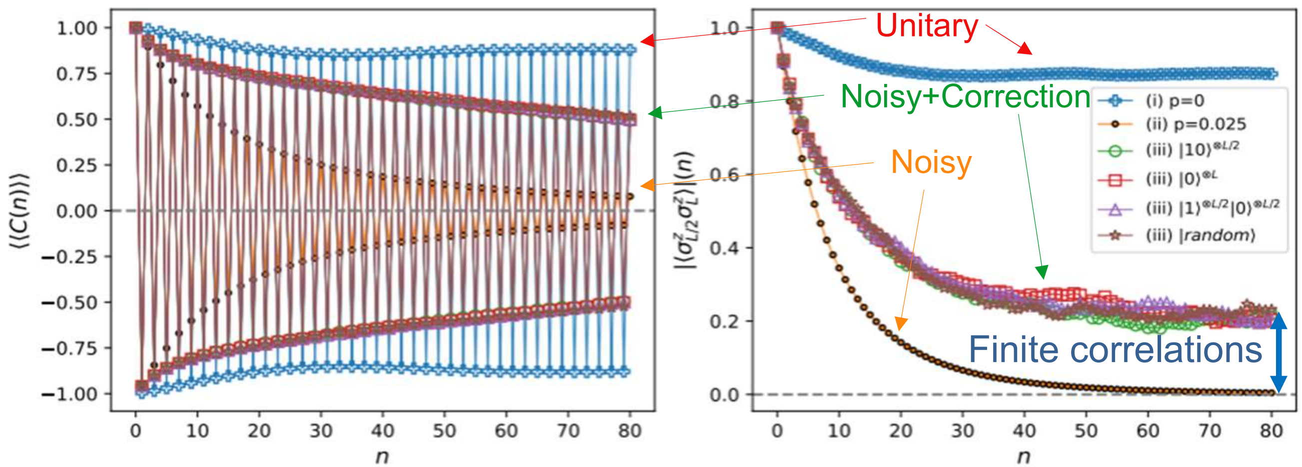
- Initial state independence
- DTC correlations beyond intrinsic decoherence times employing feedback

Correction scheme verification:

- Site and disorder averaged autocorrelation
- Bulk-edge spin correlations

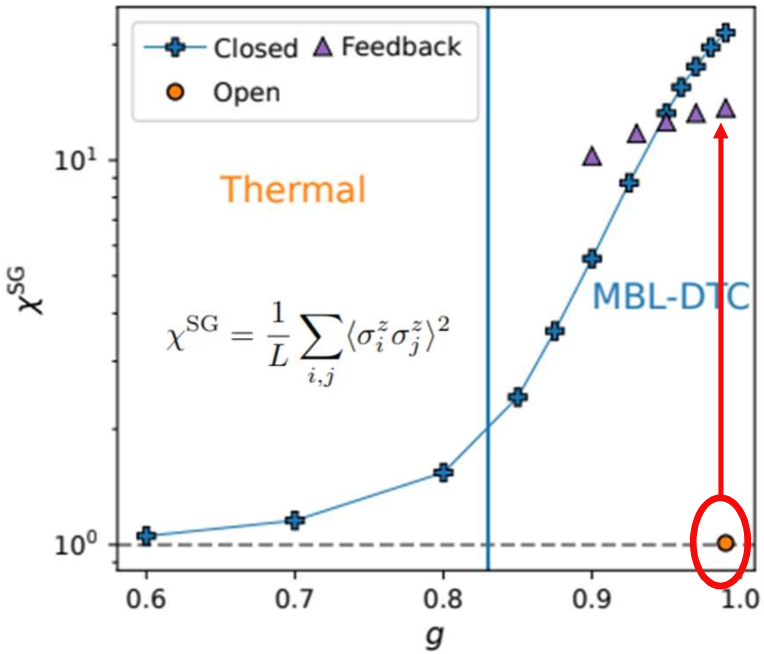


Chain L=24, g=0.97, M=6, N_{dis} =1280



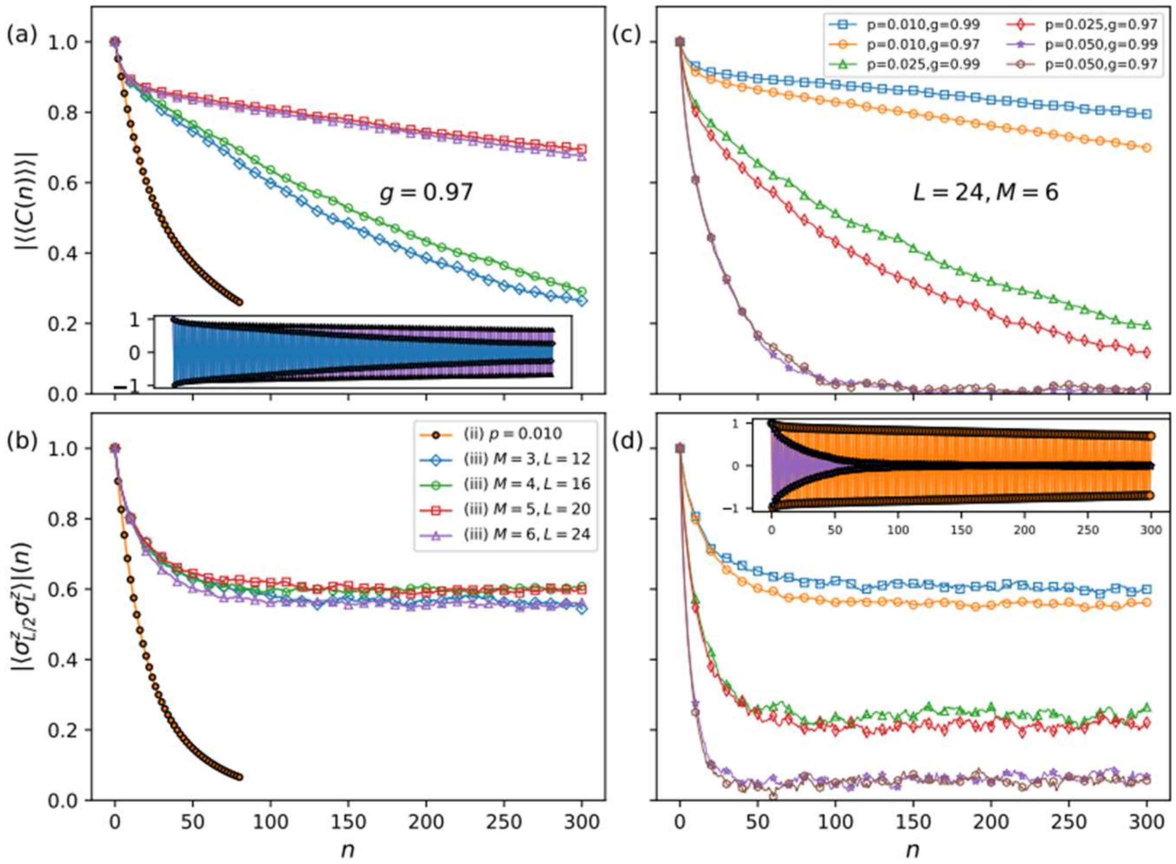
G.Camacho, B.Fauseweh, arXiv:2309.02151

Results



- Enhanced glassy spatial order employing feedback (protocol (iii))

G.Camacho, B.Fauseweh, arXiv:2309.02151



- Favourable scaling with system size
- Noise parameter is dominant over kick parameter

Summary and outlook

Main results

- ☛Feedback scheme based on mid-circuit measurements enhances DTC response on a noisy environment
- ☛Correction from feedback is essential: Beyond pure Zeno effect
- ☛Protocol independent of state preparation, and periodic with period T
- ☛Good scaling with increasing system size and domain wall size

Outlook

- ☛Implementation of feedback scheme on current hardware employing dynamic circuits functionalities
- ☛Alternative noise models, measurement protocols, generalization to qudit systems
- ☛Monitored quantum dynamics affected by feedback schemes