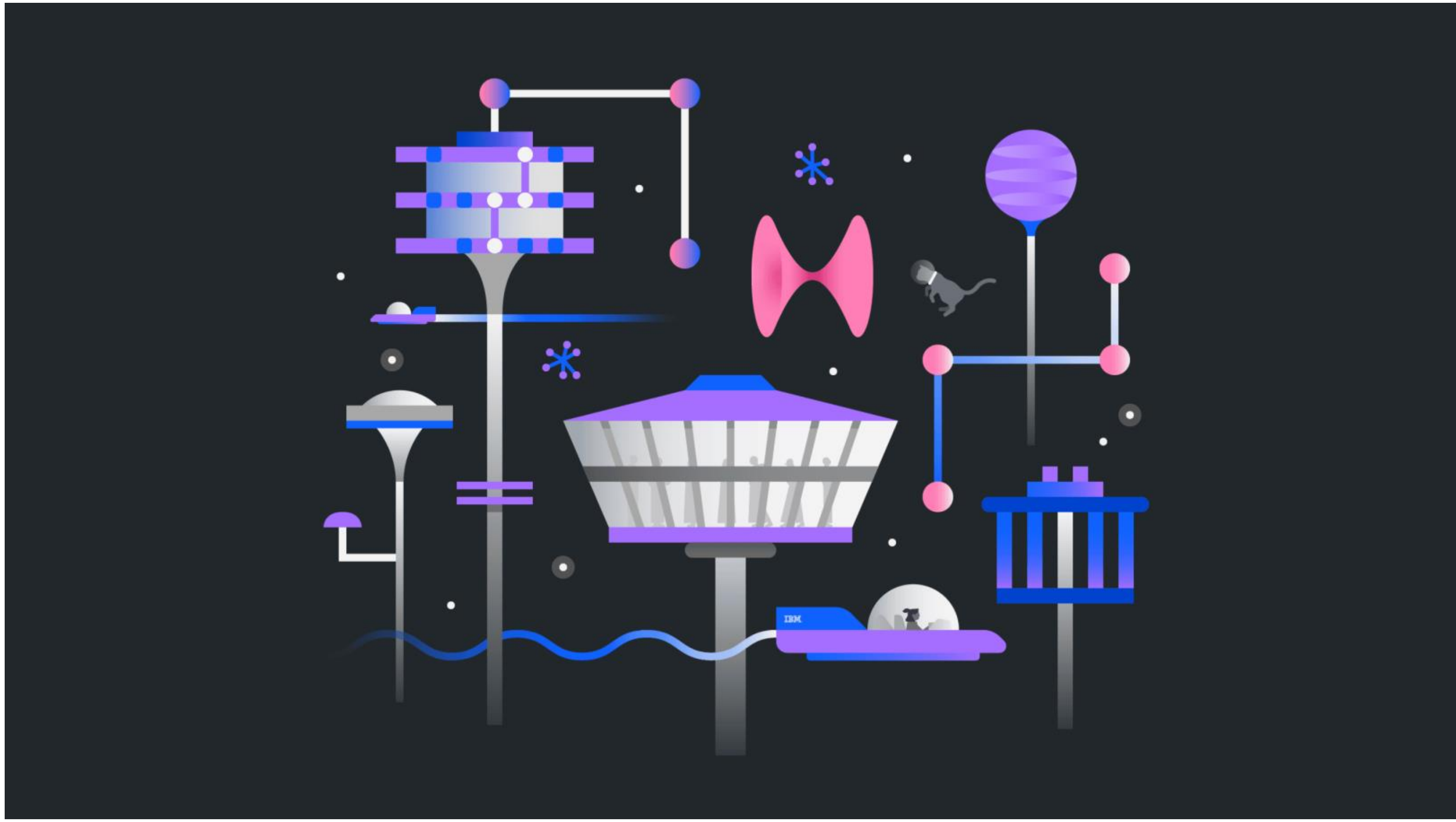
Discrete Time Crystals beyond the Ising Model



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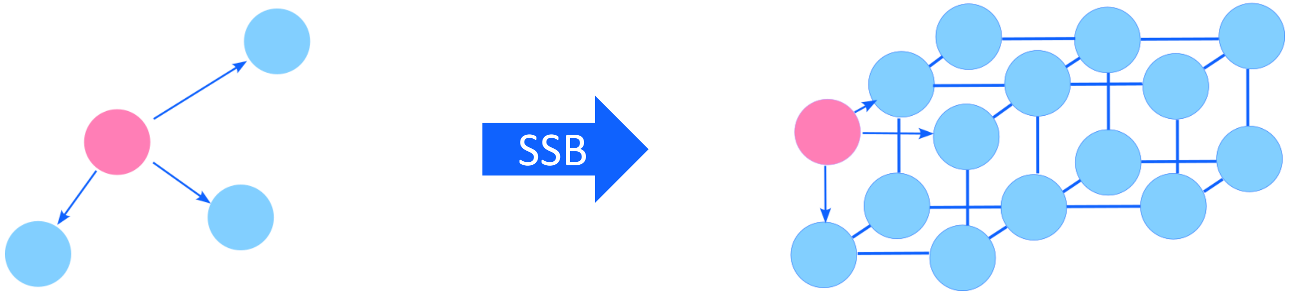
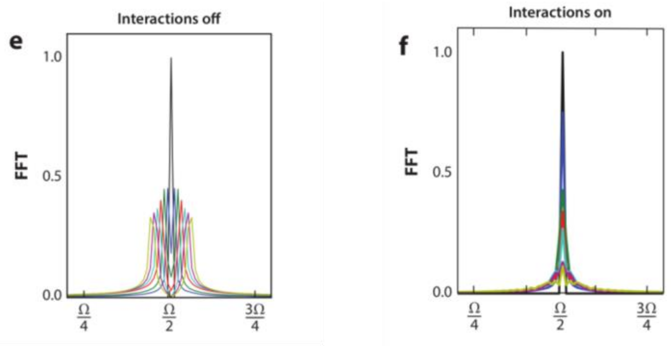
Outline

- What are Discrete Time Crystals
- Simulations on real hardware
- Results: 1D and 2D
- Conclusion and outlook

Discrete Time Crystals

Novel out-of-equilibrium phase of matter

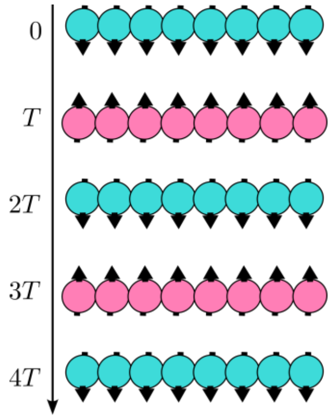




Yao *et al.*, PRL **118** 030401 (2017)

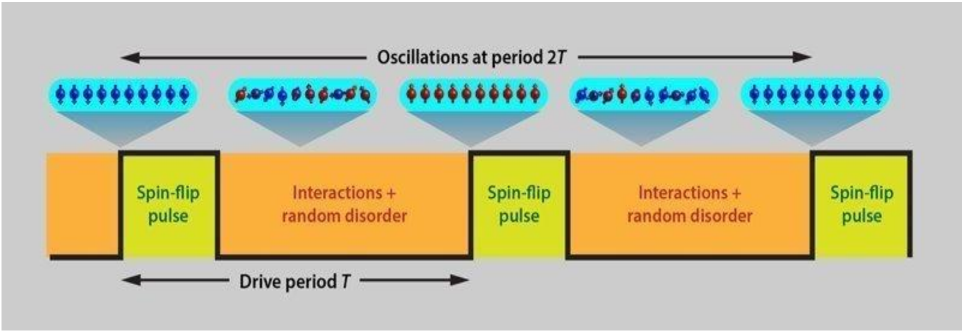
Empty space has continuous translational symmetry

Crystals only have discrete translational symmetries



Bloch's theorem $$\psi(x+a) = \mathrm{e}^{-\mathrm{i}ka}\psi(x)$$

Floquet's theorem $$|\psi_a(t+T)\rangle = \mathrm{e}^{-\mathrm{i}\epsilon_a T}\,|\psi_a(t)\rangle$$



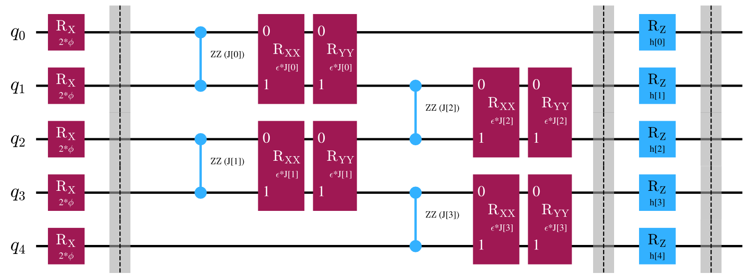
Model

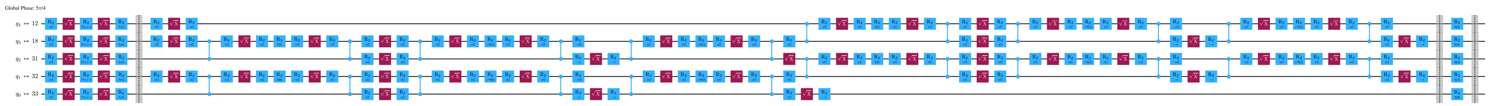
$$H(t) = \begin{cases} H_1 = \frac{\phi}{t_1} \sum_i S_i^x, & \text{for } 0 \le t < t_1 \\ H_2 = H_{\mathrm{XXZ}}, & \text{for } t_1 \le t < t_1 + t_2 = T \end{cases}$$

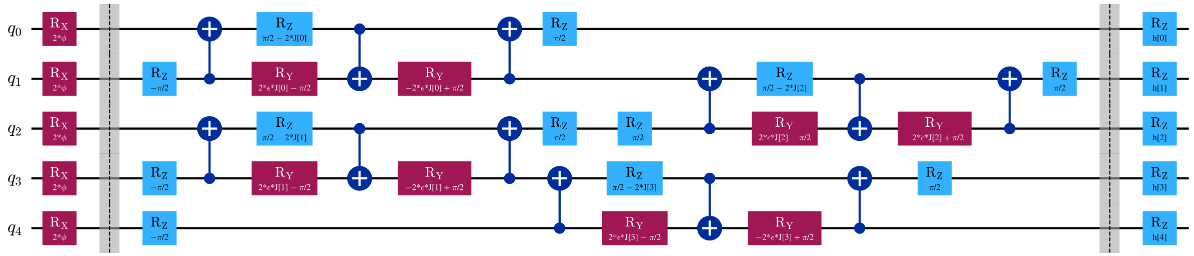
$$H_{\mathrm{XZZ}} = \sum_{\langle i,j \rangle} J_{i,j} \left[\epsilon \left(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y \right) + \sigma_i^z \sigma_j^z \right] + \sum_i^N h_i \sigma_i^z$$

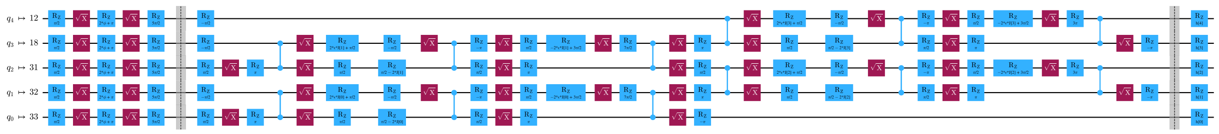
$$J_{i,j} \sim \mathcal{U}[\pi/2, 3\pi/2] \qquad \phi \in [0, \pi/2]$$

$$h_i \sim \mathcal{U}[-\pi, \pi] \qquad \epsilon \in [0, 1]$$



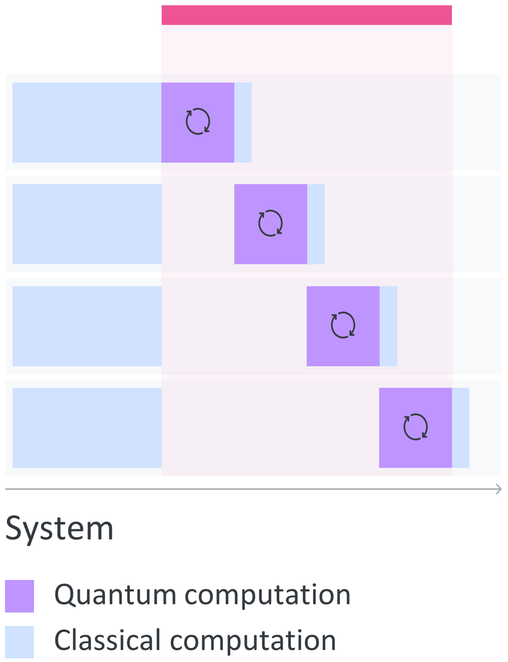






A. Smith et al. , npj Quantum Inf **5**, 106 (2019).

Simulations on real hardware



$\phi \in [0, \pi/2]$

$\epsilon \in [0, 1]$

T Floquet steps

For a unique disorder instance

For a unique initial state

Without adding DD or PT

11 kick angle values

11 anisotropy values

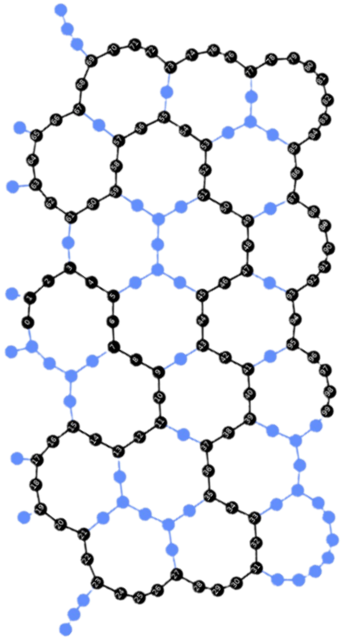
50 Floquet steps

6050 jobs

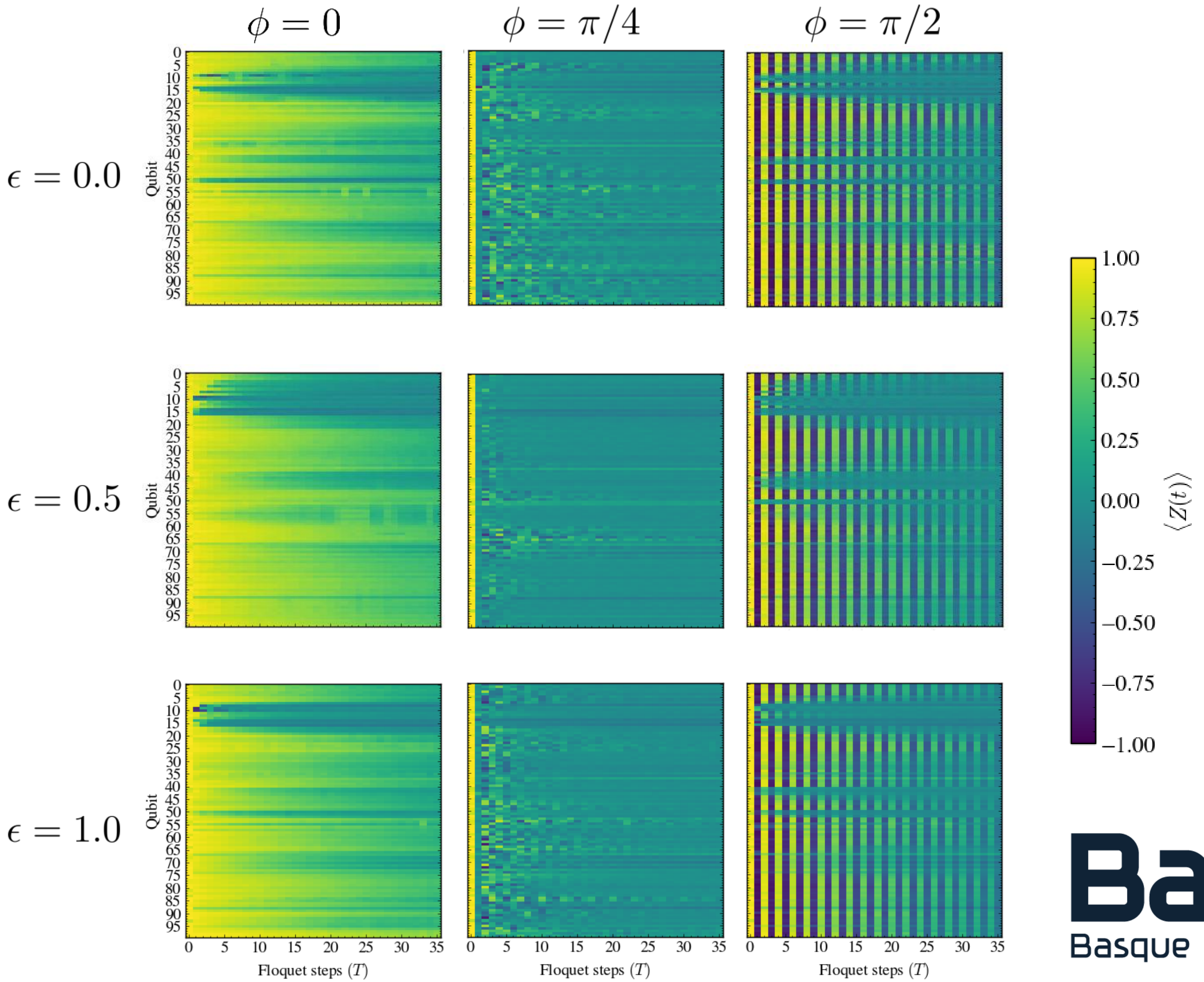
Nearly **11 hours** of simulation

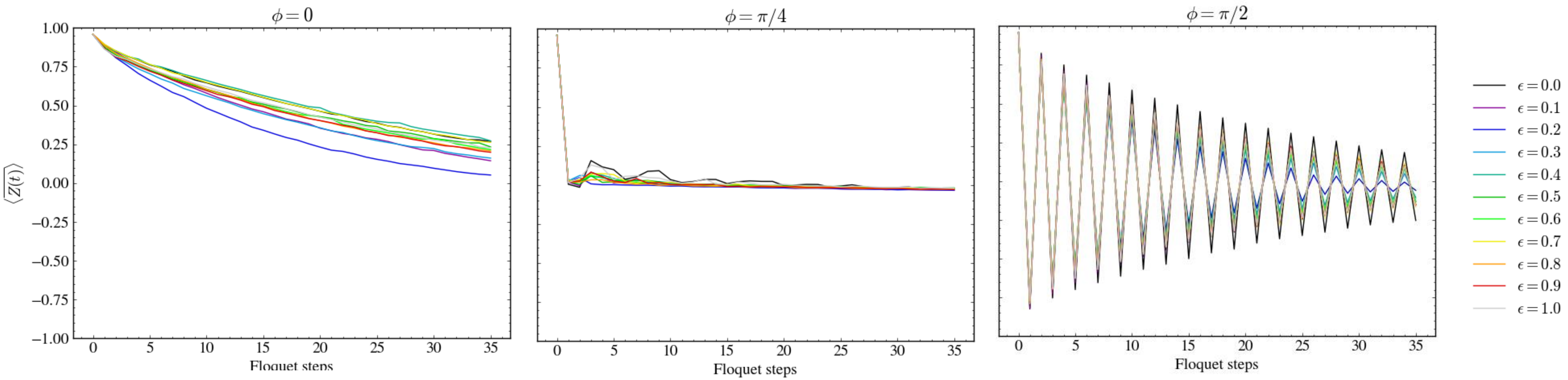
Really demanding problem

Results: 1D case

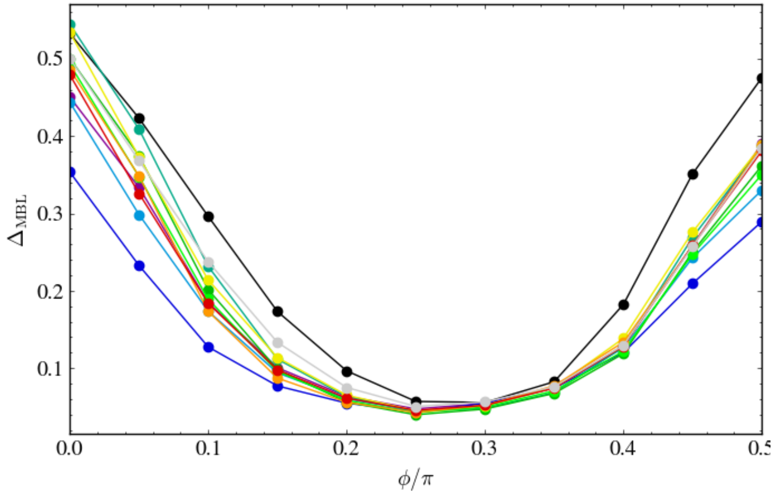


100 qubits

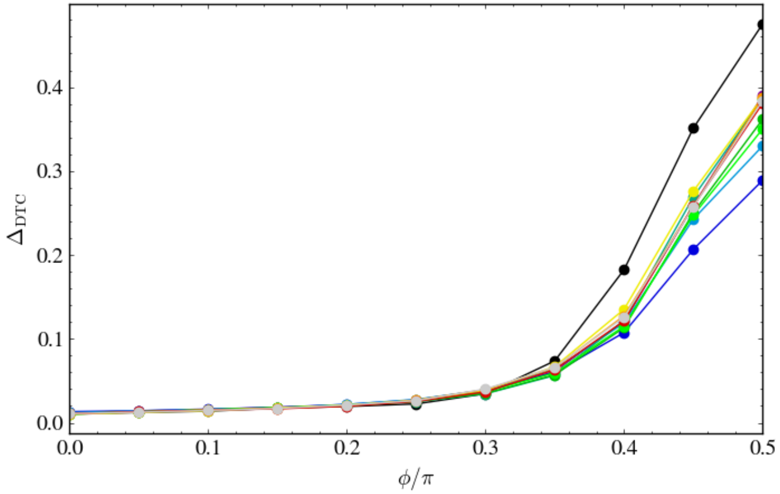


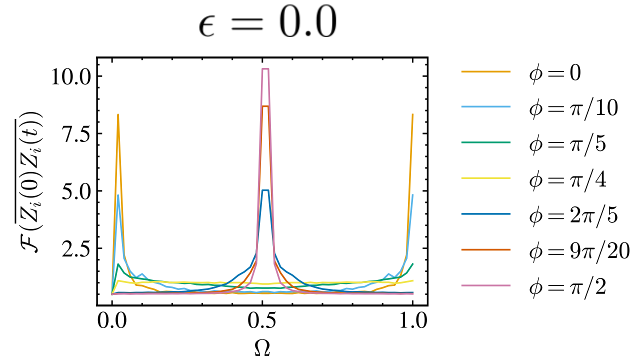


$$\Delta_{\mathrm{MBL}} = \frac{1}{NT} \sum_{n=1}^{T} \left| \sum_{i=1}^{N} z_i^0 \langle Z_i(nT) \rangle \right|$$



$$\Delta_{\mathrm{DTC}} = \frac{1}{NT} \sum_{n=1}^{T} \sum_{i=1}^{N} (-1)^n z_i^0 \langle Z_i(nT) \rangle$$





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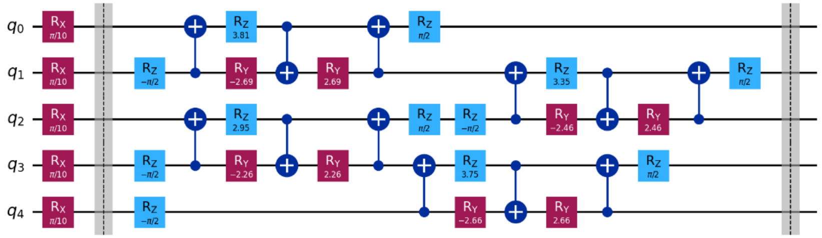
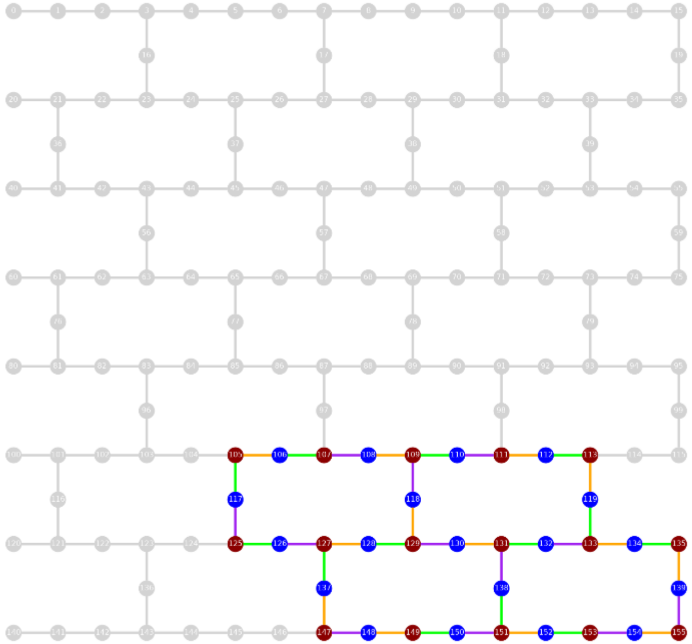
2D configurations

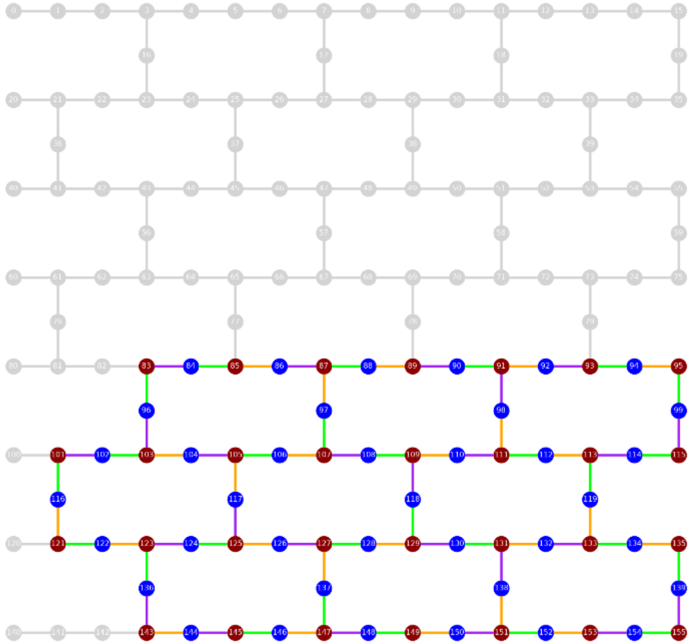


2x2



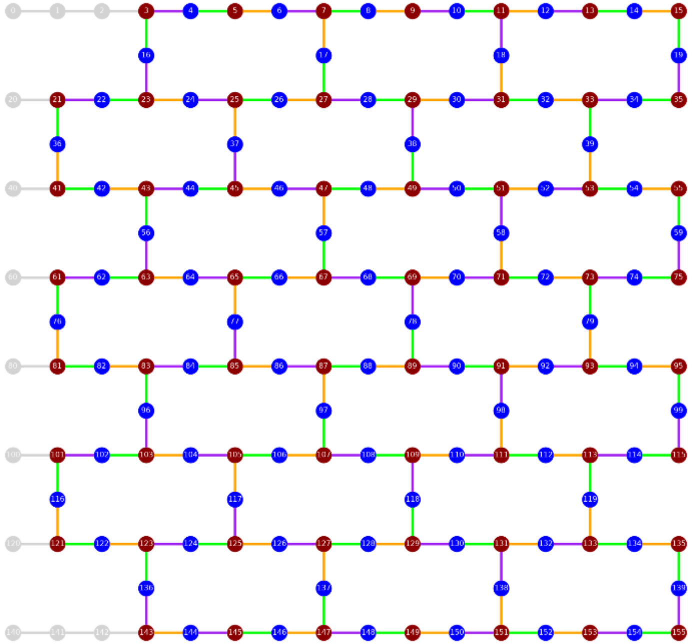
35 qubits

3x3



68 qubits

3x7

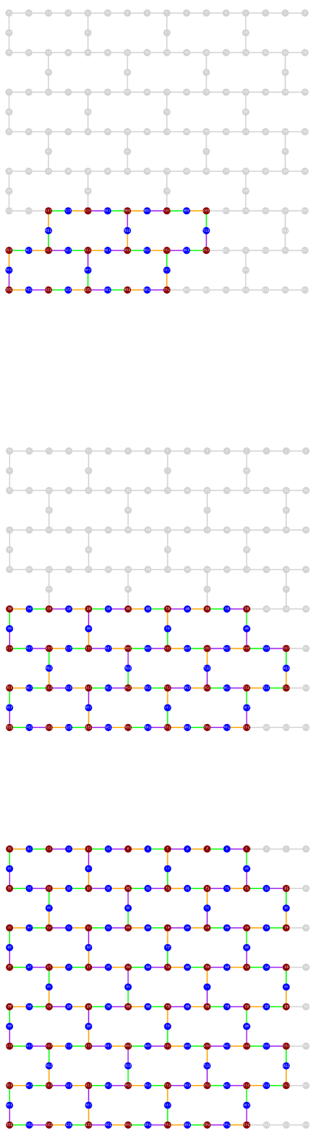


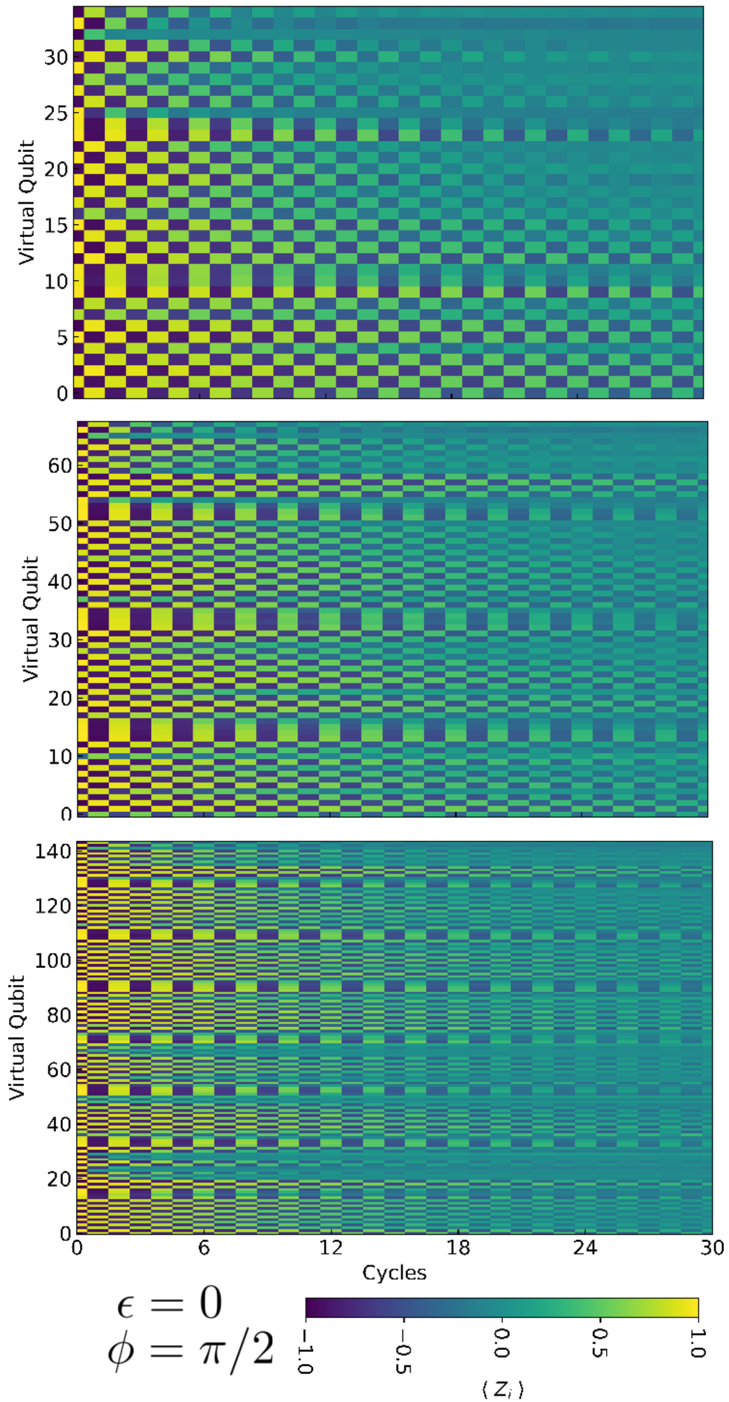
144 qubits

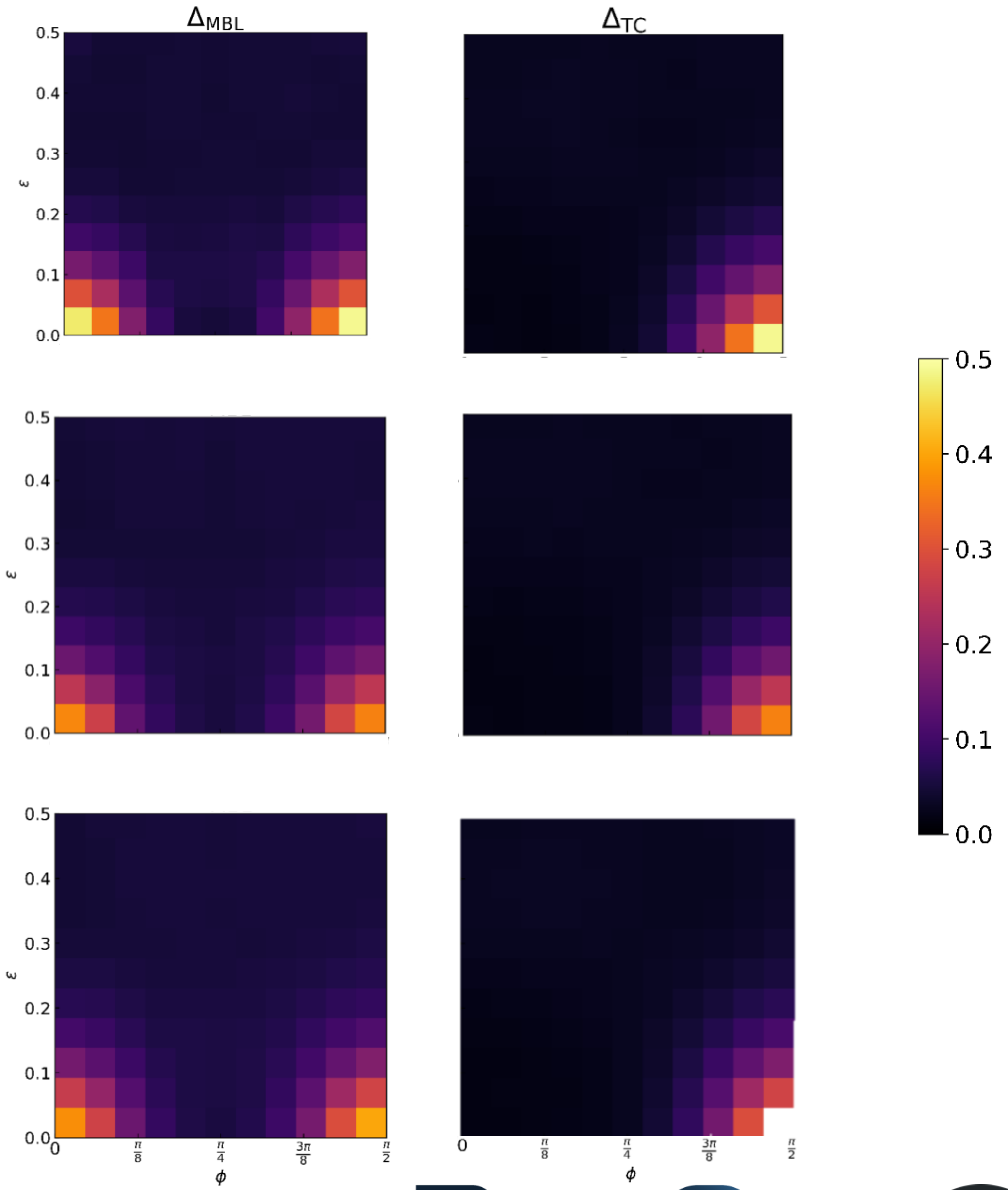
2x2
35 qubits

3x3
68 qubits

3x7
144 qubits







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Conclusion and outlook

DTC phase can be studied in current NISQ hardware

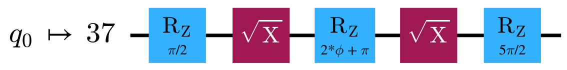
Completely characterizing the system requires a significant amount of simulation time.

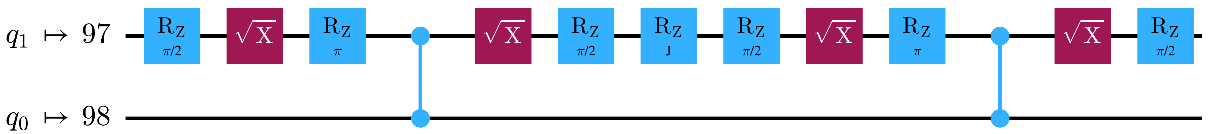
We need to go deeper...

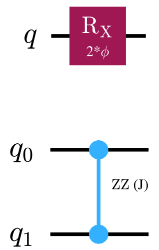
Fractional gates

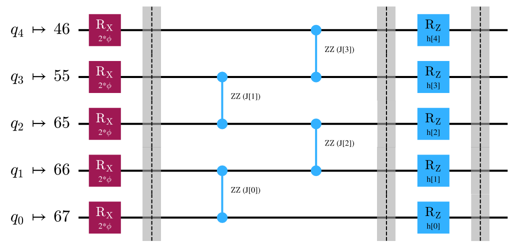
$R_X(\phi) \quad \text{for any } \phi$

$R_{ZZ}(\theta) \quad \text{for } 0 < \theta \leq \frac{\pi}{2}$









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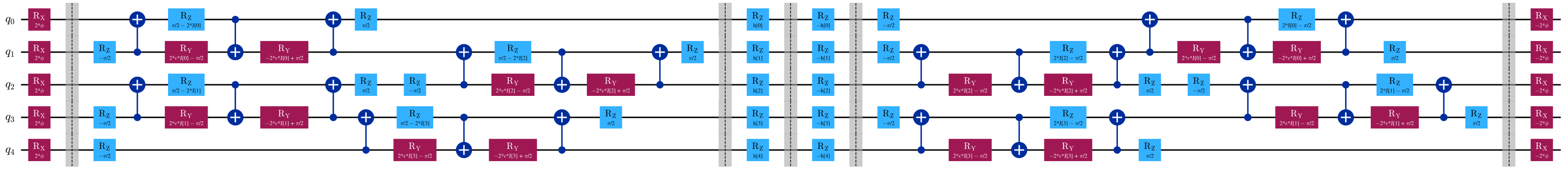
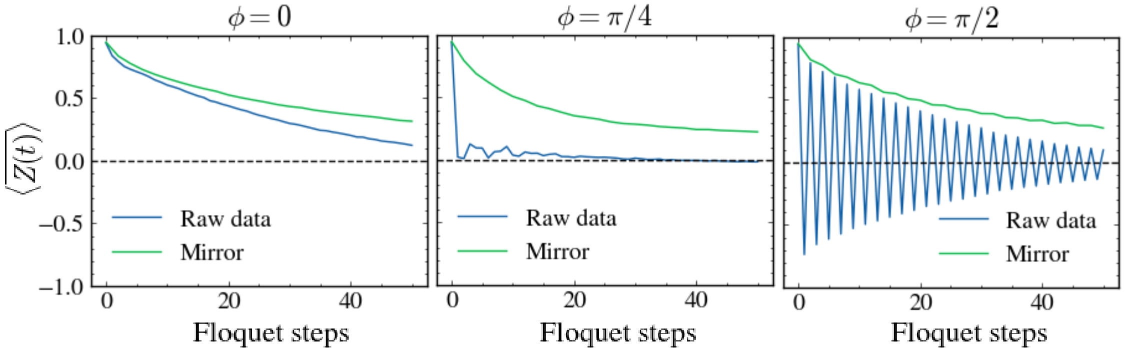




Protocol pathways to

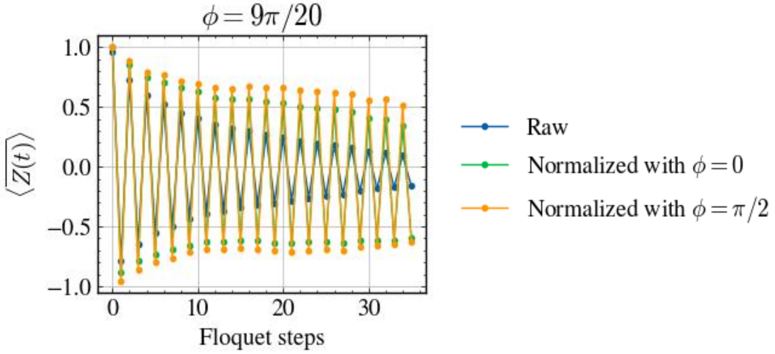
error mitigation

Compute and uncompute

Farrell et al., PRX Quantum **5**, 020315 (2024)

Farrell et al., PRD **109**, 111510 (2024)

$$\eta_O = 1 - \frac{\langle O \rangle_{\text{meas}}}{\langle O \rangle_{\text{pred}}}$$



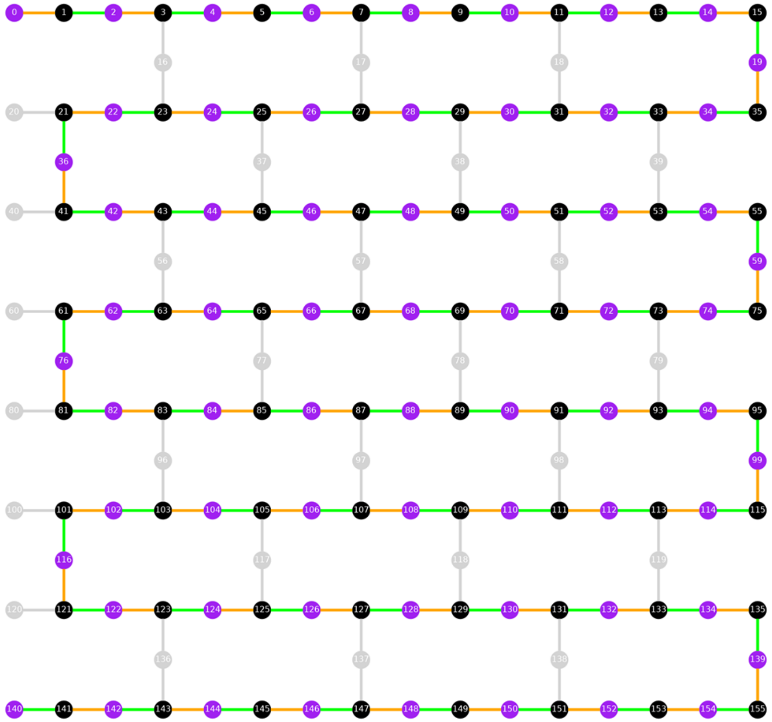
Normalization by Clifford point data

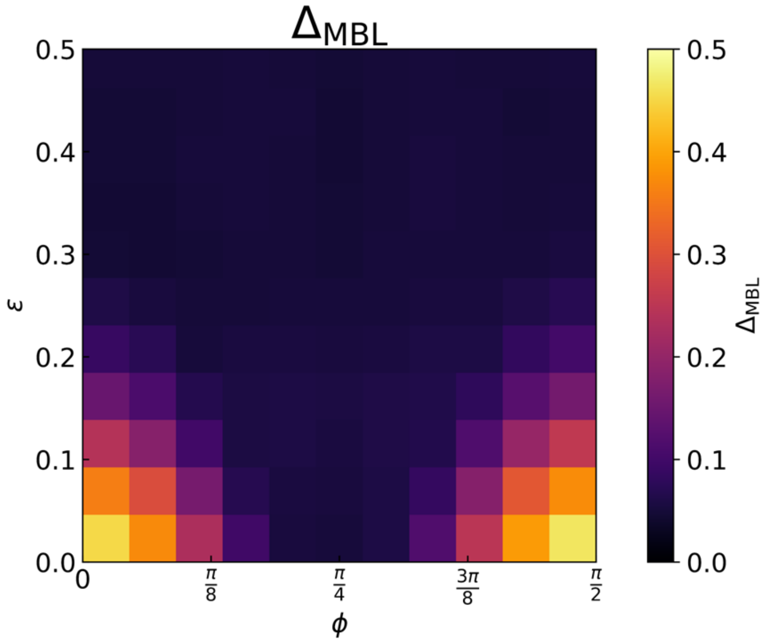
Shinjo et al., arxiv.org/abs/2403.16718

$$\langle \hat{Z}_{\text{avg}}(t) \rangle \approx \frac{\langle \hat{Z}_{\text{avg}}(t) \rangle_0}{|\langle \hat{Z}_{\text{avg}}(t) \rangle_0, \theta_x = 0, \pi|}$$

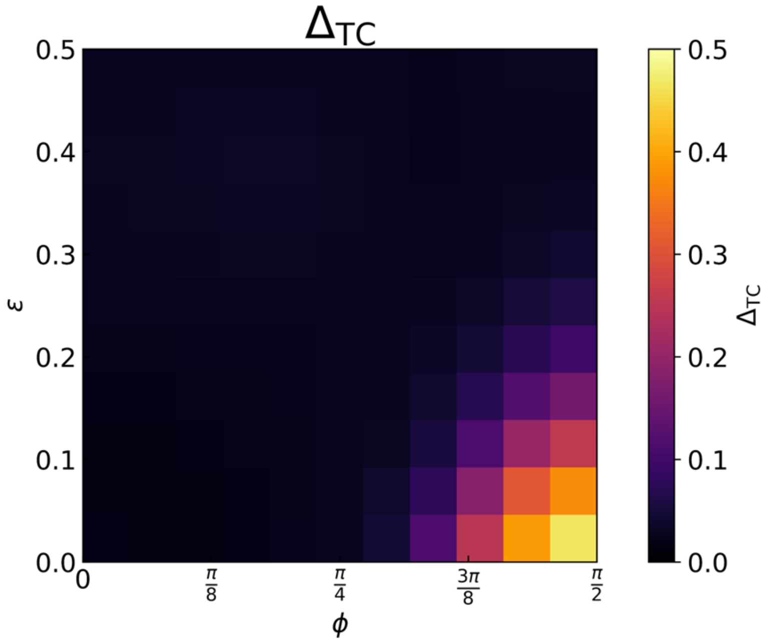
Thank you for your attention

Néel state

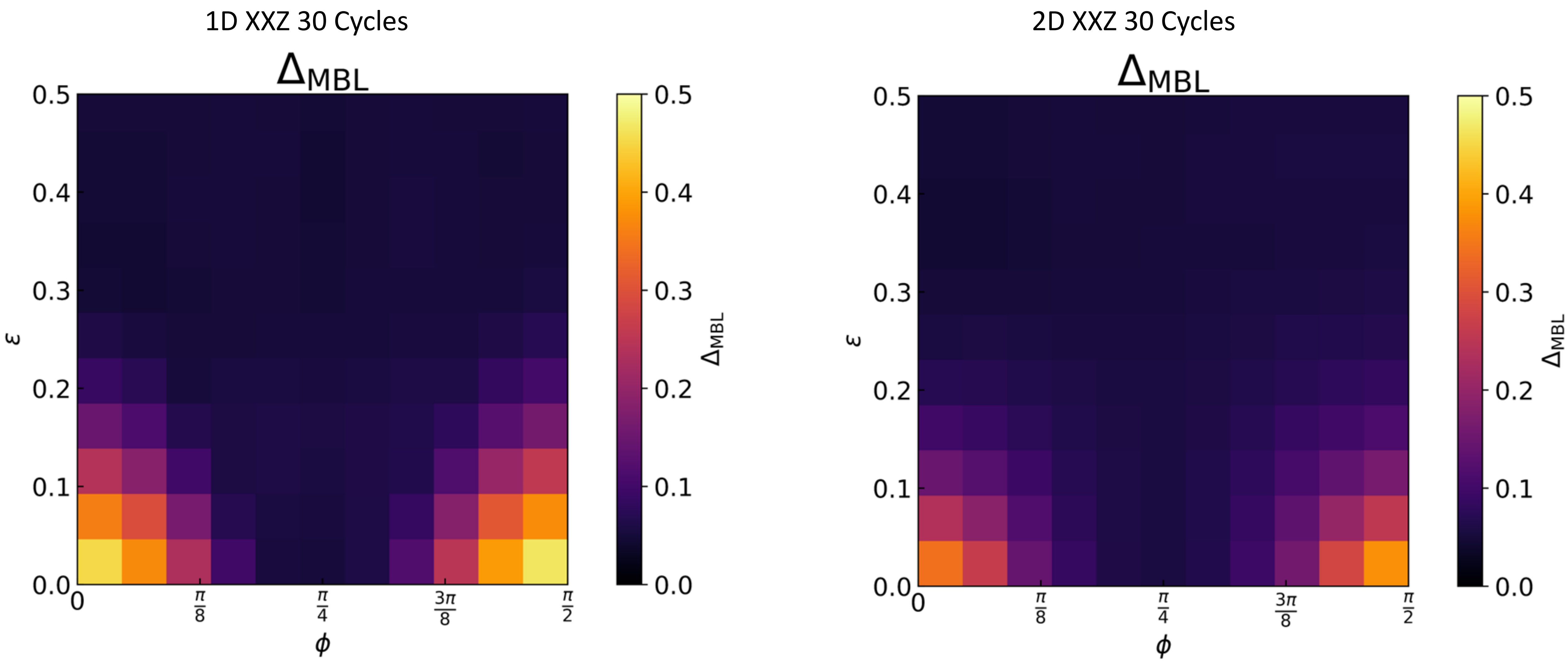




Δ_{MBL}
0.5
0.4
0.3
0.2
0.1
0.0
ϵ
0
$\frac{\pi}{8}$
$\frac{\pi}{4}$
$\frac{3\pi}{8}$
$\frac{\pi}{2}$
ϕ
Δ_{MBL}



Δ_{TC}
0.5
0.4
0.3
0.2
0.1
0.0
ϵ
0
$\frac{\pi}{8}$
$\frac{\pi}{4}$
$\frac{3\pi}{8}$
$\frac{\pi}{2}$
ϕ
Δ_{TC}



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