Ruling out (some) classical models for the D-Wave device

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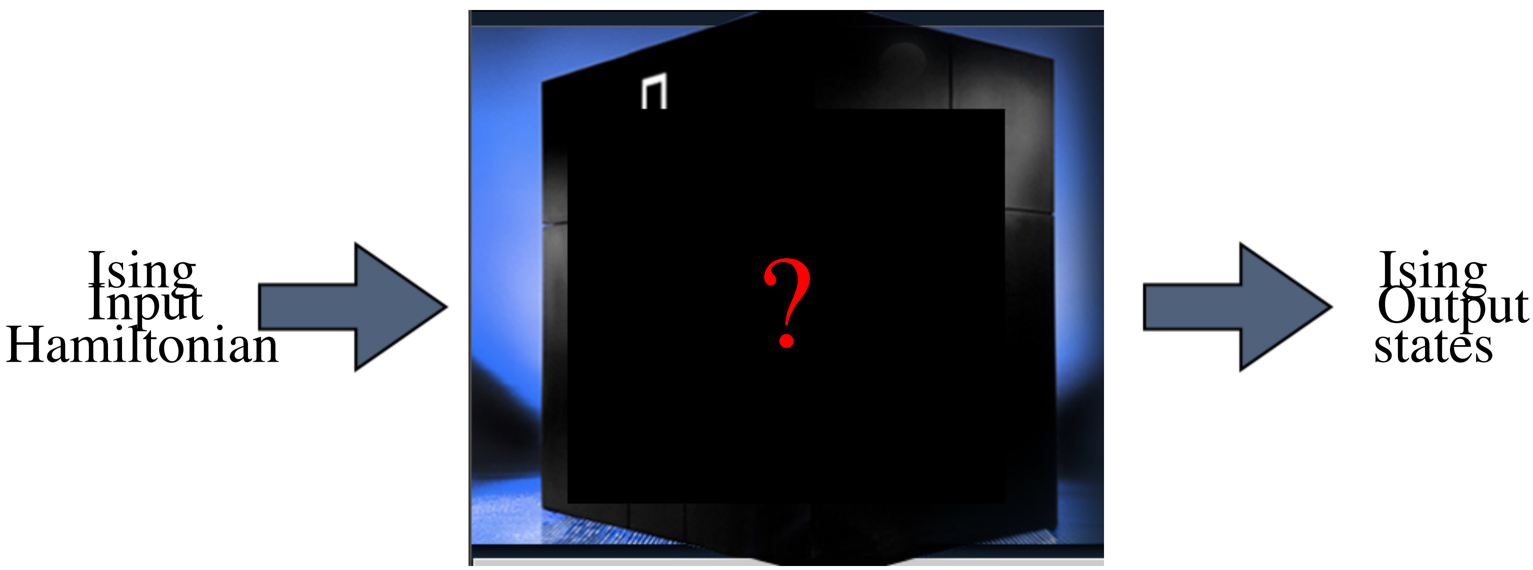
Outline

- Black box paradigm and what our goal is
- SSSV vs. Quantum Master Equation (ME)
- The test: “Quantum Signature” Hamiltonian
- Predictions of SSSV and ME
- Compare against DW2

Black box paradigm

Given a black box



can we determine whether it is quantum or classical
via *solely* its classical input-classical output behavior?

The black box paradigm
excludes the entanglement results of
T. Lanting et al., arXiv:1401.3500

A "good" model

Goal:

Find a model that fits all the data from the device

Our test is not an entanglement test
nor a no-go result for classical models

Demand predictive power
from the model

Fit parameters of model once

Does it survive a comparison with various
input-output experiments?

Where does D-Wave stand?

Lively discussion so far

Consistency of quantum models

Experimental signature of programmable quantum annealing

S. Boixo, TA, et al., arXiv:1212.1739

Quantum annealing with more than 100 qubits

S. Boixo, et al., arXiv:1304.4595

Distinguishing Classical and Quantum Models for the D-Wave Device

W. Vinci, TA, et al., arXiv:1403.4228v1

Consistency of classical models

Classical signature of quantum annealing

J. Smolin & G. Smith, arXiv:1305.4904

How “Quantum” is the D-Wave Machine?

S. Shin, et al., arXiv:1401.7087

Comment on "Distinguishing Classical and Quantum Models for the D-Wave Device"

S. Shin, et al., arXiv:1404.6499

All comparisons of success probabilities

i.e. total ground state probabilities

What is at stake?

Do quantum effects play a role
in determining the final outcome
(which is a classical state)?

So far, classical models and quantum models
correlate equally well
with the success probability of the device

Is this an issue of the type
of Ising problems being solved,
or is it an issue of the device?

Quantum Model: Open Quantum System

TA et al., New J. Phys. 14 (2012) 123016

$$H(t) = H_S(t) + H_B + H_{S-B}$$

$$H_S(t) = -A(t)\sum_i \sigma_i^x + B(t)H_{\text{Ising}}$$

$\Big\Downarrow$ Trace out bath

Markovian adiabatic master equation (ME)

Assumptions

- Weak system-bath coupling.
- Born-Markov
- Slow system evolution with respect to bath

Important features of the ME

TA et al., New J. Phys. 14 (2012) 123016

Dephasing occurs in the instantaneous energy eigenbasis

Not harmful for an adiabatic computation

Thermalizing towards instantaneous Gibbs state

Can be harmful for an adiabatic computation

Fix the bath

Independent harmonic oscillator baths with an Ohmic spectrum

Classical Model: SSSV

S.W. Shin et al., arXiv:1401.7087

$$H_{\mathrm{SSSV}}(t) = \langle \Omega | H_S(t) | \Omega \rangle$$

$$\sigma_i^x \rightarrow \sin\theta_i$$

$$\sigma_i^z \rightarrow \cos\theta_i$$

Evolution is determined by
Metropolis update steps

Can be thought of as a "mean-field" limit
of quantum Monte-Carlo, whereby
all the replicas along the imaginary time
direction are forced to be identical

Where does this model come from?

Is this a fair comparison?

ME is a microscopic model

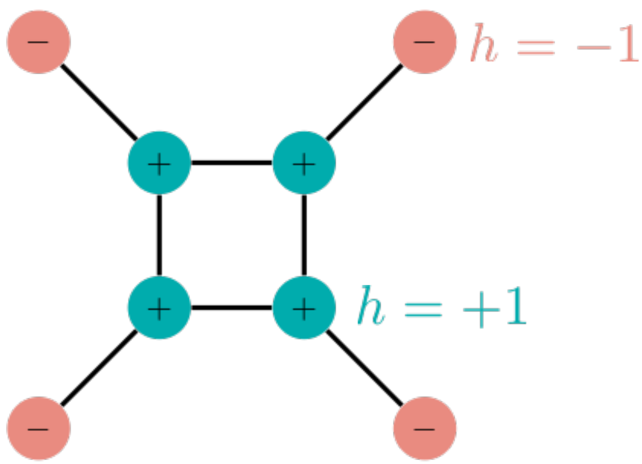
SSSV is a phenomenological model

SSSV has been very successful in reproducing the success probability of the D-Wave devices so understanding where it could fail could be useful in order to find “quantum” signatures

“Quantum Signature” Hamiltonian

S. Boixo, TA, et al., Nature Comm. 4, 3067 (2013)

$$H_{\text{Ising}} = -\sum_i h_i \sigma_i^z - \sum_{i,j} J_{ij} \sigma_i^z \sigma_j^z$$



17-fold degenerate ground state

$|\downarrow\downarrow\downarrow\downarrow\ \downarrow\downarrow\downarrow\downarrow\rangle$ isolated state

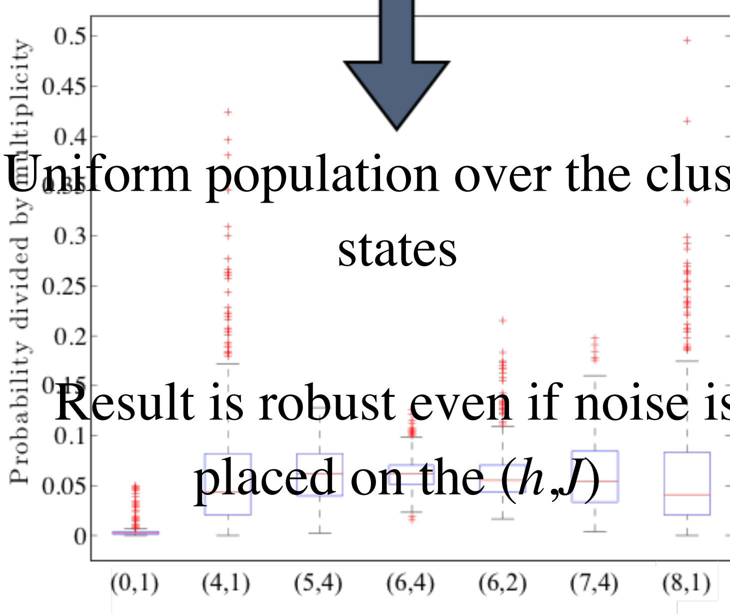
$|\uparrow\uparrow\uparrow\uparrow\ \updownarrow\updownarrow\updownarrow\updownarrow\rangle$ cluster states

Quantum Prediction

Late time ground state and excited states are uniform superposition of cluster states

W. Vinci, TA, et al., arXiv:1403.4228v2

Master equation simulations



Uniform population over the cluster states

Result is robust even if noise is placed on the (h,J)

(Hamming distance, Multiplicity

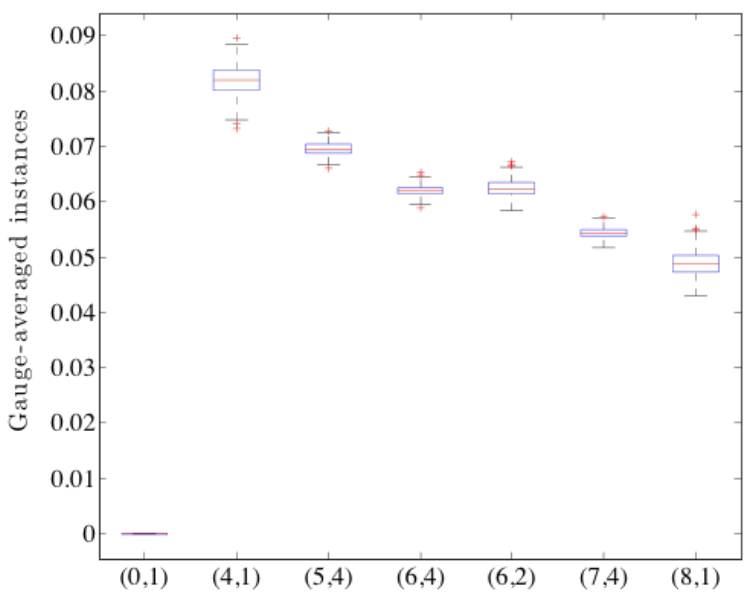
SSSV Prediction

Any slight deviation from

W. Vinci, TA, et al., arXiv:1403.4228v2

$$\theta = 0$$

for the inner spins tilts the energy landscape to favor a single cluster state



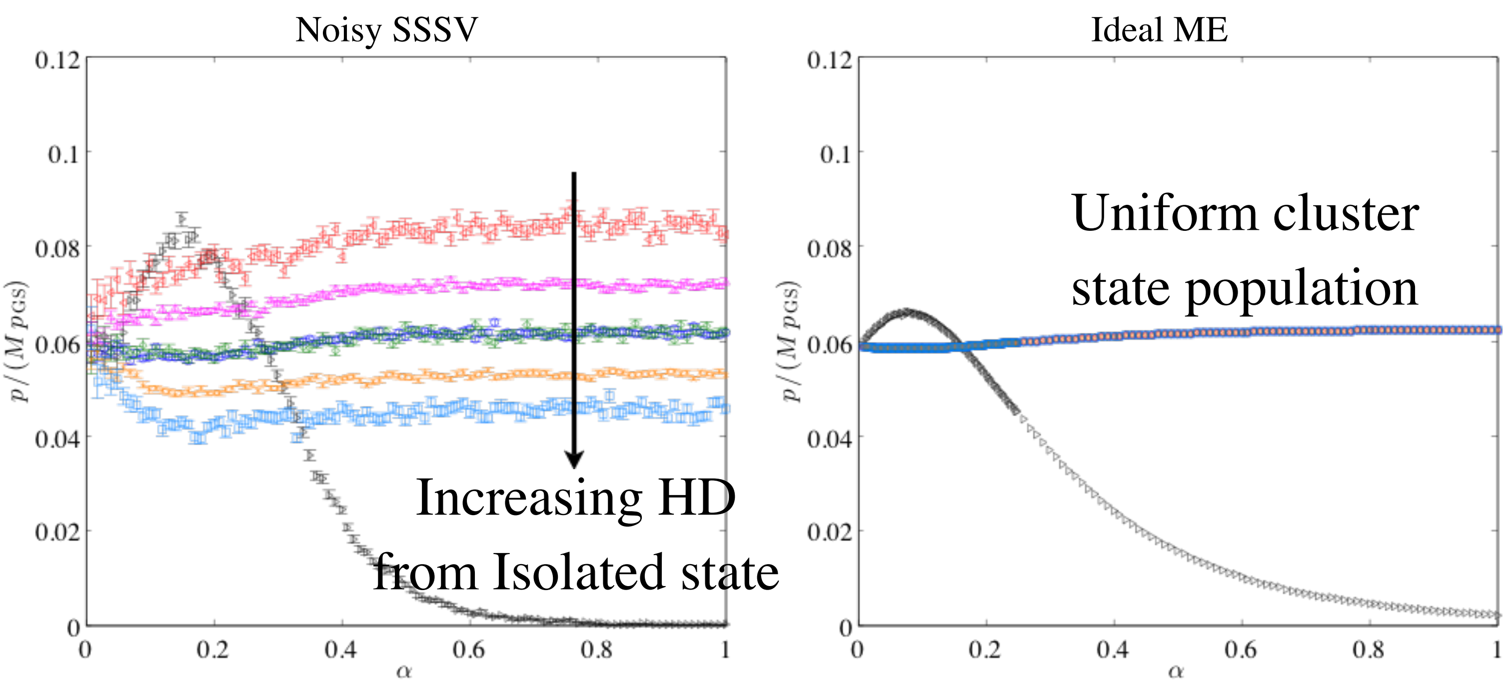
(Hamming distance, Multiplicity

Cluster state distribution

Exact cluster state distribution is a robust feature

W. Vinci, T.A., et al., arXiv 1403.4228v2

$$H_{\text{Ising}} \rightarrow \alpha H_{\text{Ising}}$$

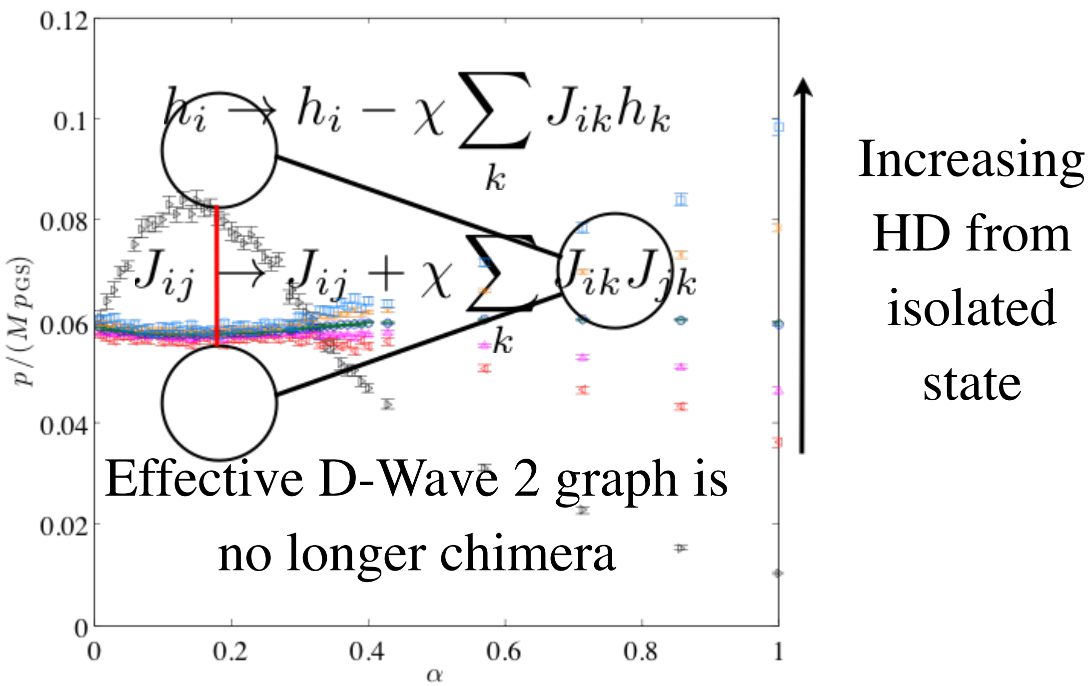


Realistic Noise Model for D-Wave 2

W. Vinci, TA, et al., arXiv:1403.4228v2

Gaussian noise on (h, J)

Cross-talk among qubits



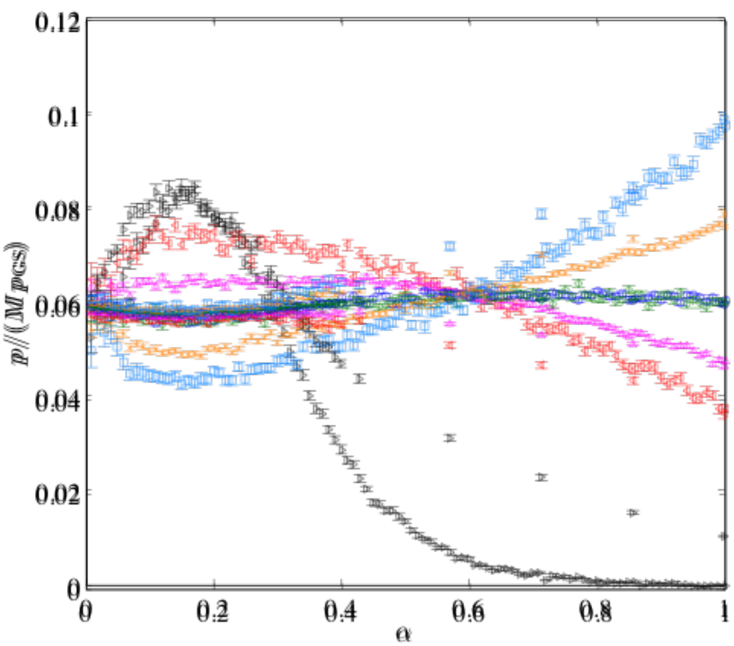
And the winner is...

Fit value of χ at $\alpha = 1$

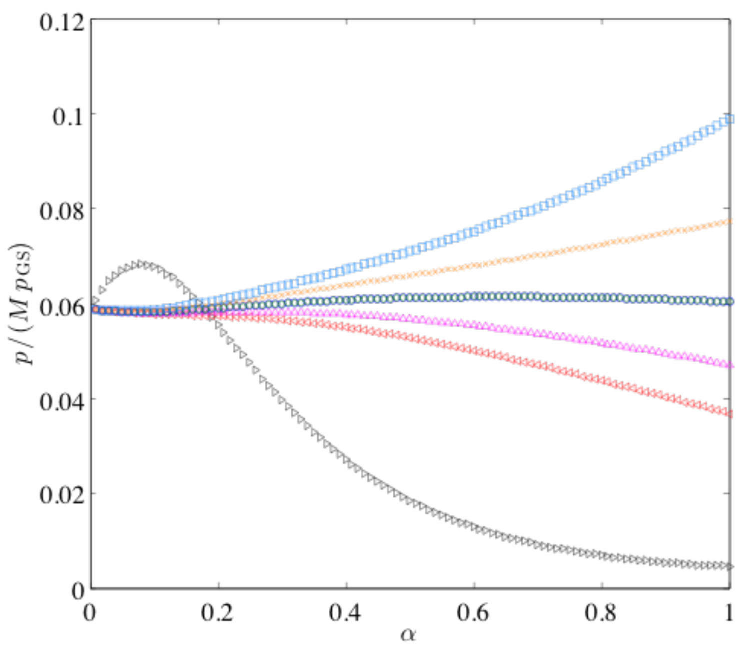
W. Vinci, T. Albash, et al., arXiv:1403.4228v2

DW2

Noisy SSSV

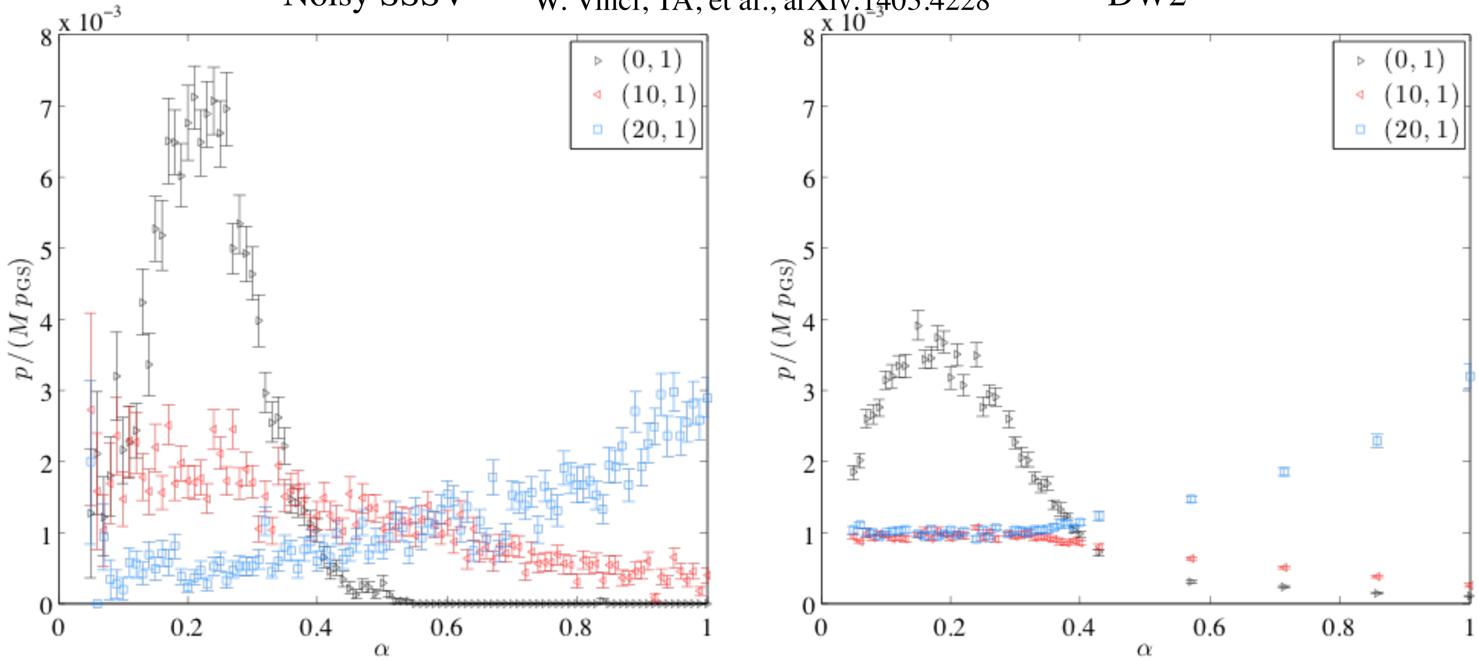


Ideal ME



Beyond 8 qubits

Noisy SSSV W. Vinci, TA, et al., arXiv:1403.4228 DW2



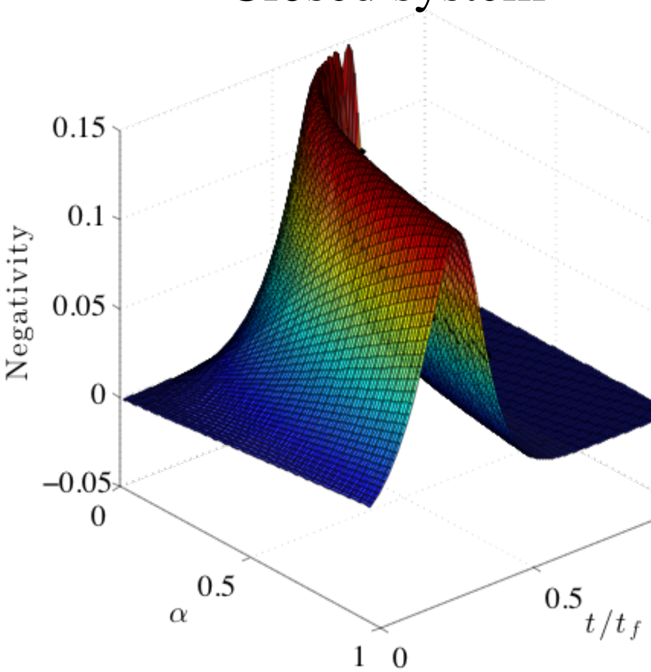
SSSV continues to fail to capture the right cluster state distribution as we increase the number of qubits to 20

Entanglement?

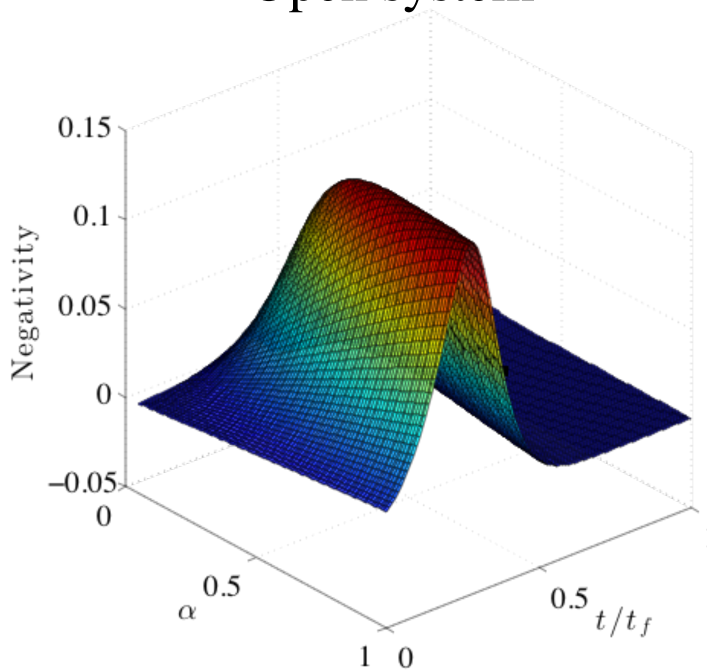
W. Vinci, TA, et al., arXiv:1403.4228

$$\mathcal{N}(\rho) = \frac{1}{2}\left(||\rho^{\Gamma_a}||_1 - 1\right)$$

Closed system



Open system



Conclusions

- "Quantum signature" Hamiltonian reveals a feature of SSSV that can be exploited: a preference for a particular cluster state.
- With a physically motivated noise model for the DW2, this feature can be used to rule out SSSV as microscopic model of the device. The quantum ME reproduces all the features of the device.
- SSSV ruled out for spin systems up to $N = 20$.
- This is *not* a proof of quantum-ness!

Acknowledgements

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arXiv:1403.4228v2

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