Title: Shortcuts in Real and Imaginary Time

Speakers: Timothy Hsieh

Collection: Machine Learning for Quantum Design

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Abstract: In the first half, I will demonstrate an efficient and general approach for realizing non-trivial quantum states, such as quantum critical and topologically ordered states, in quantum simulators. In the second half, I will present a related variational ansatz for many-body quantum systems that is remarkably efficient. In particular, representing the critical point of the one-dimensional transverse field Ising model only requires a number of variational parameters scaling logarithmically with system size. Though optimizing the ansatz generally requires Monte Carlo sampling, our ansatz potentially enables a partial mitigation of the sign problem at the expense of having to optimize a few parameters.

Shortcuts in Real and Imaginary Time

Tim Hsieh

Perimeter Institute

Machine Learning for Quantum Design
July 9, 2019

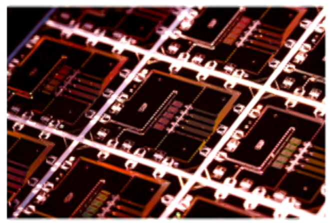
Accessing Quantum Many-Body States

On Quantum Computers		On Classical Computers
Trapped Ions	Superconducting Circuits	

Trapped Ions

e.g. Monroe group
U. Maryland/IonQ

Superconducting Circuits



e.g. Martinis group
UCSB/Google

Prepare nontrivial quantum states using real time evolution

On Classical Computers

Efficient variational wavefunction using imaginary time evolution

Collaborators

Real time

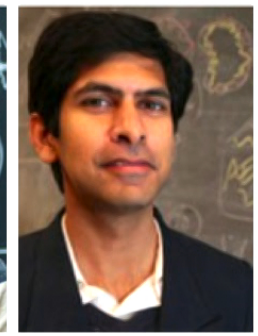
Wen Wei Ho
(Harvard)

SciPost Phys. 6, 029 (2019)

Imaginary time

Matt Beach
(UW/Perimeter)

Roger Melko
(UW/Perimeter)

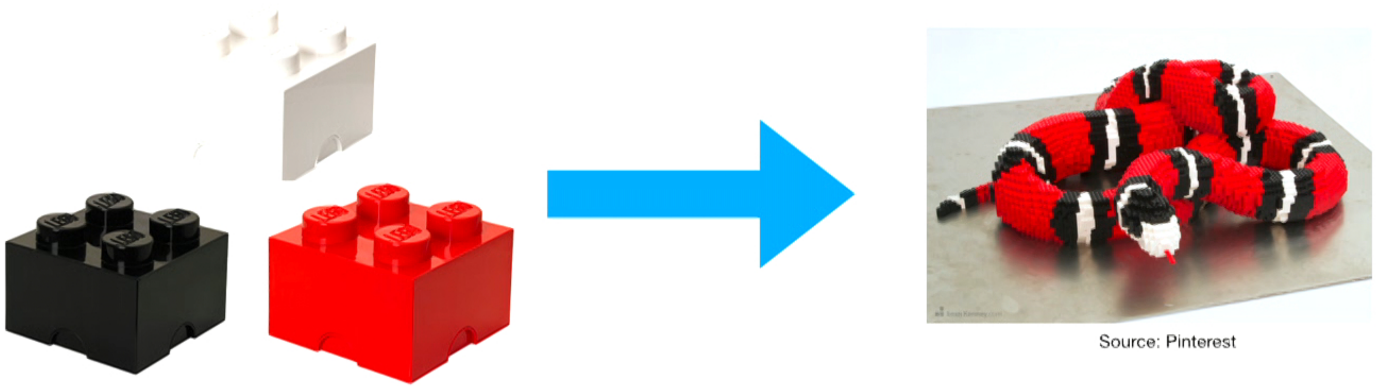


Tarun Grover
(UCSD)

arXiv: 1904.00019 (2019)

Part I

General protocol for preparing nontrivial quantum states



Source: Pinterest

QAOA

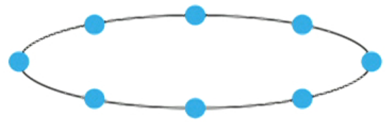
Quantum Approximate Optimization Algorithm:

Farhi, Goldstone, Gutmann (2014)
Wecker, Hastings, Troyer (2015)

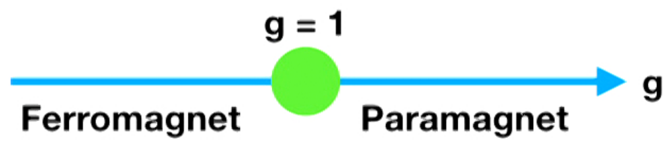
Simple Hamiltonian	Target Hamiltonian
H_X	H_t
$\|+\rangle$	$\|\psi_t\rangle$

$$|\psi\rangle = e^{-i\beta_p H_X} e^{-i\gamma_p H_t} \cdots e^{-i\beta_1 H_X} e^{-i\gamma_1 H_t} |+\rangle$$

Transverse Field Ising Model



$$H_{\mathrm{TFIM}} = -\sum_{i=1}^{L} Z_i Z_{i+1} - g \sum_{i=1}^{L} X_i$$



$|\uparrow\uparrow\uparrow \ldots\rangle + |\downarrow\downarrow\downarrow \ldots\rangle$ $\quad$ $|+ + + \ldots\rangle$

Warmup: GHZ (Cat) State

Target: $|\psi_t\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\uparrow ...\rangle + |\downarrow\downarrow\downarrow ...\rangle)$

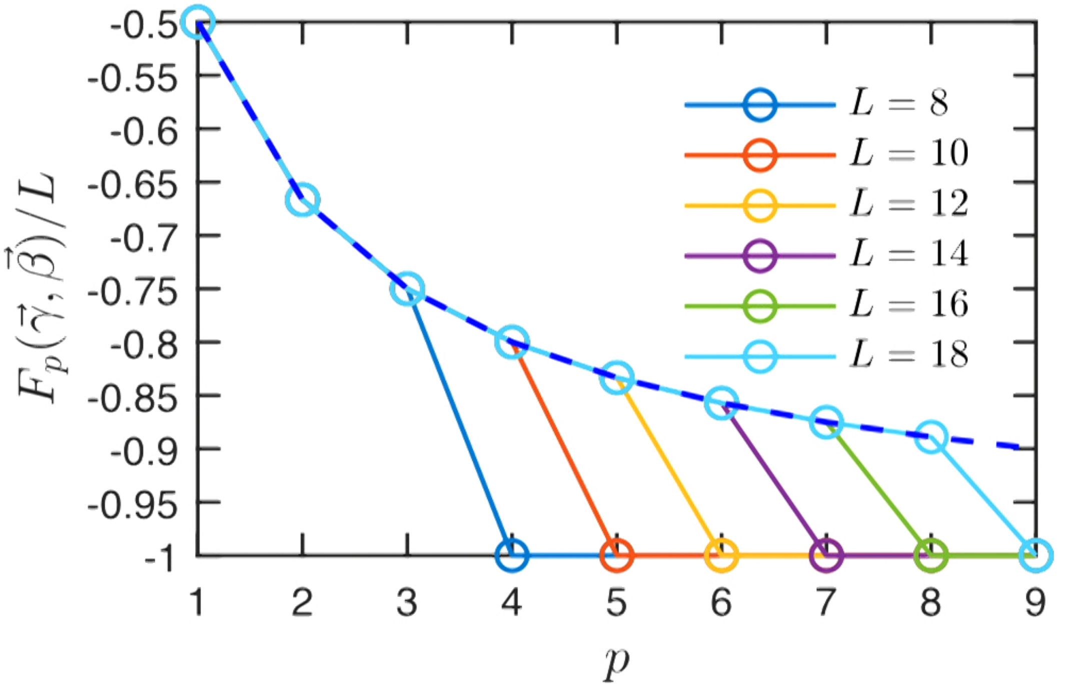
$$H_t = -\sum_{i=1}^{L} Z_i Z_{i+1}$$

$$H_X = -\sum_i X_i$$

$$H_I = -\sum_{i=1}^{L} Z_i Z_{i+1}$$

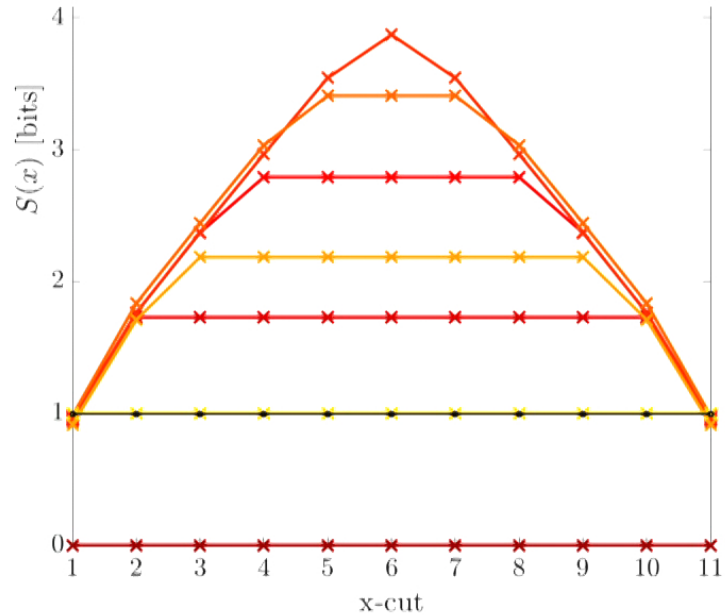
$$|\psi(\vec{\gamma}, \vec{\beta})\rangle_p = e^{-i\beta_p H_X} e^{-i\gamma_p H_I} \cdots e^{-i\beta_1 H_X} e^{-i\gamma_1 H_I} |+\rangle$$

Preparation of GHZ State



Trajectory in Hilbert Space

L = 12, optimal GHZ preparation sequence

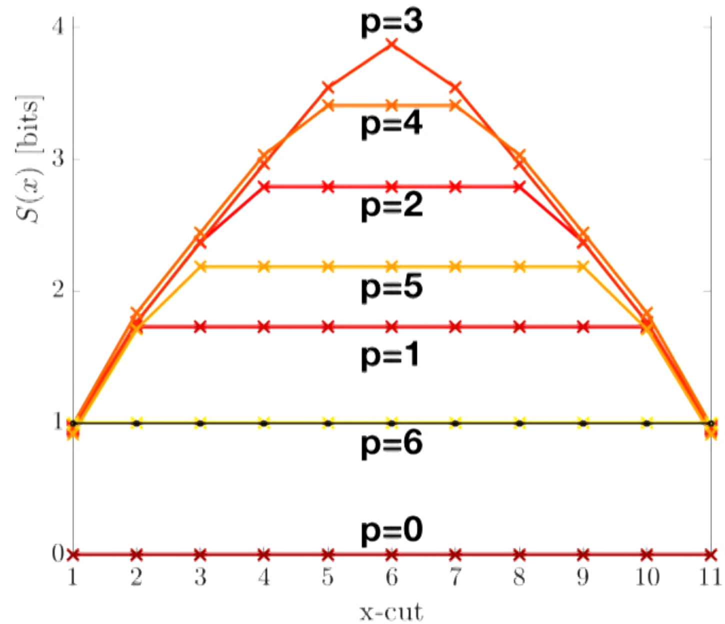


(thanks to C. Jonay)

Entanglement growth during evolution of state

Trajectory in Hilbert Space

L = 12, optimal GHZ preparation sequence



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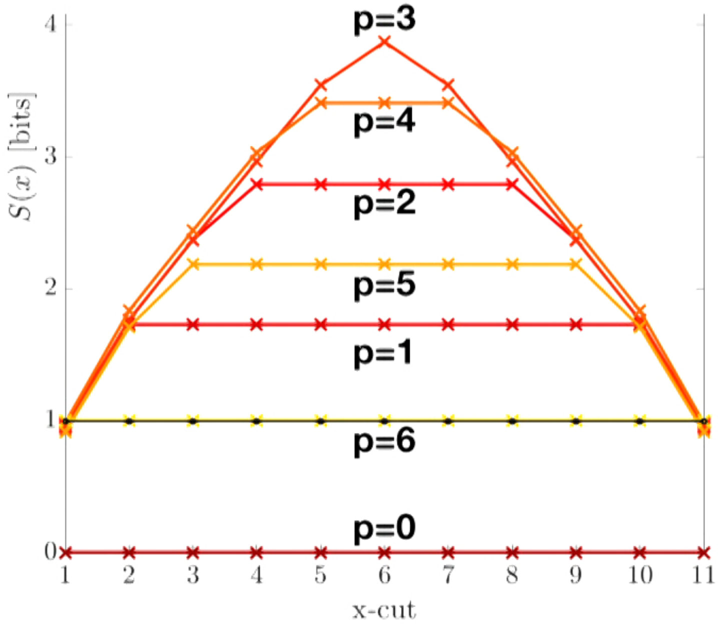

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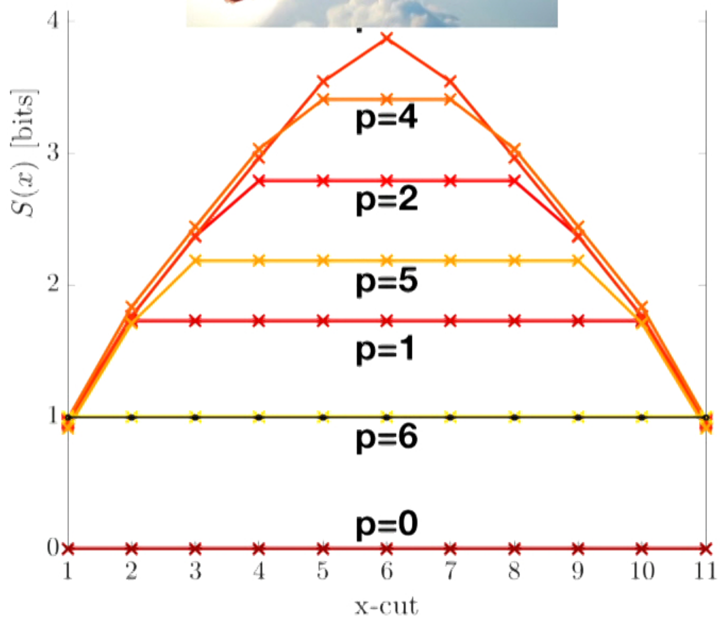
Entanglement growth during evolution of state

Trajectory ... ert Space

L = 12, optir ... ion sequence



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Trajectory in Hilbert Space

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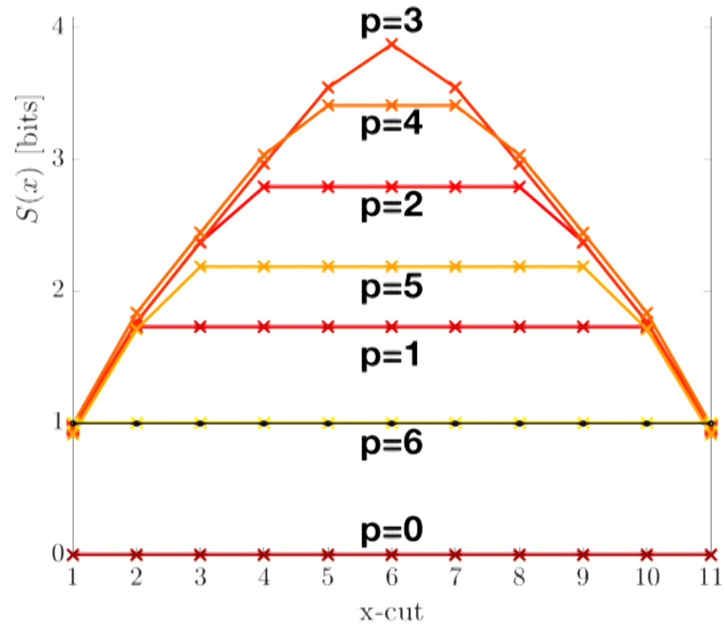


(thanks to C. Jonay)

Entanglement growth during evolution of state

Quantum Critical State

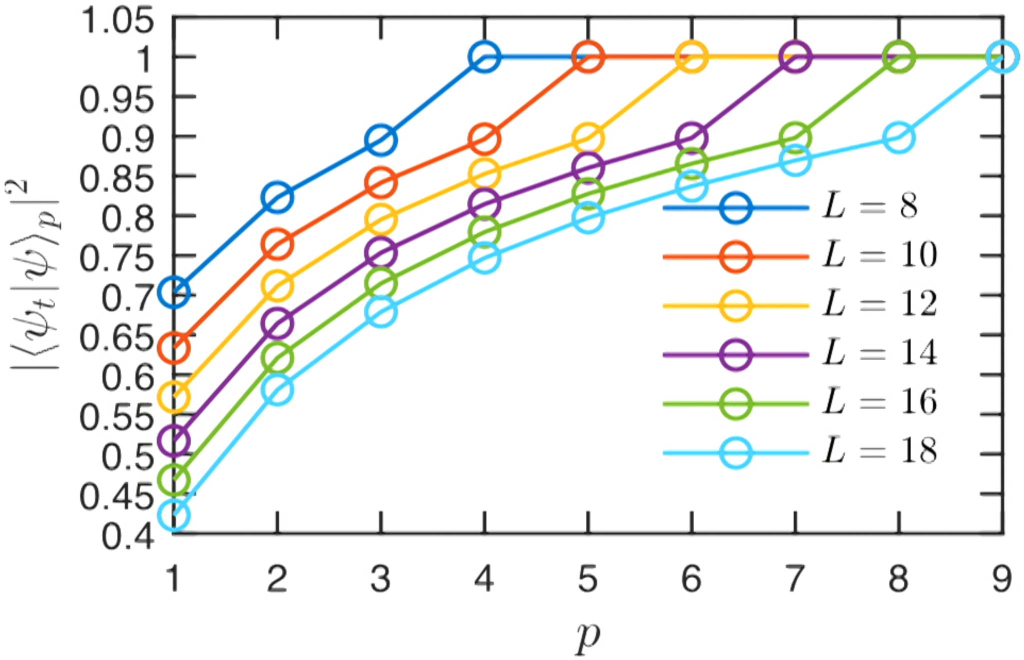
Target: ground state of

$$H_t = -\sum_{i=1}^{L} Z_i Z_{i+1} - \sum_{i=1}^{L} X_i$$

$$H_X = -\sum_i X_i$$

$$H_I = -\sum_{i=1}^{L} Z_i Z_{i+1}$$

Quantum Critical State Preparation



Experiment

Variational Generation of Thermofield Double States and Critical Ground States with a Quantum Computer

D. Zhu[1], S. Johri[2], N. M. Linke[1], K. A. Landsman[1], N. H. Nguyen[1], C. H. Alderete[1], A. Y. Matsuura[2], T. H. Hsieh[3], and C. Monroe[1]

arXiv:1906.02699 (2019)

Variational Imaginary Time Ansatz (VITA)

Given Hamiltonian $H = H_A + gH_B$

Approximate ground state by

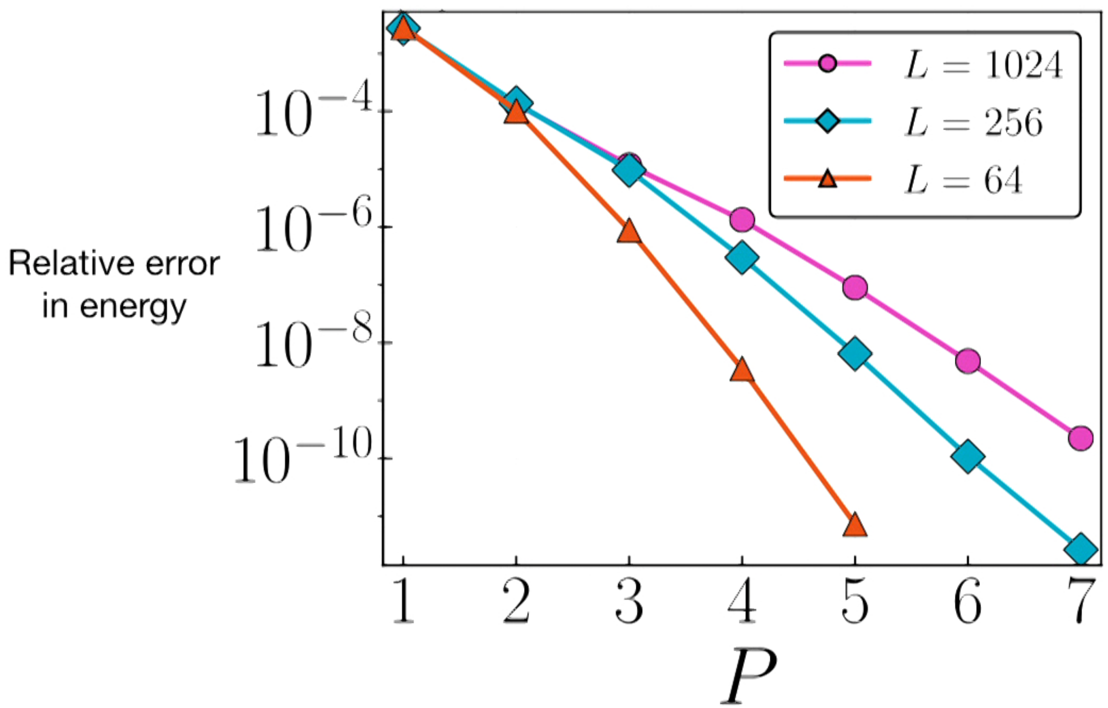
$$|\psi_P(\boldsymbol{\alpha}, \boldsymbol{\beta})\rangle = \mathcal{N} \prod_{p=1}^{P} e^{-\beta_p H_B} e^{-\alpha_p H_A} |\psi_0\rangle$$

Trotter limit of $e^{-\tau H}|\psi_0\rangle$ achieved by taking P to infinity

Small P, finite and variable time steps

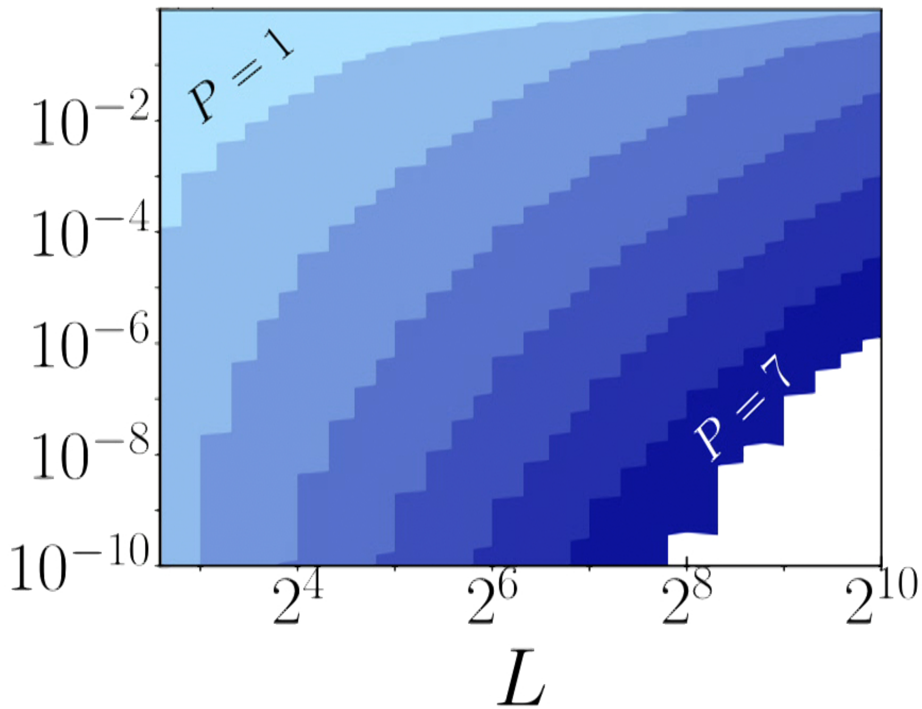
for Hubbard model: P = 1 ansatz (Gutzwiller 1963, Baeriswyl 1987, Otsuka 1992)
Related ansatz (Vaezi and Vaezi 2018)

Efficient Representation of Critical TFIM



Efficient Representation of Critical TFIM

Error in fidelity



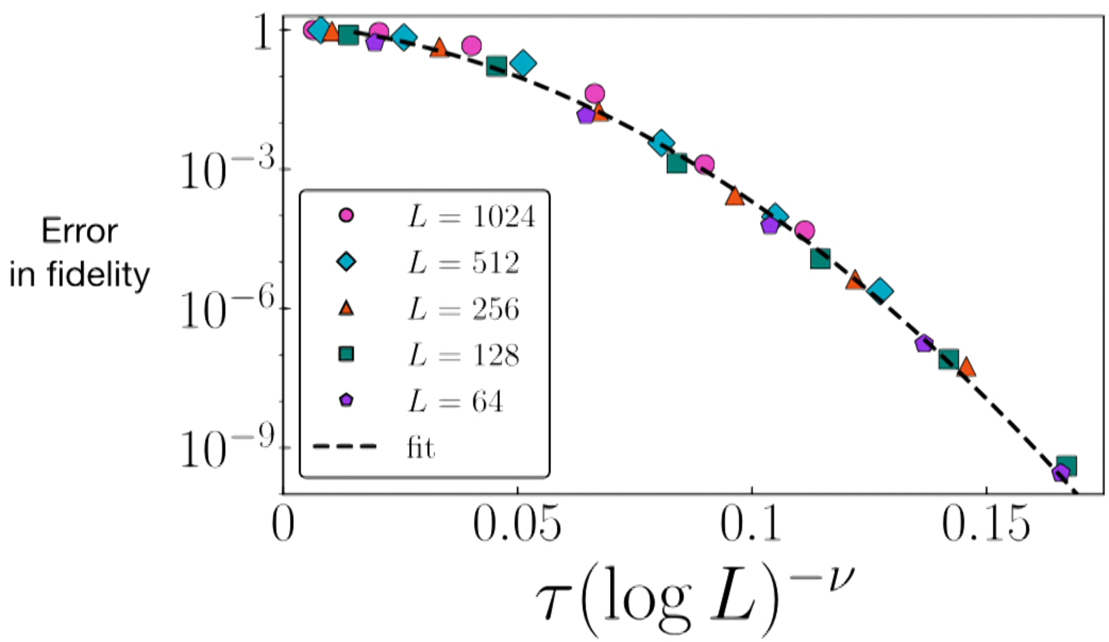
To get target fidelity, need $P \propto \log L$

Scaling Collapse

For projector method: to get target fidelity, need total imaginary time $\tau \propto L$

VITA: $\tau \equiv \frac{1}{2}\sum_{p=1}^{P}(\alpha_p + \beta_p)$

$\tau \propto (\log L)^{2.3}$



Imaginary Time 101(i)

No Lieb-Robinson bound

$|GHZ\rangle \approx e^{-\tau H_{ZZ}}|+\rangle$ for τ constant, independent of L

Local operator can generate entanglement far away

$$\eta_+|11\rangle + \eta_-|00\rangle$$

Imaginary Time 101(i)

No Lieb-Robinson bound

$|GHZ\rangle \approx e^{-\tau H_{ZZ}}|+\rangle$ for τ constant, independent of L

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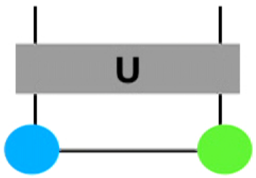

$\eta_+|11\rangle + \eta_-|00\rangle$

Imaginary Time 101(i)

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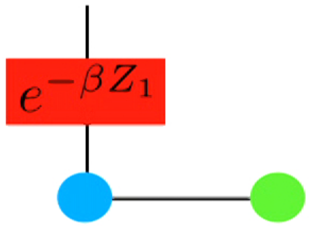
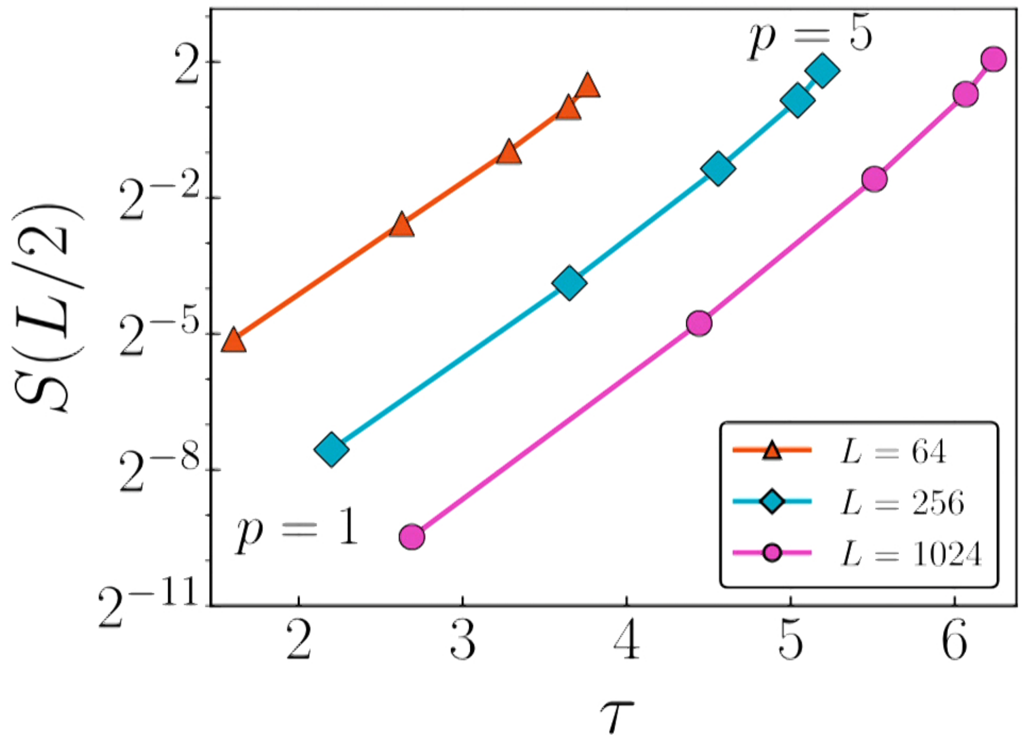


$$\eta_+|11\rangle + \eta_-|00\rangle$$

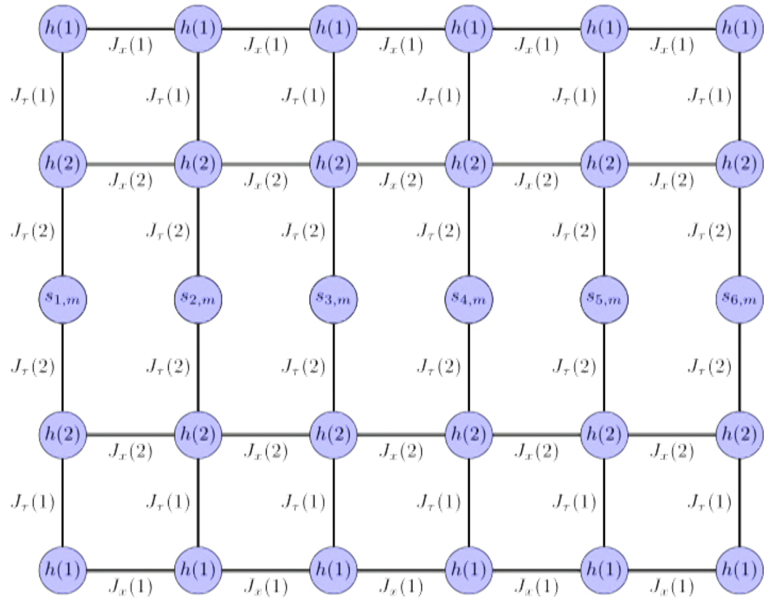
The more initial entanglement, the more imaginary time evolution can change the entanglement

Exponential Growth of Entanglement



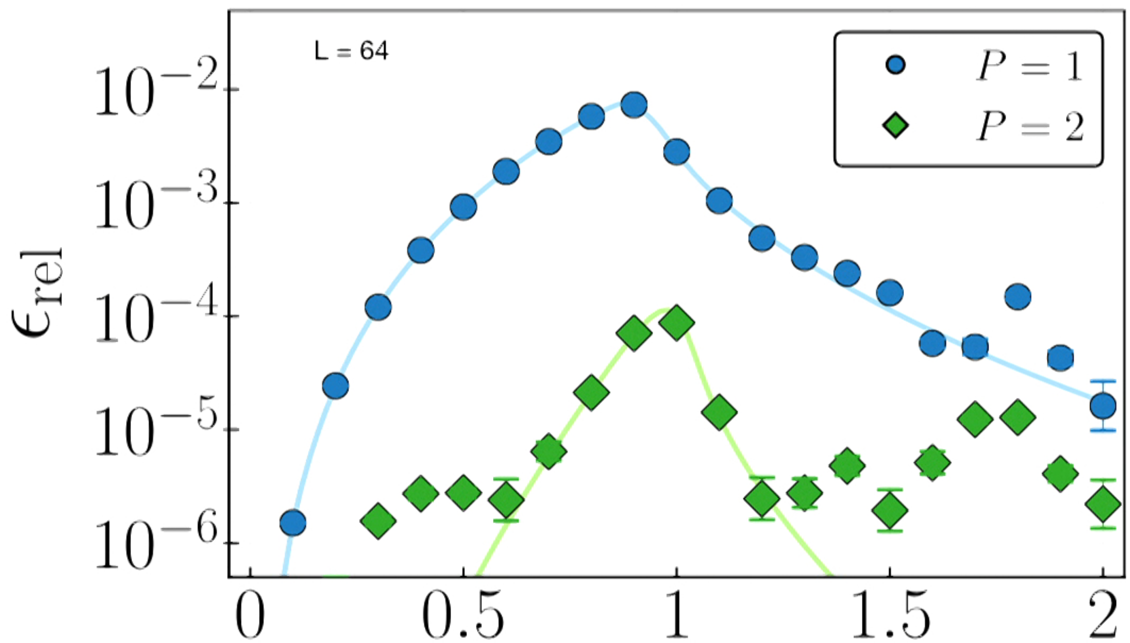
VITA via Monte Carlo

Quantum-Classical mapping: $\langle \psi_P(\boldsymbol{\alpha}, \boldsymbol{\beta}) | \mathcal{O} | \psi_P(\boldsymbol{\alpha}, \boldsymbol{\beta}) \rangle = \sum_{\{s\}} \tilde{\mathcal{O}}(s)\, p_{\boldsymbol{\alpha},\boldsymbol{\beta}}(s)$



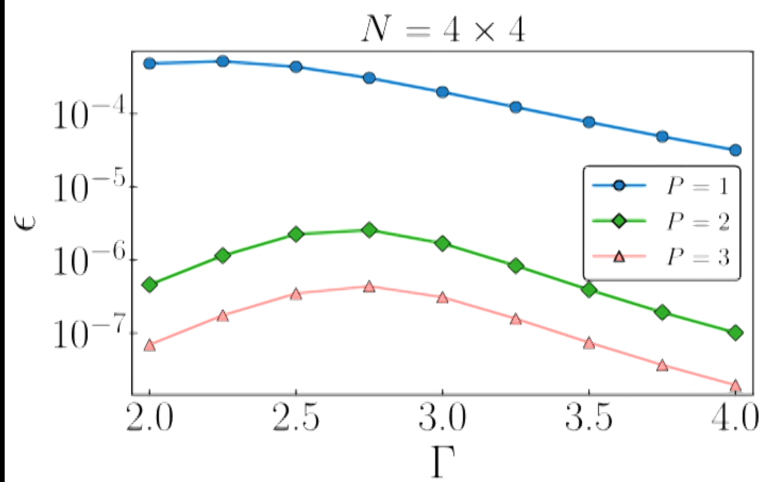
RBM: Carleo and Troyer (2017)
uRBM: Inack, Santoro, Dell'Anna, and Pilati (2018)

VITA via Monte Carlo

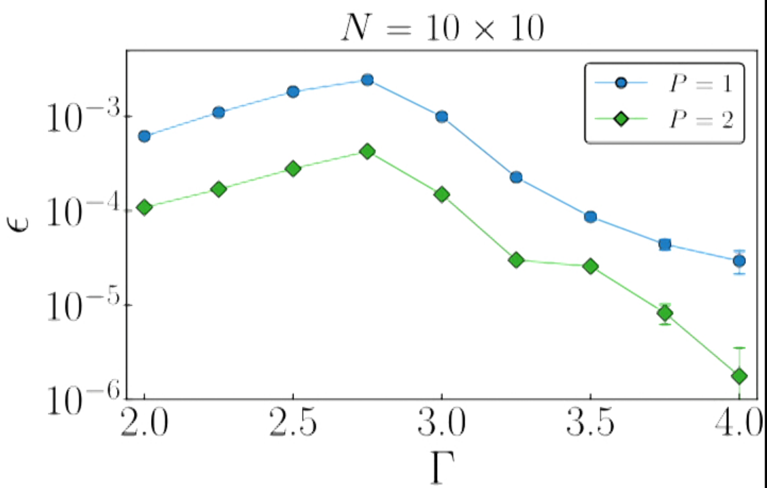


g
(transverse field)

2D TFIM



$N = 4 \times 4$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ϵ
$P = 1$
$P = 2$
$P = 3$
2.0
2.5
3.0
3.5
4.0
Γ



$N = 10 \times 10$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ϵ
$P = 1$
$P = 2$
2.0
2.5
3.0
3.5
4.0
Γ

Accessing Quantum Many-Body States

On Quantum Computers	
Protocols for preparing nontrivial quantum states Exactly prepare TFIM quantum critical state with L iterations Experiment: D. Zhu et.al. arXiv:1906.02699 (2019) (Monroe group) W.W. Ho and TH SciPost Phys. 6, 029 (2019)	

Accessing Quantum Many-Body States

On Quantum Computers	On Classical Computers
Protocols for preparing nontrivial quantum states	Highly efficient variational imaginary time ansatz (VITA)
Exactly prepare TFIM quantum critical state with L iterations	Requires ~log L parameters to represent TFIM critical state
Experiment: D. Zhu et.al. arXiv:1906.02699 (2019) (Monroe group)	In progress: application to harder models
W.W. Ho and TH SciPost Phys. 6, 029 (2019)	M. Beach, R. Melko, T. Grover, and TH arXiv: 1904.00019 (2019)

Accessing Quantum Many-Body States

On Quantum Computers

Protocols for preparing
nontrivial quantum states

Exactly prepare TFIM quantum critical state
with L iterations

Experiment:
D. Zhu et.al. arXiv:1906.02699 (2019)
(Monroe group)

W.W. Ho and TH
SciPost Phys. 6, 029 (2019)

On Classical Computers

Highly efficient
variational imaginary time ansatz (VITA)

Machine Learning??!!

In progress: application to harder models

M. Beach, R. Melko, T. Grover, and TH
arXiv: 1904.00019 (2019)