Quantum Science Seminar, Oct 8, 2020

Programmable Quantum Simulators with Atoms and Ions

Peter Zoller

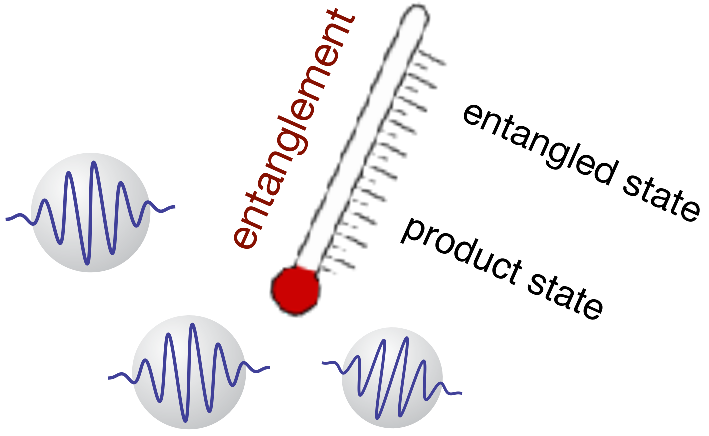
SIMONS FOUNDATION

AFOSR MURI (JILA)

This talk:

Measuring / characterizing / quantifying entanglement in quantum simulation?

`Randomized measurement' toolbox



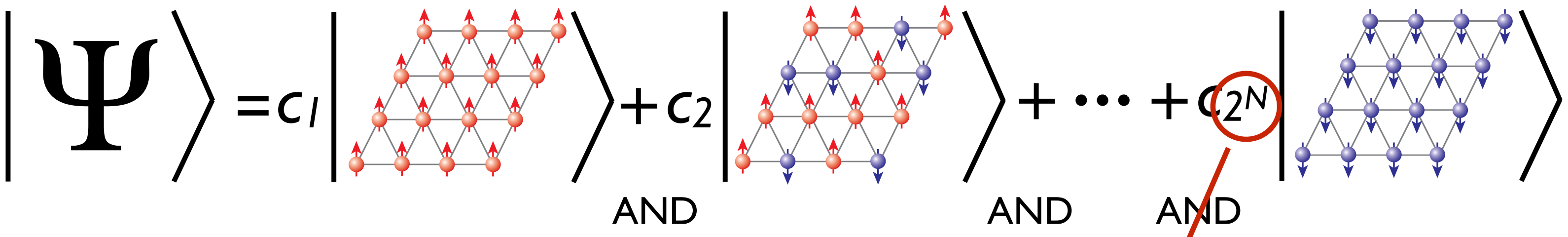
synthetic quantum matter

The Credo of Quantum Simulation

Quantum Many-Body System

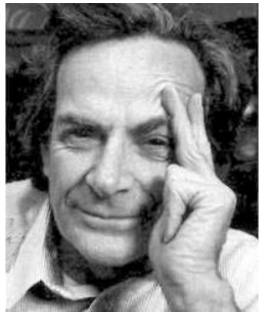
The system is in a *superposition* state
of all possible configurations …

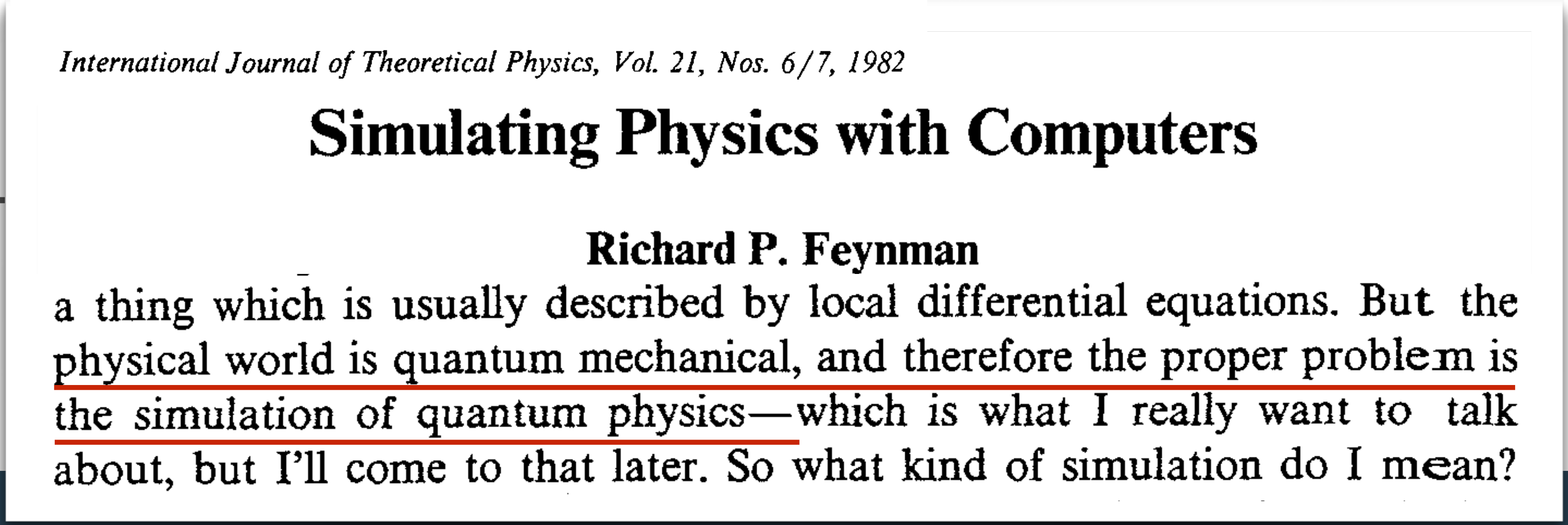
Entanglement



Exponentially large Hilbert space


Schrödinger


Feynman


International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

a thing which is usually described by local differential equations. But the physical world is quantum mechanical, and therefore the proper problem is the simulation of quantum physics—which is what I really want to talk about, but I'll come to that later. So what kind of simulation do I mean?

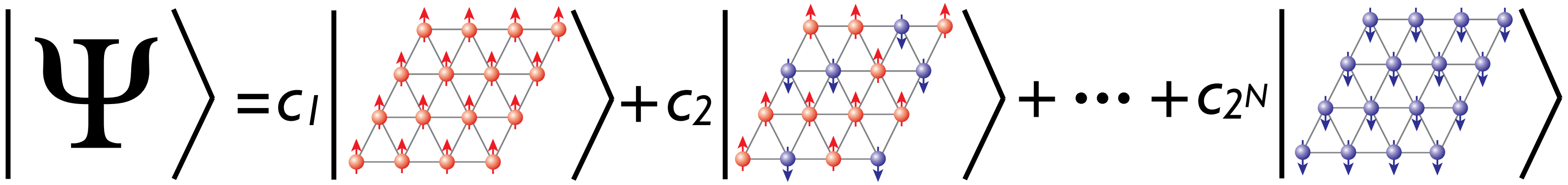
Entanglement in Quantum Simulation

Schrödinger

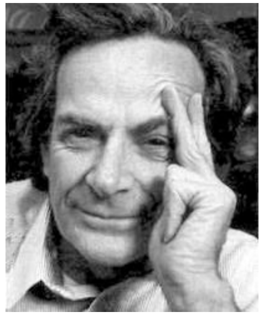
Quantum Many-Body System

The system is in a *superposition* state of all possible configurations …

Entanglement

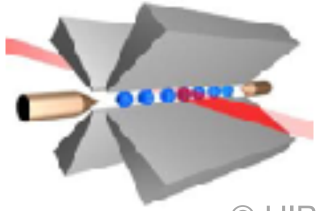


Today we build quantum simulators …



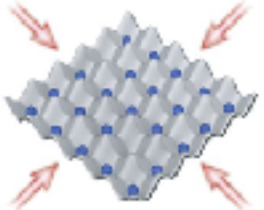
Feynman

Trapped ions



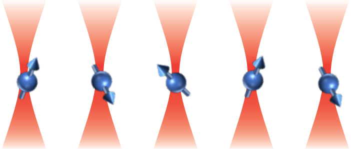
© UIBK, JQI, …

Optical Lattices



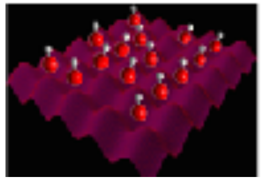
© MPQ, …

Rydberg Arrays



© Harvard, Paris …

Polar Molecules



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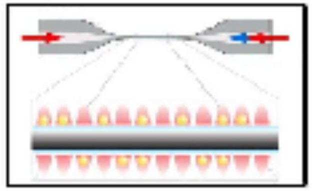
CQED & Photonic



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How to measure / characterize / quantify entanglement in quantum simulation?

Outline of this talk


A Elben


B Vermersch
→ Grenoble


C Kokail


R. van Bijnen


M. Dalmonte
→ ICTP

Programmable Quantum Simulators [Overview]

Overview: atomic platforms, and opportunities etc.

see earlier talks: M. Lukin, …

Randomized Measurement Toolbox

A. Elben, B. Vermersch et al., 2018-…

Example 1: Measuring Renyi Entanglement Entropies

Brydges et al., Science 2019

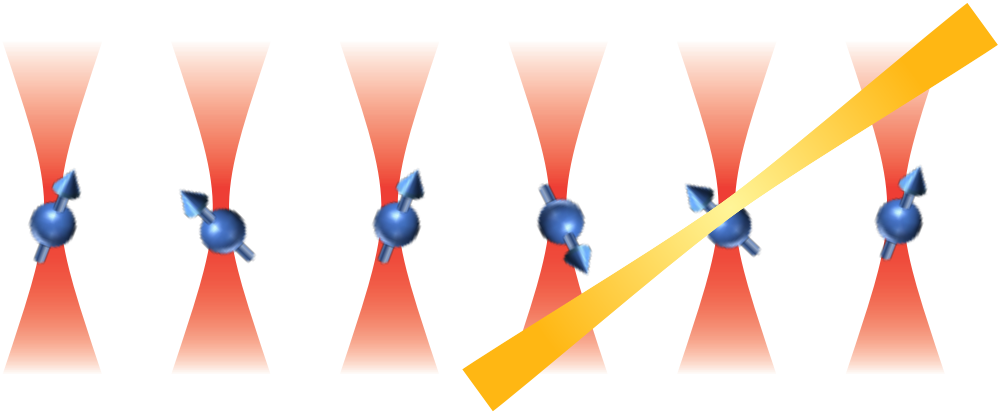
Example 2: Tomography of the Entanglement Hamiltonian

arXiv:2009.09000

development of theoretical framework, and application to experiment

Programmable Analog Quantum Simulators

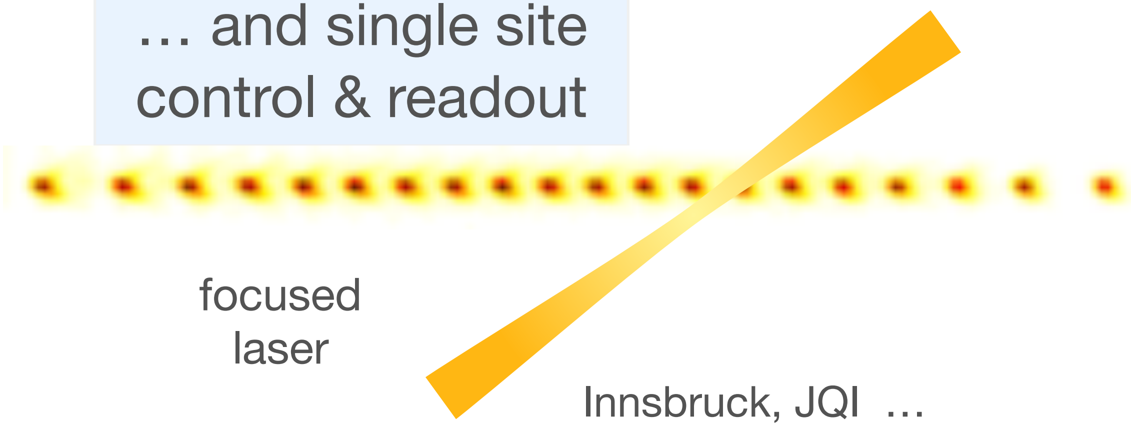
Rydberg Tweezer Arrays [1D,2D,3D]



Harvard - MIT, Palaiseau, JILA, Caltech, Wisconsin, Sandia, …

Trapped-Ions [1D, 2D]

… and single site control & readout



Innsbruck, JQI …

Engineered Spin Models & Hamiltonians

$$\hat{H} = \sum_i \frac{1}{2}\Omega_i \hat{\sigma}_x^i - \sum_i \Delta_i \hat{n}_i + \sum_{i<j} V_{ij}\hat{n}_i\hat{n}_j$$

$V_{ij} = C_6/r_{ij}^6$

spin-spin interaction as Rydberg Van der Waals

$$\hat{H}_{\text{Ising}} = \sum_{i,j} J_{ij}\hat{\sigma}_i^x\hat{\sigma}_j^x + B\sum_i \hat{\sigma}_i^z$$

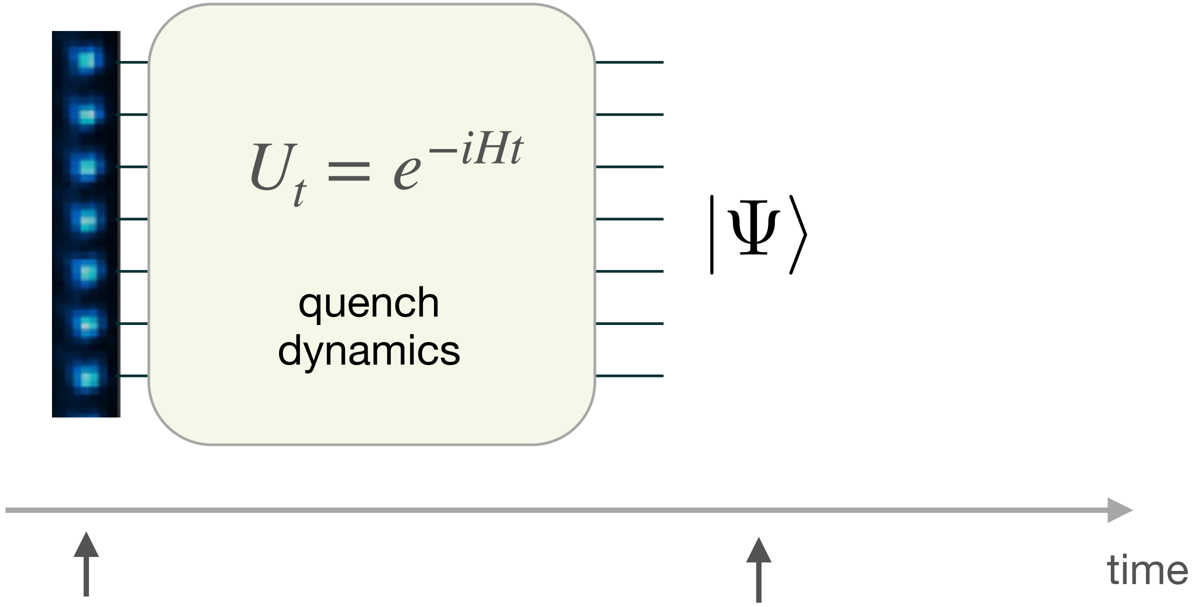
$J_{ij} \sim \frac{1}{|i-j|^\alpha}$ $\alpha = 0\ldots3$ long range

phonon-mediated spin-spin interaction

NISQ devices: few tens of atoms, scaling to ~ few hundred (no error correction)

Analog Quantum Simulators

Experiments done today …



initial product state

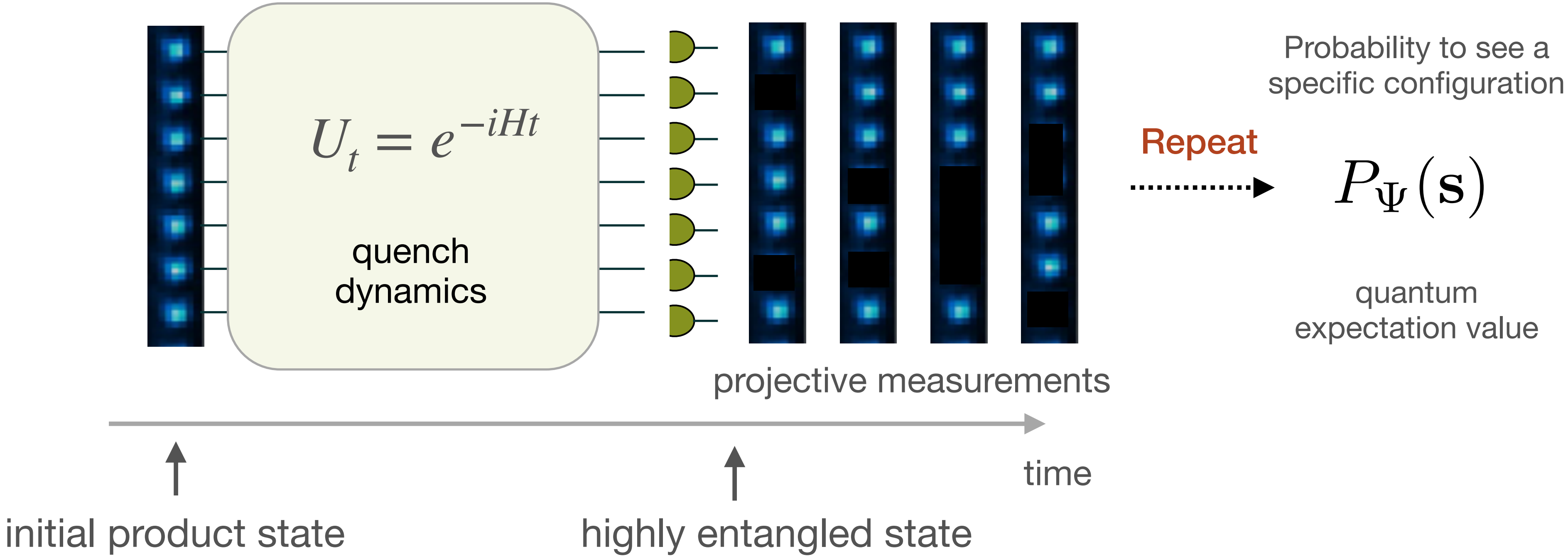
highly entangled state

Learn the entanglement properties of quantum state $|\Psi\rangle$

Entanglement as a resource

Analog Quantum Simulators

Experiments done today …



$U_t = e^{-iHt}$

quench dynamics

projective measurements

time

initial product state

highly entangled state

Repeat

Probability to see a specific configuration

$P_\Psi(\mathbf{s})$

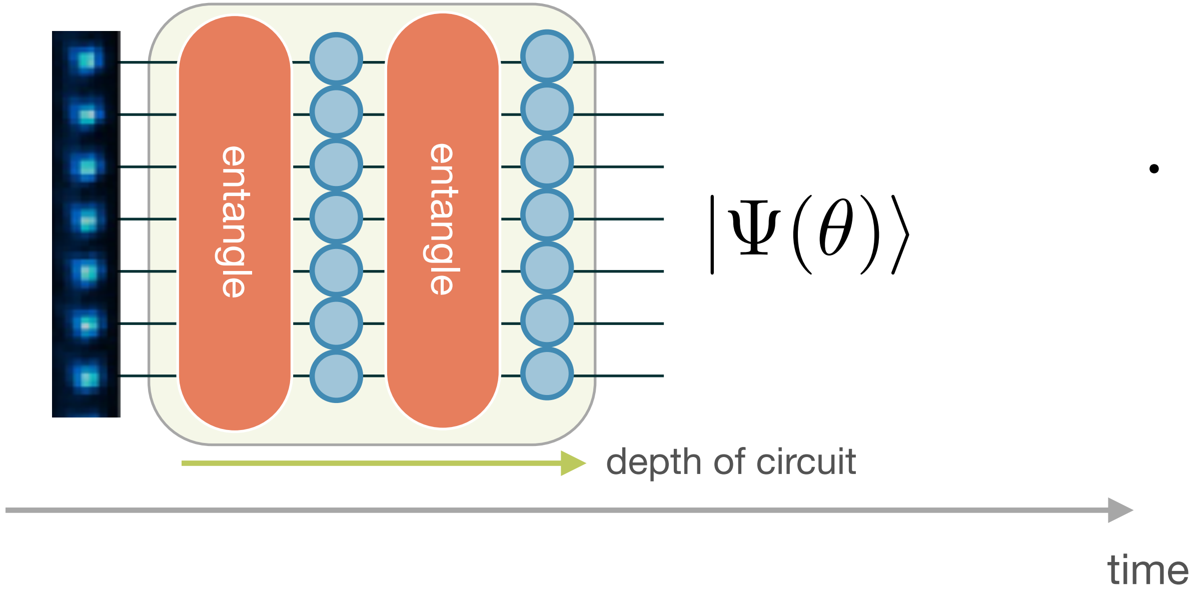
quantum expectation value

Learn the entanglement properties of quantum state $|\Psi\rangle$

Entanglement as a resource

Programming Quantum Simulators

Complex quantum circuits from available resources

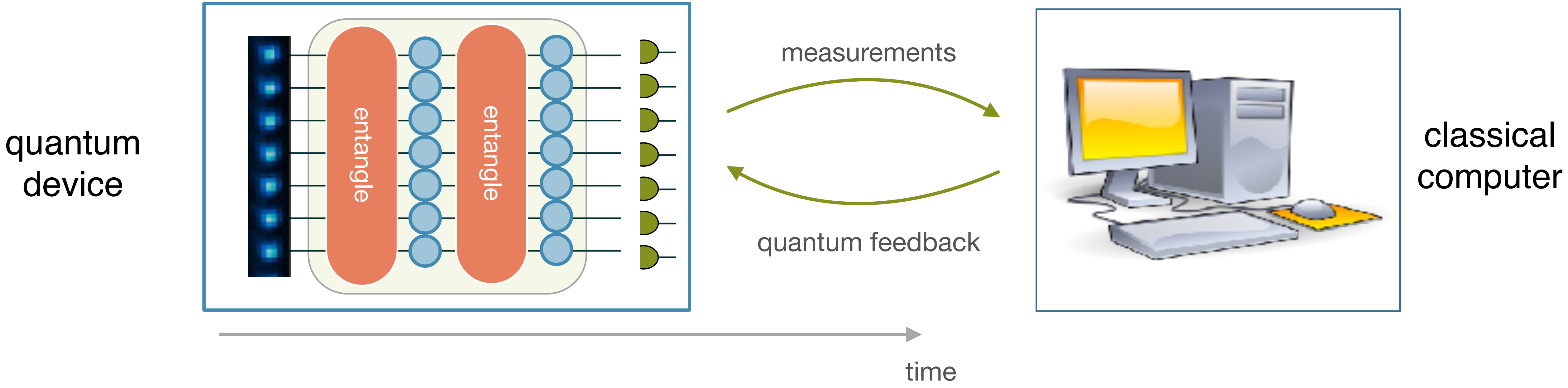


- we can build highly entangled quantum states from available quantum resources parametrized by $\theta_1, \theta_2, \ldots$

Entanglement as a resource

Programming Quantum Simulators

Complex quantum circuits from available resources



Variational Classical-Quantum Algorithms

cost function: $C(\theta) = \dots \quad \rightarrow \min$

optimize on classical machine
\# variational parameters

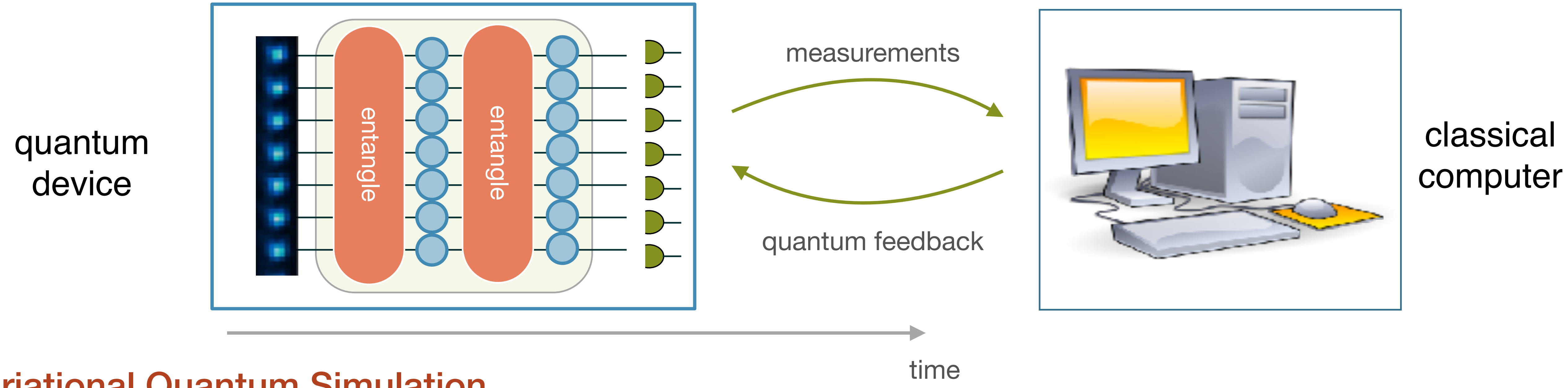
evaluate on quantum machine
… efficiently

Farhi et al., arXiv:1411.4028

McClean et al. *NJP* (2016)

Programming Quantum Simulators

Complex quantum circuits from available resources



quantum device

measurements

quantum feedback

classical computer

time

Variational Quantum Simulation

target Hamiltonian (e.g. lattice model)

$$\hat{H}_T = \sum_{n\alpha} h_n^{\alpha} \hat{\sigma}_n^{\alpha} + \sum_{n\ell\alpha\beta} h_{n\ell}^{\alpha\beta} \hat{\sigma}_n^{\alpha} \hat{\sigma}_\ell^{\beta} + \dots$$

Variational Quantum Eigensolver

$$C(\theta) = \langle \psi(\theta) | \hat{H}_T | \psi(\theta) \rangle \rightarrow \text{min}$$

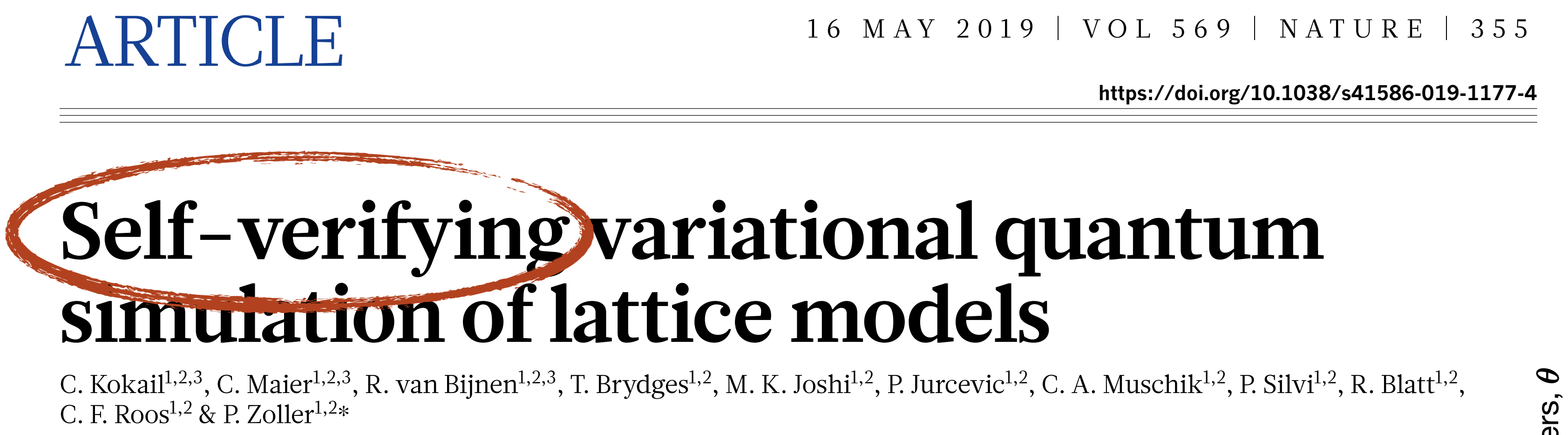
lowest energy
~ ground state

cost function with
variational parameters θ

Hamiltonian never
physically realized

on quantum computer / chemistry:
JR McClean *et al*, NJP 2016

Classical - Quantum Feedback Loop



ARTICLE

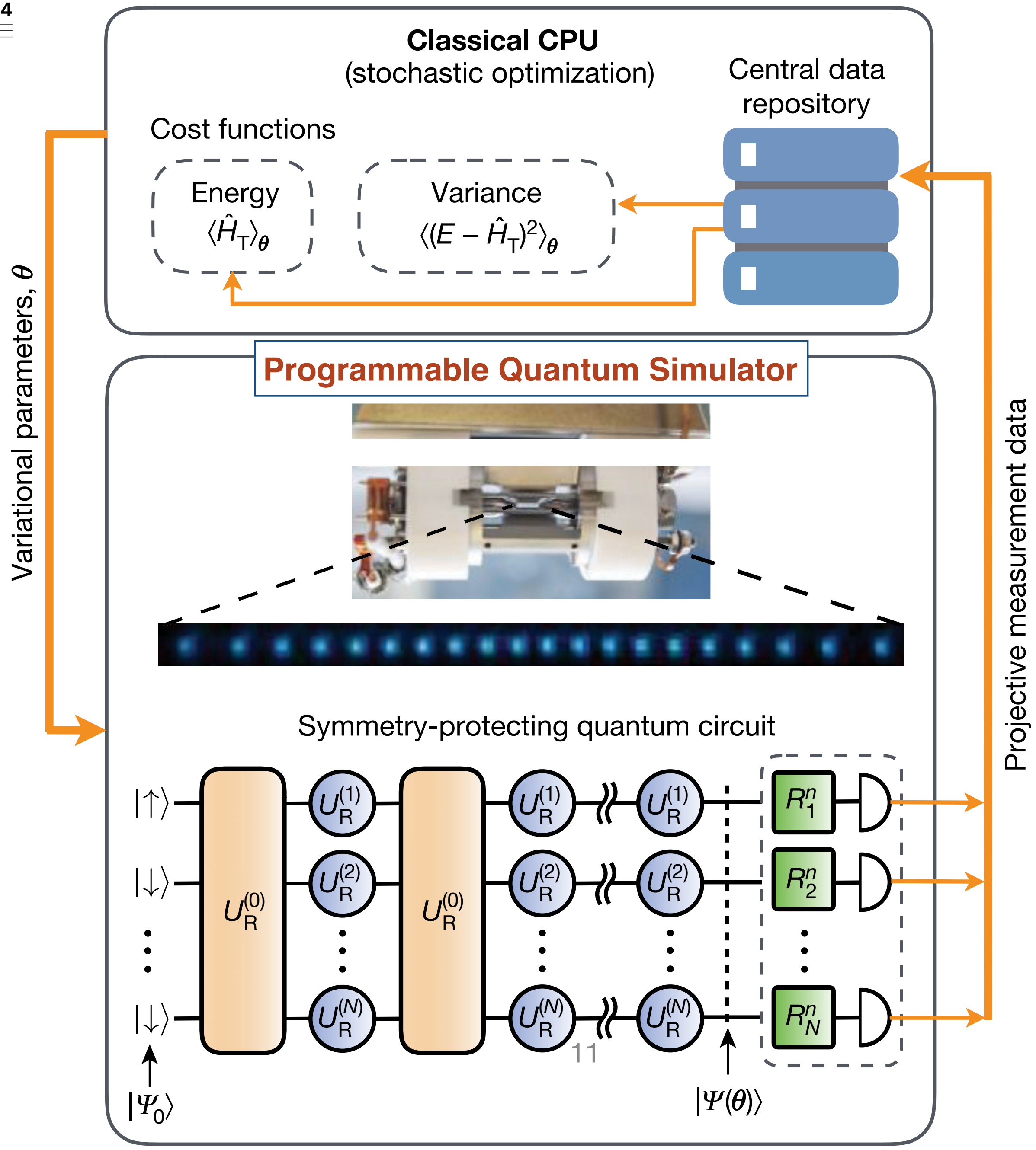
16 MAY 2019 | VOL 569 | NATURE | 355

https://doi.org/10.1038/s41586-019-1177-4

Self-verifying variational quantum simulation of lattice models

C. Kokail[1,2,3], C. Maier[1,2,3], R. van Bijnen[1,2,3], T. Brydges[1,2], M. K. Joshi[1,2], P. Jurcevic[1,2], C. A. Muschik[1,2], P. Silvi[1,2], R. Blatt[1,2], C. F. Roos[1,2] & P. Zoller[1,2]*

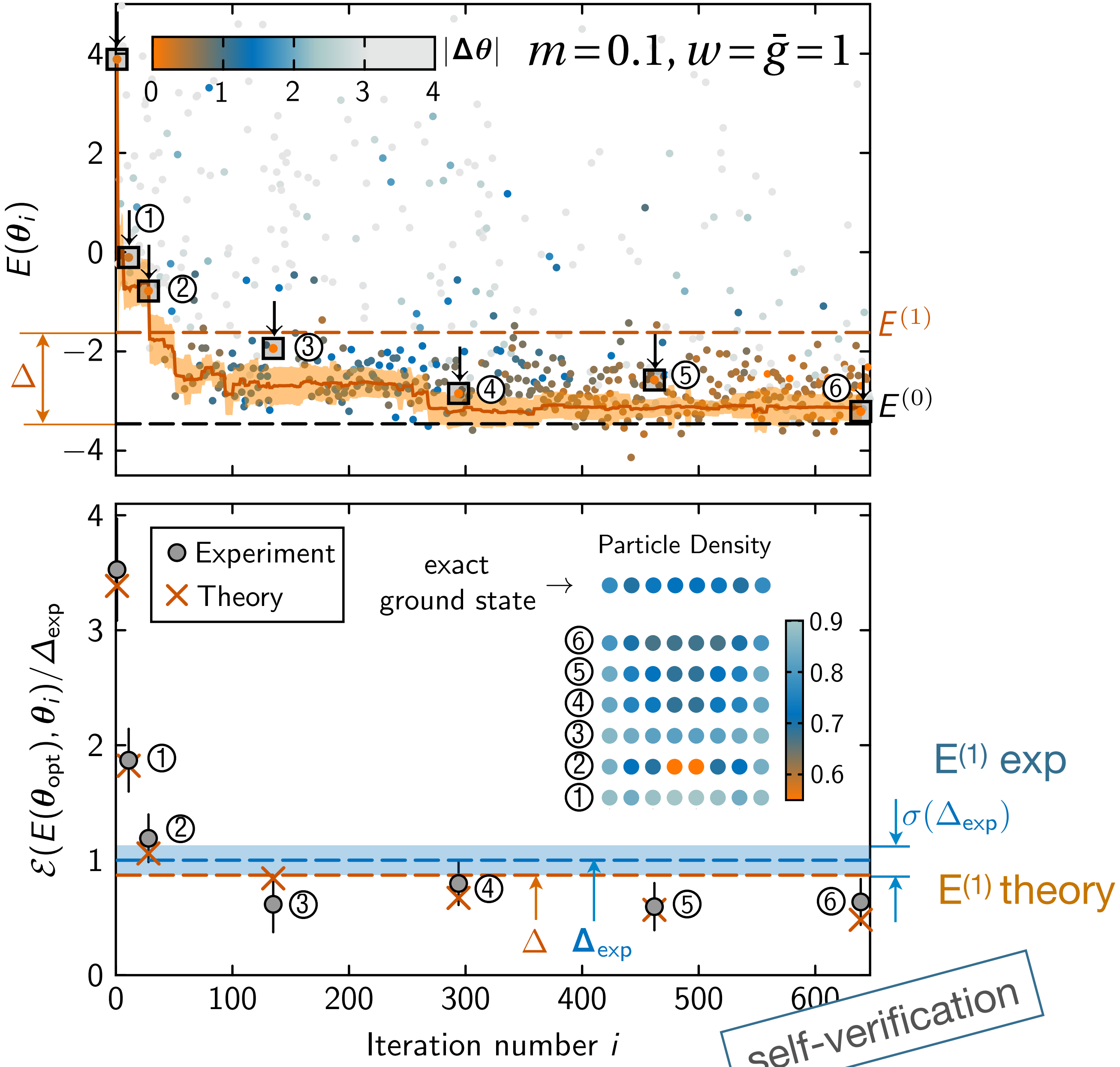
Rick van Bijnen (th-postdoc), Christine Maier (exp-PhD), Christian Kokail (th-PhD)



20 (now: 50) qubits, 10^5 call of PQS, circuit depth 6

Optimization Trajectory for Schwinger Ground State

up to 20 ions, 15 parameters, circuit depth = 6, budget: 10^5 calls to quantum simulator



self-verification

- optimal energy

$$\boxed{E_{\boldsymbol{\theta}}^{(0)} = \langle \Psi_{\boldsymbol{\theta}} \mid \hat{H}_T \mid \Psi_{\boldsymbol{\theta}} \rangle \rightarrow \min}$$

- *measure* the error bar as energy variance

$$\boxed{\left(\Delta E_{\boldsymbol{\theta}}^{(0)}\right)^2 = \langle \Psi_{\boldsymbol{\theta}} \mid \left(E_{\boldsymbol{\theta}}^{(0)} - \hat{H}_T\right)^2 \mid \Psi_{\boldsymbol{\theta}} \rangle \geq 0}$$

=0 for eigenstate


A Elben


B Vermersch
→ Grenoble

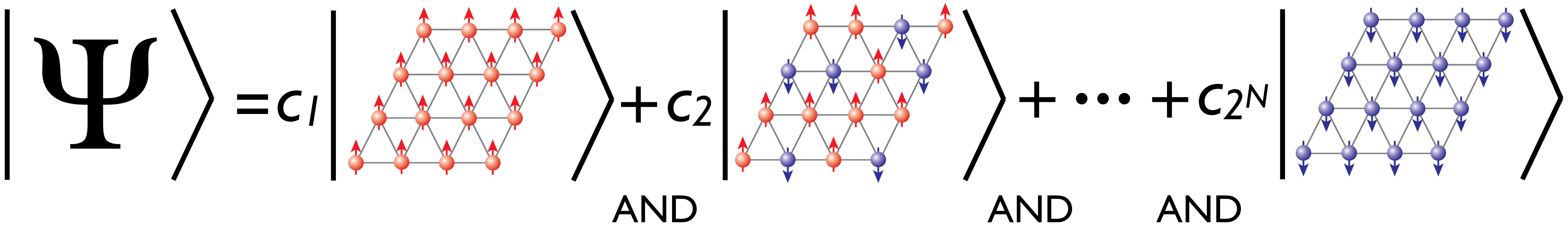

C Kokail


R. van Bijnen


M. Dalmonte
→ ICTP

New Many-Body Physics

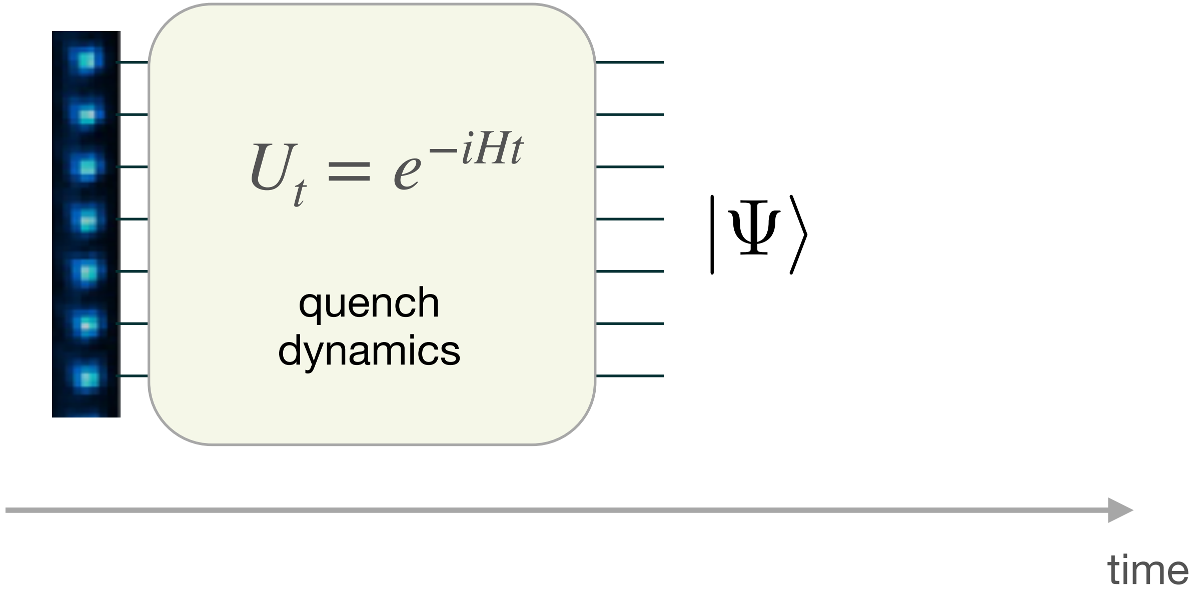
- Measuring / quantifying entanglement



… enabled by *programmable* q-simulators & classical postprocessing

Progammable Analog Quantum Simulator

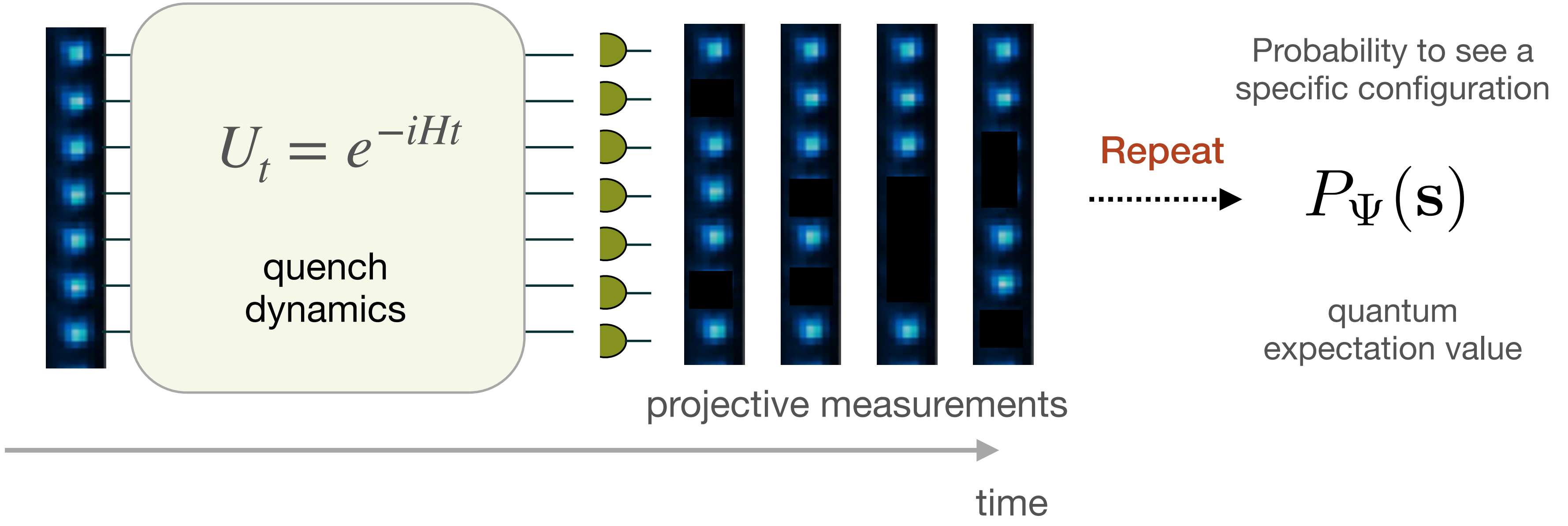
Experiments done today …



Learn the entanglement properties of quantum state $|\Psi\rangle$?

Progammable Analog Quantum Simulator

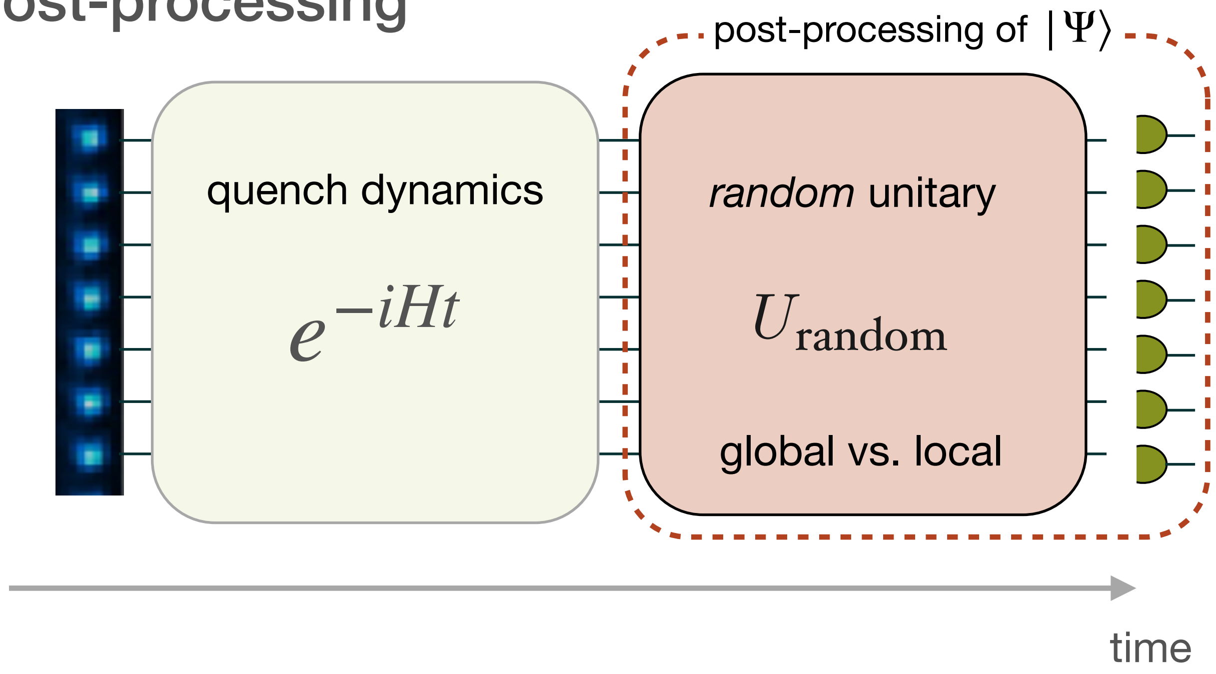
Experiments done today …



Learn the entanglement properties of quantum state $|\Psi\rangle$?

Randomized Measurements

Measurement post-processing



Repeat

Probability to see a specific configuration

$$P_{\Psi,U}(\mathbf{s})$$

is a random variable depending on U

(Cross-) Correlation of probabilities

‘Noise’ or ensemble average (e.g. CUE)

$$\overline{P_{\Psi,U}(\mathbf{s}_1)P_{\Psi,U}(\mathbf{s}_2)}$$

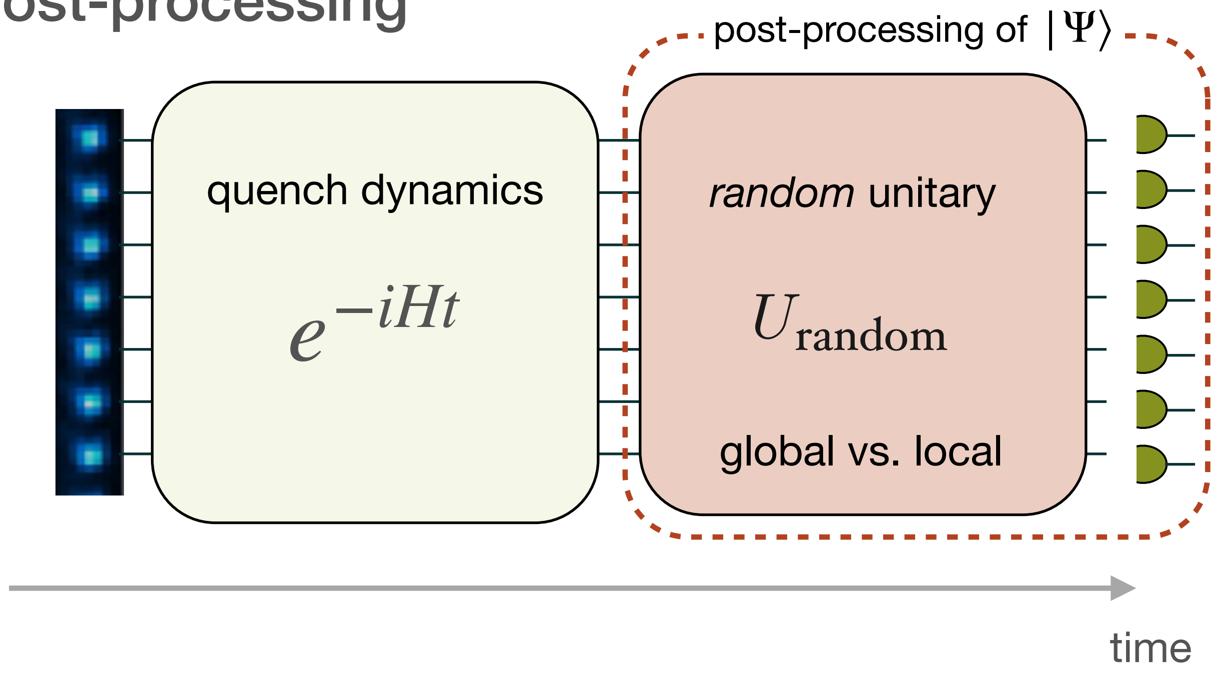
experiment `day 1, lab 1’

experiment `day 2 lab 2’

… hybrid classical-quantum protocols

Randomized Measurements

Measurement post-processing



Repeat

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$$P_{\Psi,U}(\mathbf{s})$$

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depending on U

(Cross-) Correlation of probabilities

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Renyi entropies and entanglement

A Elben et al. PRL, PRA 2018, PRA 2019
Brydges et al., Science 2019

Cross-platform verification

A Elben et al., PRL 2020

Scrambling (OTOCs)

B Vermersch, et al., PRX 2019
M. Joshi et al, PRL 2020

Renyi Negativities

A Elben, R Kueng, HY Huang, R van Bijnen, C Kokail, M Dalmonte, P Calabrese, B Kraus, J Preskill, PZ, B Vermersch, arXiv:2007.06305

Entanglement Properties of Quantum State

Quantum system in a pure state

$$|\Psi\rangle = \sum_{\mu_A,\mu_B} c_{\mu_A,\mu_B} |\mu_A\rangle \otimes |\mu_B\rangle$$

Schmidt decomposition

$$|\Psi\rangle = \sum_{\alpha=1}^{\chi_A} \lambda_\alpha |\Phi_\alpha^A\rangle \otimes |\Phi_\alpha^B\rangle$$

Schmidt values

$\chi_A = 1$ product state

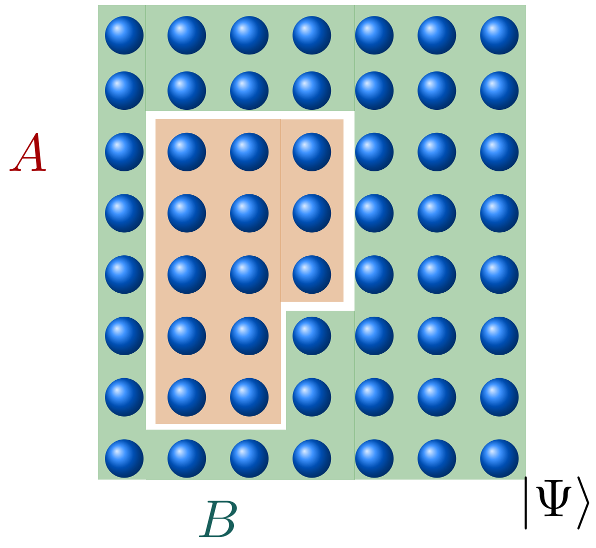
$\chi_A > 1$ entangled state

Reduced density matrix

$$\rho_A = \mathrm{Tr}_B \left[|\Psi\rangle\langle\Psi| \right] \equiv \sum_{\alpha=1}^{\chi_A} \lambda_\alpha^2 |\Phi_\alpha^A\rangle\langle\Phi_\alpha^A|$$

density matrix of rank χ_A

bipartition A:B



L. Amico, R. Fazio, A. Osterloh, and V. Vedral, RMP (2008)   V. Eisler & I. Peschel, J Phys A (2017).
B. Zeng et al., Quantum information meets quantum matter (Springer, 2019).

… what should we measure?

Entanglement Properties of Quantum State

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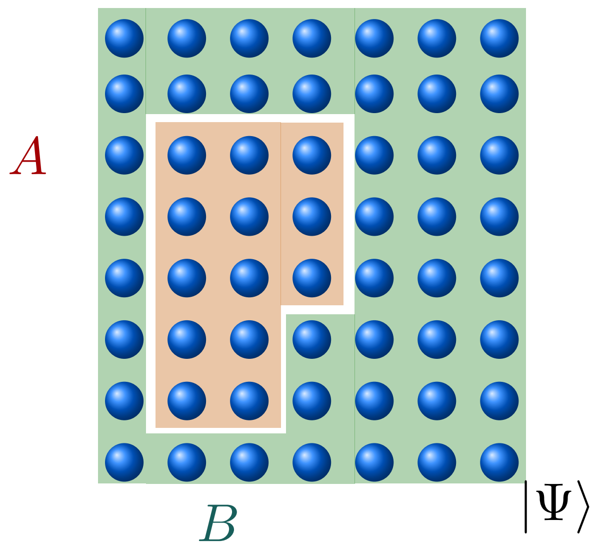


Interpretation as a Thermal State

$$\rho_A = e^{-\tilde{H}_A} = \sum_{\alpha=1}^{\chi_A} e^{-\xi_\alpha} |\Phi_\alpha^A\rangle\langle\Phi_\alpha^A|$$

λ_α^2

with the Entanglement Hamiltonian $\tilde{H}_A$

… what should we measure?

Entanglement Properties of Quantum State

Entanglement entropies

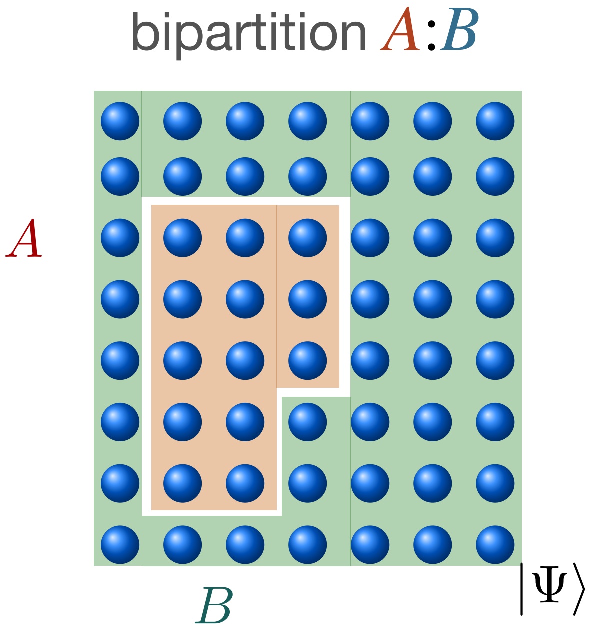
$$S_A^{(n)} = -\frac{1}{n-1}\log \mathrm{Tr}_A \rho_A^n$$ Renyi

for $n = 2$: purity $\mathrm{Tr}_A \rho_A^2$

$$S_A^{\mathrm{VN}} = -\mathrm{Tr}_A\left(\rho_A \log \rho_A\right)$$ Von Neumann

purity of ρ_A

$S_A = 0$ product vs. $S_A > 0$ entangled state, or $\mathrm{Tr}_A \rho_A^2 < 1$



Entanglement spectrum

$$\rho_A = e^{-\tilde{H}_A} = \sum_{\alpha=1}^{\chi_A} e^{-\xi_\alpha}|\Phi_\alpha^A\rangle\langle\Phi_\alpha^A|$$

Rem.: tomography $\sim \chi_A 2^{N_A}$

tomography of EH

entanglement spectrum

… what & how measure?

… with what resources?

Entanglement Properties of Quantum State

increasing complexity / information

Entanglement entropies

$$S_A^{(n)} = -\frac{1}{n-1}\log \mathrm{Tr}_A \rho_A^n$$

Renyi

for $n = 2$: purity $\mathrm{Tr}_A \rho_A^2$

purity of ρ_A

$$S_A^{\mathrm{VN}} = -\mathrm{Tr}_A\left(\rho_A \log \rho_A\right)$$

Von Neumann

$S_A = 0$ product vs. $S_A > 0$ entangled state, or $\mathrm{Tr}_A \rho_A^2 < 1$

Entanglement spectrum and Hamiltonian

$$\rho_A = e^{-\tilde{H}_A} = \sum_{\alpha=1}^{\chi_A} e^{-\xi_\alpha} |\Phi_\alpha^A\rangle\langle\Phi_\alpha^A|$$

Rem.: tomography $\sim \chi_A 2^{N_A}$

tomography of EH

entanglement spectrum

Why measure entanglement spectrum?

- Entanglement measures
- detection of topological phases
- detection of quantum phase transitions
- extremely hard to obtain numerically

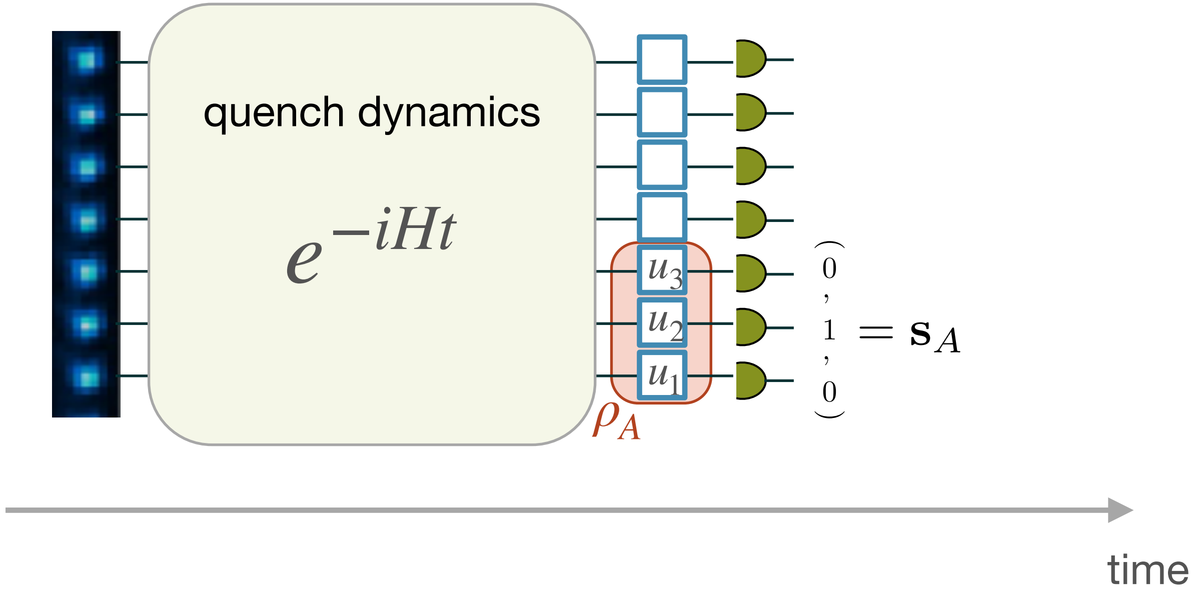
N. Regnault, arXiv:1510.07670 (Les Houches Lectures)

… protocol to measure?

… with what resources?

Randomized Measurements for second order Renyi entropy

Measurement post-processing



$$P_U(\mathbf{s}_A) = \mathrm{Tr}\left[U_A \rho_A U_A^\dagger \left|\mathbf{s}_A\right\rangle \left\langle \mathbf{s}_A\right|\right]$$

$$\boxed{U_A = \bigotimes u_i} \quad u_i \in \mathrm{CUE}(d)$$

Random single spin rotations are sufficient

purity $\boxed{\mathrm{Tr}_A \rho_A^2 = \overline{X_U}}$ with

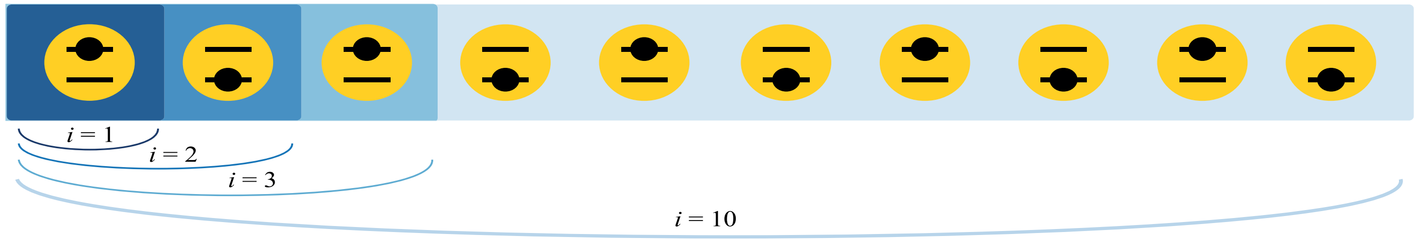
Hamming distance

$$X_U = 2^{N_A} \sum_{s_A, s'_A} (-2)^{-D[s_A, s'_A]} \underbrace{P_U(s_A) P_U(s'_A)}_{\text{Cross correlation between configurations}}$$

random variable

A. Elben et al. PRA (2019). T Brydges et al., Science (2019)

Quench dynamics with long-range XY-Model

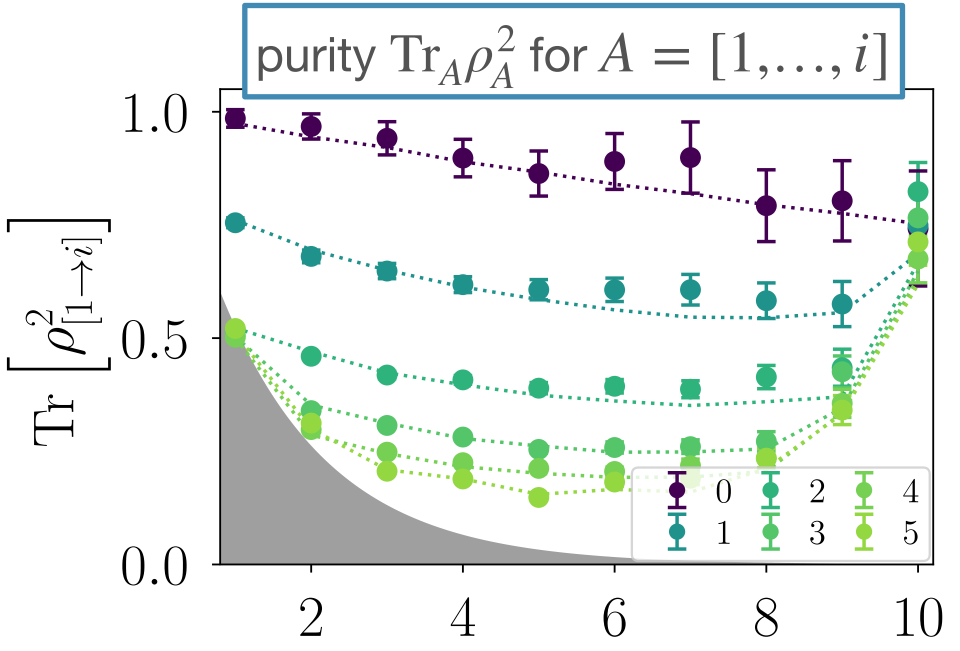


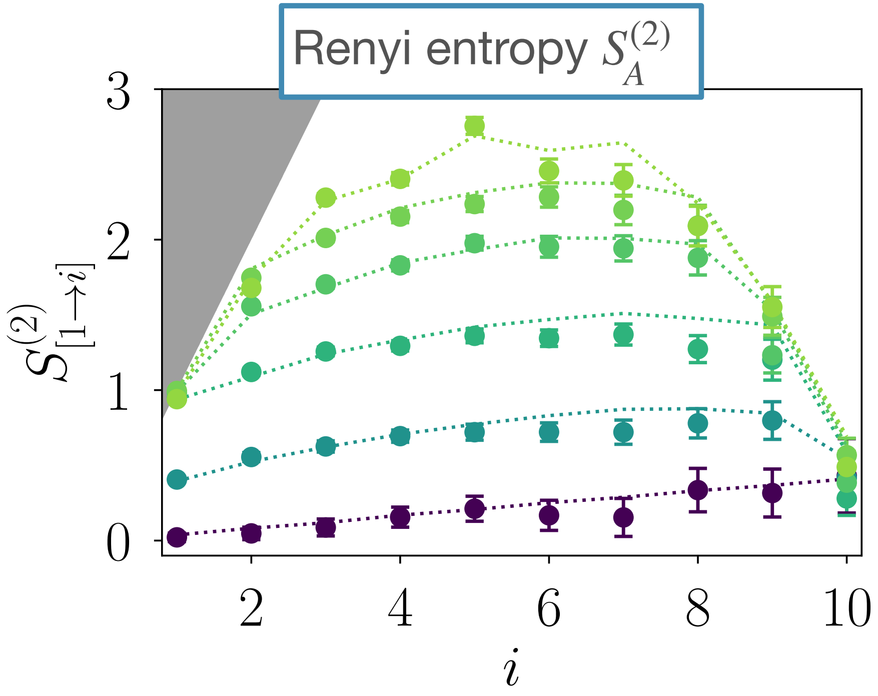
10 - 20 ion quantum simulator:

$$H = \sum_{i<j} \left(J_{ij}\sigma_i^+\sigma_j^- + \text{ h.c.} \right) + B\sum_i \sigma_i^z$$

Global quench with $B \gg \max\{J_{ij}\}$

$$|\psi(t)\rangle = e^{-iHt}\,|\psi_0\rangle \quad \text{with} \quad |\psi_0\rangle = |\uparrow\downarrow\rangle^{\otimes \frac{N}{2}}$$

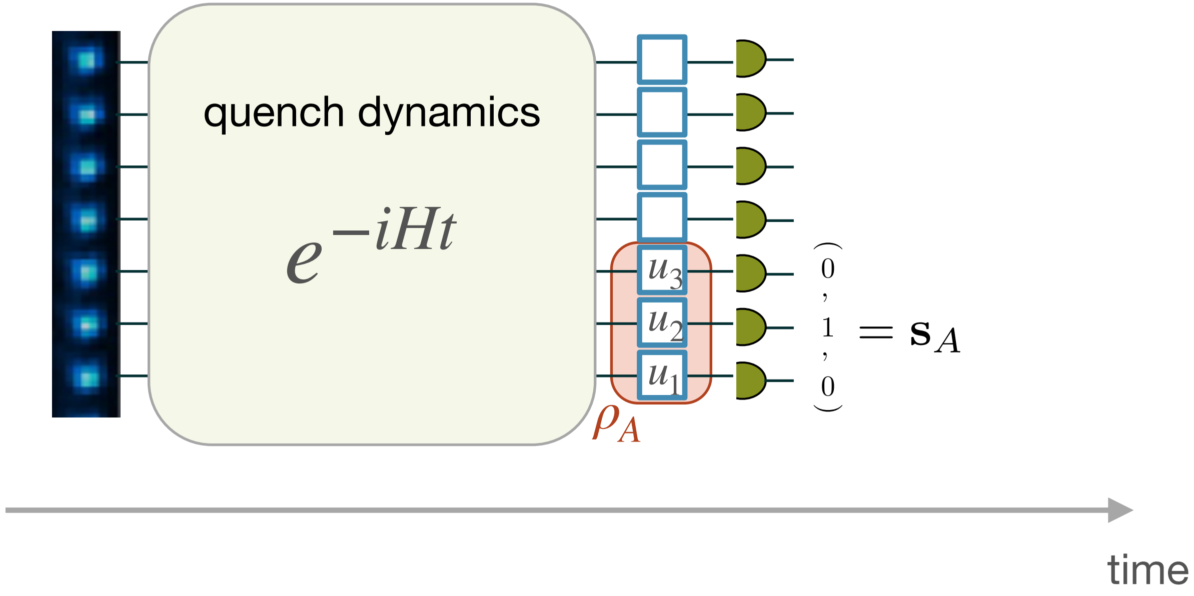

purity $\mathrm{Tr}_A \rho_A^2$ for $A = [1,\ldots,i]$


Renyi entropy $S_A^{(2)}$

T Brydges, A Elben et al., Science 2019

Randomized Measurements

Measurement post-processing



$$P_U(\mathbf{s}_A) =$$
$$\mathrm{Tr}\left[U_A \rho_A U_A^\dagger \left|\mathbf{s}_A\right\rangle \left\langle \mathbf{s}_A\right|\right]$$

$U_A = \bigotimes u_i$ $\quad u_i \in \mathrm{CUE}(d)$

Randomized Tomography

A. Elben et al., PRA (2019) (see also Eisert et al.)

Predicting Many Properties of a Quantum System from Very Few Measurements
HY Huang, R Kueng, J Preskill, Nat. Phys. (2020)

Tomography review: A Acharya et al., J Phys A (2019).

$$\rho_A^{RT} = \sum_{\mathbf{s_A},\mathbf{s_A}'} \sum_{U_A} P_U(\mathbf{s}_A)(-2)^{-D[\mathbf{s}_A,\mathbf{s}_A']} U_A \,|\, \mathbf{s}_A' \rangle\langle \mathbf{s}_A' \,|\, U_A^\dagger$$

How many random unitaries N_U and measurements N_M?

Scaling with subsystem size $|A|$

C Kokail

R. van Bijnen

A. Elben

B. Vermersch
→ Grenoble

Entanglement Hamiltonian Tomography

$$\rho_A = e^{-\tilde{H}_A} = \sum_{\alpha=1}^{\chi_A} e^{-\xi_\alpha} |\Phi_\alpha^A\rangle\langle\Phi_\alpha^A|$$

entanglement Hamiltonian

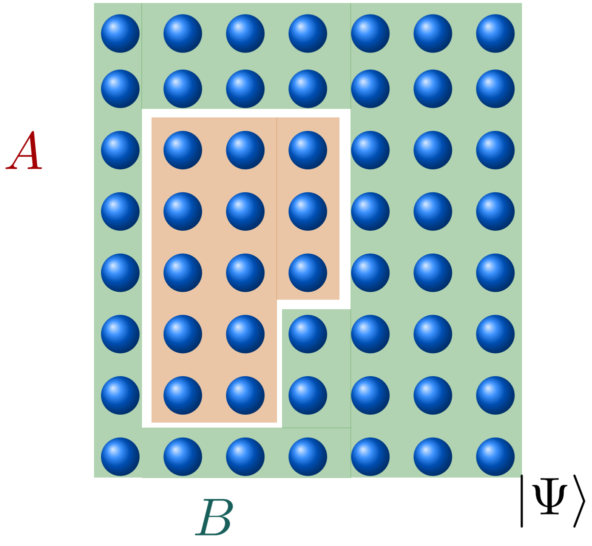
entanglement spectrum

Remarks:

- tomography exponentially expensive with size of A, $\sim \chi_A 2^{N_A}$
- efficient if we know something about the quantum state (MPS, low rank, …)

review: A Acharya et al. J Phys A (2019).

bipartition A:B



arXiv:2009.09000

Challenge: *efficient* tomography of $\tilde{H}_A$

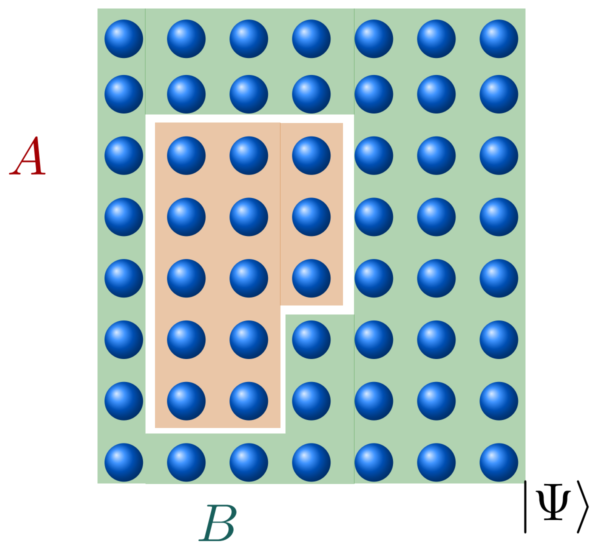
what is the operator structure of $\tilde{H}_A$? … *in quantum simulation*

Basic idea: We make an *ansatz* for $\tilde{H}_A$ with *quasi-local few-body terms*, which we fit to data, and verify with few measurements

On the quasi-local ansatz for the Entanglement Hamiltonian

Hamiltonians H of physical systems: as sum of quasi-local few-body terms

bipartition A:B



Example:

$$H = \sum_{i<j} \left(J_{ij} \sigma_i^+ \sigma_j^- + \text{ h.c.} \right) + B \sum_i \sigma_i^z$$

with $J_{ij} = \dfrac{J_0}{|i-j|^\eta}$ for $B \gg |J_{ij}|$

few parameters

Structure of Entanglement Hamiltonian $\tilde{H}_A$: quasi-local few-body terms?

example: thermal state from quench

$$\text{Tr}_B |\Psi_t\rangle\langle\Psi_t| \longrightarrow \rho_A \sim e^{-\beta H_A}$$

system Hamiltonian on A

Bisognano-Wichmann theorem (QFT)

- for ground states

Conformal Field Theory

- in quench dynamics, ground states

heuristic approach:
test & verify

Suggests ansatz for $\tilde{H}_A$ as deformation of system Hamiltonian $H_A \equiv H|_A$ + corrections (new physics?)

On the quasi-local ansatz for the Entanglement Hamiltonian

Hamiltonians H of physical systems: as sum of quasi-local few-body terms

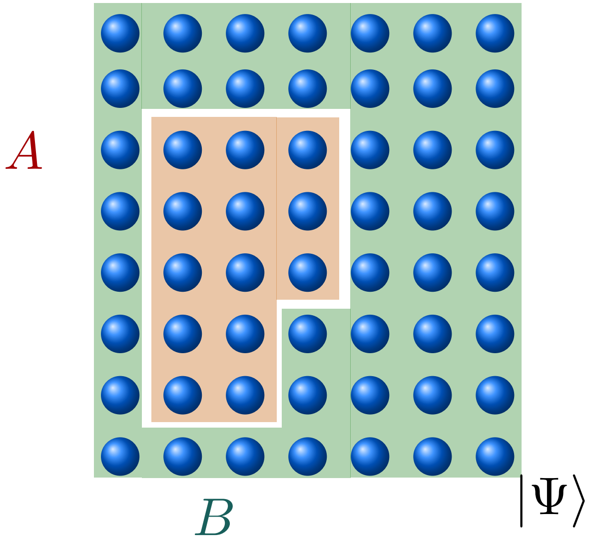
Example:

$$H = \sum_{i<j} \left(J_{ij}\sigma_i^+\sigma_j^- + \text{ h.c.} \right) + B \sum_i \sigma_i^z$$

few parameters

with $J_{ij} = \frac{J_0}{|i-j|^\eta}$ for $B \gg [J_{ij}]$

bipartition A:B



Structure of Entanglement Hamiltonian $\tilde{H}_A$: quasi-local few-body terms?

Ansatz:

$$\tilde{H}_A(\tilde{\boldsymbol{J}}, \tilde{\boldsymbol{B}}) = \sum_{ij} \left(\tilde{J}_{ij}\sigma_i^+\sigma_j^- + \text{ h.c.} \right) + \sum_i \tilde{B}_i\sigma_i^z + \sum_{ij} \tilde{B}_{ij}\sigma_i^z\sigma_j^z + \sum_{ijk} \left(\tilde{J}_{ijk}\sigma_i^+\sigma_j^-\sigma_k^z + \text{h.c.} \right)$$

few variational parameters

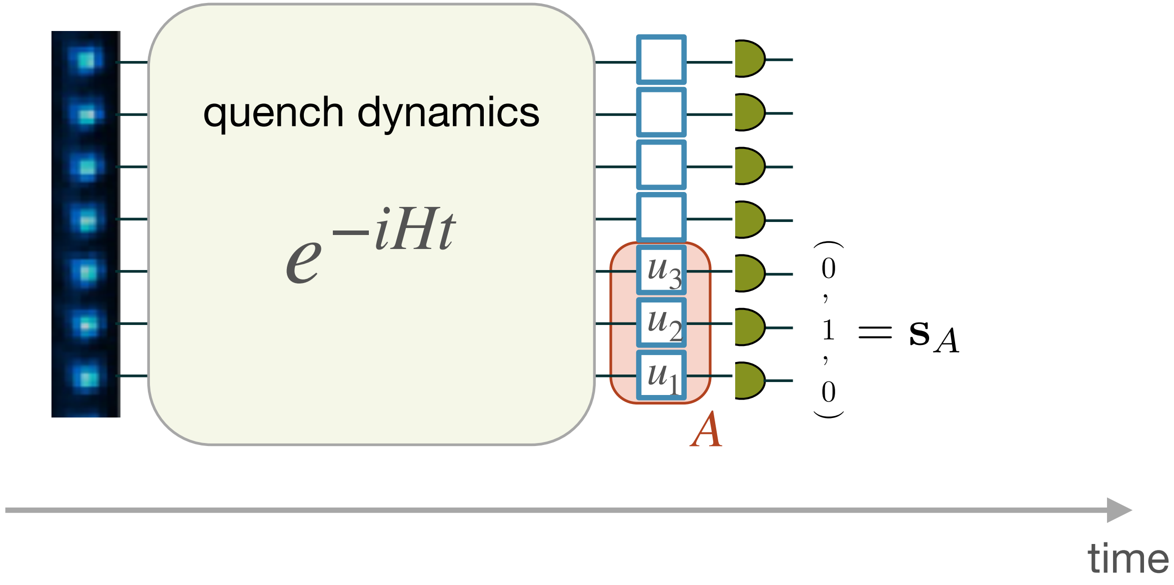
deformed system Hamiltonian (base level)

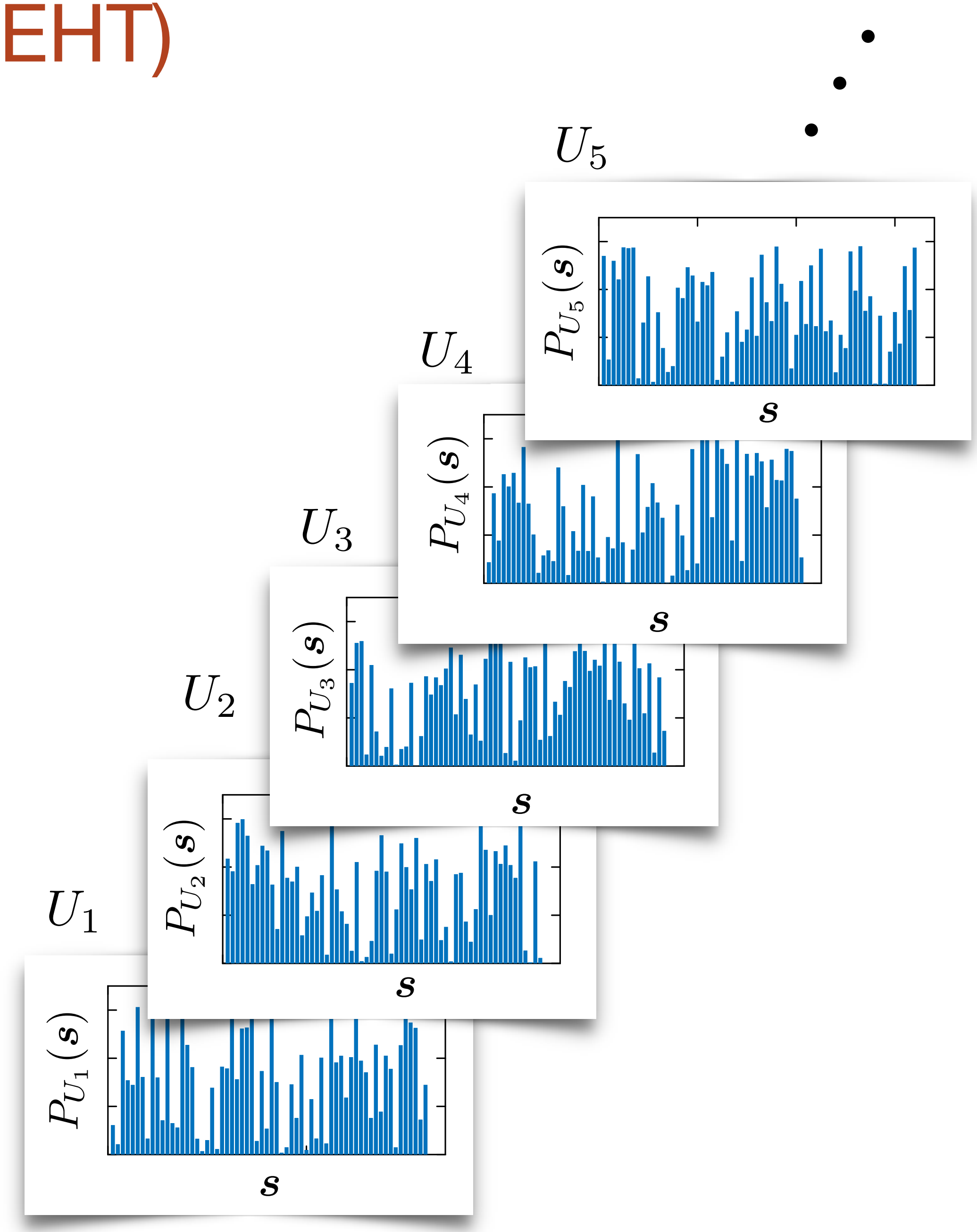
corrections (level 1)

Suggests $\tilde{H}_A$ as deformation of system Hamiltonian $H_A \equiv H|_A$ + corrections (new physics?)

Entanglement Hamiltonian Tomography (EHT)

Here: from randomized local unitaries





Protocol:

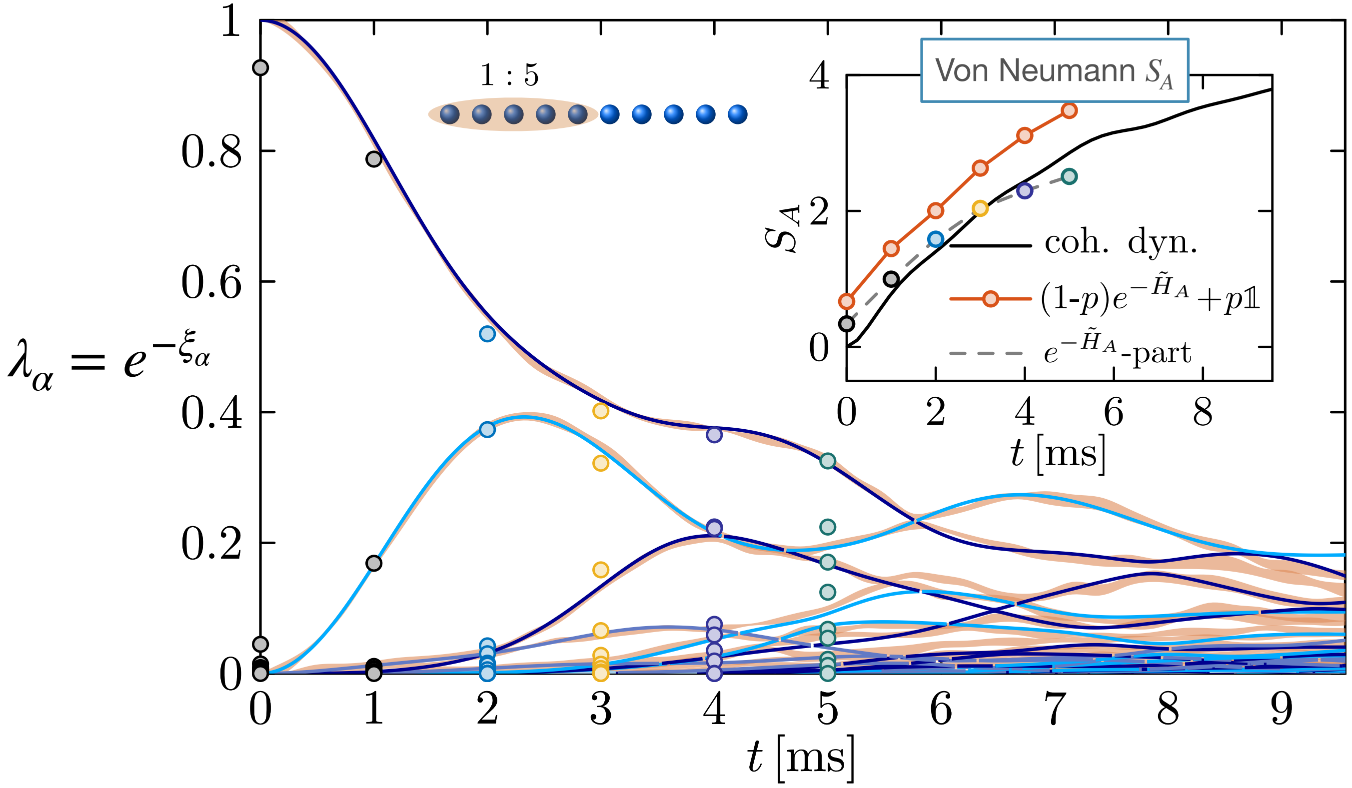
- Ansatz for $\tilde{H}_A(\tilde{\boldsymbol{g}})$, which is physically motivated
- Best fit to experimental observations: $\tilde{\boldsymbol{g}}$

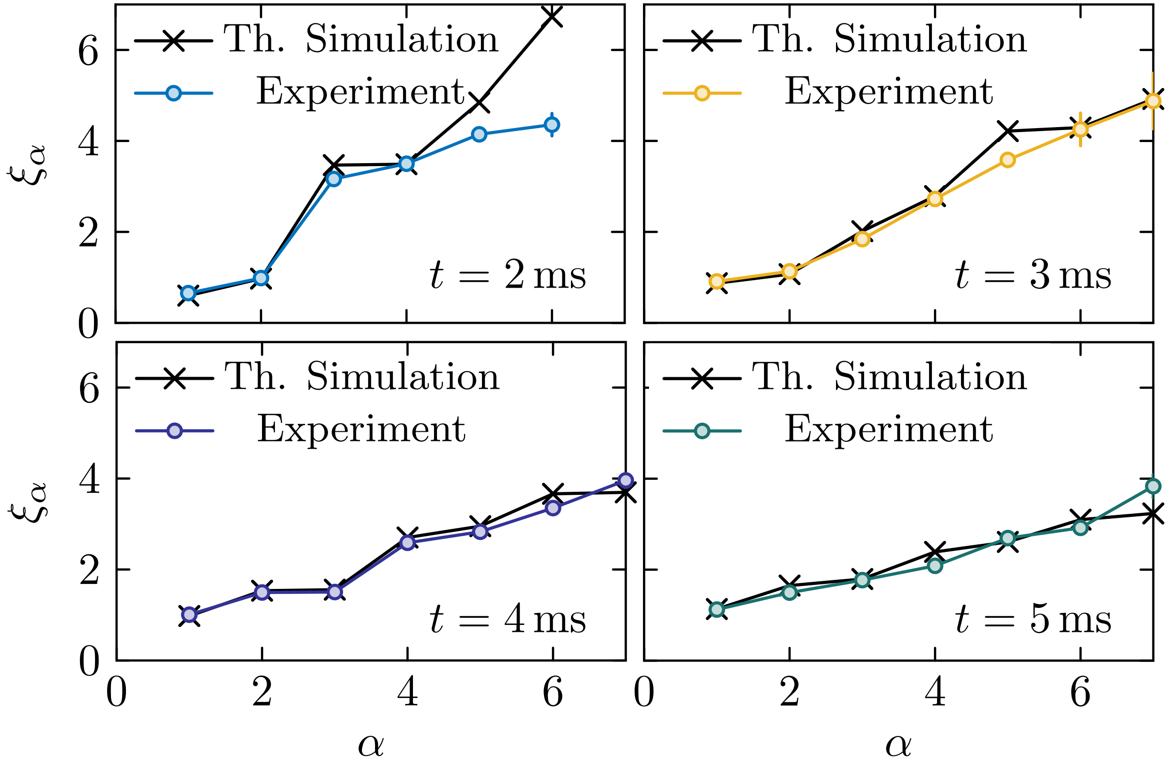
$$\chi^2(\tilde{\boldsymbol{g}}) = \sum_{U,s} \left[\mathrm{Tr}\left(U\,|\,s\rangle\langle s\,|\,U^\dagger \frac{\exp\left(-\tilde{H}_A(\tilde{\boldsymbol{g}})\right)}{Z(\tilde{\boldsymbol{g}})} \right) - P_U(s) \right]^2$$

Experiment: EH-Fit for a quench with 10 ions (sub-system 1:5)

C Kokail

Seeing Schmidt decomposition *live*: $|\Psi\rangle = \sum_{\alpha=1}^{\chi_A} \lambda_\alpha |\Phi_\alpha^A\rangle \otimes |\Phi_\alpha^B\rangle$ from data published in Brydges et al., Science 2019





Ansatz for the reduced density matrix with p decoherence parameter

$$\rho_A(\tilde{\boldsymbol{g}}) = (1-p)e^{-\tilde{H}_A(\tilde{\boldsymbol{g}})} + p\frac{\mathbb{1}}{\mathcal{D}_A}$$

$\eta \simeq 1.2$

$N_U = 500 \quad N_M = 150$

… and similar results for 20 ions and (sub-system 8:14)

Testing the Ansatz via Fidelity Estimation

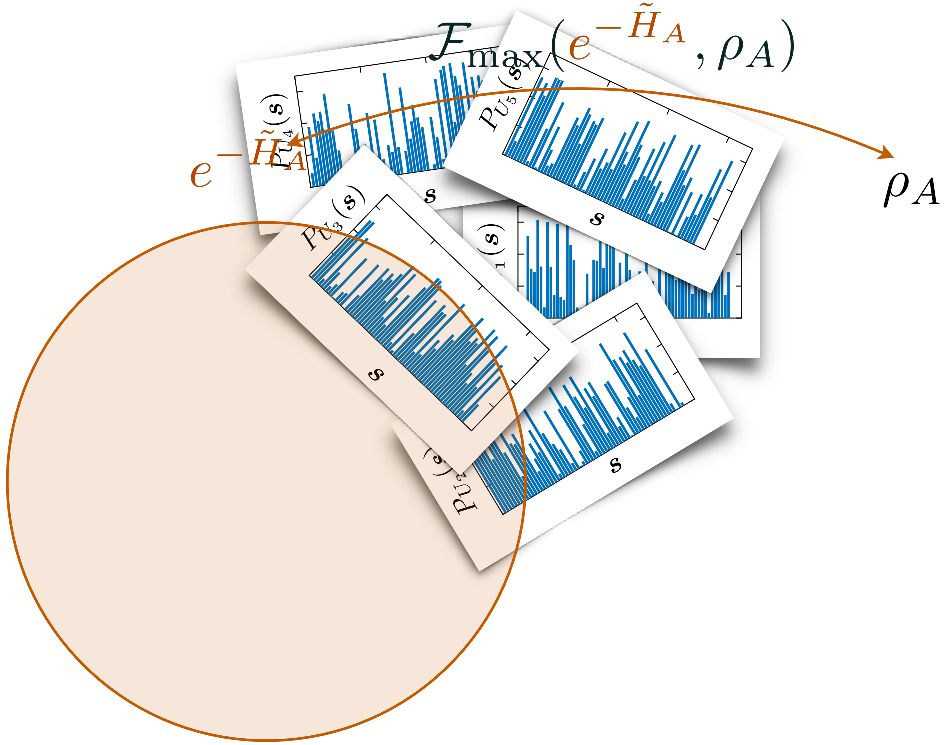

C Kokail

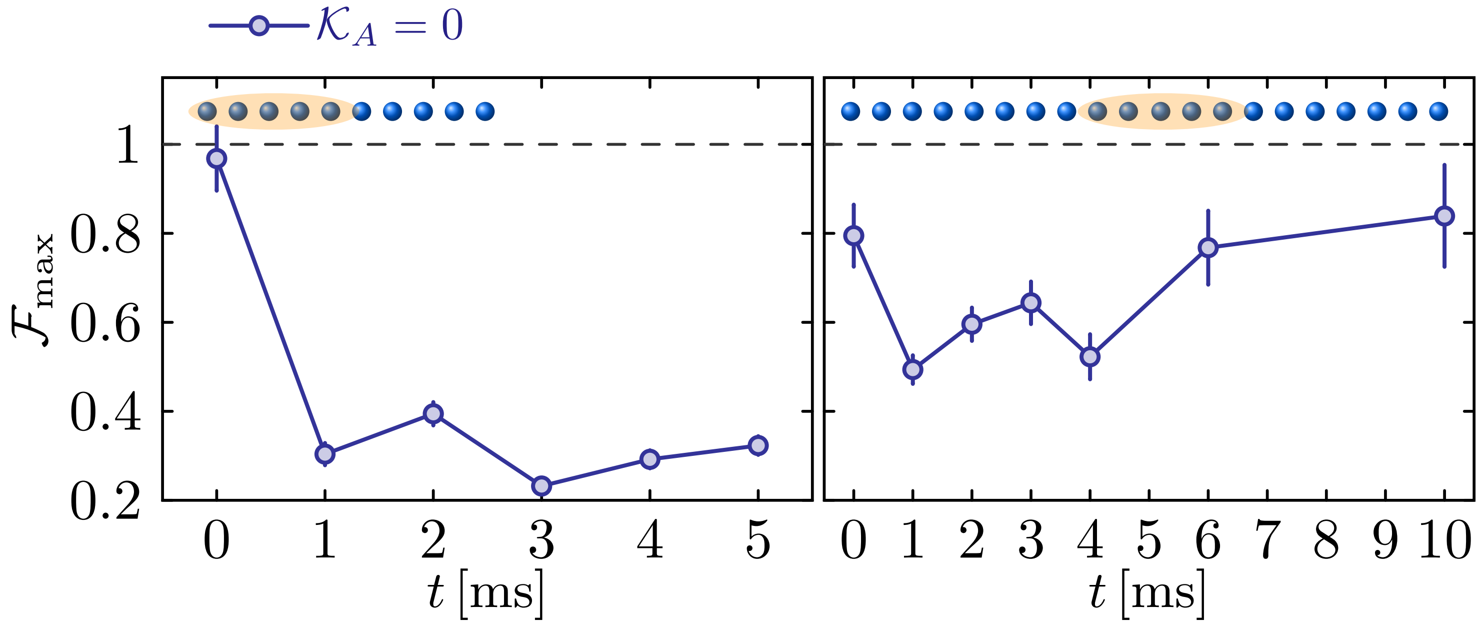
$$\mathcal{F}_{\max}(\rho_1, \rho_2) = \frac{\mathrm{Tr}[\rho_1 \rho_2]}{\max\{\mathrm{Tr}[\rho_1^2], \mathrm{Tr}[\rho_2^2]\}}$$

see cross-platform verification of NISQ

A.Elben et.al.
Phys. Rev. Lett. 124, 010504

Given Data Set





$$\tilde{H}_A = \sum_{i,j<i} \tilde{J}_{ij} \left(\sigma_i^+ \sigma_j^- + \mathrm{H.c.}\right) + \sum_i \tilde{B}_i \sigma_i^z$$

Testing the Ansatz via Fidelity Estimation


C Kokail

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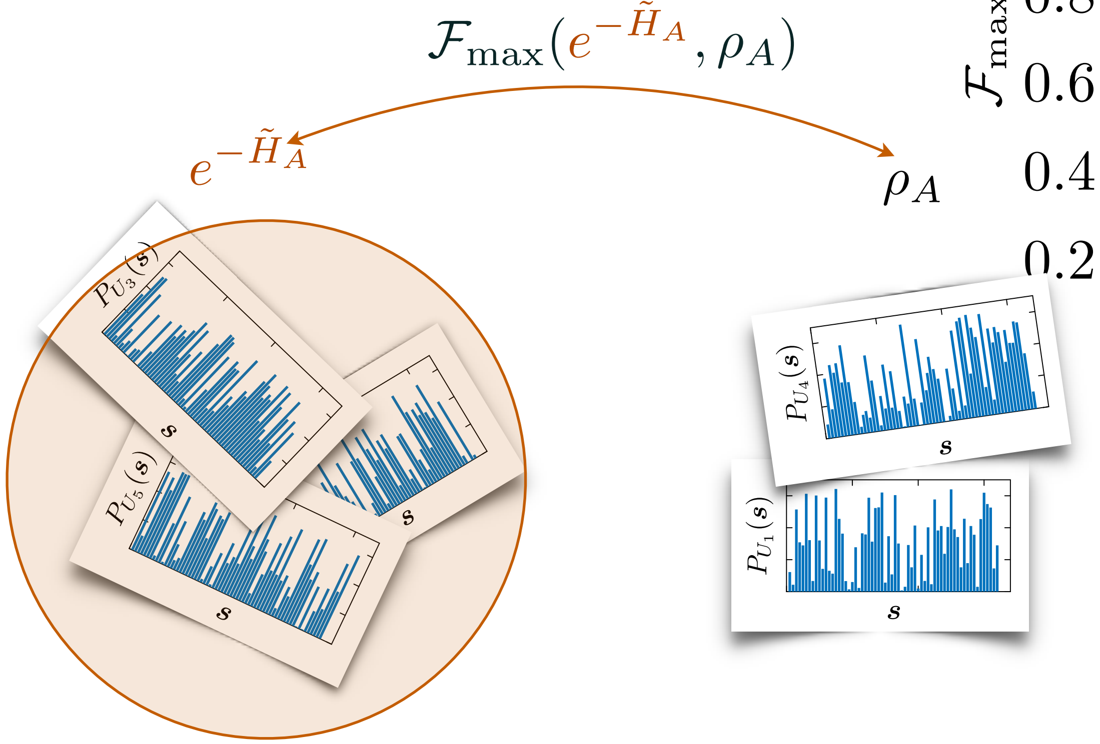

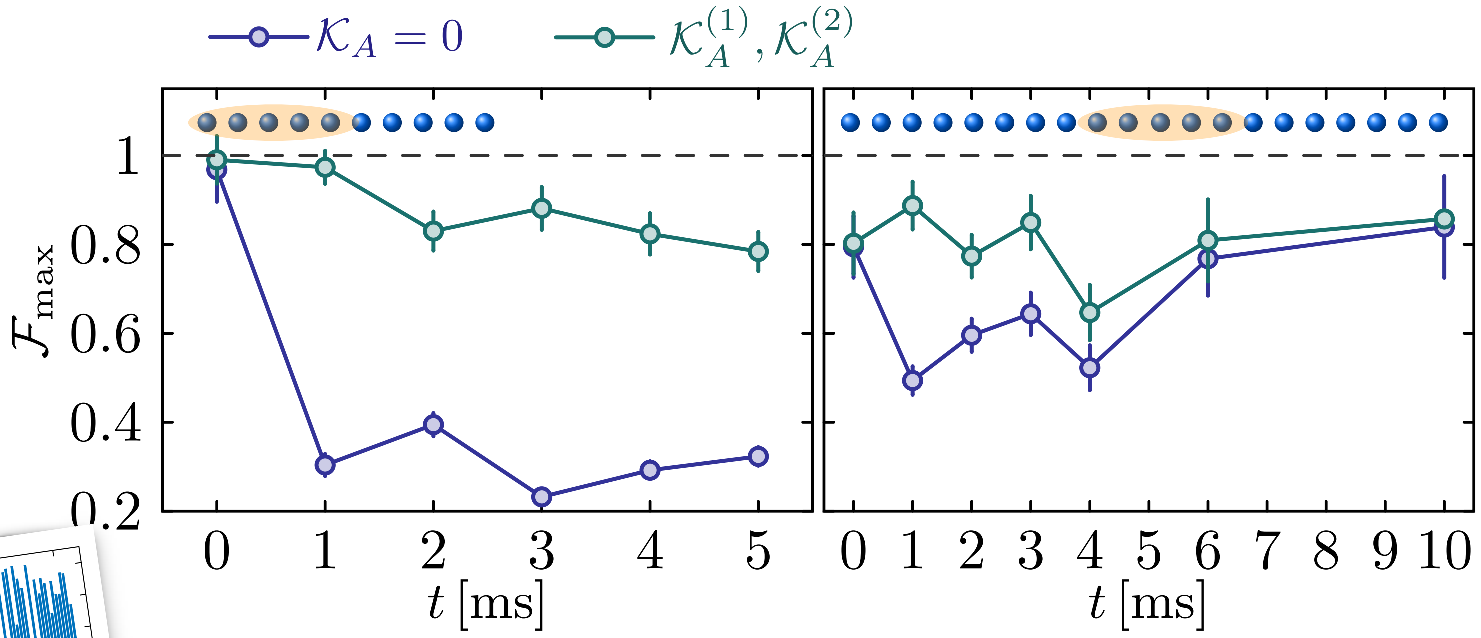

$$\mathcal{K}_A^{(1)}=\sum_{k<l\in A}\tilde{J}_{kl}^{XY}(\sigma_k^x\sigma_l^y-\sigma_k^y\sigma_l^x)$$

$$\mathcal{K}_A^{(2)}=\sum_{k<l}\sum_{m\neq k,l}\tilde{J}_{klm}^{XYZ}(\sigma_k^x\sigma_l^y\sigma_m^z-\sigma_k^y\sigma_l^x\sigma_m^z)$$

Testing the Ansatz via Fidelity Estimation

$$\mathcal{F}_{\max}(\rho_1,\rho_2) = \frac{\mathrm{Tr}[\rho_1\rho_2]}{\max\{\mathrm{Tr}[\rho_1^2],\mathrm{Tr}[\rho_2^2]\}}$$

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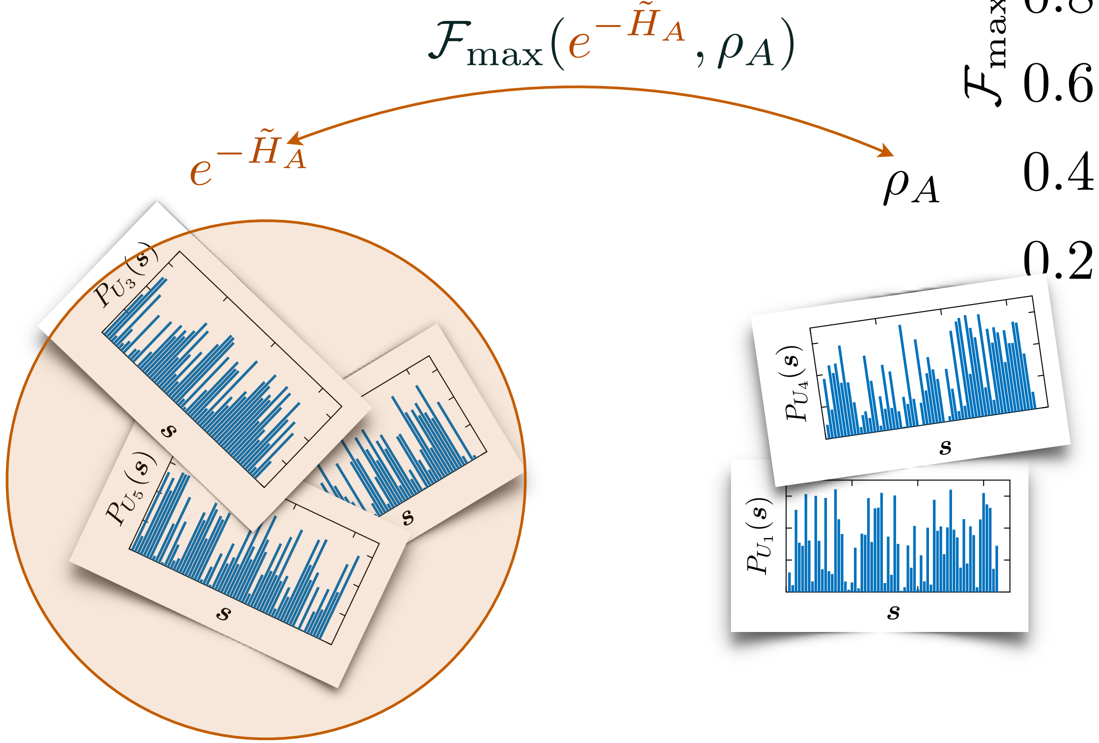
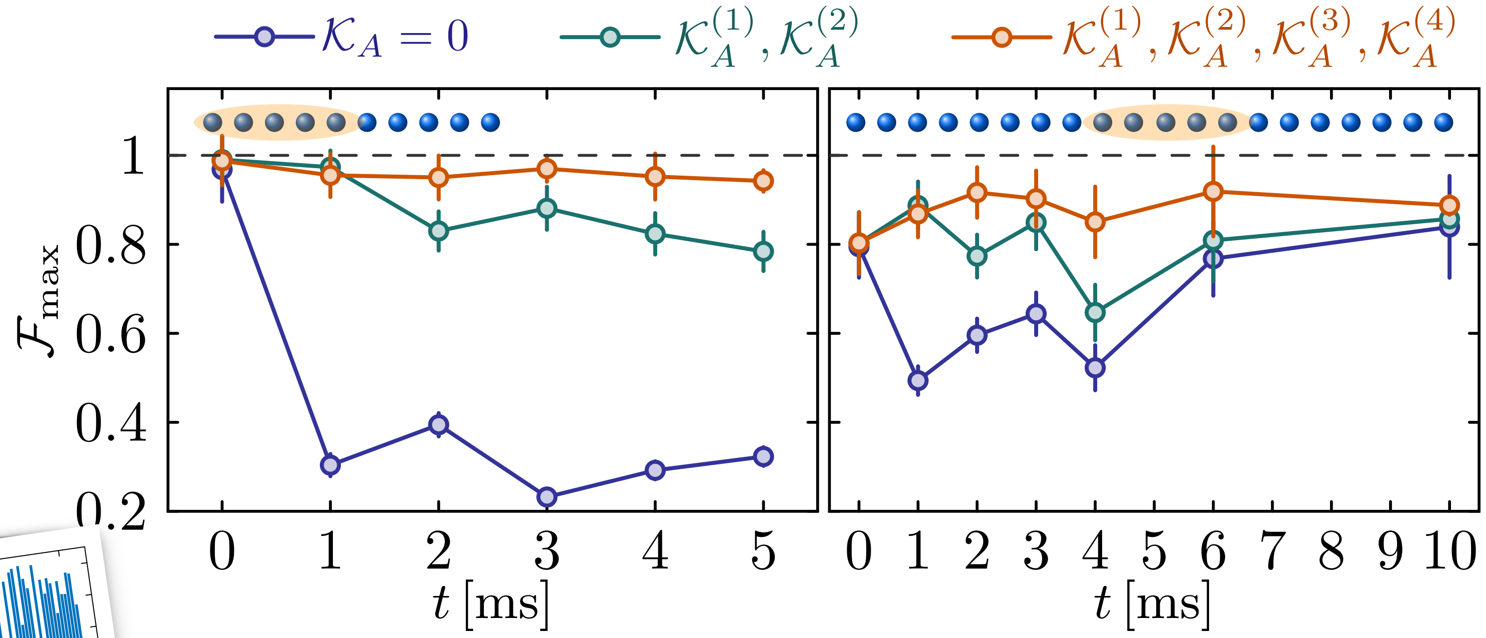




$$\mathcal{K}_A^{(3)} = \sum_{k<l\in A} \tilde{J}_{kl}^{ZZ}\sigma_k^z\sigma_l^z + \sum_{k<l<m\in A} \tilde{J}_{klm}^{ZZZ}\sigma_k^z\sigma_l^z\sigma_m^z$$

$$\mathcal{K}_A^{(4)} = \sum_{k<l}\sum_{m\neq k,l} \tilde{J}_{klm}^{XXZ}(\sigma_k^x\sigma_l^x\sigma_m^z + \sigma_k^y\sigma_l^y\sigma_m^z)$$

Q.: Why entanglement Hamiltonian
quasi-local and few-body?

Q.: Why entanglement Hamiltonian
quasi-local and few-body?

M. Dalmonte
→ ICTP

P. Calabrese
SISSA

thanks for insights and discussions

Bisognano-Wichmann Theorem of QFT

Conformal Field Theory

predict quasi-local entanglement Hamiltonian

- for ground states (BW+CFT)
- quench dynamics 1+1D (CFT) to critical point

validity, assumptions: continuum → lattice, … ?

M. Dalmonte et al., Nat. Phys. (2018); G. Giudici et al. PRB (2018).
P. Calabrese & J. Cardy, J Phys A (2009)
X Wen, S Ryu & AW Ludwig, J Stat Mech (2018).

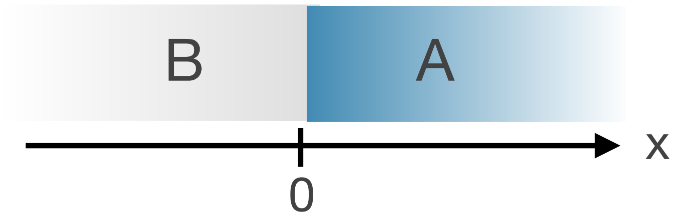
Quantum simulation as testbed for lattice-BW & CFT

Potential to `discover' new physics

Bisognano-Wichmann Theorem [ground states]

M. Dalmonte
→ ICTP

physical system

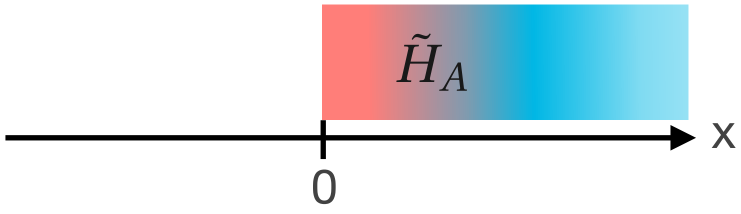


Hamiltonian density (here 1D)

$$H(x)$$

Lorentz invariance

entanglement Hamiltonian



BW Entanglement Hamiltonian (here 1D)

$$\rho_A \sim e^{-\int_{x>0} dx\, \beta(x)\, H(x)}$$

$$\tilde{H}_A \sim \int_{x>0} dx\, \Big[\underbrace{x\, H(x)}_{\tilde{H}_A(x)}\Big]$$

with `temperature' $\beta(x) \sim x$

EH as local, few-body Hamiltonian with *spatially dependent* couplings

---

Lattice models? Numerical examples show that this works well in many cases

M. Dalmonte et al., Nat. Phys. (2018).
G. Giudici et al. PRB (2018).

Can our Entanglement Hamiltonian Tomography *measure* BW?

EHT applied to ground states … *in light of Bisognano-Wichmann on lattice*

System Hamiltonian

$$H = \sum_{i,j>i} \frac{J_0}{|i-j|^{\eta}} \sigma_i^x \sigma_j^x + B \sum_i \sigma_i^z$$

$$\eta = 2.5$$

Ansatz for the entanglement Hamiltonian:

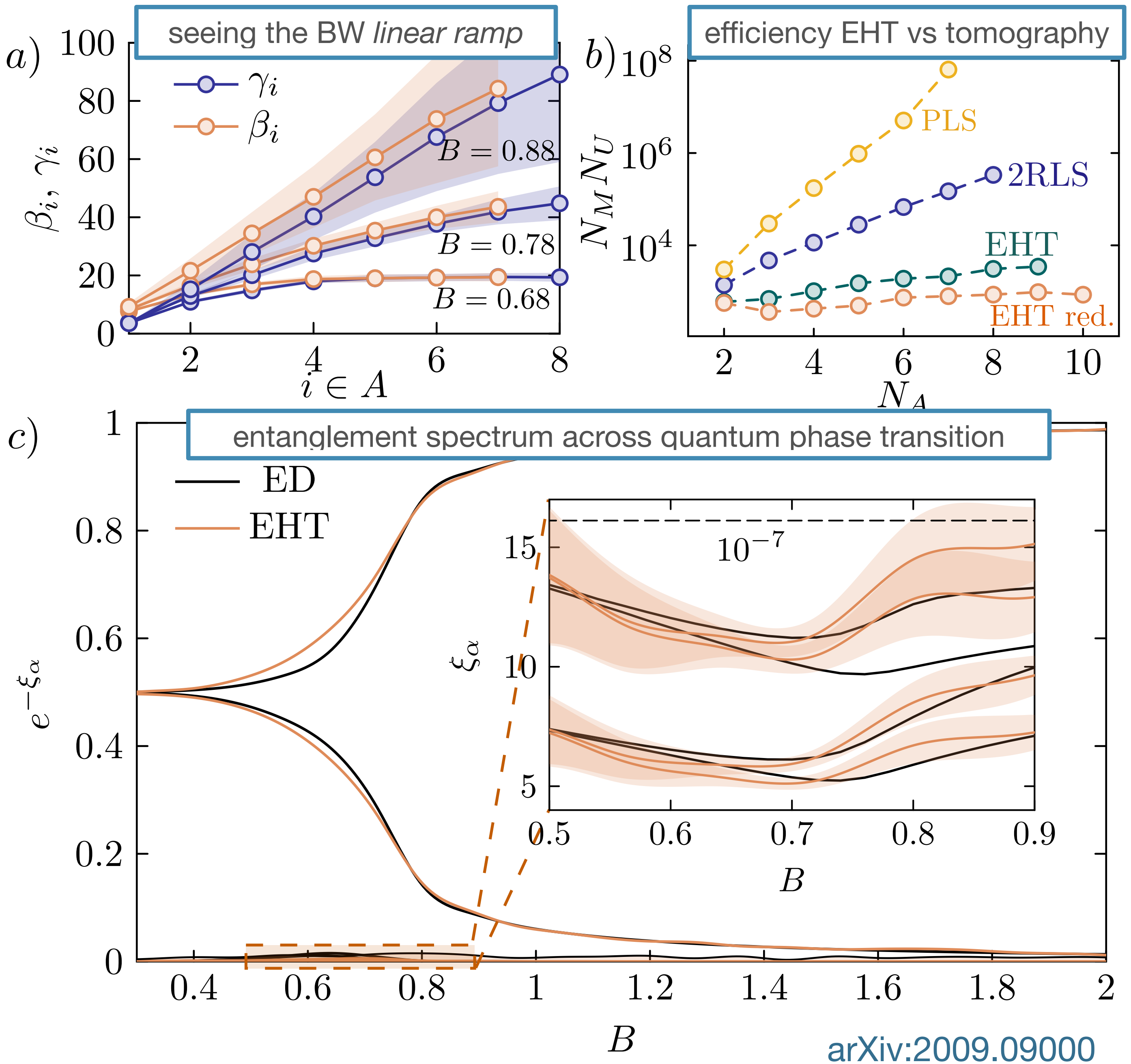
$$\tilde{H}_A = \sum_{i,j\in A} \tilde{J}_{ij} \sigma_i^x \sigma_j^x + \sum_{i\in A} \tilde{B}_i \sigma_i^z$$

where we choose a parabolic deformation

$$\tilde{J}_{ij} = \frac{\vartheta_0 + \vartheta_1 (i+j) + \vartheta_2 (i+j)^2}{2|i-j|^{\alpha}}$$

$$\tilde{B}_i = B(\vartheta_0 + \vartheta_1 i + \vartheta_2 i^2)$$

We *simulate* EHT measurement runs



seeing the BW *linear ramp*

efficiency EHT vs tomography

entanglement spectrum across quantum phase transition

arXiv:2009.09000

Revealing new physics in quench dynamics

CFT predicts corrections to EH as `distortion of the system Hamiltonian'. Can we detect them?

We simulate a global quench in the transverse field Ising model ($\eta \to \infty$)

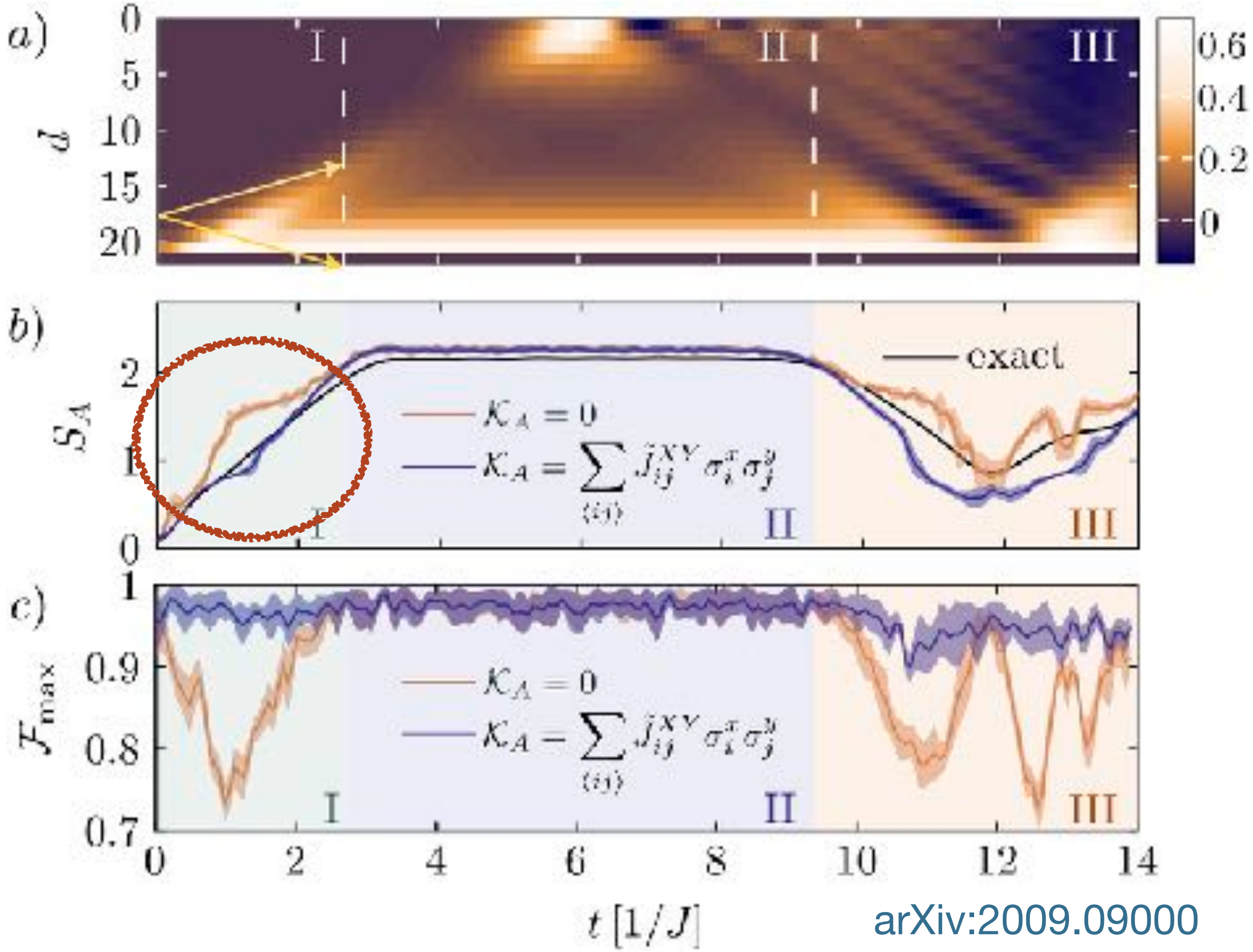
Ansatz for the entanglement Hamiltonian:

$$\tilde{H}_A = \sum_{i \in A} \left(\tilde{J}_{i,i+1} \sigma_i^x \sigma_{i+1}^x + \tilde{B}_i \sigma_i^z \right) + \mathcal{K}_A$$

with $\mathcal{K}_A$ motivated from the local lattice momenta

$$\mathcal{K}_A = \sum_{i \in A} \tilde{J}^{XY}_{i,i+1} \sigma_i^x \sigma_{i+1}^y$$

We *simulate* EHT measurement runs



arXiv:2009.09000

J. Cardy and E. Tonni. J. Stat. Mech. 2016

X Wen, S Ryu & AW Ludwig, J Stat Mech (2018)

W. Zhu, Z. Huang, Y.-C. He, & X. Wen, PRL (2020)

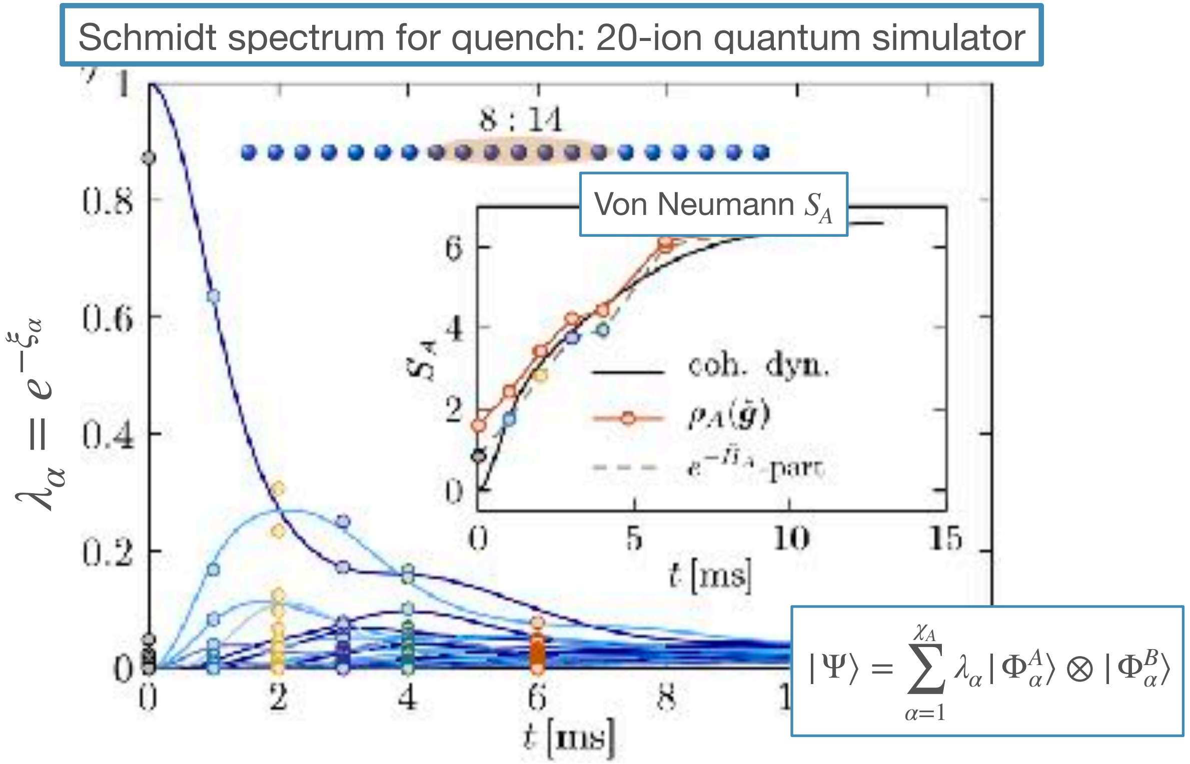
Conclusions and Outlook

- Revealing and quantifying entanglement as a key challenge in quantum simulation

Randomized measurement toolbox

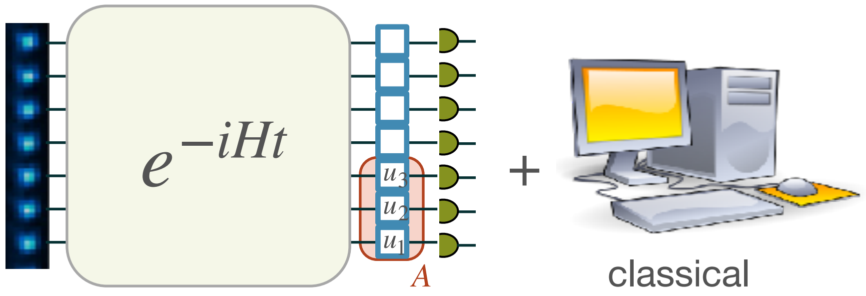
Protocols: from entanglement entropies
to entanglement Hamiltonian tomography

Tailored to today's quantum simulation platforms


Schmidt spectrum for quench: 20-ion quantum simulator

$$|\Psi\rangle = \sum_{\alpha=1}^{\chi_A} \lambda_\alpha |\Phi_\alpha^A\rangle \otimes |\Phi_\alpha^B\rangle$$

this talk:



classical
postprocessing

measure / characterize / quantify entanglement in quantum simulation

Entanglement Hamiltonian Tomography

✓ heuristic
✓ testbed for BW & CFT

Conclusions and Outlook

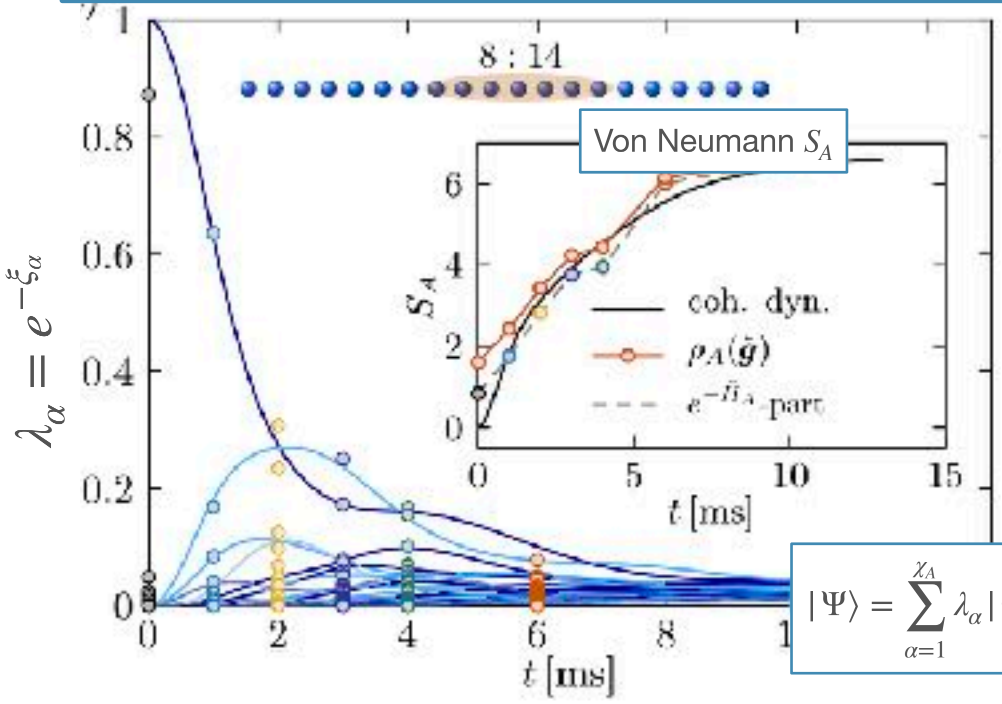
- Revealing and quantifying entanglement as a key challenge in quantum simulation

  Randomized measurement toolbox

  Protocols: from entanglement entropies
  to entanglement Hamiltonian tomography

  Tailored to today's quantum simulation platforms

Schmidt spectrum for quench: 20-ion quantum simulator

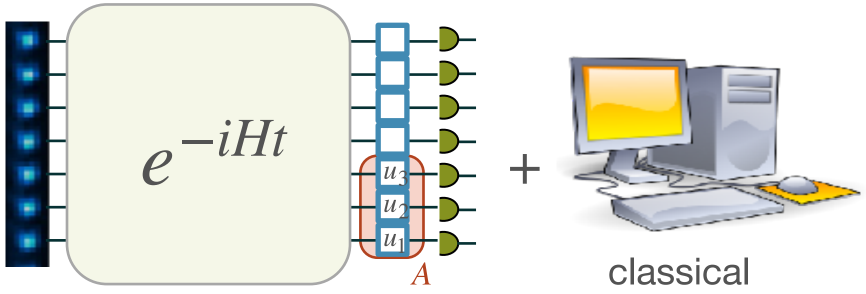


Von Neumann S_A

$$|\Psi\rangle = \sum_{\alpha=1}^{\chi_A} \lambda_\alpha |\Phi_\alpha^A\rangle \otimes |\Phi_\alpha^B\rangle$$

- Future - *quantum* protocols?

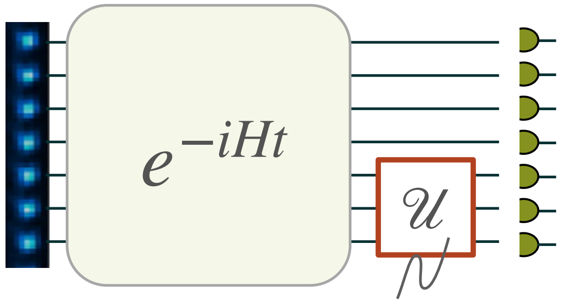
this talk:



classical
postprocessing

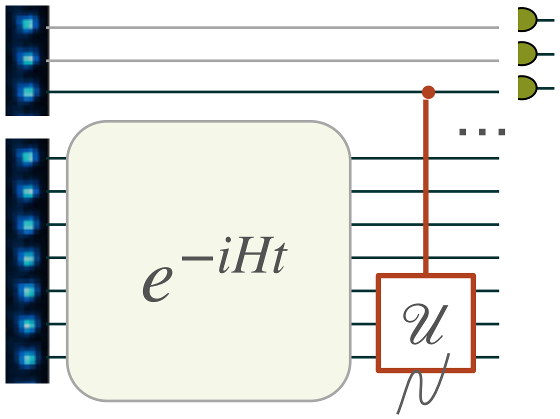
more efficient? in quantum supremacy regime/large A?

towards quantum algorithms



quantum circuits

Bhuvanesh Sundar et al.,, unpublished



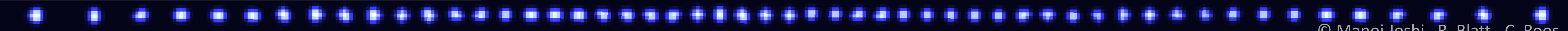
quantum
computer

quantum
simulator

quantum circuits

D Vasilyev, A Grankin et al., PRXQ in press

quantum simulators in 50 ~ few hundred regime



present group members

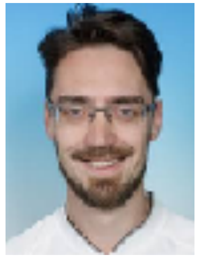

A Elben


B Vermersch
→ Grenoble


C Kokail


R. van Bijnen


B Sundar

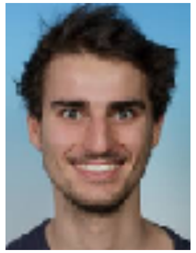

D Vasilyev


L Joshi


Jinlong Yu


M Baranov
(senior member)


R Kaubrügger


A Kruckenhauser


T Olsacher

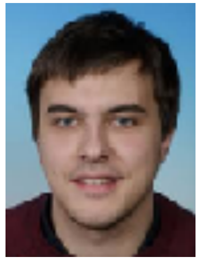

T Zache


W Hahn


M Di Liberto

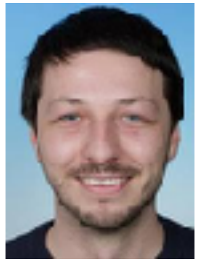
former group members involved in these / related projects


M. Dalmonte
→ ICTP


A Grankin
→ JQI


L Sieberer
→ UIBK


P Hauke
→ Trento


H Heyl
→ Dresden

Special thanks to the ion trap group of R. Blatt & C. Roos for collaborations and sharing their experimental data