Celebrating *100 years of Fermi Statistics:* Fermi Legacy in Low Energy Physics, Academica dei Lincei, Feb 5-6 2026

350 universität innsbruck

IQI

PASQuanS

FWF

|QuEra>
Computing Inc.

Q-SEnSE

AQT

Fermionic Quantum Processing & Programmable Fermi-Hubbard Q-Simulators

Peter Zoller

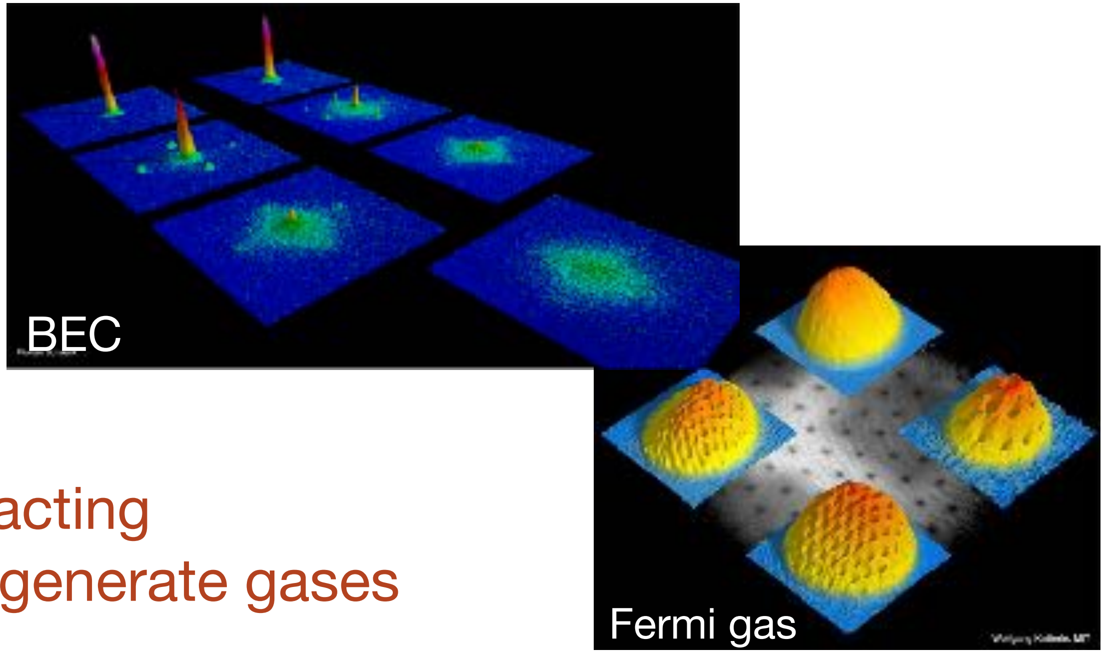
SULLA QUANTIZZAZIONE DEL GAS PERFETTO MONOATOMICO

« Rend. Lincei », 3, 145–149 (1926) (*).

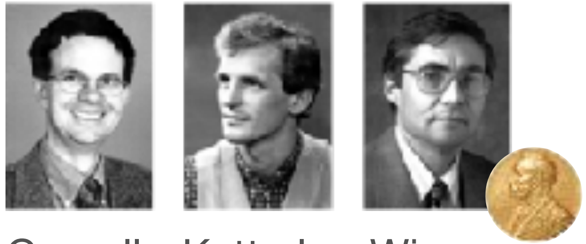
1. Nella termodinamica classica si prende come calore specifico a volume

Quantum Computing with Qubits

Fermionic Quantum Computing & Quantum Simulation



weakly interacting
quantum degenerate gases



Cornell - Ketterle - Wieman

D Kleppner   D Jin

1995 + …

… with Ultracold Atoms

Strongly-Correlated Synthetic Quantum Matter with Bosons

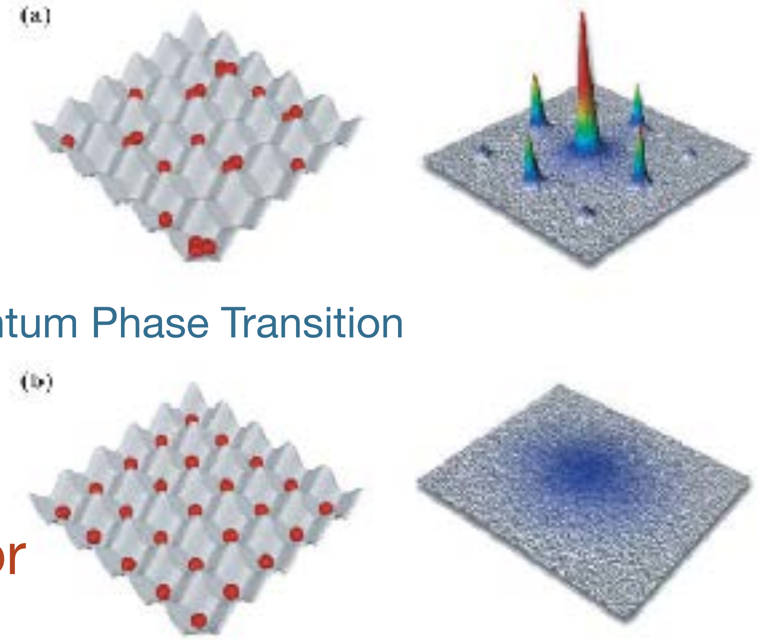
Bose-Hubbard Models in Optical Lattices

VOLUME 81, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1998

Cold Bosonic Atoms in Optical Lattices

D. Jaksch,[1,2] C. Bruder,[1,3] J. I. Cirac,[1,2] C. W. Gardiner,[1,4] and P. Zoller[1,2]
[1]*Institute for Theoretical Physics, University of Santa Barbara, Santa Barbara, California 93106-4030*
[2]*Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
[3]*Institut für Theoretische Festkörperphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[4]*School of Chemical and Physical Sciences, Victoria University*

KITP BEC '98 program



BEC

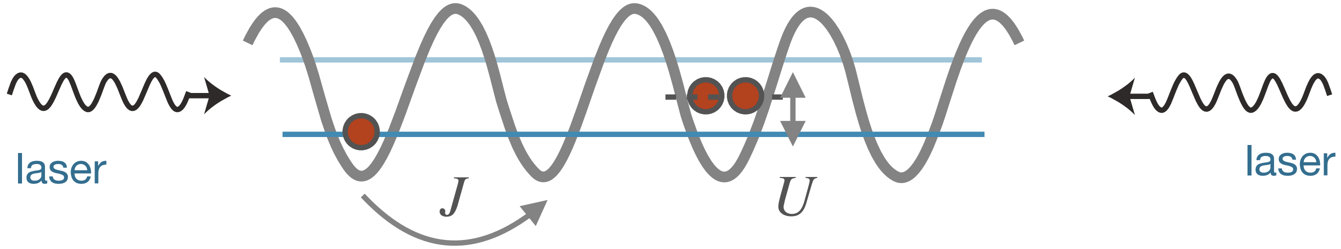
Quantum Phase Transition

Mott Insulator

© Bloch

Programmability

laser intensity as control parameter



$$H = -J\sum_{\langle i,j\rangle} b_i^\dagger b_j + \frac{1}{2}U\sum_i \hat{n}_i\left(\hat{n}_i - 1\right)$$

kinetic energy ⟷ interaction

tunable

Bose Hubbard Model in Optical Lattice

Strongly-Correlated Synthetic Quantum Matter

Greiner - Bloch - Esslinger

Bose-Hubbard Models in Optical Lattices

VOLUME 81, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1998

Cold Bosonic Atoms in Optical Lattices

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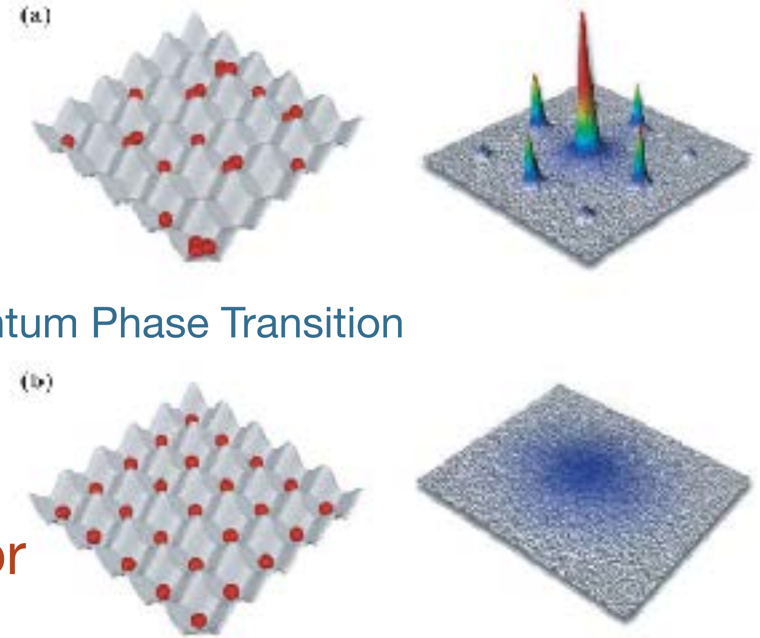
KITP BEC '98 program

BEC

Quantum Phase Transition

Mott Insulator



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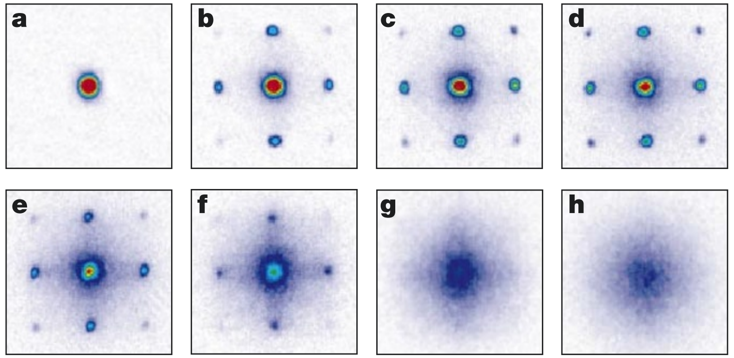
articles NATURE | VOL 415 | 3 JANUARY 2002

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*

weakly to strongly interacting quantum gases



first analog quantum simulation experiment

Strongly-Correlated Synthetic Quantum Matter with Fermions

Fermi-Hubbard Models in Optical Lattices

VOLUME 89, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 2002

High-Temperature Superfluidity of Fermionic Atoms in Optical Lattices

W. Hofstetter,[1] J. I. Cirac,[1,2] P. Zoller,[1,3] E. Demler,[1] and M. D. Lukin[1]
[1]*Physics Department, Harvard University, Cambridge, Massachusetts 02138*
[2]*Max-Planck Institute for Quantum Optics, Garching, Germany*
[3]*Institute for Theoretical Physics, University of Innsbruck, Austria*
(Received 10 July 2002; published 12 November 2002)

The cold atom Hubbard toolbox

ANNALS of PHYSICS
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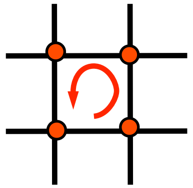
D. Jaksch[a,b,*], P. Zoller[b]
[a] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK*
[b] *Institute for Theoretical Physics, University of Innsbruck, and Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria*

Received 31 August 2004; accepted 28 September 2004
Available online 19 December 2004



$$J_{\alpha\beta} \longrightarrow J_{\alpha\beta}\, e^{ie\int_\alpha^\beta \vec{A}\cdot d\vec{l}}$$

New Journal of Physics 2003

synthetic gauge fields

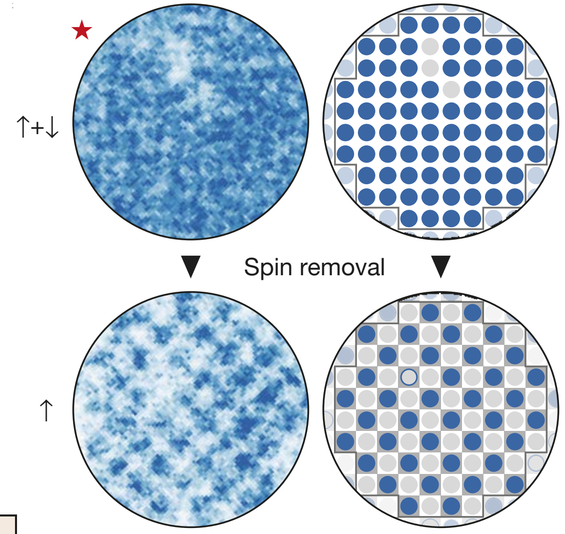
topology

adding features

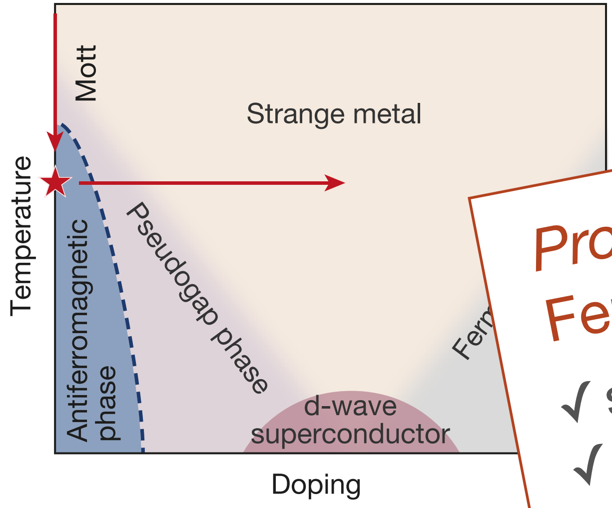
Experiment

quantum gas microscope

\`seeing single atom in a single shot'



© Greiner Lab



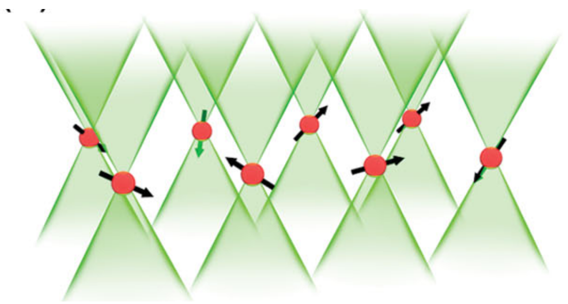
Programmable Fermionic quantum matter
- ✓ single site control
- ✓ single site / shot read out

see talks by I Bloch, L Fallani, M Zwierlein …

Programmable Quantum Devices with Atoms

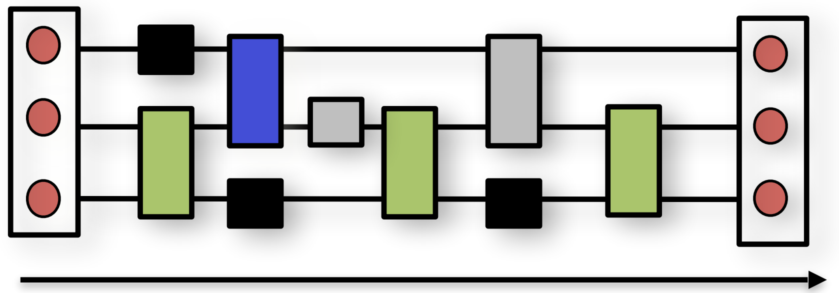
Quantum Computing [Digital]

ions, 2D Rydberg arrays



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

quantum logic network model



basic constituents

qubits (or spin-½) (distinguishable)

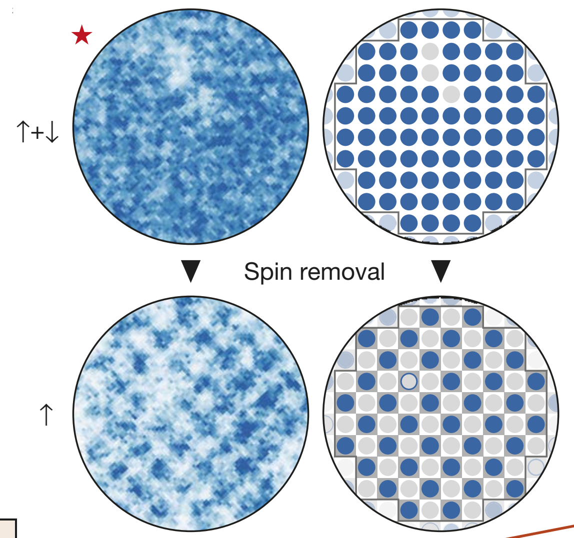
software fermions

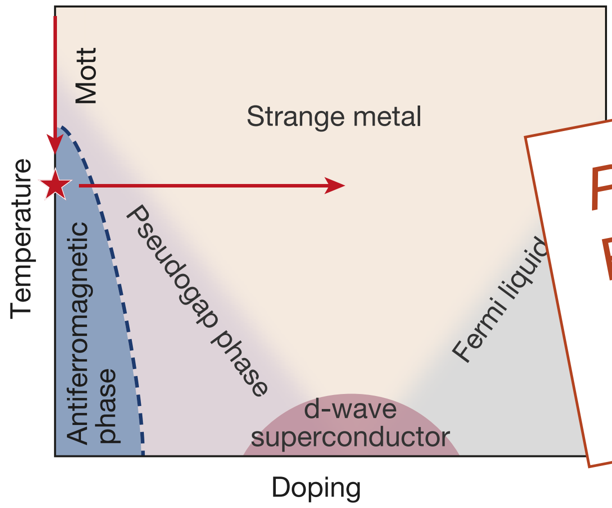
Quantum Simulation [Analog]

Fermi-Hubbard in OL

quantum gas microscope

Fermi-Hubbard Model in 2D (high Tc)





Programmable Fermionic quantum matter

✓ single site control

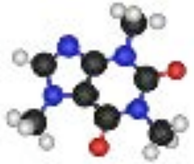
✓ single site / shot read out

bosons & fermions (quantum statistics)

native fermions

Fermionic Quantum Computing with Neutral Atom Arrays [Digital]

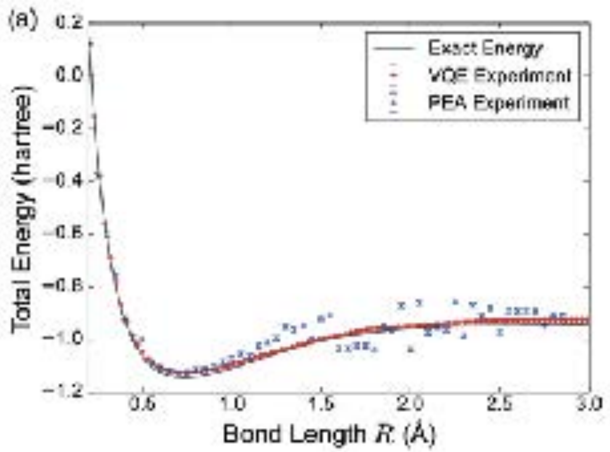
Digital quantum simulation



$$H = \sum_{ij} h_{ij}^{(1)} c_i^\dagger c_j + \sum_{ijkl} h_{ijkl}^{(2)} c_i^\dagger c_j^\dagger c_k c_l$$

Non-local mapping: $\mathcal{O}(L)$ **overhead**

e.g. JW: $c_j^\dagger = \sigma_j^+ e^{-i\pi \sum_{k<j} \sigma_j^z}$



- Photons
  Peruzzo et al., Nat. Commun. 5, 4213 (2014)
- SC qubits
  O'Malley et al., PRX. 6, 031007 (2016)
- Trapped ions
  Shen et al., PRA. 95, 020501(R) (2017)

Fermionic quantum computation

Bravyi & Kitaev, Annals of Physics 298, 210–226 (2002)

$$\{e^{i\pi/4 n_i},\ e^{i\pi/4(c_i^\dagger c_j + \mathrm{H.c.})},$$
$$e^{i\pi n_i n_j},\ e^{i\pi/4(c_i^\dagger c_j^\dagger + \mathrm{H.c.})}\}$$

Polynomial resource saving

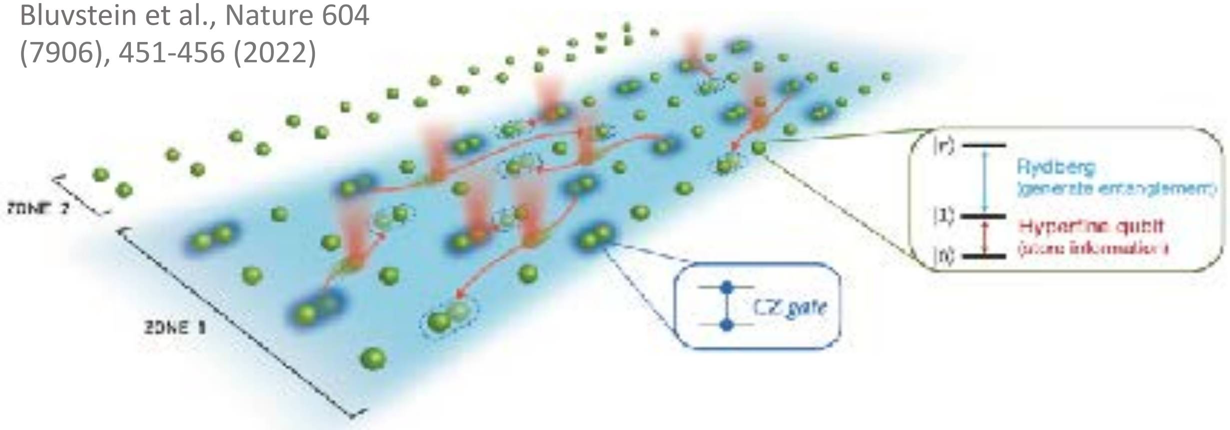
Universality

Particle number conserving sector

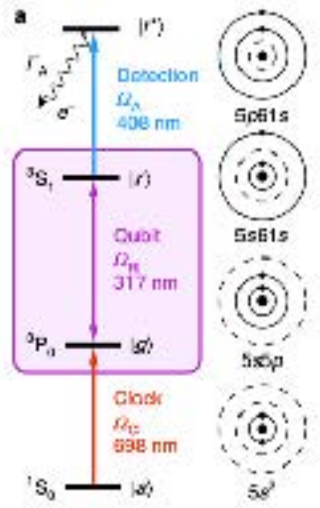
first experiments: Bloch group, Esslinger group 2025

Quantum Computing with Rydberg Atoms [Digital]

Bluvstein et al., Nature 604 (7906), 451-456 (2022)



Madjarov et al., Nat. Phys. 16, 857–861 (2020)



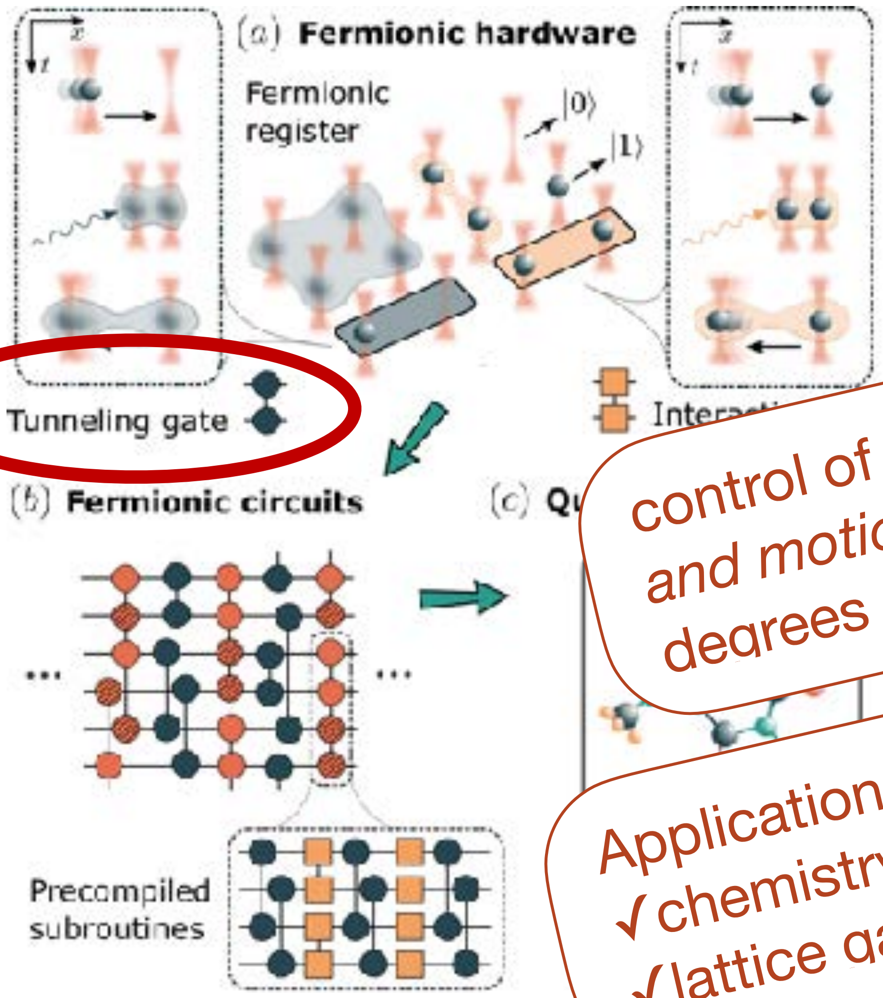
- Atomic qubits
- Local addressing
- Rydberg entanglement
- All-to-all connectivity

PNAS RESEARCH ARTICLE | PHYSICS OPEN ACCESS Check for updates

Fermionic quantum processing with programmable neutral atom arrays

D. González-Cuadra[a,b], D. Bluvstein[c], M. Kalinowski[c], R. Kaubruegger[a,b], N. Maskara[c], P. Naldesi[a,b], T. V. Zache[a,b], A. M. Kaufman[d,e], M. D. Lukin[c], H. Pichler[a,b], B. Vermersch[a,b,f], Jun Ye[d,e], and P. Zoller[a,b,1]

Fermionic quantum processor



control of internal and motional degrees of freedom

Applications
✓chemistry
✓lattice gauge theory

Fermionic Gates

Tunneling: $\mathcal{U}^{(\mathrm{t})}_{i,j}(\theta_1,\theta_2,\theta_3) = e^{-i\left[\frac{\theta_1}{2}(e^{-i\theta_2}c_i^\dagger c_j + \mathrm{H.c})\right] + \frac{\theta_2}{2}(n_i - n_j)]}$

Kaufman et al, Science 345, 306–309 (2014)

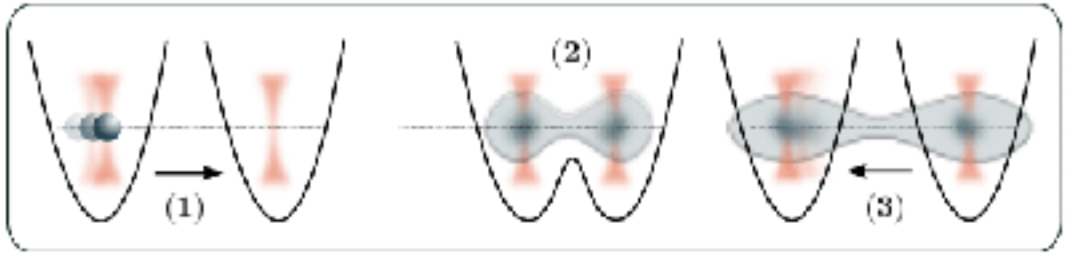
Spar et al, Phys. Rev. Lett. 128, 223202 (2022)

Young et al, Science 377, 885–889 (2022)

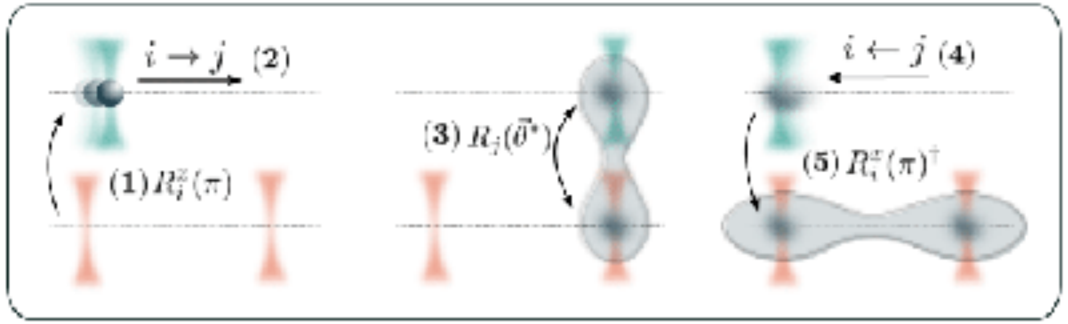
Spar et al, Phys. Rev. Lett. 129, 123201 (2022)

Daley et al, Phys. Rev. Lett. 101, 170504 (2008)

(a) **MERGE gate** → Alkaline

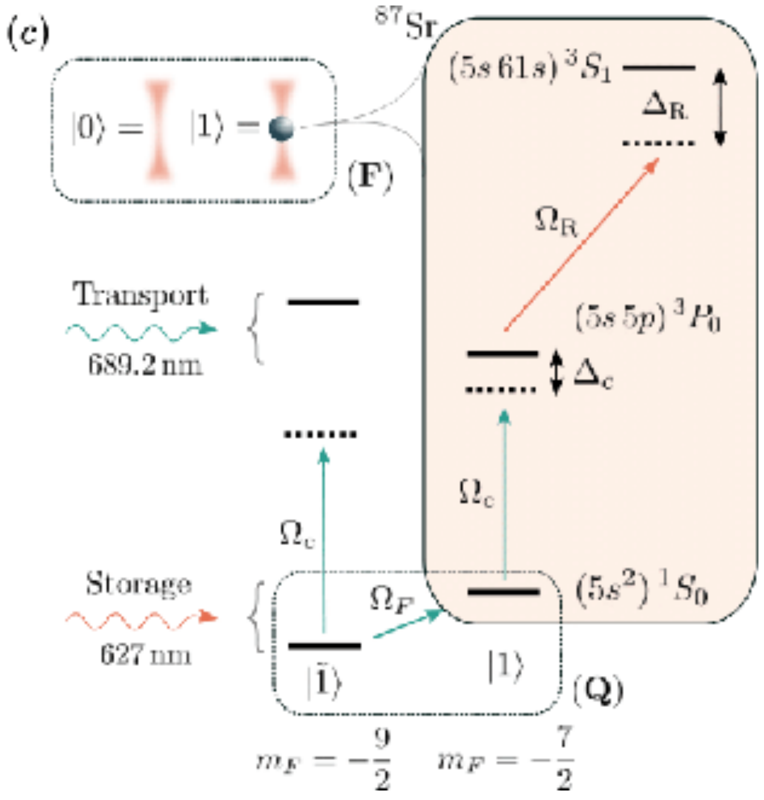


(b) **SHUTTLE gate** → Alkaline-earth



$R_i^{xyz}(\theta_1,\theta_2,\theta_3) = e^{-i\left[\frac{\theta_1}{2}(\cos\theta_2 X + \sin\theta_2 Y) + \frac{\theta_3}{2} Z\right]}$

Interaction: $\mathcal{U}^{(\mathrm{int})}_{i,j}(\theta) = e^{-i\theta\, n_i n_j}$



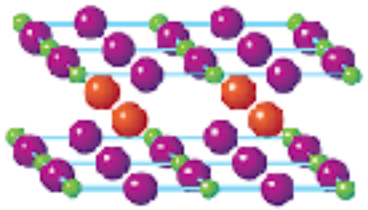
→ Fermion-qubit register

Pavel Dolgirev   Christian Kokail

Lukin-group @ Harvard

Quantum Simulation → *Inverse* Quantum Simulation

Active Design of Many-Body Hamiltonians



quantum materials

goal: design quantum many-body systems with desired properties; synthetic quantum matter → real(?) materials

Utility

Machine Learning

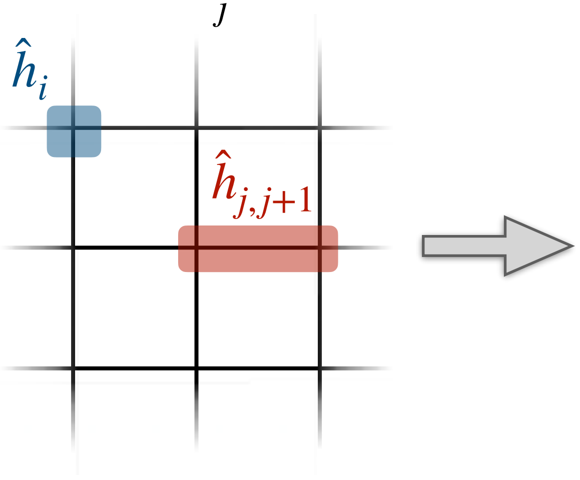
`Quantum Advantage'

C Kokail, PE Dolgirev, R van Bijnen, D Gonzalez-Cuadra, MD Lukin, PZ, arXiv:2601.12239

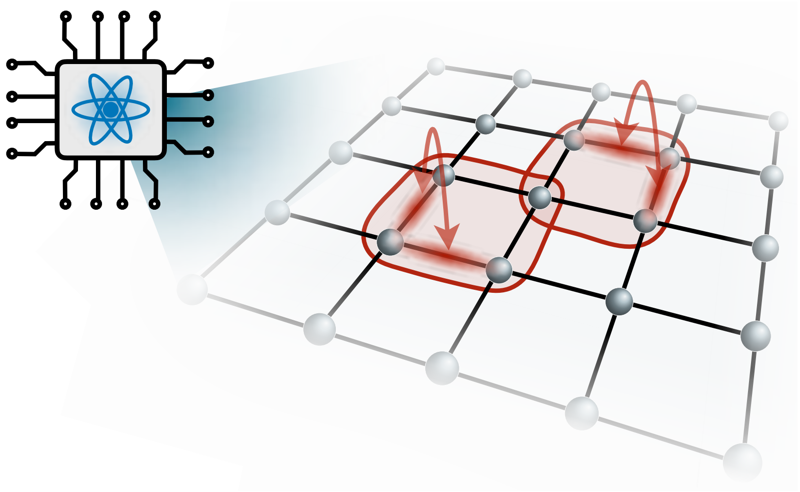
Forward Quantum Simulation

Hamiltonian

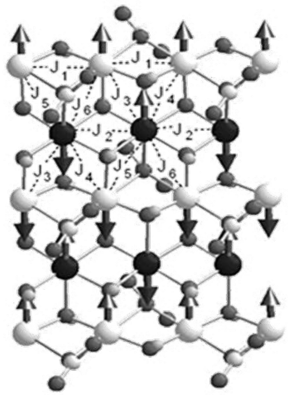
$$\hat{H} = \sum_j \hat{h}_j$$



Quantum Simulator



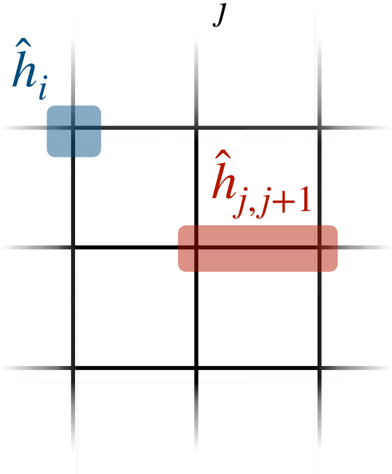
Quantum Material



Forward Quantum Simulation

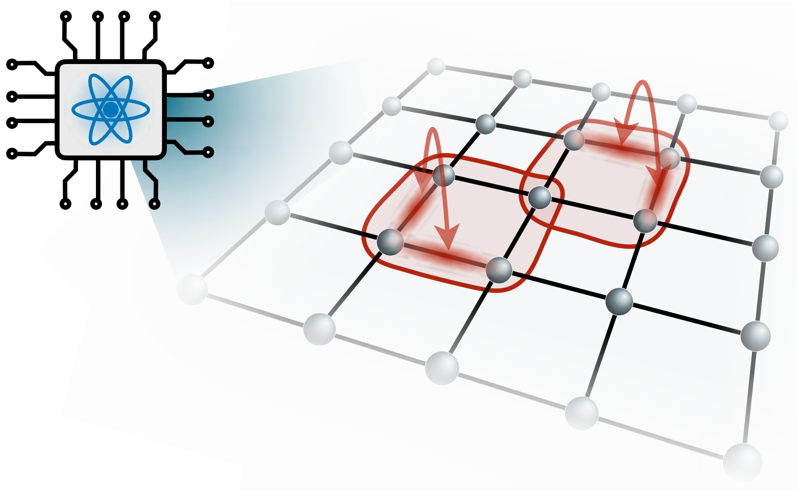
Hamiltonian

$$\hat{H} = \sum_j \hat{h}_j$$



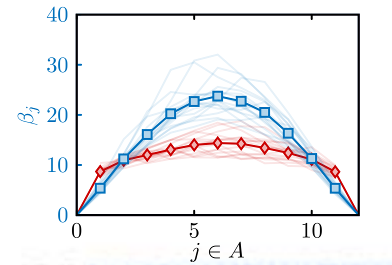
microscopic description

Quantum Simulator

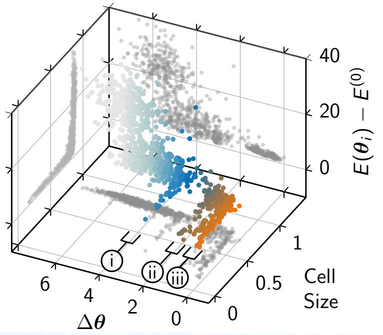


$|\Psi_n\rangle,\ e^{-\beta \hat{H}}$

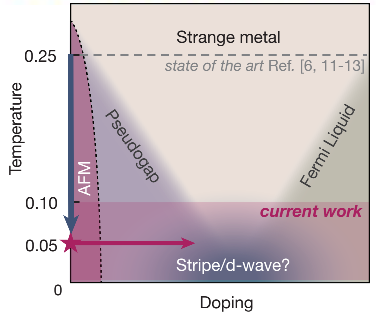
$e^{-\frac{i}{\hbar}\hat{H}t}|\Psi\rangle$

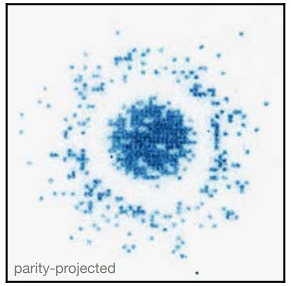


M. Joshi et al., Nature 202



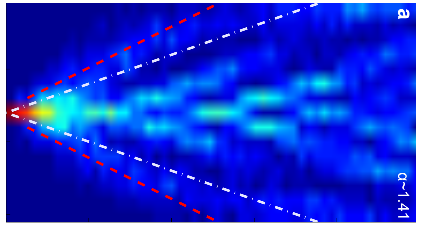
C. Kokail et al. Nature 2019



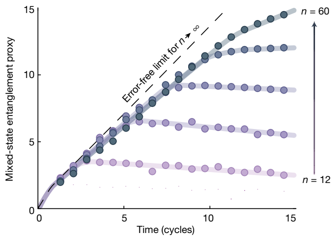


Xu et al. ArXiv 25'

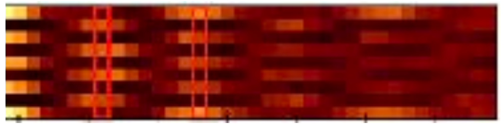
equilibrium phenomena



P. Jurcevic et al. Nature (2014)



Shaw et. al, Nature (2024)



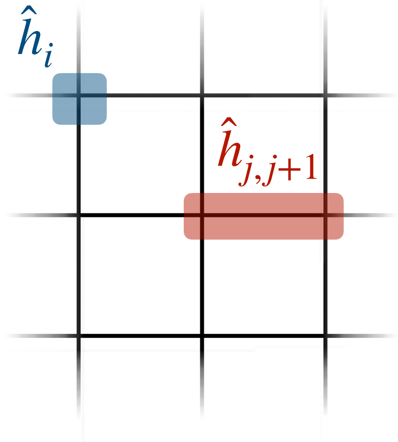
Bernien et al. Nature 2017

non-equilibrium

Forward Quantum Simulation

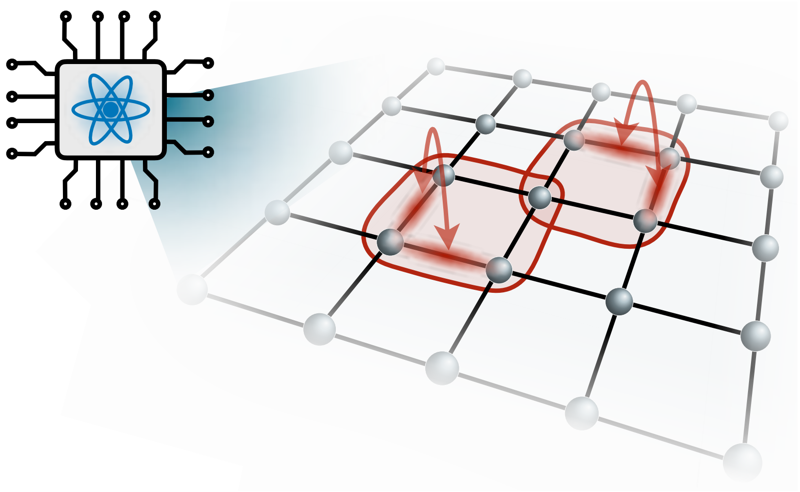
Hamiltonian

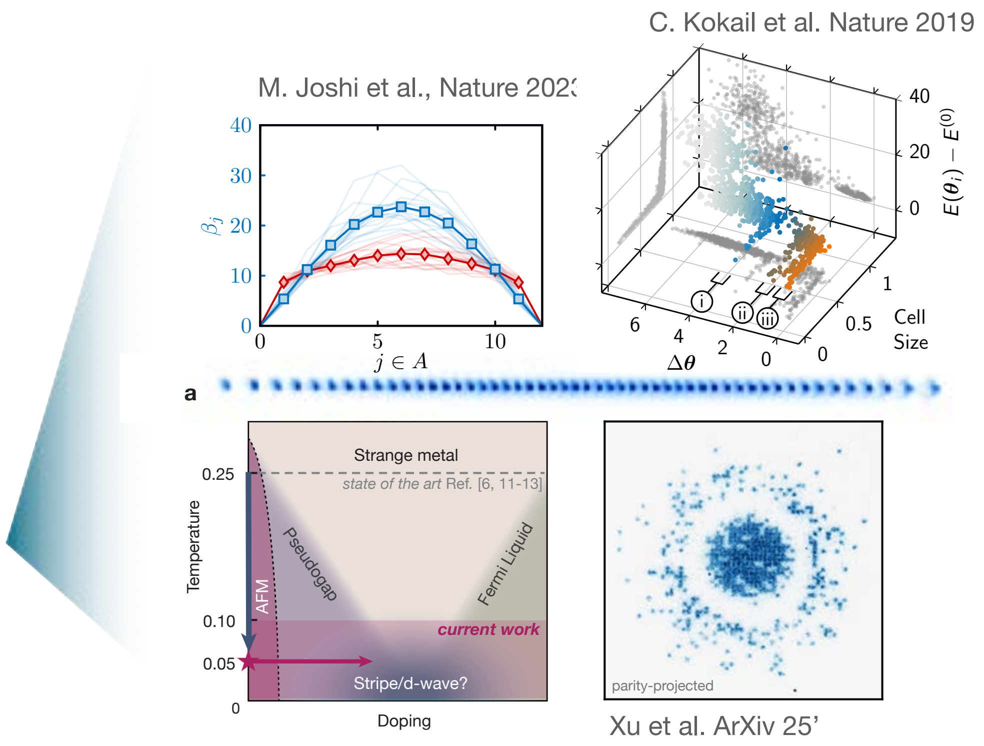
$$\hat{H} = \sum_j \hat{h}_j$$



Quantum Simulator

$|\Psi_n\rangle,\ e^{-\beta\hat{H}}$





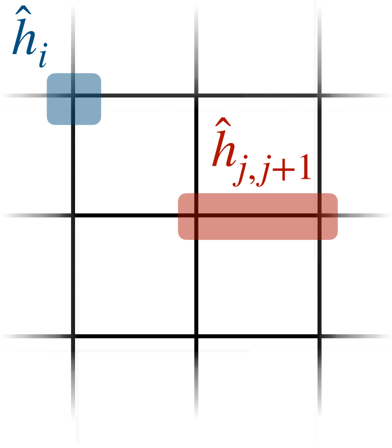
equilibrium phenomena

microscopic description → `solving' quantum many-body problem → emergent properties

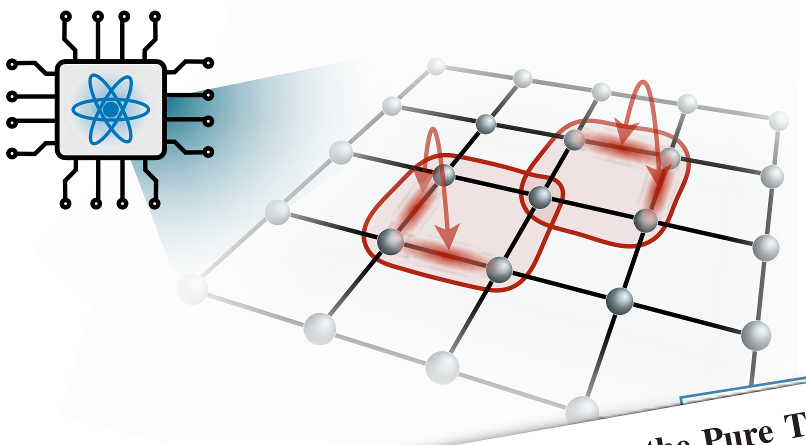
Forward Quantum Simulation: Fermi-Hubbard & d-wave

Hamiltonian

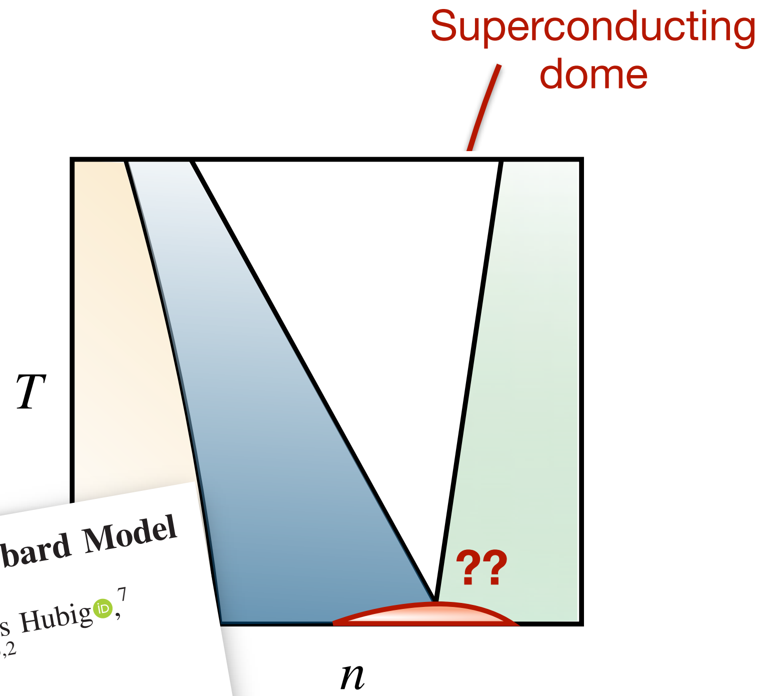
$$\hat{H} = \sum_j \hat{h}_j$$



Quantum Simulator



d-wave high-Tc SC



Absence of Superconductivity in the Pure Two-Dimensional Hubbard Model

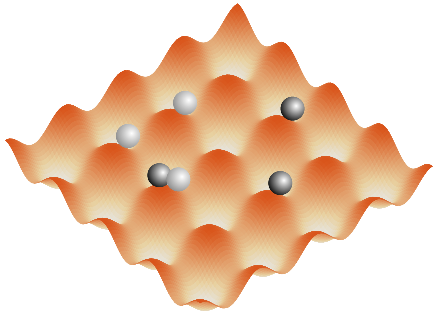
Mingpu Qin,[1,2,*] Chia-Min Chung,[3,4,*] Hao Shi,[5] Ettore Vitali,[6,2] Claudius Hubig,[7] Ulrich Schollwöck,[3,4] Steven R. White,[8] and Shiwei Zhang[5,2]

(Simons Collaboration on the Many-Electron Problem)

SUPERCONDUCTIVITY

Superconductivity in the doped Hubbard model and its interplay with next-nearest hopping t'

Hong-Chen Jiang[1*] and Thomas P. Devereaux[1,2]



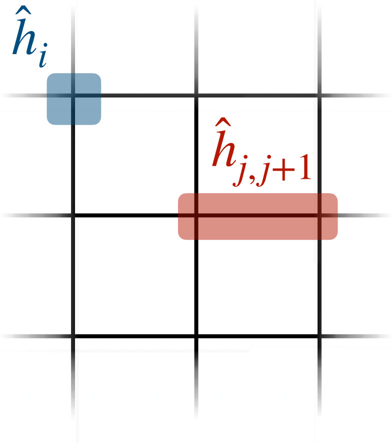
$$\hat{H}_0 = -\sum_{\langle ij \rangle} t_{ij} \left(\hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + \text{H.c.} \right)$$

Hubbard Hamiltonian

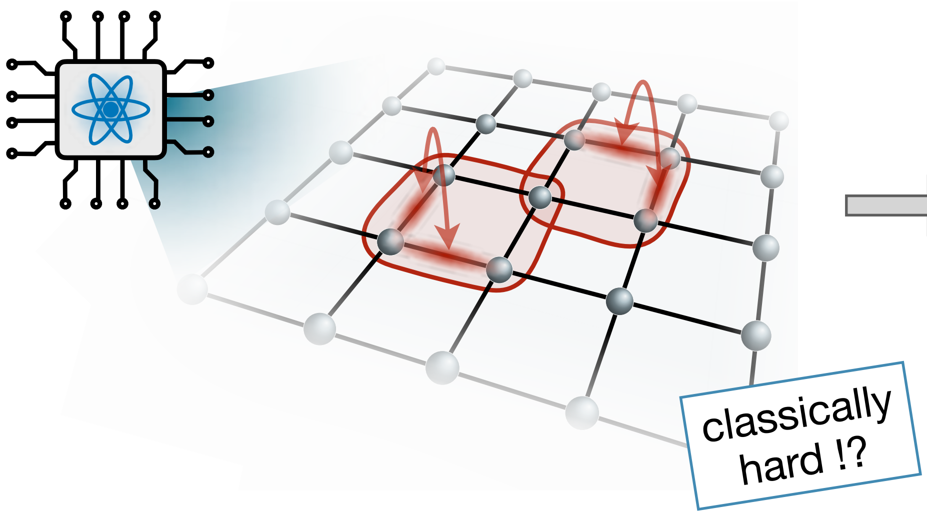
Forward Quantum Simulation: Fermi-Hubbard & d-wave

Hamiltonian

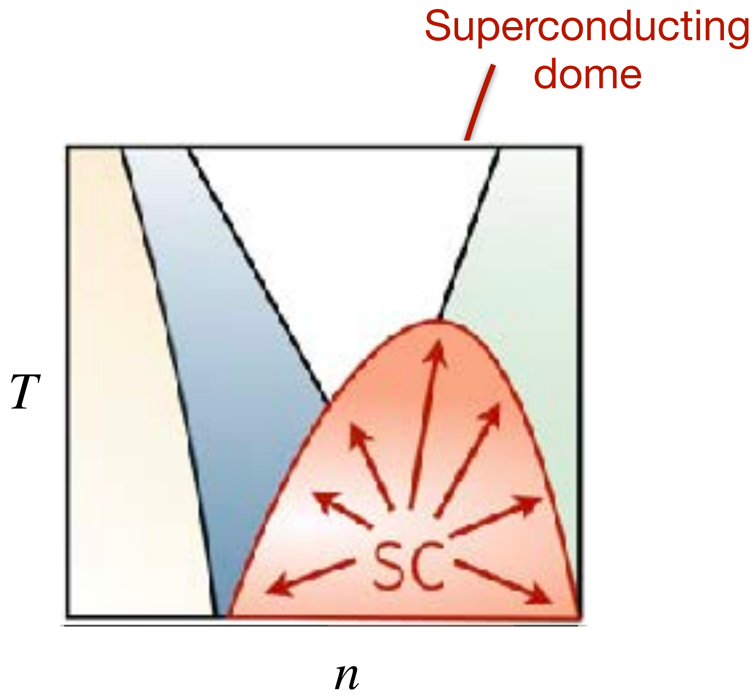
$$\hat{H} = \sum_j \hat{h}_j$$



Quantum Simulator



d-wave high-Tc SC



$$\hat{H}_0 = -\sum_{\langle ij \rangle} t_{ij} \left(\hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + \text{ H.c. } \right) + U \sum_j \hat{n}_{j\uparrow} \hat{n}_{j\downarrow}$$

Hubbard Hamiltonian

large d-wave?

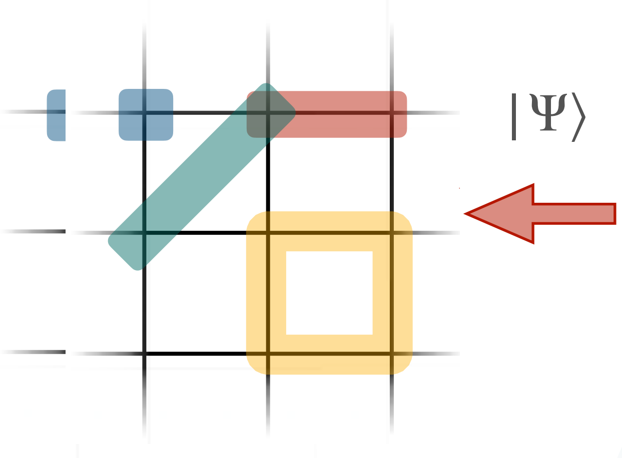
Hamiltonian?

Inverse Quantum Simulation

"inverse" ↔ "inference/learning/design" in ML

Hamiltonian

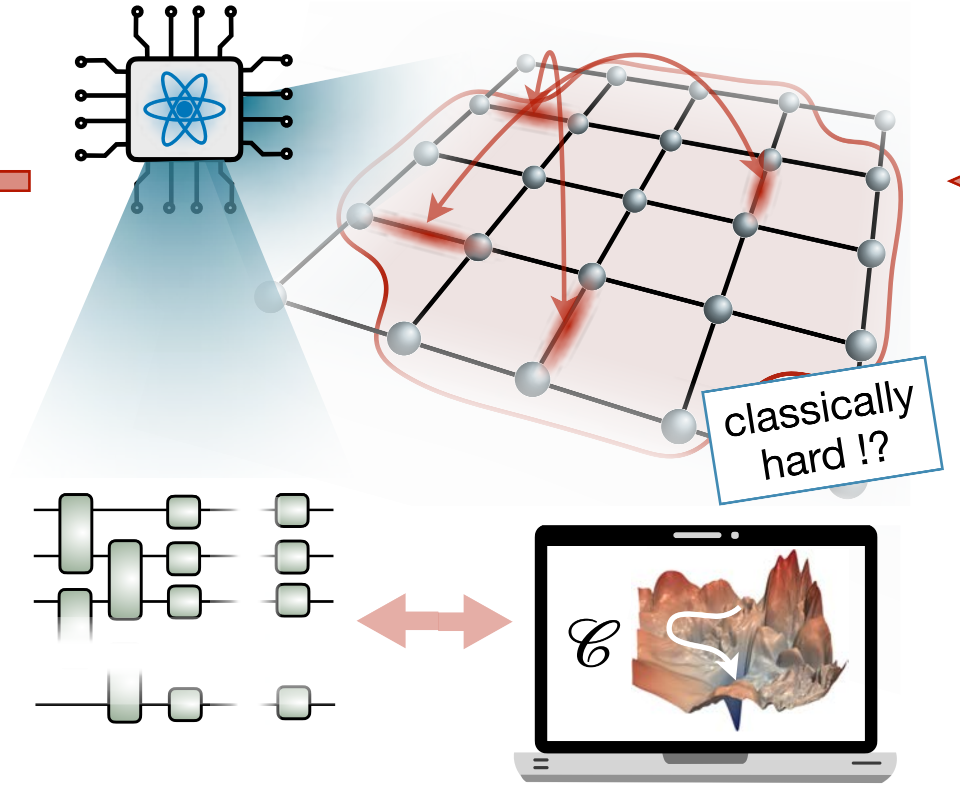
$$\hat{H} = \sum_i \hat{h}_j$$



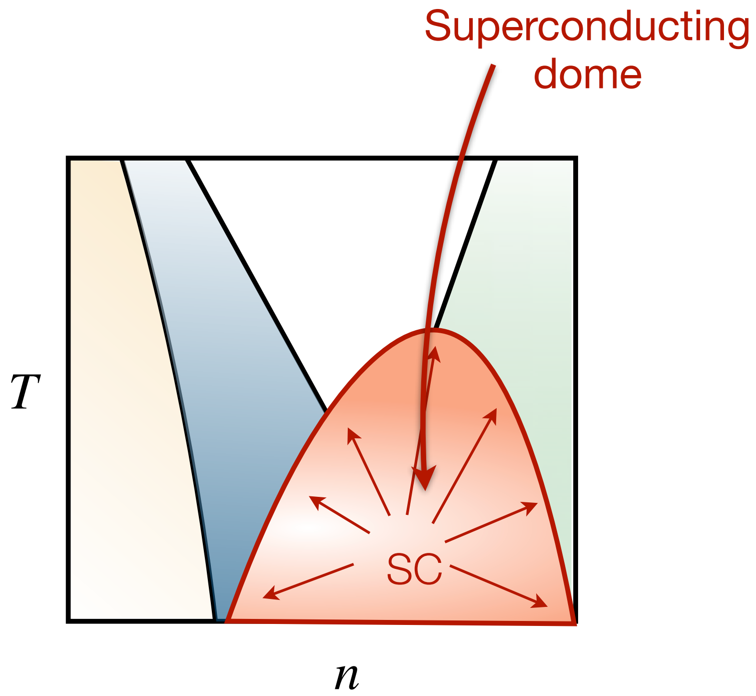
$\hat{H} = \ldots$?

with $|\Psi\rangle$ as GS

Programmable Quantum Simulator



d-wave high-Tc SC

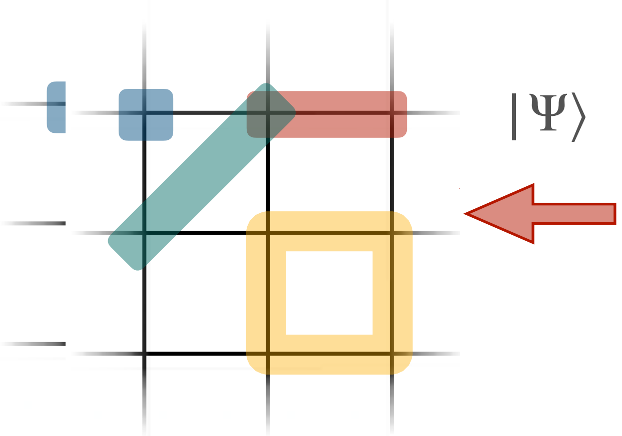


Hamiltonian Learning ← Cost Function $\mathscr{C}(|\Psi\rangle) \to \max$ ← Wishlist: material properties

Inverse Quantum Simulation

Hamiltonian

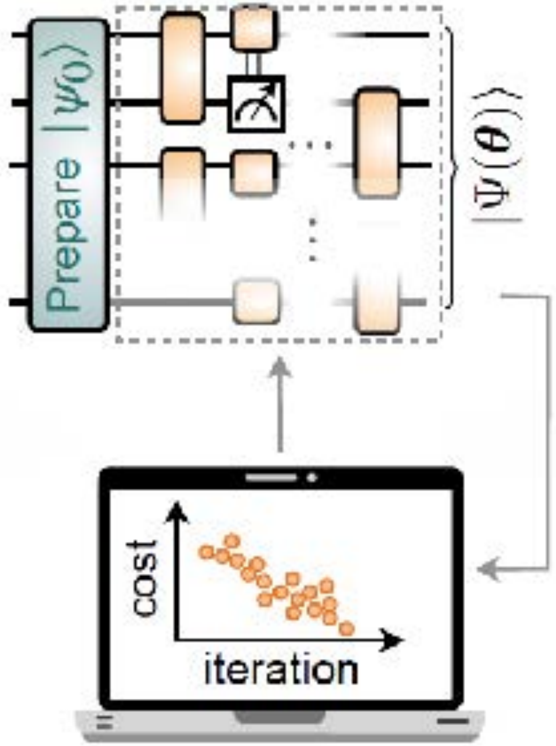
$\hat{H} = \sum_i \hat{h}_j$



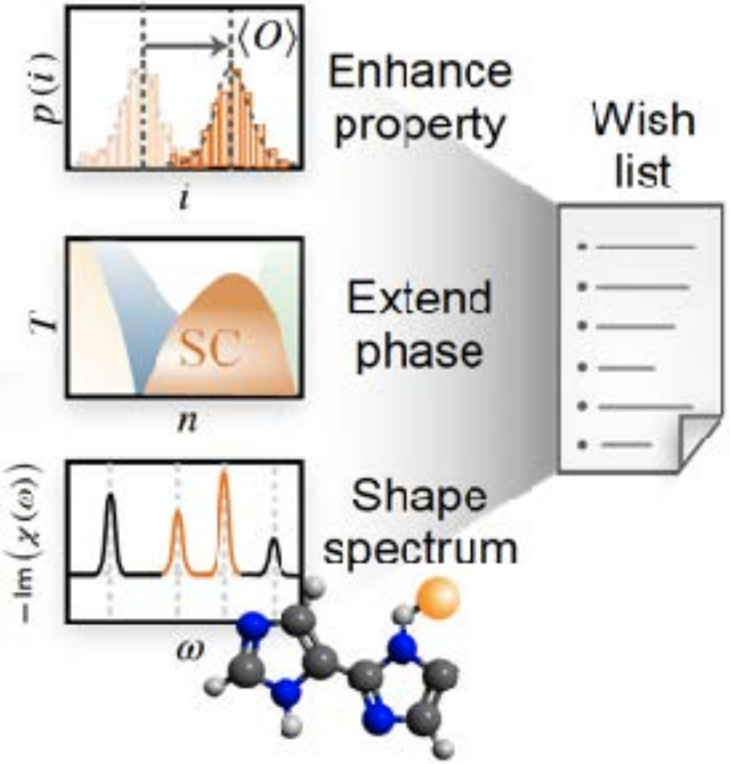
$\hat{H} = \ldots$?

with $|\Psi\rangle$ as GS

State preparation



Specify cost



Hamiltonian Learning ← Cost Function $\mathscr{C}(|\Psi\rangle) \rightarrow \max$ ← Wishlist: material properties

Hamiltonian Learning

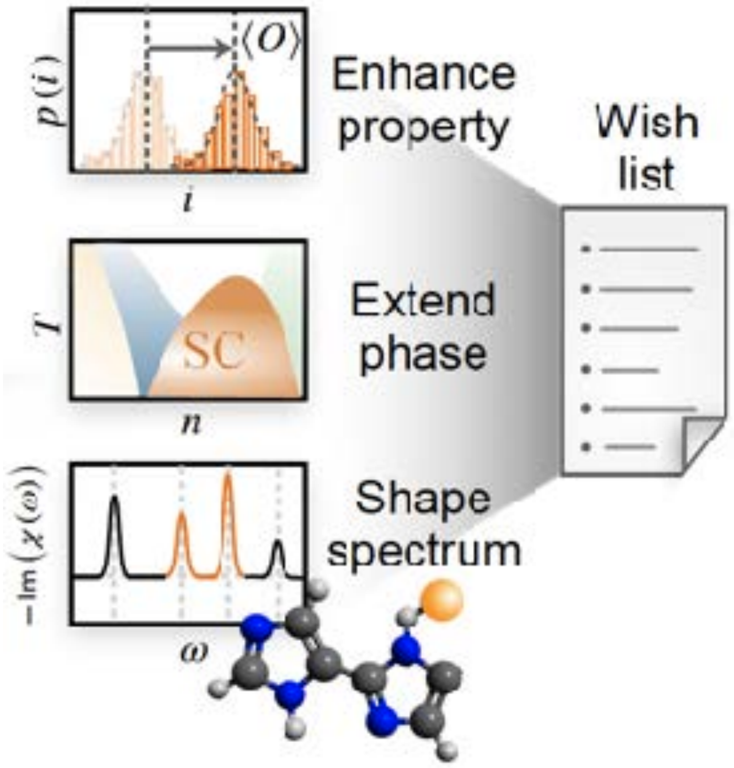
Learning Hamiltonian from single eigenstate

Algorithms for Inverse Quantum Simulation

Variational IQS

Measurement-based IQS

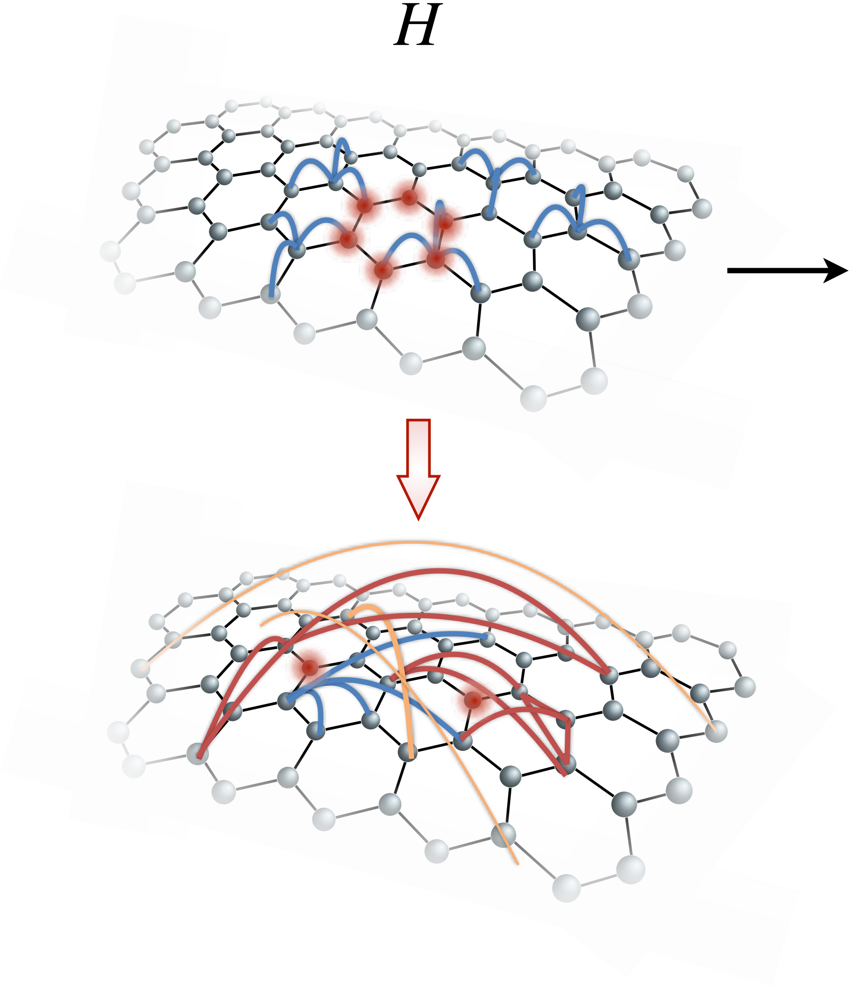
Examples

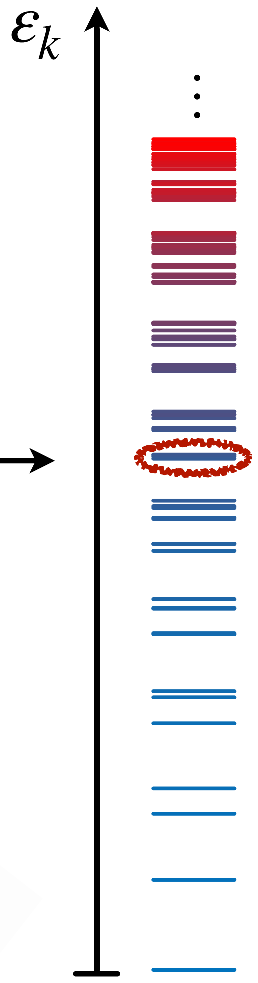


Hamiltonian Learning from Steady States

Many-body
Hamiltonian

$\hat{H}$





Select a random
eigenstate

$|\Psi_k\rangle$

Is it possible to infer
the Hamiltonian $\hat{H}$
from a single
eigenstate?

- Counterexample 1

$$\hat{H} = -\sum_i \hat{\sigma}_i^z \qquad |\Psi_G\rangle = |\downarrow\downarrow\downarrow\ldots\downarrow\rangle$$

Usually eigenstates are correlated!

- Counterexample 2

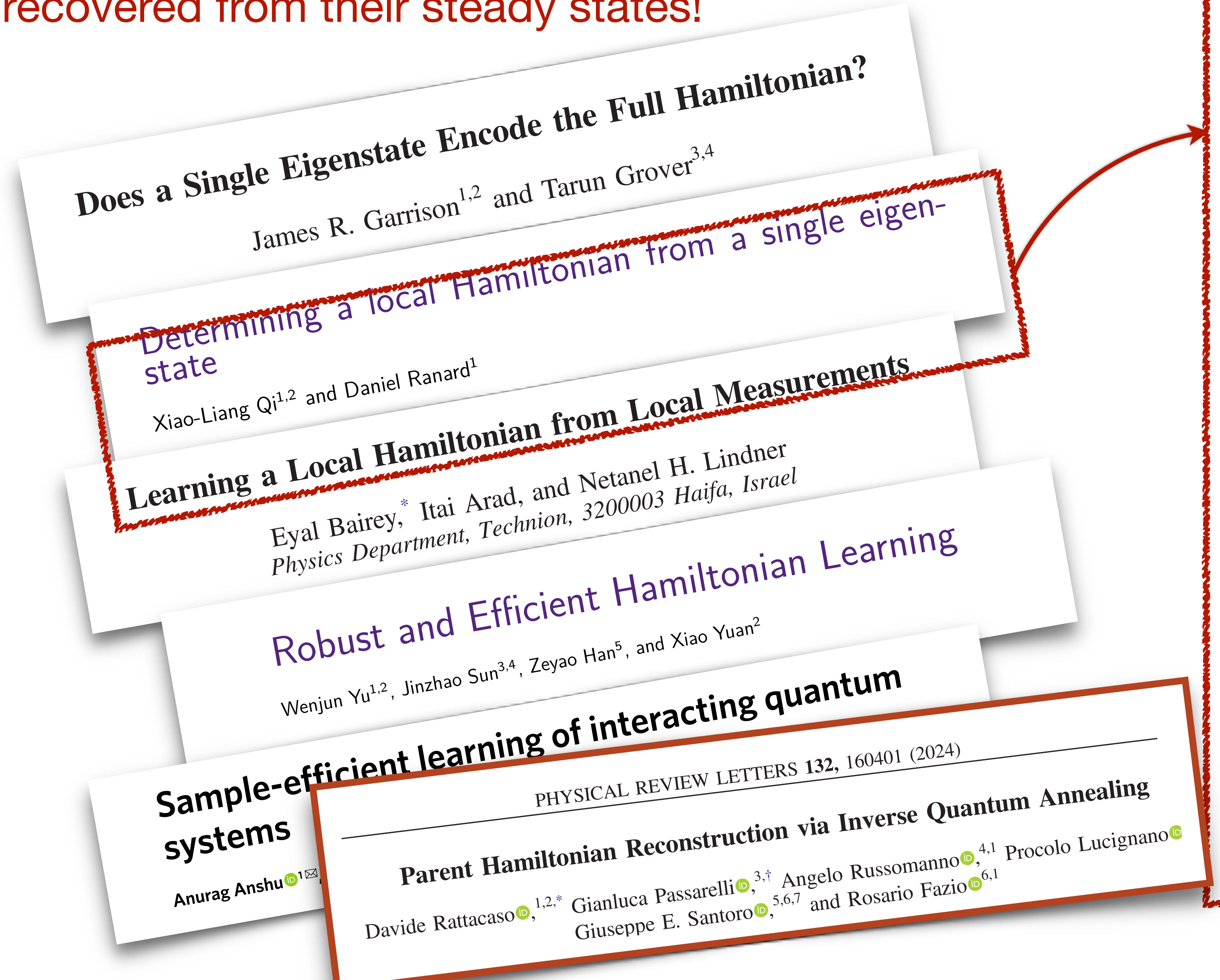
$$\hat{H} = \sum_k \varepsilon_k |\phi_k\rangle\langle\phi_k| \Rightarrow \sum_k \tilde{\varepsilon}_k |\phi_k\rangle\langle\phi_k|$$

Interesting Hamiltonians are
“local” (sparse)

See also: Netanel Lindner
@ Bar-Ilan (Youtube)

Hamiltonian Learning from Steady States

Despite specific counterexamples: Almost all local Hamiltonians can be uniquely recovered from their steady states!


Does a Single Eigenstate Encode the Full Hamiltonian?
James R. Garrison[1,2] and Tarun Grover[3,4]

Determining a local Hamiltonian from a single eigen-state
Xiao-Liang Qi[1,2] and Daniel Ranard[1]

Learning a Local Hamiltonian from Local Measurements
Eyal Bairey,* Itai Arad, and Netanel H. Lindner
Physics Department, Technion, 3200003 Haifa, Israel

Robust and Efficient Hamiltonian Learning
Wenjun Yu[1,2], Jinzhao Sun[3,4], Zeyao Han[5], and Xiao Yuan[2]

Sample-efficient learning of interacting quantum systems
Anurag Anshu[1]

PHYSICAL REVIEW LETTERS **132,** 160401 (2024)

Parent Hamiltonian Reconstruction via Inverse Quantum Annealing
Davide Rattacaso,[1,2,*] Gianluca Passarelli,[3,†] Angelo Russomanno,[4,1] Procolo Lucignano, Giuseppe E. Santoro,[5,6,7] and Rosario Fazio[6,1]

Protocol

(1) write down an ansatz for the Hamiltonian

$$\hat{H}(\boldsymbol{c}) = \sum_j c_j \hat{h}_j$$

(2) minimize the variance of the ansatz in the given state

$$\langle \Psi | \hat{H}(\boldsymbol{c})^2 | \Psi \rangle - \langle \Psi | \hat{H}(\boldsymbol{c}) | \Psi \rangle^2 \rightarrow \text{min}$$

$$\boldsymbol{c}^T G \boldsymbol{c} \rightarrow \text{min}$$

$$G_{ij} = \langle \hat{h}_i \hat{h}_j \rangle - \langle \hat{h}_i \rangle \langle \hat{h}_j \rangle$$

Q.: can we learn parent Hamiltonians for $|\Psi\rangle$ to be the ground state

Variational Inverse Quantum Simulation [Motivation]

Fixed resource quantum simulator

A quantum simulator physically realizes a fixed many-body Hamiltonian H_0 and prepares its ground state $|\psi_0\rangle$, which is classically nontrivial.

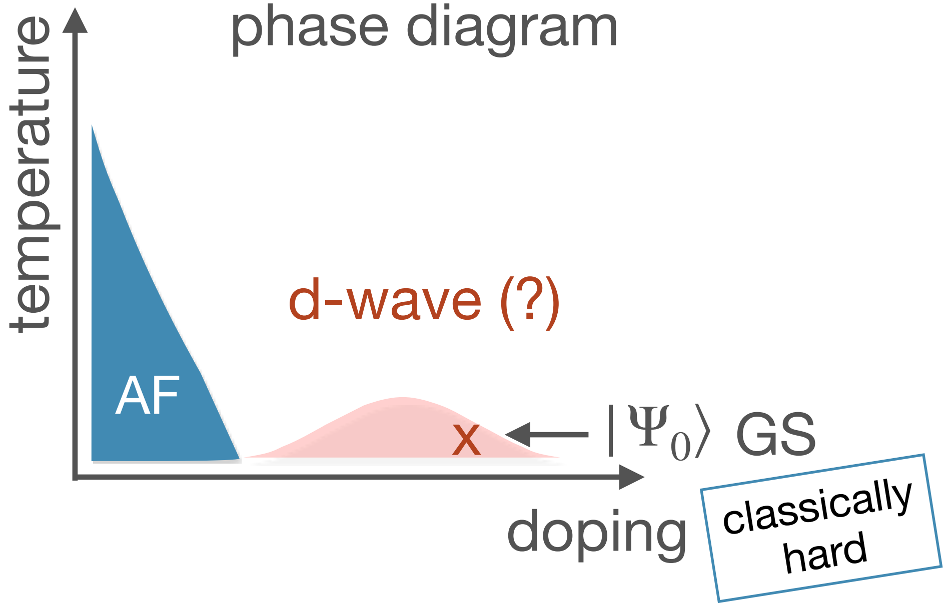
Key question:

Can fixed quantum device be used to explore Hamiltonians

$$H(\lambda) = \sum_i \lambda_i h_i \qquad \text{parametrized by } \{\lambda_i\}$$

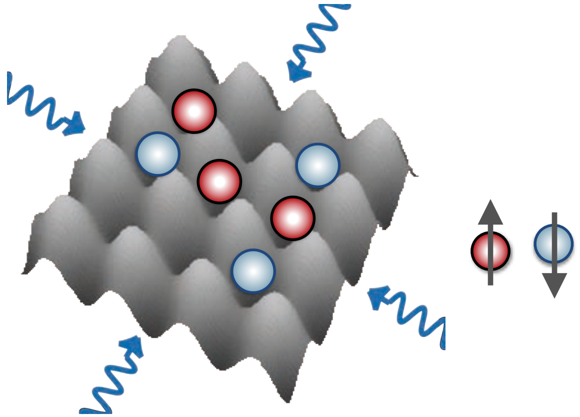
in the neighborhood of H_0, *without ever implementing* $H(\lambda)$ *physically?*

And identify the Hamiltonian maximizing cost function $\mathscr{C} \equiv \langle C \rangle$ of interest.



$$\hat{H}_0 = -\sum_{\langle ij \rangle} t \left(\hat{c}^\dagger_{i\sigma} \hat{c}_{j\sigma} + \text{h.c.} \right) + U \sum_i \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$$

tunneling — onsite interaction



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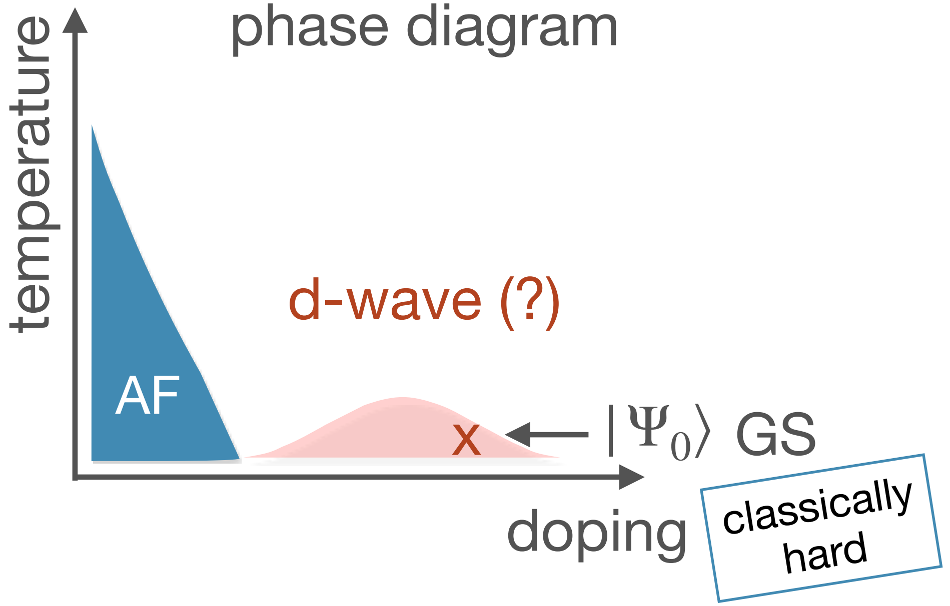

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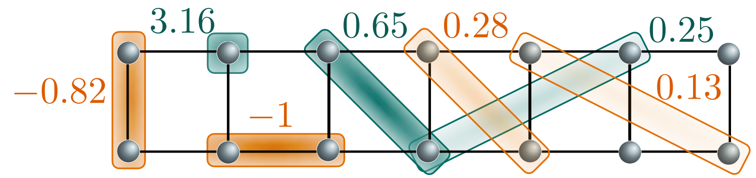
Extended Hubbard Model

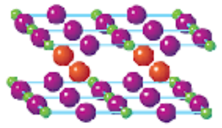


$$\hat{H} = -\sum_{\langle ij\rangle,\sigma} t_{ij}\left(\hat{c}^\dagger_{i\sigma}\hat{c}_{j\sigma} + \text{H.c.}\right) - \sum_{\langle\langle ij\rangle\rangle,\sigma} t'_{ij}\left(\hat{c}^\dagger_{i\sigma}\hat{c}_{j\sigma} + \text{H.c.}\right) + U\sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$

X hopping

$$+ \sum_{\langle ij\rangle,\sigma,\sigma'} V_{ij}\hat{n}_{i\sigma}\hat{n}_{j\sigma'} + \sum_{\langle\langle ij\rangle\rangle,\sigma,\sigma'} V'_{ij}\hat{n}_{i\sigma}\hat{n}_{j\sigma'}$$

nn & nnn interactions



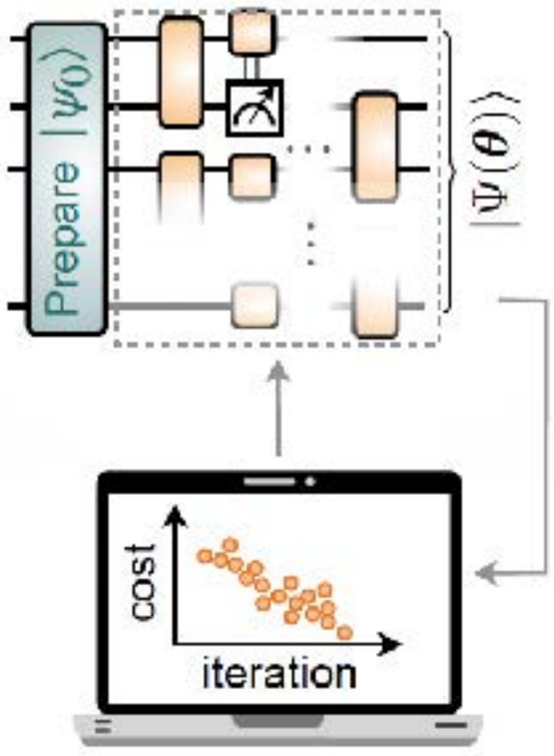
Variational Inverse Quantum Simulation [Key Idea]

Variational quantum states

Starting from $|\psi_0\rangle$, generate variational states

$$|\psi(\mu)\rangle = U(\mu)|\psi_0\rangle$$

expressivity of circuit



Central Map: *Dictionary*

For each μ, infer the Hamiltonian in a chosen model class for which $|\psi(\mu)\rangle$ is an exact or approx. eigen-/groundstate.

$$\mu \mapsto \lambda_*(\mu), \qquad H(\lambda) \iff |\psi(\mu)\rangle = U(\mu)|\psi_0\rangle$$

Hamiltonian learning

Hamiltonians near H_0 | quantum states near $|\psi_0\rangle$

Dictionary

$$H(\lambda) = \sum_i \lambda_i h_i \longleftrightarrow |\psi(\mu)\rangle = U(\mu)|\psi_0\rangle$$

quantum resource

Variational Inverse Quantum Simulation [Key Idea]

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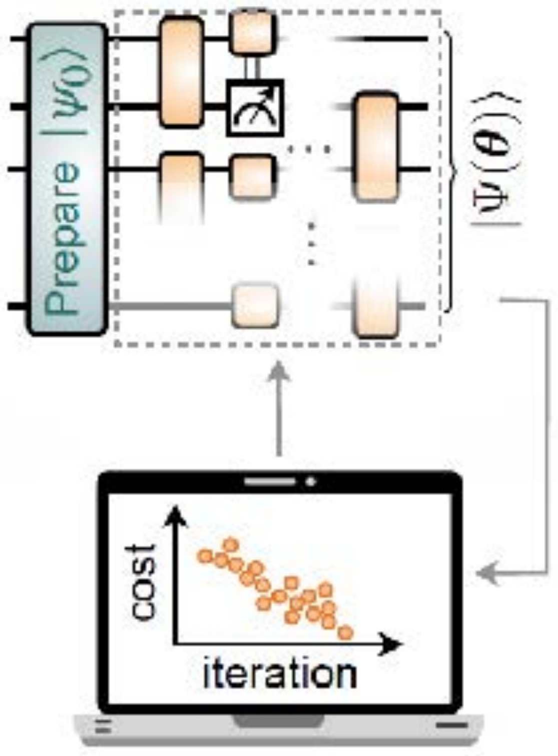

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Hamiltonian learning

Protocol: *Hamiltonian Learning*

Infer $H(\lambda) = \sum_i \lambda_i h_i$, by variance minimization:

$$\lambda_*(\mu) = \arg\min_\lambda \mathrm{Var}_{\psi(\mu)}[H(\lambda)] \quad \text{with} \quad \mathrm{Var}_{\psi(\mu)}[H(\lambda)] = \langle H(\lambda)^2\rangle_\mu - \langle H(\lambda)\rangle_\mu^2$$

Poly# in system size

$$= \sum_{ij} \lambda_i \lambda_j \Big(\langle h_i h_j\rangle_\mu - \langle h_i\rangle_\mu \langle h_j\rangle_\mu \Big).$$

Variational Inverse Quantum Simulation [Key Idea]

Variational quantum states

Starting from $|\psi_0\rangle$, generate variational states

$$|\psi(\mu)\rangle = U(\mu)|\psi_0\rangle$$

expressivity of circuit

Central Map: *Dictionary*

For each μ, infer the Hamiltonian in a chosen model class for which $|\psi(\mu)\rangle$ is an exact or approx. eigen-/groundstate.

$$\mu \mapsto \lambda_*(\mu), \qquad H(\lambda) \Longleftrightarrow |\psi(\mu)\rangle = U(\mu)|\psi_0\rangle$$

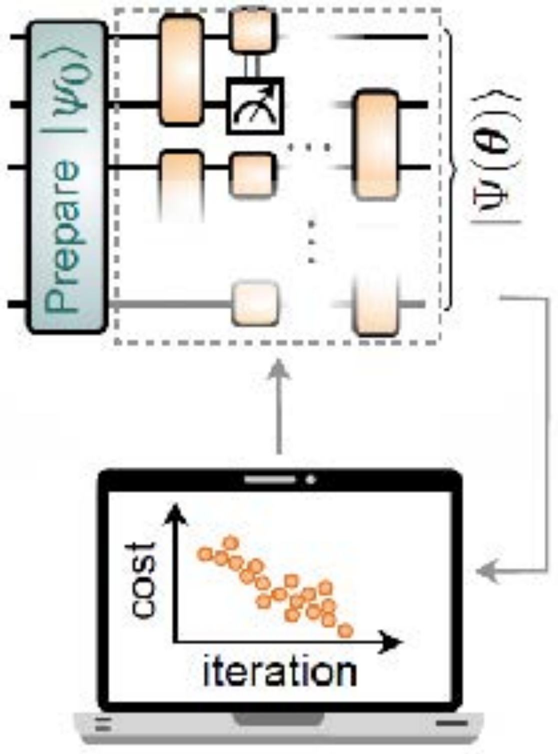
Hamiltonian learning

Observables for nearby Hamiltonians

Then the fixed simulator provides:

$$H(\lambda_*(\mu)) \mapsto \langle O \rangle_\mu = \langle \psi(\mu)|O|\psi(\mu)\rangle$$

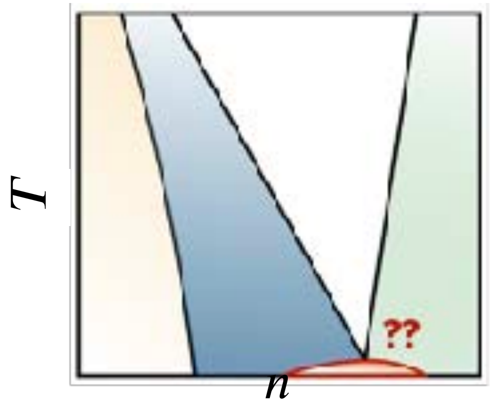
and find Hamiltonian which maximizes the cost C.



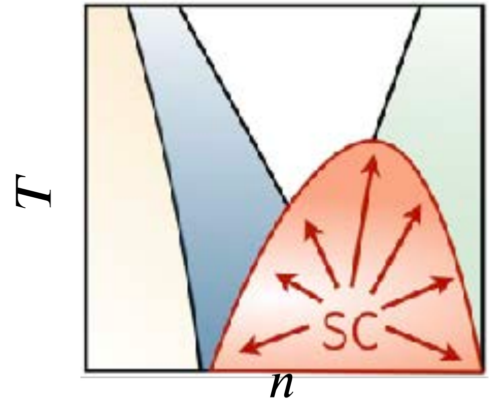
hybrid quantum-classical protocol

Inverse Quantum Simulation - Example: 2D fermionic Hubbard model

Hamiltonian: $$\hat{H}_0 = -\sum_{\langle ij \rangle} t\left(\hat{c}^\dagger_{i\sigma}\hat{c}_{j\sigma} + \text{ h.c. }\right) + U\sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$



IQS




Absence of Superconductivity in the Pure Two-Dimensional Hubbard Model

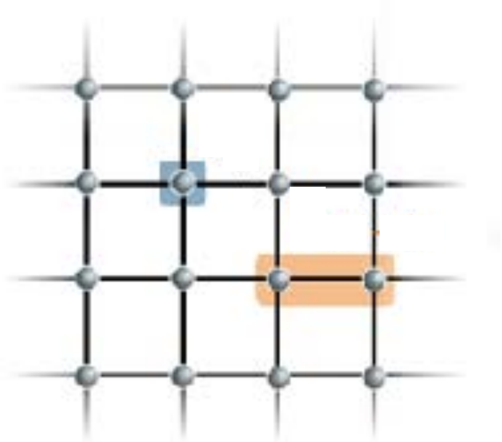
Mingpu Qin, Chia-Min Chang, Hao Shi, Ettore Vitali, Claudius Hubig, Ulrich Schollwöck, Steven R. White, and Shiwei Zhang

(Simons Collaboration on the Many-Electron Problem)

SUPERCONDUCTIVITY

Superconductivity in the doped Hubbard model and its interplay with next-nearest hopping t'

Hong-Chen Jiang and Thomas P. Devereaux

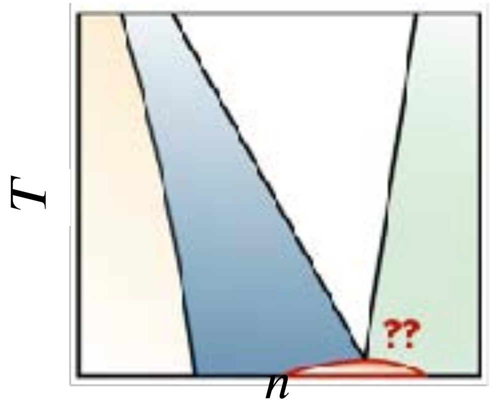


To illustrate IQS we study Hubbard ladders

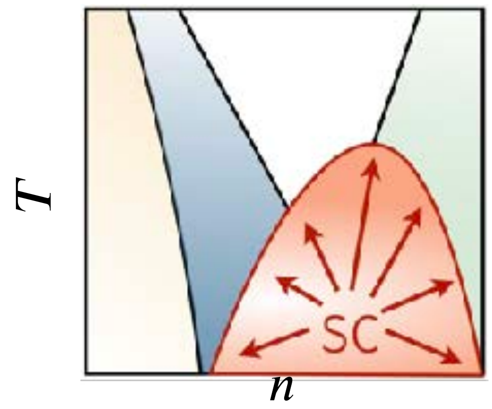
1. Fermionic sign problem, exp. growth of bond dimension

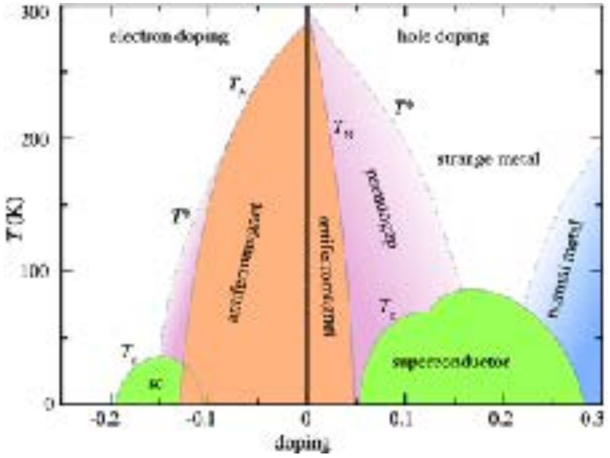
2. Many competing phases (superconductivity, charge density waves, complex magnetism)

Enhancing d-wave correlations



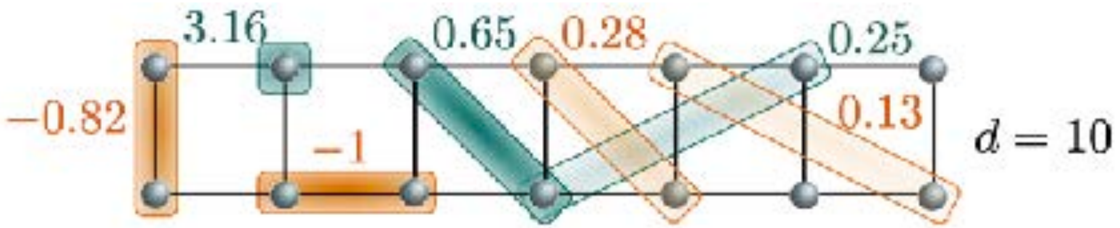
IQS



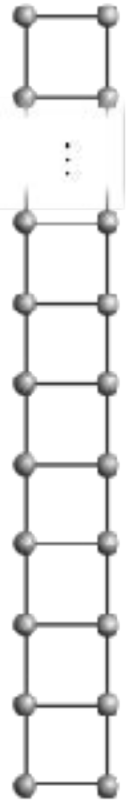


Results

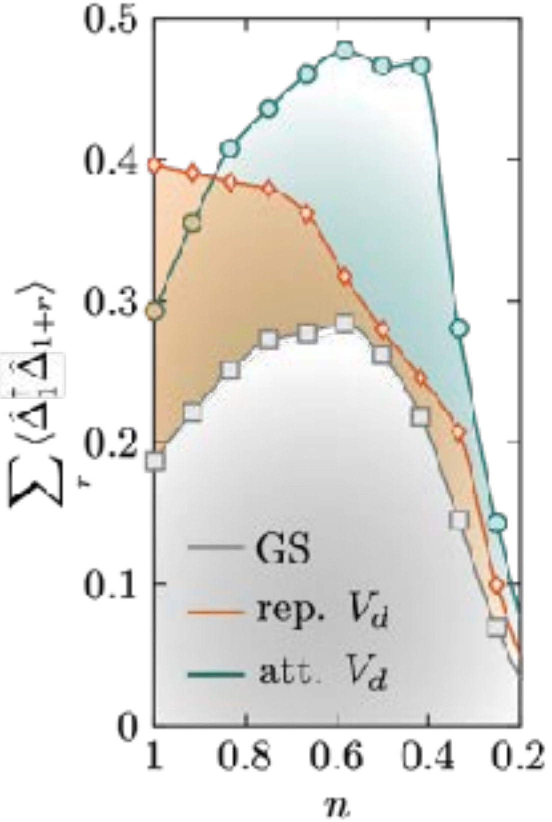
Learned Hamiltonian



2 x 24 ladder



d-wave



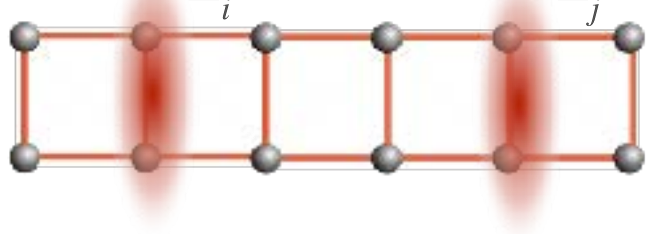
Enhancing d-wave correlations

Objective: max d-wave

$$\mathscr{C}(\boldsymbol{\theta}) = -\sum_{i,j} \left\langle \hat{\Delta}_i^\dagger \hat{\Delta}_j \right\rangle_{\boldsymbol{\theta}} \rightarrow \text{min}$$

with $\hat{\Delta}_i^\dagger = \hat{c}_{i_1\uparrow}^\dagger \hat{c}_{i_2\downarrow}^\dagger - \hat{c}_{i_1\downarrow}^\dagger \hat{c}_{i_2\uparrow}^\dagger$

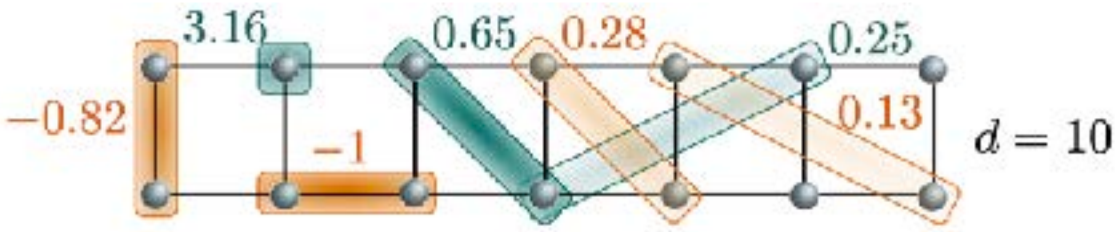
singlet on rungs



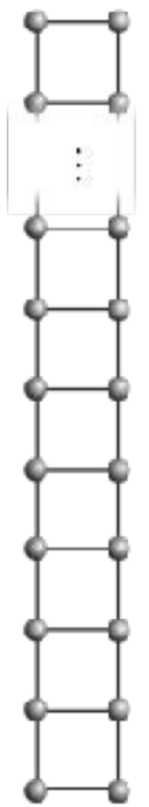
long range order

Results

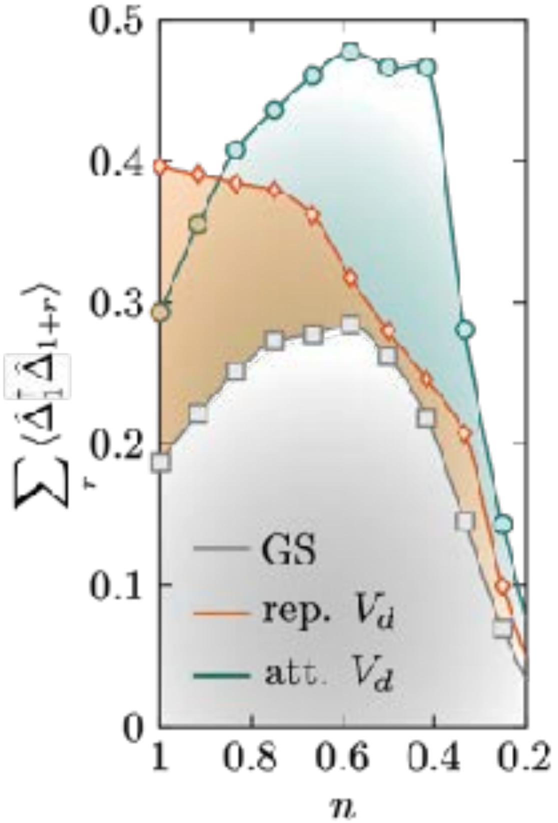
Learned Hamiltonian



2 x 24 ladder



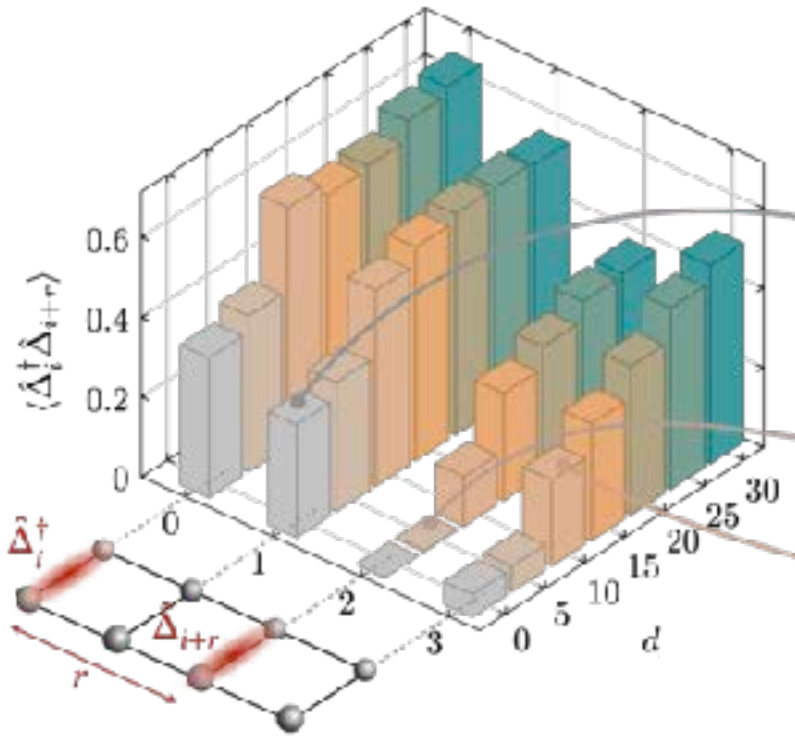
d-wave



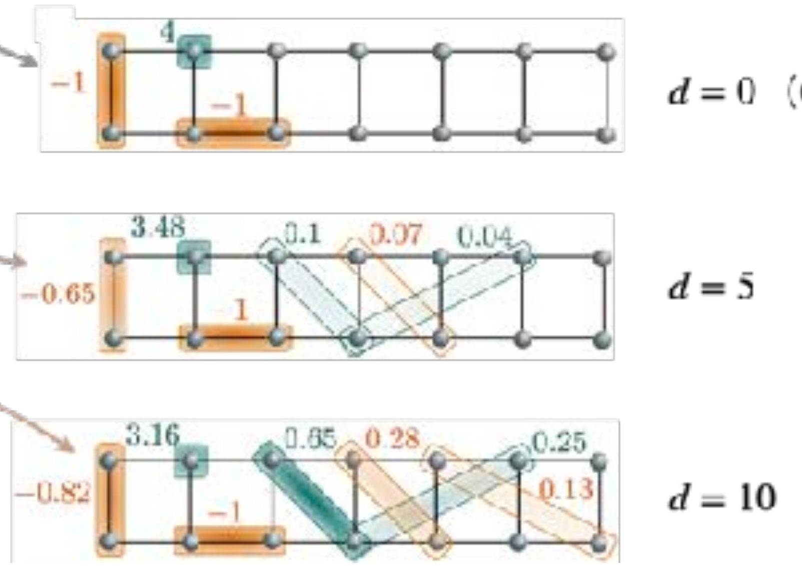
Enhancing d-wave correlations

Results

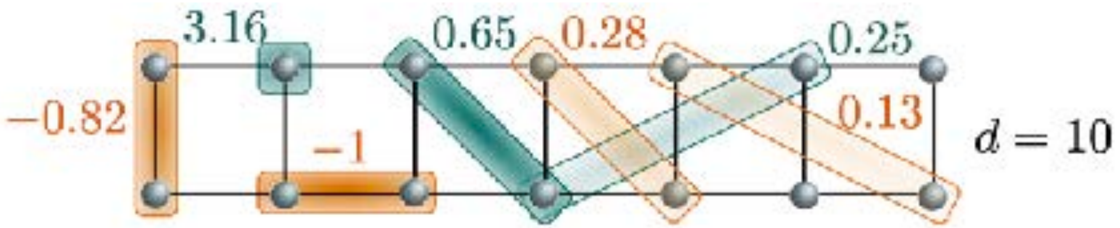
IQS to enhance d-wave like



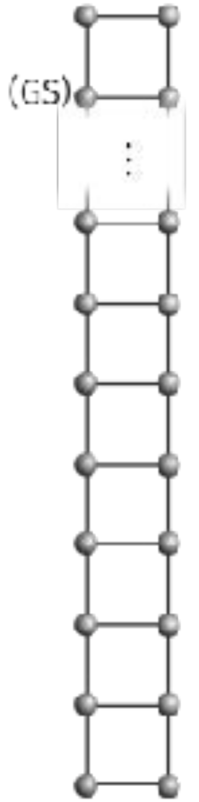
Hamiltonian Learning



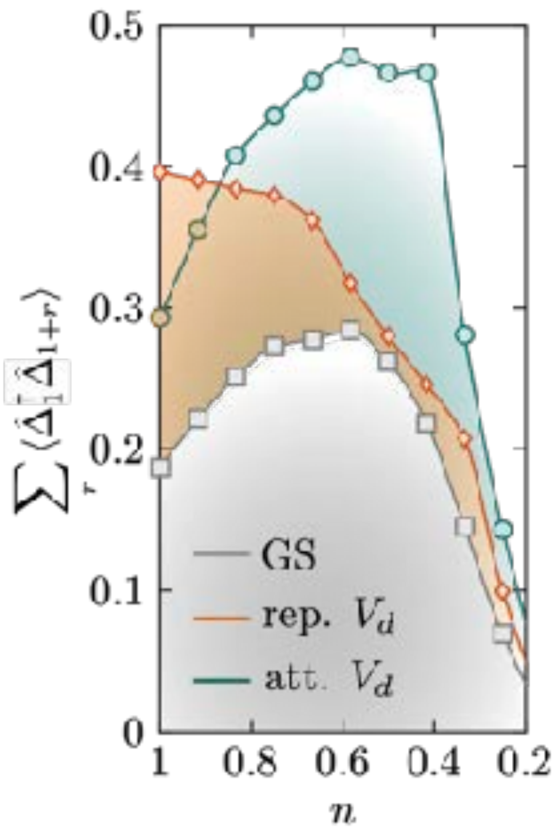
Learned Hamiltonian



2 x 24 ladder



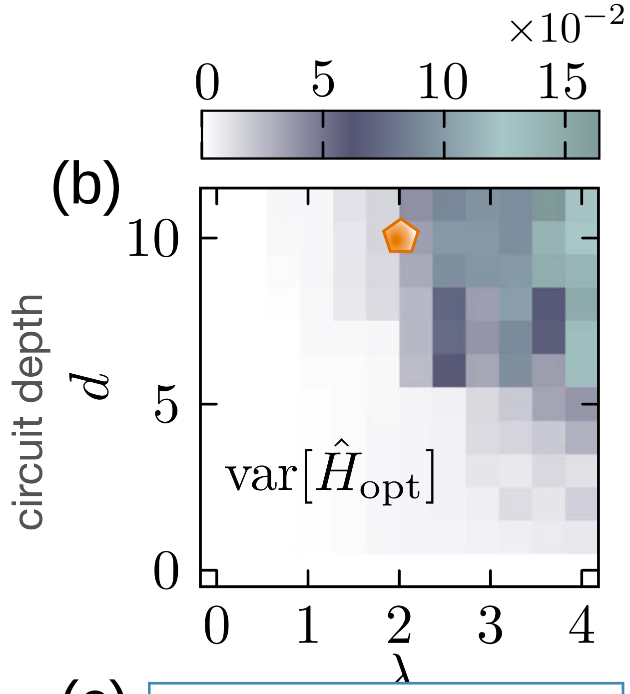
d-wave



1. cost function $\mathscr{C}[\boldsymbol{\theta};\lambda] = \left\langle \hat{H}_0 \right\rangle_{\boldsymbol{\theta}} - \lambda \sum_r \left\langle \hat{\Delta}_1^\dagger \hat{\Delta}_{1+r} \right\rangle_{\boldsymbol{\theta}}$

2. variational wave fct $|\Psi(\boldsymbol{\theta})\rangle = \cdots V(\theta_3) U_y(\theta_2) U_x(\theta_1) |\Psi_0\rangle$ circuit depth d

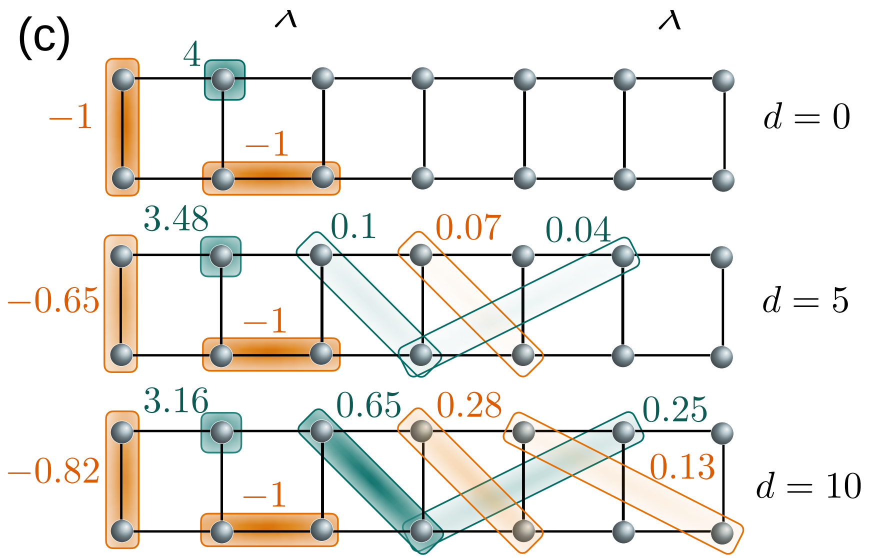
- Learning Maps: scans of (λ, d)



how close to eigenstate

how close to ground state

- Learned Hamiltonians



3. We search for optimal Hamiltonians in family

$$\hat{H} = -\sum_{\langle ij\rangle,\sigma} t_{ij}\left(\hat{c}^\dagger_{i\sigma}\hat{c}_{j\sigma} + \text{H.c.}\right) - \sum_{\langle\langle ij\rangle\rangle,\sigma} t'_{ij}\left(\hat{c}^\dagger_{i\sigma}\hat{c}_{j\sigma} + \text{H.c.}\right) + U\sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow} + \sum_{\langle ij\rangle,\sigma,\sigma'} V_{ij}\hat{n}_{i\sigma}\hat{n}_{j\sigma'} + \sum_{\langle\langle ij\rangle\rangle,\sigma,\sigma'} V'_{ij}\hat{n}_{i\sigma}\hat{n}_{j\sigma'}$$

Summary:

Forward Quantum Simulation

- Hypothesis testing (understanding materials)
- Study quantum many-body phenomena
- In and out-of-equilibrium

Exploration, Discovery

exploring Hamiltonians

Inverse Quantum Simulation

Utility

Machine Learning ○ `Quantum Advantage'

learning Hamiltonian *quantum device*

Active Design

designing Hamiltonians

shifting the quantum simulation paradigm

Hamiltonian Learning
as toolbox in quantum simulation exp

Tristan Kraft

Manoj Joshi

theory + trapped ion exp

N=10 and 51 ions

Hamiltonian (and Lindbladian) Learning

Quantum Simulation with a Certified Error

Theory & Experiment

T Kraft, MK Joshi, W Lam, T Olsacher, F Kranzl, J Franke, LKh Joshi, R Blatt, A Smerzi, D Stilck-França, B Vermersch, B Kraus, CF Roos, and PZ, arXiv:2511.23392

collaboration Innsbruck, TUM, Copenhagen, Grenoble

Hamiltonian Learning
as toolbox in quantum simulation exp

Tristan Kraft

Manoj Joshi

theory + trapped ion exp

N=10 and 51 ions

Hamiltonian (and Lindbladian) Learning

Quantum Simulation with a Certified Error

Theory & Experiment

Can we trust quantum simulators?

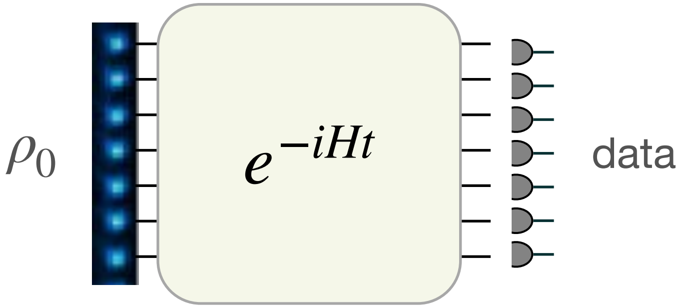
… as devices solving the many-body problem

… making predictions, with certified accuracy

… in regime of quantum advantage?

Bounded-Error Quantum Simulation

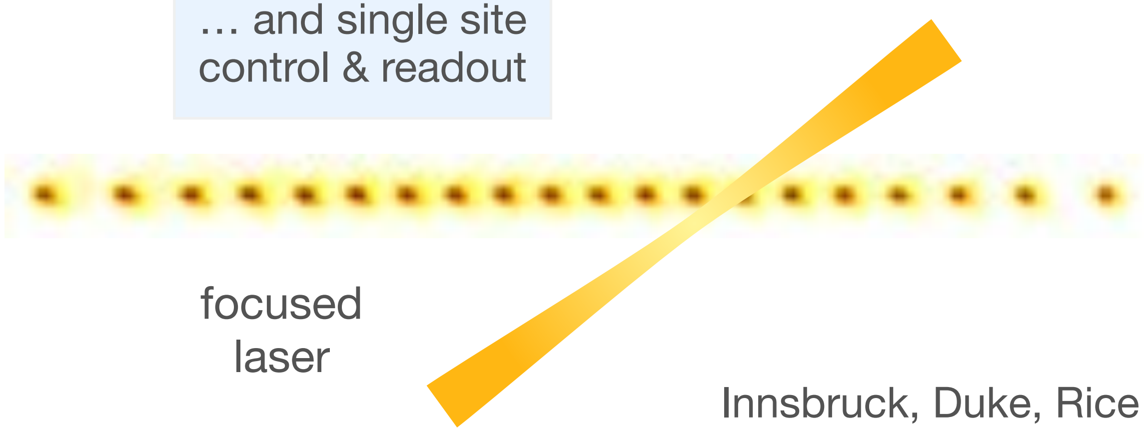
Analog QSimulator (NISQ)



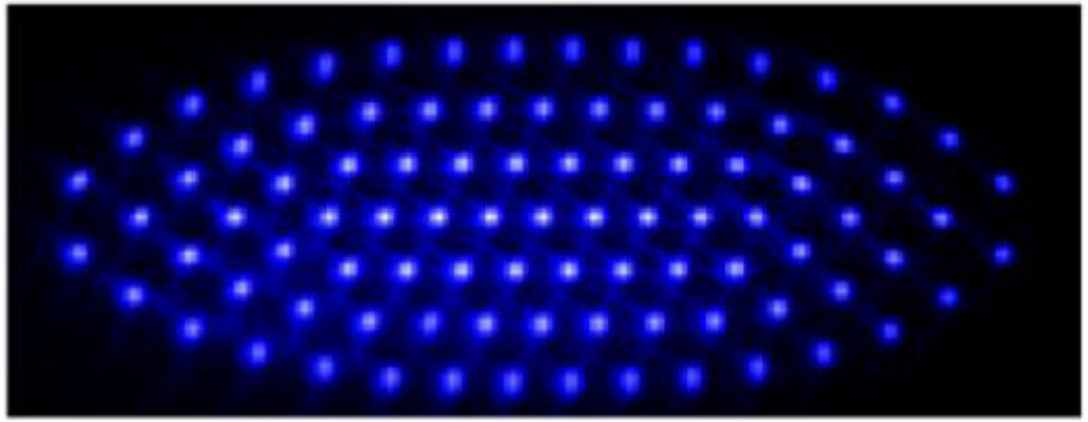
… in `regime of quantum advantage’

Programmable Trapped-Ion Quantum Simulators [1D,2D]

… and single site
control & readout



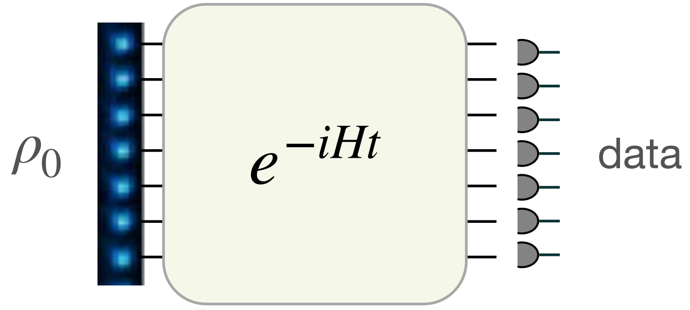
Innsbruck, Duke, Rice …



Innsbruck [Roos] ~200 ions, Tsinghua, ~1000 ions

Bounded-Error Quantum Simulation

Analog QSimulator (NISQ)



… as a Computational Device with controlled error

Hamiltonian — observable

$$H \longrightarrow \langle O_t \rangle = \mathrm{Tr}\left[O\rho_t\right] = \mathrm{Tr}\left[O e^{-iHt} \rho_0 e^{iHt}\right]$$

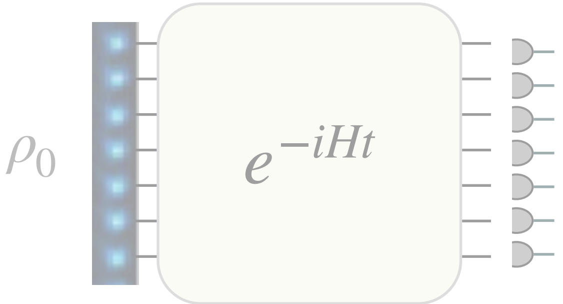
Do we *know* H ? SPAM?

… in `regime of quantum advantage'

what the quantum machine does

Bounded-Error Quantum Simulation

Analog QSimulator (NISQ)



… as a Computational Device

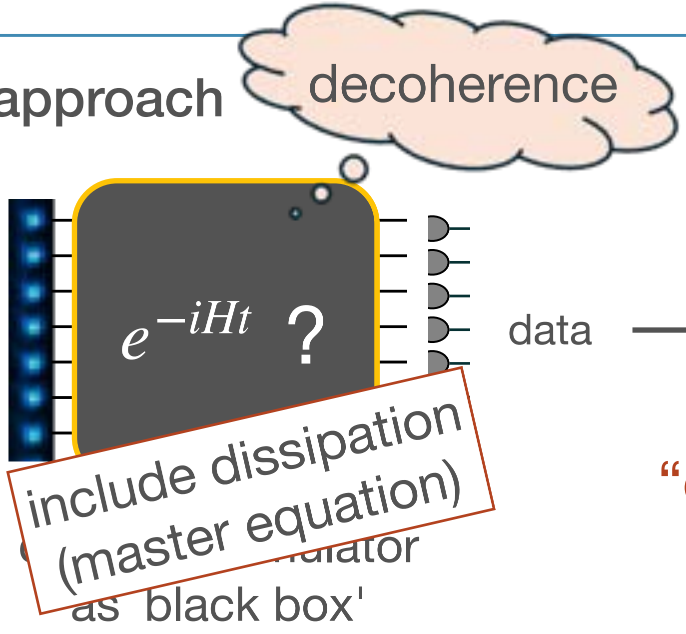
Hamiltonian — observable

$$H \longrightarrow \langle O_t \rangle = \mathrm{Tr}\left[O\rho_t\right] = \mathrm{Tr}\left[Oe^{-iHt}\rho_0 e^{iHt}\right]$$

Do we *know* H ?

… in `regime of quantum advantage'

Our approach



Step 1: Hamiltonian Learning

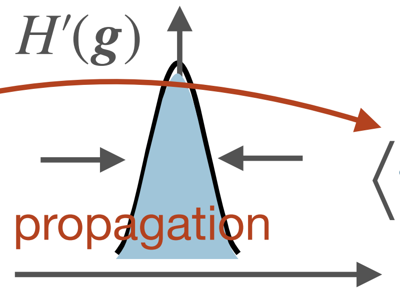
$$H_{\text{learned}} + \text{error}$$

$$+ \sum_{i=1}^{M} g_i V_i$$

- We learn from experiment H up to statistical uncertainties
- We can learn H *efficiently: poly # size*

"our knowledge of Hamiltonian" (Bayesian Learning)

Step 2: Q-Simulation



error propagation

$\langle O_t \rangle$ + error

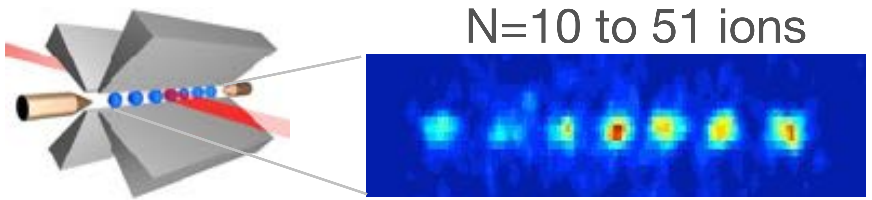
g_i stochastic, Gaussian

✓ via classical simulation [q-c]

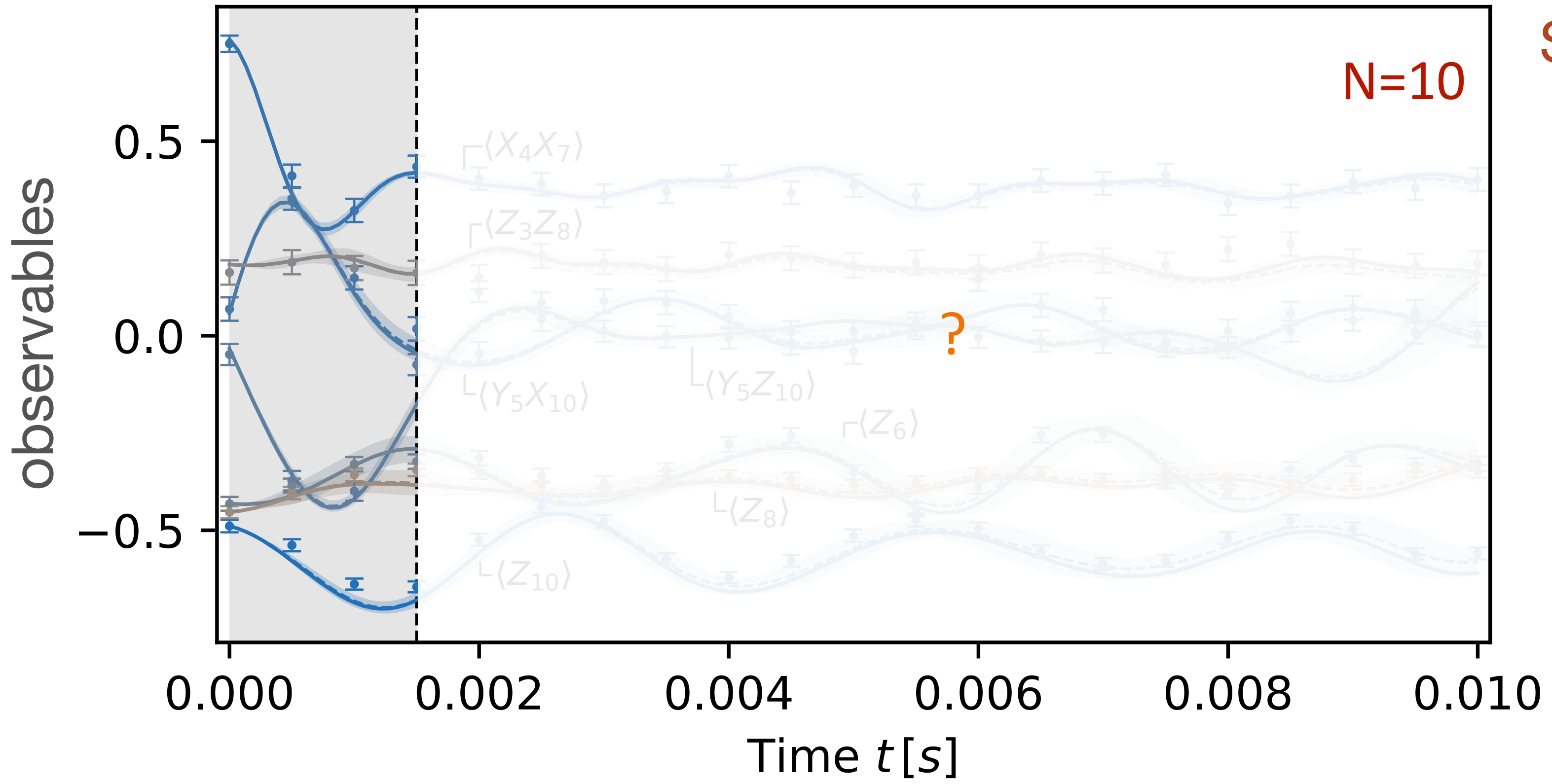
✓ from exp data alone [q-q]

We *know* ***what*** the machine does/computes, and the ***precision!*** (~ Quantum Metrology)

Step 1: Hamiltonian & Lindbladian Learning

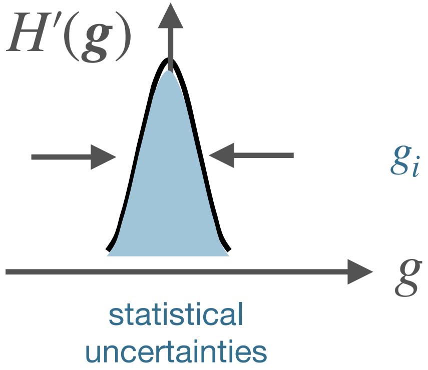


Learning Window



Step 1: Hamiltonian & Lindbladian
Learning from experimental data
including uncertainties

$$H_{\text{learned}} + \sum_{i=1}^{M} g_i V_i$$

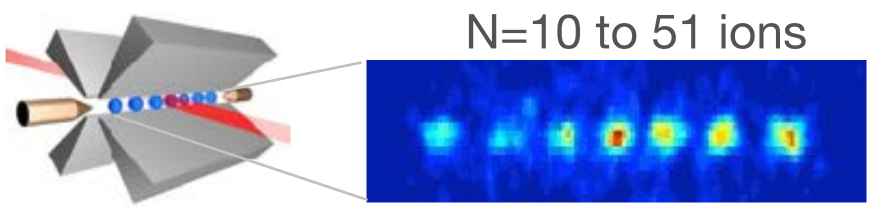


g_i stochastic, Gaussian

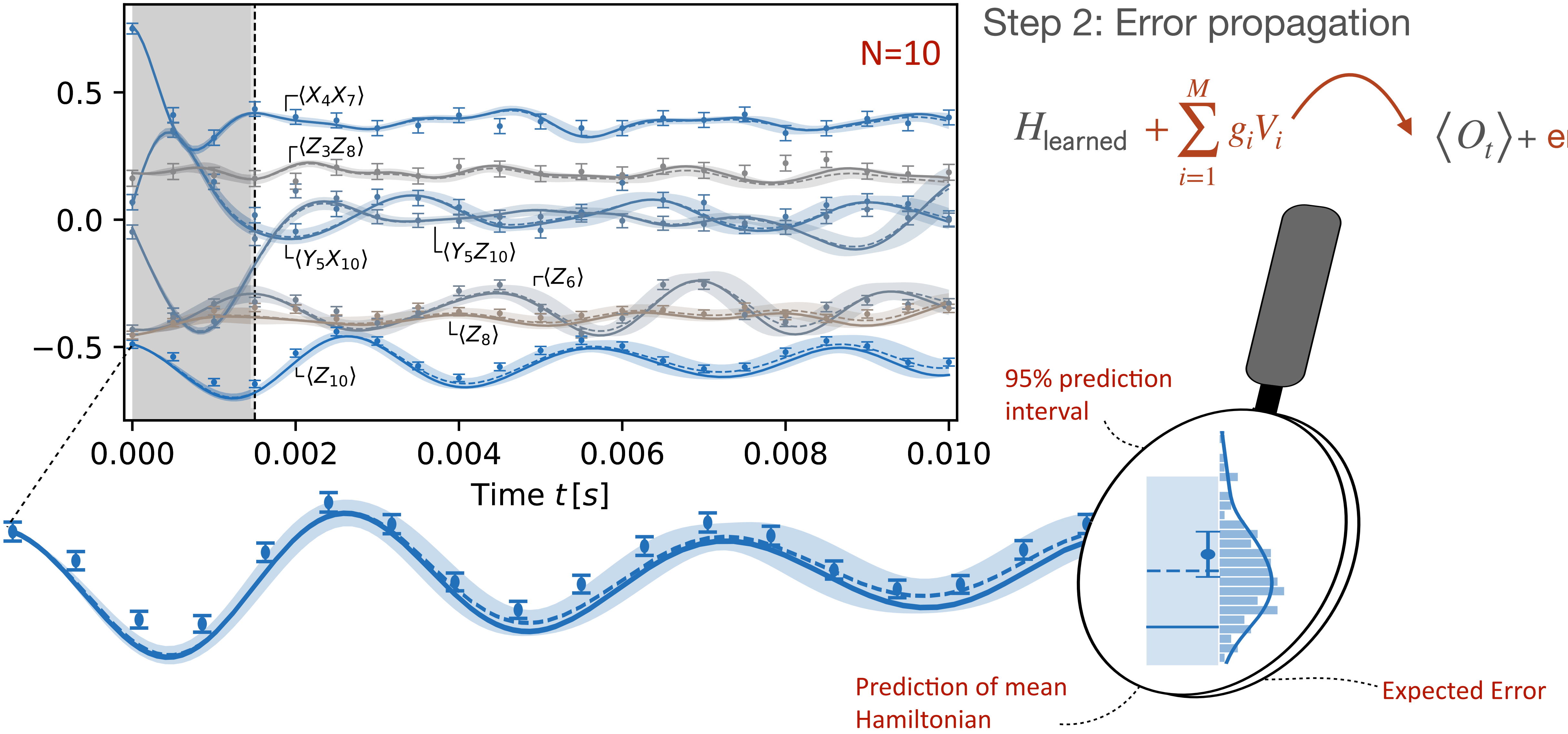
"our knowledge of Hamiltonian"

and Lindbladian …

Step 2: Bounded-Error Quantum Simulation



Learning Window | Model Predictions



Step 2: Error propagation

$$H_{\text{learned}} + \sum_{i=1}^{M} g_i V_i \rightarrow \langle O_t \rangle + \text{error}$$

Fermions in Quantum Optics

quantum optics = world of two-level atoms interacting with photons

open quantum system

photons ≙ bosons

two=level atoms = spin-½ = qubits

Inhibition of Spontaneous Emission

EUROPHYSICS LETTERS 1 October 1998
Europhys. Lett., **44** (1), pp. 1-6 (1998)

Inhibition of spontaneous emission in Fermi gases

TH. BUSCH, J. R. ANGLIN, J. I. CIRAC and P. ZOLLER
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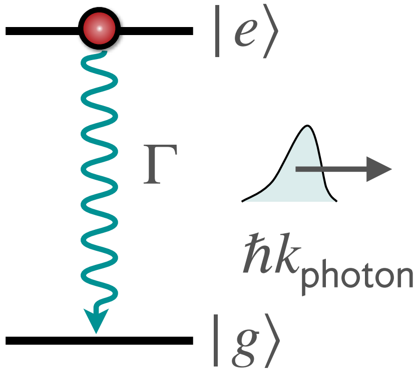

QUANTUM GASES *Science* **374**, 972–975 (2021)

Observation of Pauli blocking in light scattering from quantum degenerate fermions

Amita B. Deb* and Niels Kjærgaard

QUANTUM GASES *Science* **374**, 979–983 (2021)

Pauli blocking of atom-light scattering

Christian Sanner*†, Lindsay Sonderhouse†, Ross B. Hutson, Lingfeng Yan, William R. Milner, Jun Ye*

QUANTUM GASES *Science* **374**, 976–979 (2021)

Pauli blocking of light scattering in degenerate fermions

Yair Margalit[1,2]*, Yu-Kun Lu[1,2], Furkan Çağrı Top[1,2], Wolfgang Ketterle[1,2]

… turning off decoherence

engineered quantum reservoir

Inhibition of Spontaneous Emission

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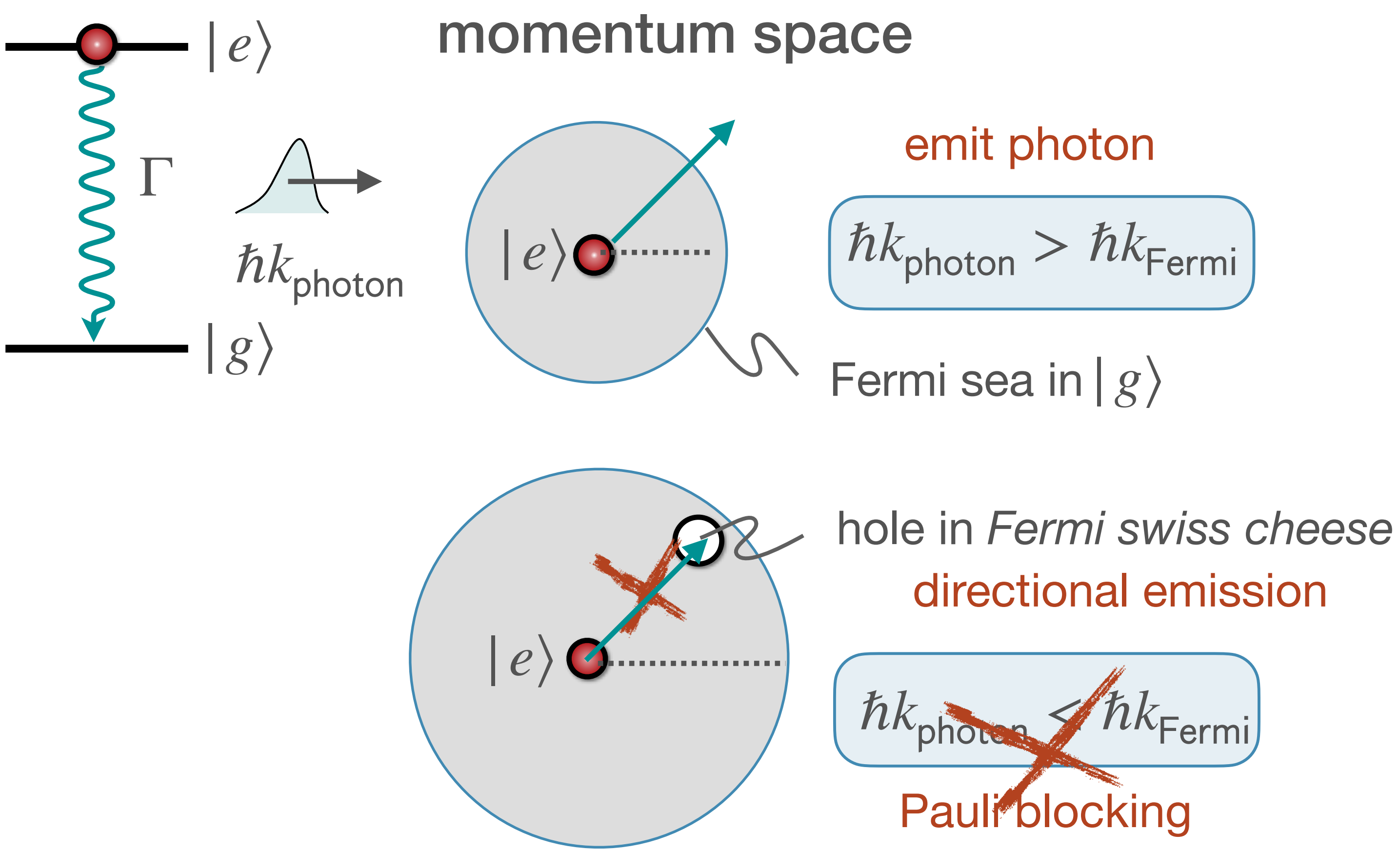

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QUANTUM GASES

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Features

- turning off spont. emission (decoherence)
- engineered directional emission
- many body system :-(

compare:
✓ collisional Pauli blocking
✓ suppression in cavity & nanophotonics

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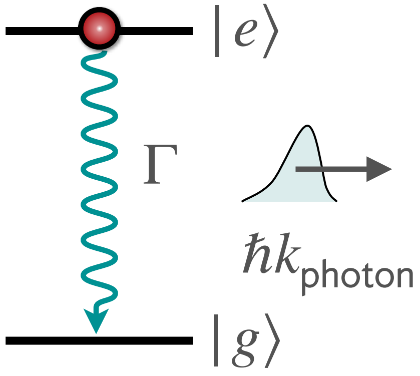

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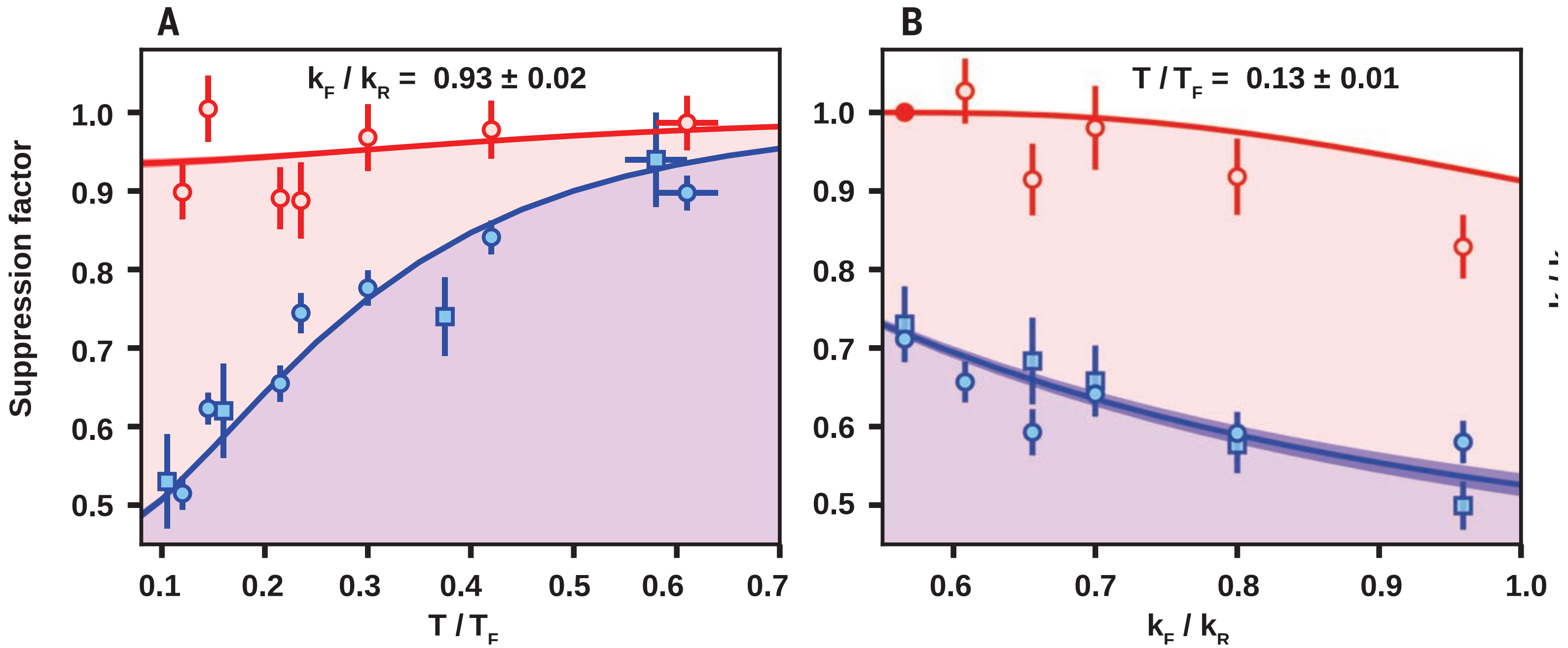

Fig. 3. Suppression of light scattering in a ^{87}Sr Fermi gas over a range of temperatures and Fermi momentums. All measurements are performed with

Summary

Fermi Quantum Processors & Simulators

analog and digital, hardware fermions

error correction, fermionic quantum advantage

Inverse Quantum Simulation: exploration → active design

phase diagram → Hamiltonian

Utility

Machine Learning

`Quantum Advantage’

Hamiltonian and Lindbladian Learning

Bounded-Error Quantum Simulation

certified error

enhance d-wave