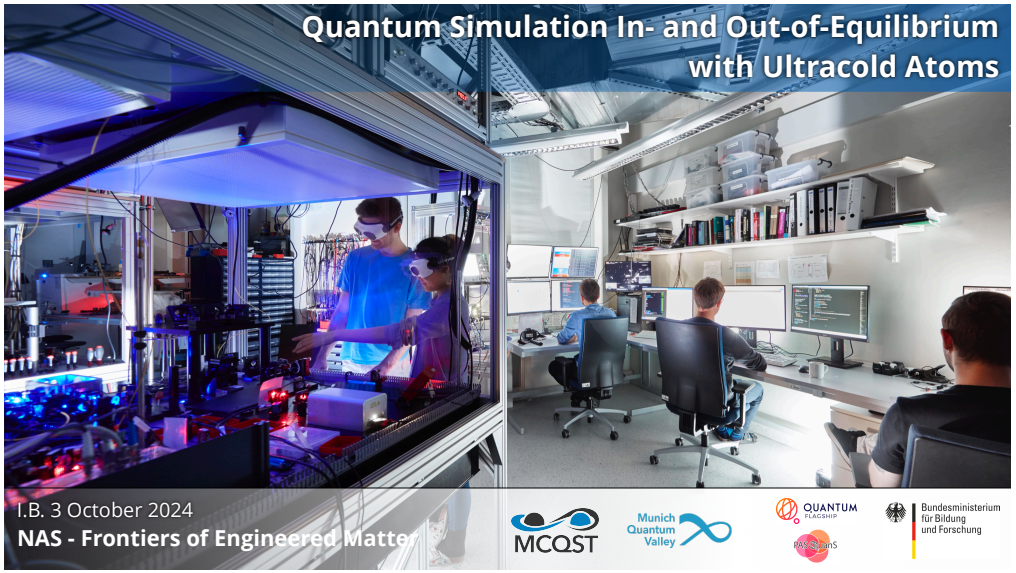
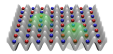
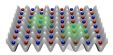


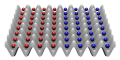
Applications in Many-Body Physics



0 **State Preparation/Engineering and Detection**
Manipulating the Orbital Bloch Sphere



1 **Strongly Correlated Electron Physics**
AFM, Polarons, Hole Pairing, Stripe Signatures,…



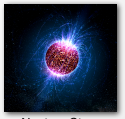
2 **Non-Equilibrium Physics**
Lieb-Robinson Bounds, Spin-Carge Factionalization,
Many-Body Localisation, Anomalous Spin Transport (KPZ)

3 **Outlook**

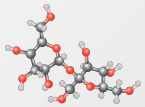
Introduction

The Challenge of Many-Body Quantum Systems

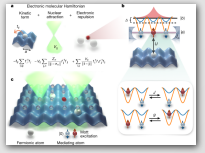
Challenge: ... towards ultimate control and understanding of many-body quantum systems



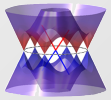
Neutron Stars



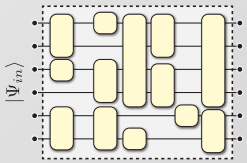
Complex Molecules



Superconductors
& Superfluids



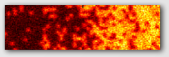
Topological Materials



R. P. Feynman's Vision

A Quantum Simulator to study the dynamics of another quantum system.

R.P. Feynman, R. P. *Int. J. Theor. Phys.* **21**, 467–488 (1982).



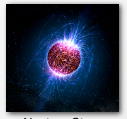
Quantum Dynamics

**Quantum Simulator/
Quantum Computer**

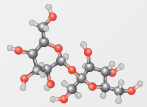
Introduction

The Challenge of Many-Body Quantum Systems

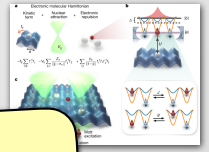
Challenge: ... towards ultimate control and understanding of many-body quantum systems



Neutron Stars



Complex Molecules



Scientific opportunity for novel understanding, tests & discoveries in Quantum Many-Body Systems

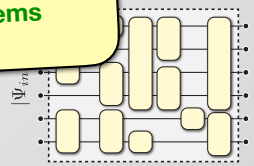
R. P. Feynman

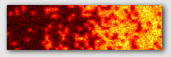
A Quantum Simulator to study the dynamics of another quantum system.

R.P. Feynman, R. P. *Int. J. Theor. Phys.* **21**, 467–488 (1982).

Superconductors
& Superfluids

Topological Materials





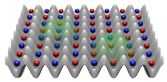
Quantum Dynamics

**Quantum Simulator/
Quantum Computer**

Two approaches

Analog

Implement ruleset H_{model} directly



$$|\psi(t)\rangle = e^{-\frac{i}{\hbar}H_{\text{model}}t}|\psi(0)\rangle$$

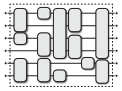
e.g. electrons, magnets,…

= powerful!
but non-universal

Digital

Approximate H_{model} ruleset digitally

$$H_{\text{model}} = \sum_{i=1}^{l} H_i$$



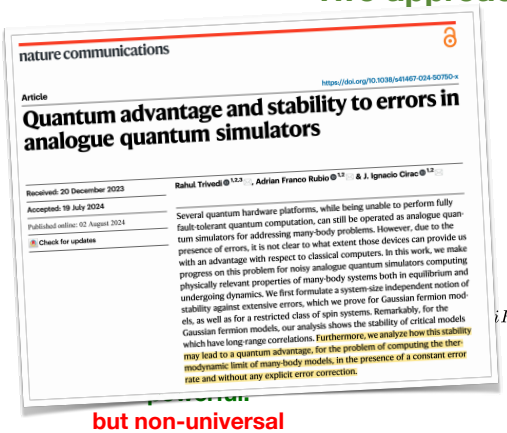
e.g. single / 2 qbit operation

$$e^{-iH_{\text{model}}t} \approx \left(e^{-iH_1 t/n} e^{-iH_2 t/n} \ldots e^{-iH_l t/n}\right)^n$$

= "universal" digital
but resource hungry

Introduction **Quantum Simulations & Quantum Computing**

Two approaches



nature communications

Article

https://doi.org/10.1038/s41467-024-50750-x

Quantum advantage and stability to errors in analogue quantum simulators

Received: 20 December 2023
Accepted: 19 July 2024
Published online: 02 August 2024
Check for updates

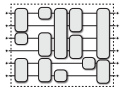
Rahul Trivedi, Adrian Franco Rubio & J. Ignacio Cirac

Several quantum hardware platforms, while being unable to perform fully fault-tolerant quantum computation, can still be operated as analogue quantum simulators for addressing many-body problems. However, due to the presence of errors, it is not clear to what extent those devices can provide us with an advantage with respect to classical computers. In this work, we make progress on this problem for noisy analogue quantum simulators computing physically relevant properties of many-body systems both in equilibrium and undergoing dynamics. We first formulate a system-size independent notion of stability against extensive errors, which we prove for Gaussian fermion models, as well as for a restricted class of spin systems. Remarkably, for the Gaussian fermion models, our analysis shows the stability of critical models which have long-range correlations. Furthermore, we analyze how this stability may lead to a quantum advantage, for the problem of computing the thermodynamic limit of many-body models, in the presence of a constant error rate and without any explicit error correction.

Digital

Approximate H_{model} ruleset digitally

$$H_{\text{model}} = \sum_{i=1}^{l} H_i$$



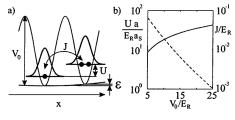
e.g. single / 2 qbit operation

$$iH_{\text{model}}t \approx \left(e^{-iH_1 t/n} e^{-iH_2 t/n} \ldots e^{-iH_l t/n}\right)^n$$

= "universal" digital
but resource hungry

but non-universal

20 Years of Quantum Simulation of Strongly Correlated States of Matter



VOLUME 81, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1998

Cold Bosonic Atoms in Optical Lattices

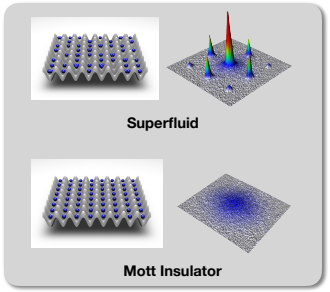
D. Jaksch,[1,2] C. Bruder,[1,3] J. I. Cirac,[1,2] C. W. Gardiner,[1,4] and P. Zoller[1,2]
[1]*Institute for Theoretical Physics, University of Santa Barbara, Santa Barbara, California 93106-4030*
[2]*Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
[3]*Institut für Theoretische Festkörperphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[4]*School of Chemical and Physical Sciences, Victoria University, Wellington, New Zealand*
(Received 26 May 1998)

D. Jaksch et al. Phys. Rev. Lett. **81**, 3108 (1998)

Bose Hubbard Model: M. P. A. Fisher et al., Phys. Rev. B **40**, 546 (1989)

I. Cirac

P. Zoller



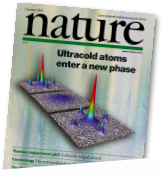
Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

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

M. Greiner, O. Mandel, T. Esslinger. T.W. Hänsch & I. Bloch Nature **415**, 39 (2002)

I. Bloch & M. Greiner Nat. Rev. Phys. (2022)

articles



COMMENT

The superfluid-to-Mott insulator transition and the birth of experimental quantum simulation

Pre-quantum gases optical lattices: A. Hemmerich & T.W. Hänsch (LMU) / S.L Rolston & W.D. Phillips (NIST)

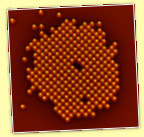
20 Years of Quantum Simulation of Strongly Correlated States of Matter

VOLUME 81, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1998

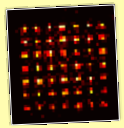
Cold Bosonic Atoms in Optical Lattices

P. Zoller

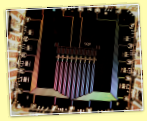
Ion Traps
(Innsbruck,NIST, Quantinuum, Duke, ETHZ, Tsinghua, Mainz, Rice, Oxford,..)



Optical Lattices
(MPQ/LMU, ETHZ, Harvard, MIT, USTC, Beijing, Cambridge, Cambridge (UK), Chicago, Princeton, Virgina, Heidelberg, ENS, Hamburg, KAIST, UCSB, RIKEN, Stanford…)



Rydberg Tweezers
(IO, Harvard, Wisconsin,JILA, Caltech, Princeton, Waterloo, Tübingen, Berkeley, ETHZ…)



Superconducting Devices
(Tokyo, UCSB, Yale, Google, IBM, USTC, ETHZ, Princeton, Chalmers, Delft, Chicago, TUM/WMI, FZ Jülich,…)

Quantum Simulation major research field across platforms!

I. Bloch & M. Greiner Nat. Rev. Phys. (2022)

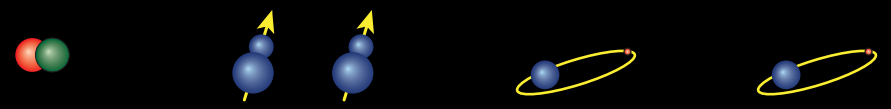
Mott Insulator

COMMENT

The superfluid-to-Mott insulator transition and the birth of experimental quantum simulation

Pre-quantum gases optical lattices: A. Hemmerich & T.W. Hänsch (LMU) / S.L Rolston & W.D. Phillips (NIST)

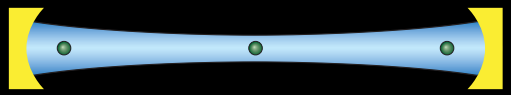
Interaction Control



Collisional
(onsite few kHz)

Dipolar
Magnetic or Electric
(several sites Hz to 10 kHz)

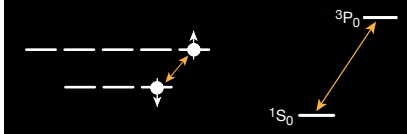
Rydberg Dipole-Dipole
(several sites 1-500 MHz)



Cavity Mediated
(All-to-All few Hz-kHz)

Particles: Fermions, Bosons, Mixtures

Spin degree of freedom:



Hyperfine
(Microwave)

Clock
(Optical)

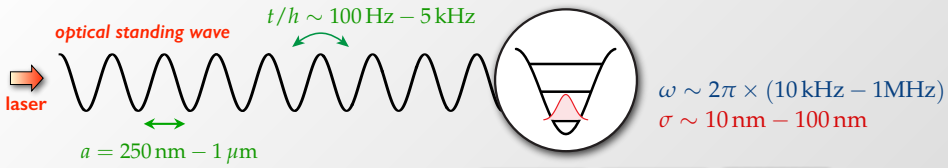
System size: up to few thousands of particles

Mobility: itinerant or static

courtesy: T. W. Hänsch

Introduction

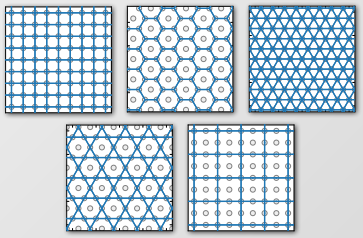
Primer on Optical Lattices



$\omega \sim 2\pi \times (10\,\mathrm{kHz} - 1\mathrm{MHz})$
$\sigma \sim 10\,\mathrm{nm} - 100\,\mathrm{nm}$

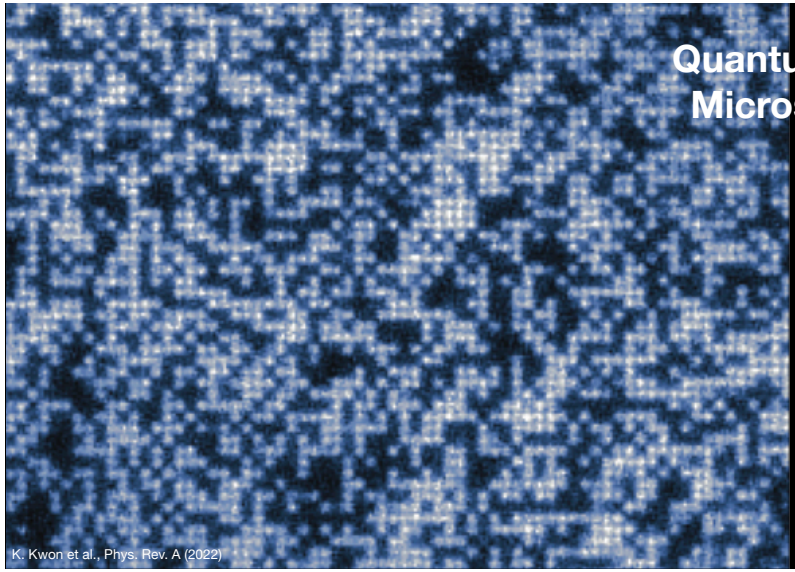
Fourier synthesize aribtrary lattices:

- Square
- Hexagonal/Triangular/Brick Wall
- Kagomé
- Superlattices
- *Spin dependent lattices*
- *Flux Lattices*



Full **dynamical** control over **lattice depth, geometry, dimensionality!**

D. Wei *et al.* Phys. Rev. X **13**, 021042 (2023), recently used: W. Bakr group Nature **629**, 323 (2024) (Princeton)
related: D. Greif *et al.* Nature **535** 217 (2014), M. Xu *et al.* Nature **620**, 971-976 (2023)

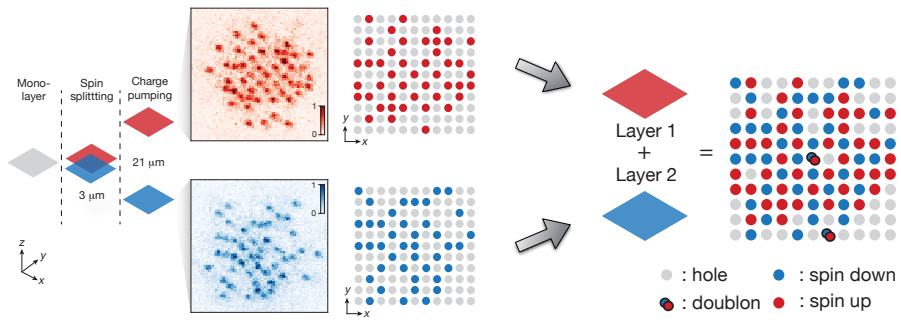


Quantum Gas Microscopy

K. Kwon et al., Phys. Rev. A (2022)

W. Bakr et al., Science (2010)
J. Sherson et al., Nature (2010)

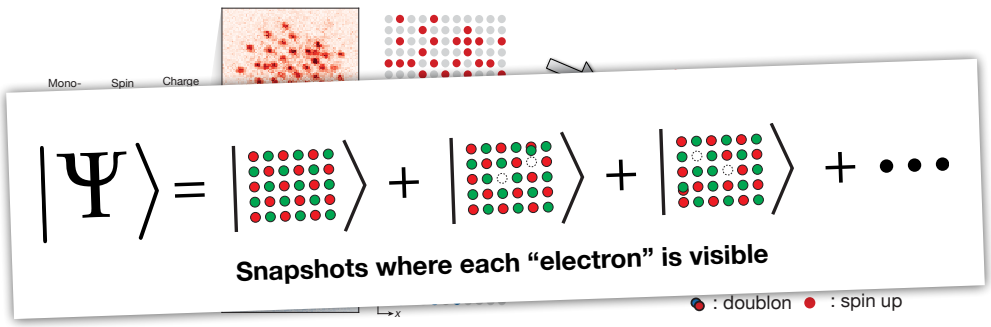
Full Spin & Density Resolved Detection



Density and spin readout: M. Boll et al. Science **353**, 1257 (2016), J. Koepsell *et al.* Phys. Rev. Lett. **125**, 010403 (2020),
see also: Harvard (Greiner), Princeton (Bakr) Phys. Rev. Lett. **129**, 123201 (2022), MIT (Zwierlein) Science **381**, 82 (2023)

FHM Microscope

Full Spin & Density Resolved Detection



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FHM Microscope

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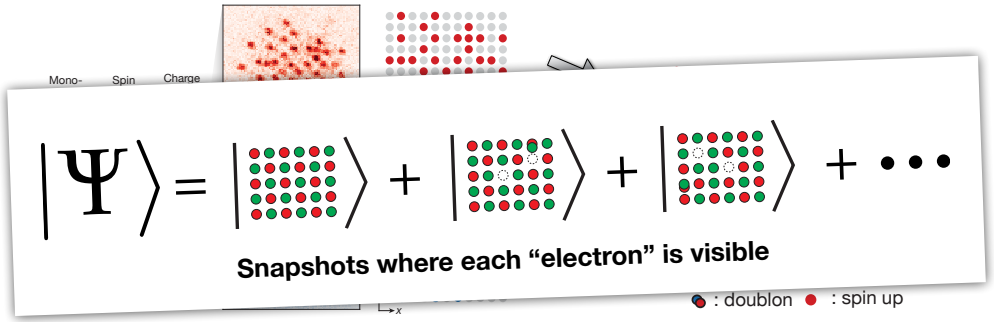
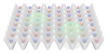


.... and also current snapshots! A. Impertro *et al.* Phys. Rev. Lett. (2024)
B. Du, *et al.* Phys. Rev. Lett. (2024).

Density and spin readout: M. Boll et al. Science **353**, 1257 (2016), J. Koepsell *et al.* Phys. Rev. Lett. **125**, 010403 (2020),
see also: Harvard (Greiner), Princeton (Bakr) Phys. Rev. Lett. **129**, 123201 (2022), MIT (Zwierlein) Science **381**, 82 (2023)

Applications in Many-Body Physics



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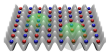
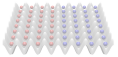
Manipulating the Orbital Bloch Sphere



1 **Strongly Correlated Electron Physics**
AFM, Polarons, Hole Pairing, Stripe Signatures,…



2 **Non-Equilibrium Physics**
Lieb-Robinson Bounds, Spin-Carge Factionalization,
Many-Body Localisation, Anomalous Spin Transport (KPZ)

3 **Outlook**

Fermi Hubbard

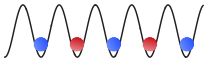
Fermi Hubbard Model (FHM)

Fermi-Hubbard Model

$$\hat{H} = -t \sum_{\langle i,j \rangle, \sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + U \sum_i \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

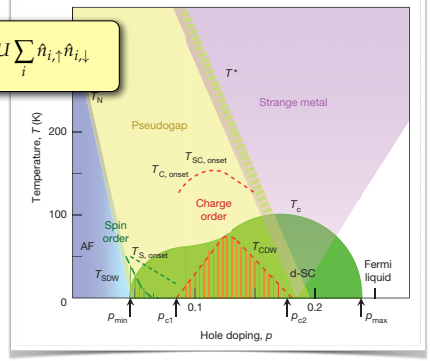
AFM Heisenberg Model

Half filling & strong interaction



$$H = J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j \qquad J = \frac{4t^2}{U}$$

B. Keimer *et al.*, Nature **518** 2015



Away from half filling: ***t-J* model**

competition between

hole delocalization ↔ ***magnetic order***

A. Maruzenko et al. Nature (2017), M. Boll et al. Science (2016), T. Hilker et al. Science (2017), L. Cheuk et al. Science (2016), P. Brown et al. Science (2017)

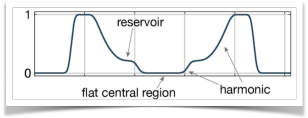
T. Esslinger, Fermi-Hubbard Physics with Atoms in an Optical Lattice. *Annu. Rev. Cond. Mat. Phys.* **1**, 129–152 (2010).

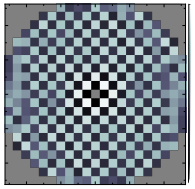
FHM

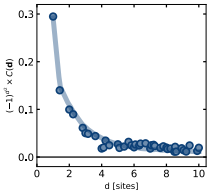
2D Spin Correlations

$$\frac{\langle \hat{S}^z_i \hat{S}^z_j \rangle - \langle \hat{S}^z_i \rangle \langle \hat{S}^z_j \rangle}{\sigma(\hat{S}^z_j)\sigma(\hat{S}^z_i)}$$

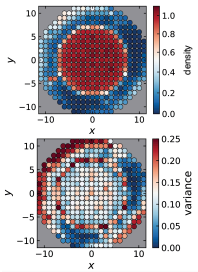
Idea:
T.-L. Ho, Q. Zhou, arXiv:0911.5506
J.S. Bernier *et al.* Phys. Rev. A (2009)
related: B. Yang *et al.* Science (2020)







Theory QMC
Z. Wang, L. Pollet (LMU)



$T/t \sim 0.25$ $\quad T/J \sim 0.4$

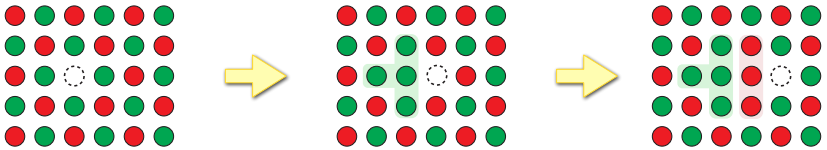
$U/t = 6.5$ $\quad t/J \simeq 1.6$

See also: Harvard: Parsons et al., Science (2016), Mazurenko et al. Nature (2017), **MIT:** Cheuk et al., Science (2016), **Princeton:** Brown et al., Science (2017), **Bonn:** Drewes et al., PRL (2017), **Rice:** A. Hart et al. Nature (2015).

Spinon-Holon

Polaron Formation in 2D

Holes cannot move freely in 2D - holon and spinon are bound



Moving hole leaves frustrated bonds behind - CONFINEMENT!
Spinon and Holon form "Parton"

J.M.F. Gunn & B.D. Simons Phys. Rev. B **42**, 4370 (1990)
F. Grusdt *et al.*, PRX **8**, 011046 (2018)

Bulaevskii, L. N., Nagaev, E. L. & Khomskii, D. I. *Sov. Phys. JETP* **27**, 836 (1968)
S. A. Trugman, Phys. Rev. B **37**, 1579 (1988)
J. R. Schrieffer, X. G. Wen & S. C. Zhang, Phys. Rev. B **39** (1989)
C. Kane, P. Lee & N. Read Phys. Rev. B **39**, (1989)
B. D. Simons and J. M. F. Gunn, Phys. Rev. B **41**, 7019 (1990)
P. Lee *et al.*, Rev. Mod. Phys. **78** (2006)
K. K. Nielsen, M. A. Bastarrachea-Magnani, T. Pohl, & G. M. Bruun Phys. Rev. B **104**, 155136 (2021)

J. Koepsell *et al.* Nature **572**, 358 (2019) & J. Koepsell *et al.* Science **374**, 82 (2021)
See also recent results on frustrated systems: Princeton & Harvard
related: imprints of string patterns Ch. Chiu *et al.* Nature (2019)
attractive U: T. Hartke *et al.* Science **381**, 82 (2023)

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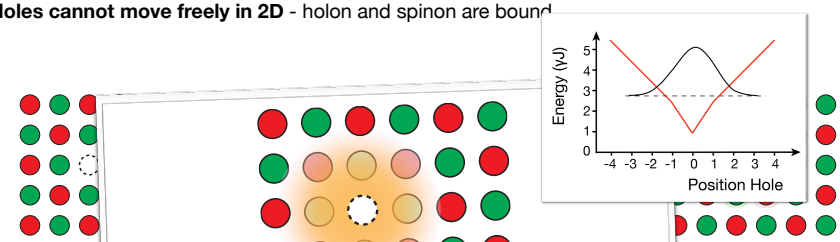

Magnetic polaron is formed!

ole leaves frustrated bonds
ind - CONFINEMENT!
and Holon form "Parton"

D. Simons Phys. Rev. B **42**, 4370 (1990)
dt *et al.*, PRX **8**, 011046 (2018)

Bulaevskii, L. N., Nagaev, E
S. A. Trugman, Phys. Rev. B
J. R. Schrieffer, X. G. Wen &
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B. D. Simons and J. M. F. Gunn, Phys. Rev. B **41**, 7019 (1990)
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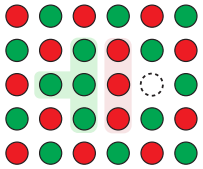
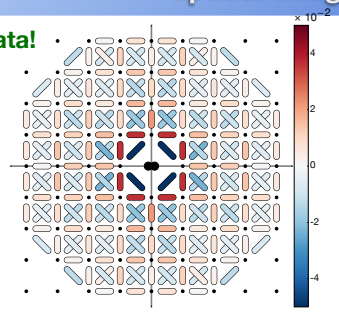
See also recent results on frustrated systems: Princeton & Harvard
related: imprints of string patterns Ch. Chiu *et al.* Nature (2019)
attractive U: T. Hartke *et al.* Science **381**, 82 (2023)

Spinon-Holon

Spatial Image of Magnetic Poltroon

New Data!





J. Koepsell *et al.* Nature **572**, 358 (2019)
J. Koepsell *et al.* Science **374**, 82 (2021)

$$\langle \hat{n}^h_{\mathbf{r}} \hat{S}^z_{\mathbf{r+i}} S^z_{\mathbf{r+j}} \rangle^c$$

Three point hole-spin-spin correlator
(connected & symmetrized)

Kinetic Induced Polarons on Triangular Lattice:
M. Greiner arXiv:2308.12269 (Harvard)
W. Bakr arXiv:2308.12951 (Princeton)

Spinon-Holon

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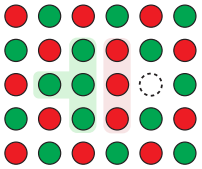

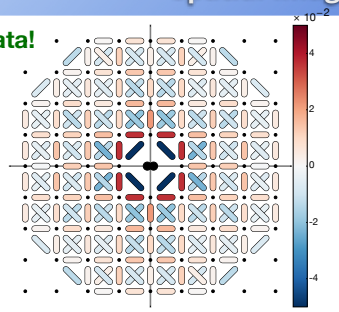

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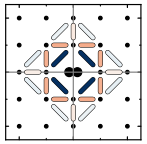

QMC Numerics
Z. Wang & Lode Pollet
Quantitative Match!

Kinetic Induced Polarons on Triangular Lattice:
M. Greiner arXiv:2308.12269 (Harvard)
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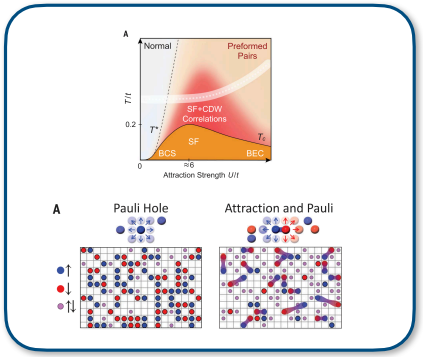
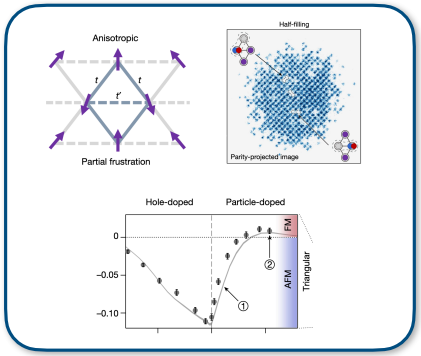
Fermi Hubbard QGM

Recent Highlights



Attractive Interactions

Hartke *et al. Science* **381**, 82–86 (2023)
M. Zwierlein group (MIT)



Tunable Frustration

Xu, M. *et al. Nature* 1–6 (2023)
doi:10.1038/s41586-023-06280-5.
Greiner group (Harvard)
see also W. Bakr (Princeton)

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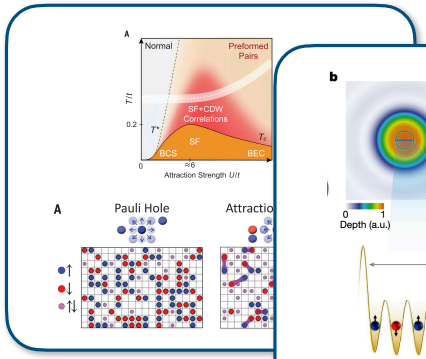
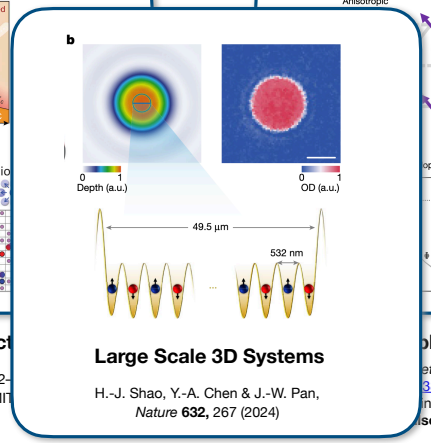
Recent Highlights



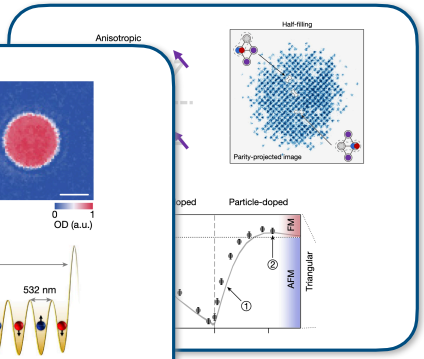
Attractive Interact

Hartke *et al. Science* **381**, 82-
M. Zwierlein group (MI



Large Scale 3D Systems

H.-J. Shao, Y.-A. Chen & J.-W. Pan,
Nature **632,** 267 (2024)



ole Frustration

et al. Nature 1–6 (2023)
38/s41586-023-06280-5.
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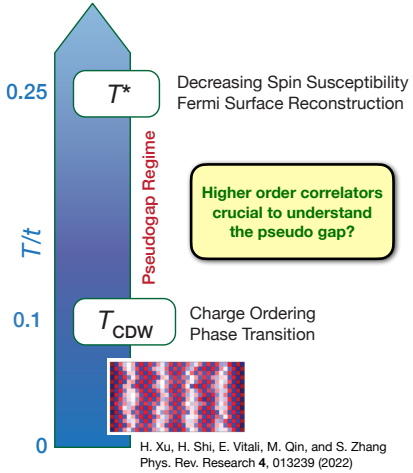
Square Lattice Hubbard Model - Phases (Low Doping)



H.J. Schulz *Phys. Rev. Lett.* **64**, 1445 (1990)

What is the physical mechanism for the Pseudogap?

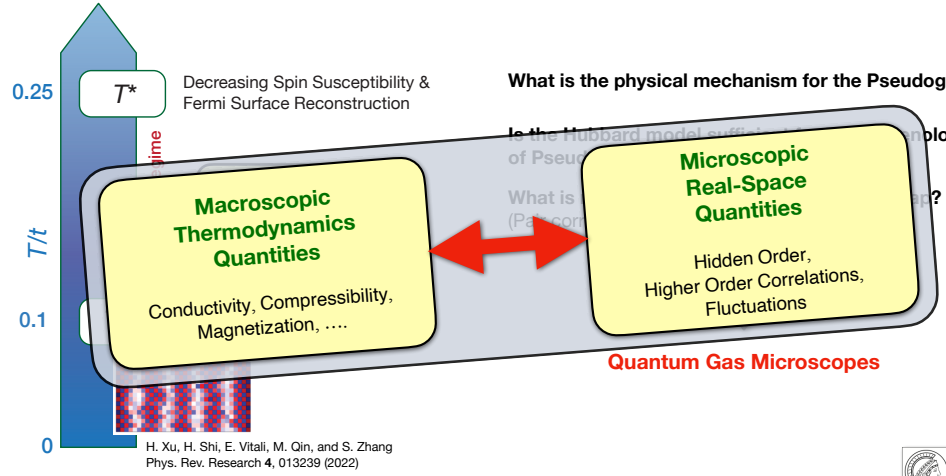
Is the Hubbard model sufficient for Phenomenology of Pseudogap?

What is real space manifestation of Pseudogap?
(Pair correlations, spin background,…)

Quantum Gas Microscopes

FHM

Square Lattice Hubbard Model - Phases (Low Doping)



H.J. Schulz *Phys. Rev. Lett.* **64**, 1445 (1990)

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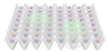
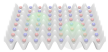
Quantum Gas Microscopes

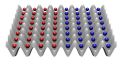
Applications in Many-Body Physics



0 **State Preparation/Engineering and Detection**
Manipulating the Orbital Bloch Sphere



1 **Strongly Correlated Electron Physics**
AFM, Polarons, Hole Pairing, Stripe Signatures,…



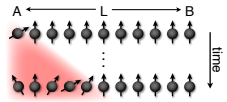
2 **Non-Equilibrium Physics**
Lieb-Robinson Bounds, Spin-Carge Factionalization,
Many-Body Localisation, Anomalous Spin Transport (KPZ)

3 **Outlook**

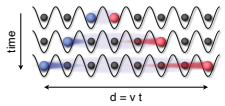
Non-Equilibrium Dynamics

1 **Information Spreading in Many-Body Systems**
Lieb-Robinson Bounds

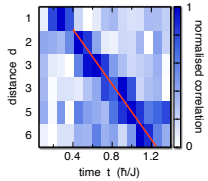
E.H. Lieb & D.W. Robinson Comm. Math. Phys. (1972)



$$\left|\langle A(t)B(t)\rangle - \langle A(t)\rangle\langle B(t)\rangle\right| \leq \lambda' \exp\left(\frac{vt - L/2}{\zeta'}\right)$$



M. Cheneau et al., Nature (2012)
Ion traps: P. Jurcevic et al. Nature (2014),
Ph. Richerme et al. Science (2014)



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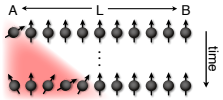

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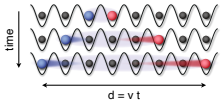

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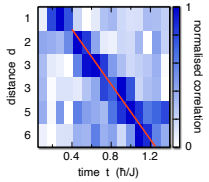

Optical Lattices **Non-Equilibrium Dynamics**

1 Information Spreading in Many-Body Systems
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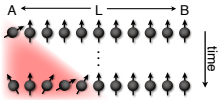
E.H. Lieb & D.W. Robinson Comm. Math. Phys. (1972)



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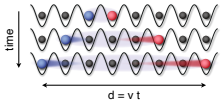

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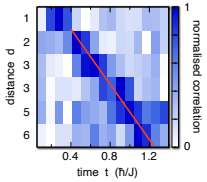
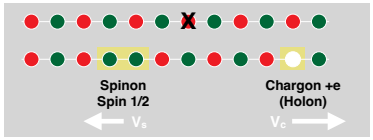
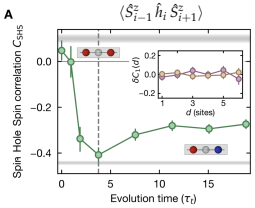


2 Spin-Charge Fractionalization

Real space, time-resolved observation

Experiment:
J. Vijayan *et al.* Science 367, 186 (2020)
Spectroscopic determination:
C. Kim, et al. Phys. Rev. Lett. **77**, 4054 (1996)
O.M. Auslaender et al. Science **308**, 88 (2005)





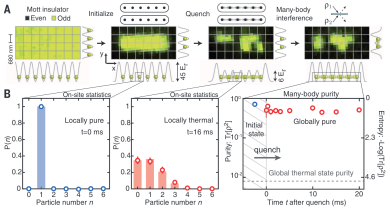
Optical Lattices **Non-Equilibrium Dynamics**

3 Thermalisation in Quantum Many-Body Systems

How do isolated Quantum Many-Body systems thermalise?

$$S_{VN} = -\,tr\left(\rho_A \log \rho_A\right) = S_{th}$$

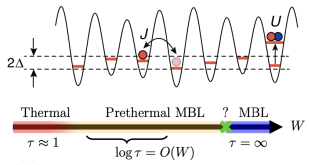
Measure entanglement entropy via Many-Body Hong-Ou-Mandel:
R. Islam et al. Nature 528, 77–83 (2015).
Theory:
C.M. Alves & D. Jaksch Phys. Rev. Lett. 2004
A. Daley et al. Phys. Rev. Lett. 2012



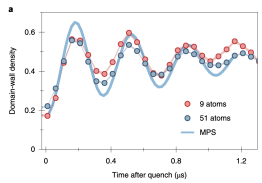
A. Kaufmann *et al.* Science 2016

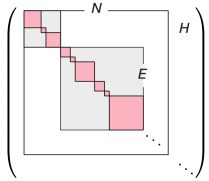
Optical Lattices **Non-Equilibrium Dynamics**

4 Non-Thermalizing Behaviour



D.M. Long et al. Phys. Rev. Lett. 131, 106301 (2023)





Many-Body Localization

review:
R. Nandkishore & D. A. Huse
Annu. Rev. Condens. Matter Phys. 6, 15 (2015)
D.A. Abanin, E. Altman, I. Bloch & M. Serbyn
Rev. Mod. Phys. 91, 021001 (2019)
exp: M. Schreiber *et al.* Science (2015)
J.Y. Choi *et al.* Science (2016)
M. Rispoli, et al. Nature (2019)
A. Lukin et al. Science (2019)
GS: Kondov et al. Phys. Rev. Lett. (2015)

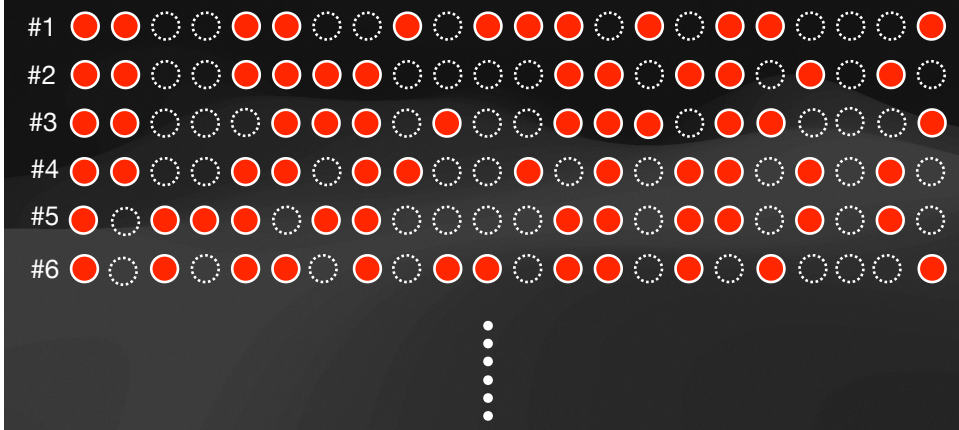
Many-Body Quantum Scars

review:
M. Serbyn, D.A. Abanin & Z. Papić
Nature Phys. **17**, 675 (2021)
exp: H. Bernien et al. Nature **551**, 579 (2017)

Hilbert Space Fragmentation

V. Khemani, M. Hermele, and R. Nandkishore
Phys. Rev. B **101**, 174204 (2020)
P. Sala, … & F. Pollmann
Phys. Rev. X **10**, 011047 (2020)
exp: 1D S. Scherg et al. Nat. Commun. **12**, 4490 (2021)
2D D. Adler et al., arXiv:2404.14896

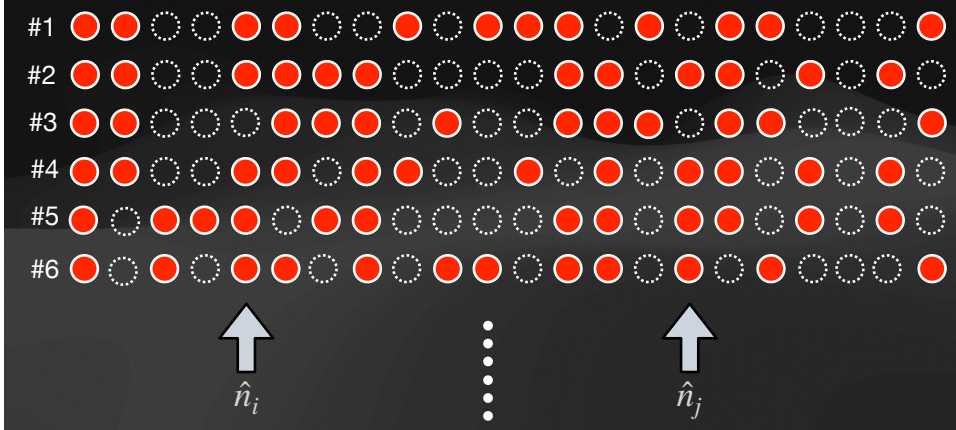
Quantum Transport - Atom-by-Atom



J.F. Wienand *et al*. Nature Physics (2024)

See also: (Endres group) J. Choi *et al*., Nature **613**, 468 (2023)

Quantum Transport - Atom-by-Atom



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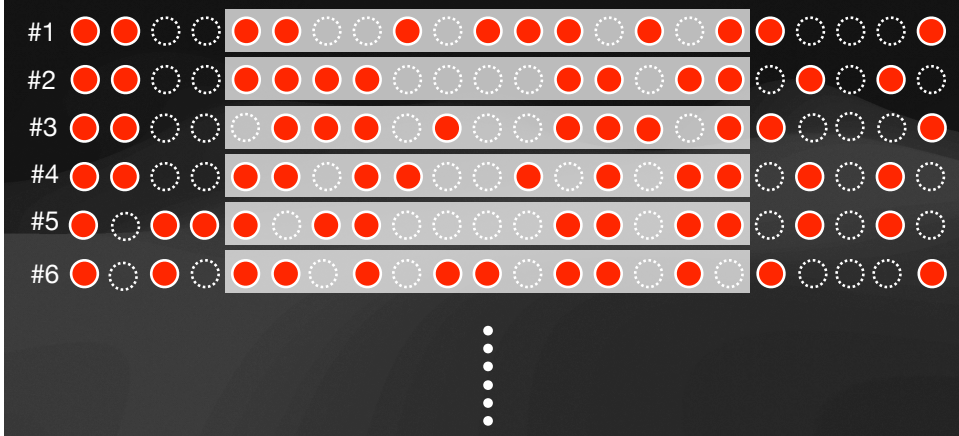

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Quantum Transport - Atom-by-Atom

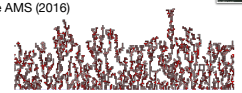
J.F. Wienand *et al*. Nature Physics (2024)

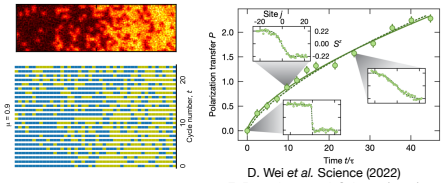
See also: (Endres group) J. Choi *et al*., Nature **613**, 468 (2023)

Non-Equilibrium Dynamics

5 Anomalous Spin Transport - Kardar-Parisi-Zhang Universality

M. Kardar, G. Parisi & Y.-C. Zhang Phys. Rev. Lett. (1986)
M. Ljubotina *et al.*, Phys. Rev. Lett. (2019)
Review: V. Bulchadini, S. Gopalakrishnan, E. Ilievski
J. Stat. Mech. 084001 (2021)
I. Corwin, Notices of the AMS (2016)

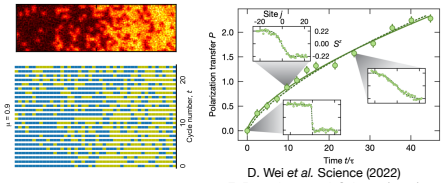




D. Wei *et al.* Science (2022)
E. Rosenberg *et al.* Science (2023)

Optical Lattices

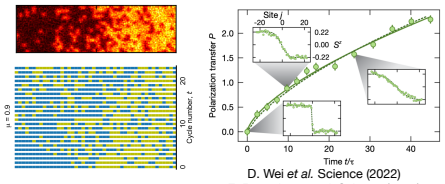
Non-Equilibrium Dynamics



D. Wei *et al.* Science (2022)
E. Rosenberg *et al.* Science (2023)

Optical Lattices

Non-Equilibrium Dynamics

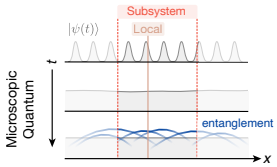


D. Wei *et al.* Science (2022)
E. Rosenberg *et al.* Science (2023)

6 (Hydro) Dynamics of Fluctuations (?)

in diffusive systems

Dynamics of Subsystem Fluctuations



$$\partial_t n + \partial_x j = 0, \quad j = -D(n)\,\partial_x n + \sqrt{2\,D(n)\,\chi(n)}\,\xi$$

J.F. Wienand *et al.* Nature Physics (2024)
MFT: Bertini, L., De Sole, A., Gabrielli, D., Jona-Lasinio, G. & Landim, C. Rev. Mod. Phys. **87**, 593–636 (2015).

Where Next?

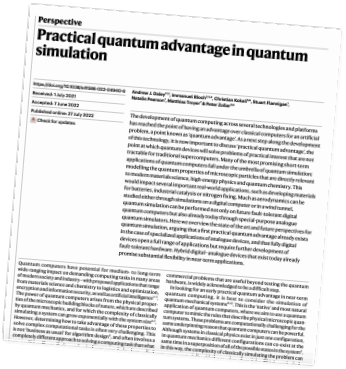
A Joint Look Ahead…

Quantum Simulation & Computation Platforms
(Atoms, Ions, SC Qubits, Photons, NV Centers...)

(Digital) Circuit Model

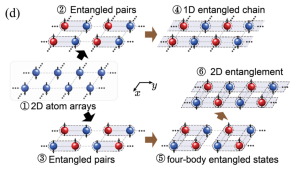
Analog-Digital Hybrid Operation

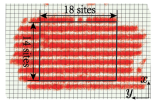
(Analog) Direct Modelling


Perspective
Practical quantum advantage in quantum simulation

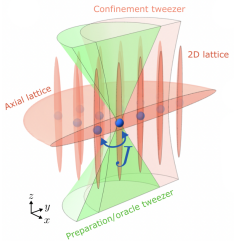
A.J. Daley, I. Bloch, C. Kokail, S. Flannigan, N. Pearson, M. Troyer, P. Zoller
Nature **607**, 667–676 (2022)

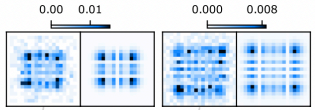
Enhanced Programmability



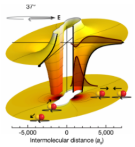


Scalable Entanglement Generation
(USTC)





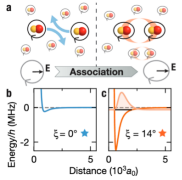
Tweezer sorted Optical Lattice
(Boulder/JILA)



X. Chen, A. Schindewolf, *et al.*, Nature **614**, 59 (2023)

A. Schindewolf *et al.* Nature **607**, 677 (2022)

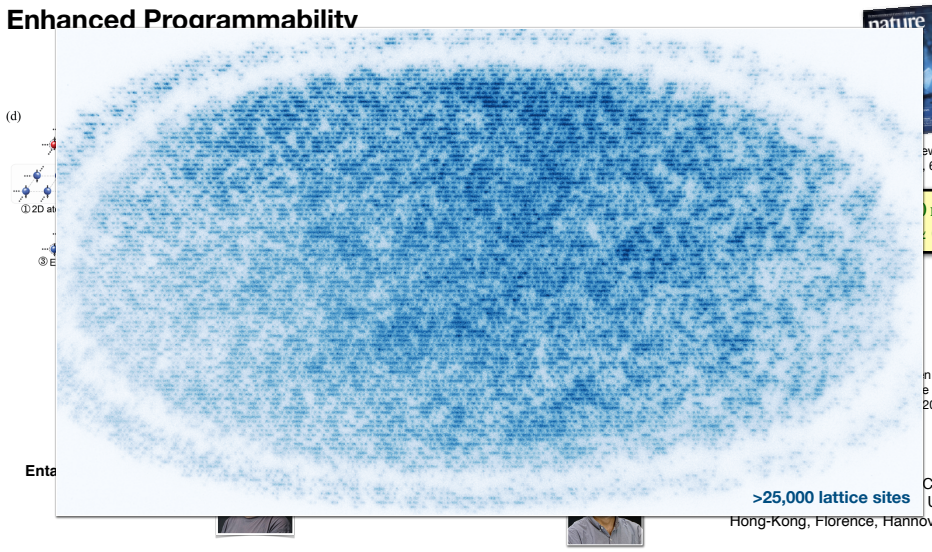
$T \simeq 20\,\mathrm{nK}$
$T/T_F \simeq 0.3$



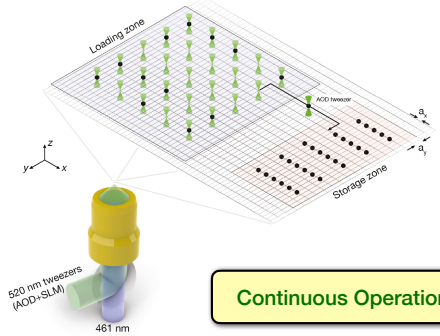
X. Chen *et al.* Nature **626,** 283 (2024)

Polar Molecules
(JILA, MPQ, MIT, Columbia, Chicago, Durham, Harvard, Princeton, USTC, Hong-Kong, Florence, Hannover,…)

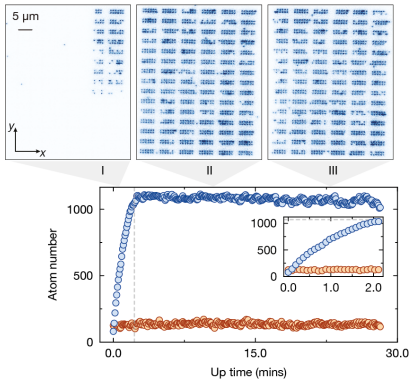
Enhanced Programmability



Continuously Loaded & Sorted Optical Lattice



Continuous Operation !

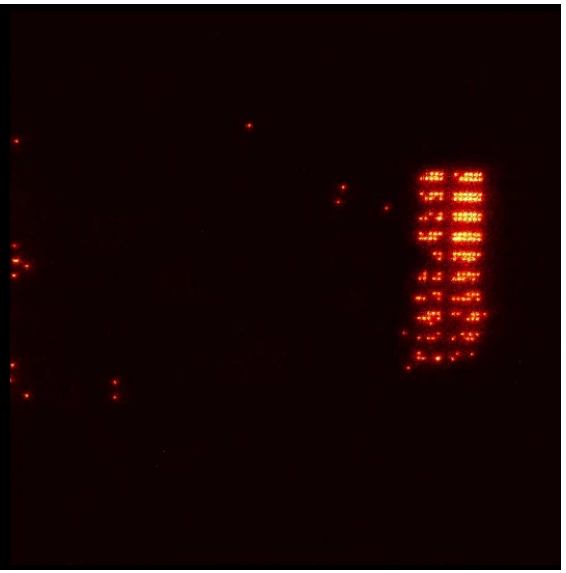


F. Gyger *et al. Phys. Rev. Res.* **6**, 033104 (2024)
see also: M. Norcia et al. arXiv.2401.16177 (2024).

Continuous Loading in Action

Continuously operated array for up to **1.5h with > 1200 atoms**

Readily scalable to **>10,000 atoms**



F. Gyger *et al.* PRR **6**, 033104 (2024)
see also: M. Norcia et al. arXiv.2401.16177 (2024).

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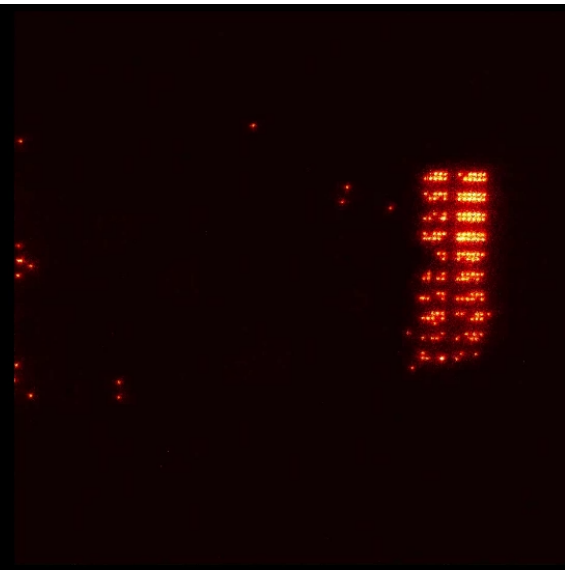
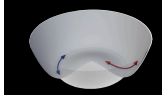
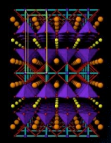


F. Gyger *et al.* PRR **6**, 033104 (2024)
see also: M. Norcia et al. arXiv.2401.16177 (2024).

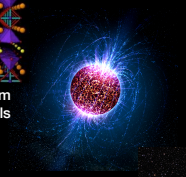
Quantum Universe in the Lab



Particle Physics

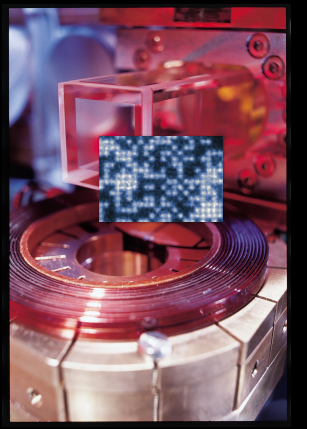


Quantum Materials



Neutron Stars

Our Universe



[redacted]