

Quantum simulation - Engineering & understanding quantum systems atom-by-atom

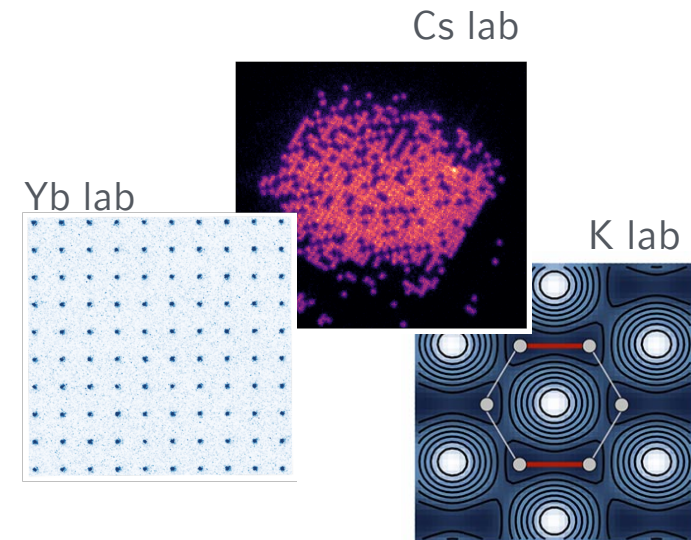
Monika Aidelsburger

Max-Planck Institut für Quantenoptik

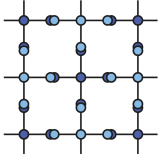
Ludwig-Maximilians Universität München

Munich Center for Quantum Science & Technology

www.mpg.de/eng-quantum-systems

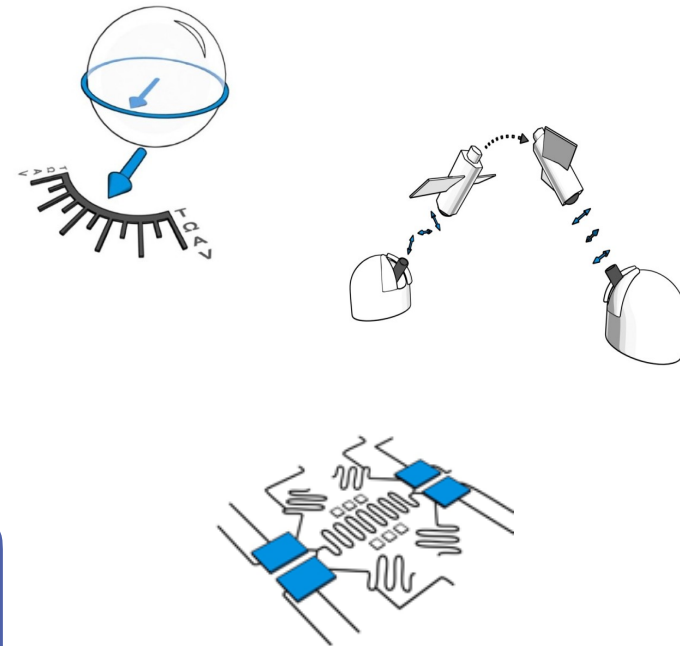


Quantum technologies



Applications

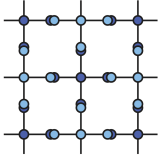
- Material science / magnetism
- Quantum computers / algorithms
- Metrology applications & sensing
- Quantum Communication



Challenge:

Computational complexity grows exponentially!

Quantum simulation



Idea: Use a *quantum simulator* to study the dynamics of another quantum system!

R.P. Feynman

Superconducting qubits

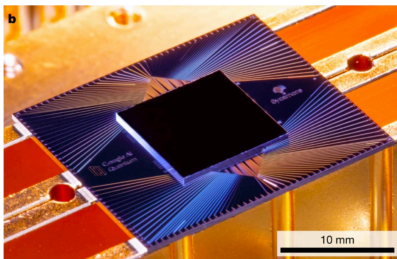


Image: Sycamore Chip

Trapped ions

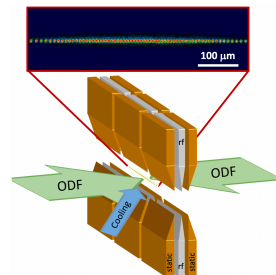


Image: C. Monroe

Rydberg atom arrays

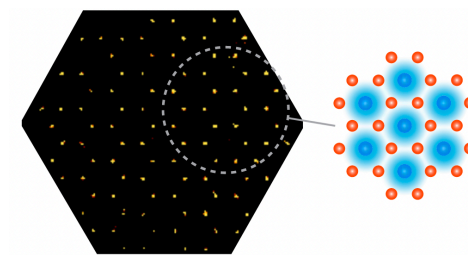
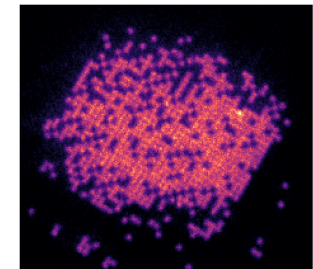


Image: A. Browaeys

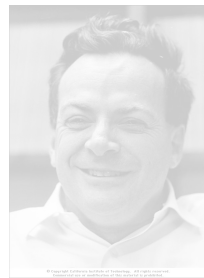
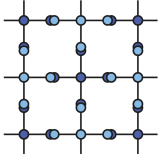
Atoms in lattices



Cs atoms @ LMU

and many more research groups around the world!!

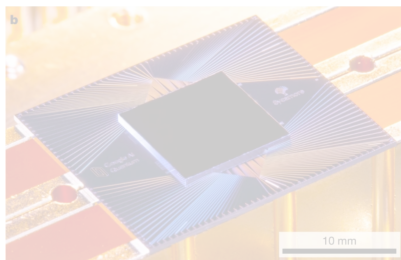
Quantum simulation



*Idea: Use a **quantum simulator** to study the dynamics of another quantum system!*

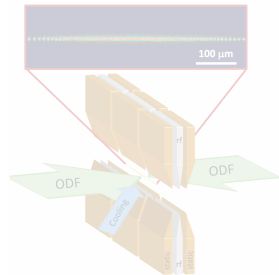
R.P. FEYNMAN

Superconducting qubits



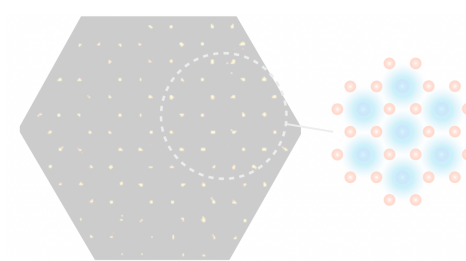
SYCAMORE CHIP

Trapped ions



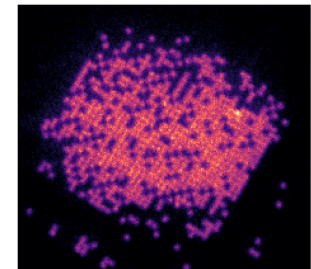
C. MONROE

Rydberg atom arrays



A. BROWAEYS

Atoms in lattices



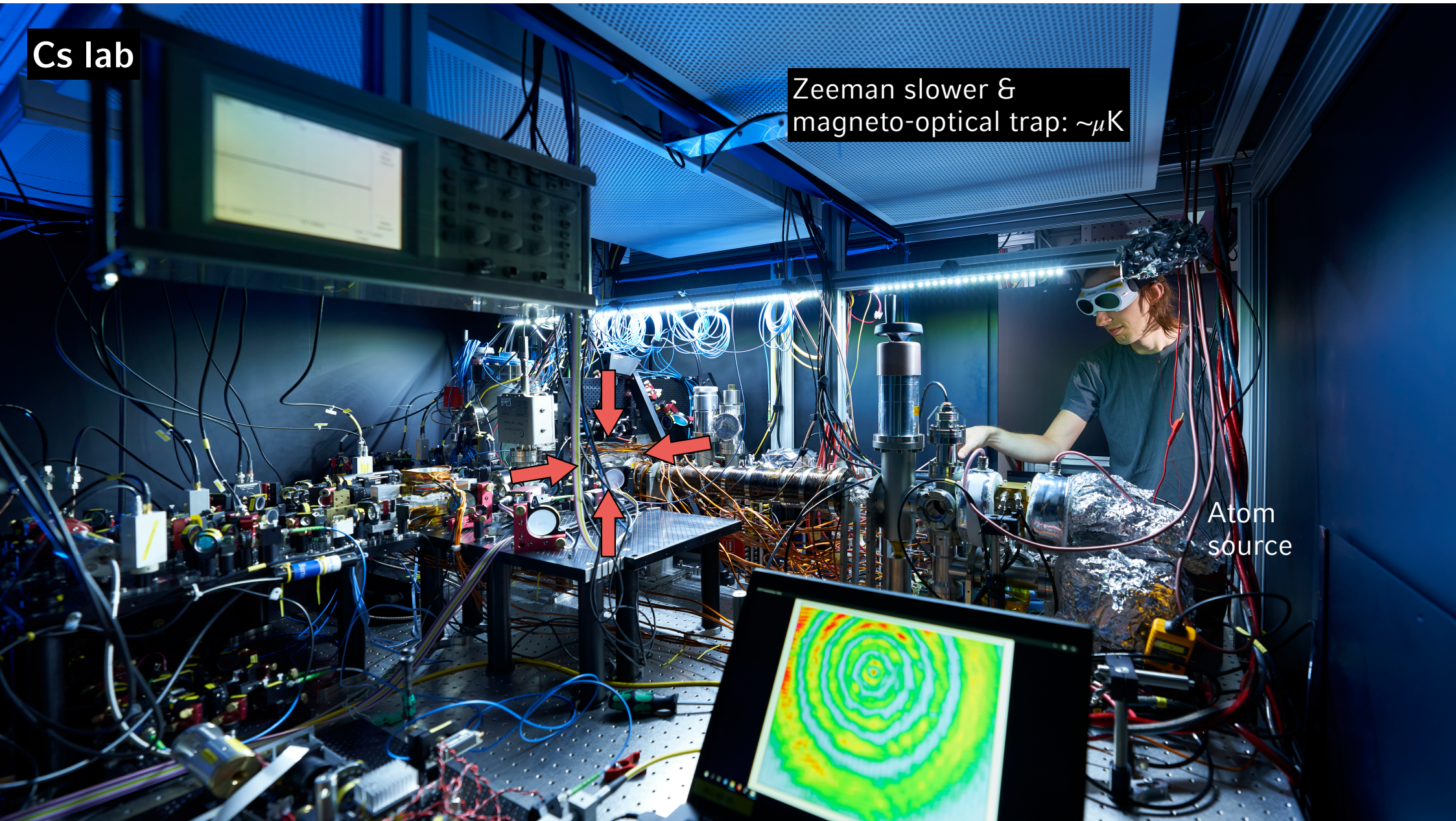
Cs atoms @ LMU

and many more research groups around the world!!

Cs lab

Zeeman slower &
magneto-optical trap: $\sim \mu\text{K}$

Atom
source

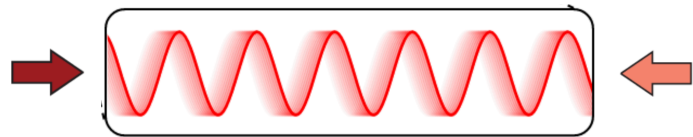


Cs lab

Zeeman slower &
magneto-optical trap: $\sim \mu\text{K}$

Transport

Atom
source



Klostermann, ..., Aidelburger, PRA **105**, 043319 (2022)

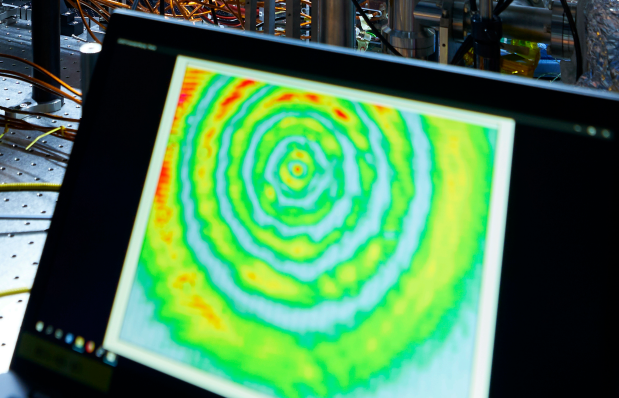
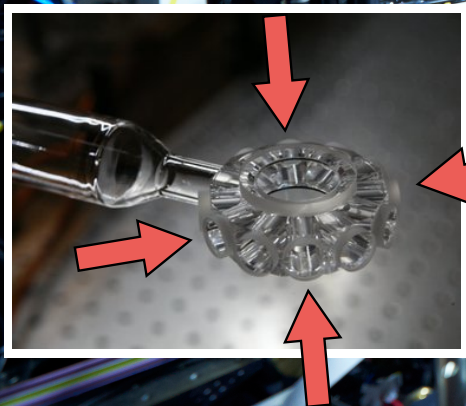
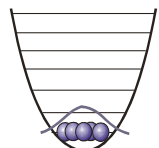
Cs lab

Zeeman slower &
magneto-optical trap: $\sim \mu\text{K}$

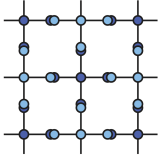
Science cell:
 $\sim 10^{-11}\text{mbar}$ / $\sim \text{nK}$
degenerate quantum gas

Atom
source

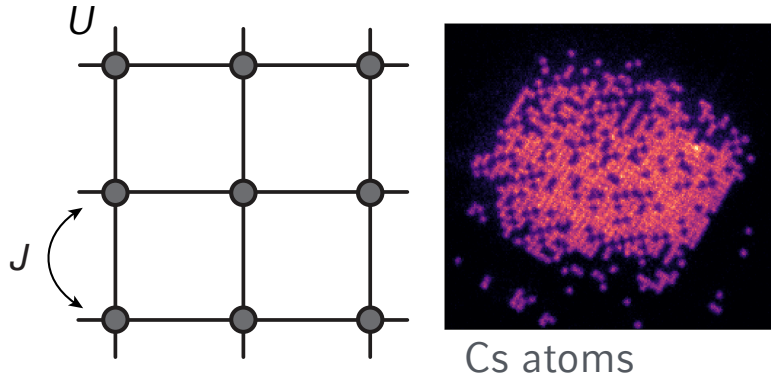
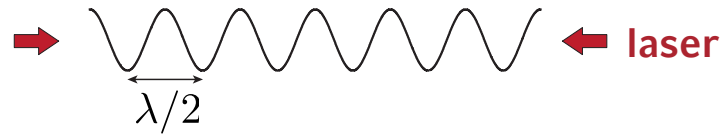
Bose-Einstein
condensate



Quantum simulation with neutral atoms



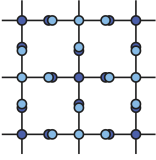
Optical lattices:



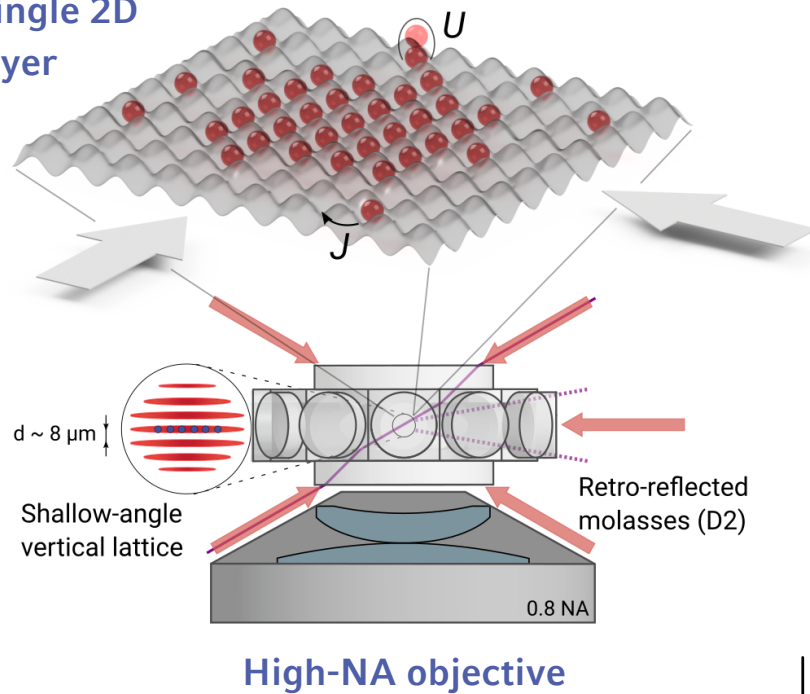
Quantum simulation of
Hubbard models

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

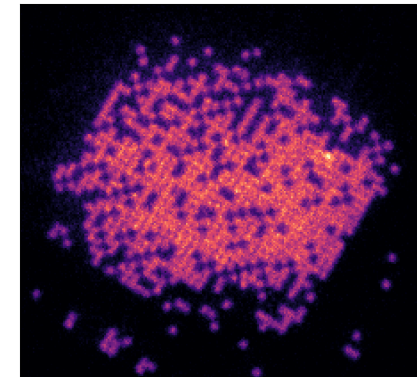
Quantum Gas Microscopy



Single 2D
layer



Fluorescence imaging in deep lattices



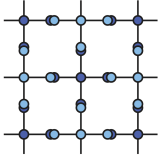
- Single-site resolved observables (correlations, full counting statistics, ...)
- Site-selective addressing

$$|\psi\rangle = c_0 \left| \begin{array}{cc} \bullet & \bullet \\ \bullet & \bullet \end{array} \right\rangle + c_1 \left| \begin{array}{cc} \bullet & \bullet \\ \bullet & \bullet \end{array} \right\rangle + c_2 \left| \begin{array}{cc} \bullet & \bullet \\ \bullet & \bullet \end{array} \right\rangle + c_3 \left| \begin{array}{cc} \bullet & \bullet \\ \bullet & \bullet \end{array} \right\rangle + \dots$$

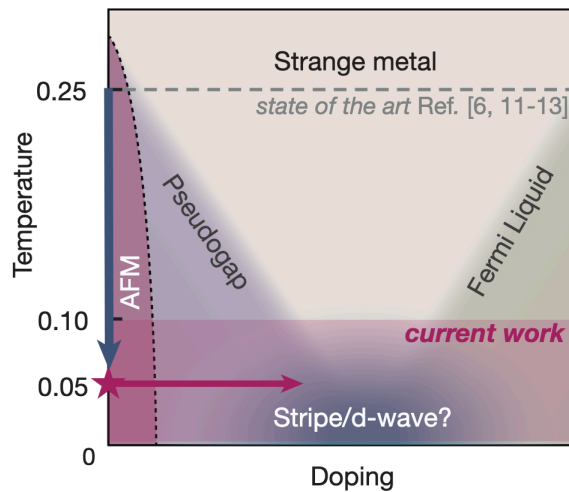
W. S. Bakr *et al.*, Nature **462**, 74 (2009); J. F. Sherson *et al.* Nature **467**, 68 (2010)

L. Cheuk *et al.* PRL **114**, 193001 (2015); E. Haller *et al.* Nat. Phys. **11**, 738 (2015); M. F. Parsons *et al.*, PRL **114**, 213002 (2015), ...

Quantum simulation with neutral atoms in optical lattices

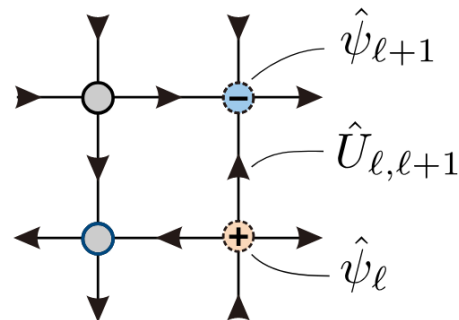


Doped Fermi-Hubbard



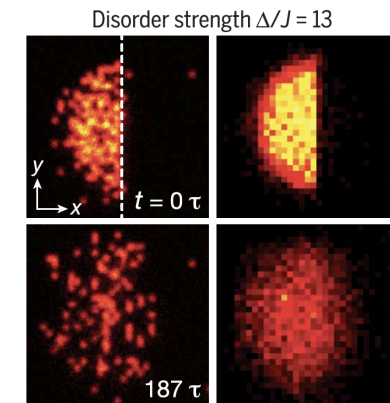
Xu,...,Greiner, arXiv:2502.00095
Bohrdt et al., Annals of Physics (2021)

Lattice gauge theories



Halimeh,..., Aidelburger,
Nature Physics (2025)

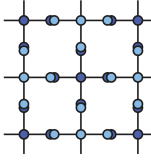
Out-of-equilibrium dynamics



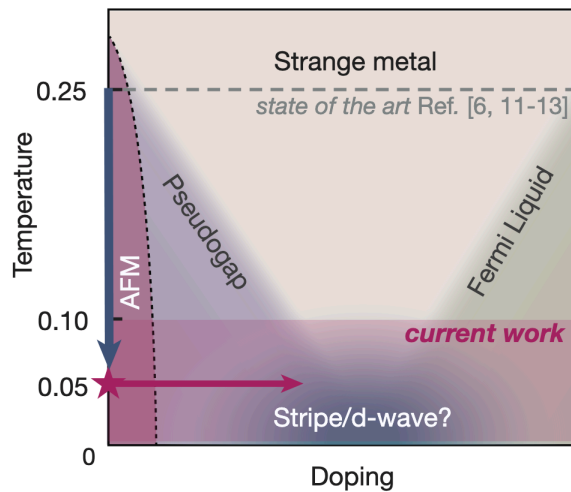
$$|\psi(t)\rangle = e^{-i\hat{H}t/\hbar}|\psi_0\rangle$$

Choi, ..., Bloch,
Science **352**, 1547 (2016)

Quantum simulation with neutral atoms in optical lattices

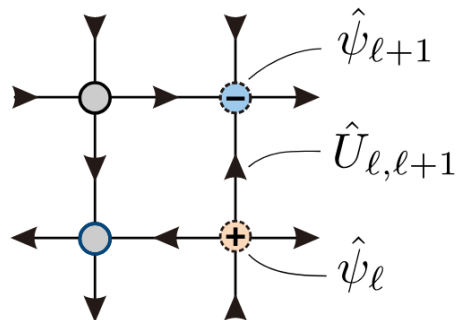


Doped Fermi-Hubbard



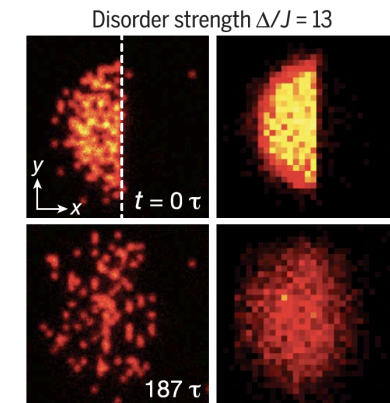
Xu,...,Greiner, arXiv:2502.00095
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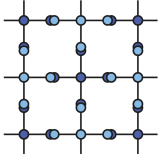
$$|\psi(t)\rangle = e^{-i\hat{H}t/\hbar}|\psi_0\rangle$$

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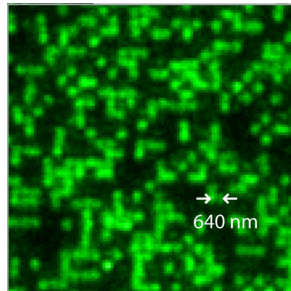
Direct implementation of Hamiltonian

Stability to errors & quantum advantage: Rahul Trivedi, Adrian Franco Rubio, Ignacio J. Cirac, Nature Commun. 15, 6507 (2024)

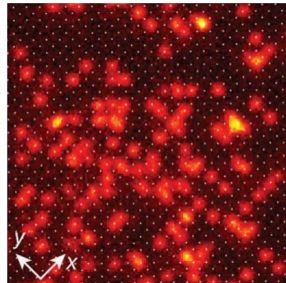
Quantum Gas Microscopy



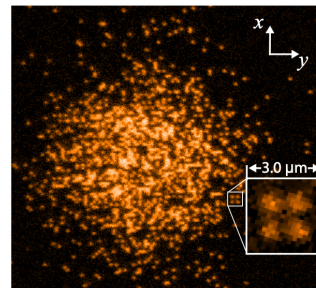
Selected examples:



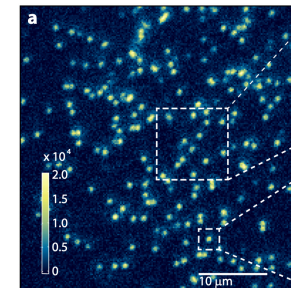
Rb atoms, Greiner



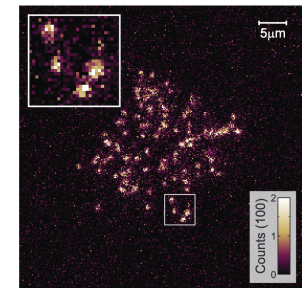
Rb atoms, Bloch



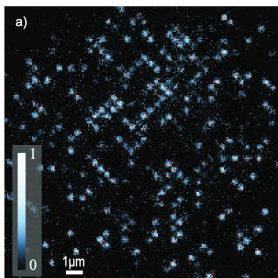
K atoms, Zwierlein



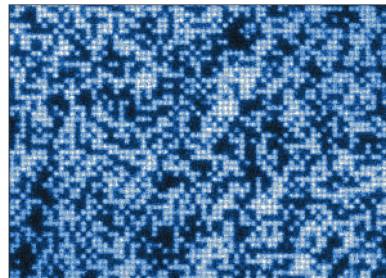
K atoms, Kuhr



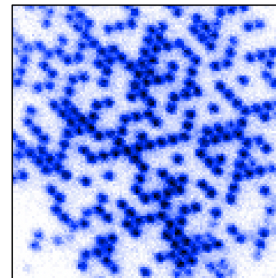
K atoms, Thywissen



Yb atoms, Kozuma



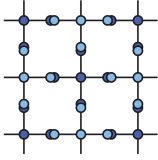
Li atoms, Choi



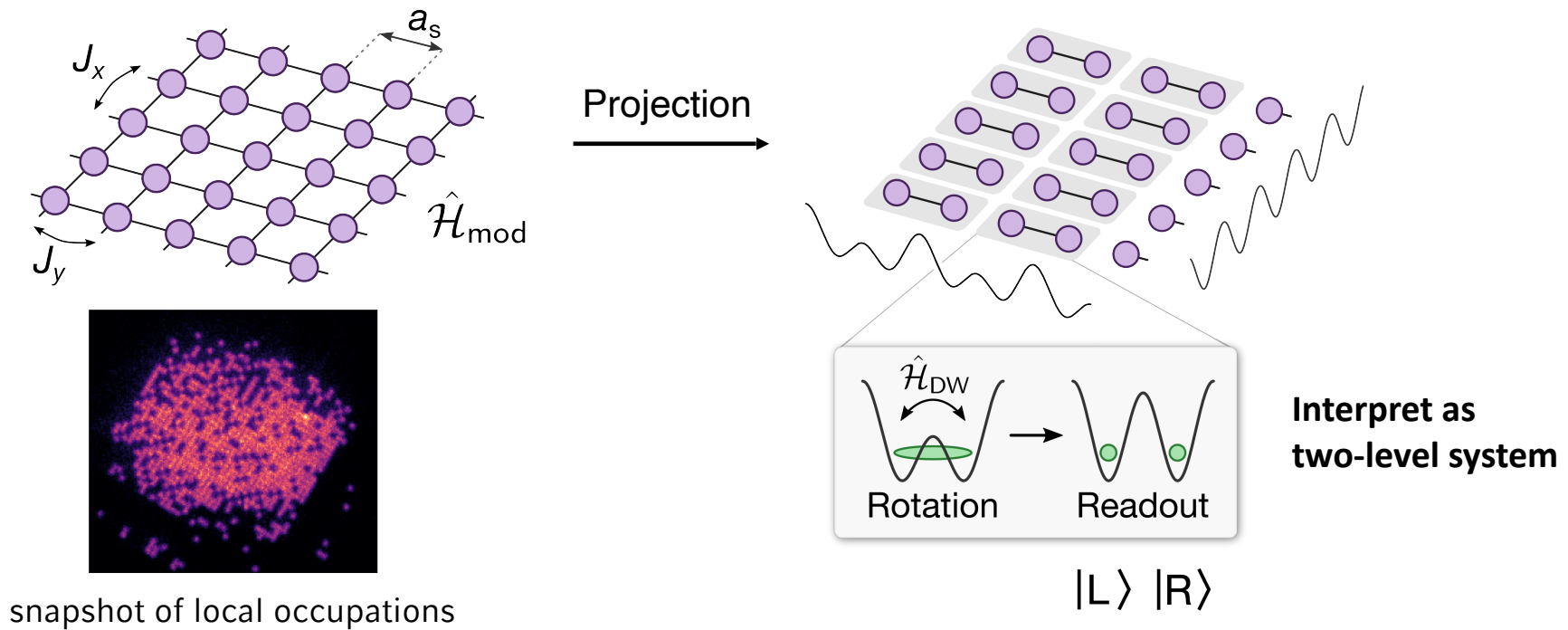
Li atoms, Schauss

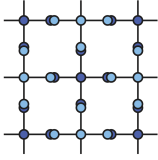
- Novel observables
- Novel model Hamiltonians
- Verification & benchmarking

Beyond density observables



Novel observables beyond local densities

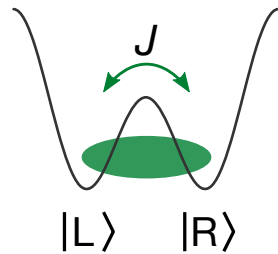




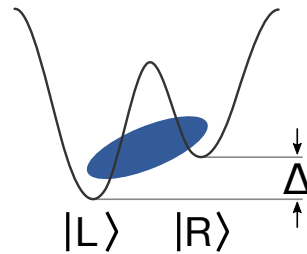
Double-well rotations for read-out

Double-well as two-level system

σ_x -rotations

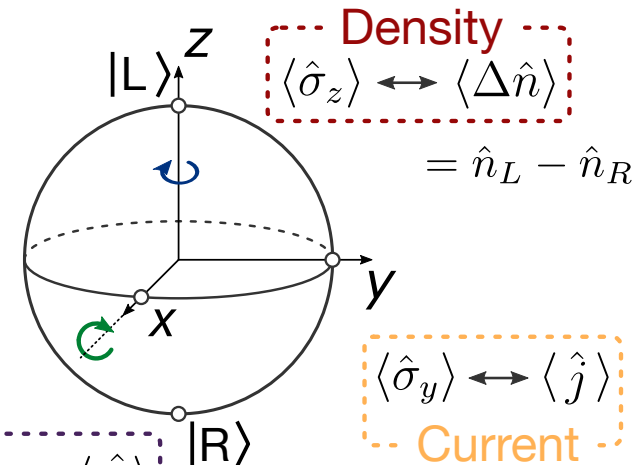


σ_z -rotations



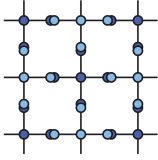
$$\hat{\mathcal{H}}_{\text{DW}} = -J\hat{\sigma}_x - \frac{\Delta}{2}\hat{\sigma}_z$$

Bloch sphere representation



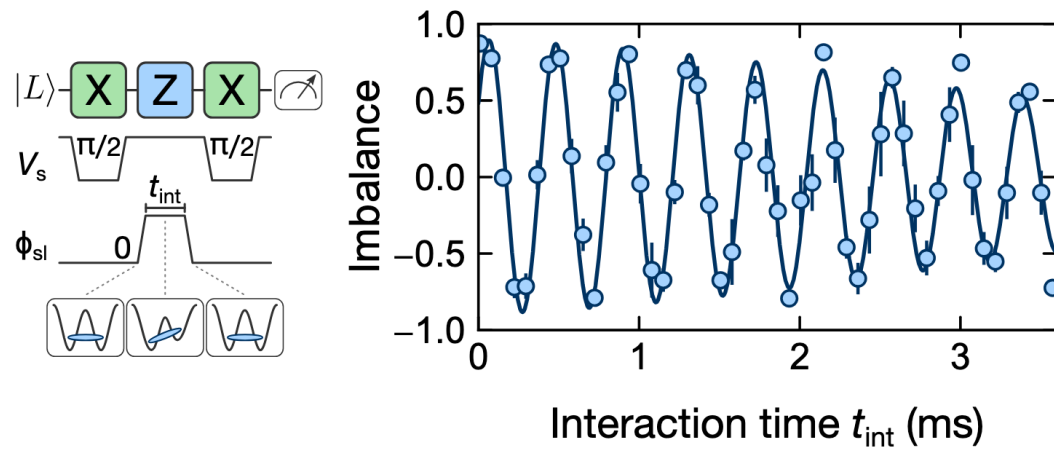
$$= -J \left(\hat{a}_R^\dagger \hat{a}_L + \hat{a}_L^\dagger \hat{a}_R \right)$$

**Single-shot,
local read-out**



Global operations

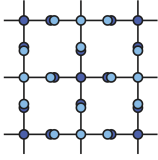
Ramsey sequence:



Measured T_2^* -time 6(1)ms

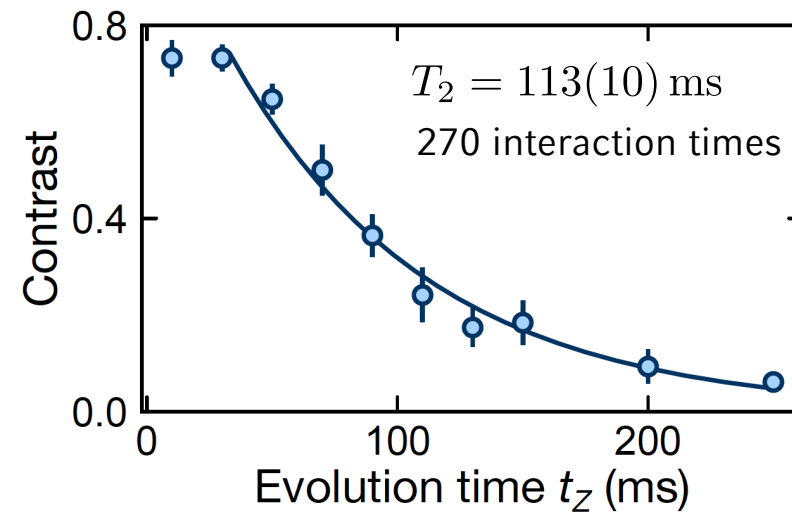
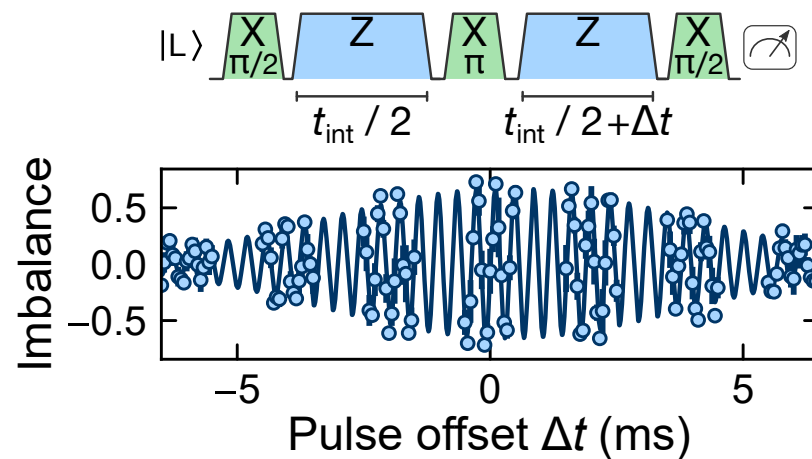
Limitation mostly due to static potential energy offsets

→ Spin-echo sequence



Global operations

Spin-echo:



- Arbitrary parallel operations: typically 500-1500 double wells
- Combination with local control → complex correlators!

See also:

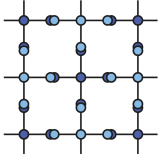
G. Bornet et al., PRL **132**, 263601 (2024)

B. Du et al., PRL **133**, 060601 (2024)

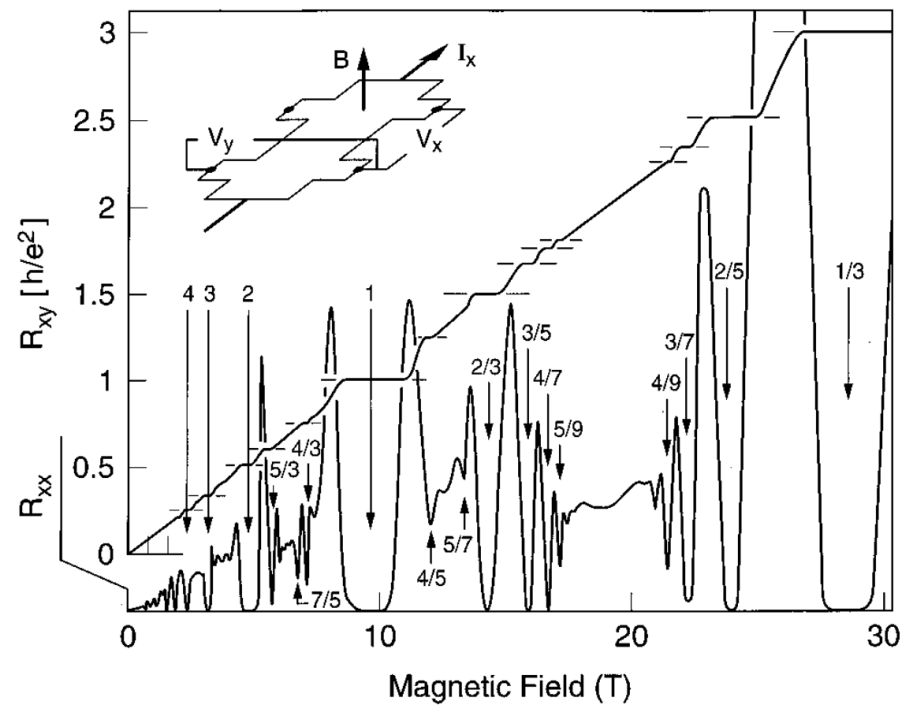
Weitenberg et al., Nature **471**, 319-324 (2011)

Quantum simulation of topological phases of matter

Fractional quantum Hall states



Strongly-correlated topological phases of matter

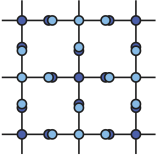


- fractional quasiparticles
- non-local topological entanglement
- anyonic exchange statistics

K. Klitzing, Rev. Mod. Phys. (1986)
Stormer et al., Rev. Mod. Phys. (1999)

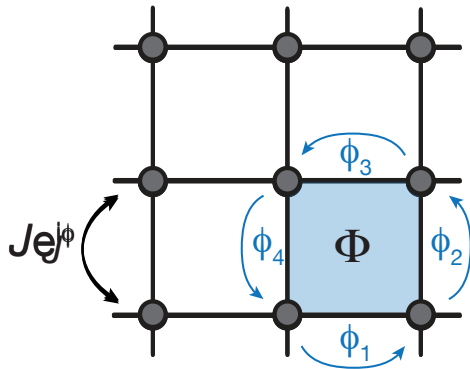
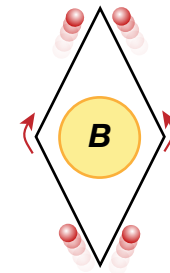
Review: X.-L. Qi & S.-C. Zhang, Rev. Mod. Phys. (2011)

Realizing artificial magnetic fields



Non-interacting
lattice Hamiltonian:

$$\hat{H} = - \sum_{\langle i,j \rangle} J_{ij} \hat{a}_i^\dagger \hat{a}_j + \text{h.c.}$$



Charged particles in magnetic field
→ acquire geometric phase

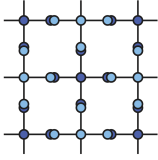
Peierls substitution: $J_{ij} \rightarrow J_{ij} e^{i\phi_j}$

$$\phi_j = \frac{q}{\hbar} \int_{x_j}^{x_i} \mathbf{A} d\mathbf{l}, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

Phase around
closed loop:

$$\Phi = \sum_{\square} \phi_j = 2\pi \frac{\Phi_B}{\Phi_0}$$

Φ_B : magn. flux
 $\Phi_0 = h/q$: magn. flux quantum



Floquet engineering

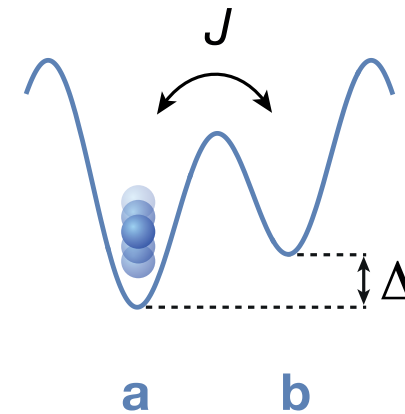
- Time-periodic driven Hamiltonian

$$\hat{H}(t) = \hat{H}(t + T)$$

- Stroboscopic time evolution governed by effective Floquet Hamiltonian $\hat{H}^F$

$$\hat{U}(T, 0) = \exp \left(-\frac{i}{\hbar} T \hat{H}^F \right)$$

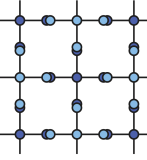
Engineer $\hat{H}_F$ with topological properties!



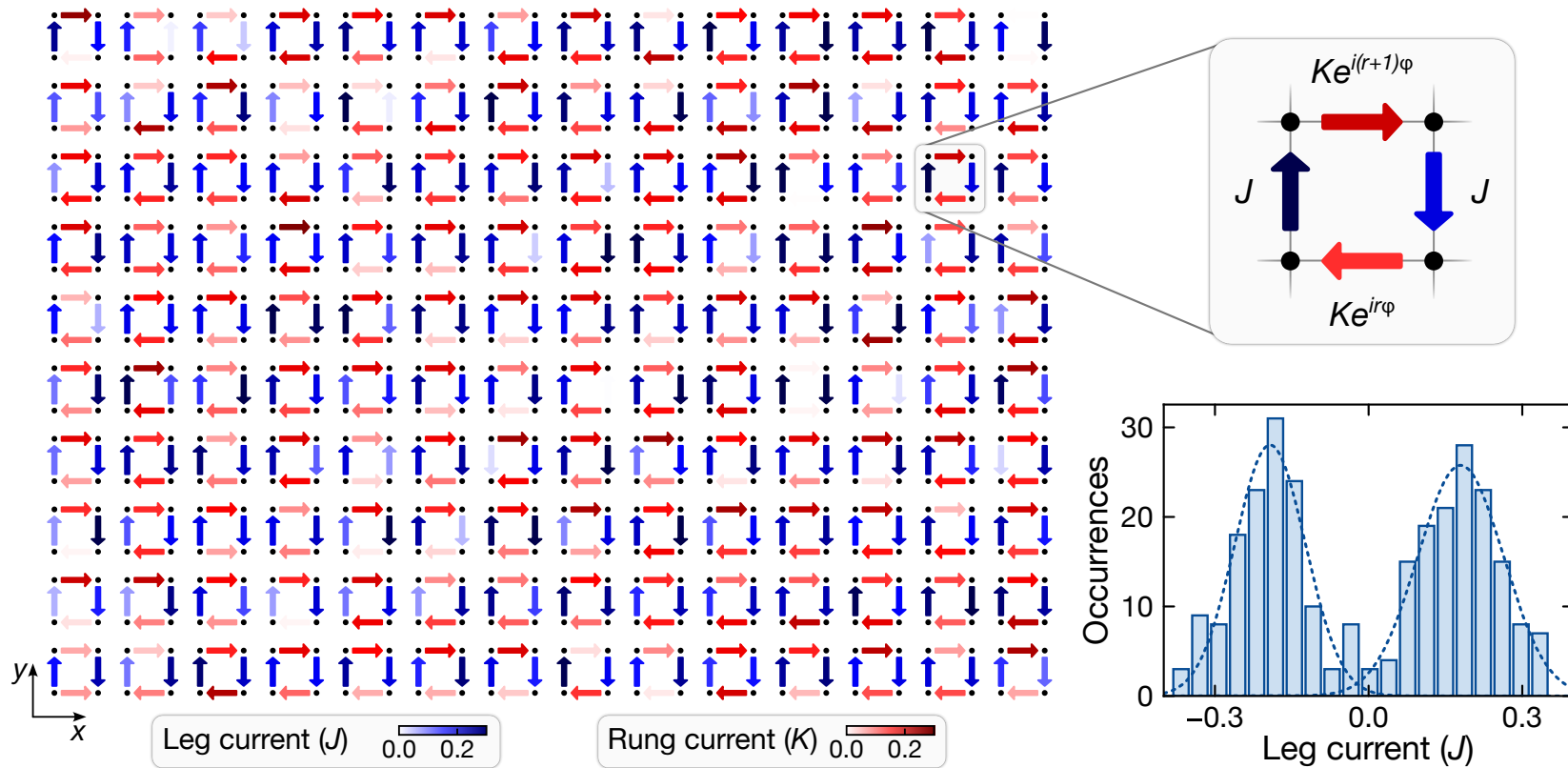
eff. tunneling:

$$J_{\text{eff}} = J \mathcal{J}_{\nu}(\chi) e^{i\nu\phi}$$

Ground-state of interacting plaquettes

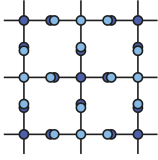


$$U/K \simeq 9.8$$

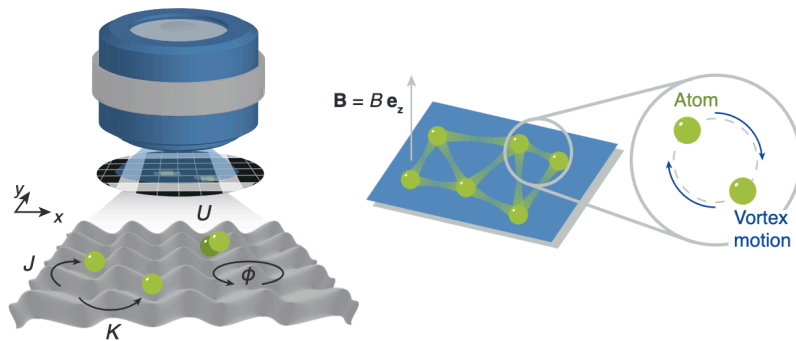


Interacting Mott-Meissner phase

Bottom-up approach: from few to many

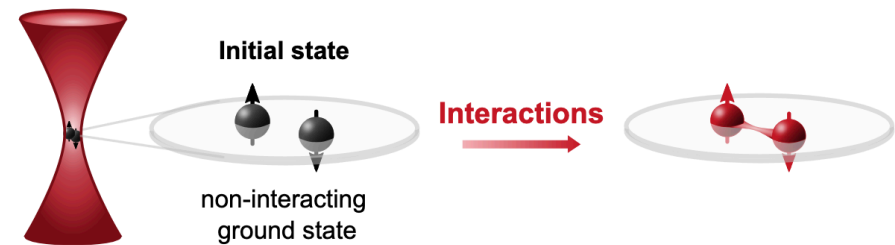


Two bosons on 16 lattice sites laser-assisted tunneling



Léonard, ..., Greiner, *Nature* **619**, 495-499 (2023)

Two fermions in a rotation tweezer:

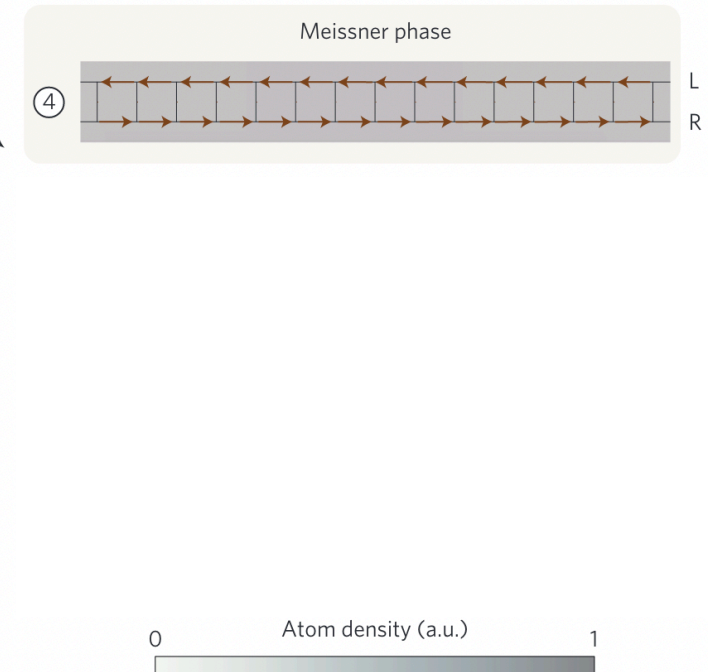
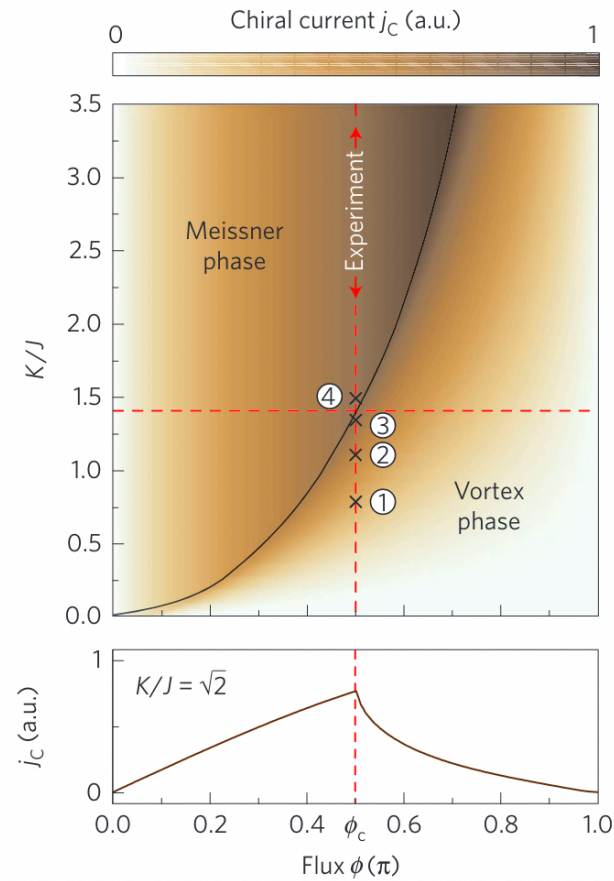
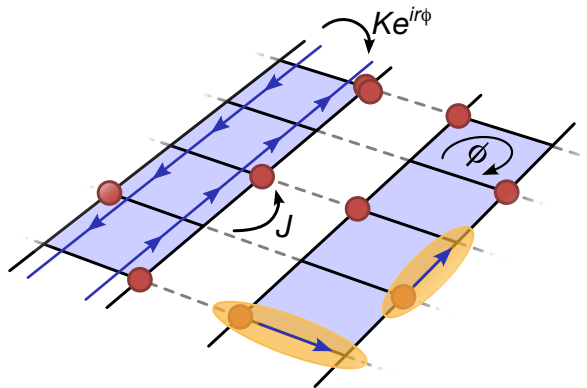
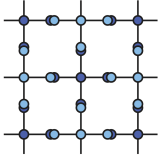


Lunt, ..., Jochim, arXiv:2402.14814

Here: start with many particles → identify stable parameter regimes!

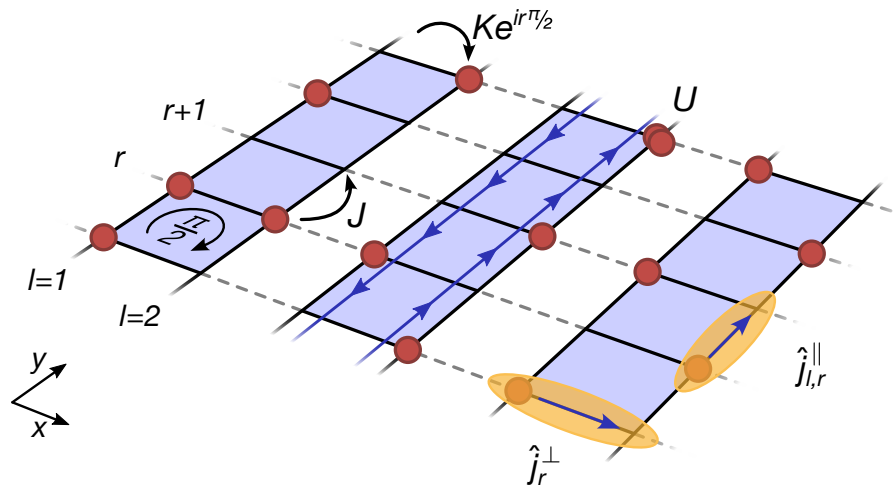
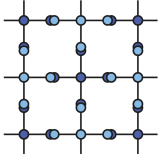
other platforms: Clark, ..., Simon, *Nature* **582**, 41 (2020)
Jan-Wei Pan, *Science* **384**, 579-584 (2024)

Flux ladders



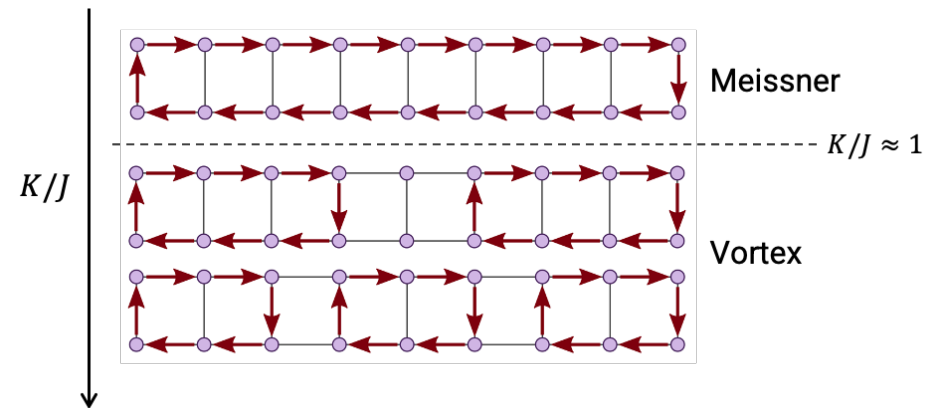
Orignac & Giamarchi, PRB **64**, 144515 (2001)
 Cha & Shin, PRA **83**, 055602 (2011)
 Atala *et al.*, Nat. Phys. **10**, 588-593 (2014); Hgel & Paredes, PRA **89**, 023619 (2014)

Flux ladders



Ground-state phase diagram:

hard-core bosons, half filling, $U \gg J$



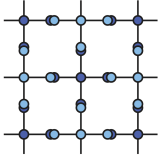
Insulating phases with equilibrium currents!

~homogeneous density profile

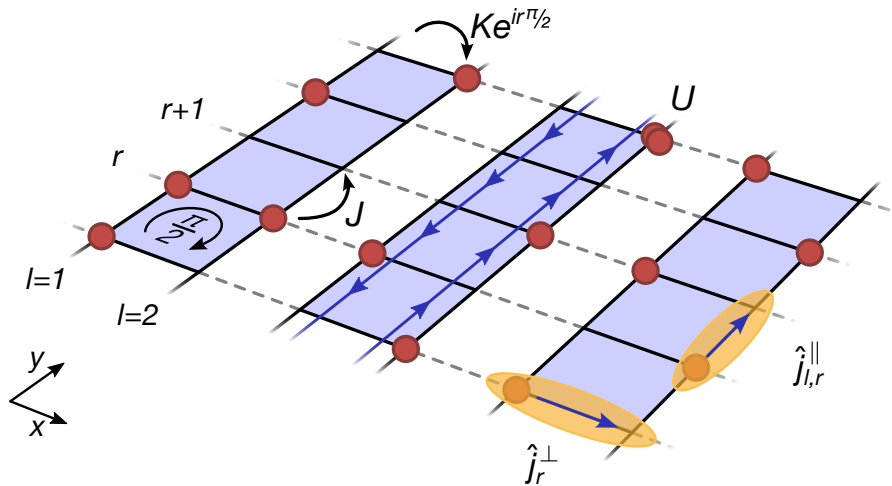
M. Piraud, ..., U. Schollwöck, PRB 91 (2015);
 Buser et al, PRA **105**, 033303 (2022);
 B. Wang, ..., A. Eckardt, SciPostPhys 12 (2022)

see also:
 Tai, ..., Greiner, Nature **546**, 519-523 (2017)
 Zhou, ..., Fallani, Science **381**, 427-430 (2023)

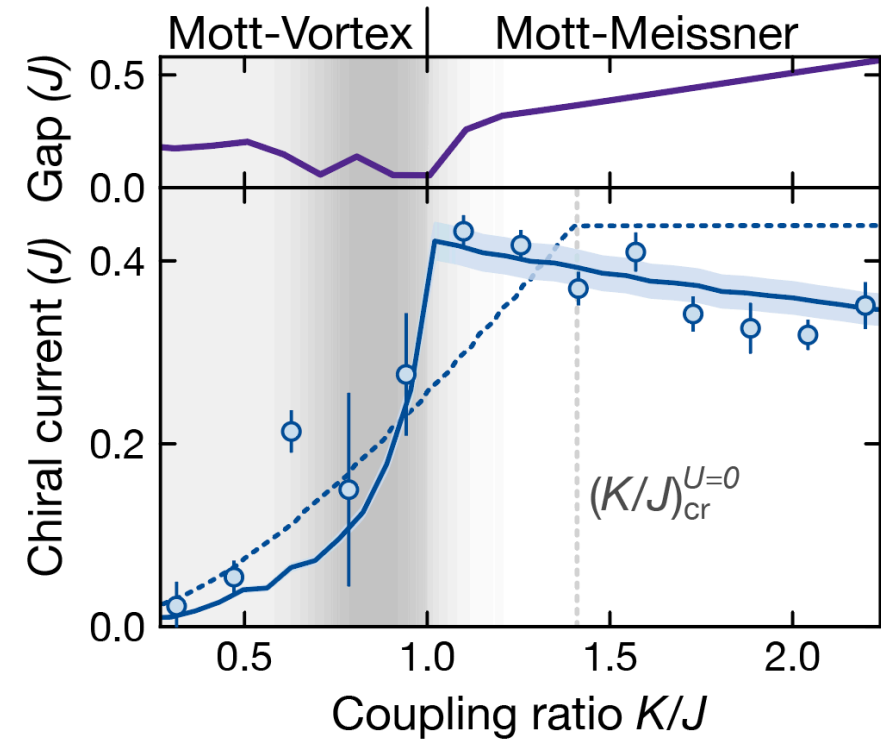
Interacting flux ladders



$$U/J = 11.02(5)$$



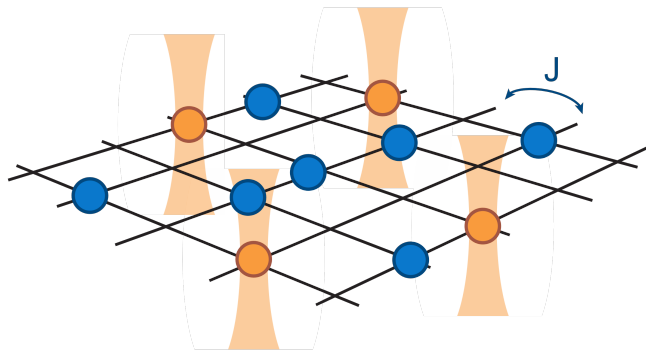
Large many-body system:
48 sites at half filling!



Other projects

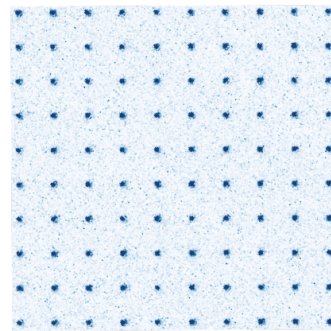
Quantum science with neutral Yb atoms

Fermionic quantum simulation



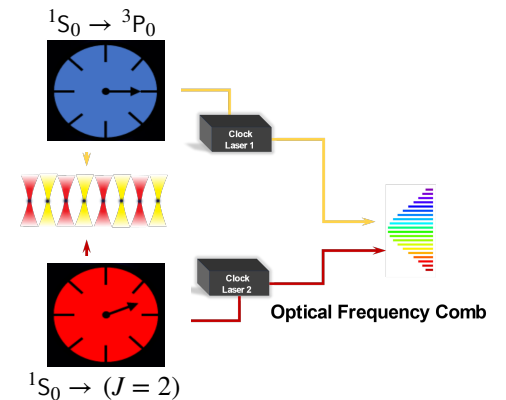
- Fast repetition rates
- Direct ground-state cooling
- State-dependent mobility
- Quantum simulation of open systems

Digital quantum computing



- Auxiliary and data qubits
- Robust nuclear spin-1/2 qubit
- Fast Raman gates
- Error-correction protocols

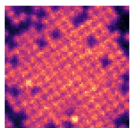
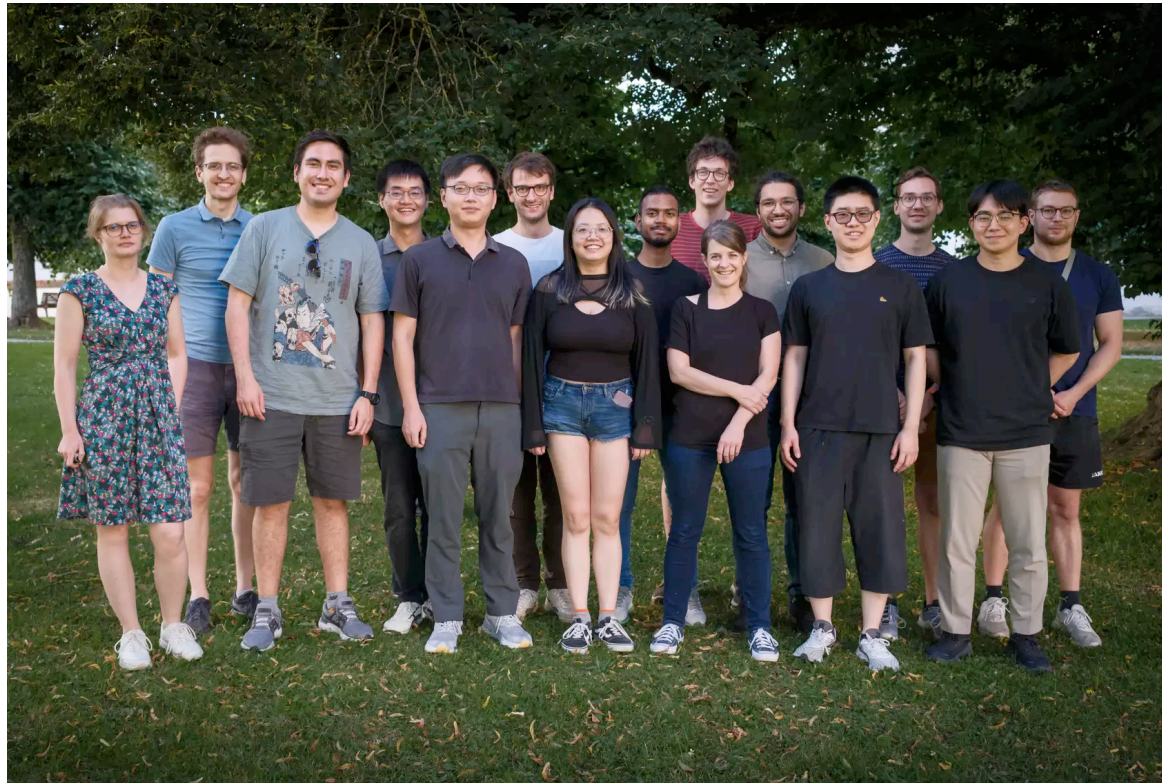
Fundamental physics & quantum metrology



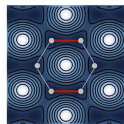
- α -variation
- Local position invariance
- Quantum mechanics & gravity
- Quantum enhanced metrology

The Team

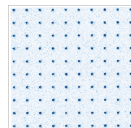
www.mpq.mpg.de/eng-quantum-systems



Cs quantum gas
microscope



K honeycomb
lattice



Yb hybrid
tweezer-lattice



Ryd-Yb



Yb double-
frequency clock

Thank you