Rapid Fermionic Quantum Simulation for Random Unitary Observables

MAX PLANCK INSTITUTE OF QUANTUM OPTICS

Kirill Khoruzhii[1,2], Pragya Sharma[1], Jun Ong[1,2], Marcus Culemann[1,2], Jin Zhang[1], Naman Jain[1,2], and Philipp Preiss[1,3]

[1]Max-Planck-Institut für Quantenoptik, [2]Ludwig-Maximilians-Universität München, [3]Munich Centre for Quantum Science and Technology

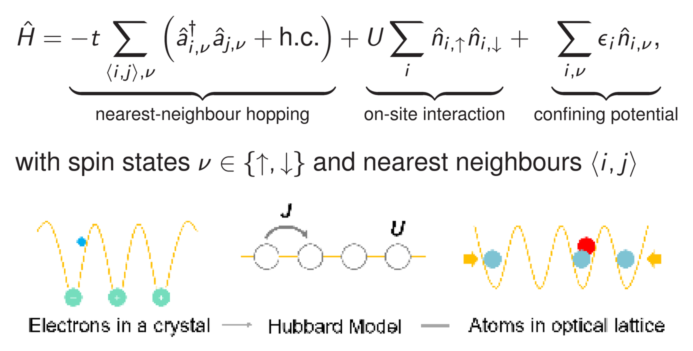
Scientific Perspectives

Condensed Matter Theory
Solid State Systems | Phase Transitions | Material Properties

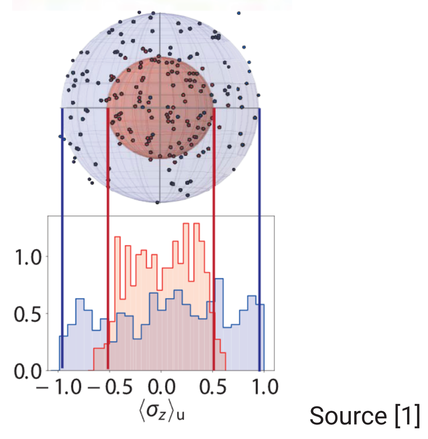
Quantum Information Theory
Entanglement | Physics of Information | Complexity Theory

New questions to ask:

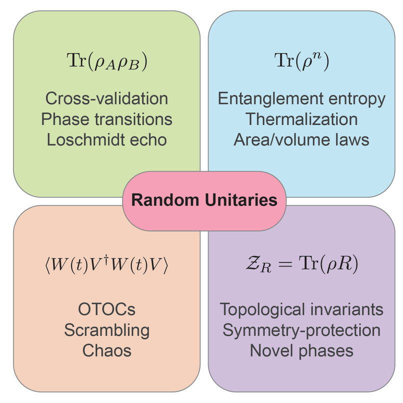
- Can entanglement be used to characterize quantum phases?
- What happens to entanglement at a quantum phase transition?
- How does information propagate in many-body dynamics?
- Does a closed system retain memory of its initial state?



Fast Fermi-Hubbard quantum simulator can provide better insights for correlation observables

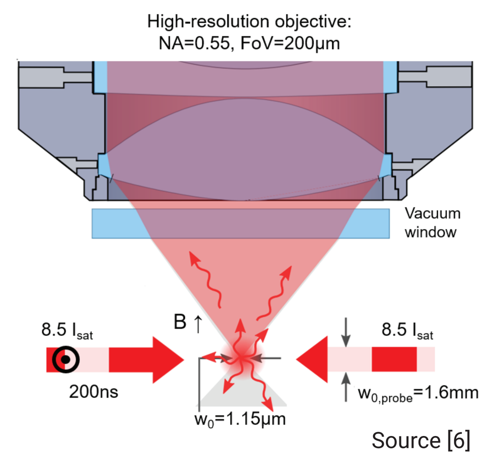


Randomized measurements harness quantum fluctuations for state characterization

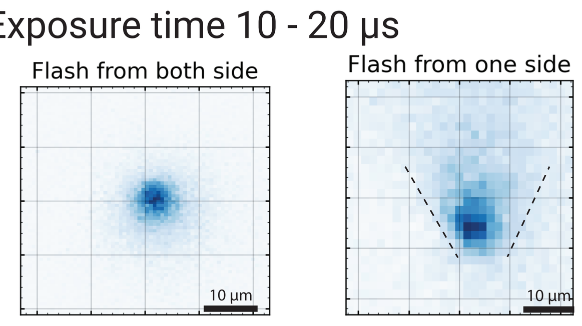


New toolbox based on random unitary observables

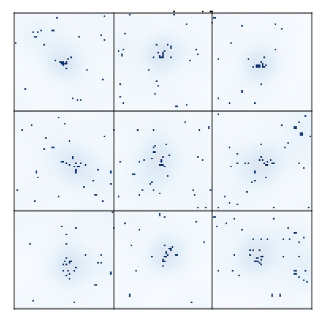
Free-Space Spin Resolved Imaging

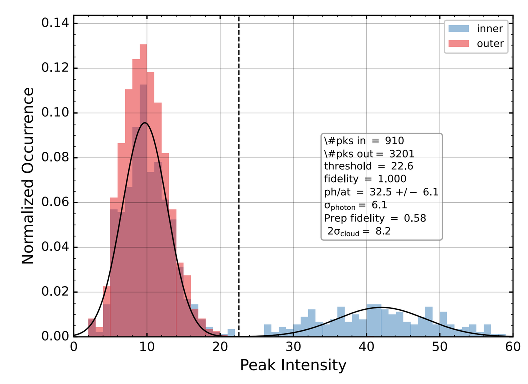


- Counter-propagating beams with 1 mW each
- Flashing frequency at 1MHz
- Exposure time 10 - 20 μs



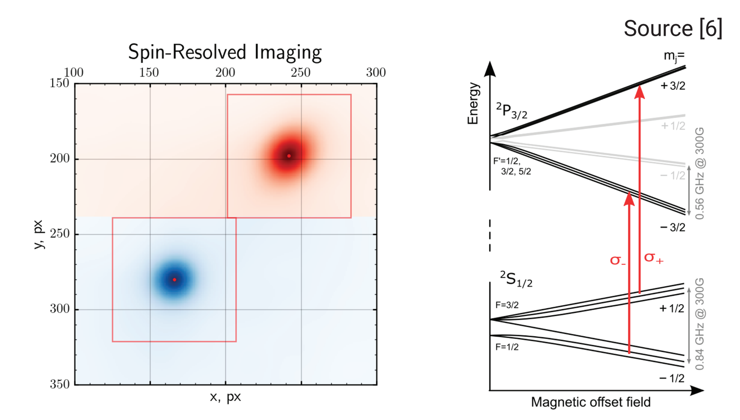
- Determinstically prepare 2 atoms in tweezer
- RF pulse to flip state 2 -> state 3 @ 520G
- MW pulse to flip state 1 -> state 6 @ 520G
- Imaging at fully stretched states





- EMCCD camera with low CIC density (<0.3%)
- Collected 30 photons / atoms
- Achieved detection fidelity > 99.9%

- RF Rabi rate 70 kHz
- RF pi-pulse gate fidelity 99.7%
- RF coherence time 0.5 ms
- MW Rabi rate 90 kHz



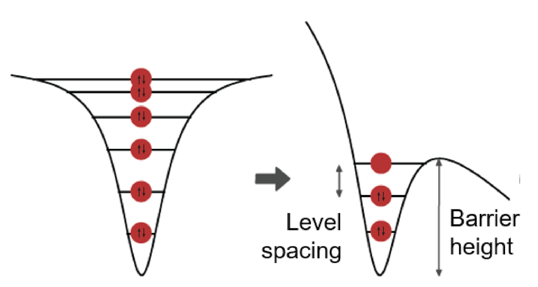
Experimental Sequence

Loading from a 2D-MOT

- Elliptical beam in bowtie configuration
- Push beam for transport to 3D MOT
- Loading rates >10^7 atoms/s

Fast Sample Preparation in Tweezers

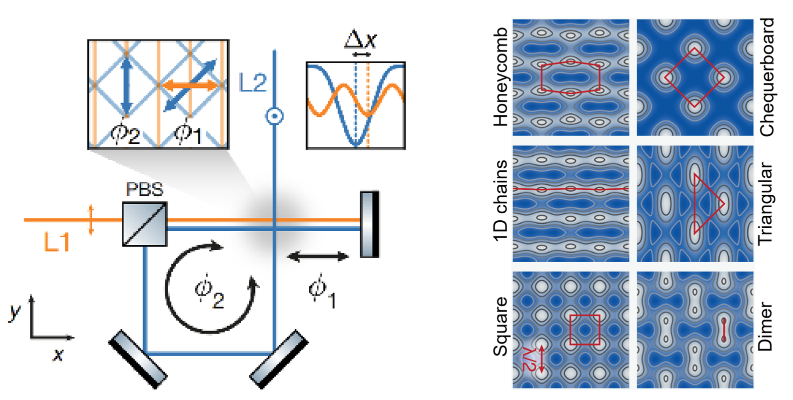
- 808 nm tweezers for loading from ODT or directly from 3D MOT
- Parallel preparation in 2D AOD tweezer array
- Spilling to prepare controlled ultracold system
- Adiabatic loading from tweezers to lattice



Source [3]

Bowtie Lattice & Dynamic Geometries

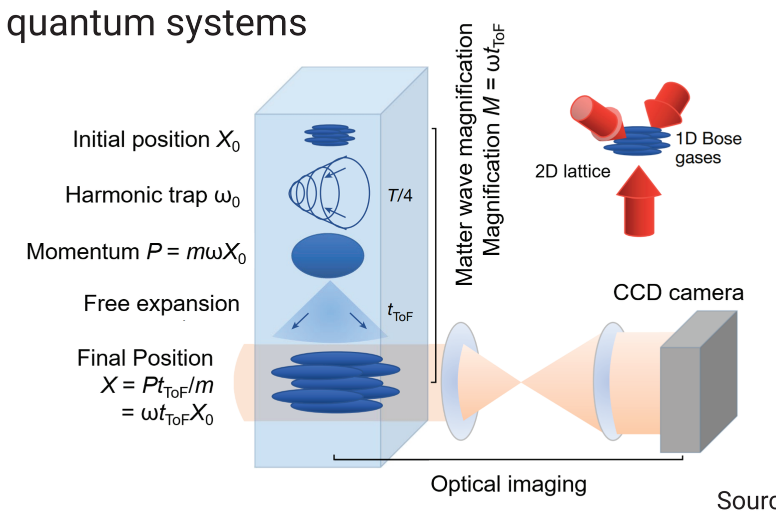
- Passively phase-stablized 1064 nm optical lattices using common retroreflection
- Dynamically tunable lattice geometries
- Independently tunable 2D hopping rates



Source [4]

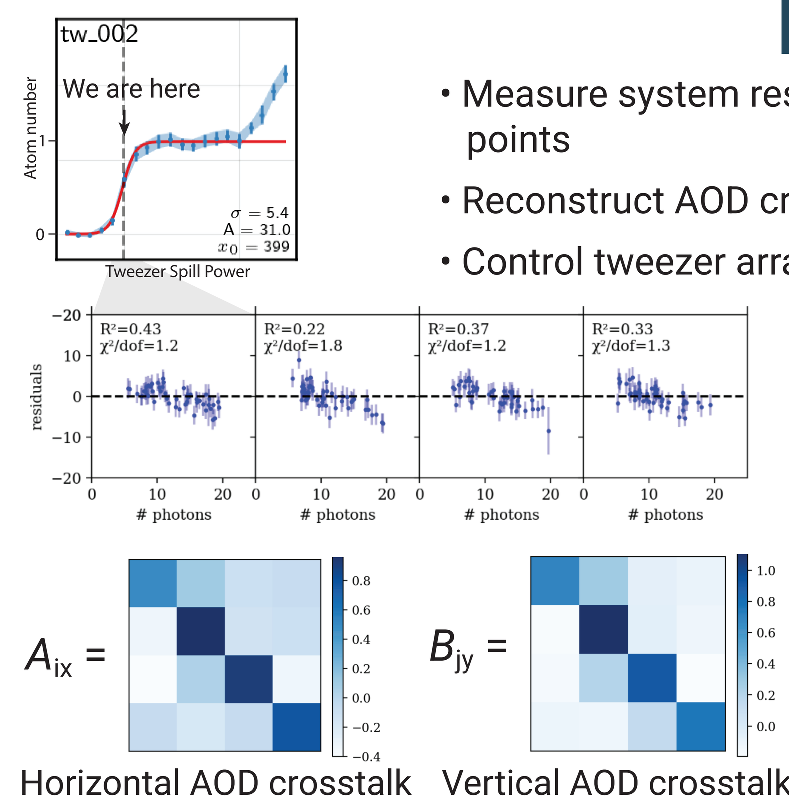
Matter Wave Magnification

- Time-dependent evolution in harmonic trap
- Final quantum state magnification from the 2D-lattice system
- Fast single-site-resolved imaging of compact quantum systems



Source [5]

Tweezer Array Crosstalk



- Measure system response at randomly sampled points
- Reconstruct AOD crosstalk with linear model
- Control tweezer array depth with crosstalk matrix

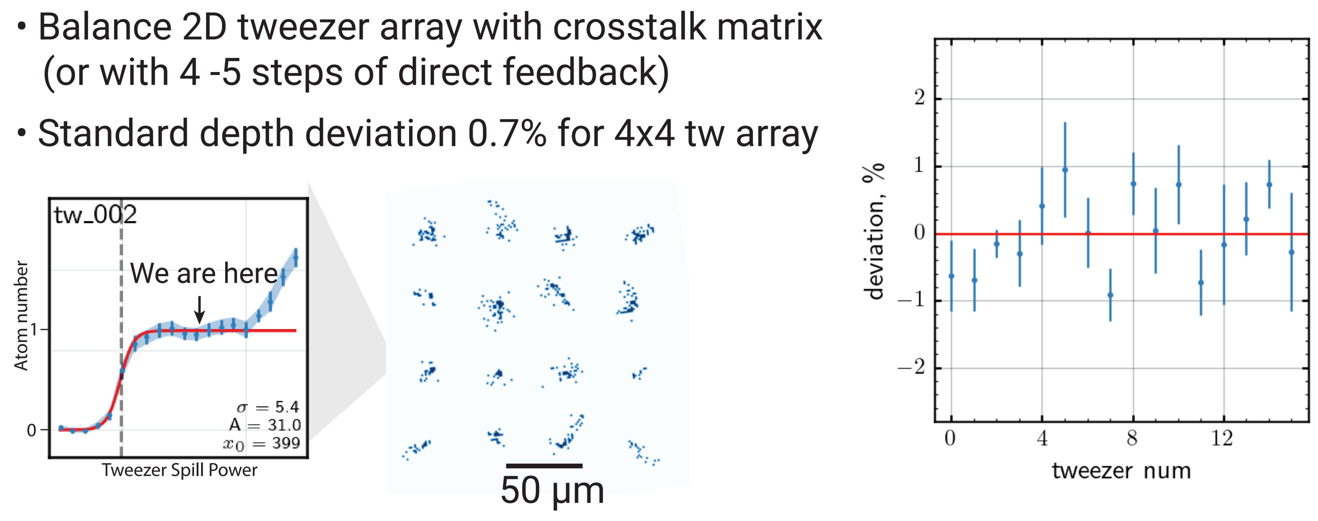
$H_i = A_{ix} h_x$ $V_j = B_{jy} v_y$

$M_{ij} = H_i V_j$

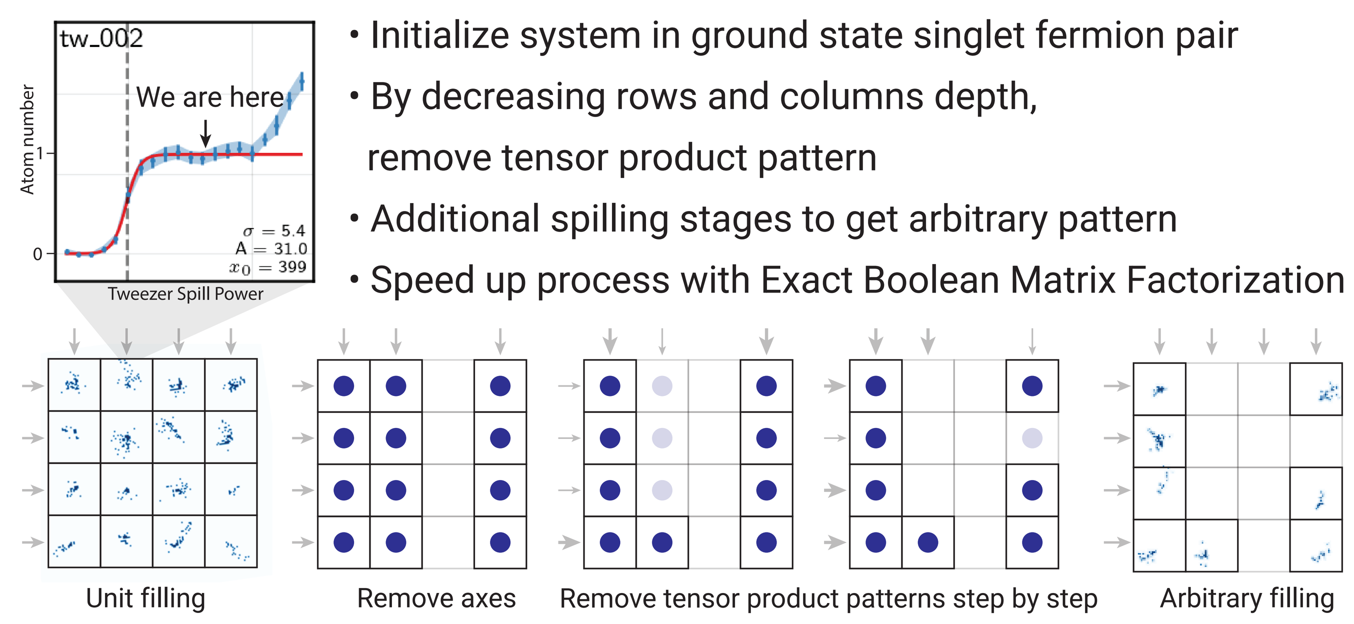
- Generation of arbitrary tensor product potentials
- Achieved depth control up to 2%

Tweezer Array Balancing

- Balance 2D tweezer array with crosstalk matrix (or with 4 -5 steps of direct feedback)
- Standard depth deviation 0.7% for 4x4 tw array



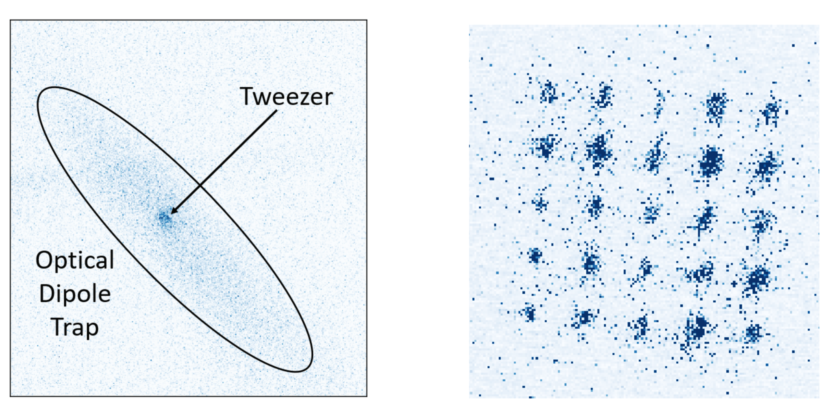
Arbitrary Fermionic Mode with AOD



- Initialize system in ground state singlet fermion pair
- By decreasing rows and columns depth, remove tensor product pattern
- Additional spilling stages to get arbitrary pattern
- Speed up process with Exact Boolean Matrix Factorization

Load Arrays from Dipole Trap

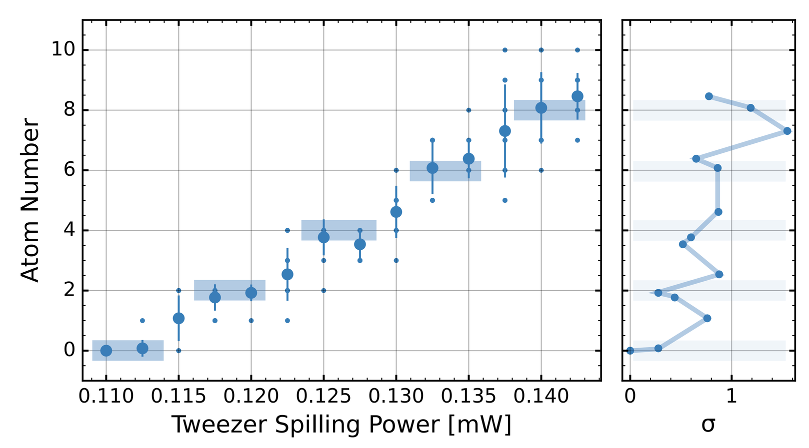
- Evaporation in ODT for 1s
- Adiabatically transfer into tweezer in 0.4s
- 300 atoms in 10 mW tweezer & 0.55 μm waist
- Large tweezer array generated by crossed AODs
- 2 atom ground state lifetime of 10 s
- >99% ground state fidelity MJT up to 35 μm/ms



Determinstic State Preparation

Evaporate and Spill in Tweezer

- Further evaporation in tweezer in 0.05 s
- Spill tweezer with non-interacting atoms
- Two atoms preparation with fidelity 95%



References

[1] T. Brydges et al., Science 364, 260-263 (2019)
[2] K. Li et al., PRA 92, 013419 (2015)
[3] Jochim group, Heidelberg University.
[4] L. Tarruell et al., arXiv::1111.5020v1(2011)
[5] L. Asteria et al., Nature 599, 571-575 (2021)
[6] A. Bergschneider et. al., PRA 97, 063613 (2018)

Funding

European Research Council
Established by the European Commission
MCQST
Bundesministerium für Bildung und Forschung