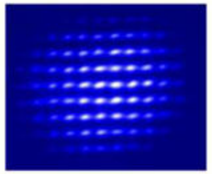
TWO- AND THREE-DIMENSIONAL ARRAYS OF INDIVIDUAL ATOMS: an introduction to novel potential implementations of ATOMTRONICS

Gerhard Birkl – TU Darmstadt

TECHNISCHE UNIVERSITÄT DARMSTADT

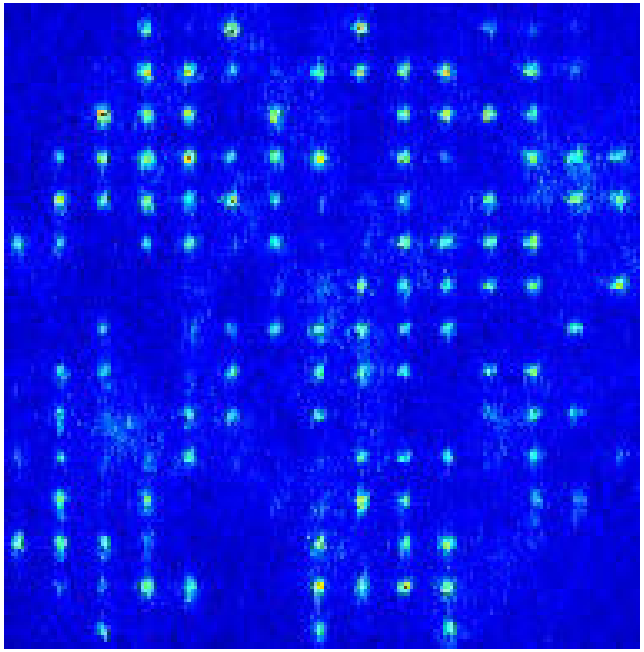


ATOME - PHOTONEN - QUANTEN
Prof. Dr. Gerhard Birkl
Institut für Angewandte Physik
Fachbereich Physik

Bundesministerium für Bildung und Forschung

quanten technologien

DFG Priority Programme 1929
iRyd



Our Team: Projects, Group Members, and Co-Workers

BEC and Integrated Atom Optics

Dominik Pfeiffer, Ludwig Lind, Sophie Reißig
Former: Daniel Derr, Felix Schmaltz

Quantum Information Processing

Malte Schlosser, Tobias Schreiber, Lukas Sturm, Marcel Mittenbühler, Justus Götzinger, Christiph Rützel
Former: Daniel Ohl de Mello, Dominik Schäffner, Lars Pause, Tilman Preuschoff

Interactions of Metastable Neon Atoms

Jan Schütz, Alexander Martin, Thomas Feldker,
Theory: Christian Cop, Reinhold Walser

Laser Spectroscopy with Highly Charged Ions (@GSI/FAIR)

Patrick Baus, Arya Krishnan, Manuel Vogel, Wolfgang Quint, and the SPECTRAP & ARTEMIS collaborations
Former: Alexander Martin, Tobias Murböck, Marco Wiesel, Mouwafak Shaaban

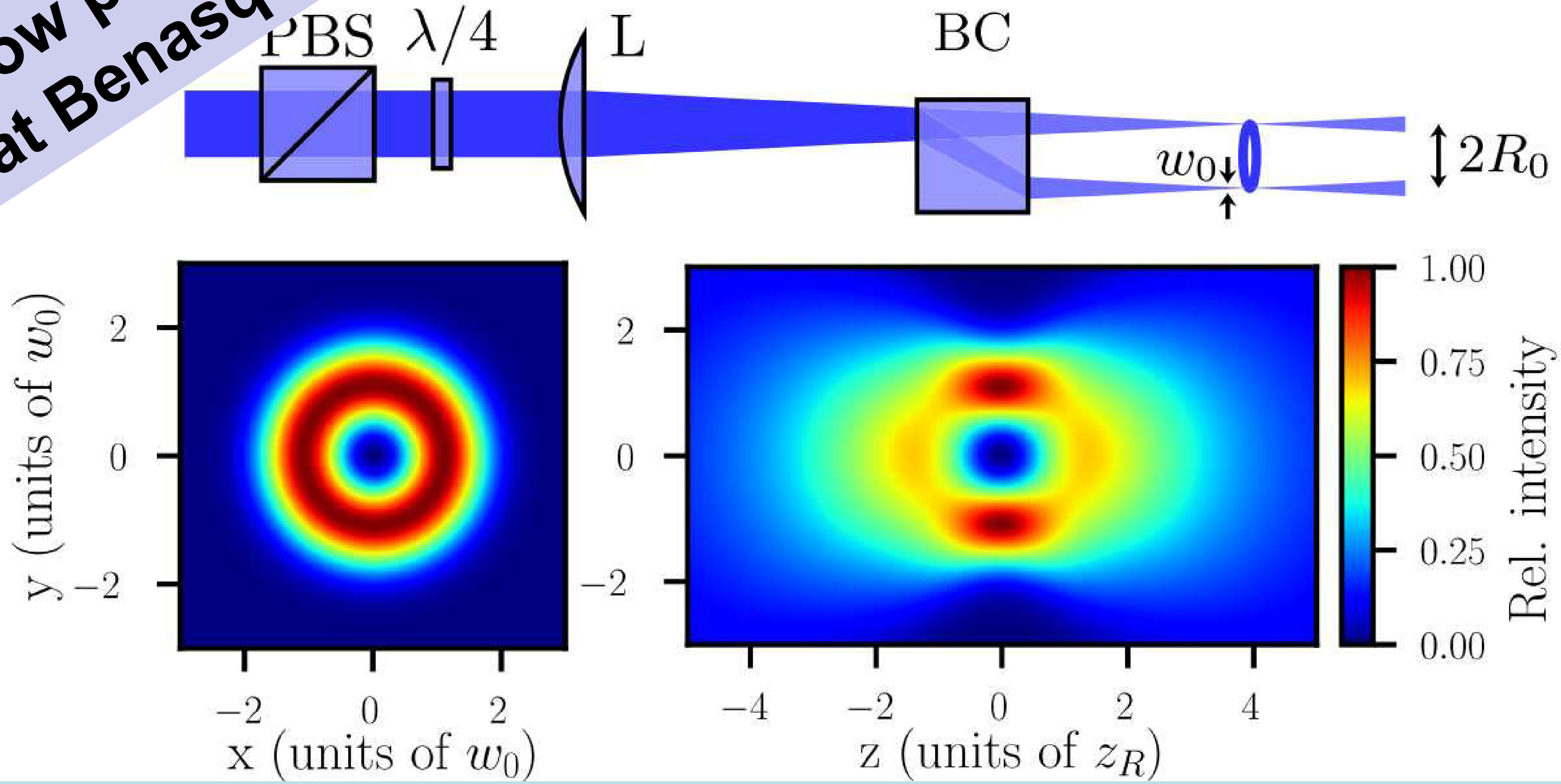
Collaborations

Veronica Ahufinger, Jordi Mompart, Anna Sanpera, Alex Turpin, Maciej Lewenstein (Barcelona)
Rainer Dumke (NTU), Reinhold Walser (Darmstadt), Alexander Yakimenko (Kiev)

Trapping of BE… in a 3D dark focus generated by conical refraction

Now playing at Benasque

- **ATOMTRO… …tion:** Dominik Pfeiffer, Ludwig Lind, Verónica Ahufinger, GB, Jordi Mompart …

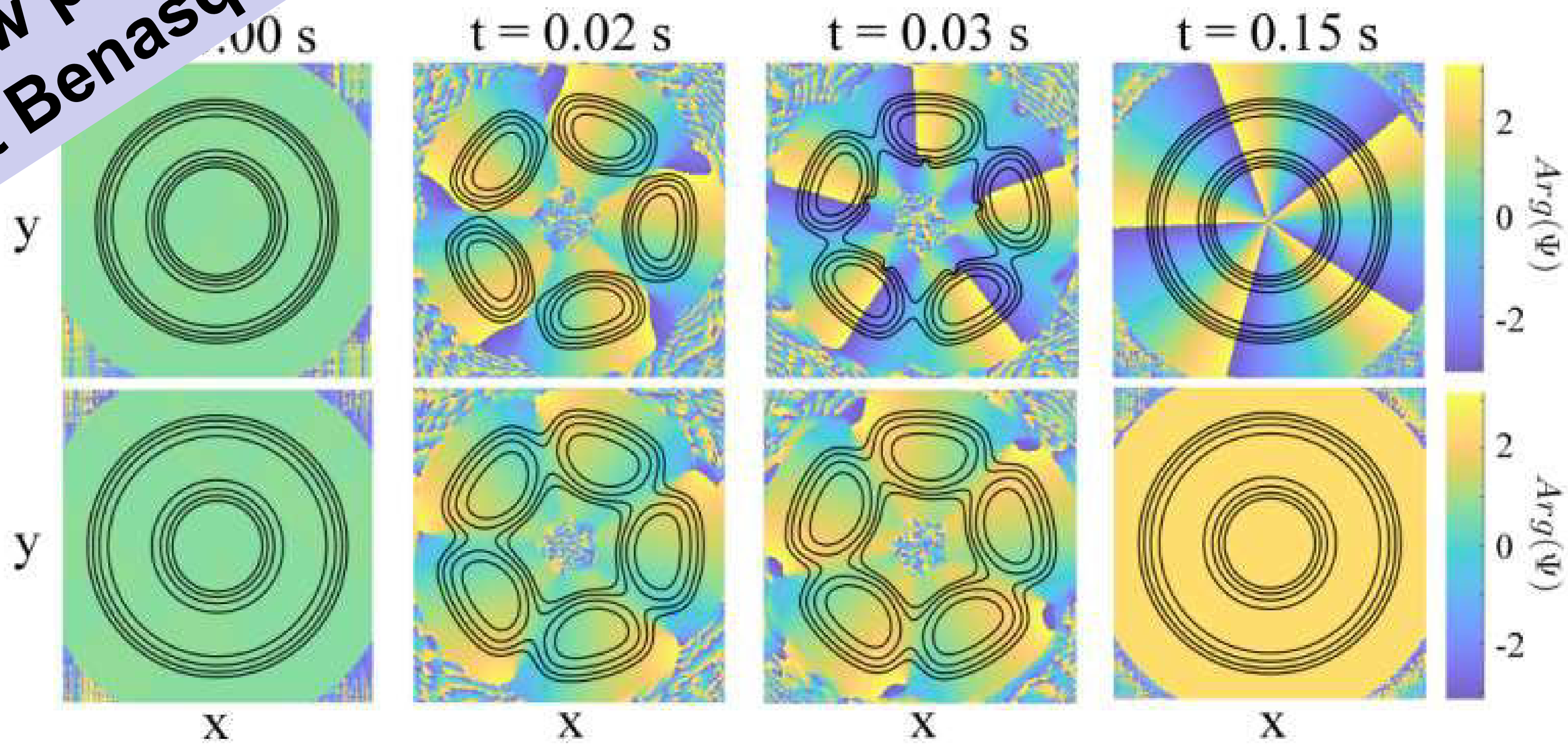


D. Pfeiffer, L. Lind, J. Küber, F. Schmaltz, A. Turpin, V. Ahufinger, J. Mompart, G. Birkl, Phys. Rev. A **108**, 053320 (2023)

Trapping Gen[...]ion of Josephson vortices in stacked toroidal BECs

Now playing at Benasque

- **ATOMTR[...]ation:** Dominik Pfeiffer, Ludwig Lind, Alexander Yakimenko, GB …

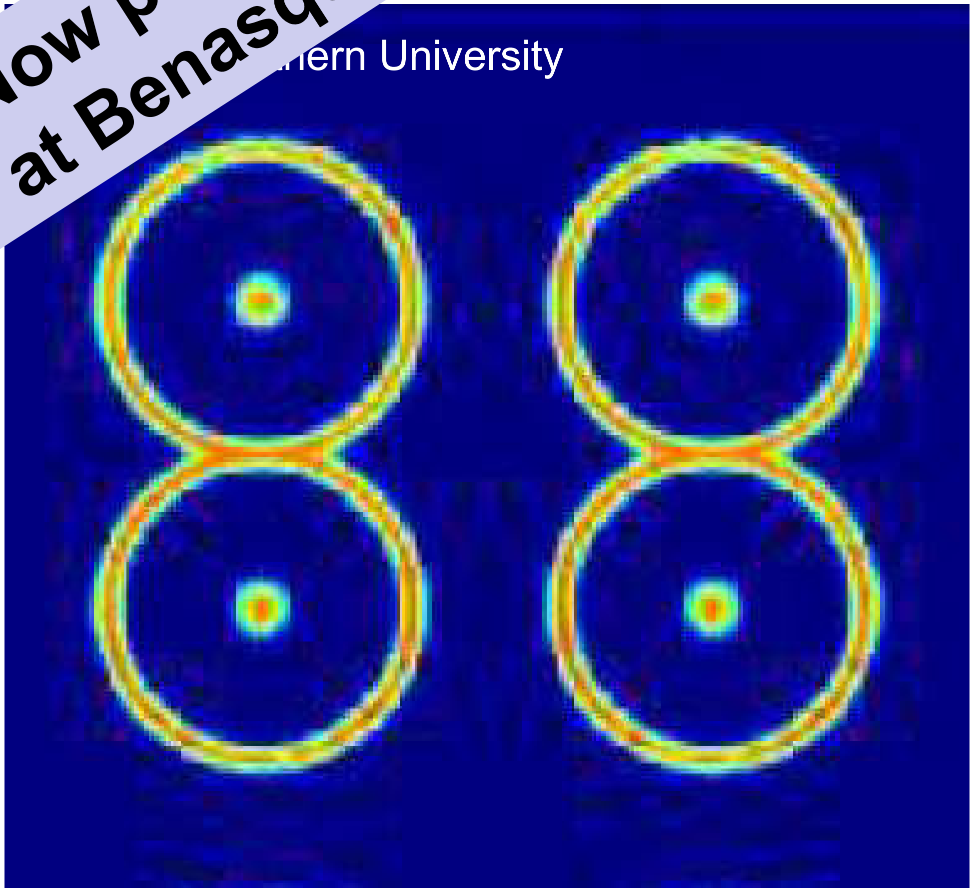


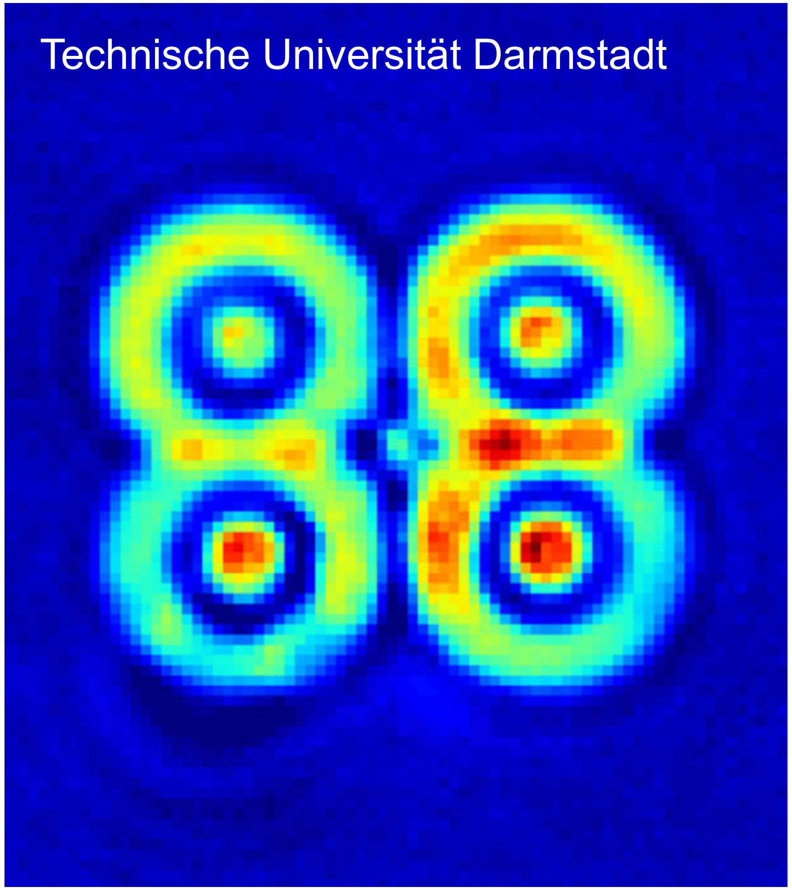
N. Bazhan, A. Svetlichny, D. Pfeiffer, D. Derr, A. Yakimenko, G. Birkl, Phys. Rev. A **106**, 043305 (2022)

A double-targ… EC array atomtronic rotation sensor

Now playing at Benasque

- **ATOMTR… ation:** Dominik Pfeiffer, Ludwig Lind, Mark Edwards, Charles Clark, GB …



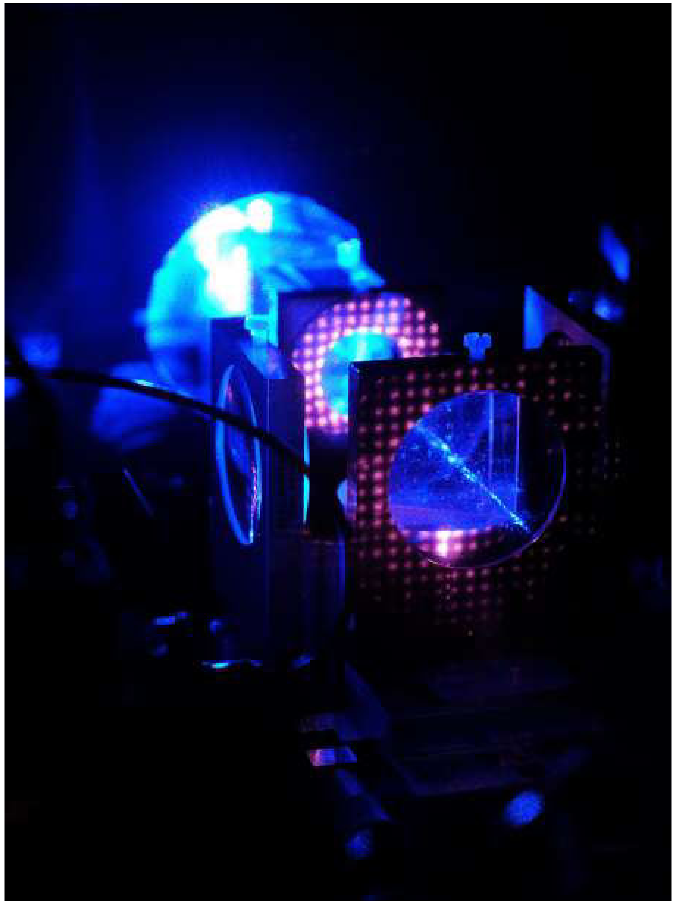


What to Expect from this Talk?

- This Talk is about **Fundamental Research** on **Quantum Proces-sing Hardware**.

- The **Technology** Behind this Hardware Platform is **In Many Respects Different** from the one you are used to work with.

- This Quantum Hardware Platform Fulfills **All Requirements** for Quantum Information Processing and has a Key Advantage: **Scalability.** It might be very inter-esting for **ATOMTRONICS.**



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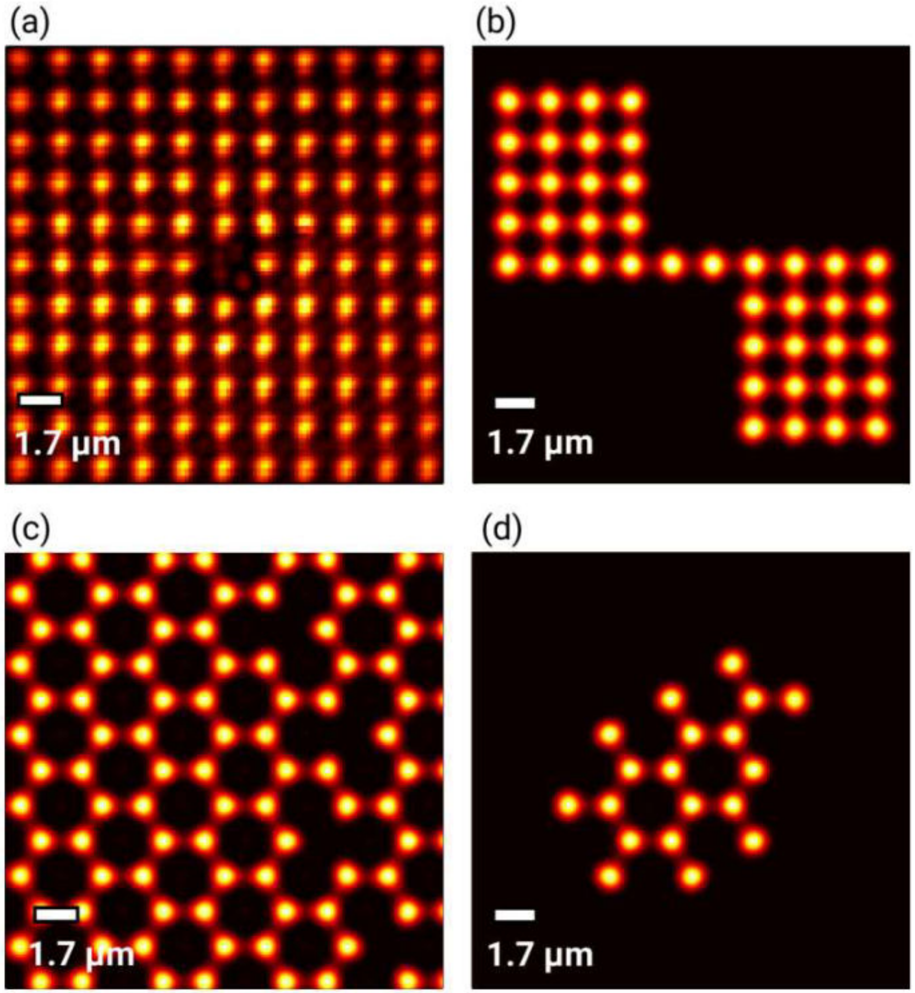
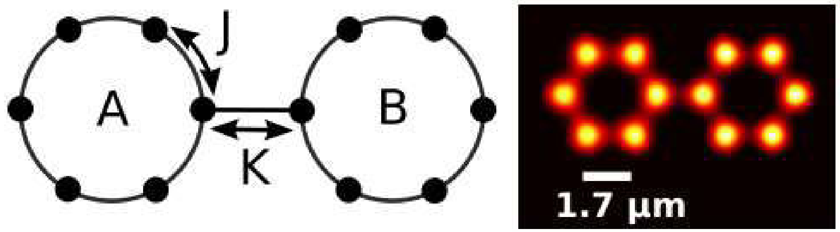
Many-body physics in reconfigurable arrays of tunnel-coupled traps

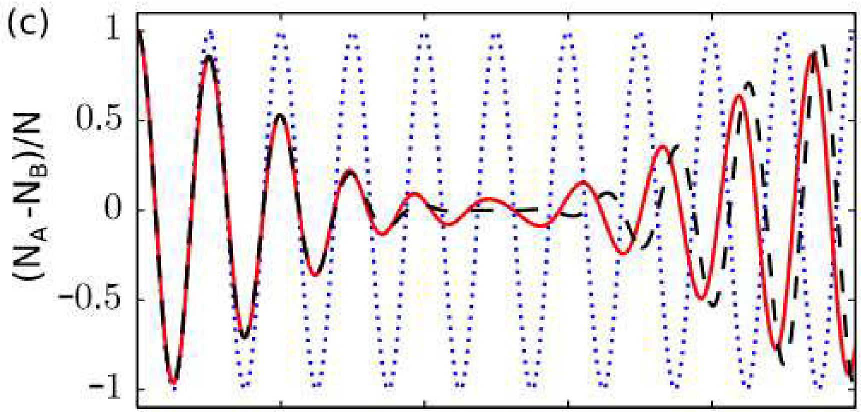


PHYSICAL REVIEW A **95**, 063625 (2017)

Quantum simulators by design: Many-body physics in reconfigurable arrays of tunnel-coupled traps

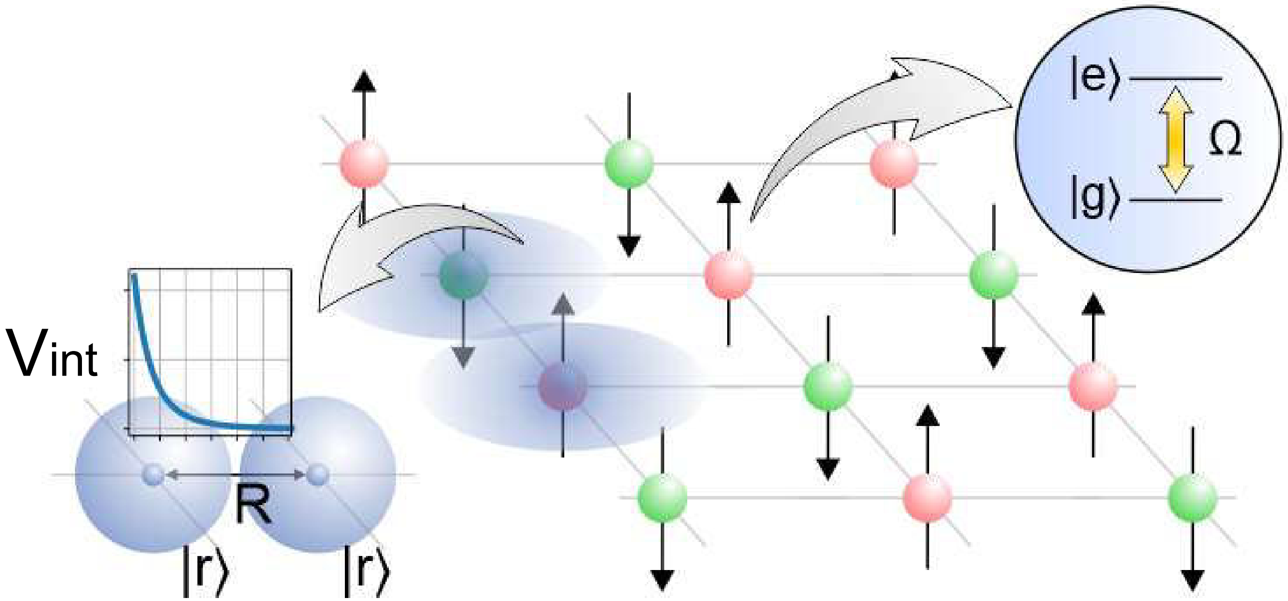
M. R. Sturm,* M. Schlosser, R. Walser, and G. Birkl
Institut für Angewandte Physik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
(Received 21 December 2016; published 29 June 2017)





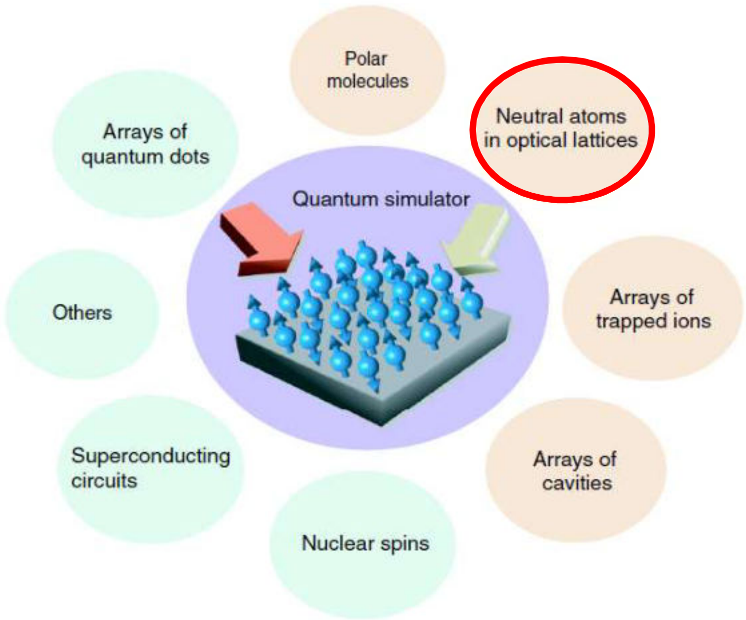
Platforms for Quantum Information Processing

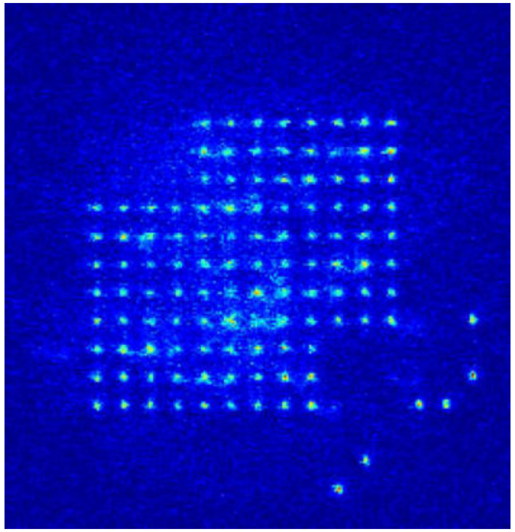
Typical concept: Interacting spin-1/2 systems in a regular lattice



Engineering effective Hamiltonians: Coherent quantum-state control, tunable interactions, site- and time-resolved dynamics

Platforms for Quantum Information Processing





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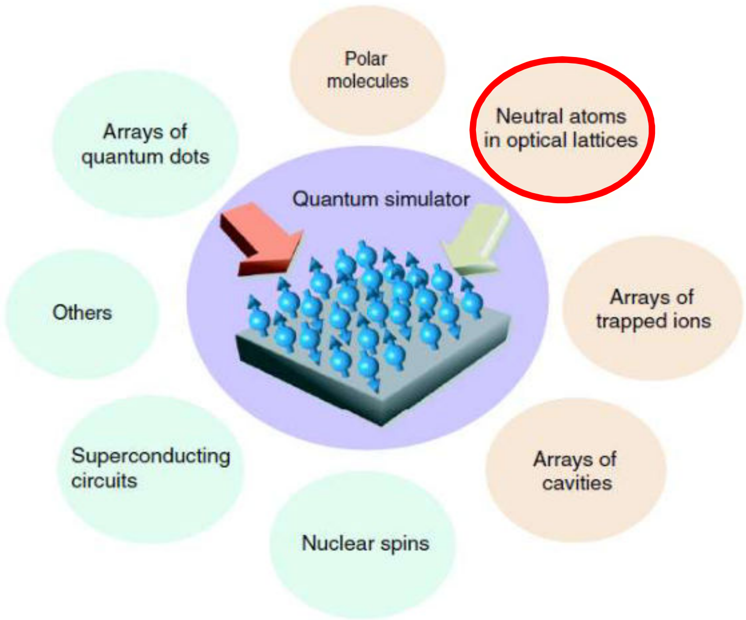
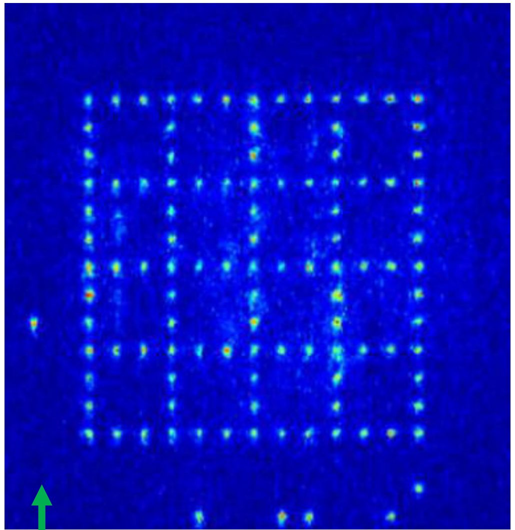
Quantum simulator	Strength	Weakness
Neutral atoms	Scaling*	Individual control and readout
Trapped ions	Individual control and readout*	Scaling
Cavity arrays	Individual control and readout	Scaling
Electronic spins (quantum dots)	Individual control and readout,* tunability	Scaling
Superconducting circuits	Individual control and readout,* tunability	Scaling (some recent progress)
Photons (linear optics)	Flexibility*	Scaling
Nuclear spins (NMR)	Well-established, readily available technology*	Scaling, no individual control

I. M. Georgescu et al., Rev. Mod. Phys. ***86,*** *153 (2014)*

Platforms for Quantum Information Processing





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Not a weakness any more!

Quantum simulator	Strength	
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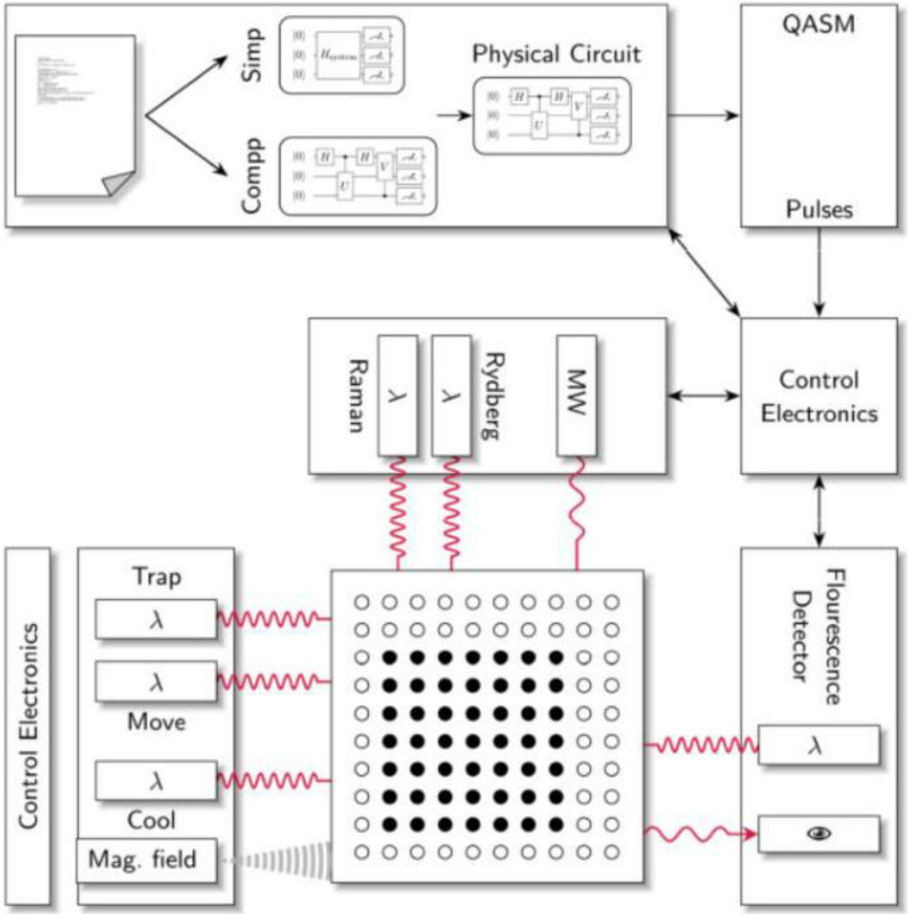
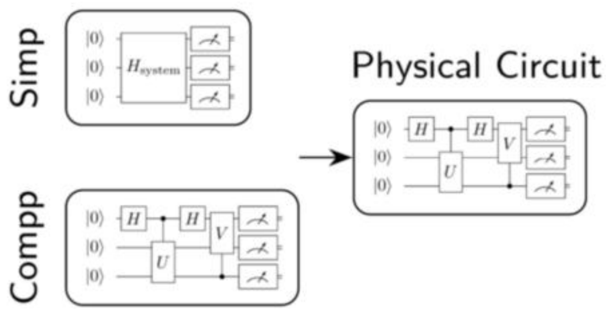
Schematic Overview of Cold-Atom Quantum Computer



Quantum Computation and Simulation require very similar Hardware




Wintersperger et al. EPJ Quantum Technology (2023) 10:32
https://doi.org/10.1140/epjqt/s40507-023-00190-1
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EPJ Quantum Technology
a SpringerOpen Journal
REVIEW Open Access

Neutral atom quantum computing hardware: performance and end-user perspective

Karen Wintersperger[1*], Florian Dommert[2], Thomas Ehmer[3], Andrey Hoursanov[4], Johannes Klepsch[5], Wolfgang Mauerer[1], Georg Reuber[6], Thomas Strohm[7], Ming Yin[8] and Sebastian Luber[9]

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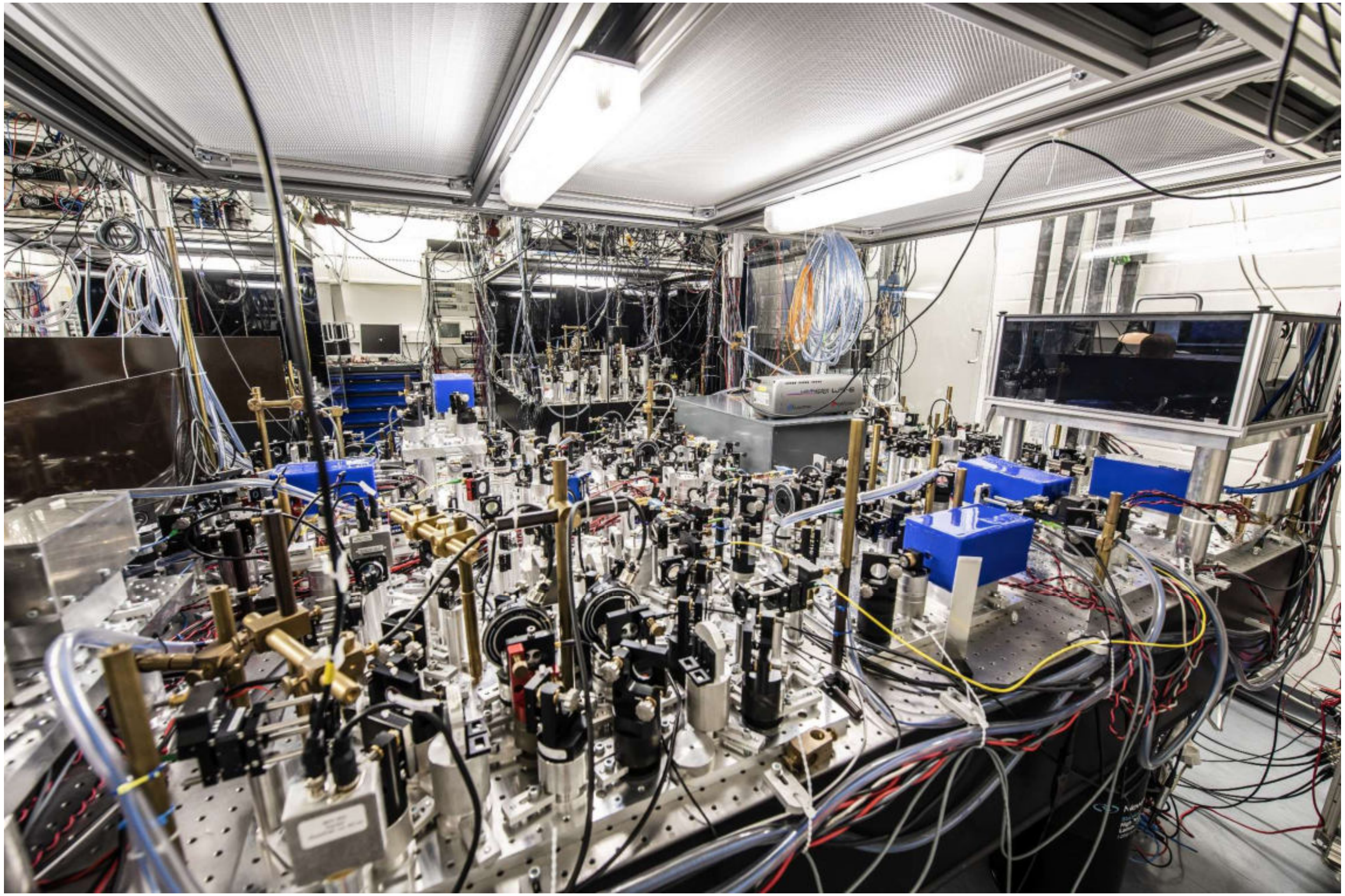
Darmstadt Neutral-Atom Quantum Technology Platform



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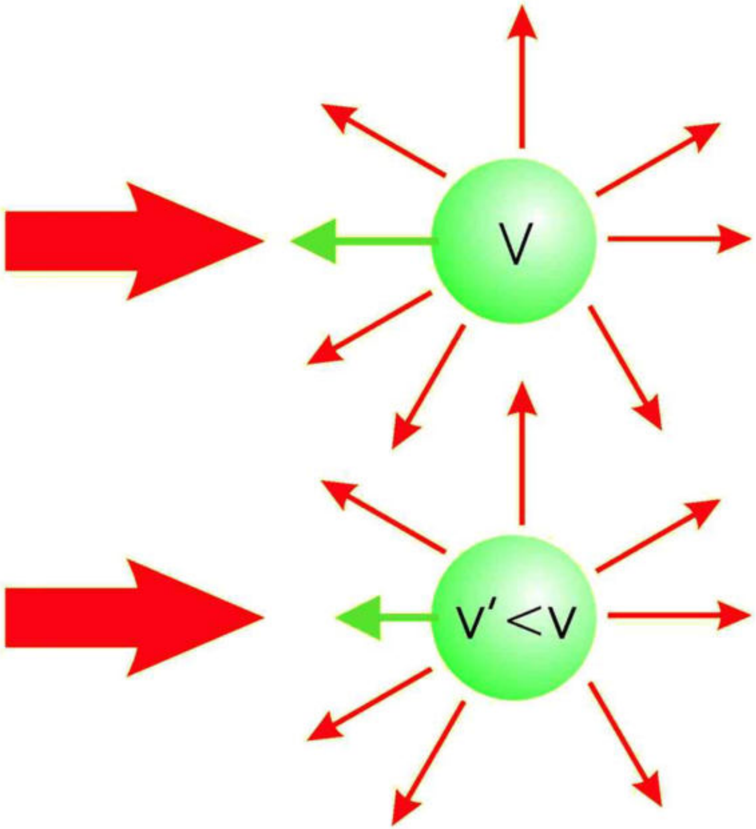
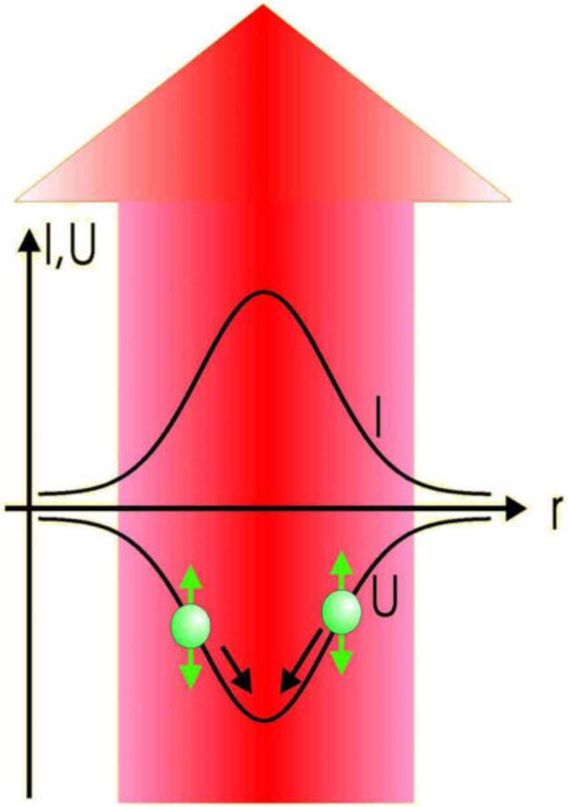
Optical Control of Atoms

Dissipative: Spontaneous Scattering



Laser Cooling, Preparation, and Readout

Conservative: Dipole Force



Dipole Trapping

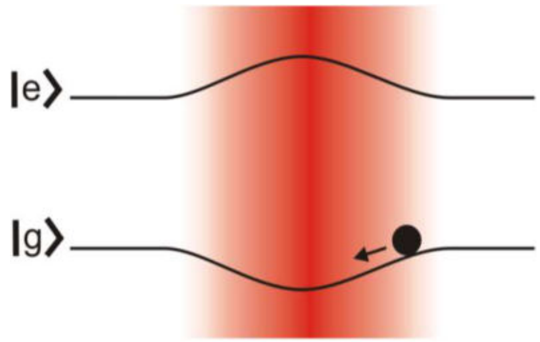
Trapping of Atoms: Dipole Potential

- Energy Shift Proportional to Intensity

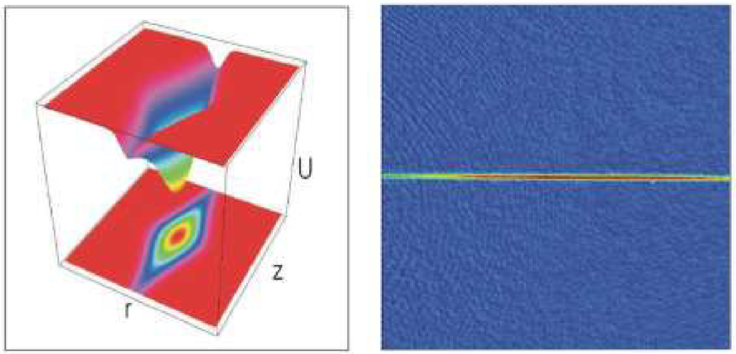
$$U(r) \sim -\frac{I(r)}{\Delta}$$

- Red detuning: $\omega_0 > \omega_L$
  → Atoms attracted to intensity maximum

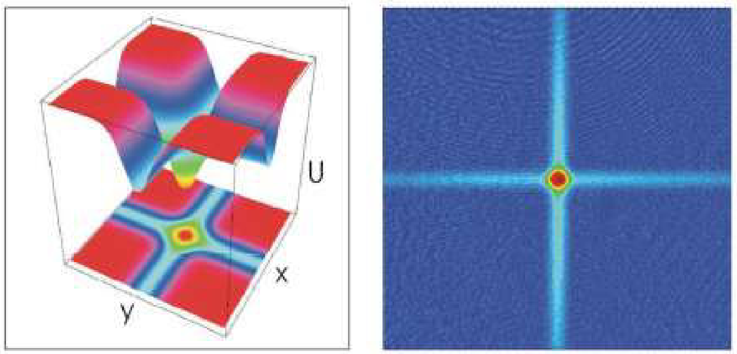
- Large Detuning → Conservative Potential



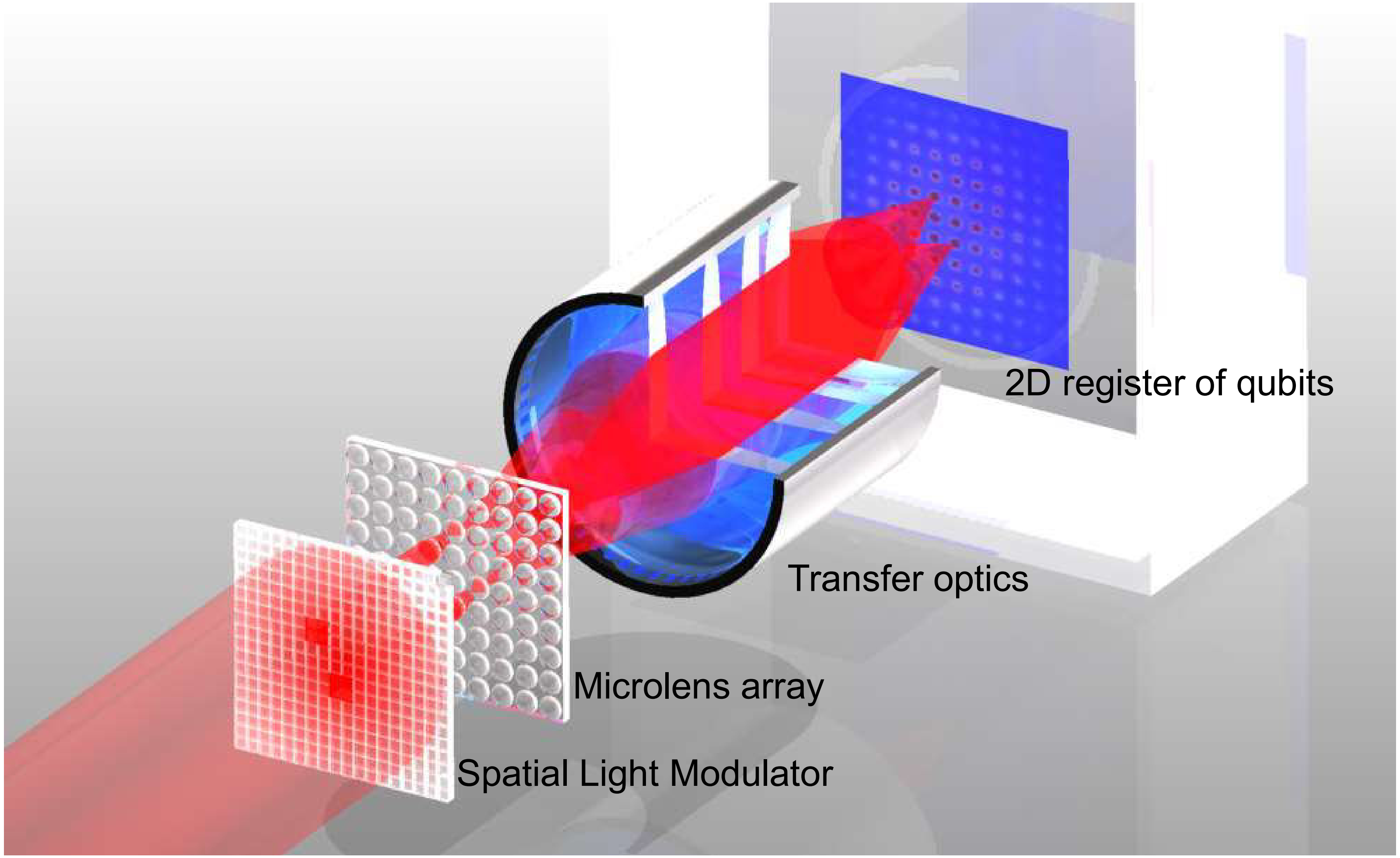
Single Beam Dipole Trap



Crossed Beam Dipole Trap

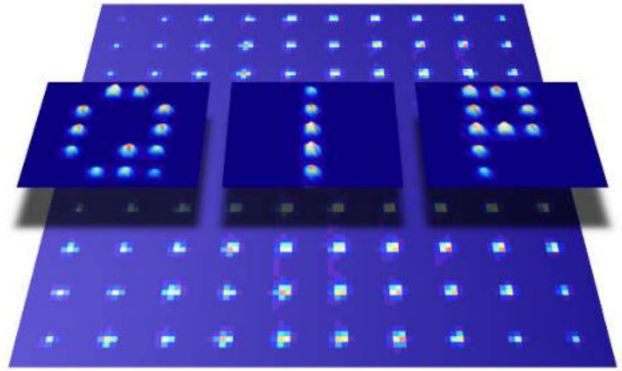


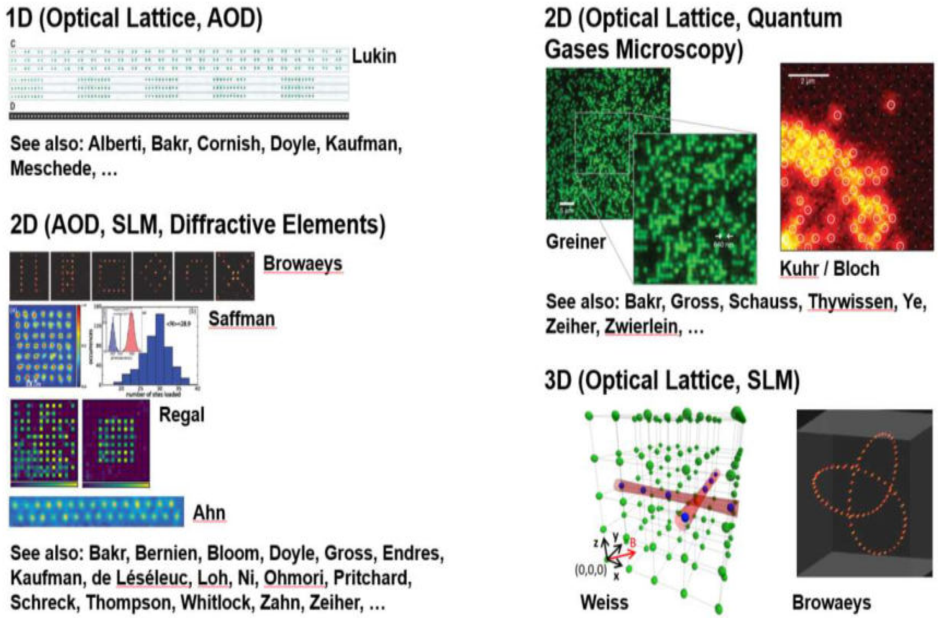
Reconfigurable Generation of Trap Structures

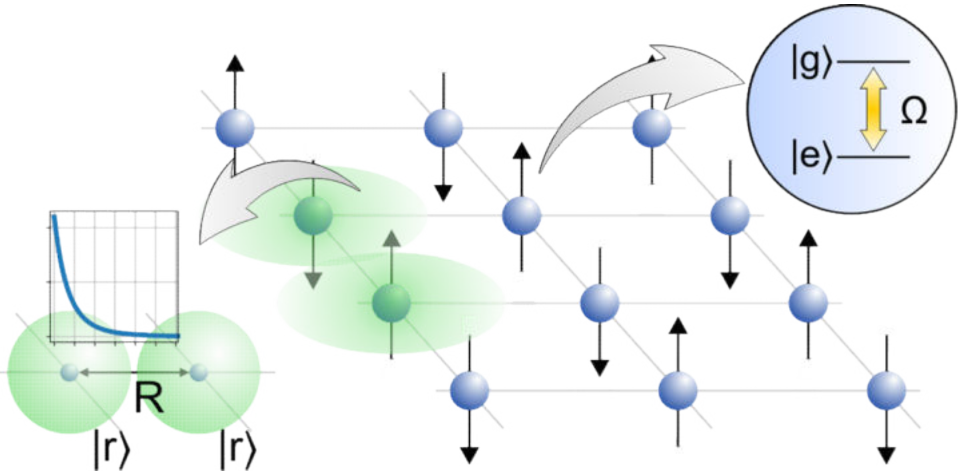


Quantum Technology Platform for Quantum Information Science based on Neutral-Atom Qubits

- Tweezer array of neutral atoms
- Robust microlens-based setup
- Laser induced Rydberg interactions
- Comprehensive parallelized & site-selective qubit control

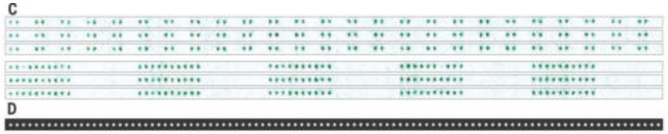






Related Work: Arrays of Individually Detectable Atoms

1D (Optical Lattice, AOD)

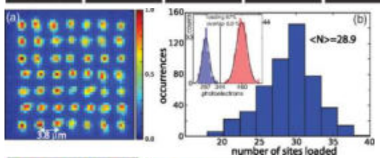


Lukin

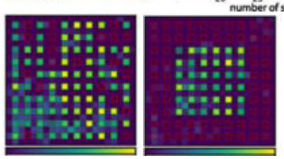
See also: Alberti, Bakr, Cornish, Doyle, Kaufman, Meschede, …

2D (AOD, SLM, Diffractive Elements)

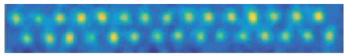
Browaeys



Saffman



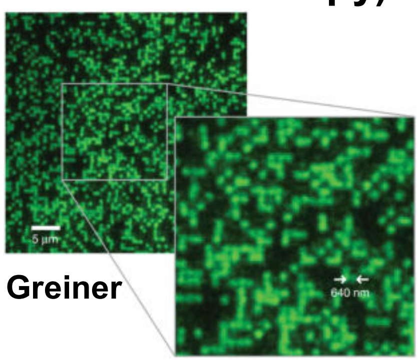
Regal



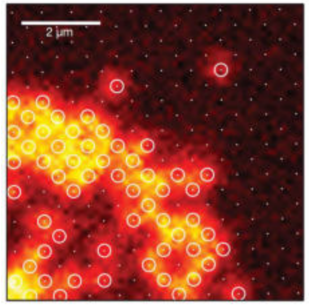
Ahn

See also: Bakr, Bernien, Bloom, Doyle, Gross, Endres, Kaufman, de Léséleuc, Loh, Ni, Ohmori, Pritchard, Schreck, Thompson, Whitlock, Zahn, Zeiher, …

2D (Optical Lattice, Quantum Gases Microscopy)



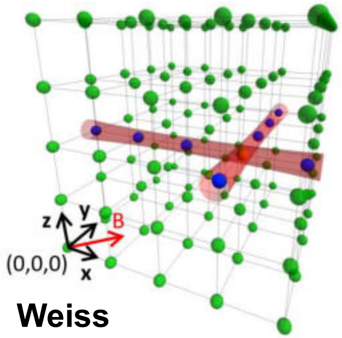
Greiner



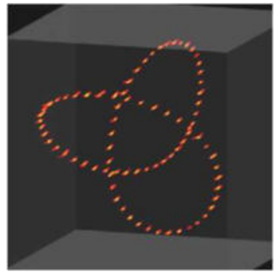
Kuhr / Bloch

See also: Bakr, Gross, Schauss, Thywissen, Ye, Zeiher, Zwierlein, …

3D (Optical Lattice, SLM)

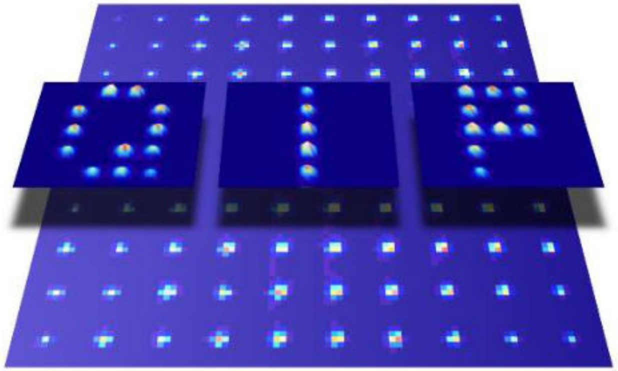


Weiss



Browaeys

Quantum Technology Platform for Quantum Information Science based on Neutral-Atom Qubits



- Tweezer array of neutral atoms
- Robust microlens-based setup
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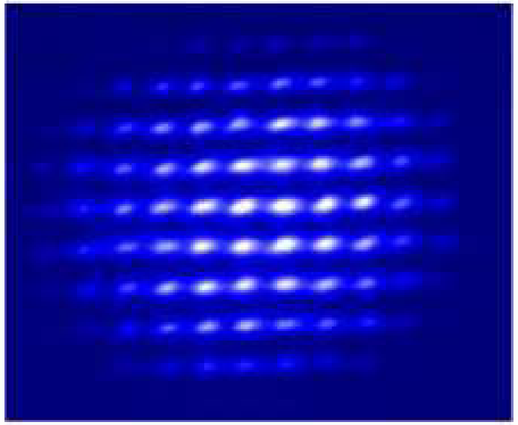
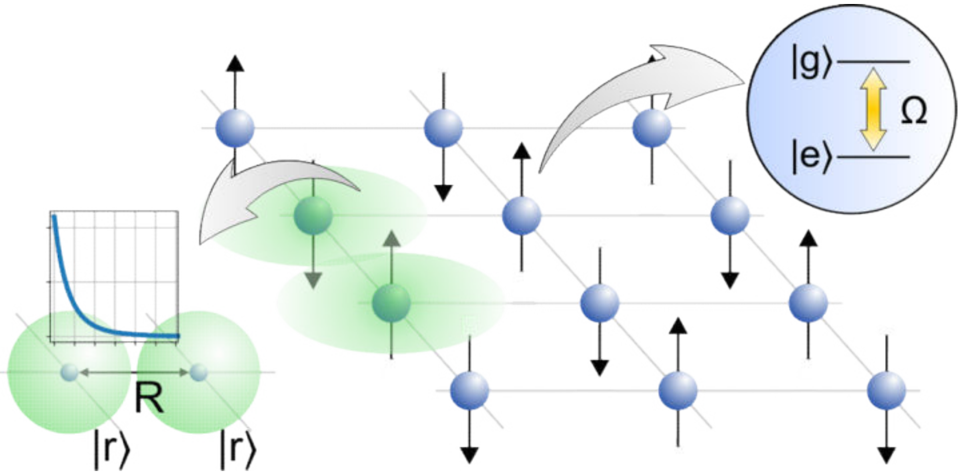
- Comprehensive parallelized & site-selective qubit control

"Micro-optical Realization of Arrays of Selectively Addressable Dipole Traps: A Scalable Configuration for Quantum Computation with Atomic Qubits"



2002

R. Dumke, M. Volk, T. Müther, F.B.J. Buchkremer, G. Birkl, W. Ertmer, Phys. Rev. Lett. ***89****, 097309 (2002)*



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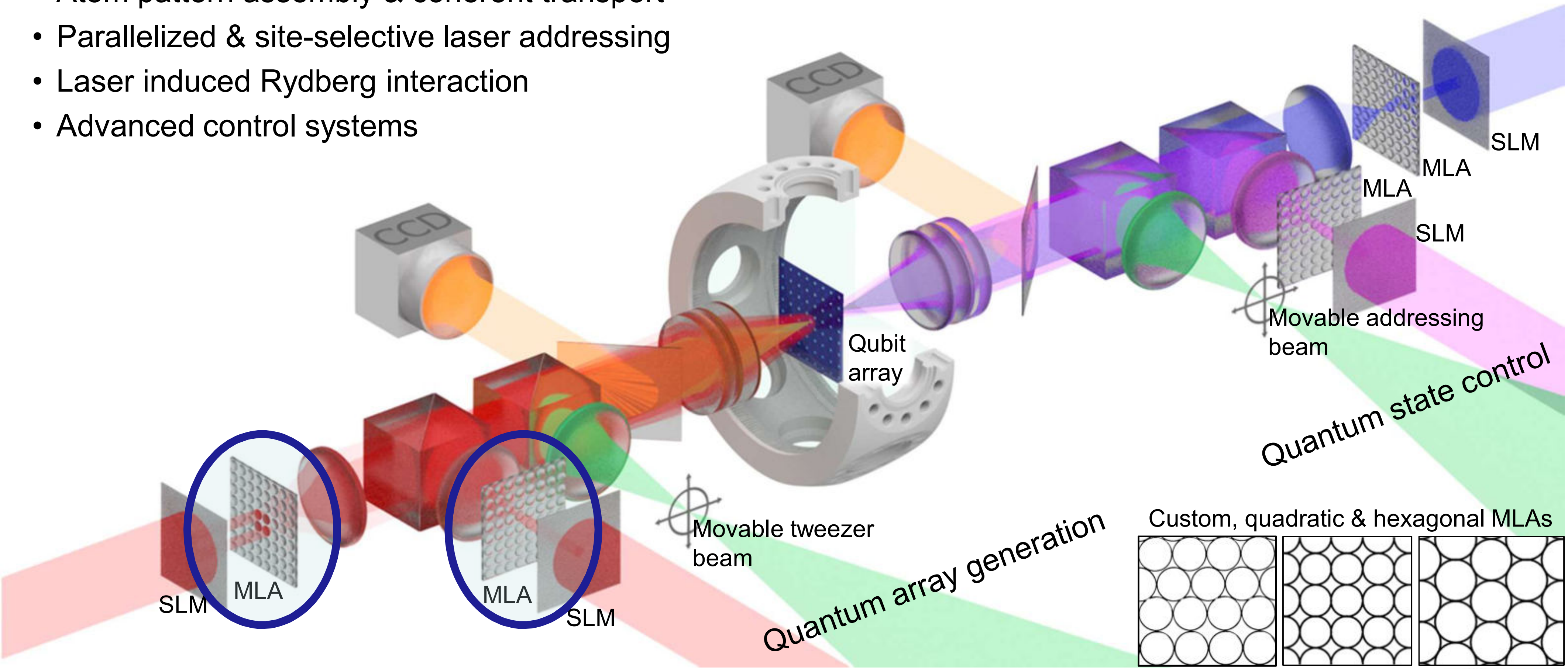
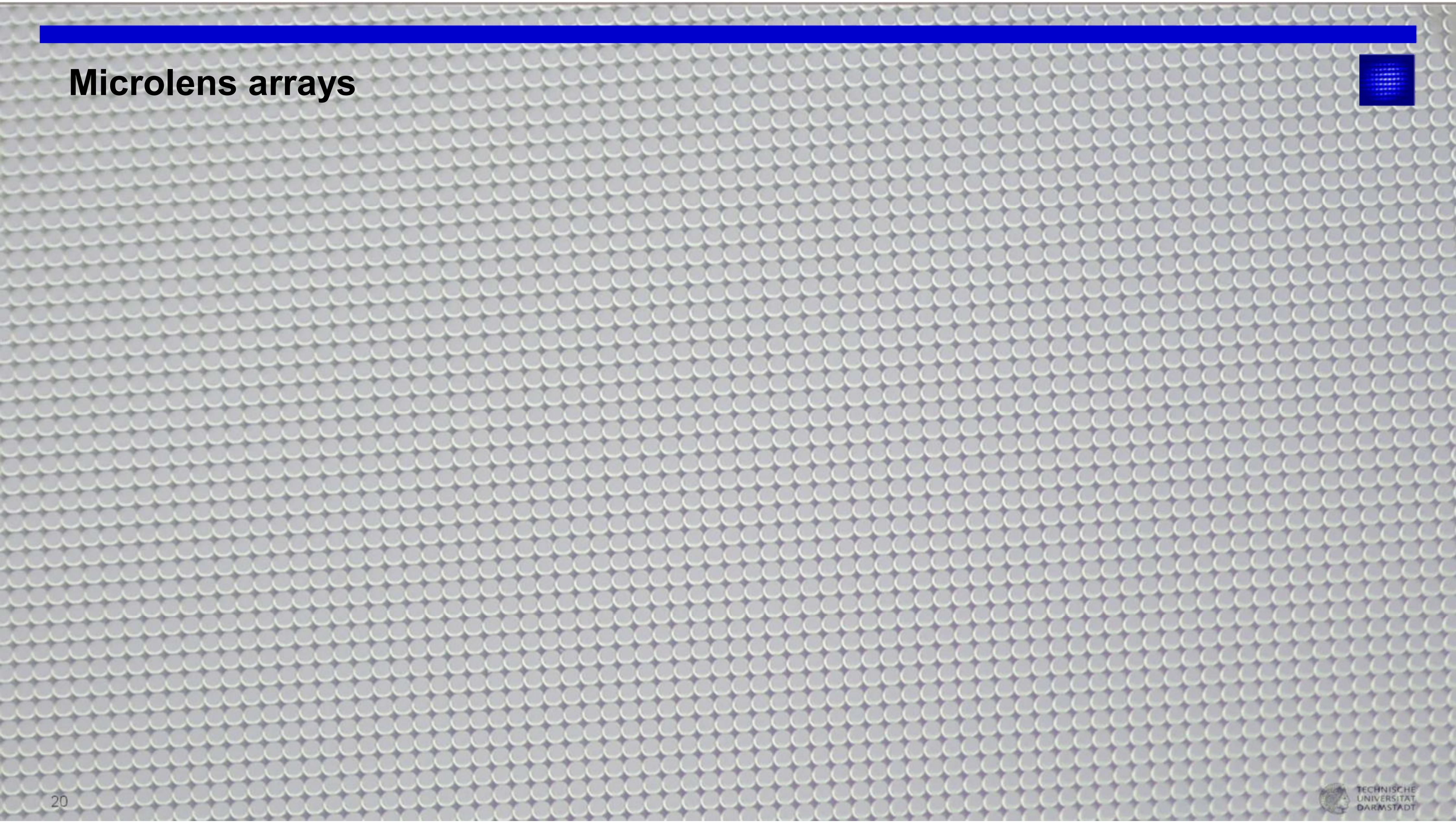
Building blocks

- Microlens generated single atom tweezer arrays
- Atom pattern assembly & coherent transport
- Parallelized & site-selective laser addressing
- Laser induced Rydberg interaction
- Advanced control systems



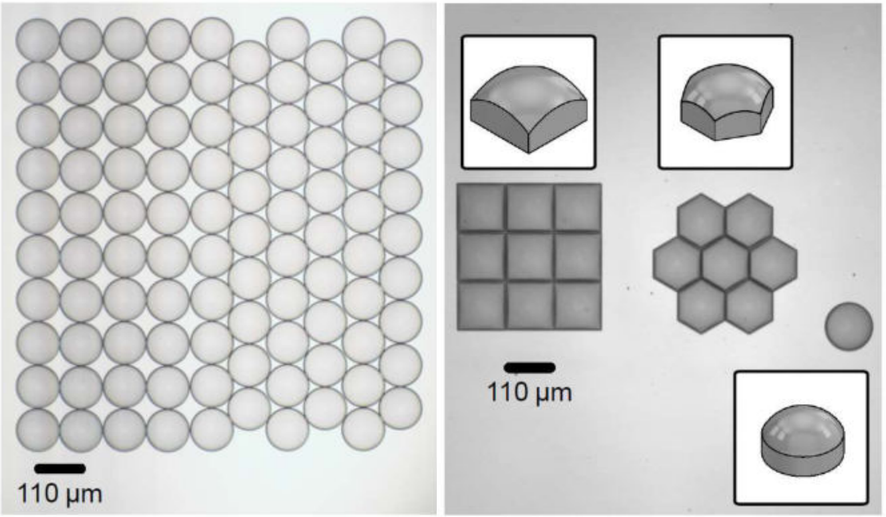
Microlens arrays



Microlens arrays

Additive Manufacturing

Custom geometries (small scale)

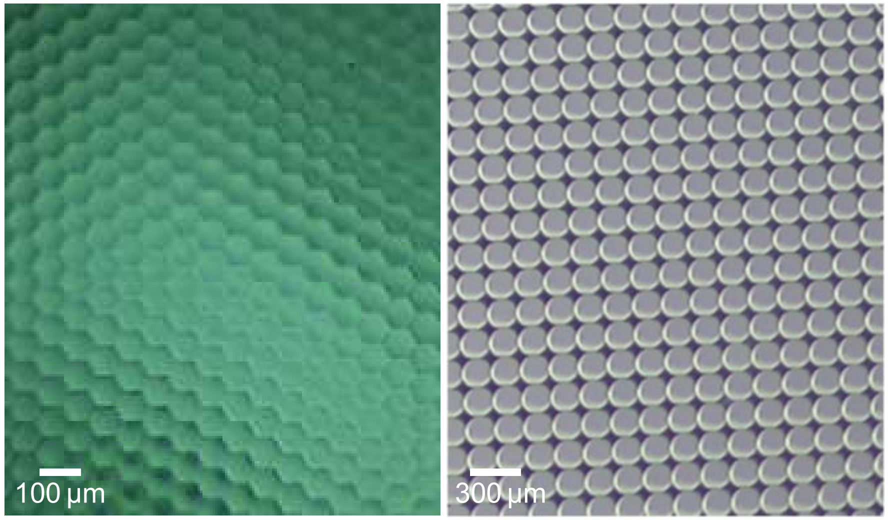


iRyd Collaboration with Prof. Giessen, Stuttgart

- Two-photon polymerization (Nanoscribe System)
- Resolution < 100 nm
- Writing speed: ~10 microlenses per hour

Lithographic process

Large-scale quadratic and hexagonal geometries



Commercial product, various vendors

- Reactive ion etching of fused silica substrate
- Tolerances on xy-pos. ~250 nm, focal length ~3%
- ~100 000 lenslets / cm^2

*D. Schäffner et al., Opt. Express **28**, 8640 (2020)*

Microlens arrays

Additive Manufacturing

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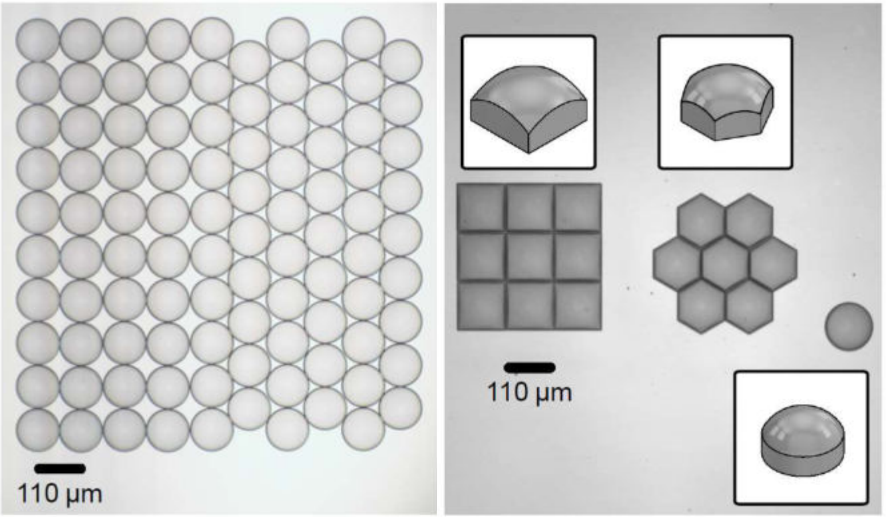

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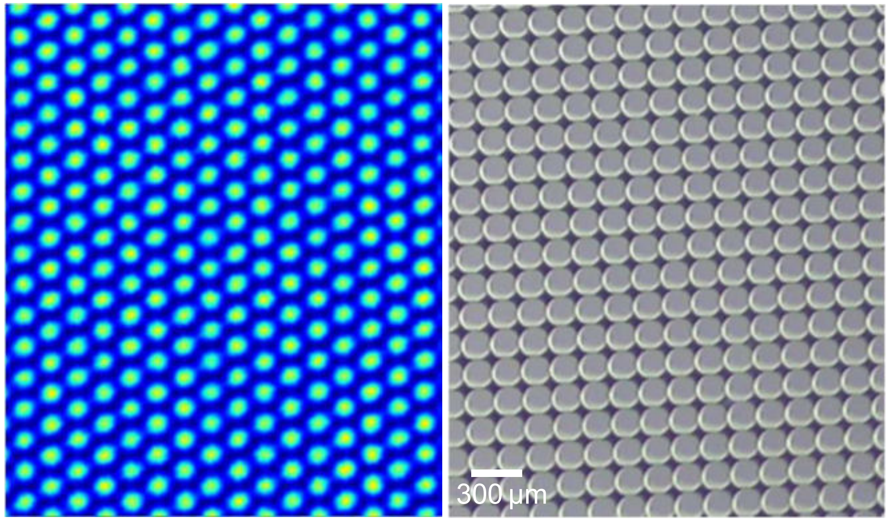

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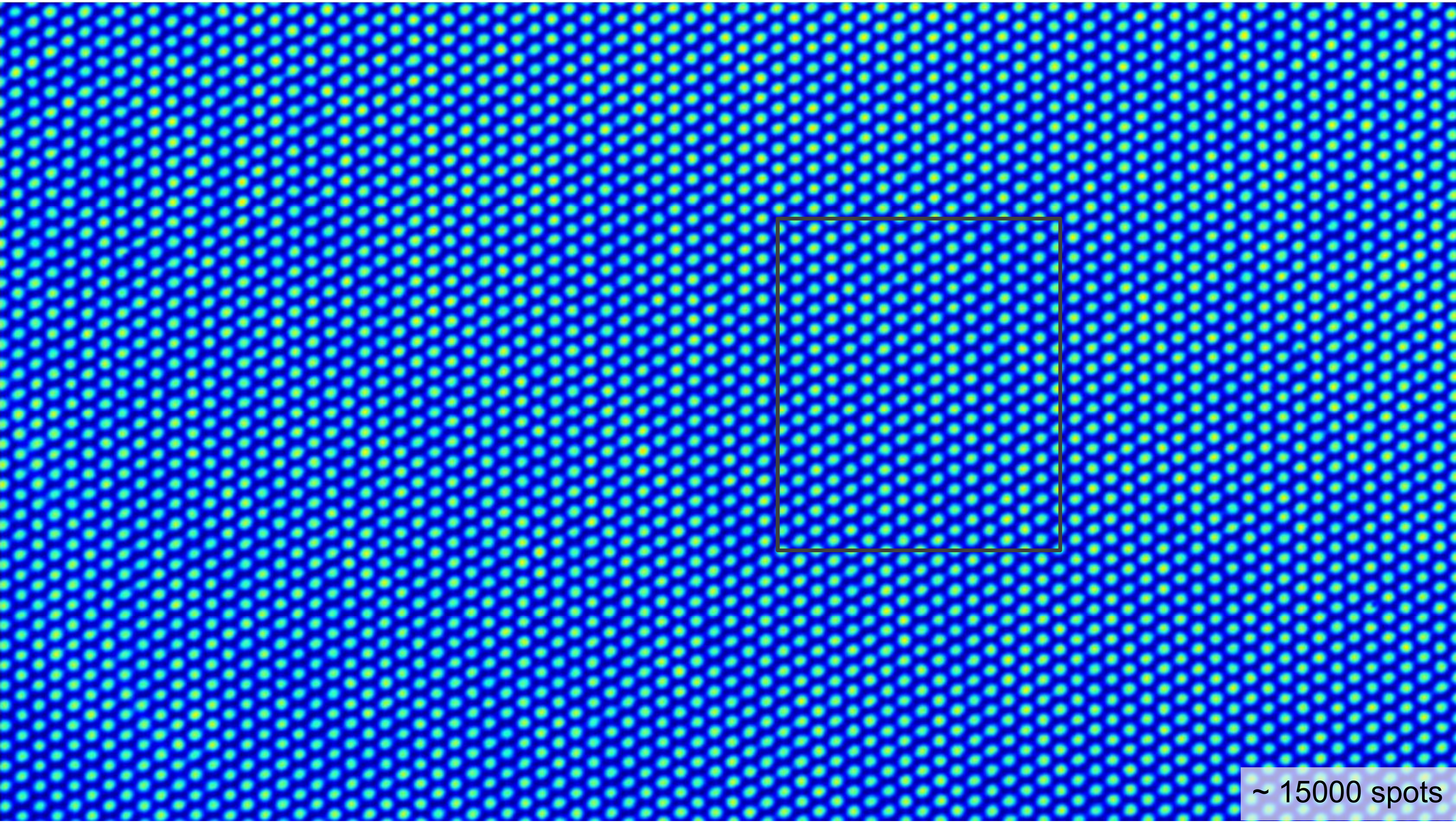
D. Schäffner et al., Opt. Express ***28****, 8640 (2020)*


~ 15000 spots

Current Development

- *Supercharged two-dimensional tweezer array with more than 1000 atomic qubits*
- *Reservoir-based deterministic loading of single-atom tweezer arrays*
- *Scalable multilayer architecture of assembled single-atom qubit arrays in a three-dimensional Talbot tweezer lattice*
- *Site-selective Rydberg interactions with atom arrays*

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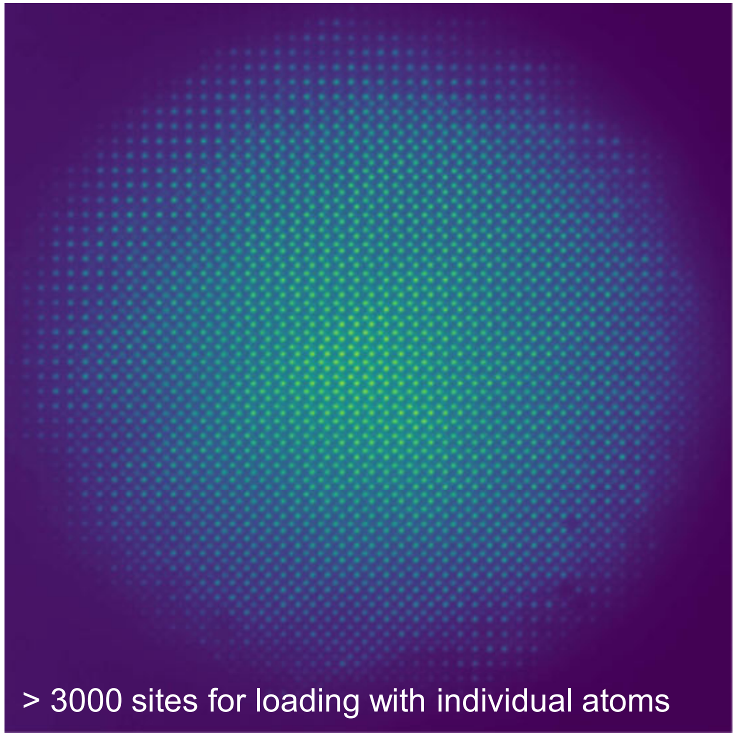
Overcoming laser power limitations with multiple tweezer arrays

- Passive micro-structured elements* sustain high optical powers while producing stable trap arrays
- Rubidium tweezers of $w_0 = 1\,\mu m$ require for $U_0 = k_B \cdot 1\,mK$: (0.6 mW @ 800 nm / 10 mW @ 1064 nm) × 5 (losses etc.) × 10000 sites = (30 W @ 800 nm / 500 W @ 1064 nm)

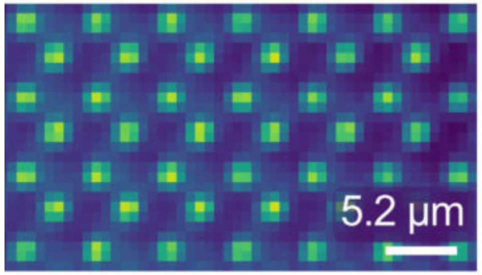
→ Large-scale 2D arrays require multiple laser sources that are combined with high efficiency

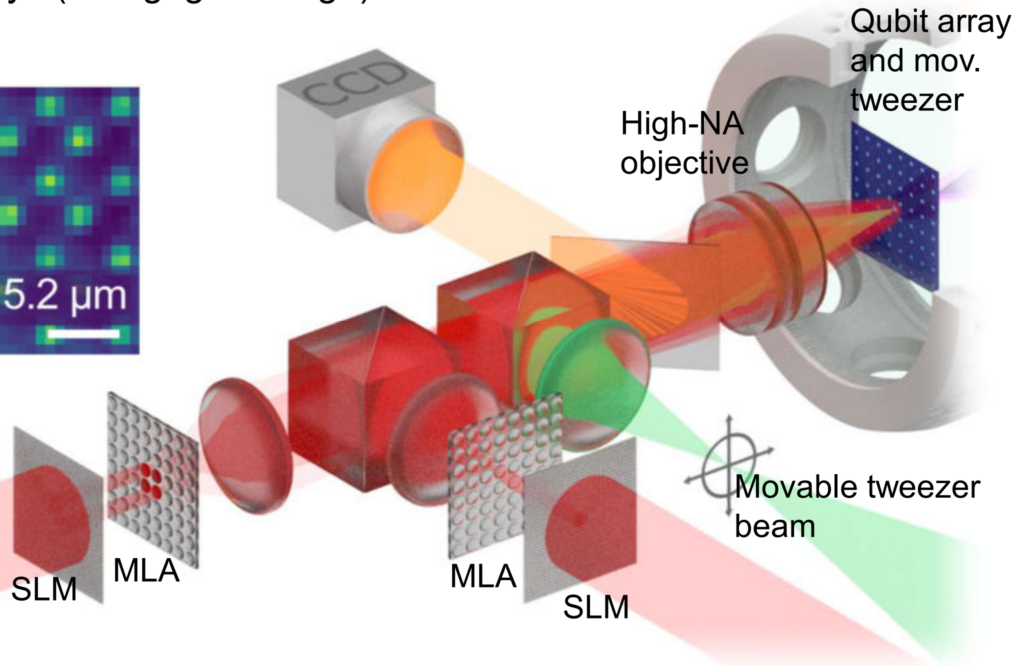


Averaged image

Two interleaved arrays (Avergaged image)

Detail

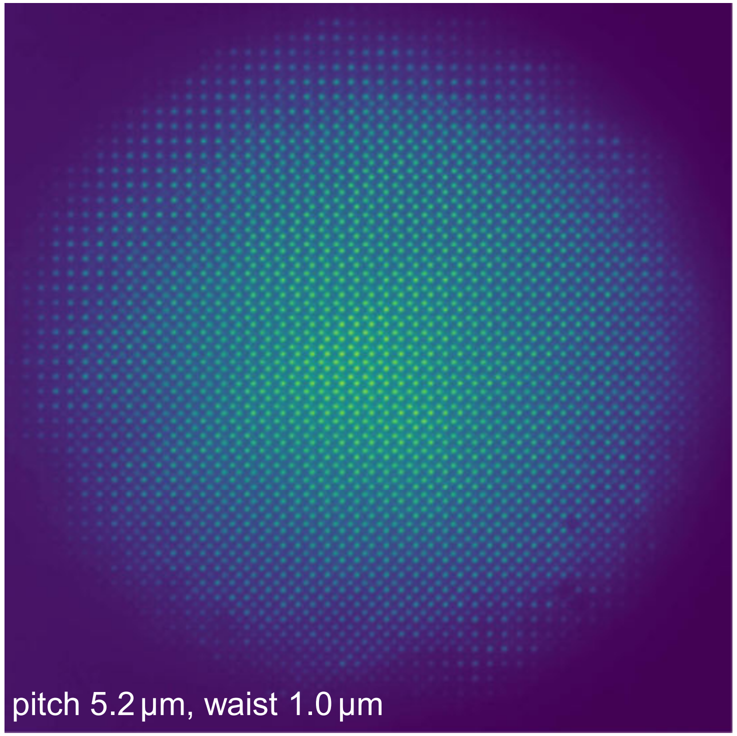




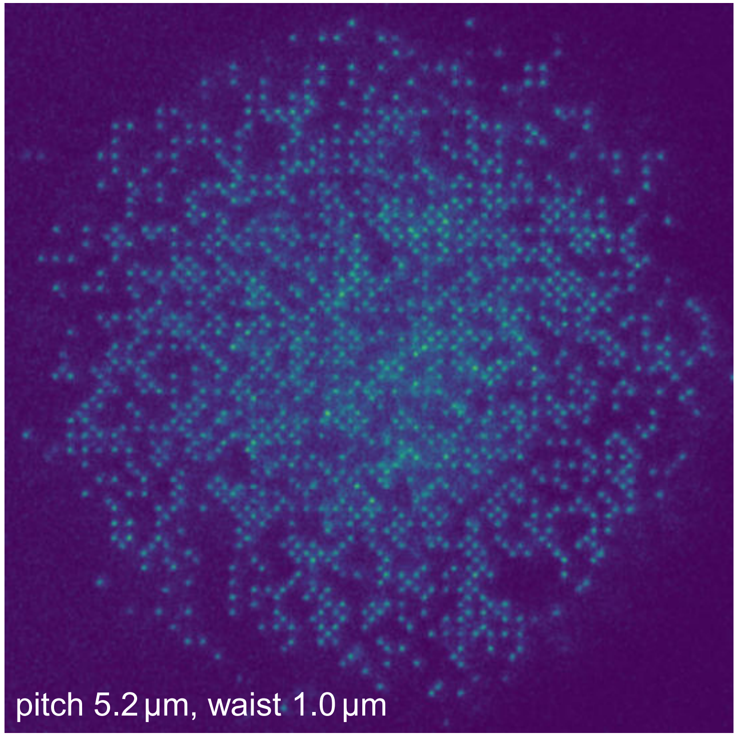
Interleaved multi-MLA tweezer arrays

- Passive micro-structured elements sustain high optical powers while producing stable trap arrays
  → Large-scale 2D arrays require multiple laser sources that are combined with high efficiency

Experimental realization (two titanium-sapphire lasers)



Averaged image (> 3000 sites)



Single shot (1305 atoms)

Two arrays operated in parallel
→ > 3000 sites
→ 1167 atoms on average

Parameters

Gaussian beam waist on MLA
Radius ≈ *32 lens pitches*

Sites per laser source
> 1500

Wavelength
≈ *798 nm*

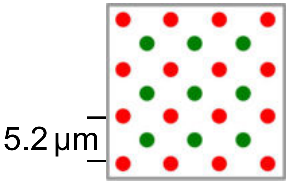
Central trap depth
≈ $k_B \cdot 0.5\,mK$

TECHNISCHE UNIVERSITÄT DARMSTADT

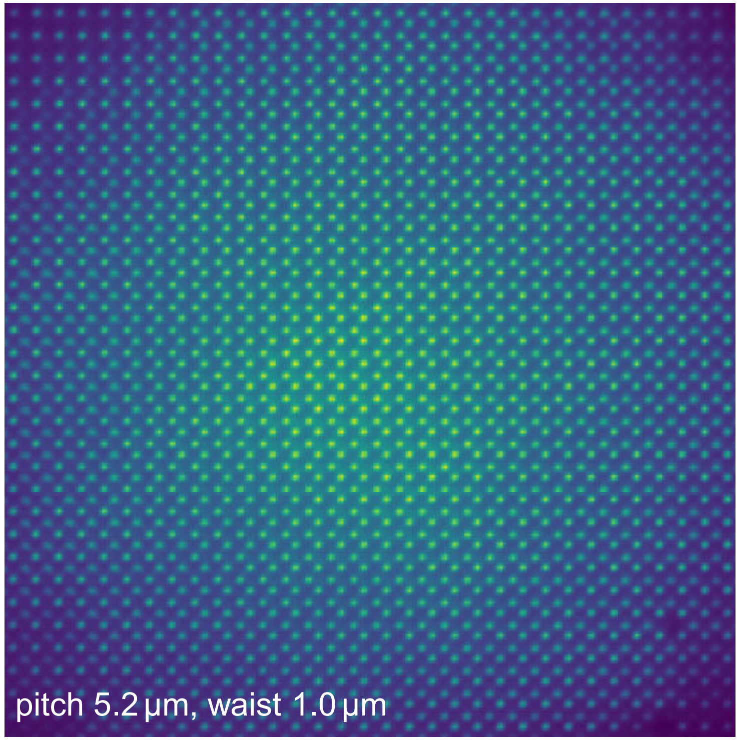
Supercharging one array as quantum processing unit (QPU)

- Passive micro-structured elements sustain high optical powers while producing stable trap arrays
  → Large-scale 2D arrays require multiple laser sources that are combined with high efficiency

Experimental realization (two titanium-sapphire lasers)



- Initial loading:
  two interleaved arrays operated in parallel



Two arrays operated in parallel
→ 2048 addressable sites
→ 1960 atoms on average

Dual-array quantum processor
→ 3000 sites
→ ≈ 1700 atoms on average

Parameters

32 × 32 array per laser source
Sites per laser source
1024
Wavelength
≈ 799.5 nm
Central trap depth
≈ $k_B \cdot 0.5\,mK$

Gaussian beam waist on MLA
Radius ≈ *32 lens pitches*
Sites per laser source
≥ 1500
Wavelength
≈ 798 nm
Central trap depth
≈ $k_B \cdot 0.5\,mK$

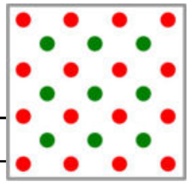
TECHNISCHE UNIVERSITÄT DARMSTADT

Supercharging one array as quantum processing unit (QPU)

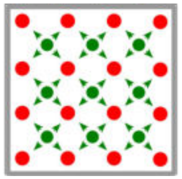
- Passive micro-structured elements sustain high optical powers while producing stable trap arrays
  → Large-scale 2D arrays require multiple laser sources that are combined with high efficiency

Experimental realization (two titanium-sapphire lasers)

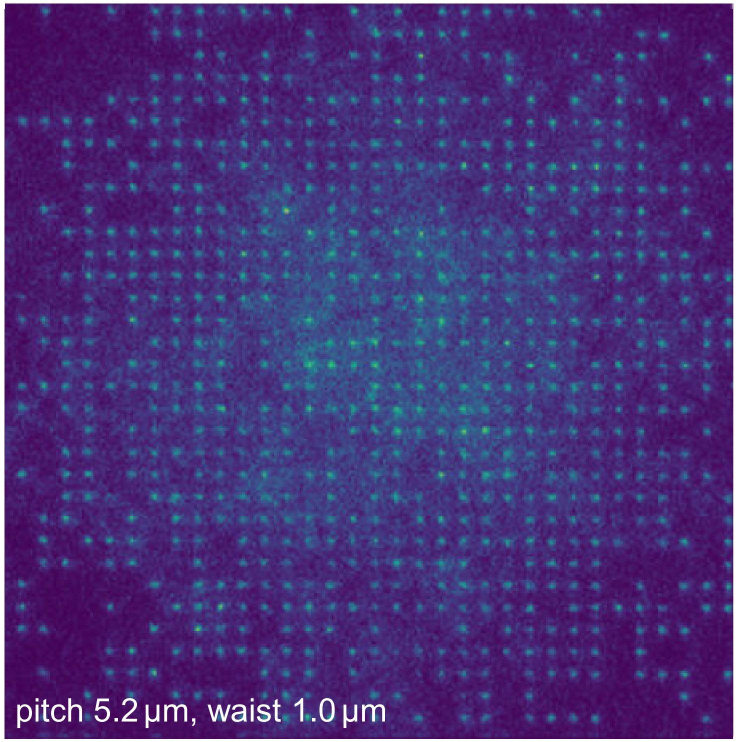
5.2 µm



- Initial loading:
  two interleaved arrays operated in parallel



- Inter-array transfer for
  → increased filling
  → increased number of reservoir atoms



Quantum processing unit
→ 1024 addressable sites
→ ≈ 690 atoms on average

Parameters

32 x 32 array per laser source

Sites per laser source
1024

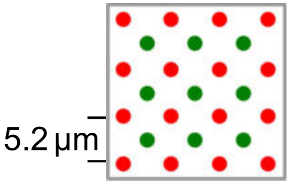
Wavelength
≈ *799.5 nm*

Central trap depth
$\approx k_B \cdot 0.5\,mK$

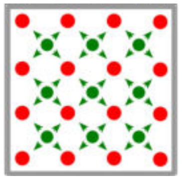
Supercharging one array as quantum processing unit (QPU)

- Passive micro-structured elements sustain high optical powers while producing stable trap arrays
  → Large-scale 2D arrays require multiple laser sources that are combined with high efficiency

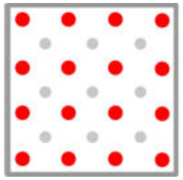
Experimental realization (two titanium-sapphire lasers)



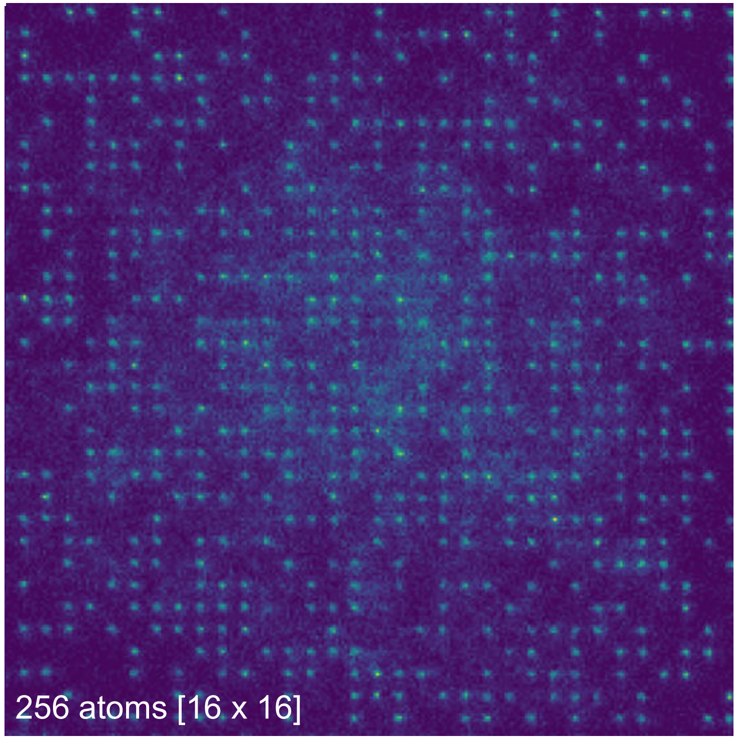
- Initial loading:
  two interleaved arrays operated in parallel



- Inter-array transfer for
  → increased filling
  → increased number of reservoir atoms



- Enhanced target pattern assembly in one array



Quantum processing unit
→ 1024 addressable sites
→ ≈ 690 atoms on average

Parameters

32 x 32 array per laser source

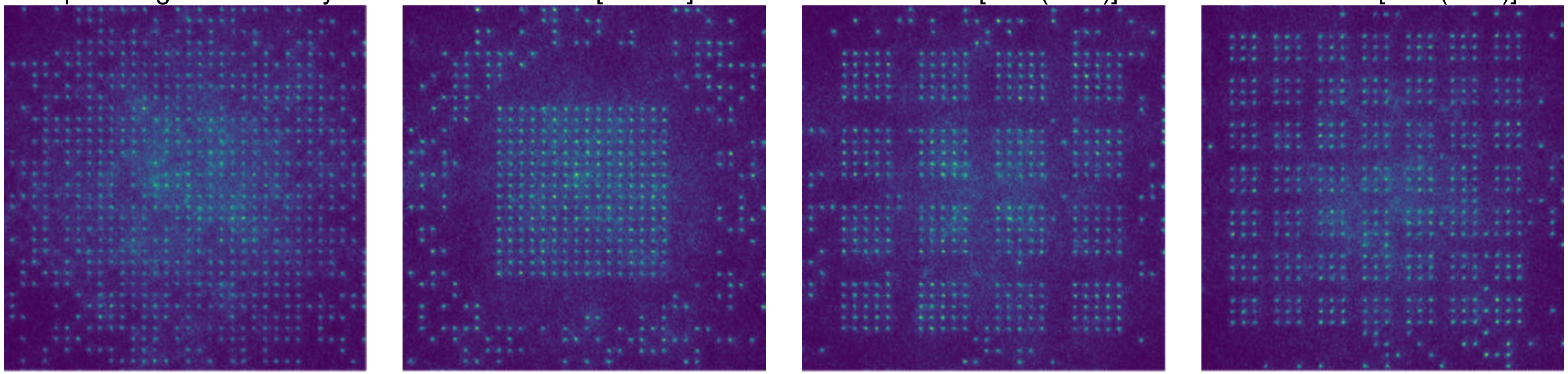
Sites per laser source
1024

Wavelength
≈ *799.5 nm*

Central trap depth
$\approx k_B \cdot 0.5\,mK$

Supercharged QPU: defect-free clusters of up to 441 qubits

- Increased number of reservoir atoms & increased initial filling fraction
- Enhanced attainable target sizes and success probabilities



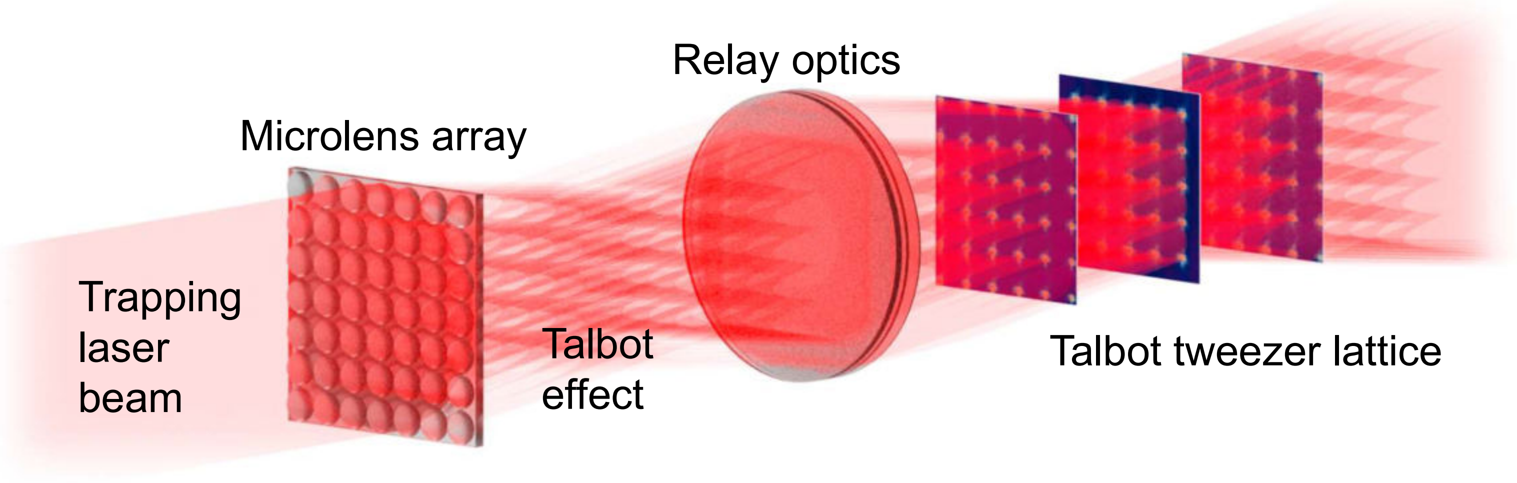
Supercharged main array | 256 atoms [16 × 16] | 400 atoms [16 × (5 × 5)] | 441 atoms [49 × (3 × 3)]

*L. Pause et al., Optica **11**, 222 (2024), arXiv:2310.09191 (13. 10. 2023)*

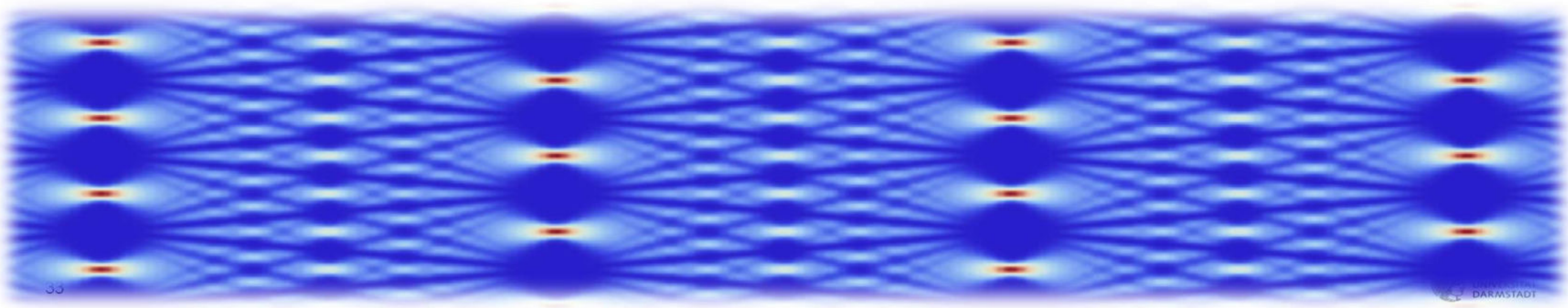
Current Development

- *Supercharged two-dimensional tweezer array with more than 1000 atomic qubits*
- *Reservoir-based deterministic loading of single-atom tweezer arrays*
- *Scalable multilayer architecture of assembled single-atom qubit arrays in a three-dimensional Talbot tweezer lattice*
- *Site-selective Rydberg interactions with atom arrays*

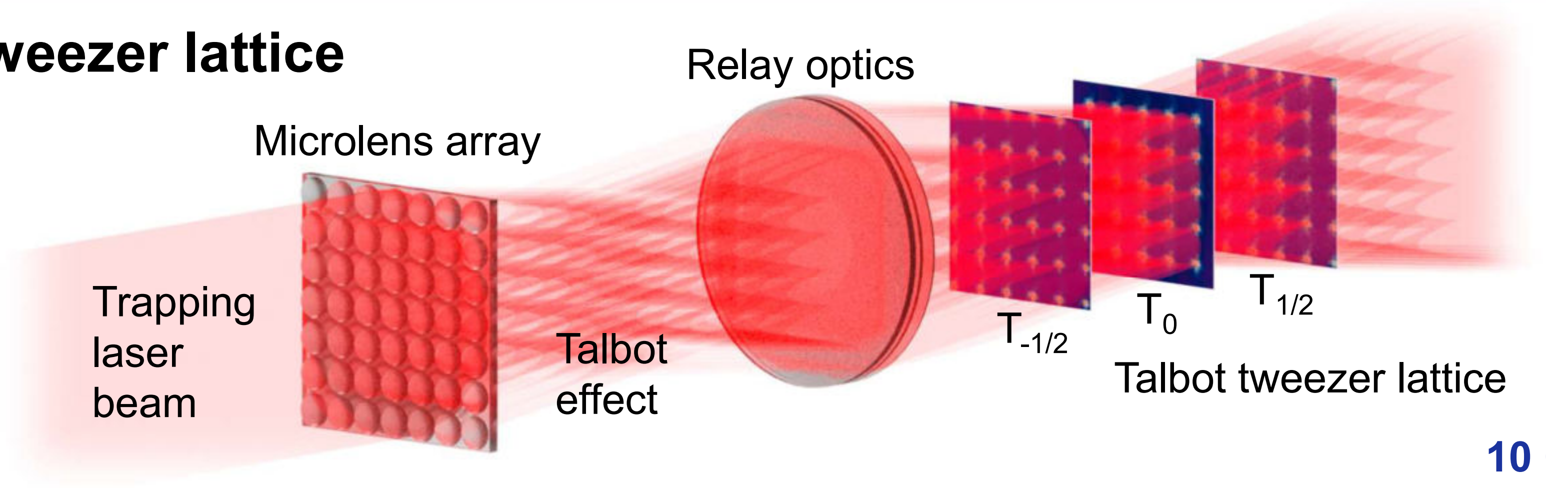
Scalable multilayer architecture: 3D Talbot tweezer lattice



Talbot effect gives access to **multilayer** trap configuration at no additional cost.



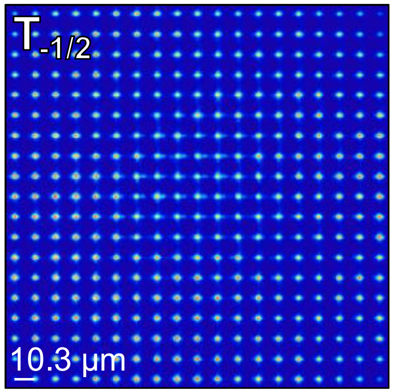
Talbot tweezer lattice



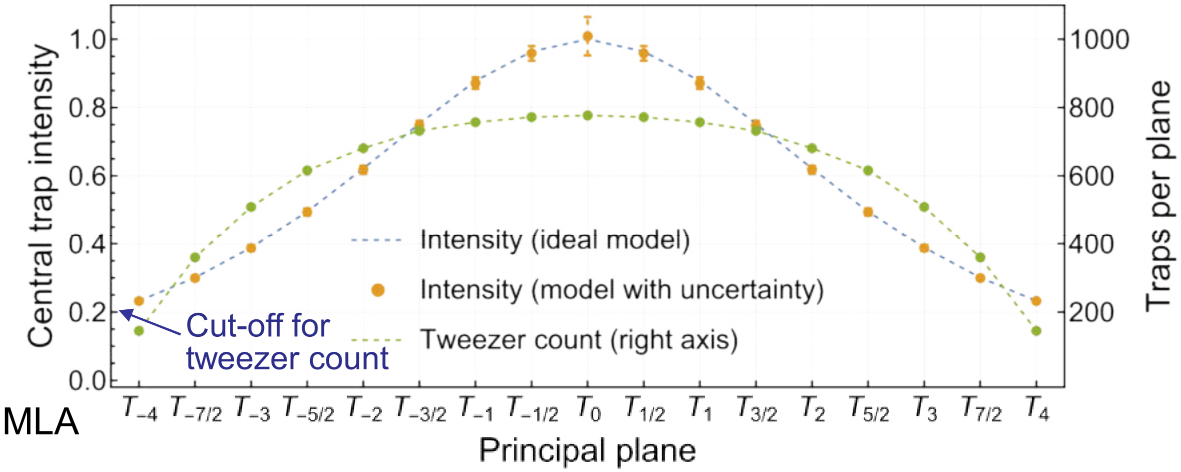
10 000 sites in 3D accessible to loading of individual atoms

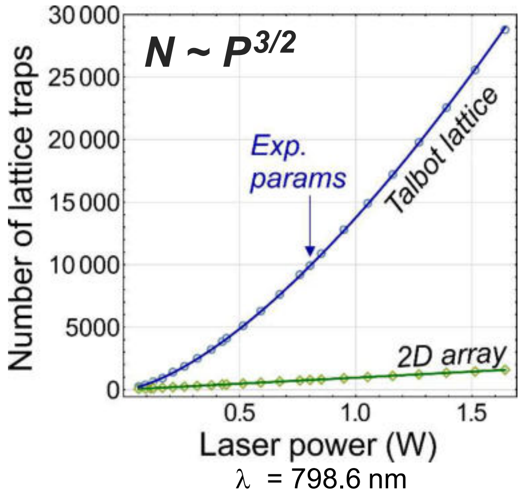
How many lattice planes & how many tweezers?

Trapped atoms (averaged)



Gaussian beam waist on MLA
17.5 lens pitch



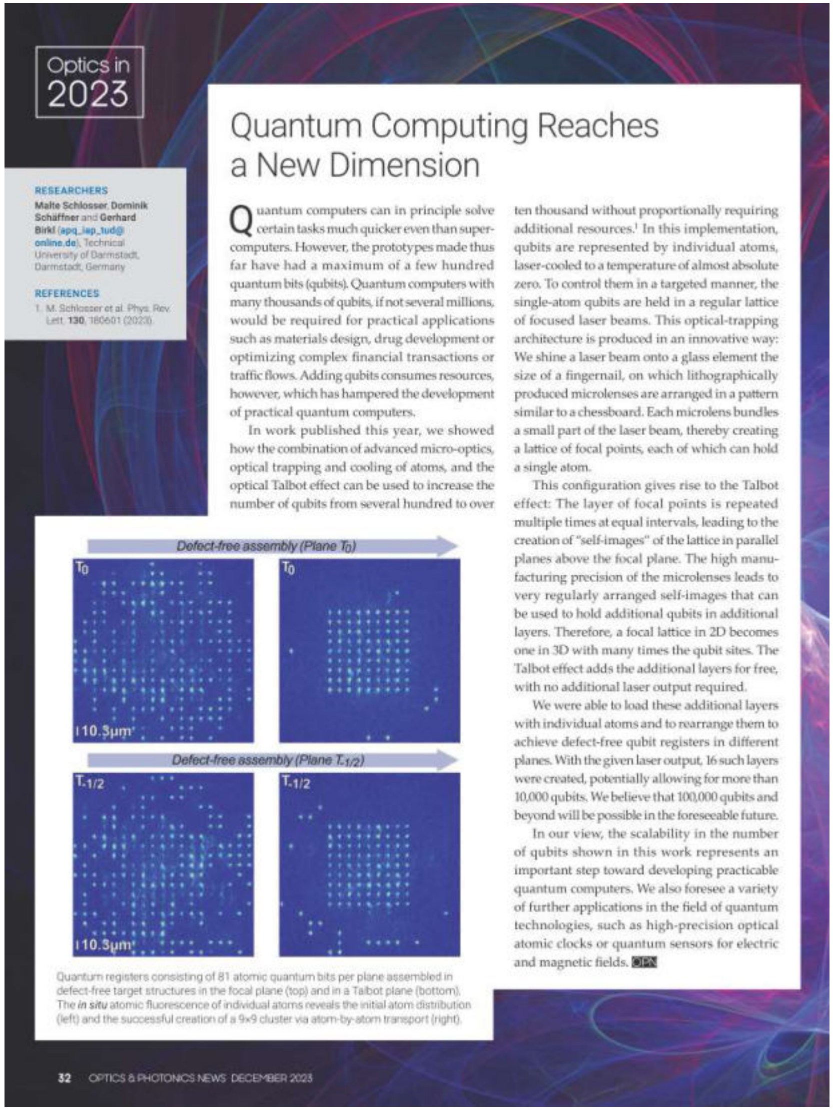


M. Schlosser et al., Phys. Rev. Lett. ***130****, 180601 (2023)*

Optics in 2023

This special issue of *Optics & Photonics News* highlights exciting peer-reviewed optics research that has emerged over the past year.

Our panel of editors reviewed 115 summaries of work by researchers from around the world. They selected for publication 30 stories that they felt communicated breakthroughs of particular interest to the broad optics community. OPN thanks all who submitted summaries, as well as our panel of guest editors.



Optics in 2023

Quantum Computing Reaches a New Dimension

RESEARCHERS
Malte Schlosser, **Dominik Schäffner** and **Gerhard Birkl** (apq_iap_tud@online.de), Technical University of Darmstadt, Darmstadt, Germany

REFERENCES
1. M. Schlosser et al. Phys. Rev. Lett. **130**, 180601 (2023).

Quantum computers can in principle solve certain tasks much quicker even than supercomputers. However, the prototypes made thus far have had a maximum of a few hundred quantum bits (qubits). Quantum computers with many thousands of qubits, if not several millions, would be required for practical applications such as materials design, drug development or optimizing complex financial transactions or traffic flows. Adding qubits consumes resources, however, which has hampered the development of practical quantum computers.

In work published this year, we showed how the combination of advanced micro-optics, optical trapping and cooling of atoms, and the optical Talbot effect can be used to increase the number of qubits from several hundred to over ten thousand without proportionally requiring additional resources.[1] In this implementation, qubits are represented by individual atoms, laser-cooled to a temperature of almost absolute zero. To control them in a targeted manner, the single-atom qubits are held in a regular lattice of focused laser beams. This optical-trapping architecture is produced in an innovative way: We shine a laser beam onto a glass element the size of a fingernail, on which lithographically produced microlenses are arranged in a pattern similar to a chessboard. Each microlens bundles a small part of the laser beam, thereby creating a lattice of focal points, each of which can hold a single atom.

This configuration gives rise to the Talbot effect: The layer of focal points is repeated multiple times at equal intervals, leading to the creation of "self-images" of the lattice in parallel planes above the focal plane. The high manufacturing precision of the microlenses leads to very regularly arranged self-images that can be used to hold additional qubits in additional layers. Therefore, a focal lattice in 2D becomes one in 3D with many times the qubit sites. The Talbot effect adds the additional layers for free, with no additional laser output required.

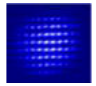
We were able to load these additional layers with individual atoms and to rearrange them to achieve defect-free qubit registers in different planes. With the given laser output, 16 such layers were created, potentially allowing for more than 10,000 qubits. We believe that 100,000 qubits and beyond will be possible in the foreseeable future.

In our view, the scalability in the number of qubits shown in this work represents an important step toward developing practicable quantum computers. We also foresee a variety of further applications in the field of quantum technologies, such as high-precision optical atomic clocks or quantum sensors for electric and magnetic fields.

Defect-free assembly (Plane T_0)

Defect-free assembly (Plane $T_{-1/2}$)

Quantum registers consisting of 81 atomic quantum bits per plane assembled in defect-free target structures in the focal plane (top) and in a Talbot plane (bottom). The *in situ* atomic fluorescence of individual atoms reveals the initial atom distribution (left) and the successful creation of a 9×9 cluster via atom-by-atom transport (right).



Current Development

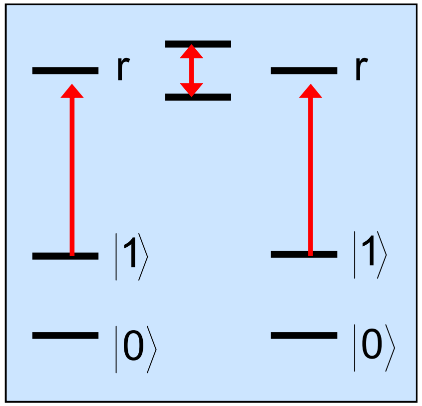
- *Supercharged two-dimensional tweezer array with more than 1000 atomic qubits*
- *Reservoir-based deterministic loading of single-atom tweezer arrays*
- *Scalable multilayer architecture of assembled single-atom qubit arrays in a three-dimensional Talbot tweezer lattice*
- *Site-selective Rydberg interactions with atom arrays*

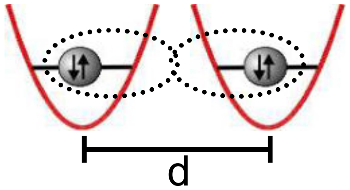
2-Qubit Gates for Quantum Information Processing

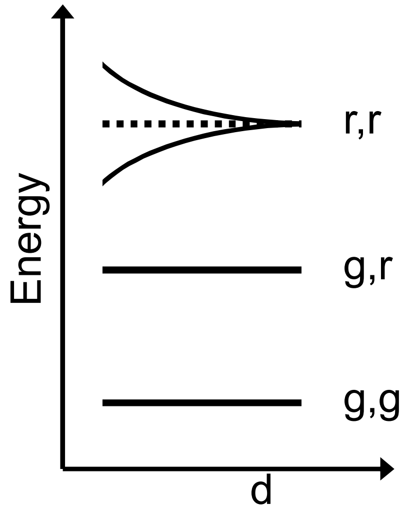
2-Qubit Gates using Rydberg Blockade

Requirement: Trap separation d < 10µm

Interaction of atoms in separated sites → 2-Qubit Gate





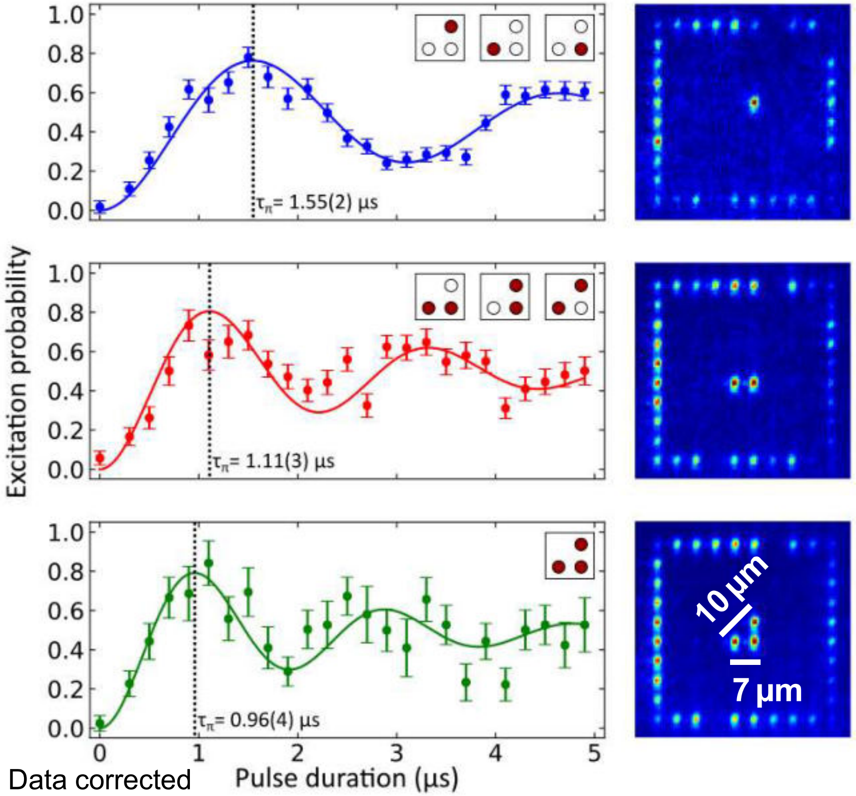


D. Jaksch *et al.,* Phys. Rev. Lett. **85**, 2208 (2000)
T. Wilk *et al.,* Phys. Rev. Lett. **104**, 010502 (2010)
L. Isenhower *et al.,* Phys. Rev. Lett. **104**, 010503 (2010)

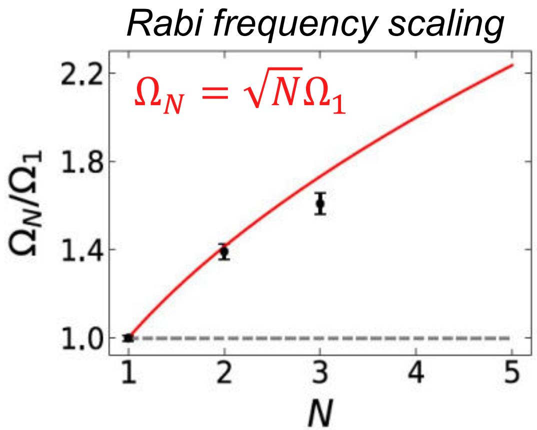
Implementing site-selective Rydberg interactions with atom arrays

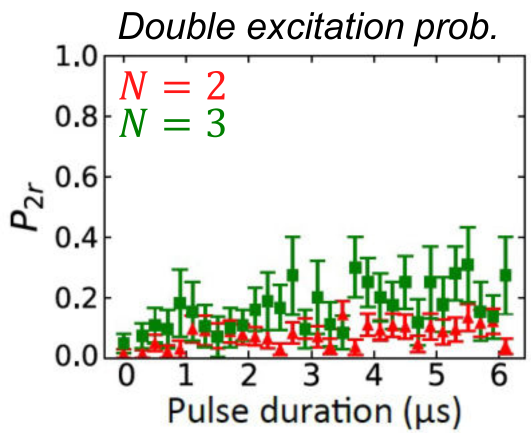
- Collective enhancement

$$|5S_{1/2}, F = 3, m_F = -3\rangle \leftrightarrow |87D_{5/2}, m_J = -3/2\rangle$$



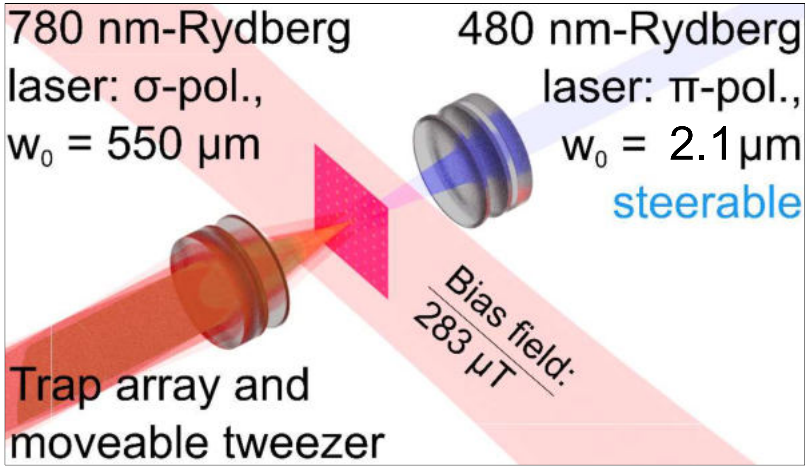
Data corrected for static errors





M. Schlosser et al., J. Phys. B: At. Mol. Opt. Phys. ***53*** *144001 (2020)*

Site-selectively induced Rydberg Rabí oscillations

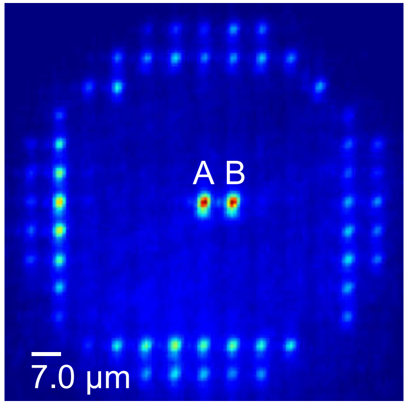


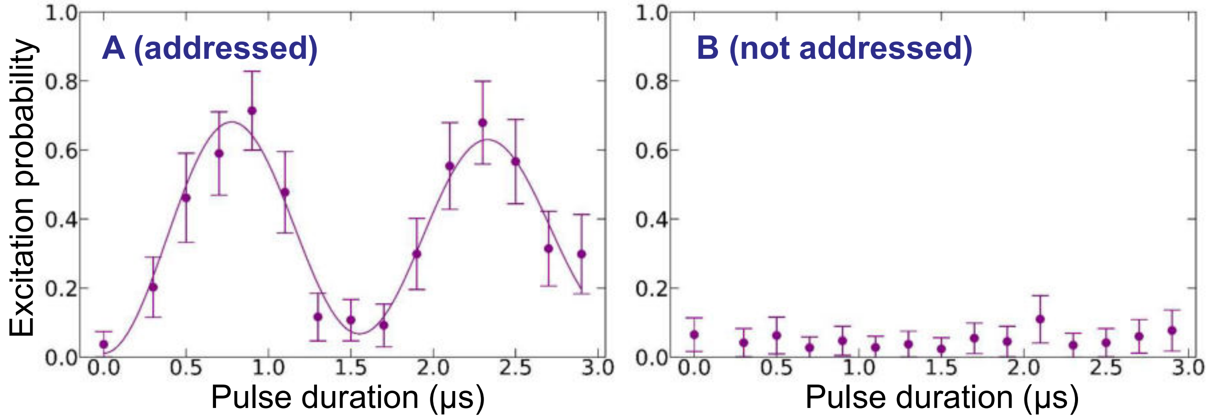
Position-controlled 480 nm beam

- 2D steering via two perpendicular acousto-optical deflectors (AODs)
- Addressing time between traps: 1.2(1) µs
- Shortest blue addressing pulse: 0.4(1) µs

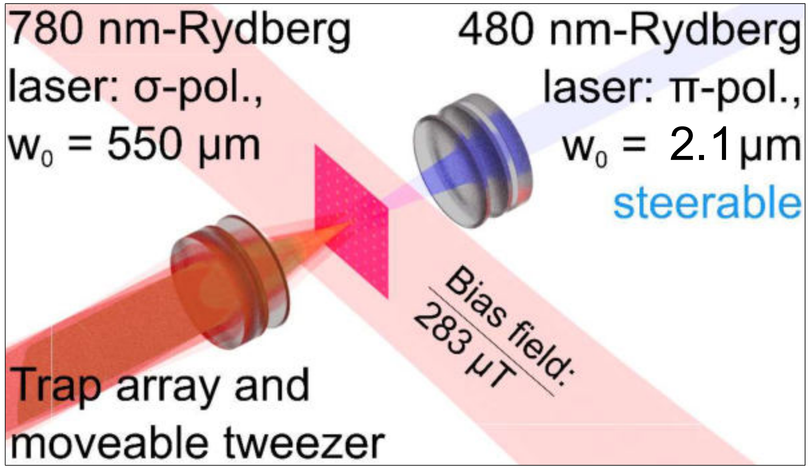
Site-selective Rydberg excitation

$$|5S_{1/2}, F = 3, m_F = -3\rangle \leftrightarrow |87D_{5/2}, m_J = -3/2\rangle$$

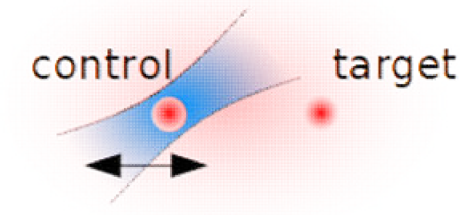




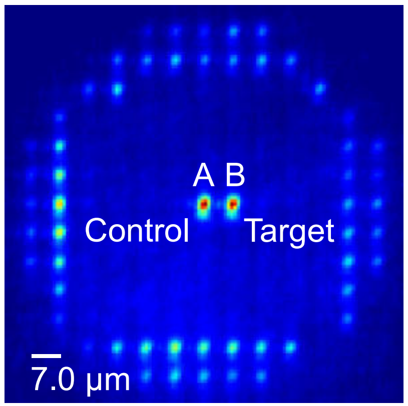
Site-selectively induced Rydberg blockade

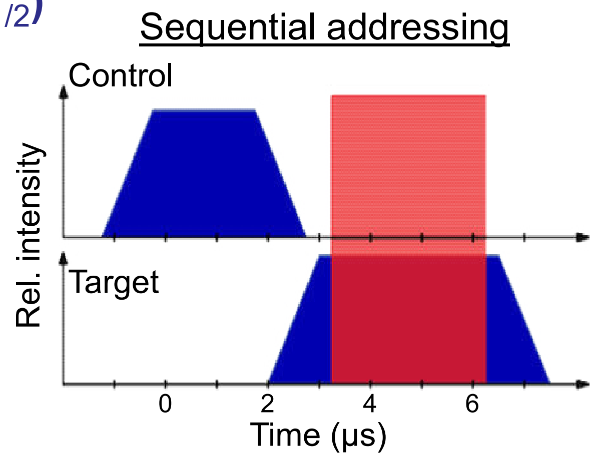


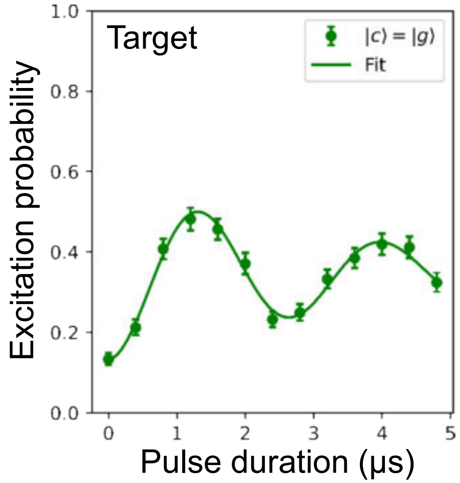
Position-controlled 480 nm beam



Rydberg blockade ($82S_{1/2}$)







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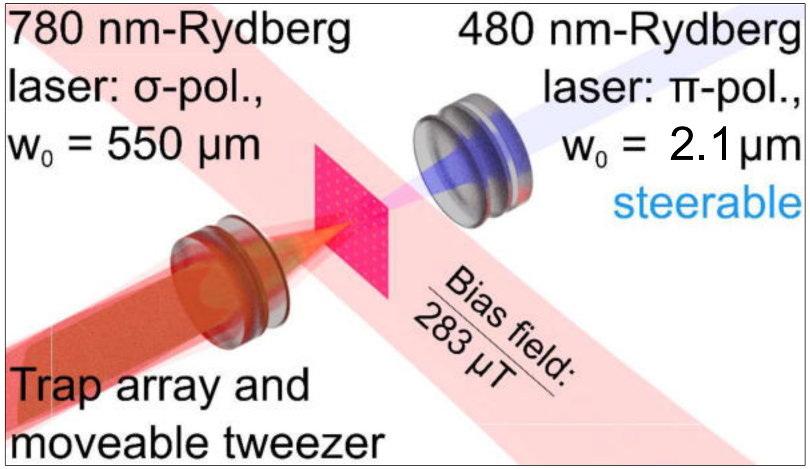
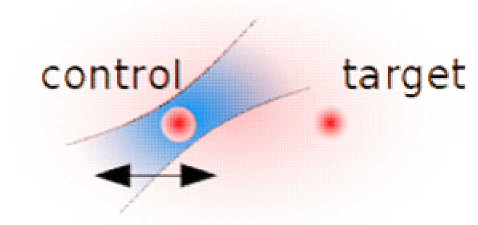


Position-controlled 480 nm beam



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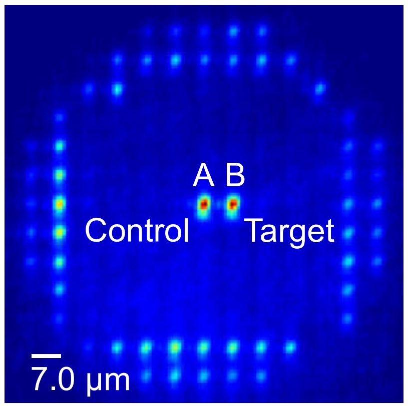
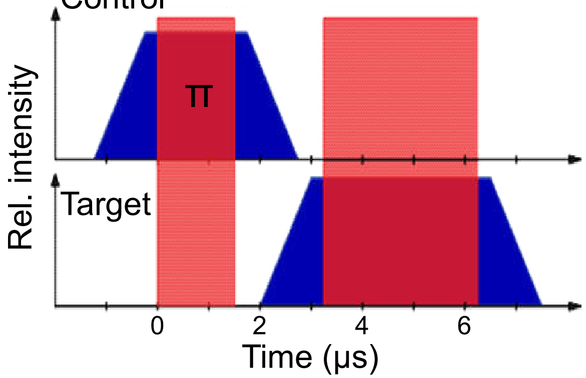
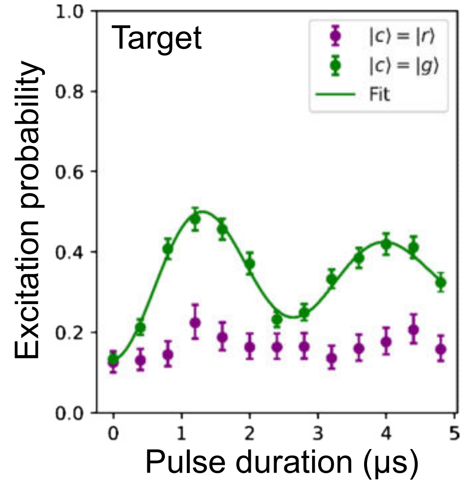
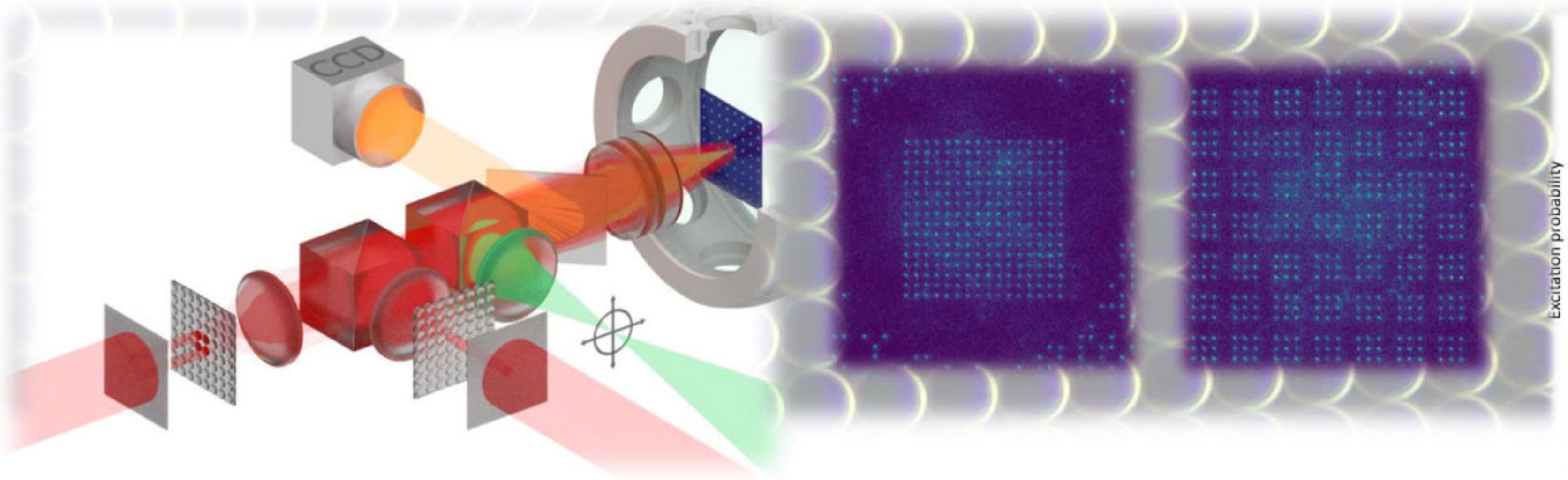
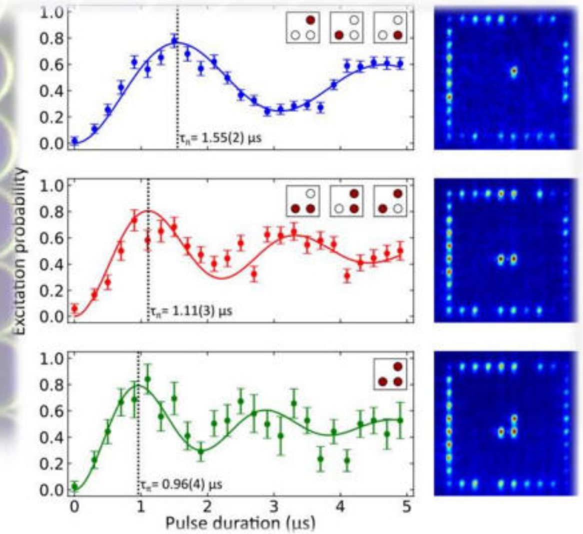


Sequential addressing









Two- and Three-Dimensional Arrays of Laser-Cooled Neutral Atoms for ATOMTRONICS implementations