Novel approaches to A T O M T R O N I C devices in optical potentials

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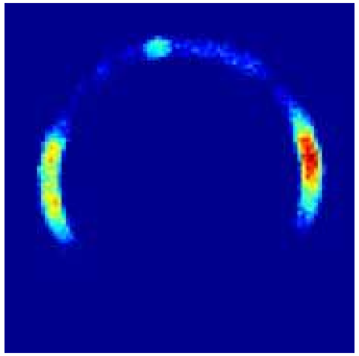
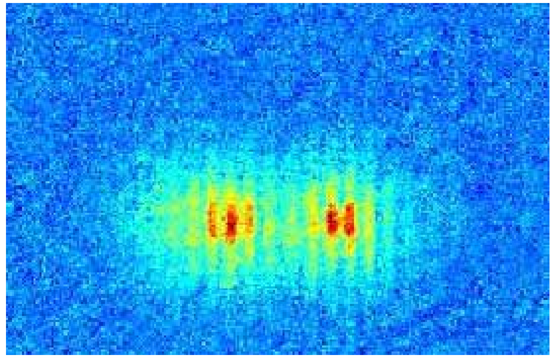
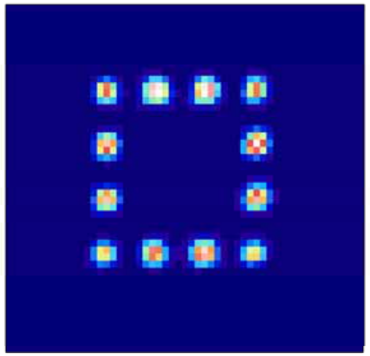


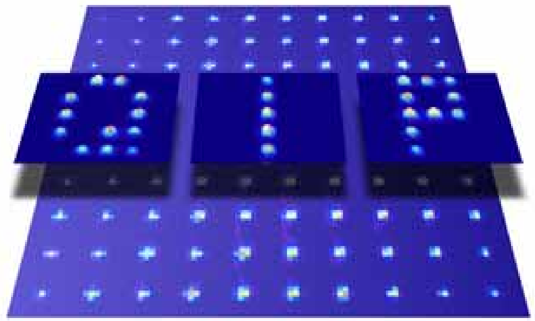


Gerhard Birkl

Institut für Angewandte Physik
Technische Universität Darmstadt

www.iap.physik.tu-darmstadt.de/apq





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Research Program

Atoms as
Research Objects

Quantum Optical
Methods for the
Control of Atoms

Quantum Physics as
Research Objective

→

**Quantum Physics
and Technology
with Atoms
and Photons**

Projects, Group Members, and Co-Workers

BEC and Integrated Atom Optics

Felix Schmaltz, Johannes Küber, Philip Prediger, Patrick van Beek, Felix Weigand, Mathias Hagen

Quantum Information Processing

Malte Schlosser, Daniel Ohl de Mello,
Dominik Schäffner, Tilmann Preuschoff
Lars Kohfahl, Jan-Niklas Schmidt

Interactions of Metastable Neon Atoms

Jan Schütz, Alexander Martin, Thomas Feldker, Holger John, Lars Bannow

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

Sebastian Albrecht, Alexander Martin, Tobias Murböck, Marco Wiesel, Patrick Baus, Manuel Vogel, Wolfgang Quint, and the SPECTRAP and ARTEMIS collaborations

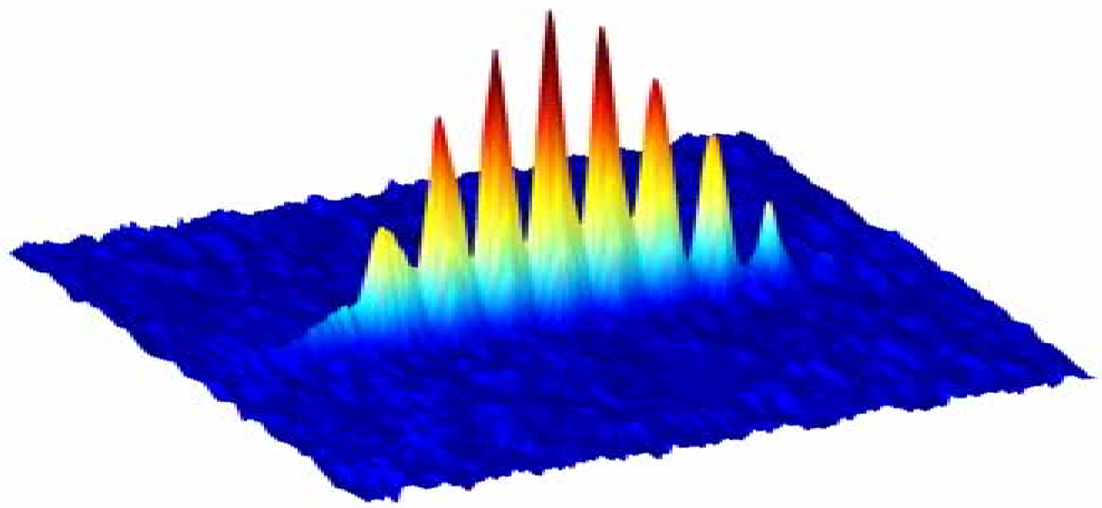
Collaborations

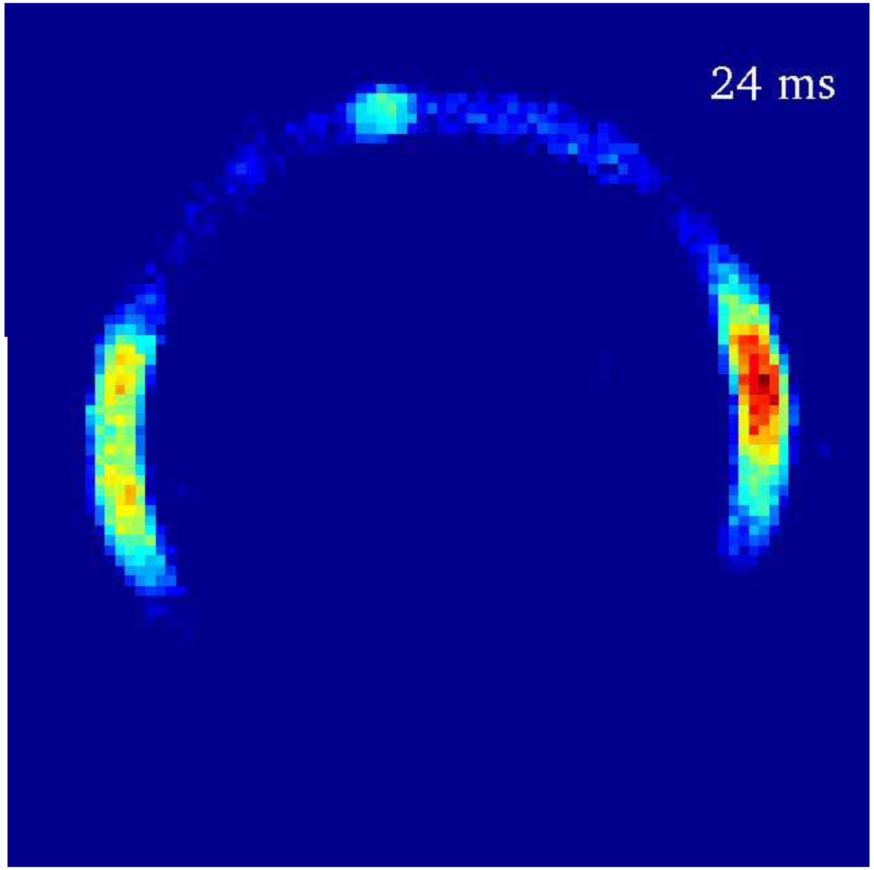
Jordi Mompart, Anna Sanpera, Veronica Ahufinger, Alex Turpin, Maciej Lewenstein(Barcelona)
R. Dumke (NTU), Jürgen Jahns (FernUniversität Hagen), Reinhold Walser (Darmstadt)

+ Gabriele Jenny-Deußer (Management)

Novel approaches to A T O M T R O N I C devices in optical potentials

Part 1:
Coherent Matter Wave Optics in Waveguides and Optical Storage Rings: ATOMTRONICS

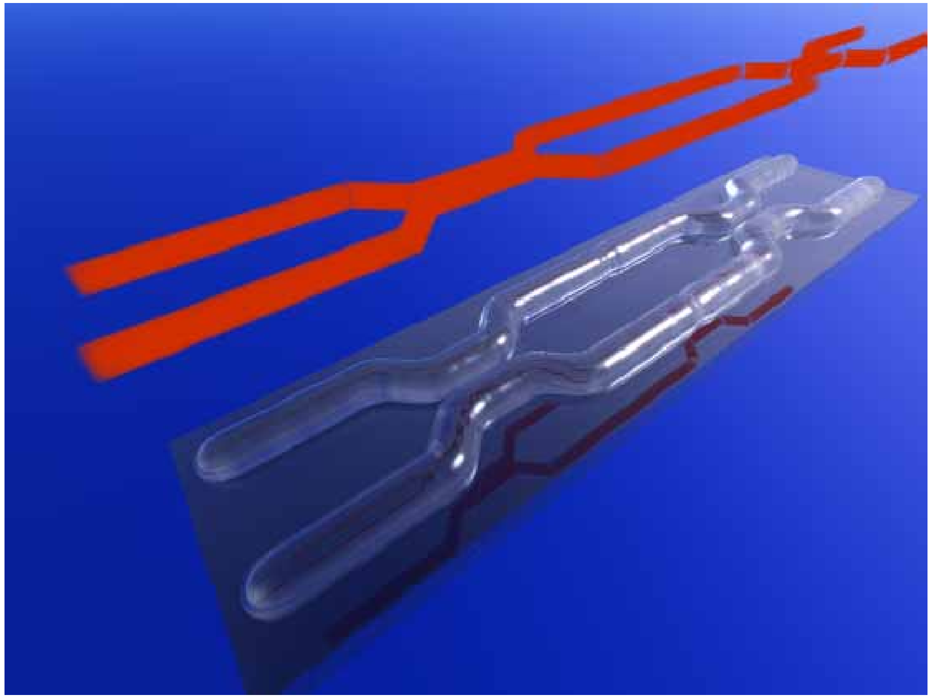


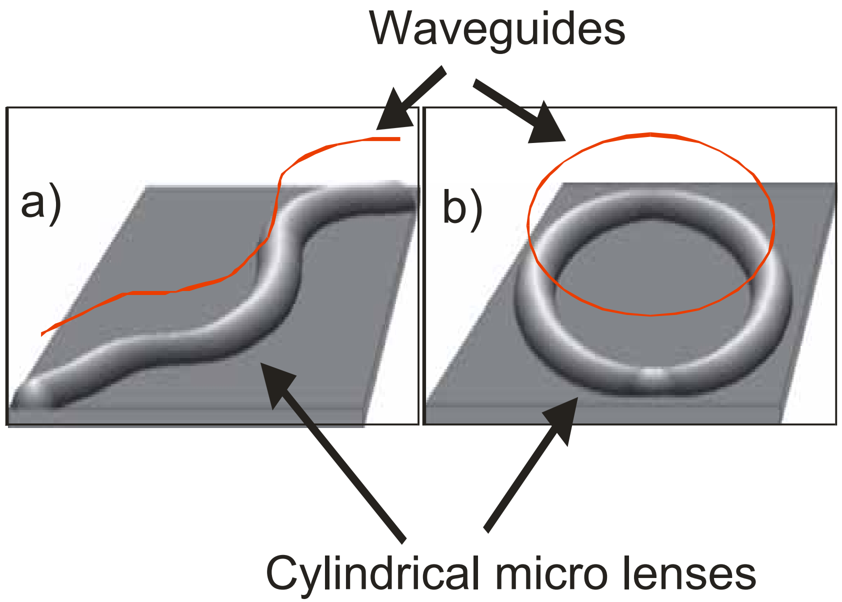


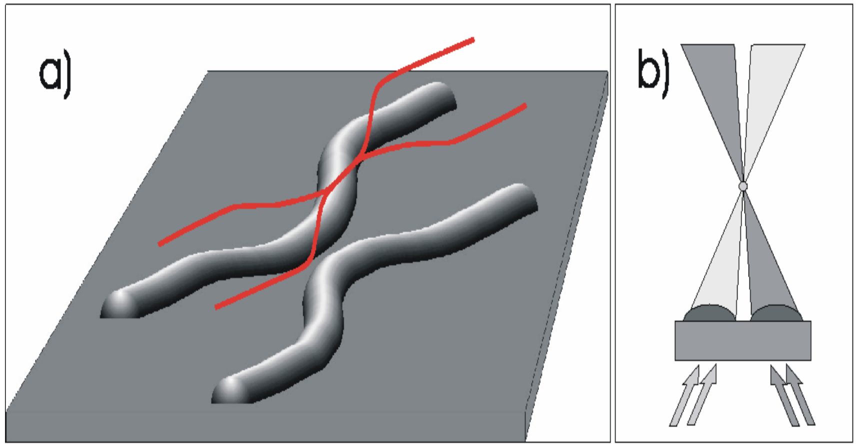
ATOMTRONICS: Matter Wave Optics in Complex Geometries

Matter wave optics in optimized and complex micro- and nano- structures

- Compact atom interferometer geometries as quantum sensors
- Resonator for atomic matter waves

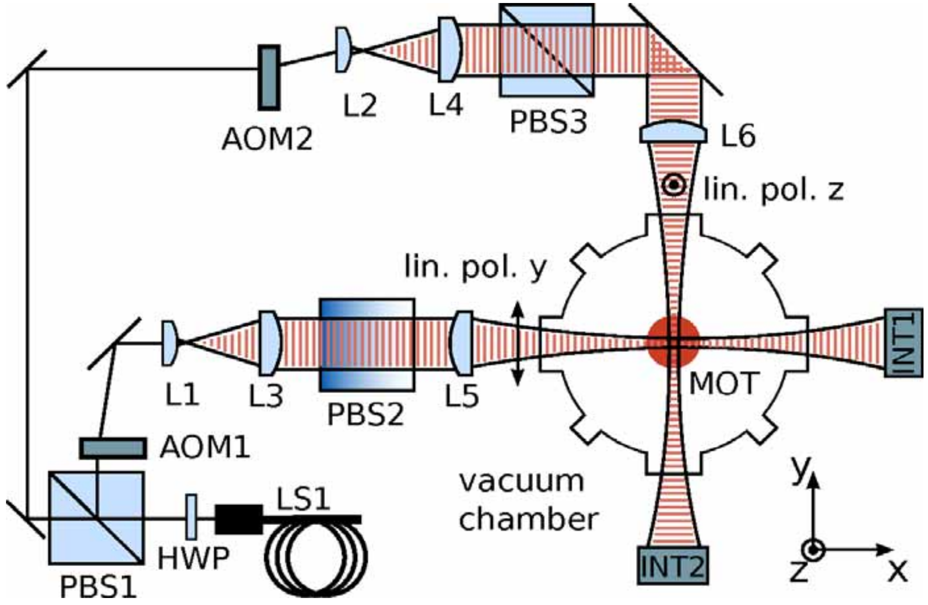


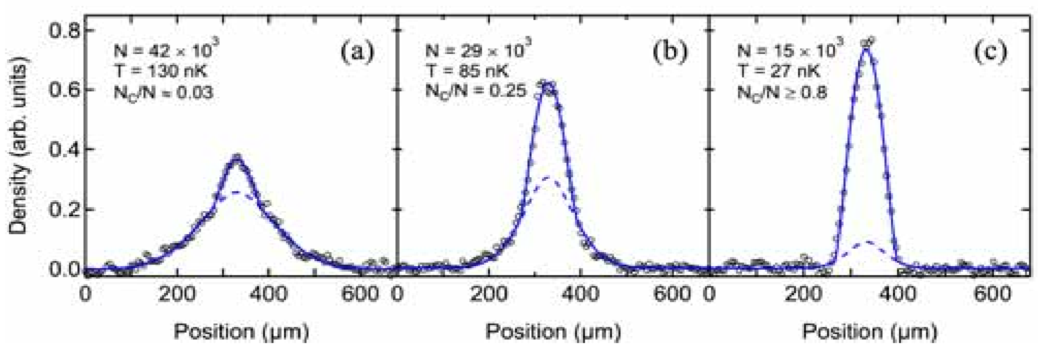




Bose-Einstein Condensation in Dipole Trap

- ^{87}Rb Atoms loaded directly from MOT
  - approx. 500 000 atoms
  - T = 100 µK
- Crossed optical dipole trap
  - 25 W **multi-frequency fiber laser** at 1070 nm
  - Beam waists ~45 µm
  - Trapping frequencies around 1 kHz
- Bose-Einstein condensate
  - N=30 000
  - T=27nK
  - $N_C/N>0.8$

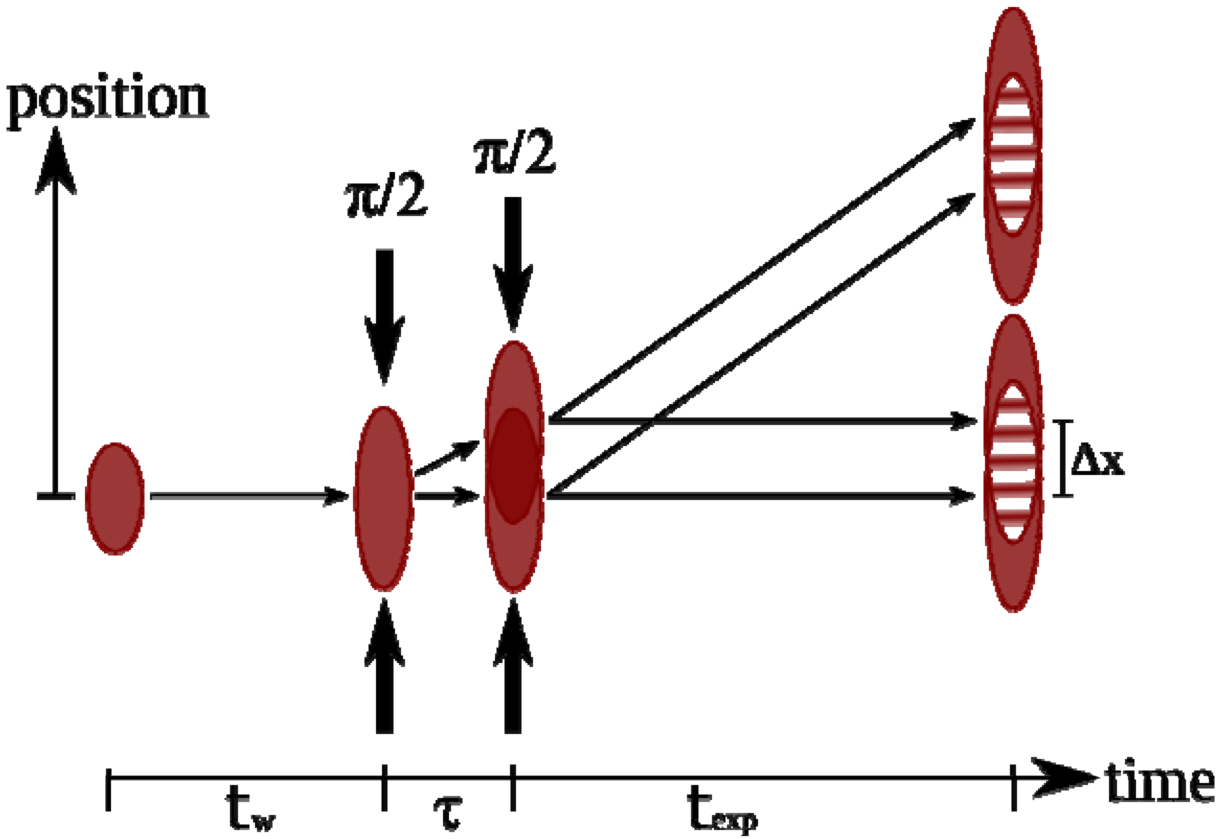




*T. Lauber, J. Küber, O. Wille, and G. Birkl, Phys. Rev. A **84**, 043641 (2011)*

Ramsey-type Interferometer for BEC wave function

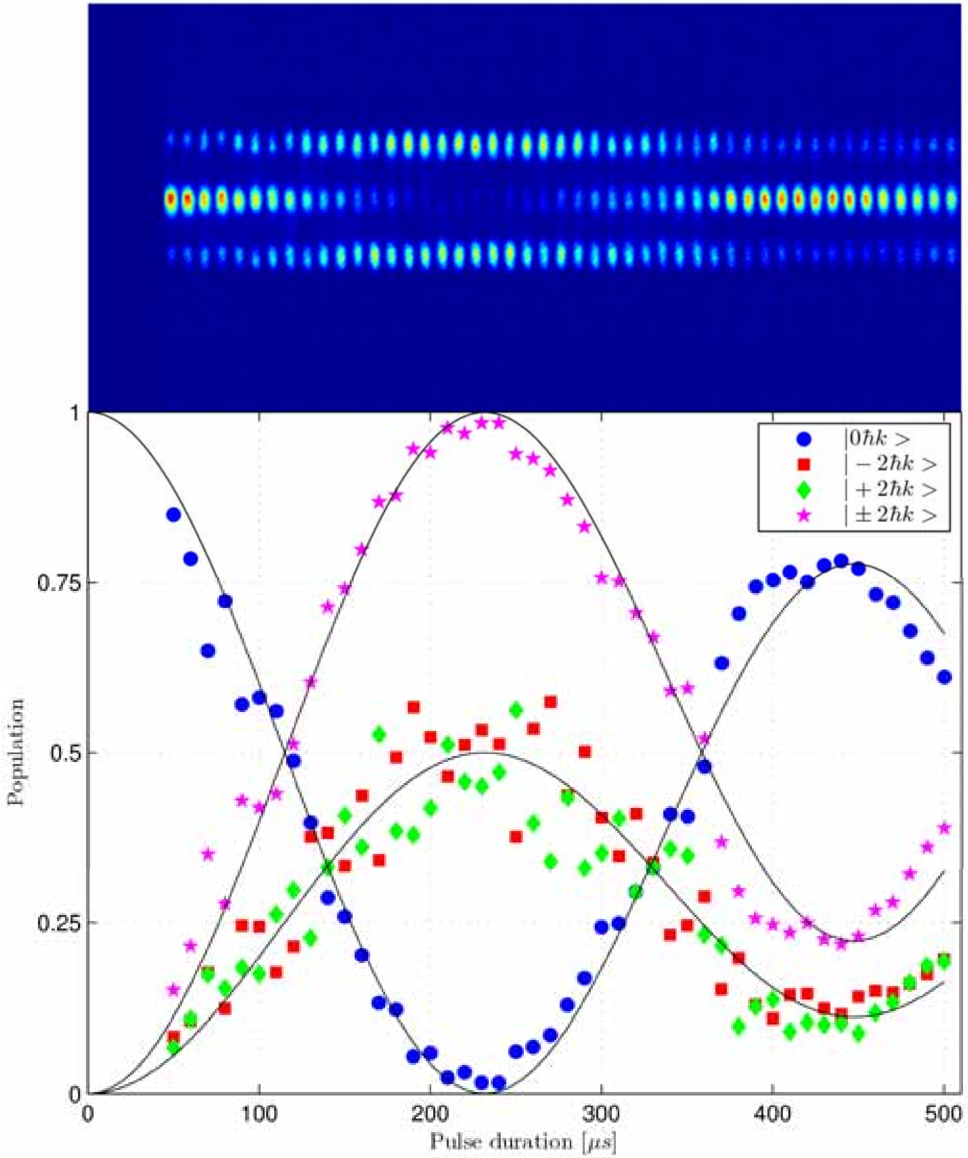
Ramsey-type interferometry with π/2 – π/2 pulses



J.E. Simsarian, et al., Phys. Rev. Lett. ***85****, 2040 (2000)*

Interferometer based on Double Bragg Diffraction

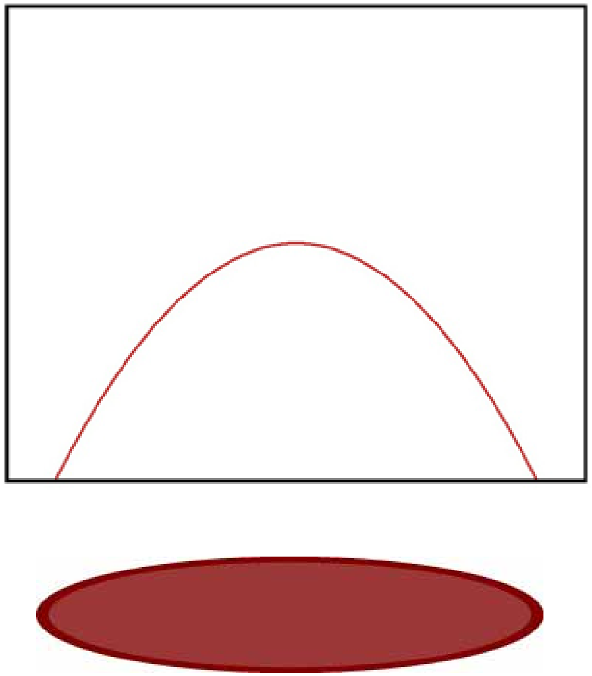
- After creation of BEC, it is released from crossed dipole trap
- Immediatley afterwards a double Bragg pulse of varying duration is applied
- After an additional waiting time of 18ms the density distribution is imaged
- Up to 99% of the atoms are transfered into +/– 2ħk for a pulse duration of 230 μs



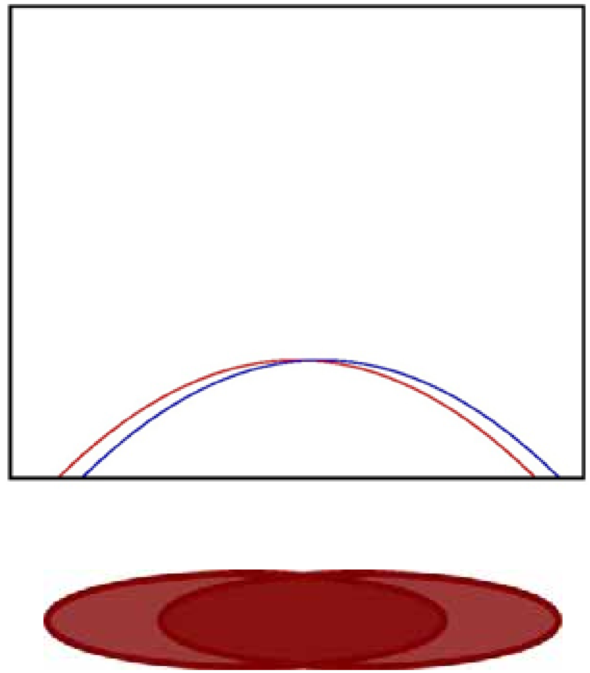
J. Küber, F. Schmaltz, G. Birkl, 'Experimental realization of double Bragg diffraction: robust beamsplitters, mirrors, and interferometers for Bose-Einstein condensates', arXiv:1603.08826.

Autocorrelation Measurement of BEC Phase Evolution

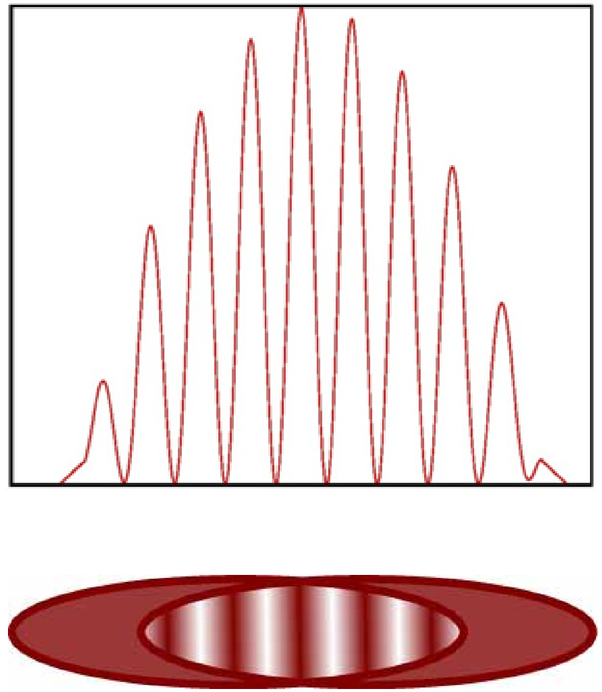
BEC wave function



Two partial wave functions displaced by $\Delta x = v\,\tau$



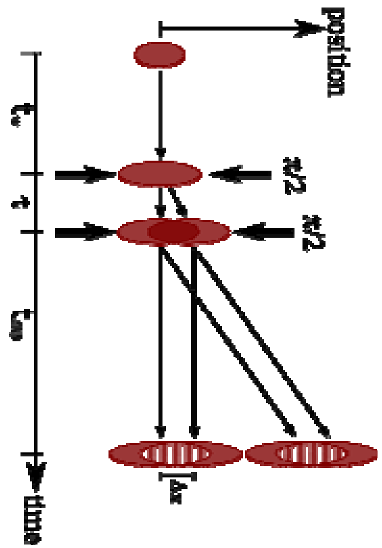
Interferometric measurement of phase of BEC wave function

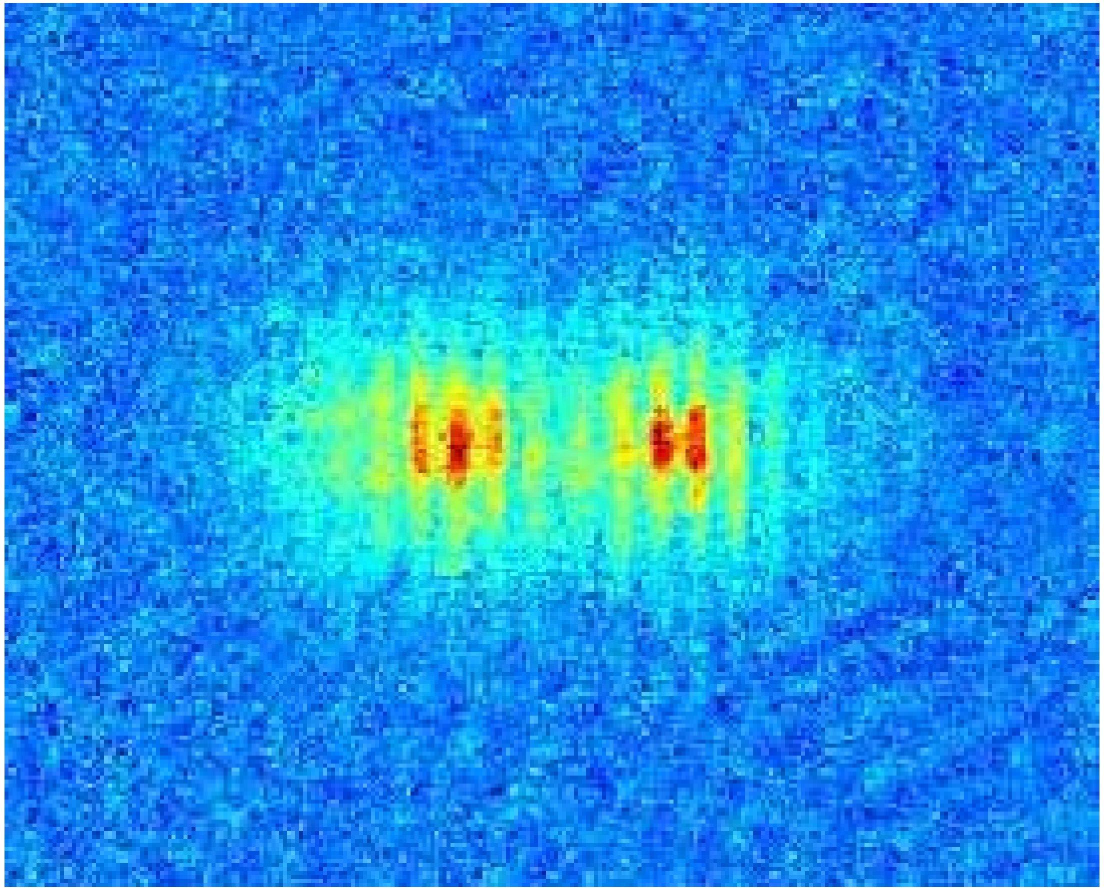


J.E. Simsarian, et al., Phys. Rev. Lett. ***85****, 2040 (2000)*

Interference of two freely expanding BECs

Two superimposed BECs show interference.





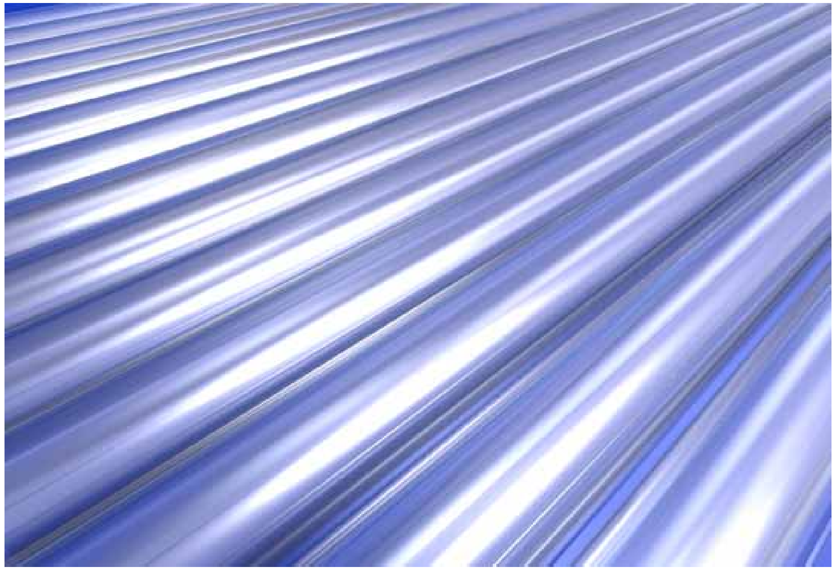
Bose-Einstein condensates behave like waves.

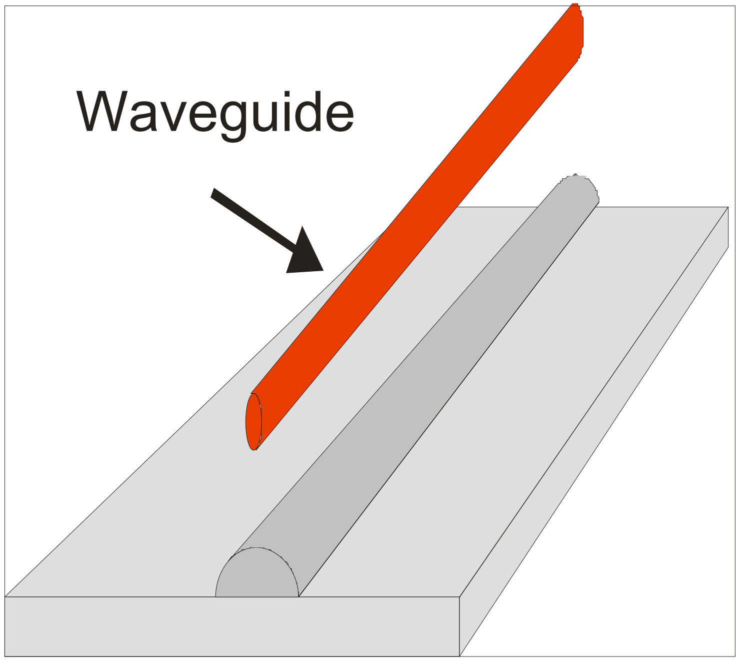
Guiding Structures based on Cylindrical Microlenses

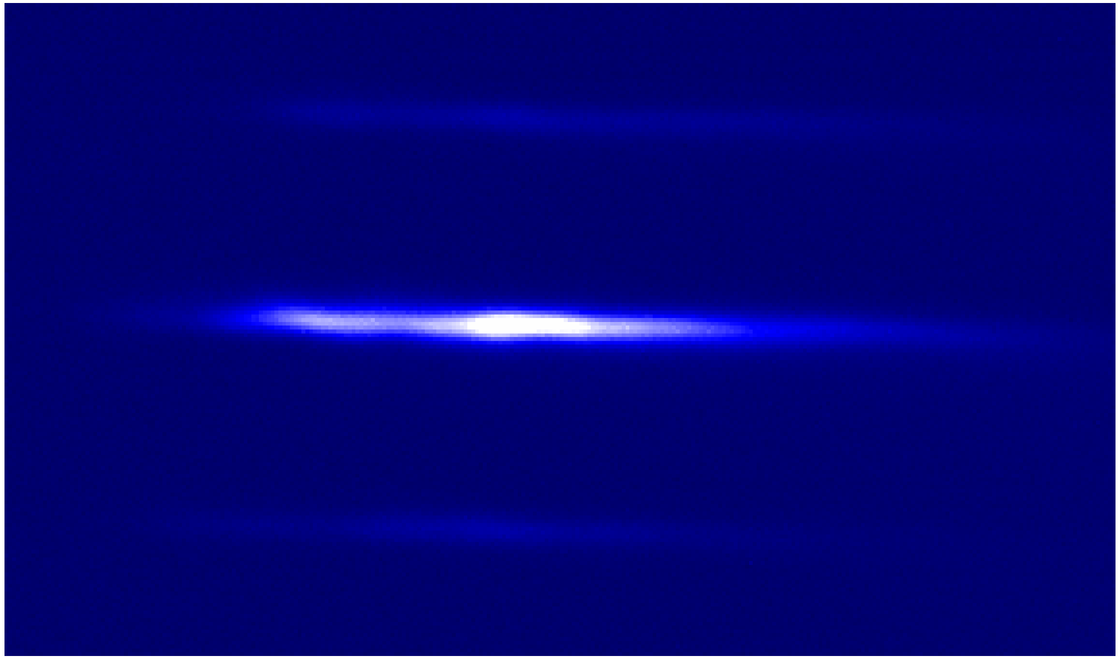
Micro-optical Lens Arrays:

Guiding of atoms along the linear potential minimum in the focus of a cylindrical lens

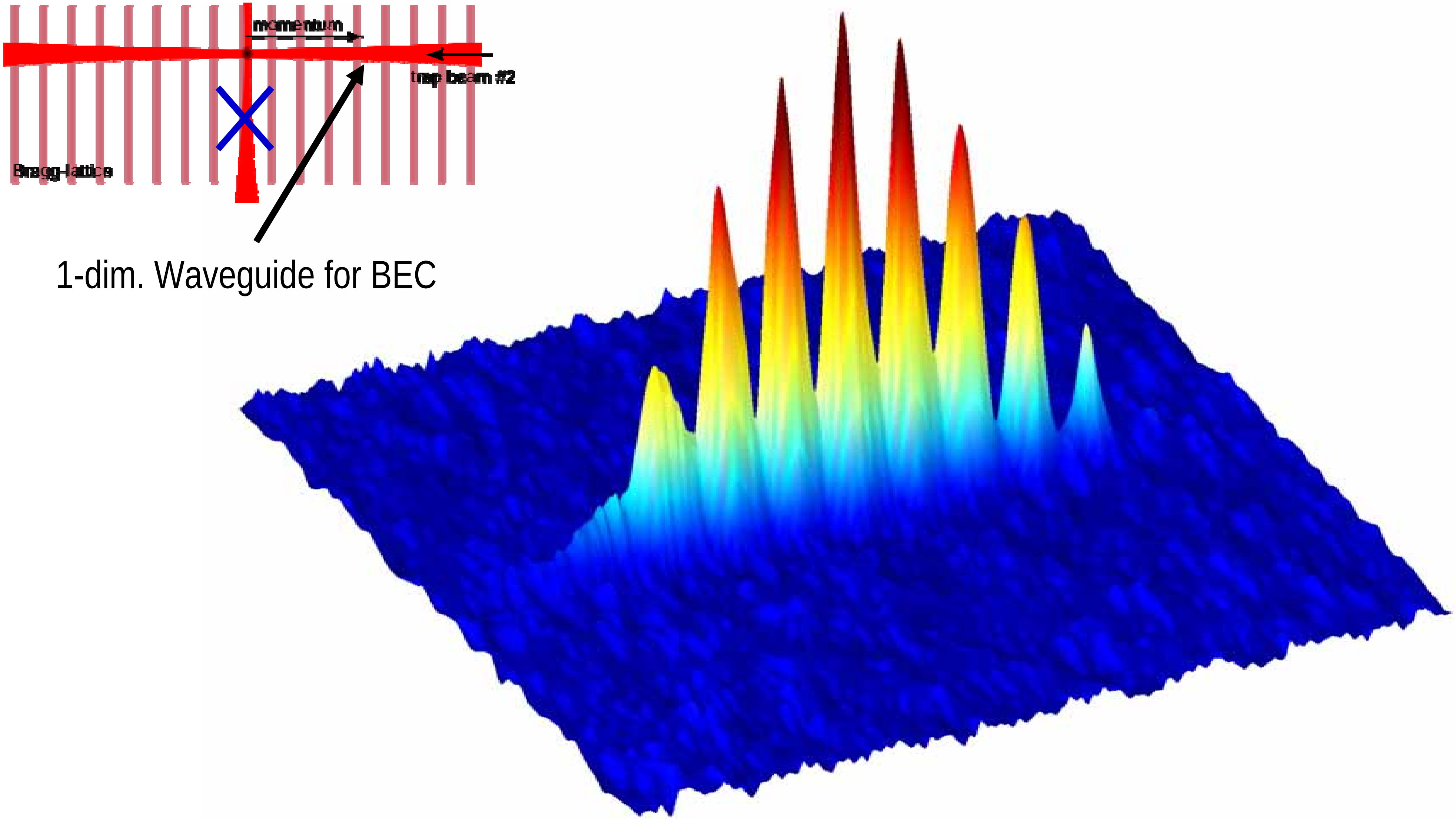
⇒ Waveguide for atoms similar to optical fibers





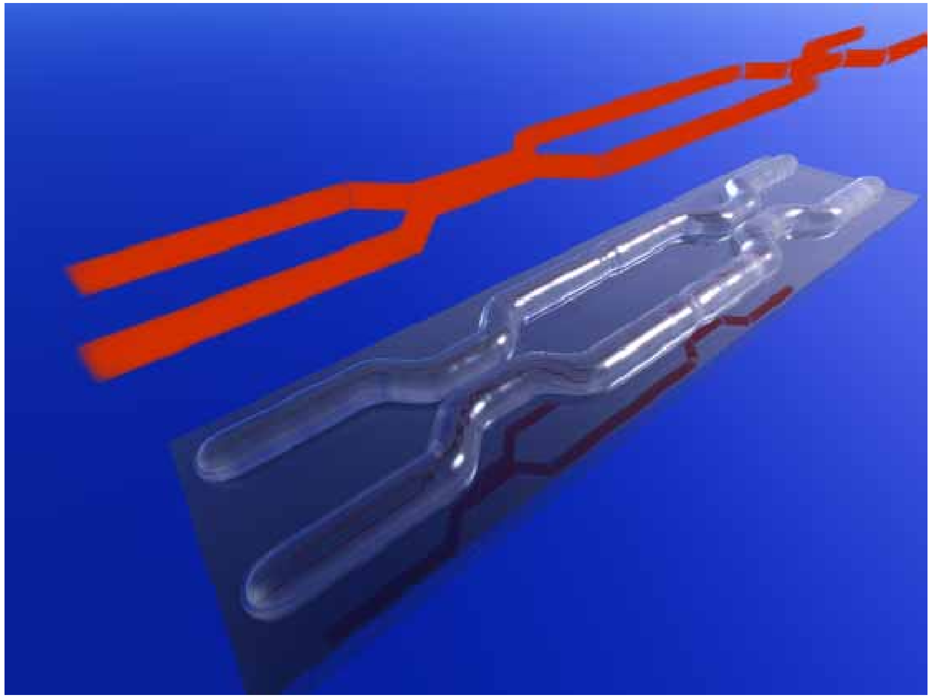


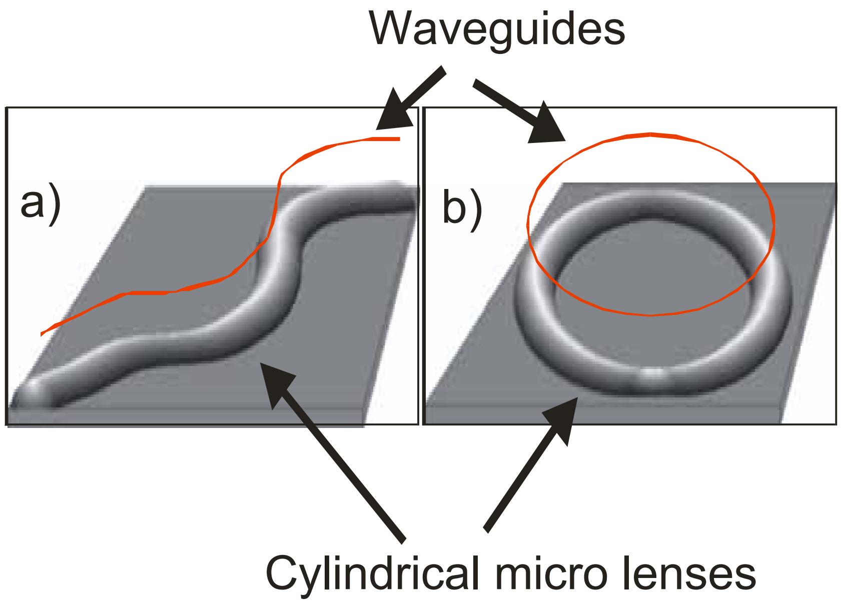
Phase Evolution of Expanding BEC in 1D Waveguide

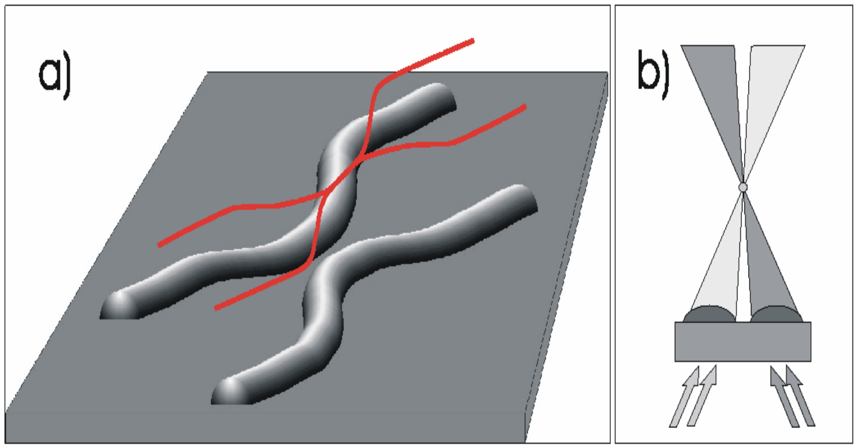


Matter wave optics in optimized and complex micro- and nano- structures

- Compact atom interferometer geometries as quantum sensors
- Resonator for atomic matter waves

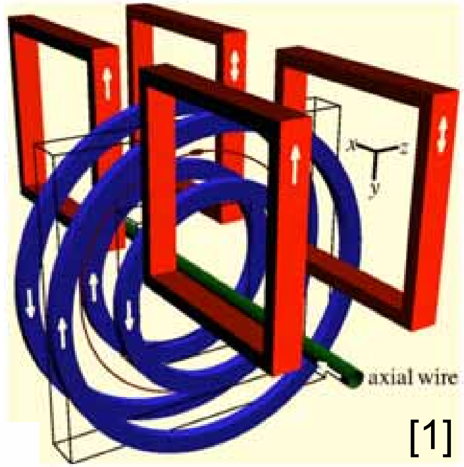






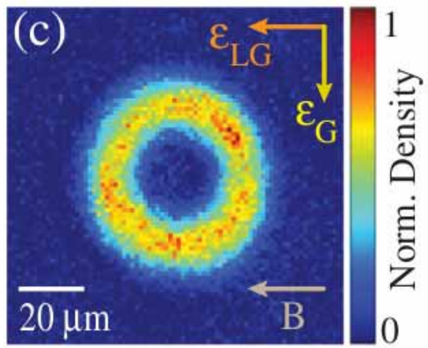
Ring Potentials for Neutral Atoms

- **Magnetic Ring Traps:**
  macroscopic, rf-dressed,
  atom chips, super-conducting chips
  (Georgia Tech, Strathclyde, Berkeley, Amsterdam, Paris-Nord, Tuscon, Harvard, Singapore, Vienna, Oxford, …)



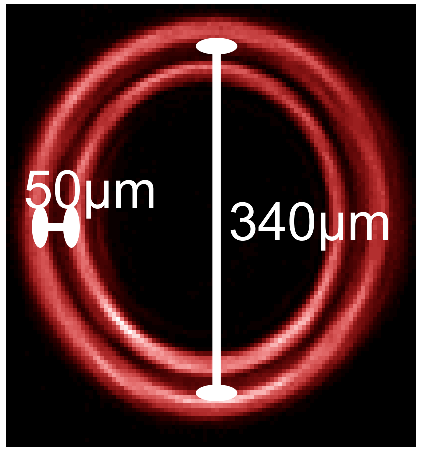
[1]

- **Optical Ring Traps:**
  Laguerre-Gaussian beams,
  scanning beam traps
  (NIST, St. Andrews, Los Alamos, Monash, Wisconsin, LKB, Paris-Sud, Brisbane, …)



[2]

- **Our Optical Approaches:**
  Red-detuned ring based on diffractive optics
  Blue detuned double ring based on conical refraction



[3]

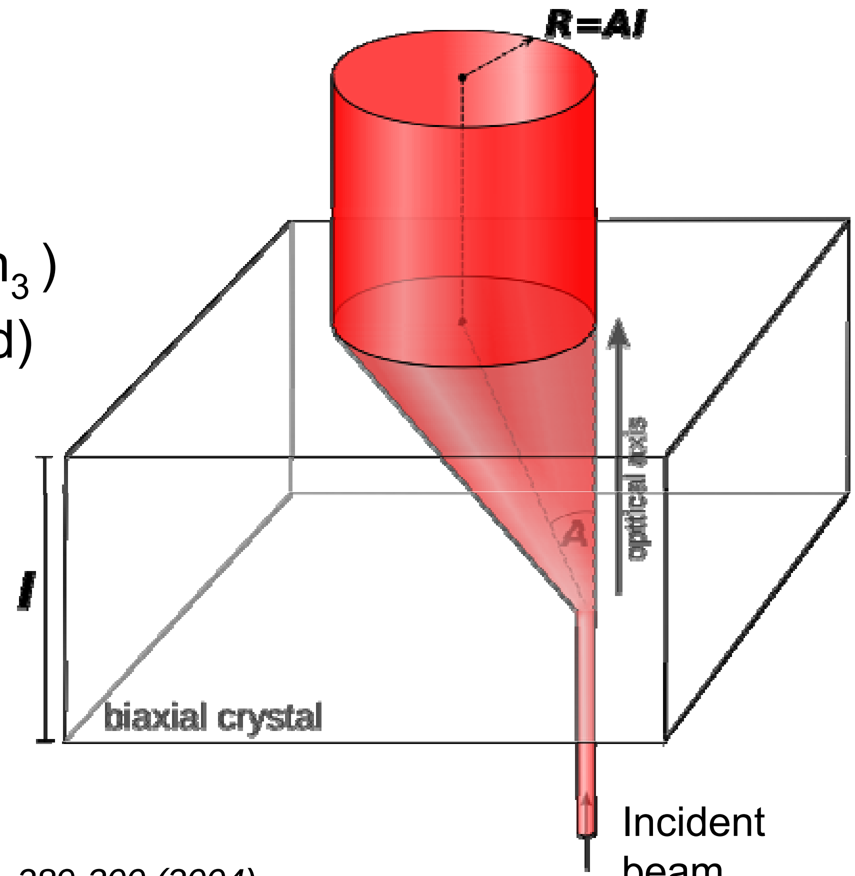
[1] *A. Arnold, C. Garvie, and E. Riis, Physical Review A* ***73****, 041606 (2006)*
[2] *A. Ramanathan, et. al., Physical Review Letters* ***106****, 130401 (2011)*
[3] *A. Turpin et al., Opt. Express* ***23****, 1638-1650 (2015).*

Conical Refraction

In collaboration with Jordi Mompart, Yury Loiko, Todor Kirilov (UAB, Barcelona)

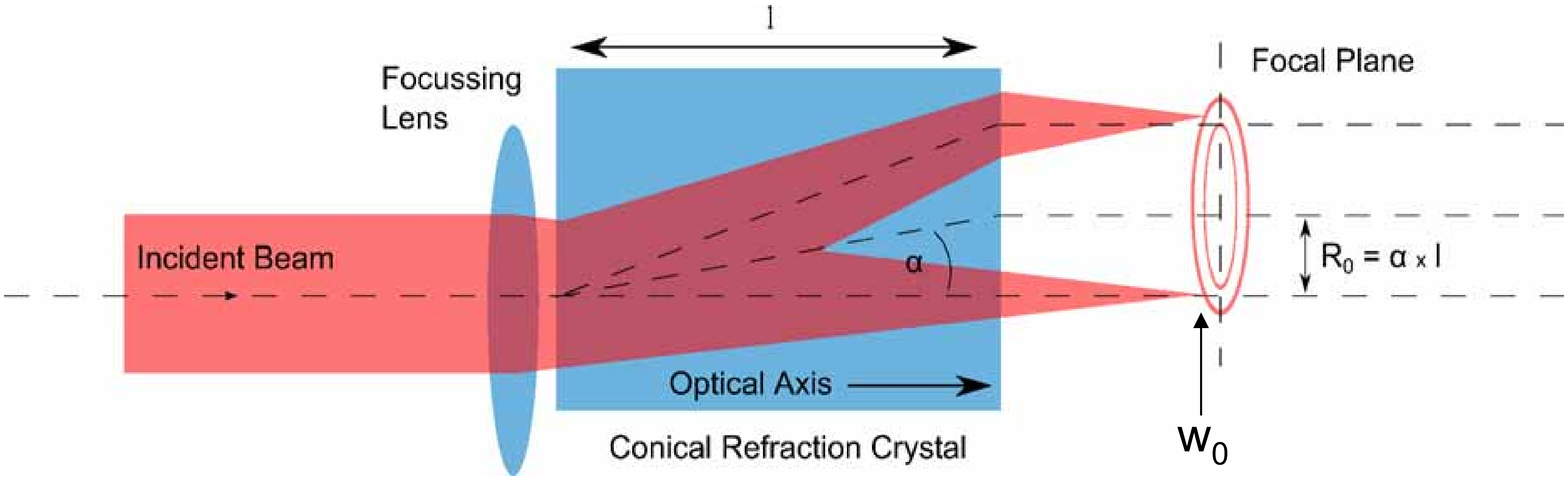
- Linear optical effect in biaxial crystals (predicted in 1832 by Hamilton)
  First observed by Lloyd in aragonite crystals the same year

- Light is diffracted into a cone,
  under the following conditions:
  - Propagating in a biaxial crystal ($n_1 < n_2 < n_3$)
  - Light is unpolarized (or circularly polarized)
  - Incidence along one of the optical axes
  - Surface of the crystal is polished
    perpendicular to this optical axis



See e.g.: M. V. Berry, Journal of Optics A: Pure and Applied Optics ***6****, 289-300 (2004)*

Important Parameters for Conical Refraction



$$\alpha = \sqrt{(n_3^2 - n_2^2)(n_2^2 - n_1^2)}/n_2$$

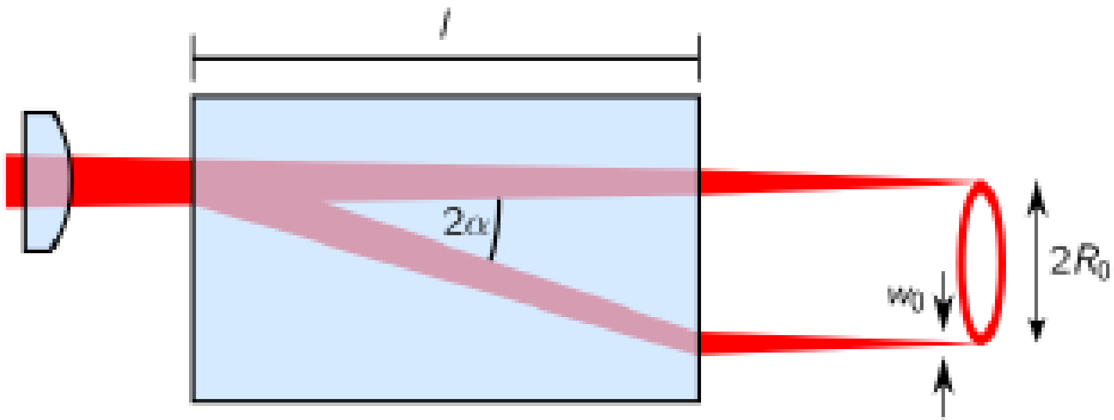
$$n_1 < n_2 < n_3$$

$$R_0 = l \times \alpha$$

$$\rho_0 = \frac{R_0}{w_0}$$

- **Parameters of Crystal:**
- Material: $KGd(WO_4)_2$ or *KGW*
- Length: *l* =16,55 mm
- Cone Angle: α = 1°

Different Regimes of Conical Refraction

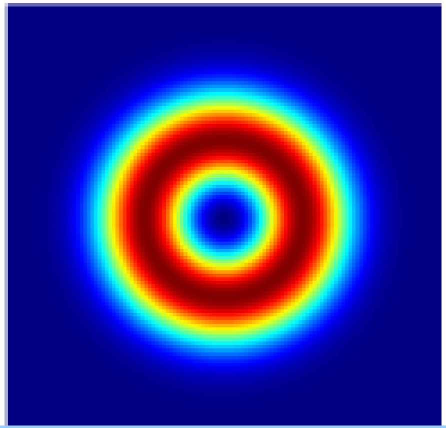


$$\alpha = \frac{1}{n_2}\sqrt{(n_2 - n_1)(n_3 - n_2)}$$

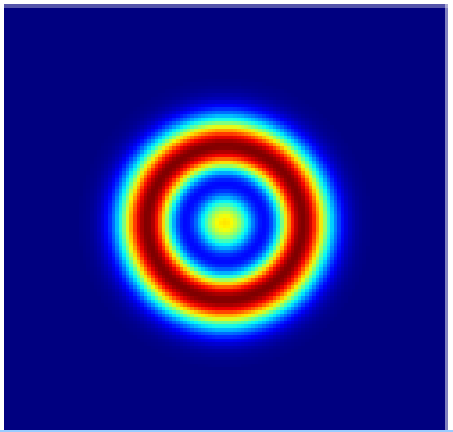
$$R_0 = \alpha \cdot l \qquad \rho_0 = \frac{R_0}{w_0}$$

Conversion efficiency 100% Ring width prop. to beam waist

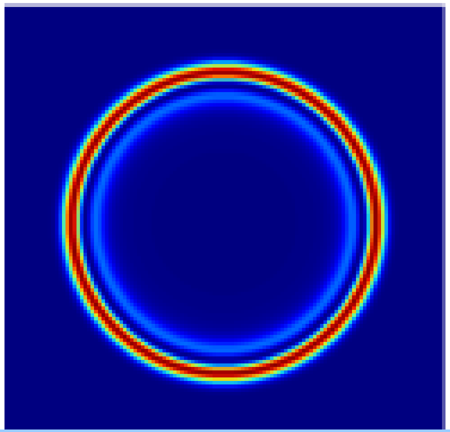
$\rho_0 = 0.92$



$\rho_0 = 1.5$

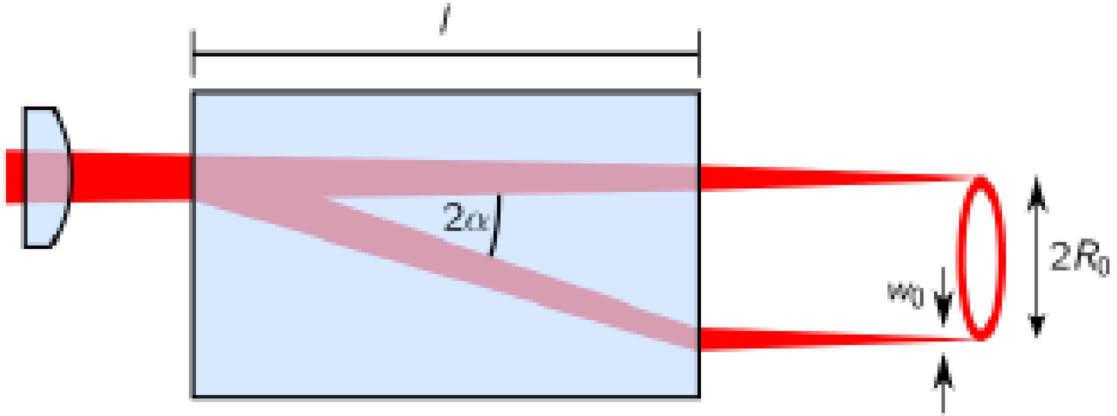


$\rho_0 = 10$



A. Turpin, J. Polo, Yu V. Loiko, J. Küber, F. Schmaltz, T.K. Kalkandjiev, V. Ahufinger, G. Birkl, J. Mompart, 'Blue-detuned optical ring trap for Bose-Einstein condensates based on conical refraction', Optics Express ***23****, 1638-1650 (2015). arXiv: 1411.1587*

Different Regimes of Conical Refraction



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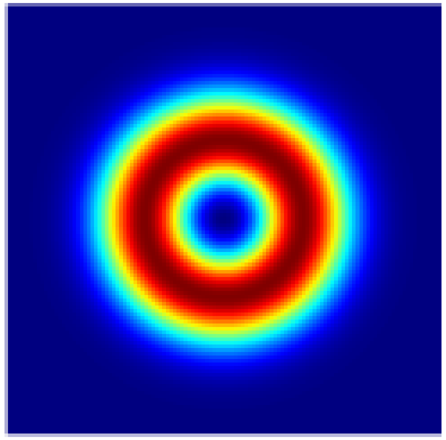

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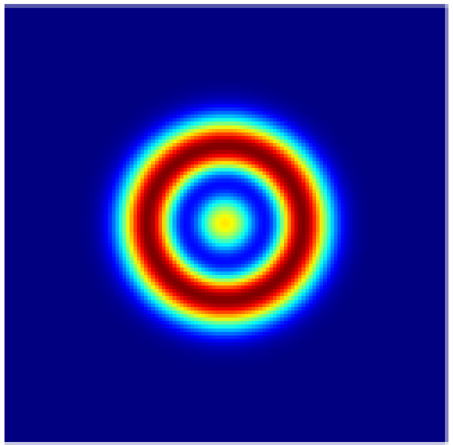

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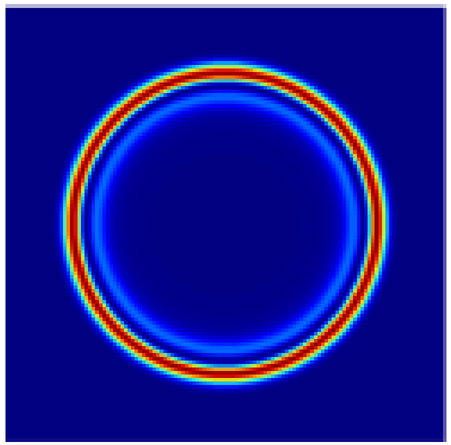
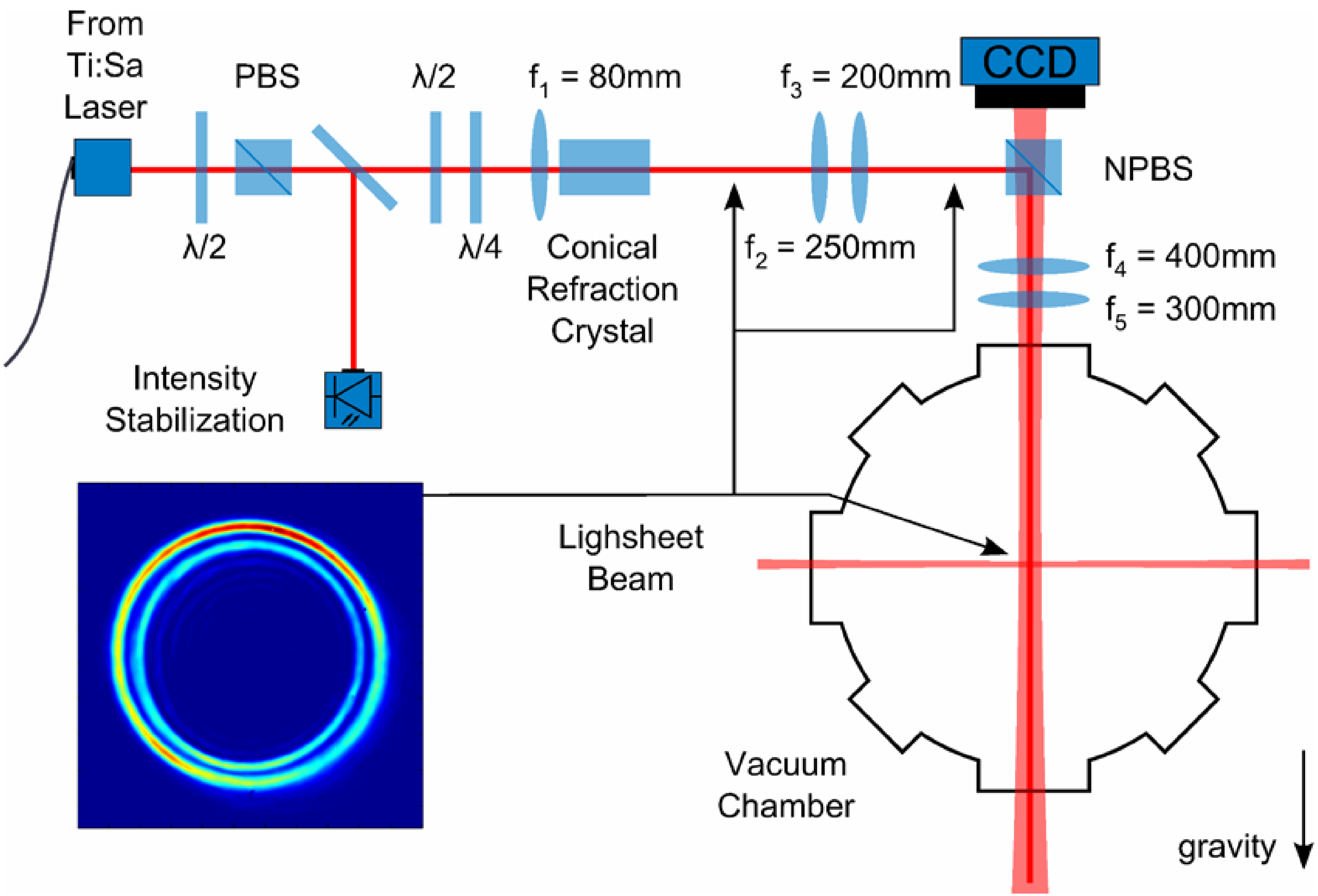
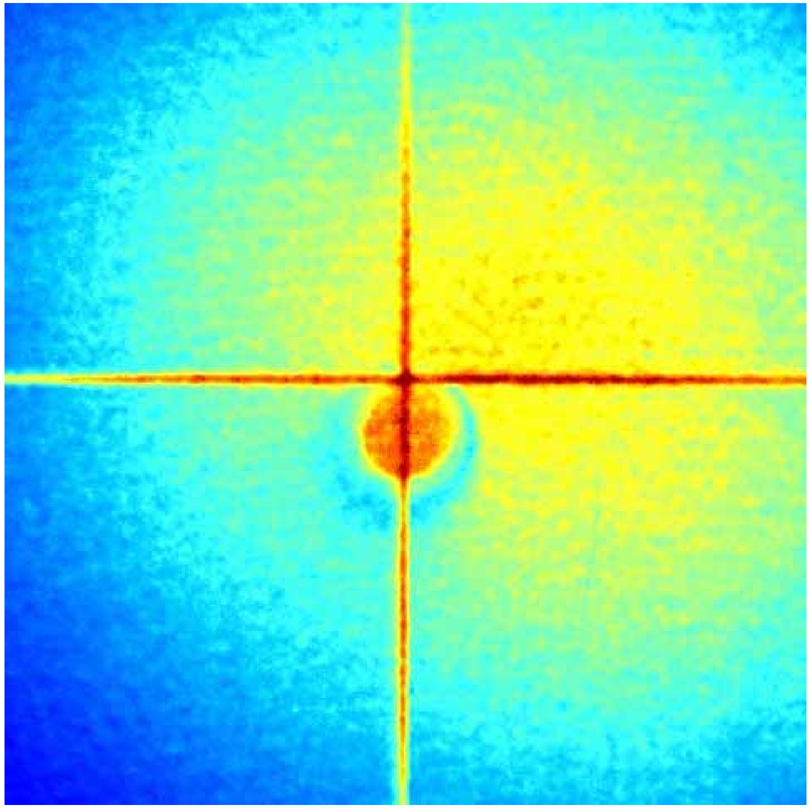


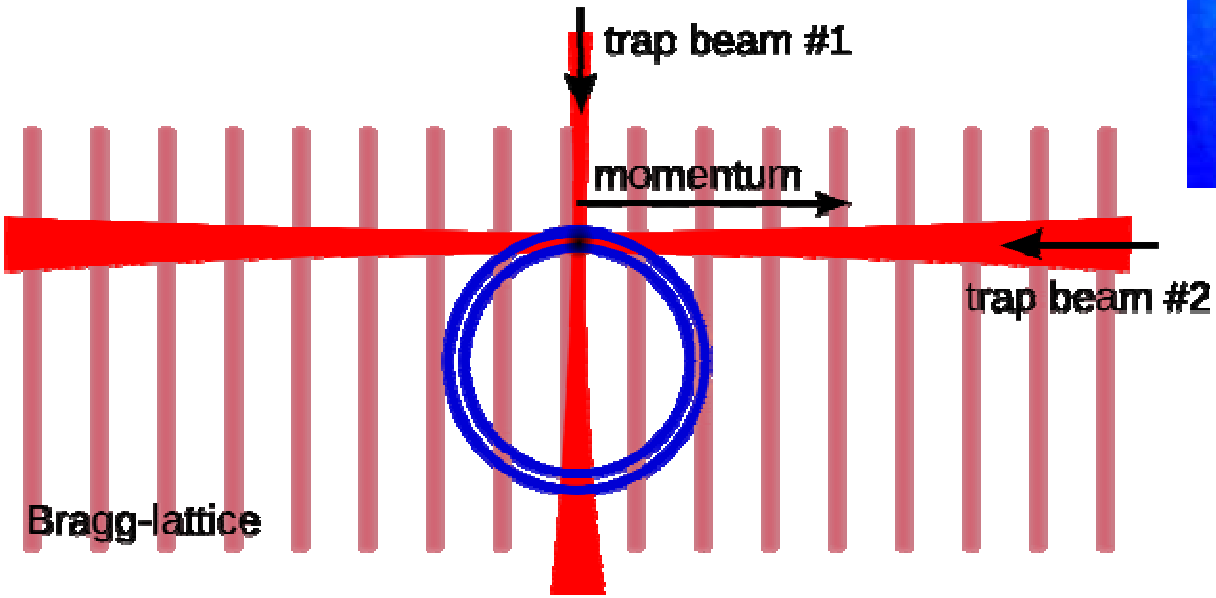
Optical Setup for a Storage Ring Potential



Storage Ring for Bose-Einstein Condensates

- Production of BEC in crossed dipole trap
- Loading by linear ramping of intensities
- Acceleration and autocorrelation measurements using Bragg lattice
- Free propagation along the ring

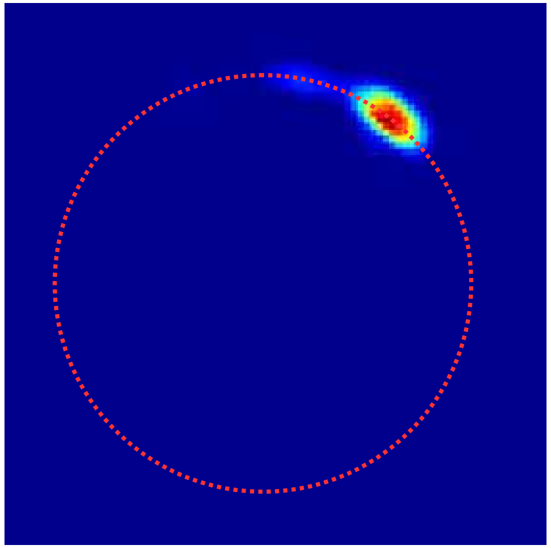




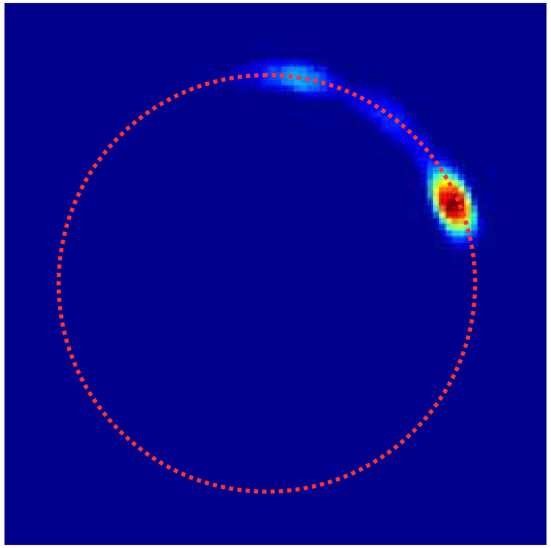
Rotating BECs in Optical Storage Ring

- Transferred Momentum: n x 2ħk
- Achieved: 2ħk, 4ħk, 6ħk, ± 2ħk
- Up to two round trips observed for 4ħk
- Spread of wave packet given by mean-field expansion

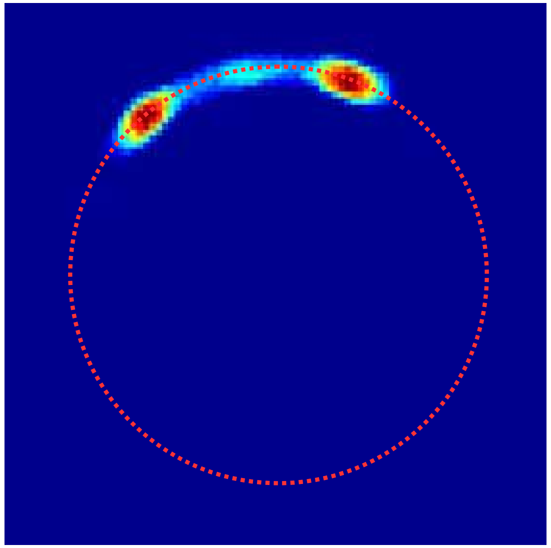
BEC momentum: 2ħk



BEC momentum: 4ħk



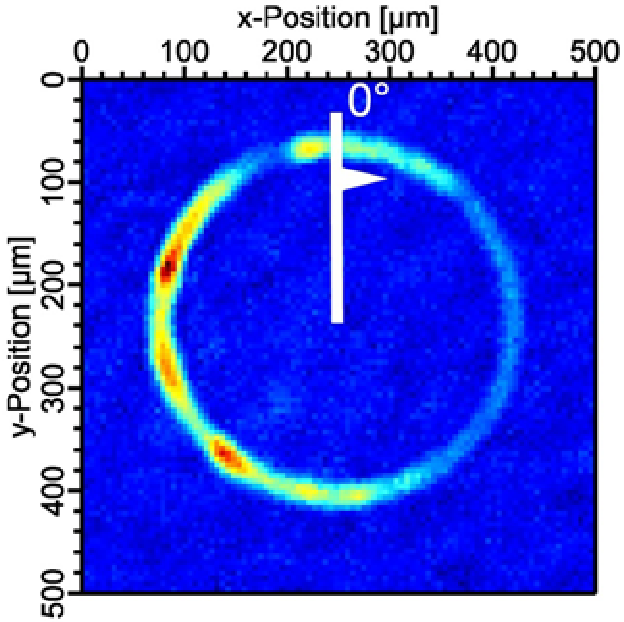
Split BEC: ± 2ħk

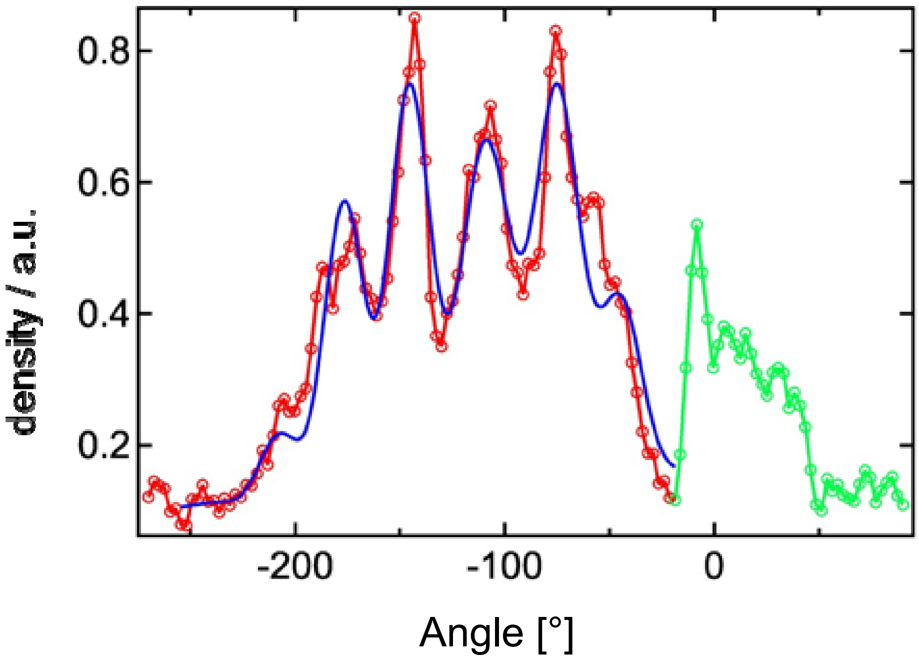


Phase Coherence after Rotation in Storage Ring

Ramsey type interferometer after propagation inside the ring potential

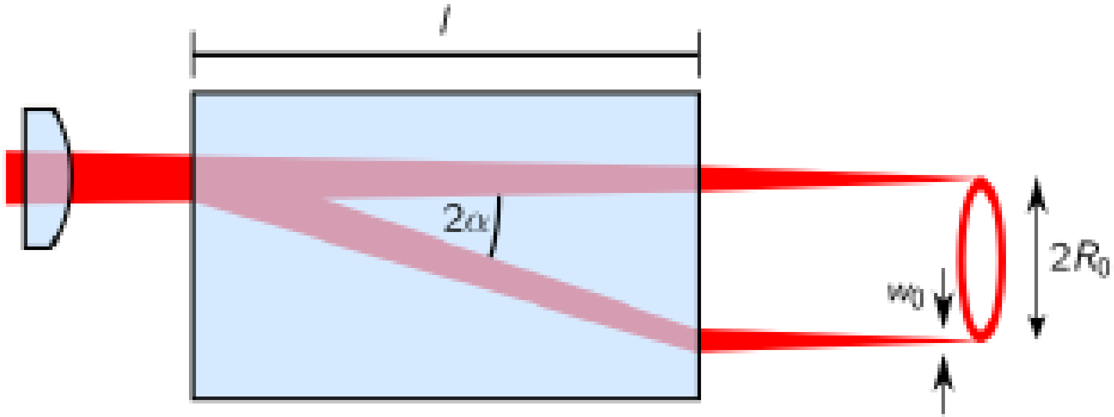
- π-Pulse (4ħk) after loading the BEC into storage ring
- 26 ms of free evolution (atoms travel half way along the ring, 530 μm); limited for avoiding overlap with atoms remaining at original position of BEC
- Autocorrelation measurement (± 4ħk) with pulse separation τ =100 μs
- Free expansion: 14 ms





Fringe Contrast: (23 +/- 4) %

Different Regimes of Conical Refraction



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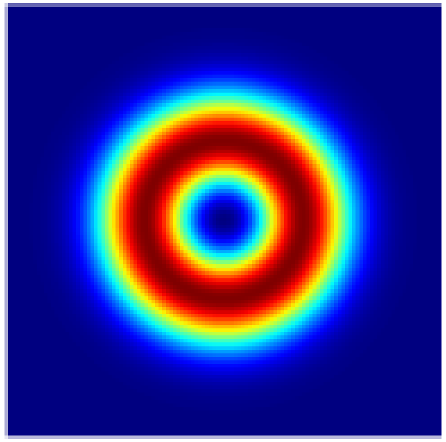

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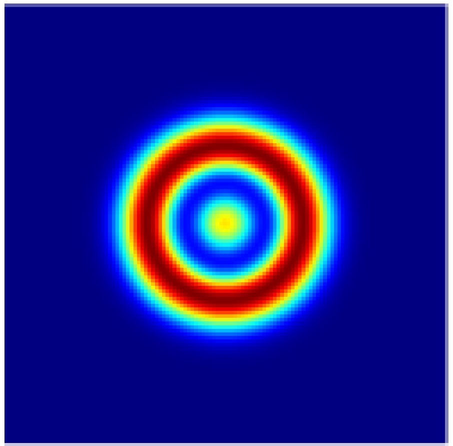
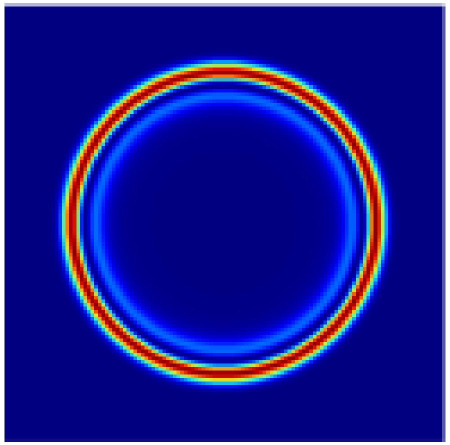
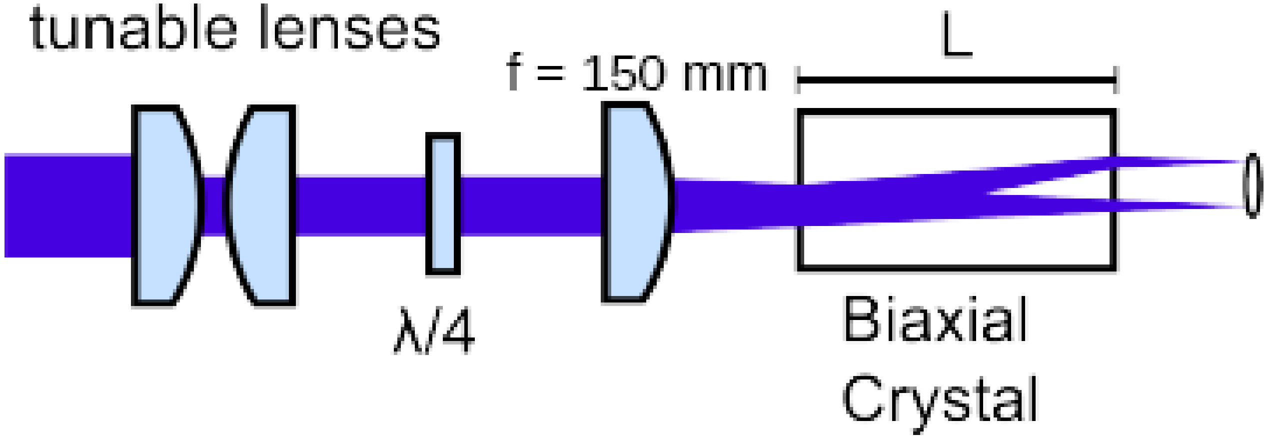


$\rho_0 = 10$



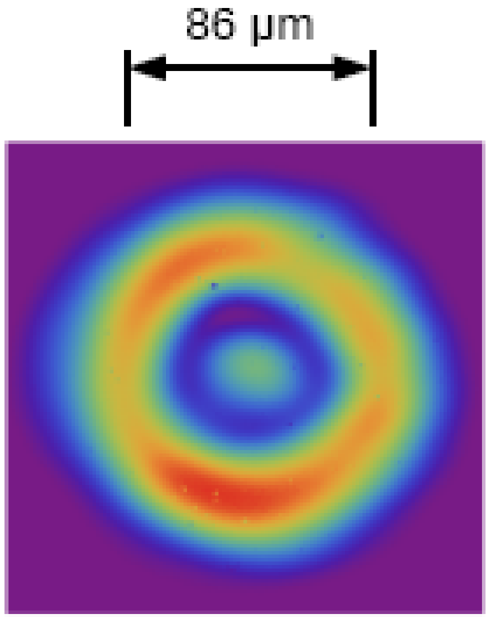
ATOMTRONICS Device Based on Dynamical Ring Trap



- Tunable lenses*: focal length of 50 to 120 mm
- Magnification 0.4 to 2.4
- W_0 = 25 µm → ρ_0 = 1.6

- Changing magnification from 0.7 to 1.0
  → transform geometry dynamically from simply to multiply connected

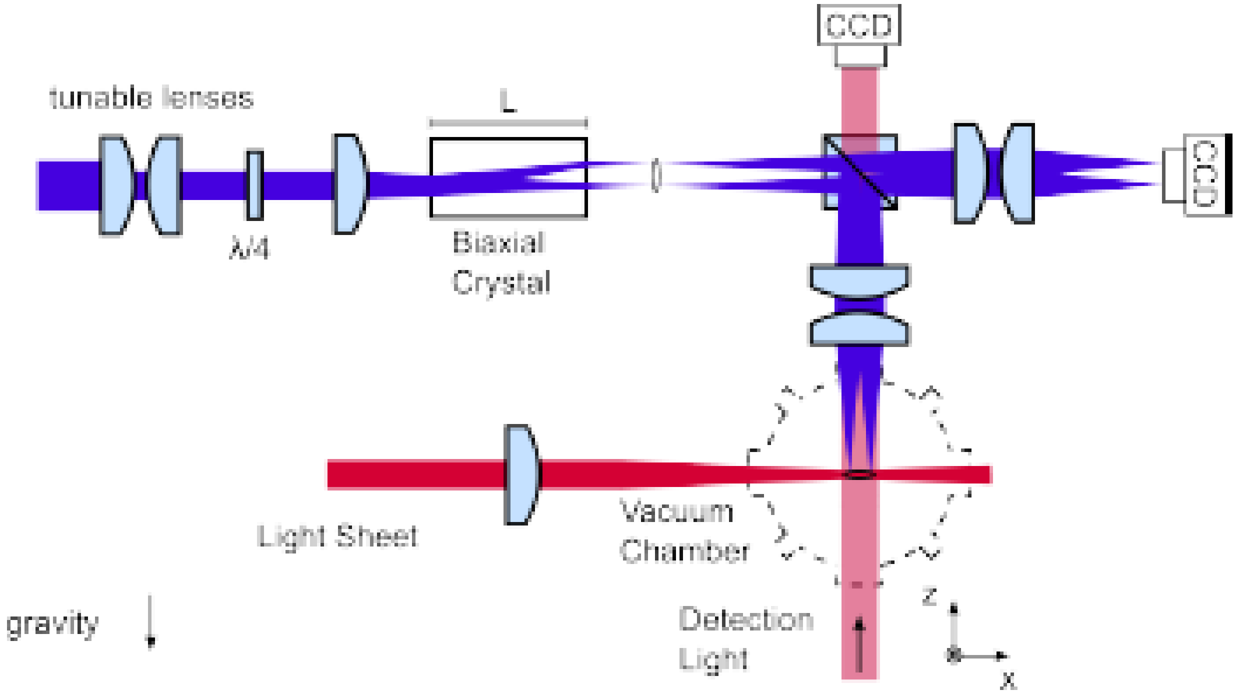
*Optotune "EL-10-30 LD"



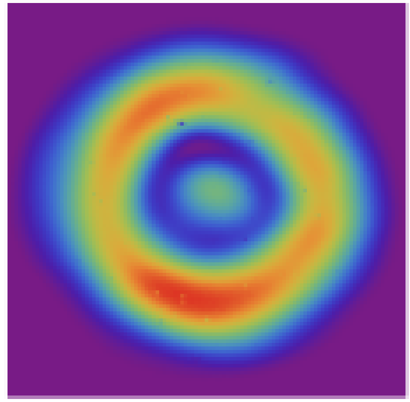
Light field in focal plane with 1:1 telescope

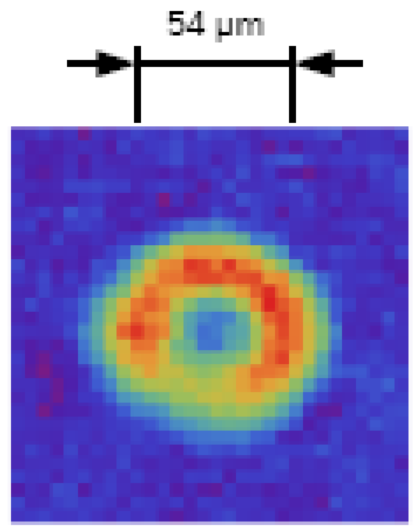
TECHNISCHE UNIVERSITÄT DARMSTADT

ATOMTRONICS Device Based on Dynamical Ring Trap



light field



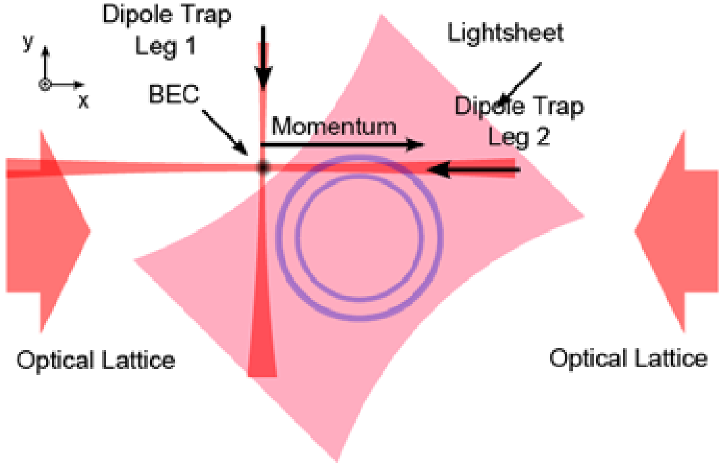


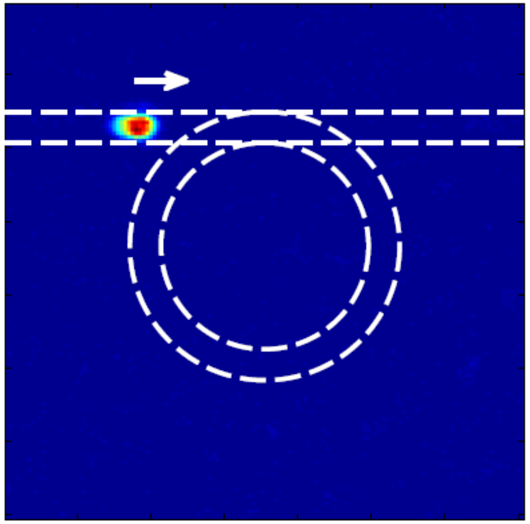
- BEC loaded into static repulsive ring potential from crossed dipole trap within 40 ms
- Almost homogenous density distribution after 120 ms expansion time

Towards complex ATOMTRONICS Circuits

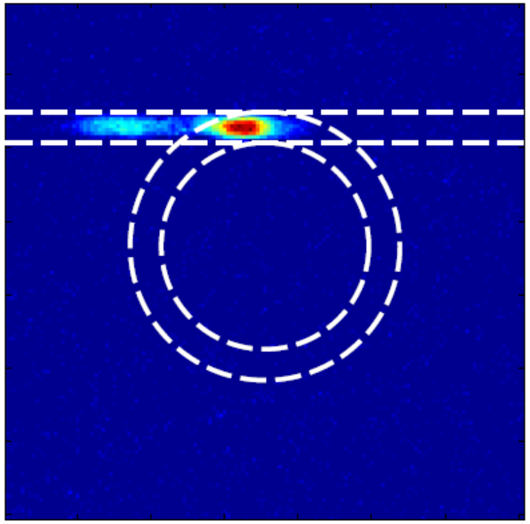
- **First steps towards more complex and integrated circuits:**

Transfer of an externally created coherent matter wave packet into the toroidal potental

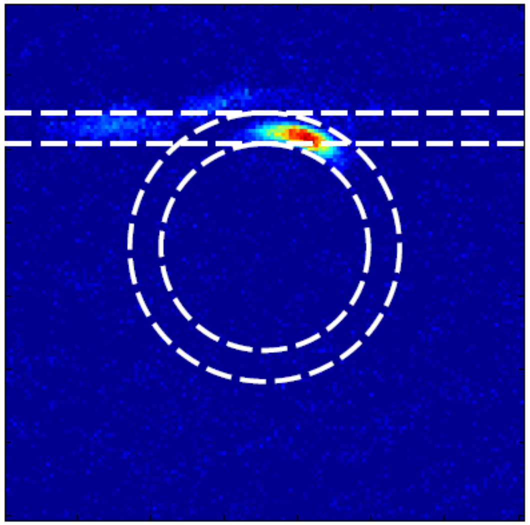




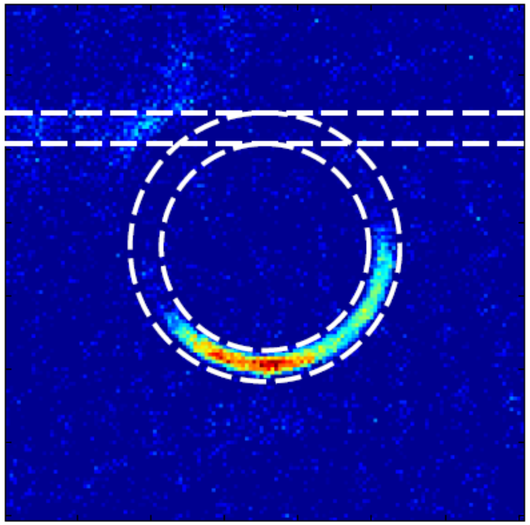
(a) $t_w = 0ms$



(b) $t_w = 7ms$

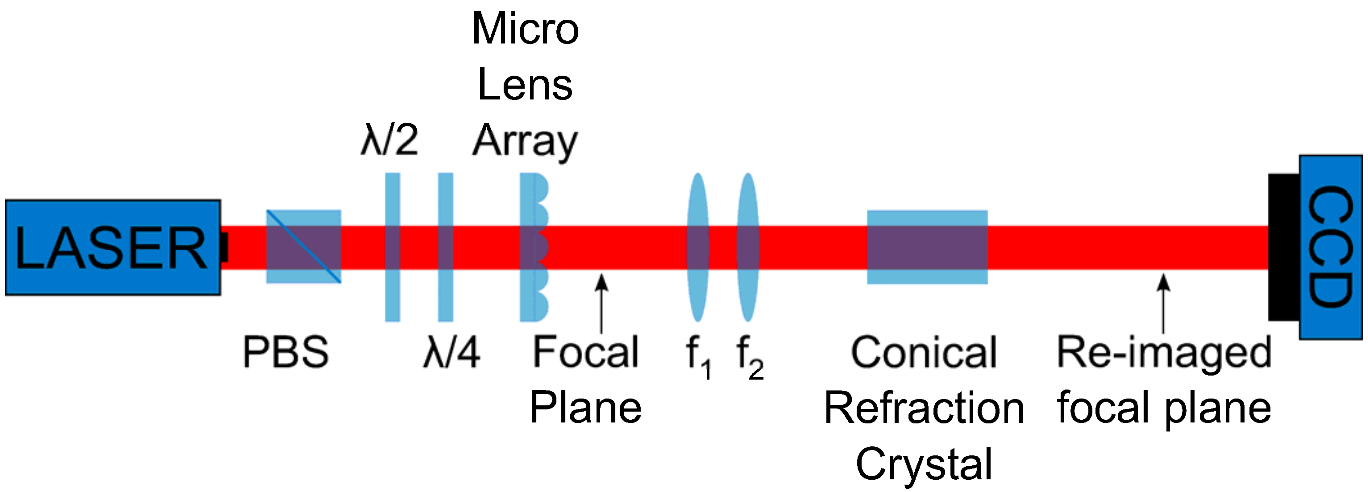


(c) $t_w = 10.5ms$

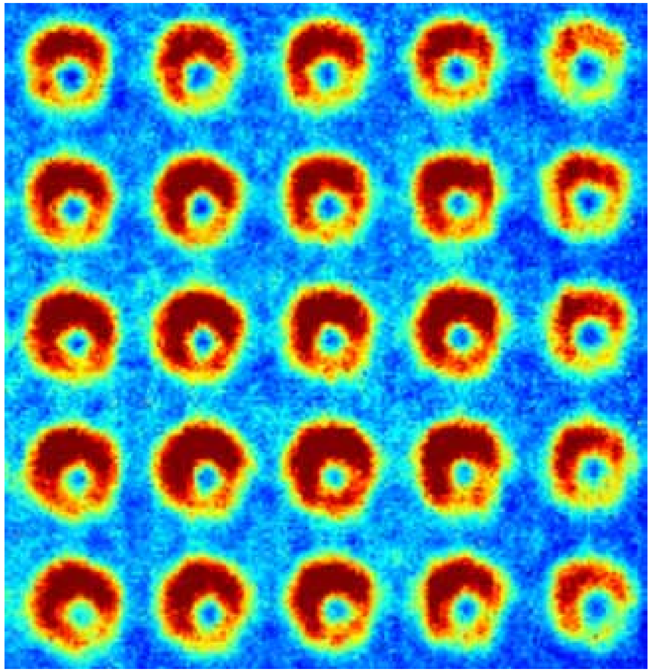


(d) $t_w = 26ms$

Towards complex ATOMTRONICS Circuits



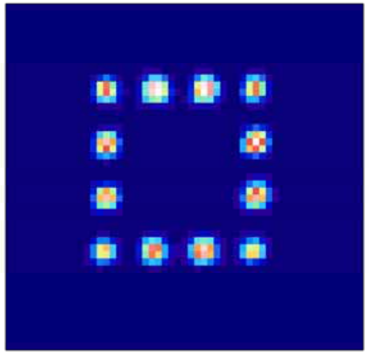
- A two-dimension register of toroidal trapping potentials or dark focus traps is created by combining focusing with a microlens array and conical refraction
- The pitch of the microlens array introduces a third independent parameter
- Separated or connected potential geometries can be generated

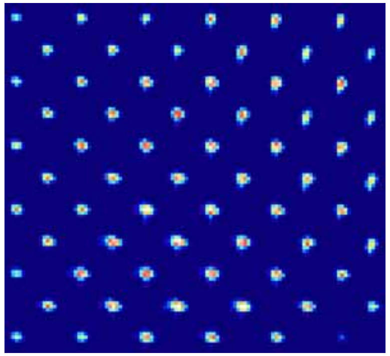


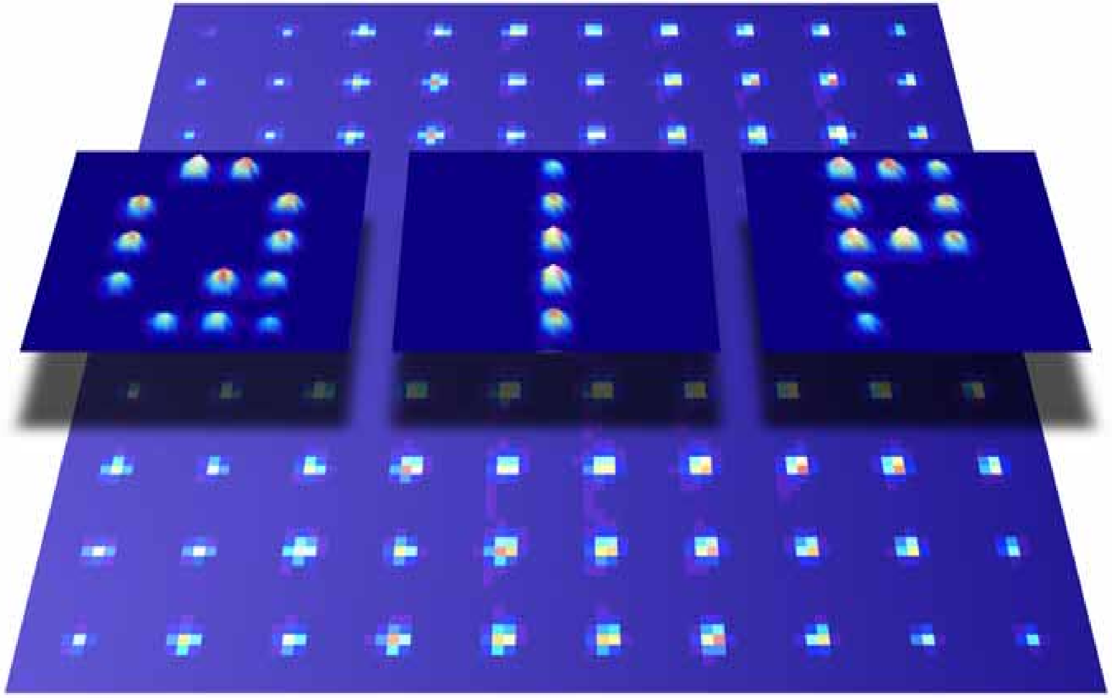
Novel approaches to A T O M T R O N I C devices in optical potentials

Part 2:

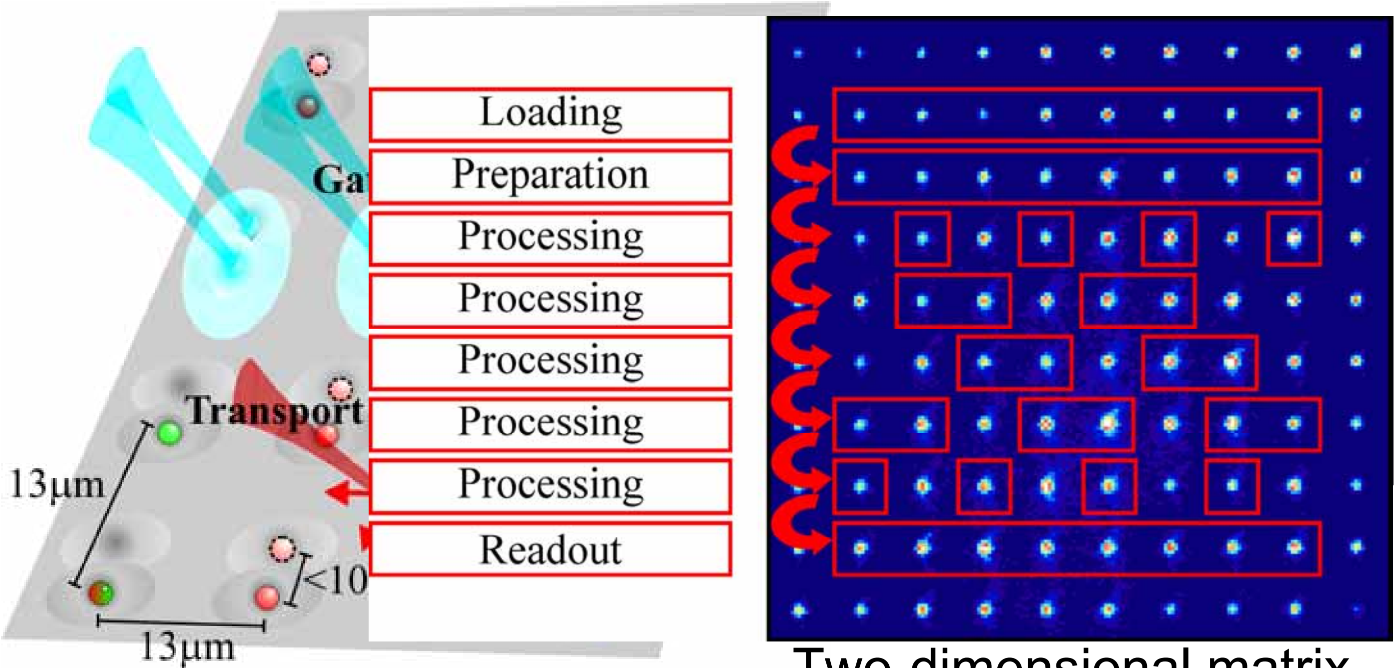
Quantum information processing and simulation with arrays of trapped neutral atoms







Architecture for Single-Atom-Array ATOMTRONICS

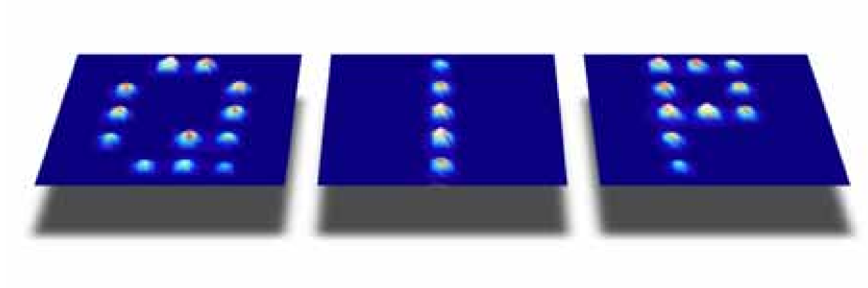


Two-dimensional matrix of atomic qubits

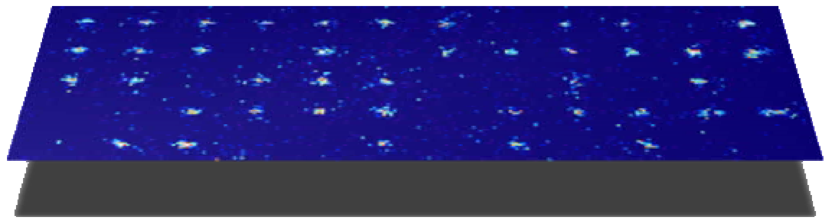
Complex processor architecture based on 2D quantum shift register with single-site addressability

Outline

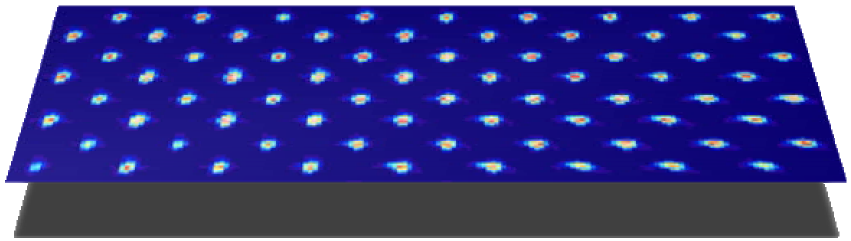
Neutral atoms in dipole trap arrays as a scalable system for QIP



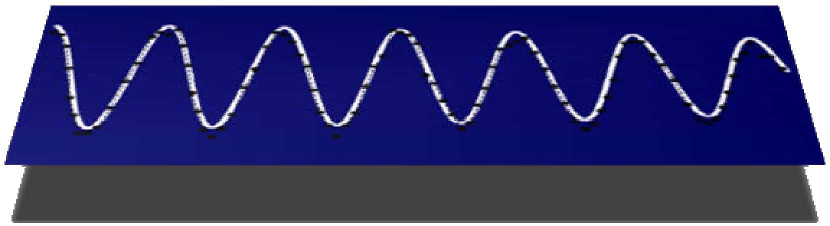
Two-dimensional arrays of single atoms



Interleaved trap arrays with adjustable separation

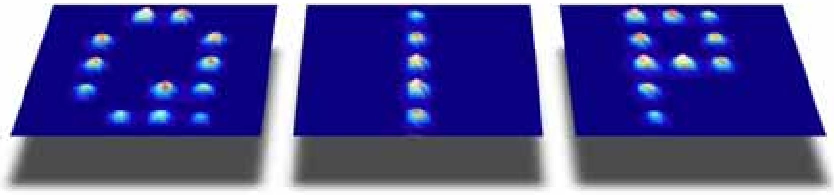


Coherent manipulation of single atoms

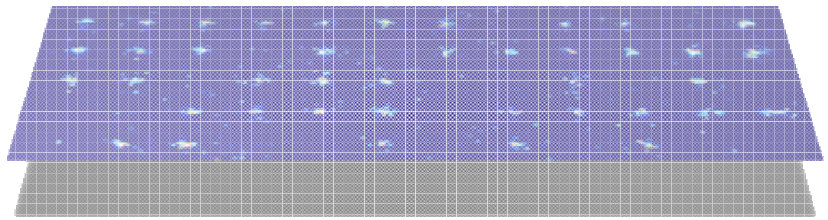


Outline

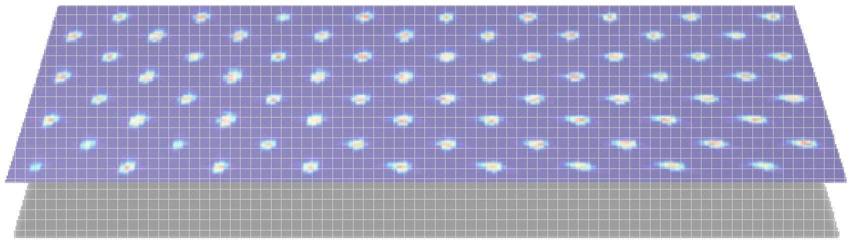
Neutral atoms in dipole trap arrays as a scalable system for QIP



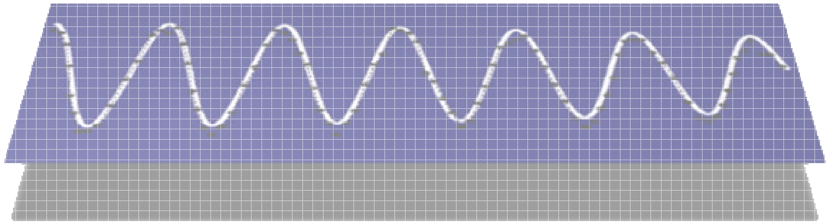
Two-dimensional arrays of single atoms



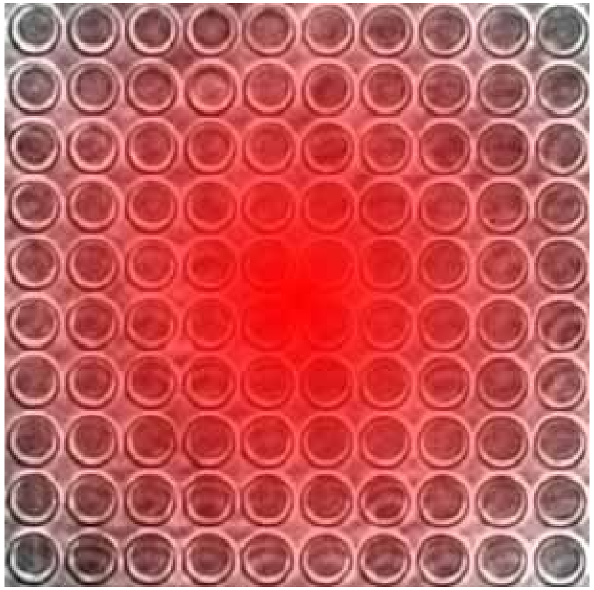
Interleaved trap arrays with adjustable separation



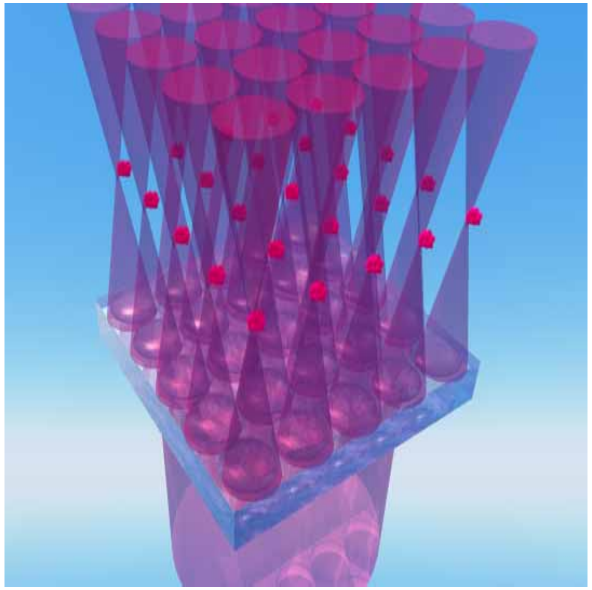
Coherent manipulation of single atoms



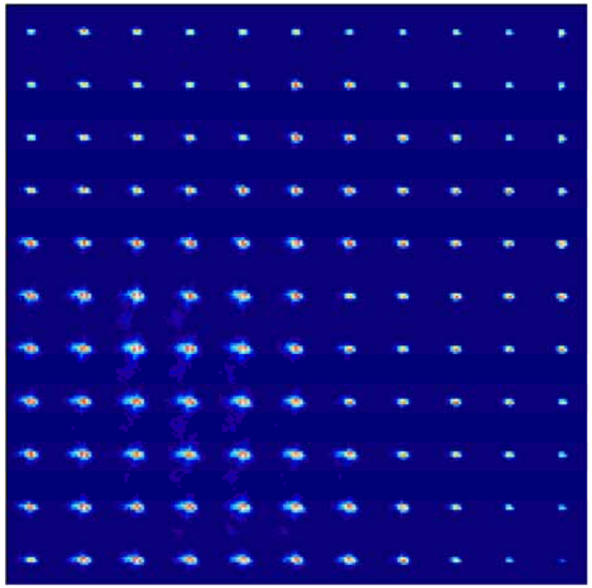
2D Register of Neutral-Atom Qubits



Microlens array



Dipole trap array



Fluorescence Image of trapped ^{85}Rb atoms

Typical Parameters

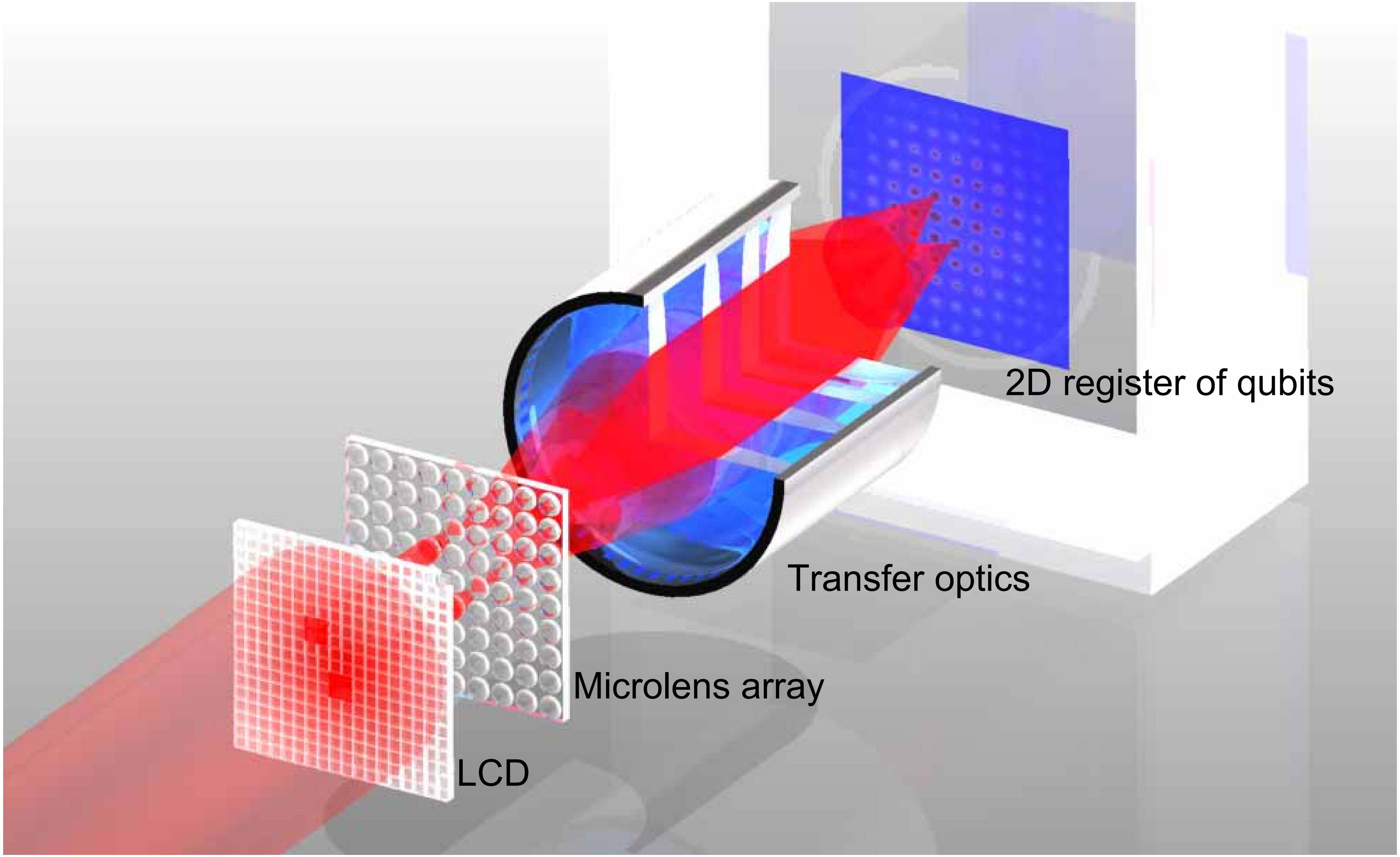
- Trapping wavelength: 796 - 810 nm
- Trap depth: up to $k_B \cdot 10$ mK
- Trap waist: down to 1.3 µm
- Trap separation: down to 3 µm
- Number of Atoms: 1 per site

R. Dumke et al., Phys. Rev. Lett. ***89****, 097309 (2002)*

M. Schlosser et al., Quant. Inf. Proc. ***10****, 907 (2011)*

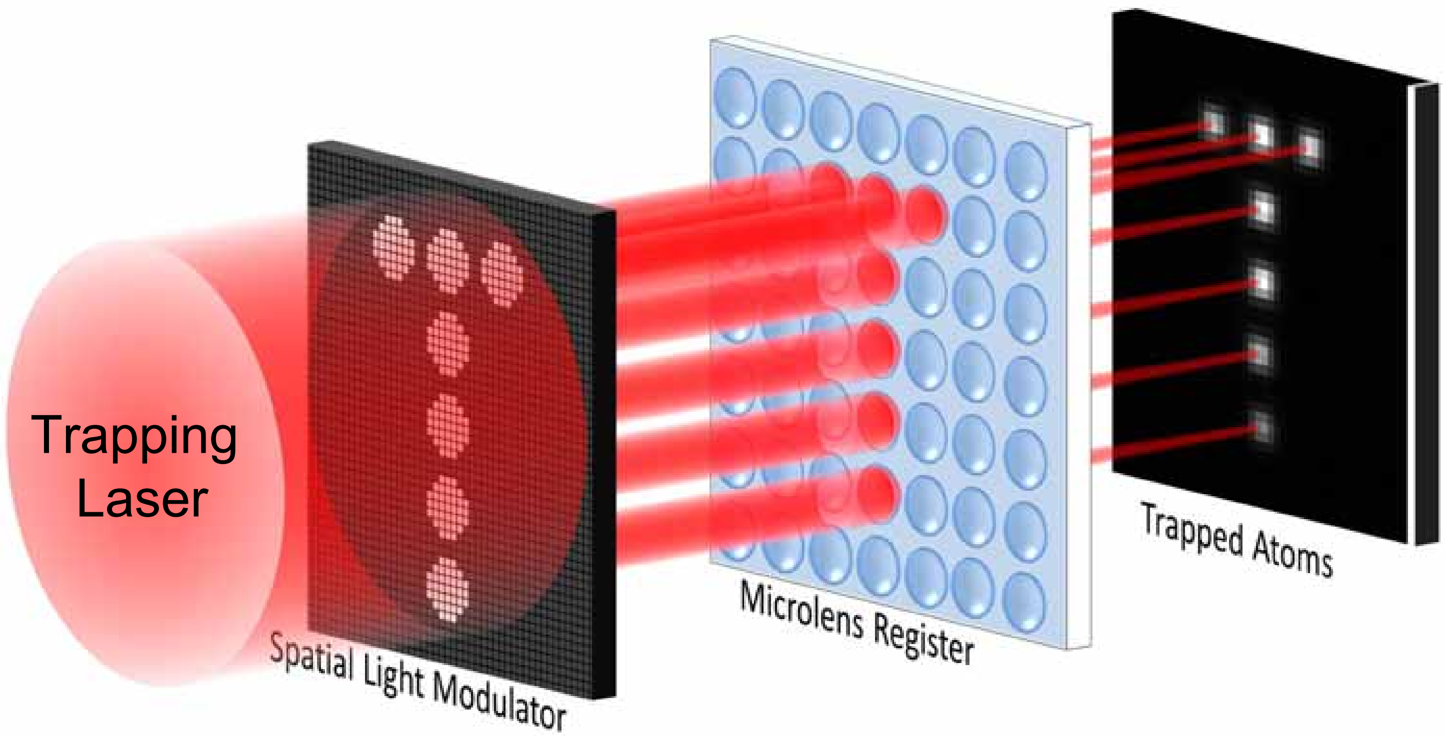
M. Schlosser et al., New J. Phys. ***14****, 123034 (2012)*

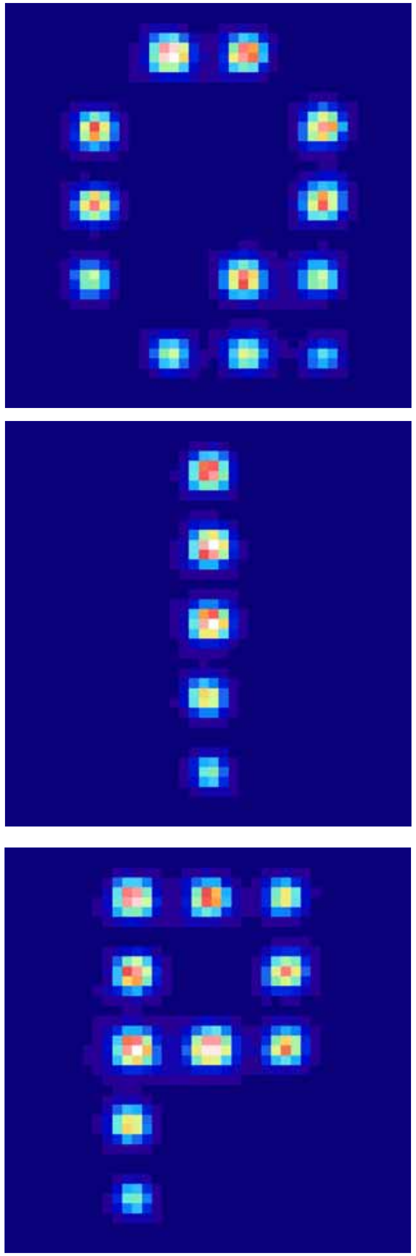
Reconfigurable Addressing of Selected Traps



Reconfigurable Addressing of Selected Traps

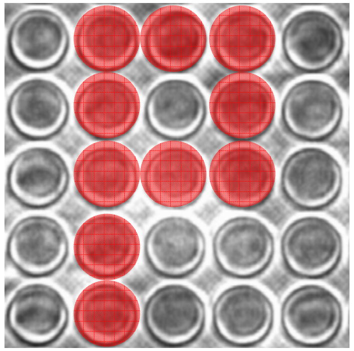
Adressing single microlenses → **Adressing single sites**

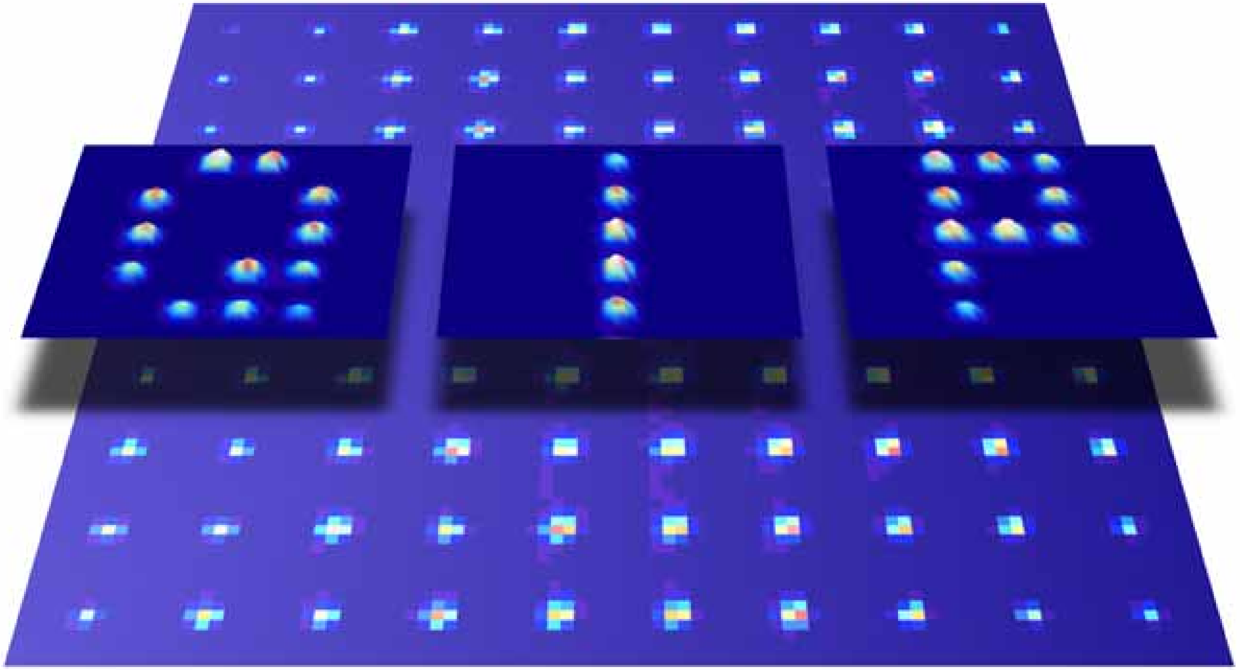




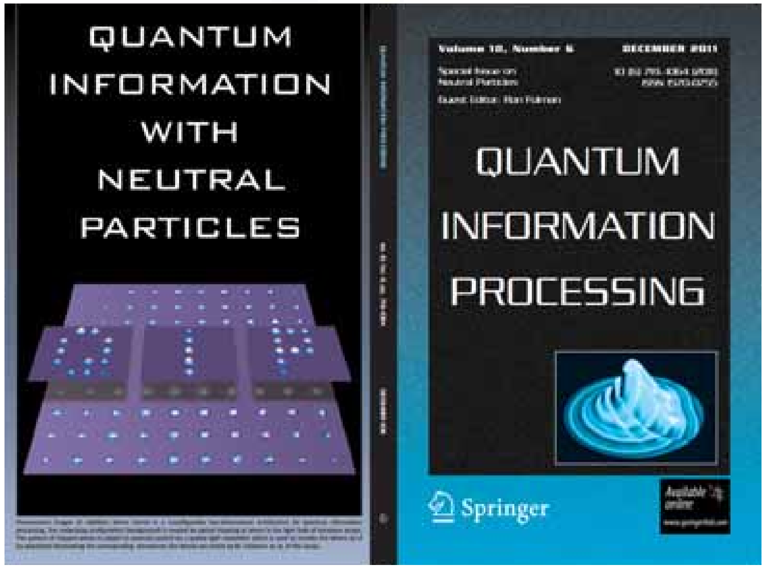
Combined system of microlenses
and spatial light modulator

Reconfigurable Addressing of Selected Traps



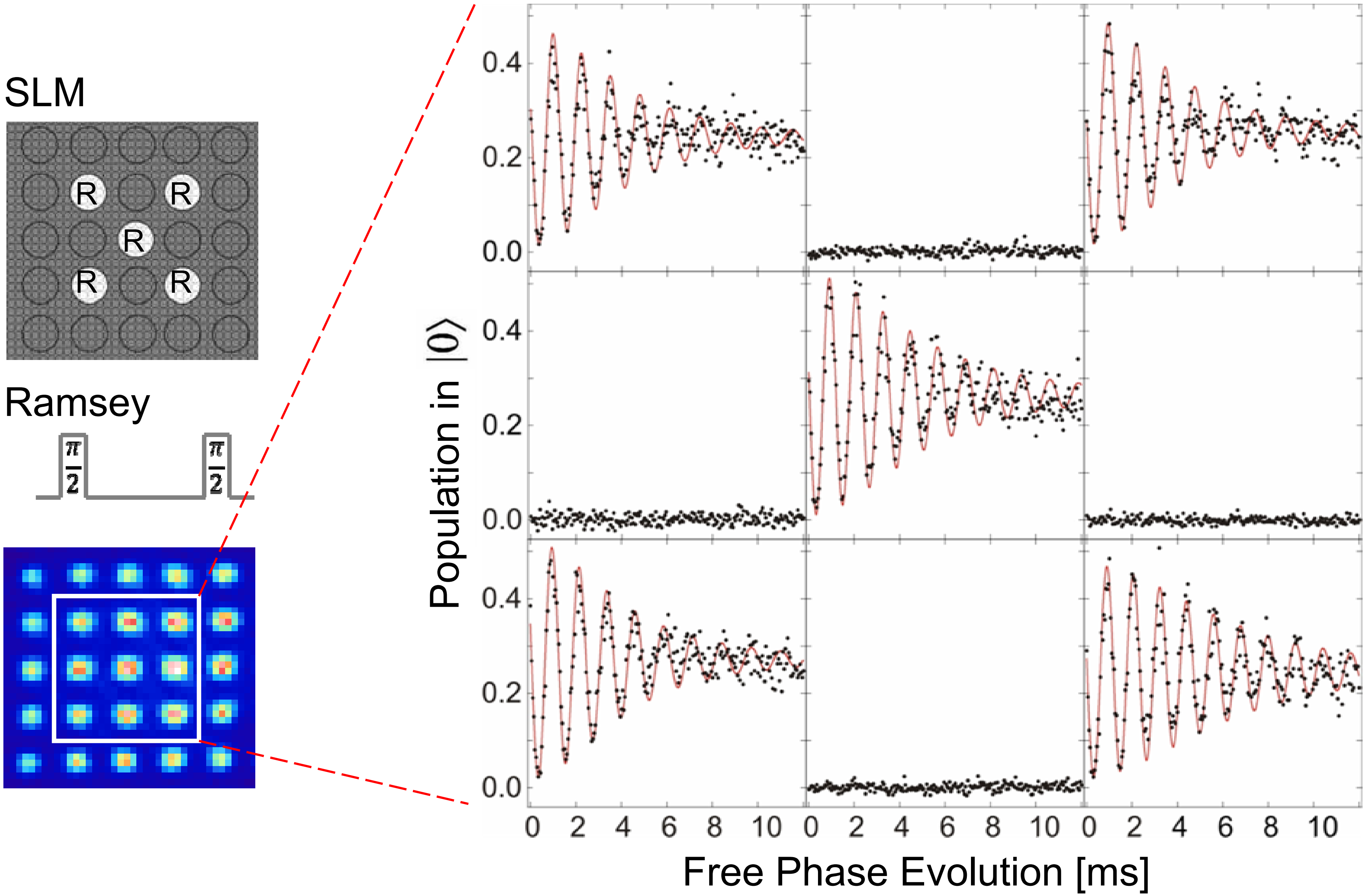


- Global illumination of microlens register:
  2D periodic trap array
- Reconfigurable addressing of selected lenses:
  Versatile geometries



M. Schlosser et al., Quant. Inf. Proc. ***10****, 907 (2011)*

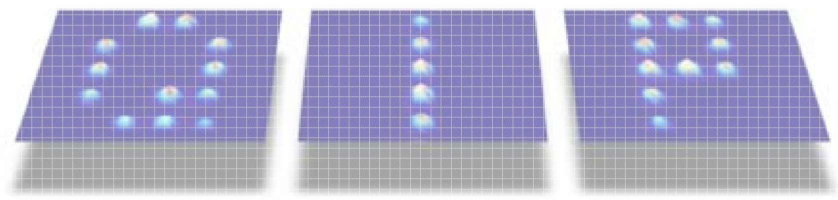
Coherent Qubit Manipulation in Selected Traps



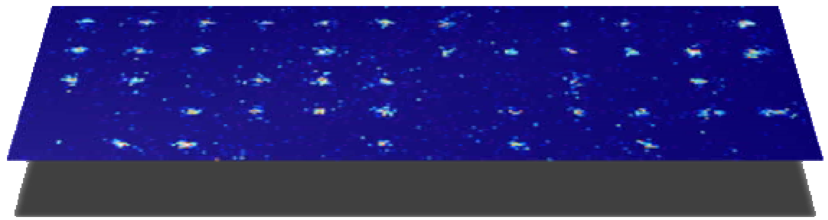
*J. Kruse et. al., Phys. Rev. A **81**, 060308 (2010)*

Outline

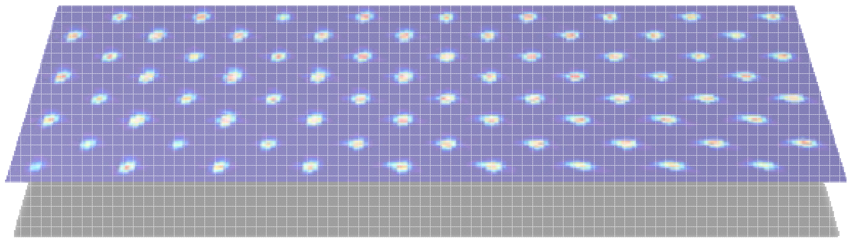
Neutral atoms in dipole trap arrays as a scalable system for QIP



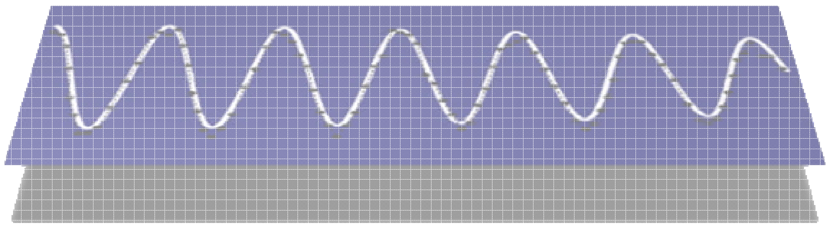
Two-dimensional arrays of single atoms



Interleaved trap arrays with adjustable separation

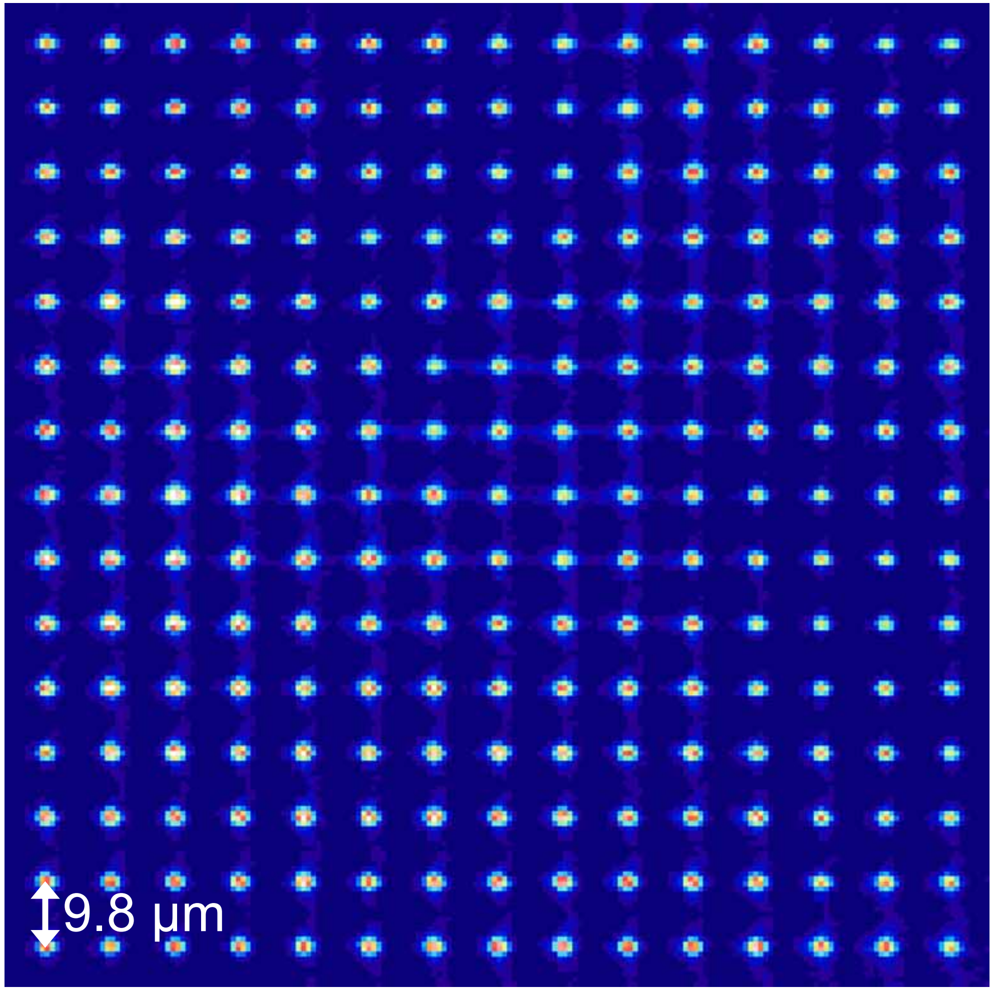


Coherent manipulation of single atoms

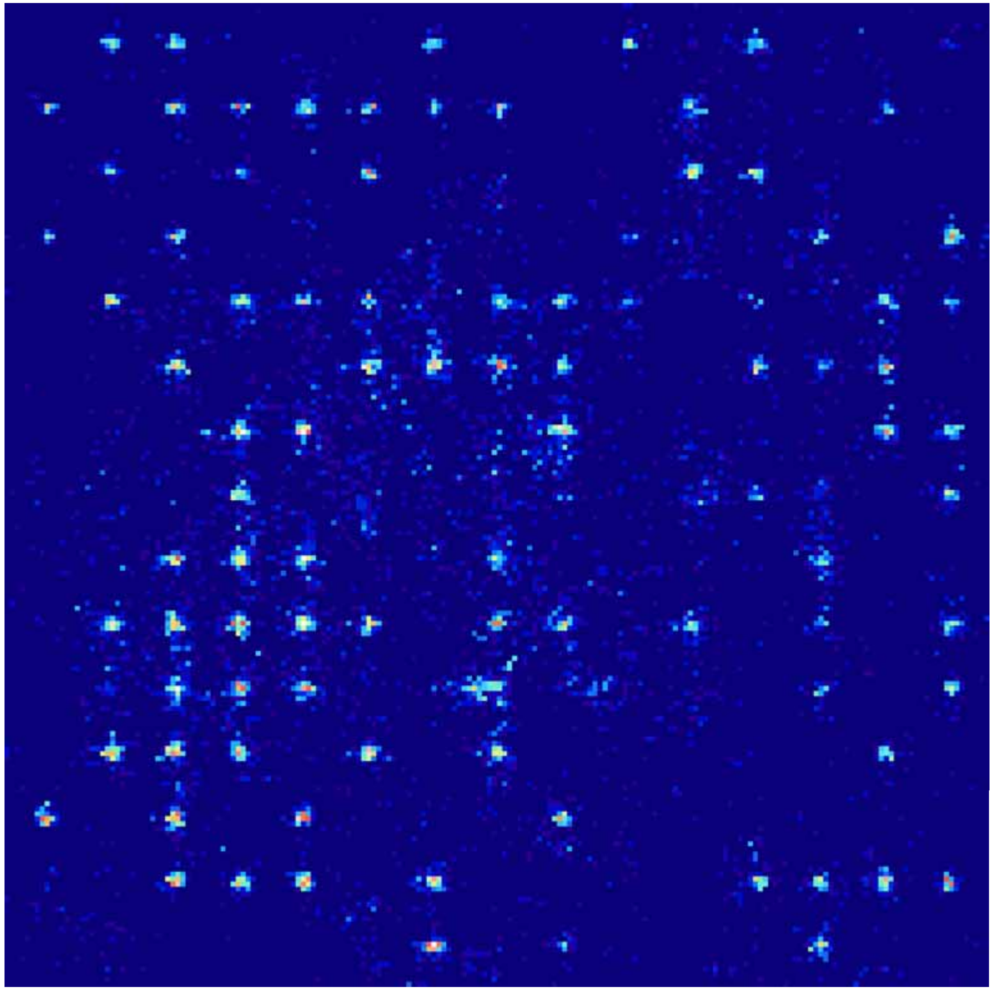


380 Site Single-Atom Array

15x15 site detail (averaged)

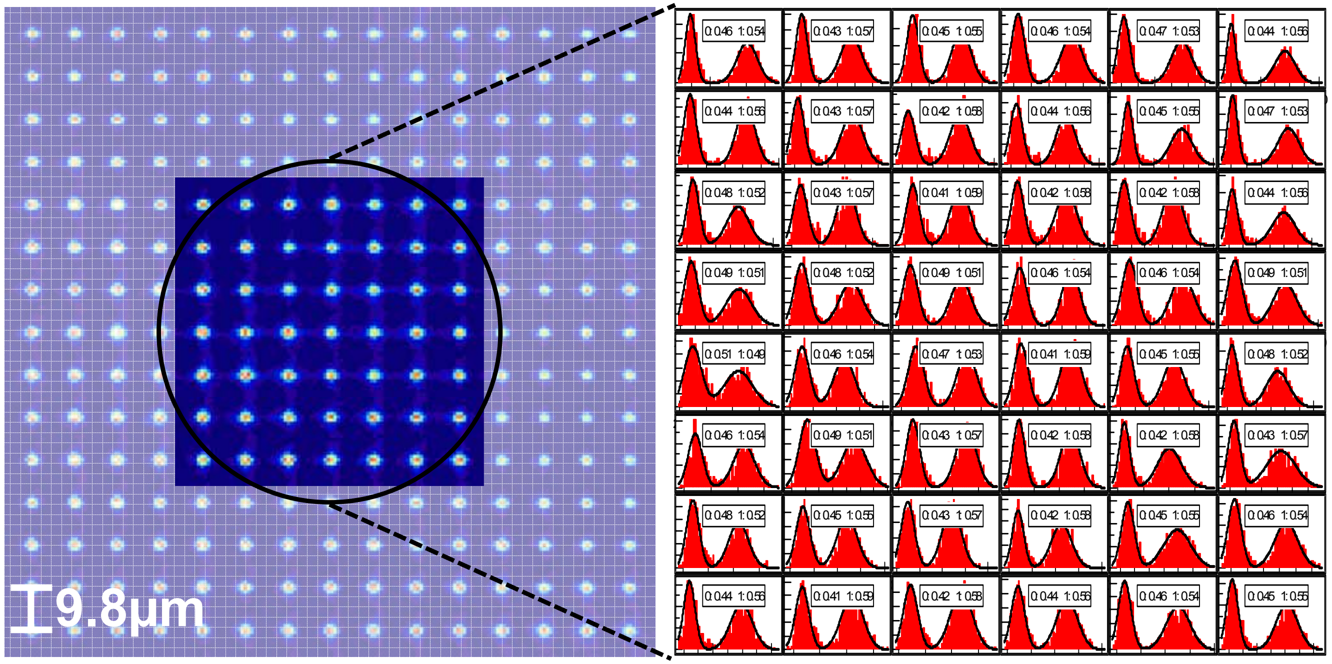


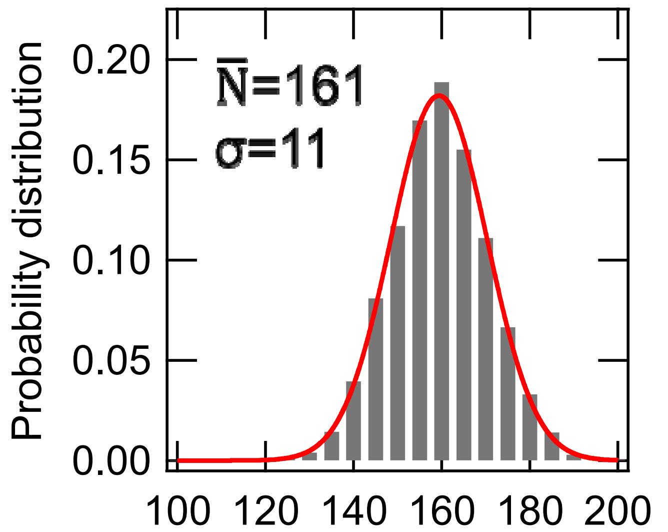
Single shot images



380 Site Single-Atom Array → More Than 100 Qubits

15x15 site detail (averaged) **Atom number statistics** (individual site resolution in 380 traps)

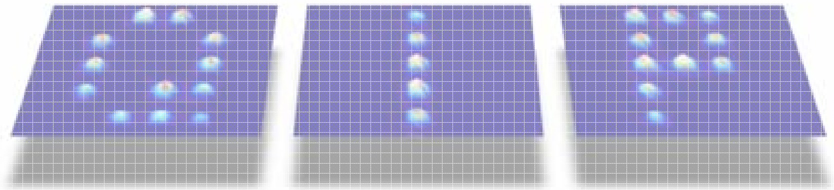




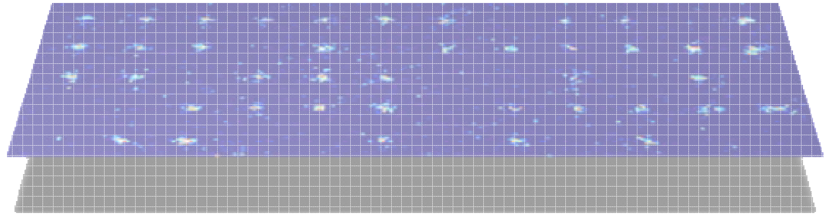
More than 380 traps with ≥ 37% single atom events → **About 160 single-atom qubits in each realization**

Outline

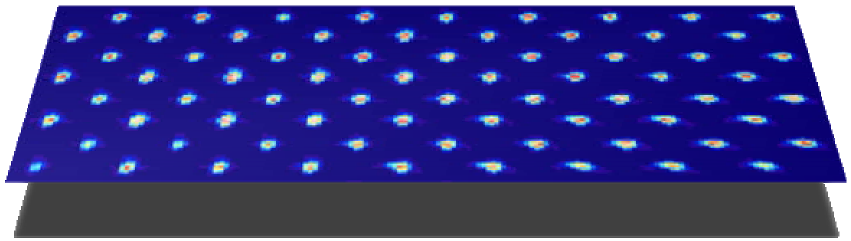
Neutral atoms in dipole trap arrays as a scalable system for QIP



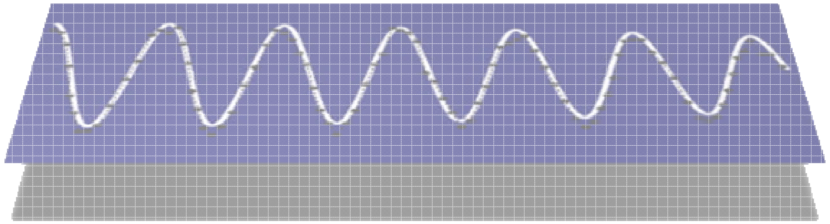
Two-dimensional arrays of single atoms



Interleaved trap arrays with adjustable separation



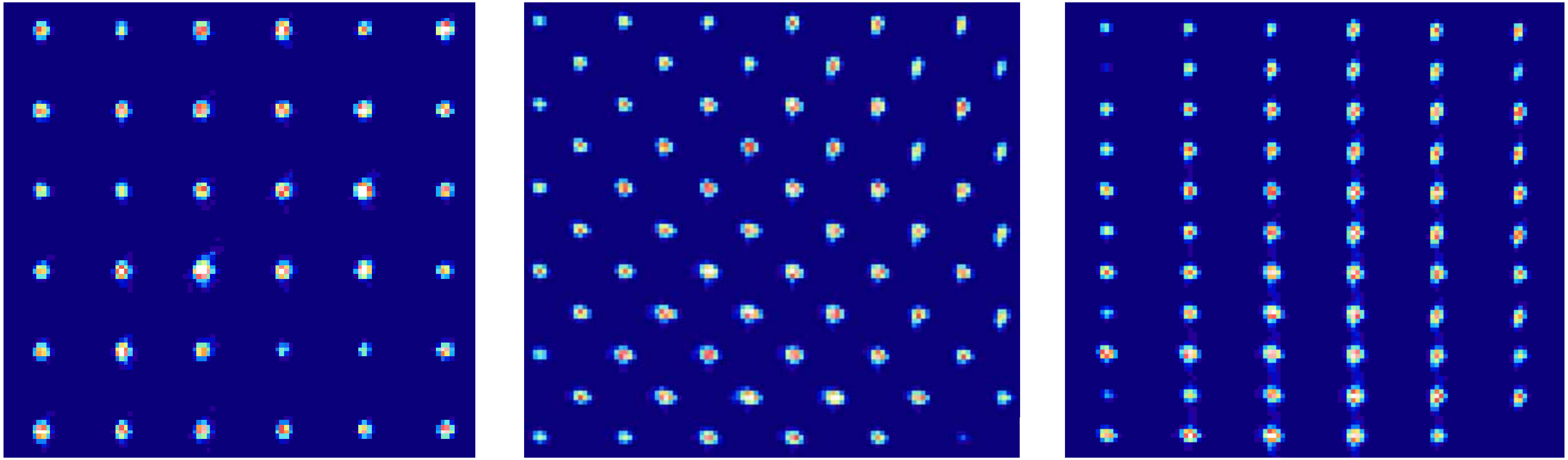
Coherent manipulation of single atoms



Interleaved Trap Arrays

Superimposing two dipole trap registers → Adjustable trap separation

Averaged images

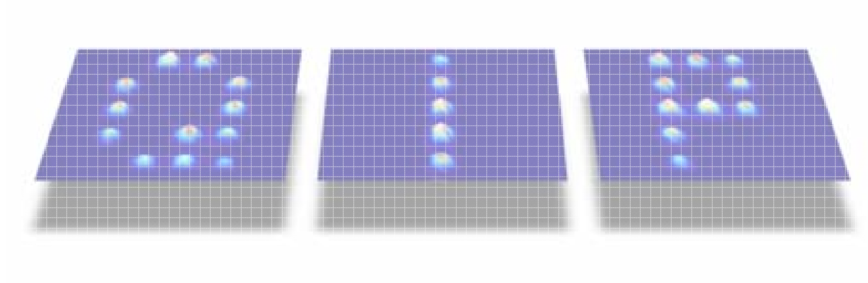


13 µm | 9.2 µm | 6.5 µm

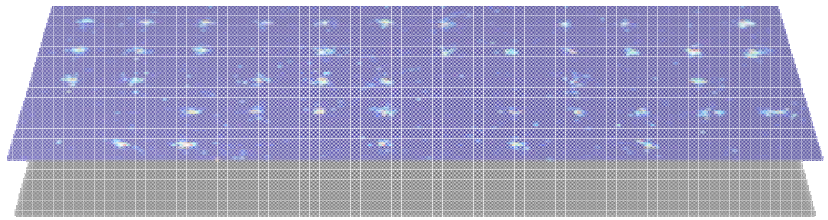
More than 50 traps
≥ 50% single atom events
→ About 25 single-atom qubits in each realization

Outline

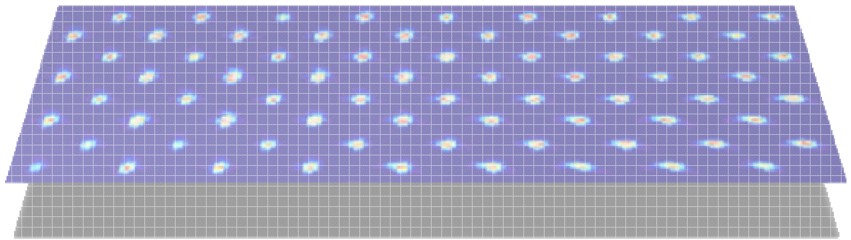
Neutral atoms in dipole trap arrays as a scalable system for QIP



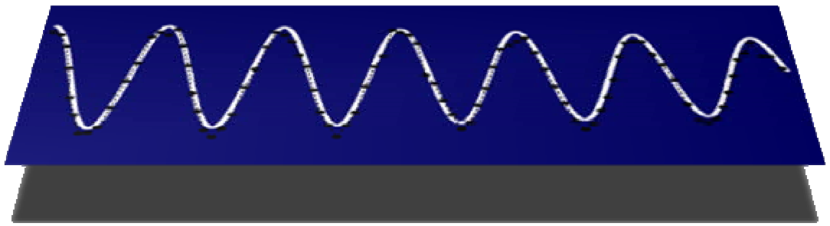
Two-dimensional arrays of single atoms



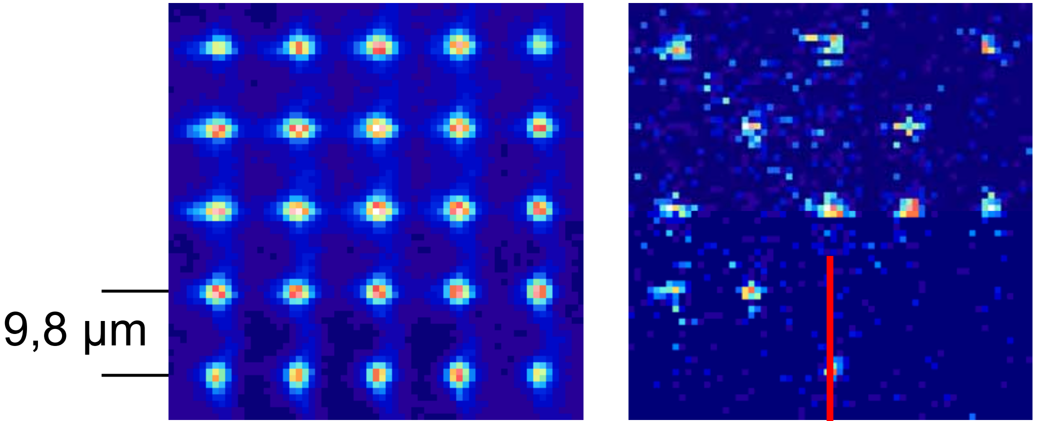
Interleaved trap arrays with adjustable separation



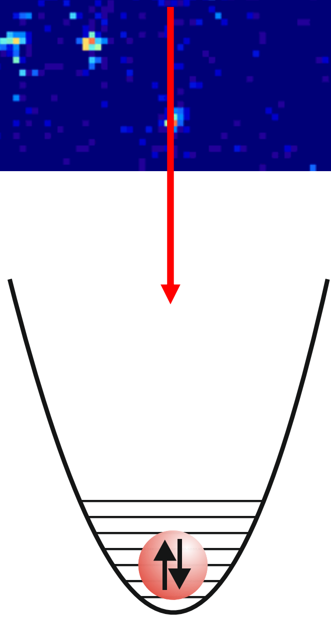
Coherent manipulation of single atoms



Qubit Basis

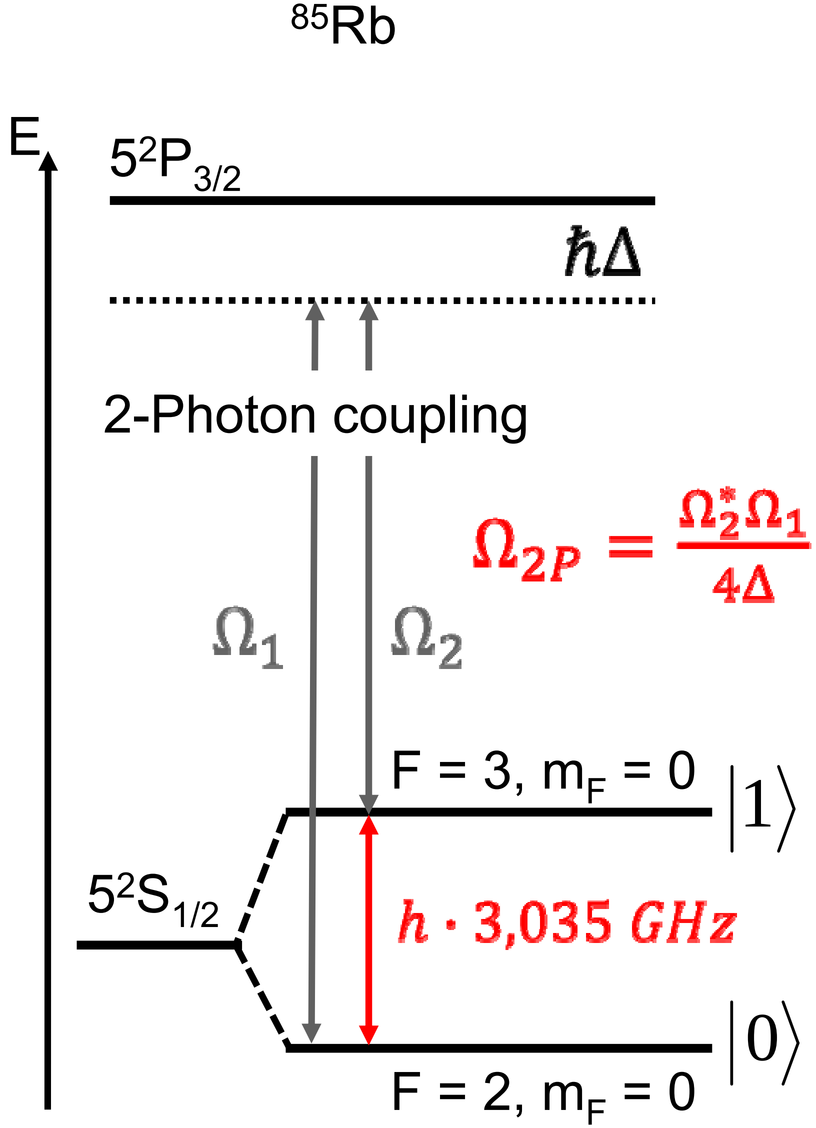


λ = 805,1 nm
$U_0 = k_B \cdot 0{,}25$ mK
w_0 = 1,5 µm

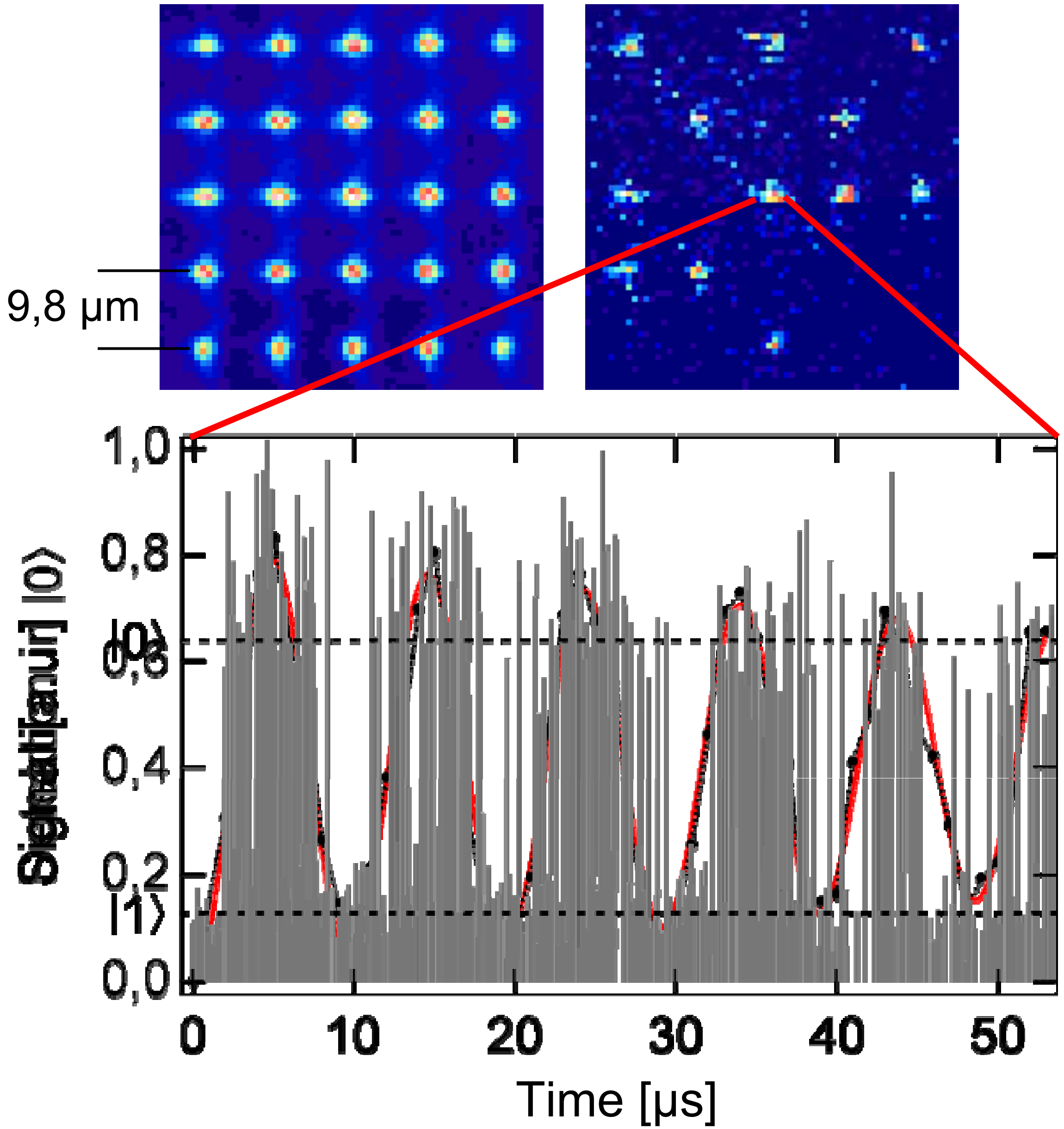


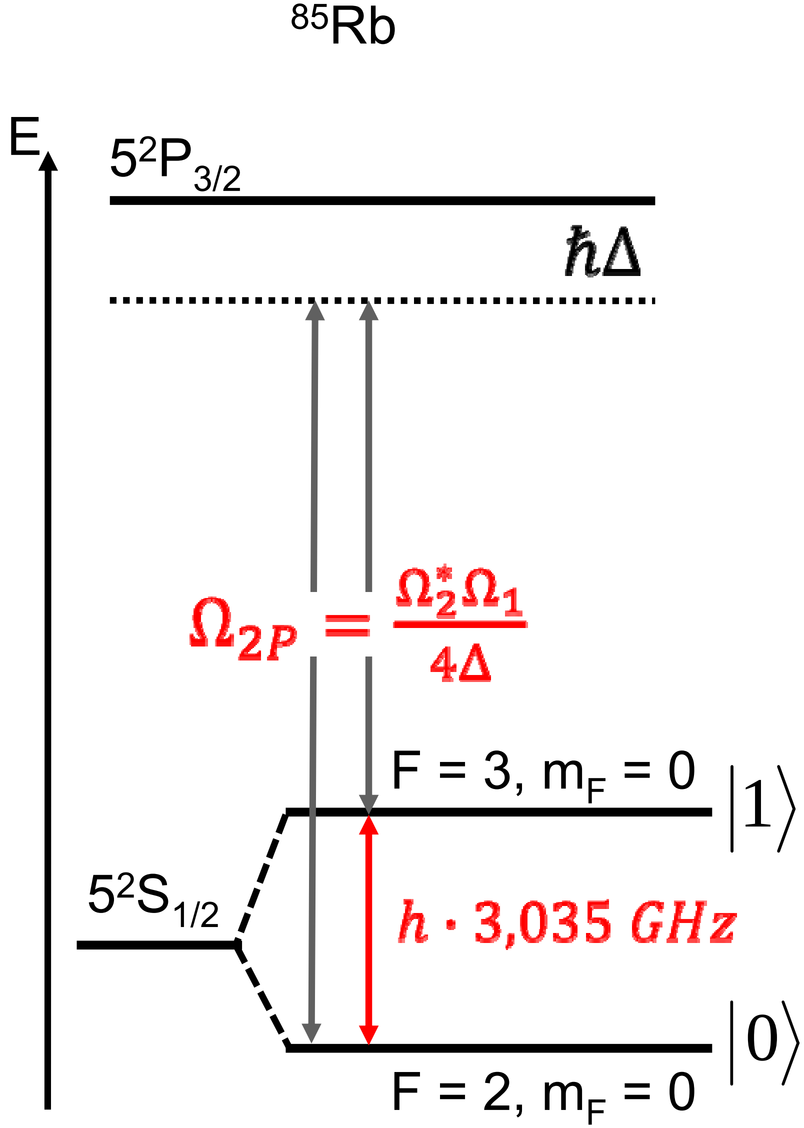
$$|\psi\rangle = a|0\rangle + b|1\rangle$$

$$|a|^2 + |b|^2 = 1$$



Fast Qubit Rotation



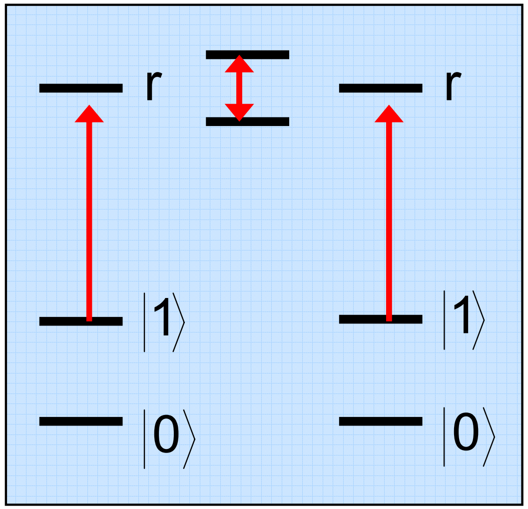


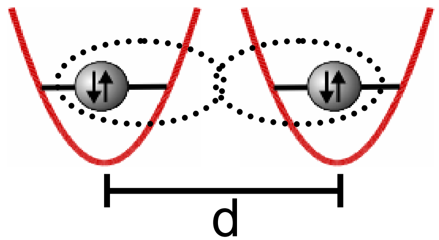
Work in Progress: 2-Qubit Gates and Entanglement

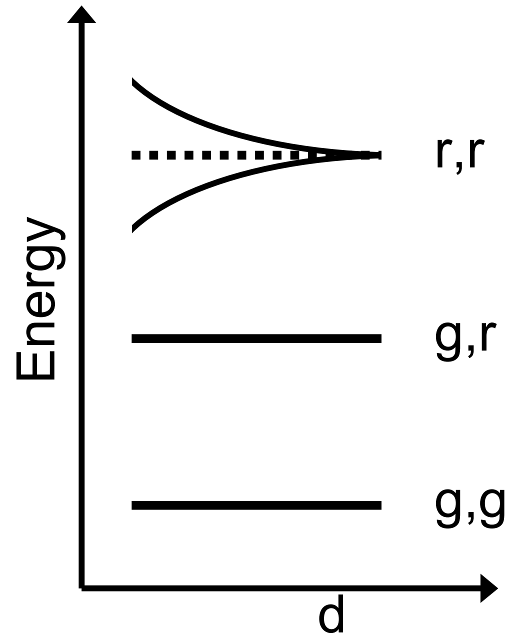
2-Qubit Gates using Rydberg Blockade

Requirement: Trap separation d < 10μm

Interaction of atoms in separated sites → 2-Qubit Gate



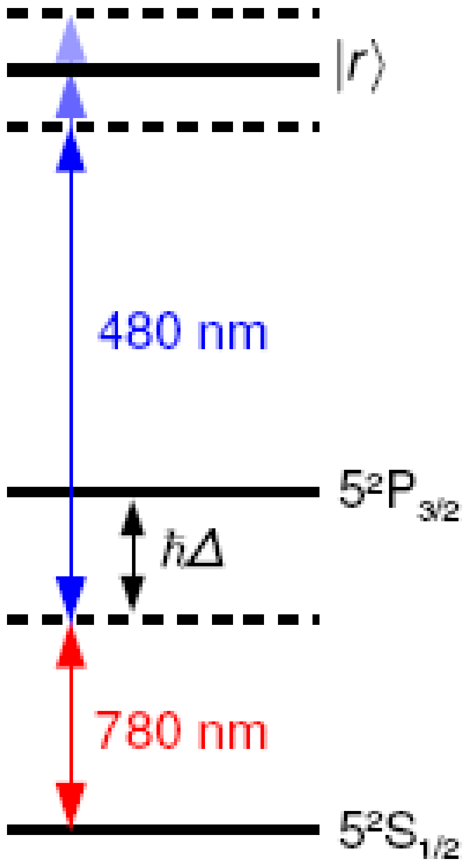


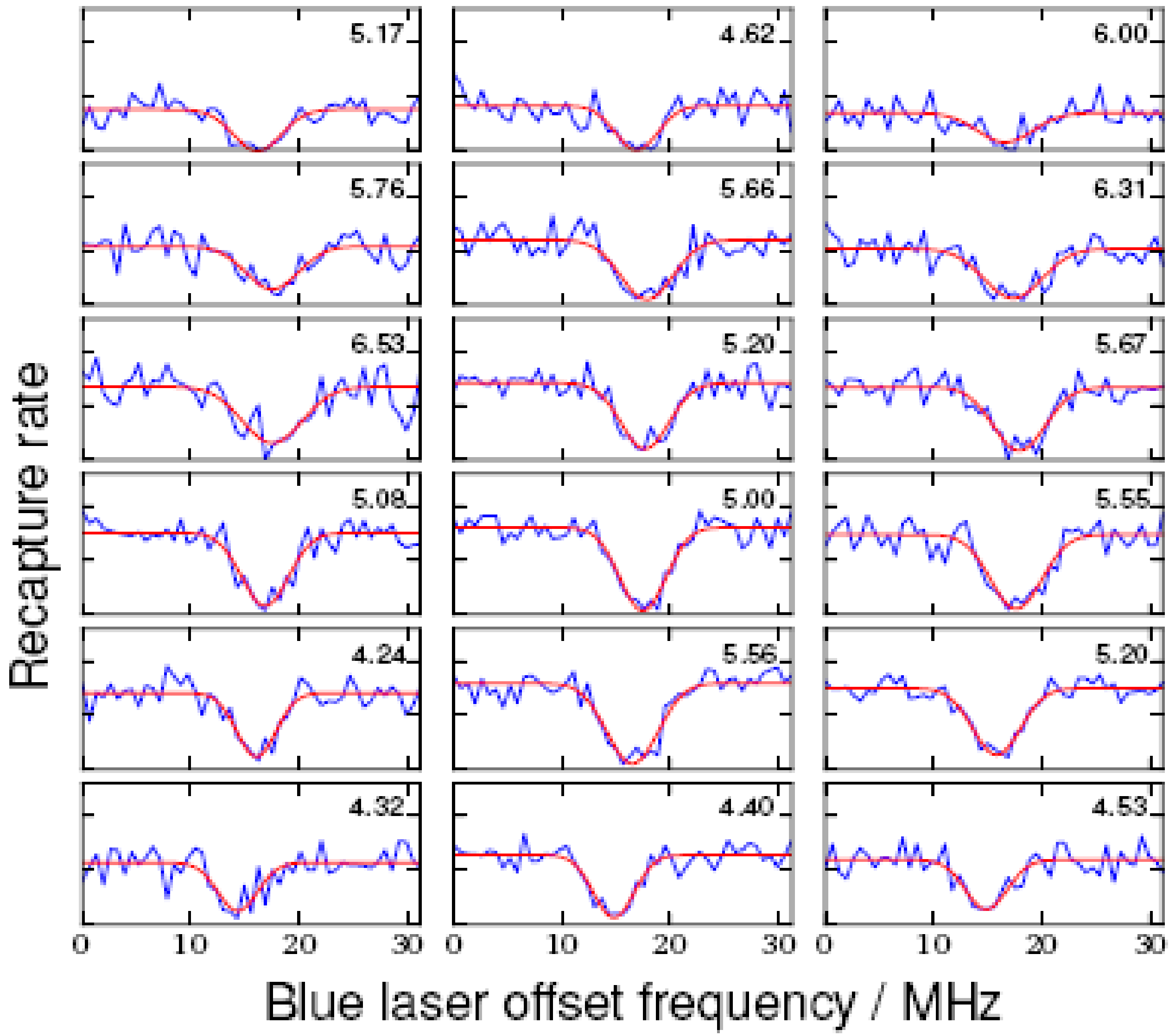


D. Jaksch *et al.,* Phys. Rev. Lett. **85**, 2208 (2000)
T. Wilk *et al.,* Phys. Rev. Lett. **104**, 010502 (2010)
L. Isenhower *et al.,* Phys. Rev. Lett. **104**, 010503 (2010)

Rydberg Excitation in Arrays of Single Atoms

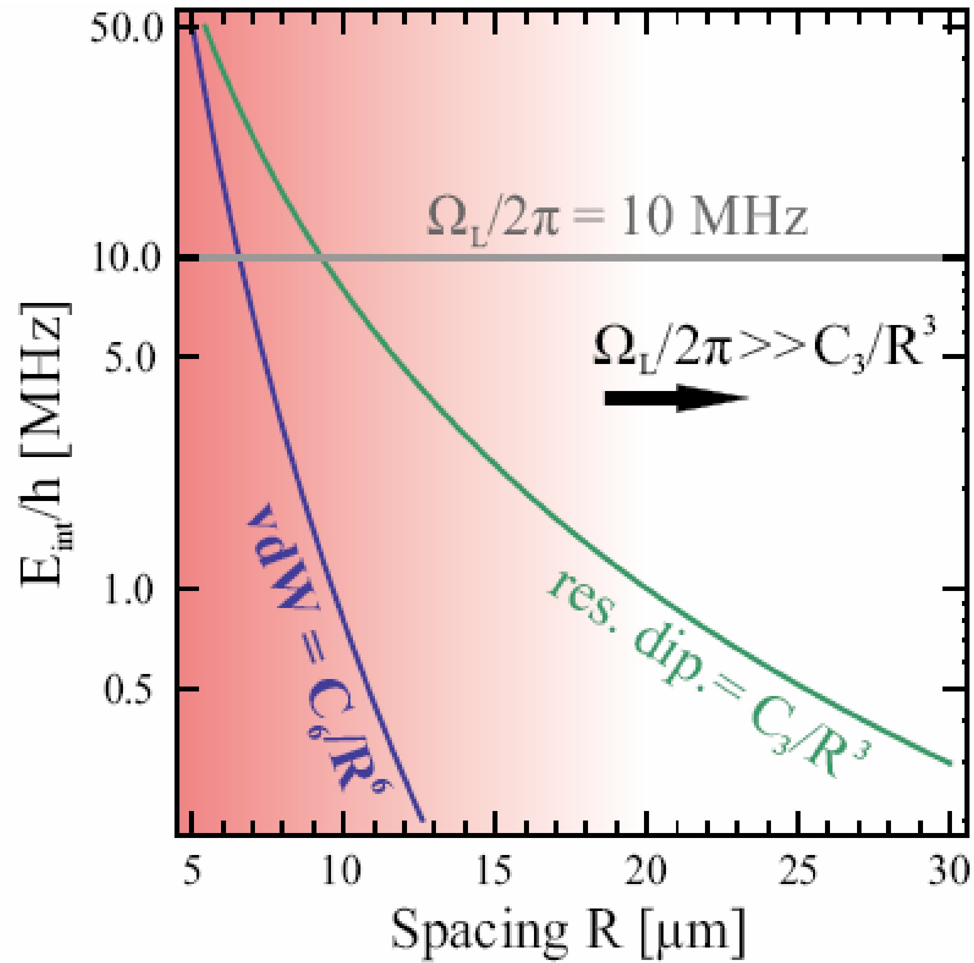
Coupling to Rydberg state $|r\rangle$
via two-photon transition

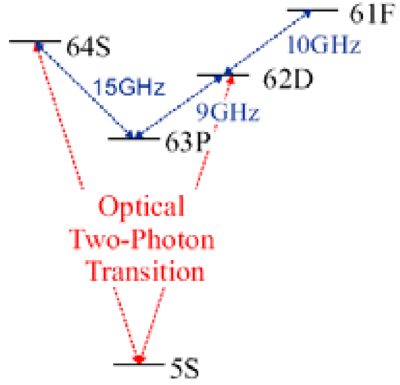


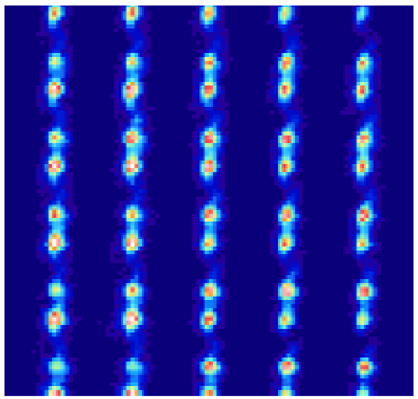


Many-Body Rydberg Physics with Interaction Control

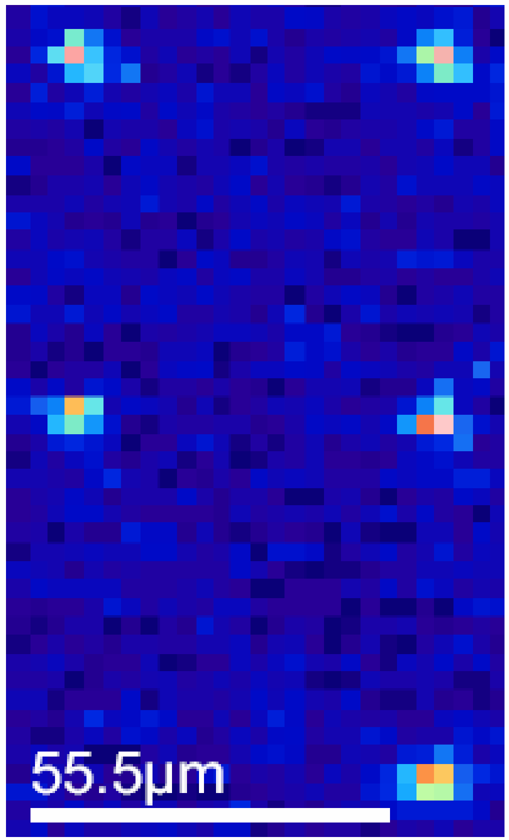
Investigation of Excitation Transport and XY Spin Exchange Hamiltonians in Rydberg Arrays with Controlled Interactions: Resonant dipolar or van der Waals Couplings with MHz Strengths



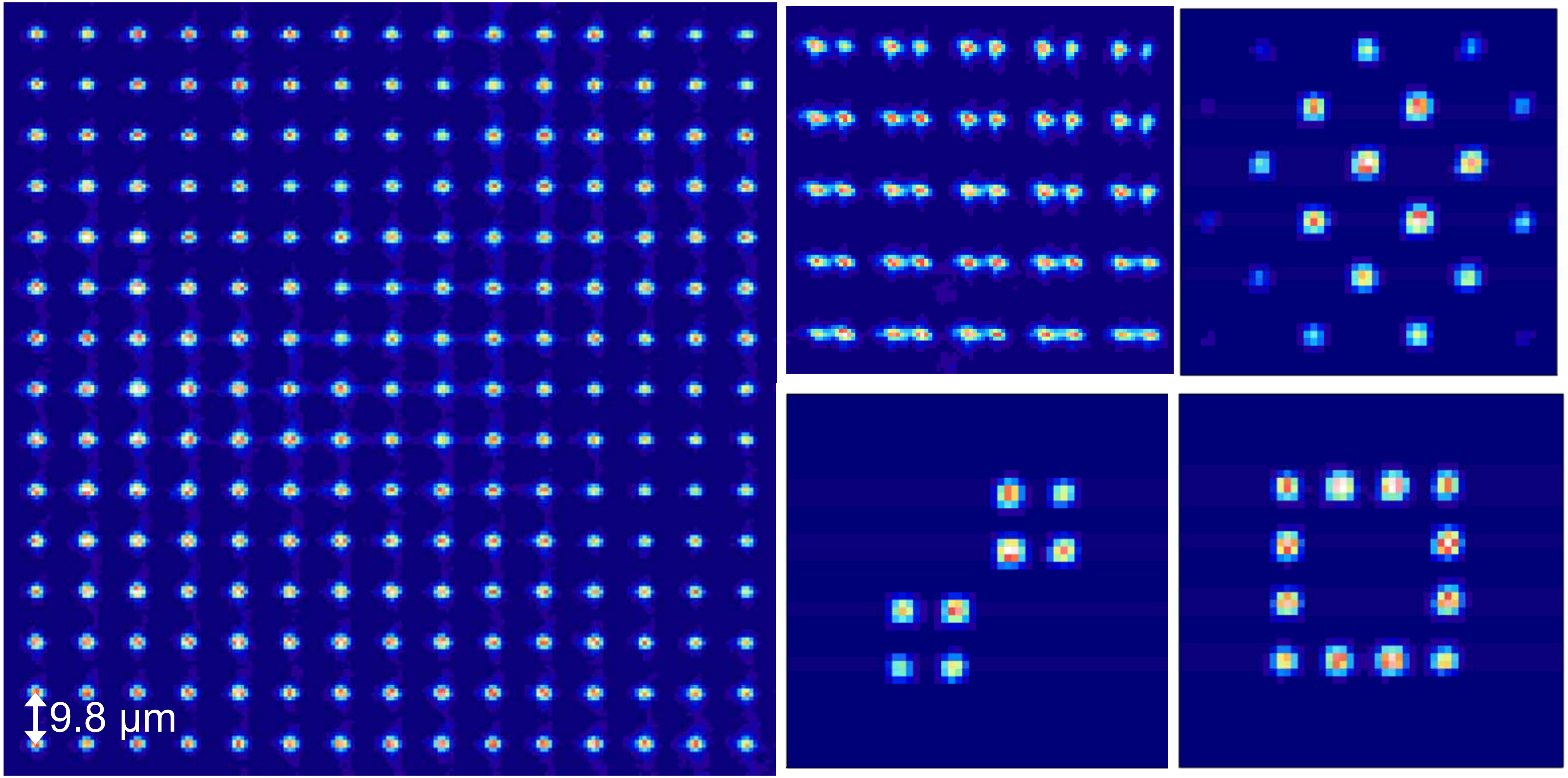




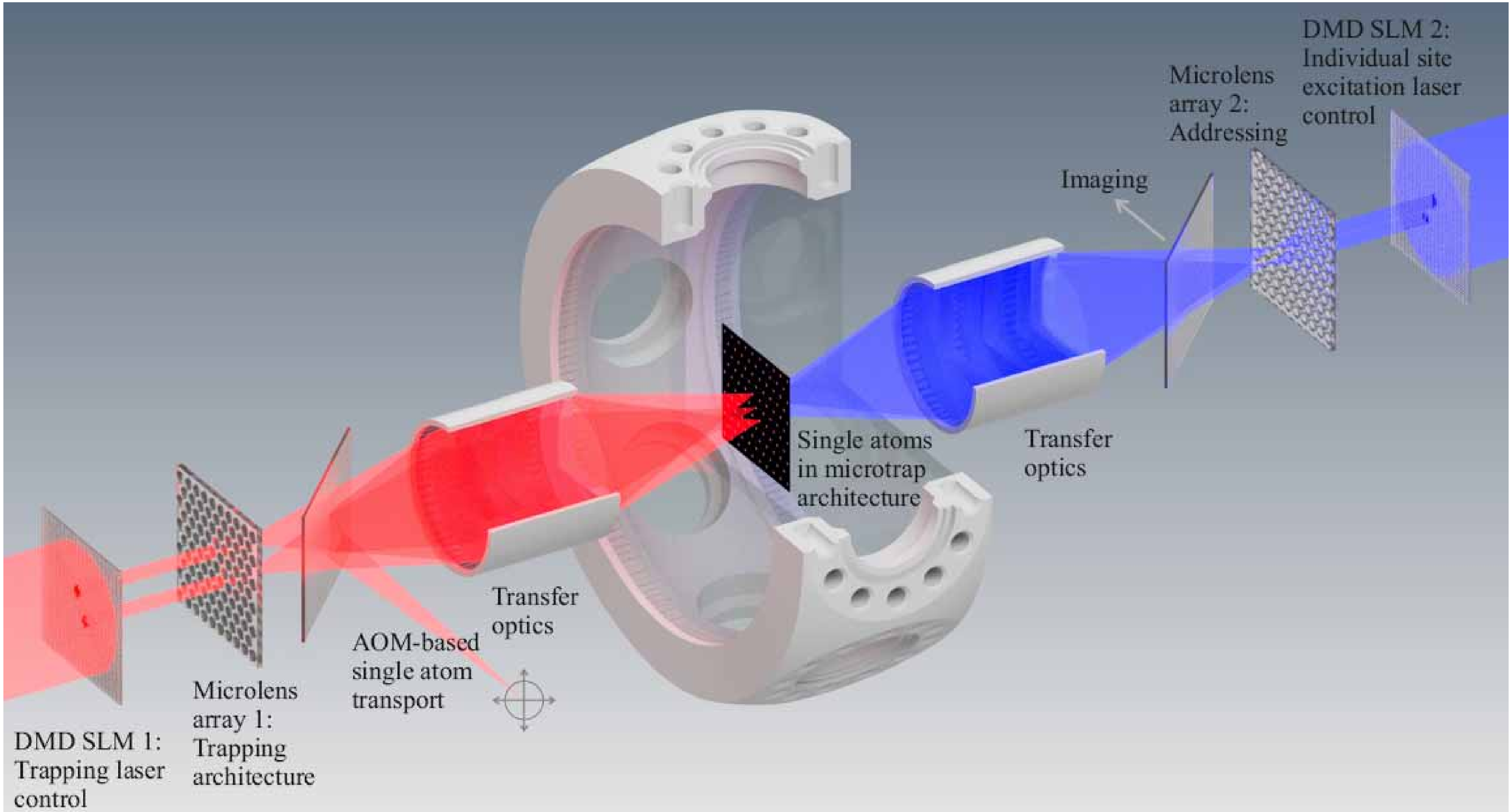
Separation: 4.8 µm



Large-Scale Array of Individually Controlled Rydberg Atoms in Versatile Geometries for Quantum Simulation and Many Body Physics

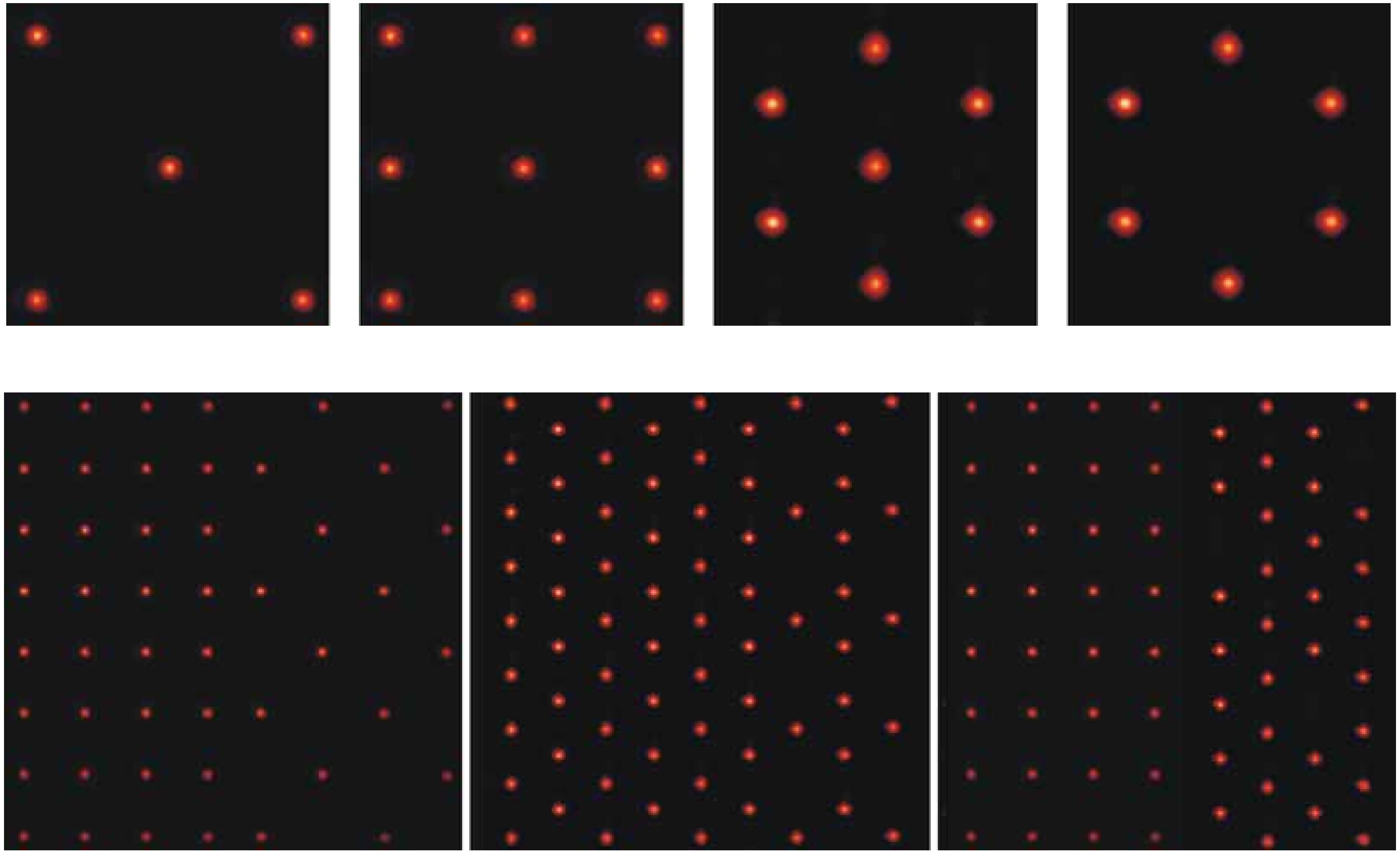


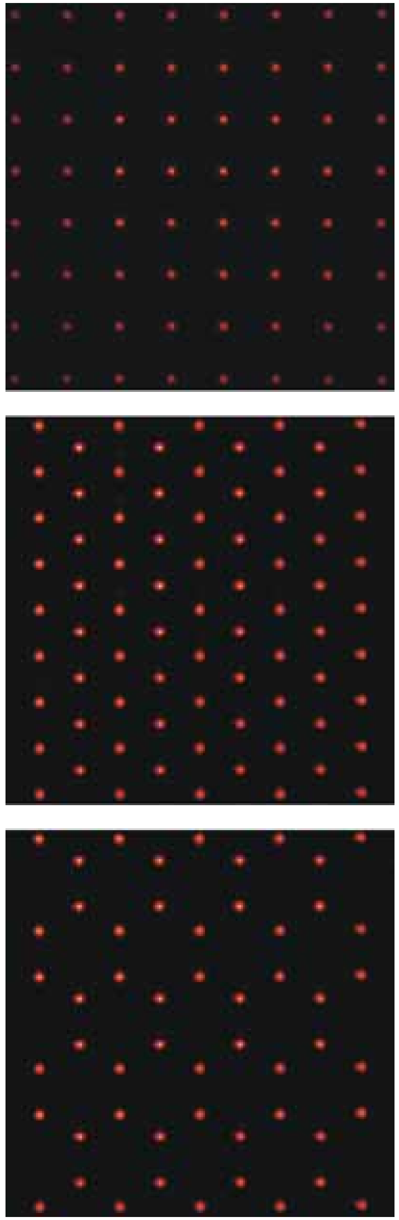
Single-Atom Array Setup with Local Control



Rydberg Many Body Physics in Single-Atom Arrays

Large-Scale Array of Individually Controlled Rydberg Atoms in Versatile Geometries for Quantum Simulation and Many-Body Physics



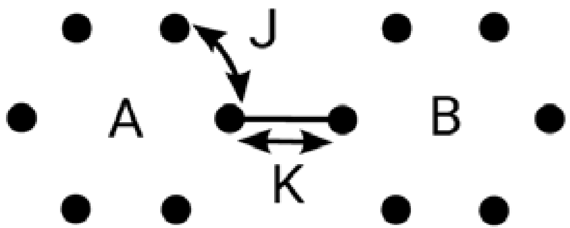


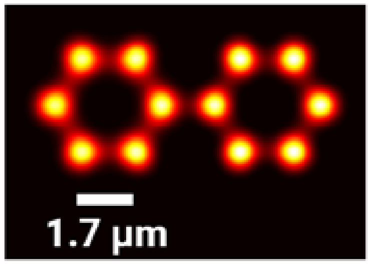
Tunneling-Coupled Many Body Physics in Atom Arrays

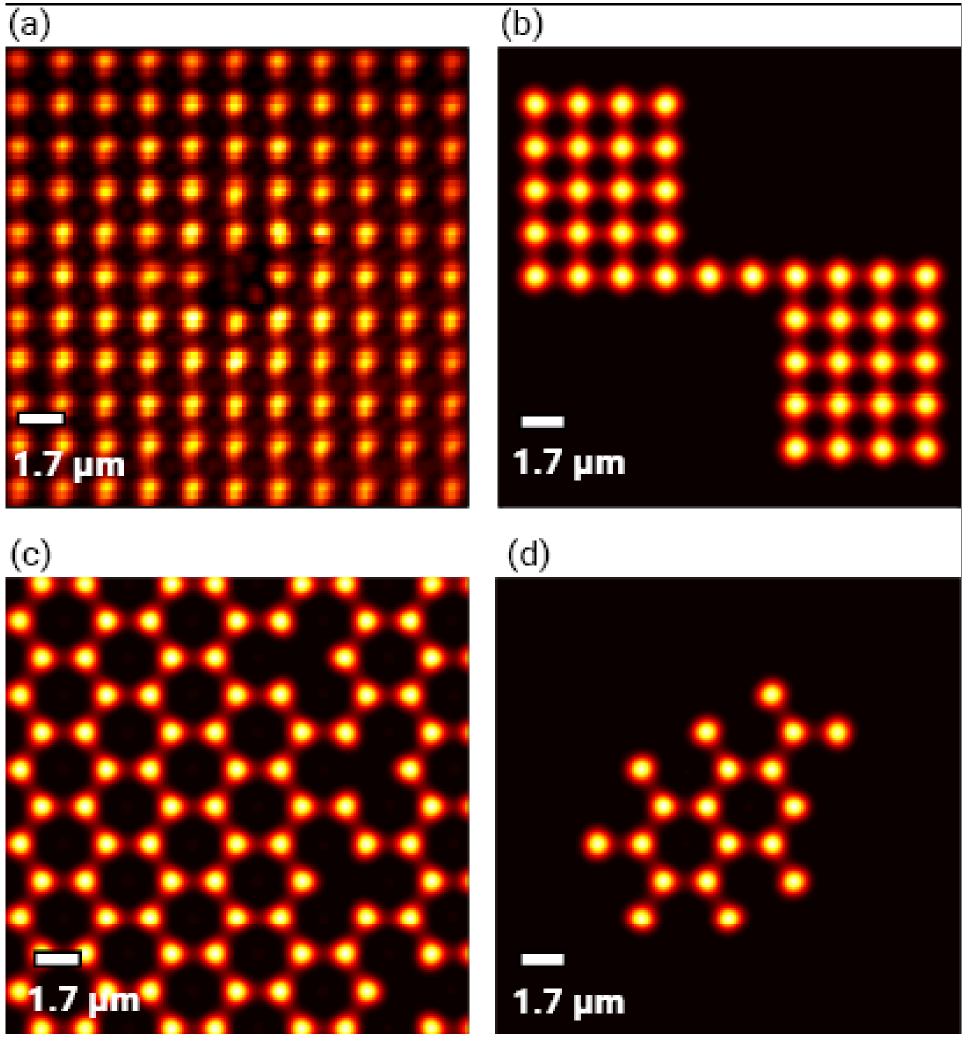
Quantum simulators by design: many-body physics in reconfigura-ble arrays of tunnel-coupled traps

See:

Talk by Reinhold Walser
and
Poster by Martin Sturm







M. Sturm, M. Schlosser, R. Walser, G. Birkl,
'Quantum simulators by design – many- body physics in reconfigurable arrays of tunnel-coupled traps',
arXiv: 1705.01271

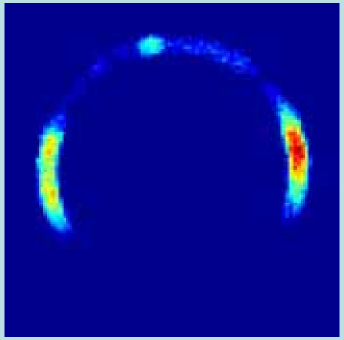
ATOMTRONICS based Quantum Technology

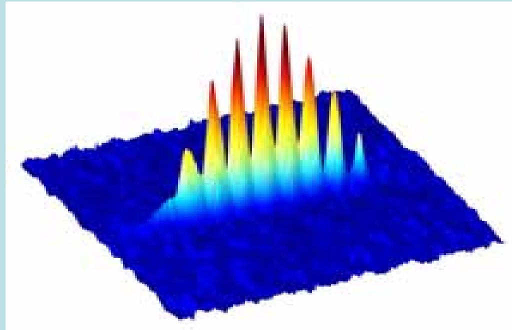
Atoms as Research Objects

Quantum Optical Methods for the Control of Atoms

Quantum Physics as Research Objective

BEC in Optical Potential





Quantum Information