Title: Quantum simulation and computing with Rydberg atoms

Speakers: Johannes Zeiher

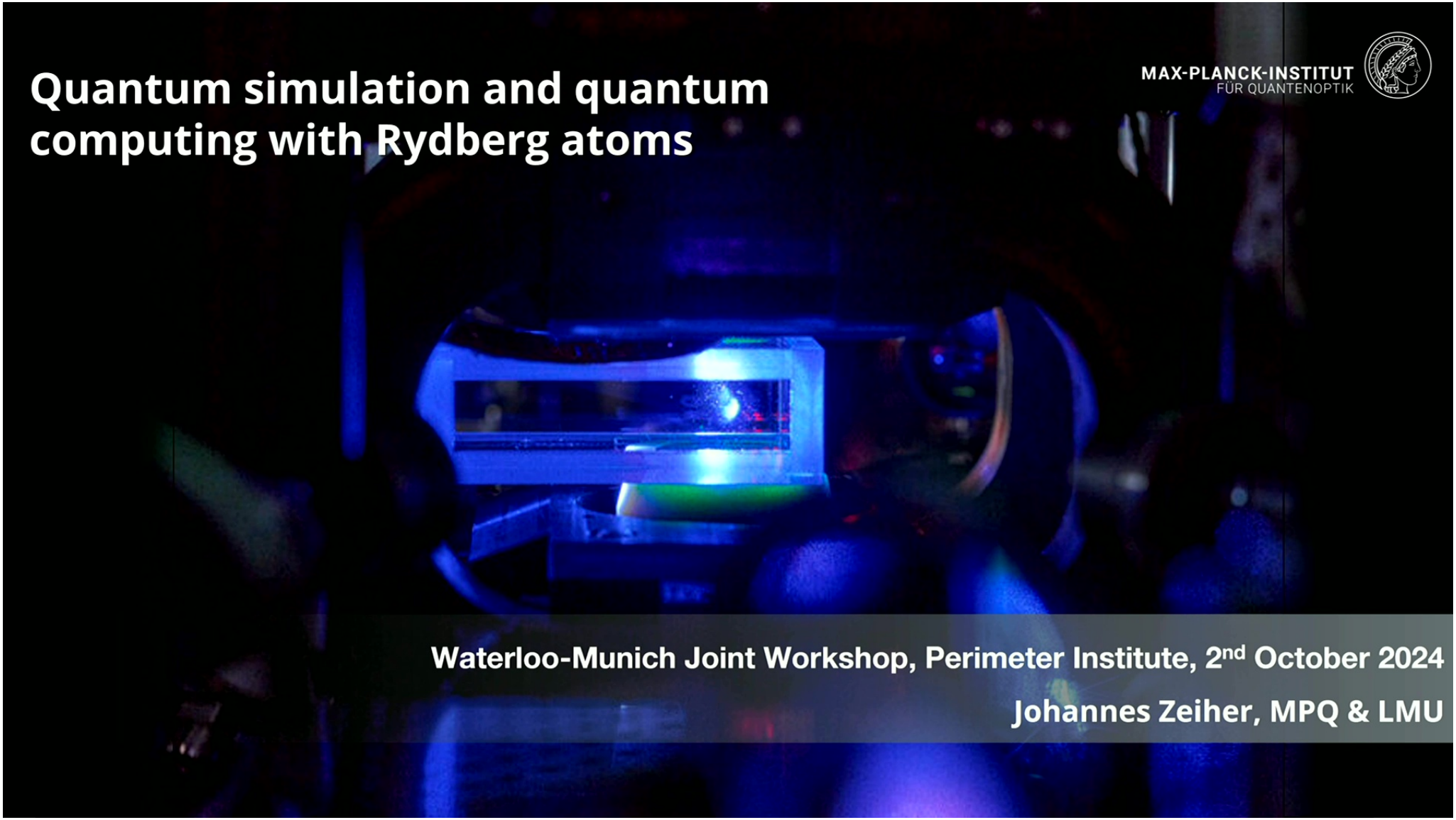
Collection/Series: Waterloo-Munich Joint Workshop

Subject: Quantum Information

Date: October 02, 2024 - 9:00 AM

URL: https://pirsa.org/24100052

Quantum simulation and quantum computing with Rydberg atoms



MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

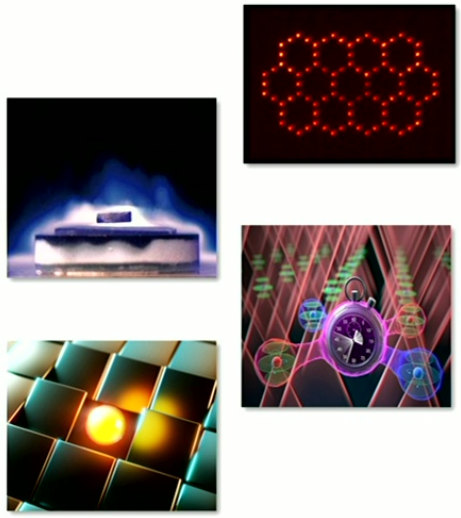
Waterloo-Munich Joint Workshop, Perimeter Institute, 2nd October 2024

Johannes Zeiher, MPQ & LMU

Many-body systems

Motivation: Understanding, controlling and creating **many-body systems**

- Fundamental research
  Strongly correlated systems, transport, phase transitions, ...
- New technological applications
  High-Tc superconductors, quantum computing, ...
- Improved measurement/sensing
  Atomic clocks (e.g. time), atom interferometers (e.g. gravity, dark matter)
- Novel light-matter interfaces
  Controlled & enhanced light-matter coupling



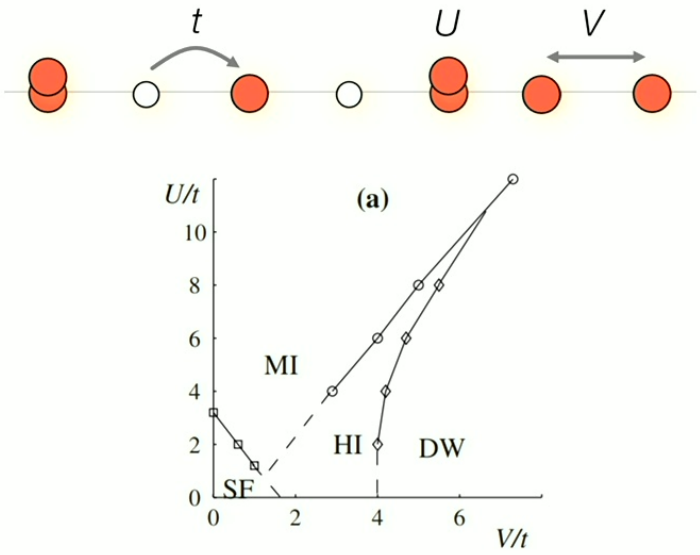
This talk: Extended-range interacting quantum systems

Feynman, Int. J. Theor. Phys. **21**, 467 (1982)
Lloyd, Science **273**, 1073 (1996)
Mann, Nature **475**, 280 (2011)
Young, ..., Kaufman, Nature **588**, 408 (2020)

Extended-range interactions

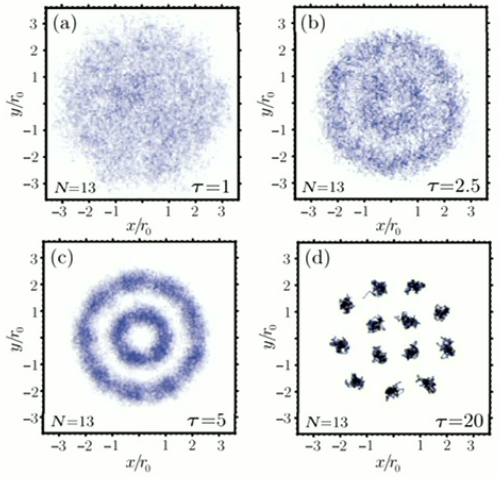
Quantum simulations: Competing length scales lead to new physics!

Non-local order: **Haldane insulator**



Berg, ... Altman, PRB **77**, 245119 (2008)
Dalla Torre, ... Altman, PRL **97**, 260401 (2006)

Superfluidity and density order: **Supersolid**



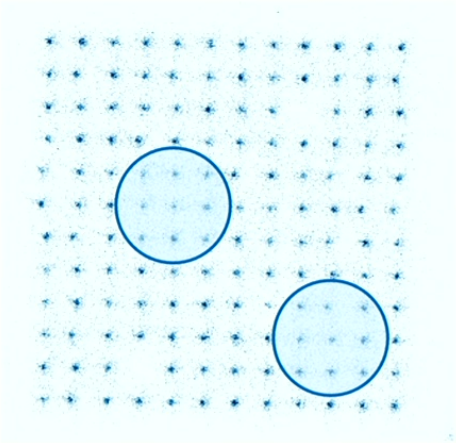
Pupillo, ... Zoller, PRL **104**, 223002 (2010)
Henkel, ... Pohl, PRL **108**, 265301 (2012)

Johannes Zeiher

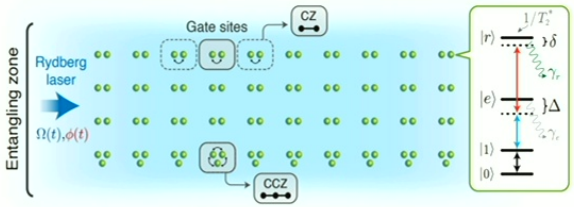
MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

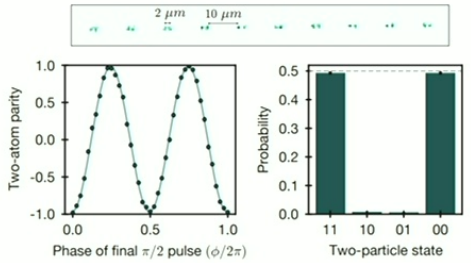
Extended-range interactions

Quantum computing: Long-range interactions allow for realizing entangling gates



Interaction radius spanning multiple atoms





Evered, ... Lukin, Nature **622**, 268 (2023)

Johannes Zeiher

Review: Saffman, J. Phys. B, **49**, 202001 (2016)
Levine, ... Lukin, PRL **123**, 170503 (2019)
Ma, ... Thompson, Nature **622**, 279 (2023)

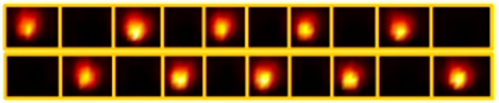
Barredo, ... Browaeys, Science **345**, 1021 (2016)
Endres, ... Lukin, Science **345**, 1024 (2016)
Ebadi, ... Lukin, Nature **595**, 227 (2021)
Scholl, ... Browaeys, Nature **595**, 233 (2021)

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Extended-range interactions

Trapped ions

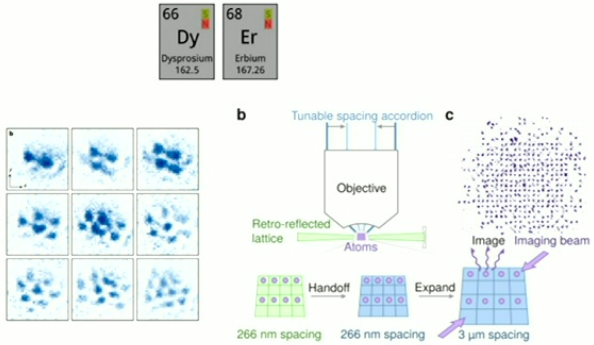
Quantum information
Quantum simulation of spin models



Islam, ... Monroe, Science **340**, 583 (2013)
Jurcevic, ... Blatt, Roos, Nature **511**, 202 (2014)
Richerme, ... Monroe, Nature **511**, 198 (2014)
Debnath, ... Monroe, Nature **536**, 63 (2016)
…

Magnetic atoms

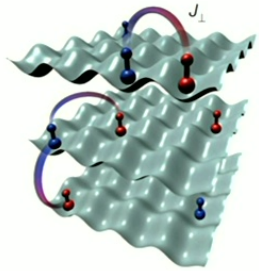
Quantum simulation of itinerant physics



Kadau, ... Pfau, Nature **530**, 194 (2016)
Baier, ... Ferlaino, Science **352**, 6282 (2016)
Norcia, ... Ferlaino, Nature **596**, 257 (2021)
Su, ... Greiner, Nature **622**, 724 (2023)
…

Dipolar molecules

Quantum simulation of itinerant physics & spin models



Ni, Ospelkaus, ... Ye, Science **322**, 231 (2008)
Yan, ... Ye, Nature **501**, 521 (2013)
Park, ... Zwierlein, PRL 113, 205302 (2015)
Gregory, ... Cornish, Nat. Phys. **17**, 1149 (2021)
Rosenberg, ... Bakr, Nat. Phys. **18**, 1062 (2022)
Schindewolf, ... Bloch, Luo, Nature **607**, 677 (2022)
…

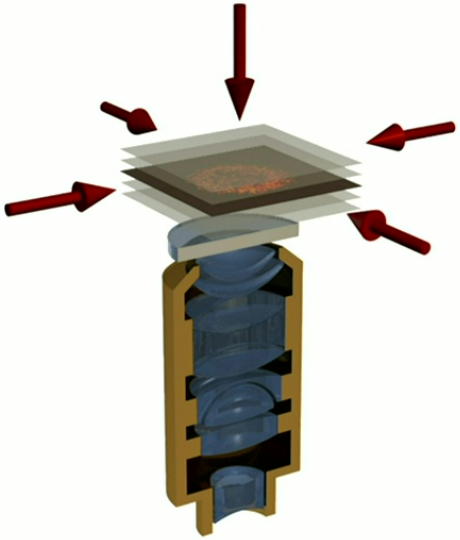
Johannes Zeiher

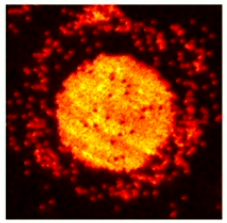
MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Atomic arrays

Top down

Quantum gas microscope & optical lattices

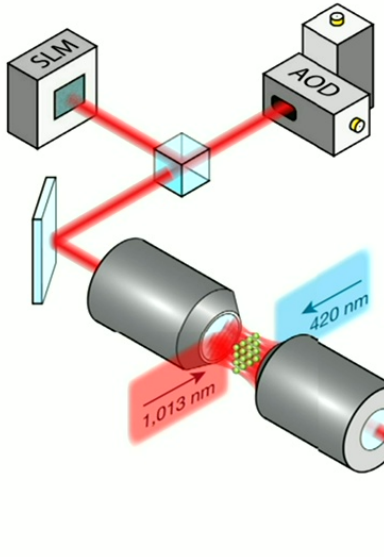


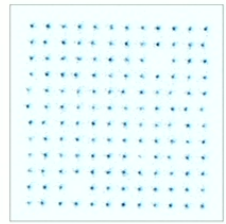


Static traps

Bottom up

Optical microtraps





Dynamic traps

Bakr, ... Greiner, Nature **462**, 74 (2009)
Sherson, ... Bloch, Kuhr, Nature **467**, 68 (2010)
Haller, ... Kuhr, Nat. Phys. **11**, 738 (2015)
Cheuk, ... Zwierlein, PRL **114**, 193001 (2015)
Parsons, ... Greiner, PRL **114**, 213002 (2015)

Barredo, ... Browaeys, Science **345**, 1021 (2016)
Endres, ... Lukin, Science **345**, 1024 (2016)
Ebadi, ... Lukin, Nature **595**, 227 (2021)
Scholl, ... Browaeys, Nature **595**, 233 (2021)

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

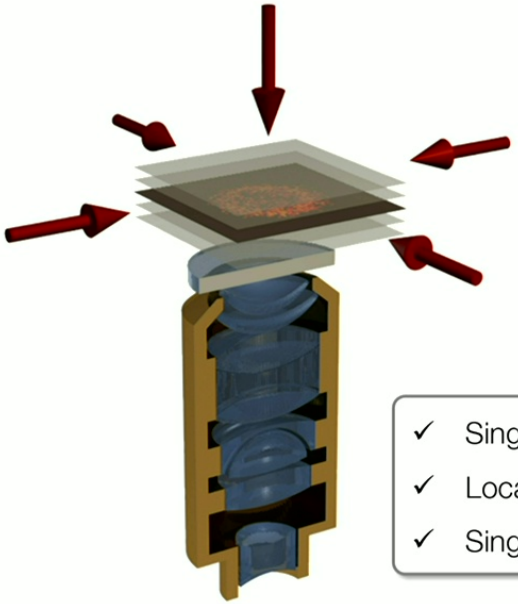
Outline

1. Quantum gas microscopes
2. Realization of extended Hubbard models with Rydberg dressing
3. Quantum computing with strontium atoms
4. Summary & outlook

Quantum gas microscope

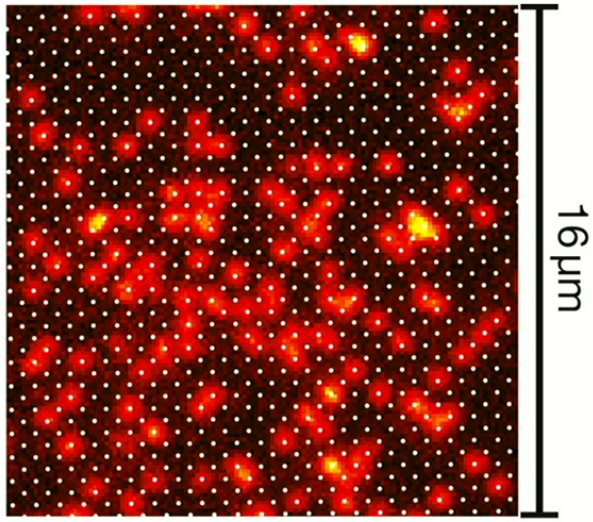
Top down

Quantum gas microscope
for ^{87}Rb



- ✓ Single-atom sensitivity
- ✓ Local resolution
- ✓ Single-atom control

Reconstruction of occupation
for each lattice site, $a = 532\ \mathrm{nm}$



Review: Gross & Bloch, Science **357**, 995 (2017)
Sherson, ... Bloch, Kuhr, Nature **467**, 68 (2010)
Bakr, ... Greiner, Nature **462**, 74 (2009)

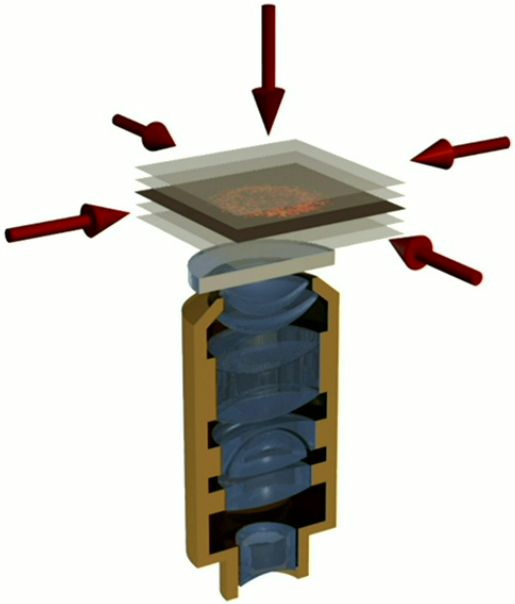
Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Quantum gas microscope

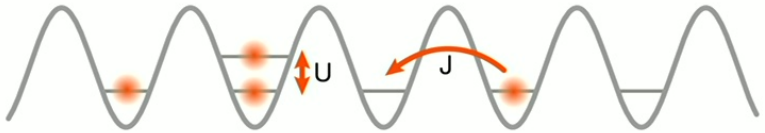
Top down

Quantum gas microscope
for ^{87}Rb



Hubbard regime: Tunneling J, on-site interaction U

$$\hat{H} = -J \sum_i \left(\hat{a}_{i+1}^\dagger \hat{a}_i + \hat{a}_{i+1} \hat{a}_i^\dagger\right) + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$



Typical parameters:

$J/h = 0 - 100$ Hz

$U/h = 250$ Hz

Review: Gross & Bloch, Science **357**, 995 (2017)
Sherson, ... Bloch, Kuhr, Nature **467**, 68 (2010)
Bakr, ... Greiner, Nature **462**, 74 (2009)

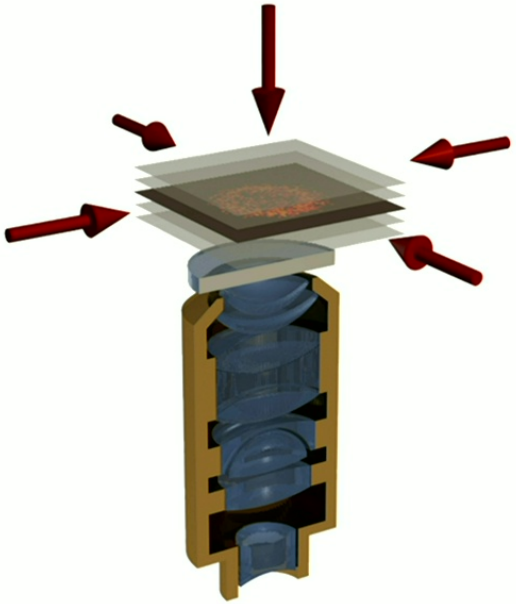
Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Quantum gas microscope

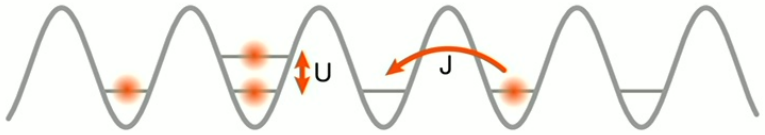
Top down

Quantum gas microscope
for ^{87}Rb

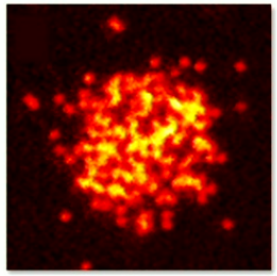


Hubbard regime: Tunneling J, on-site interaction U

$$\hat{H} = -J \sum_i \left(\hat{a}_{i+1}^\dagger \hat{a}_i + \hat{a}_{i+1} \hat{a}_i^\dagger\right) + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$

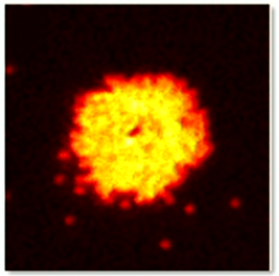


Superfluid



Increase U/J

Mott insulator



Review: Gross & Bloch, Science **357**, 995 (2017)
Sherson, ... Bloch, Kuhr, Nature **467**, 68 (2010)
Bakr, ... Greiner, Nature **462**, 74 (2009)

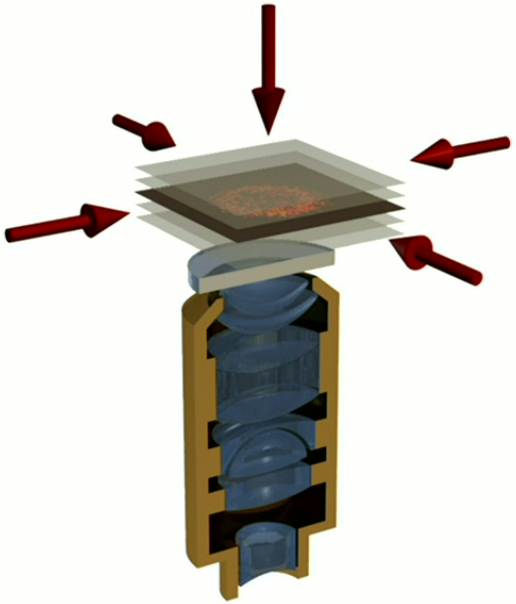
Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Quantum gas microscope

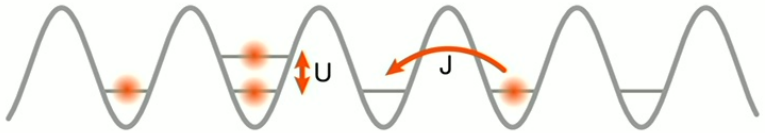
Top down

Quantum gas microscope
for ^{87}Rb



Hubbard regime: Tunneling J, on-site interaction U

$$\hat{H} = -J \sum_i \left(\hat{a}_{i+1}^\dagger \hat{a}_i + \hat{a}_{i+1} \hat{a}_i^\dagger\right) + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$



Atomic limit $U \gg J$ and **two species** (hyperfine states):

$$\hat{H} = -J \sum_j \left(\hat{S}_j^x \hat{S}_{j+1}^x + \hat{S}_j^y \hat{S}_{j+1}^y + \Delta \hat{S}_j^z \hat{S}_{j+1}^z\right)$$

Ferromagnetic Heisenberg model: KPZ-transport

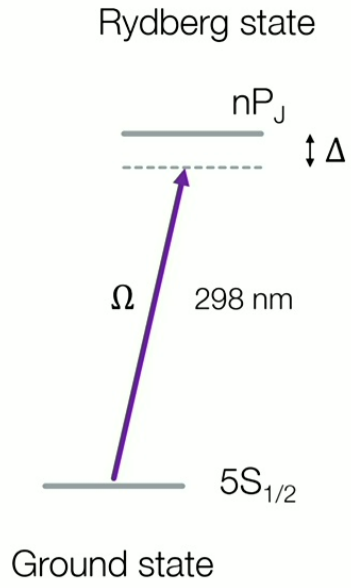
Wei, ..., Zeiher, Science **376**, 716 (2022)

Review: Gross & Bloch, Science **357**, 995 (2017)
Sherson, ... Bloch, Kuhr, Nature **467**, 68 (2010)
Bakr, ... Greiner, Nature **462**, 74 (2009)

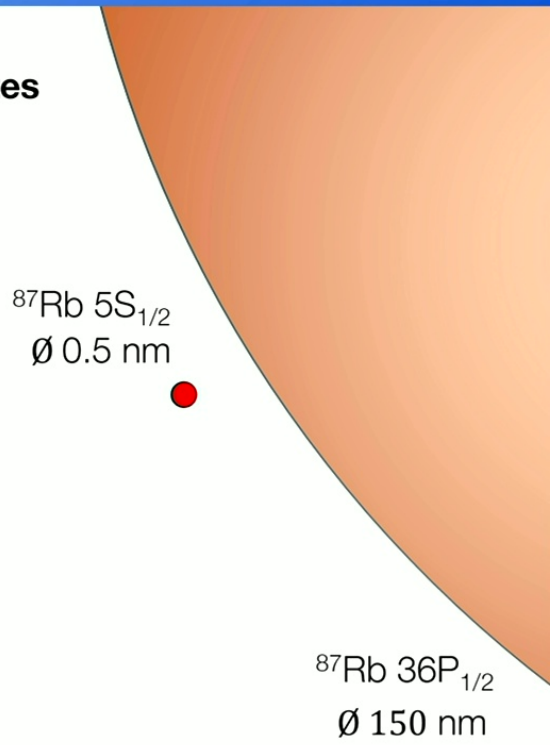
Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Long-range interactions through **highly-excited Rydberg states**



Property	Scaling	^{87}Rb 31P$_{3/2}$
Diameter	n^2	150 nm
Lifetime	n^2	28 μs
Polarizability	n^7	83 MHz at 1V/cm
Interaction energy	n^{11}	200 MHz at 1 μm

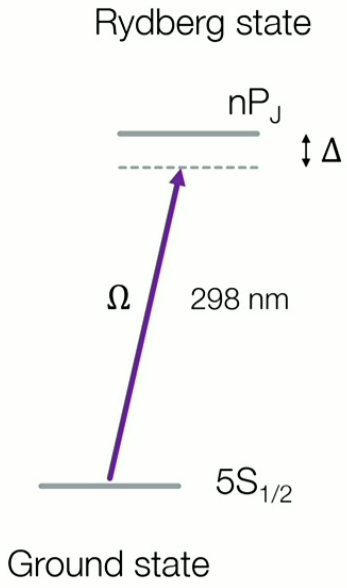


Johannes Zeiher

Review: Saffman, Rev. Mod. Phys. **82**, 2313 (2010)

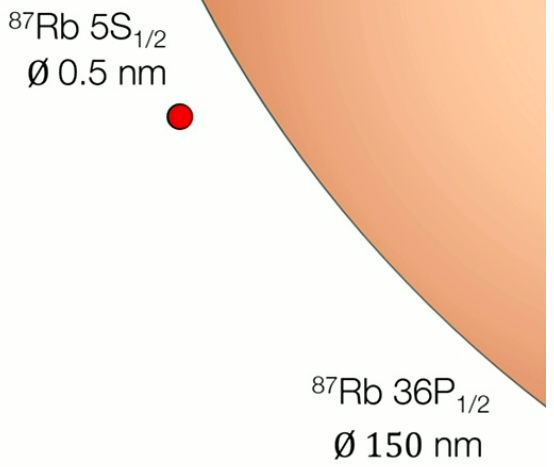
MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Long-range interactions through **highly-excited Rydberg states**



Property	Scaling	^{87}Rb 31P$_{3/2}$
Diameter	n^2	150 nm
Lifetime	n^2	28 µs
Polarizability	n^7	83 MHz at 1V/cm
Interaction energy	n^{11}	200 MHz at 1 µm

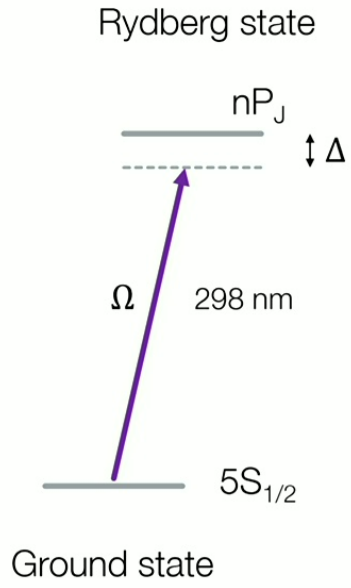
Frozen-gas regime: Neglect atomic motion on timescale of Rydberg lifetime

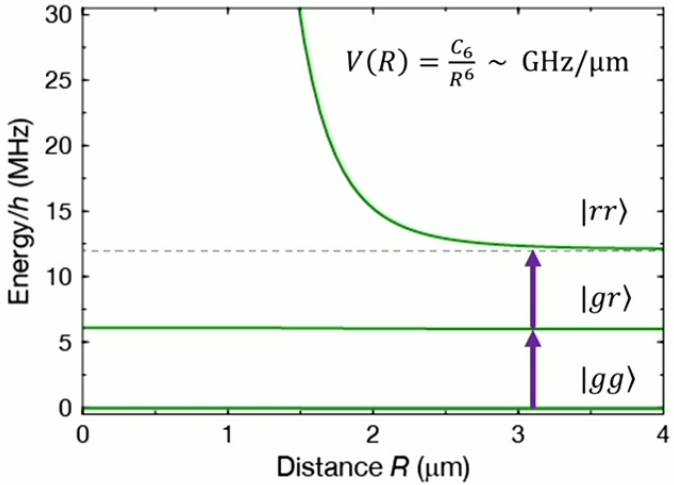


Rydberg blockade

Long-range interactions through **highly-excited Rydberg states**

$$\hat{H} = \frac{\Omega}{2}\sum_i \hat{\sigma}_i^x + \sum_{i,j}\frac{V_{ij}}{2}\hat{\sigma}_i^e\hat{\sigma}_j^e$$





Reviews: Saffman, Rev. Mod. Phys. **82**, 2313 (2010)
Browaeys & Lahaye, Nat. Phys. **16**, 132 (2020)

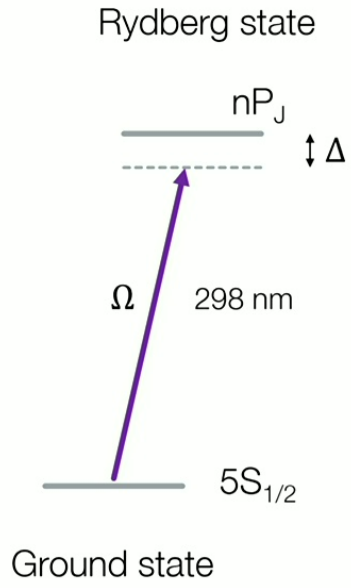
Johannes Zeiher

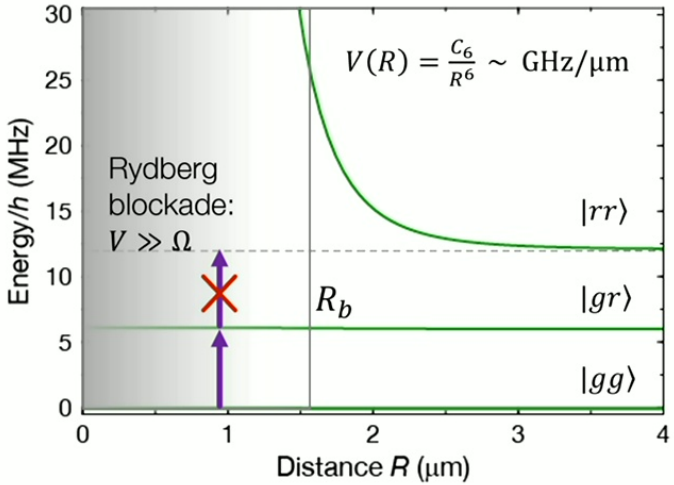
MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Rydberg blockade

Long-range interactions through **highly-excited Rydberg states**

$$\hat{H} = \frac{\Omega}{2}\sum_i \hat{\sigma}_i^x + \sum_{i,j}\frac{V_{ij}}{2}\hat{\sigma}_i^e\hat{\sigma}_j^e$$





Reviews: Saffman, Rev. Mod. Phys. **82**, 2313 (2010)
Browaeys & Lahaye, Nat. Phys. **16**, 132 (2020)

Johannes Zeiher

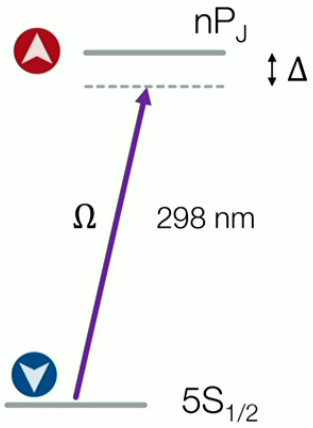
MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Rydberg blockade

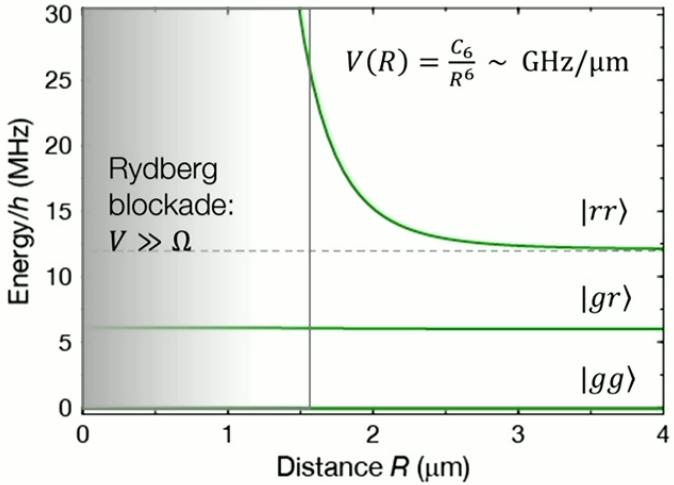
Long-range interactions through **highly-excited Rydberg states**

$$\hat{H} = \frac{\Omega}{2}\sum_i \hat{\sigma}_i^x - \Delta\sum_i \hat{\sigma}_i^e + \sum_{i,j}\frac{V_{ij}}{2}\hat{\sigma}_i^e\hat{\sigma}_j^e$$

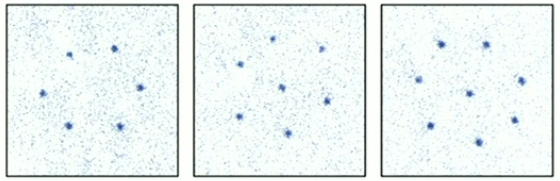
Spin-up state



Spin-down state



Quantum simulation



Ordering of (spin) excitations

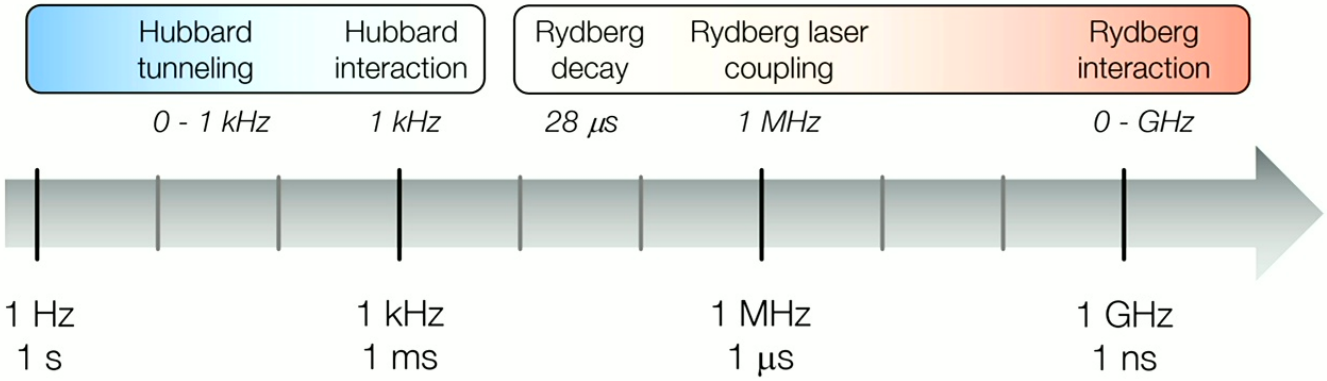
See Rydberg array experiments at
Harvard, Paris, KAIST, Caltech, Princeton,
Singapore, Glasgow and others

Schauss, ... Bloch, Gross, Science **347**, 1455 (2015)
Reviews: Saffman, Rev. Mod. Phys. **82**, 2313 (2010)
Browaeys & Lahaye, Nat. Phys. **16**, 132 (2020)

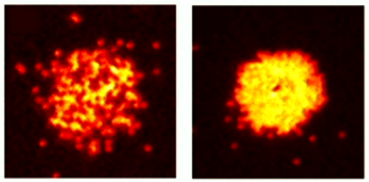
Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

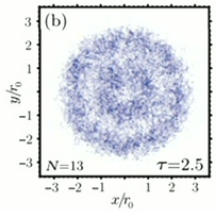
Unfreezing the Rydberg gas



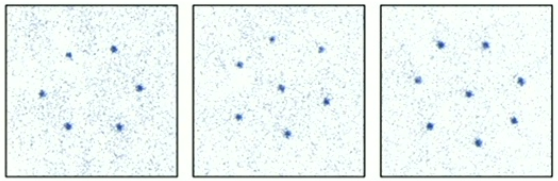
Itinerant Physics



Supersolid?



Frozen Rydberg Physics

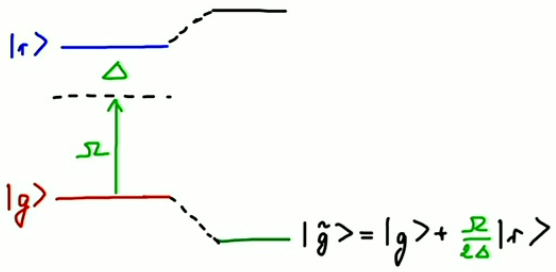


Henkel, ... Pohl, PRL **104**, 195392 (2010)
Pupillo, ... Zoller, PRL **104**, 223002 (2010)
Henkel, ... Pohl, PRL **108**, 265301 (2012)
Geissler, ... Hofstetter, PRA **95**, 063608 (2017)

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Admixing interactions



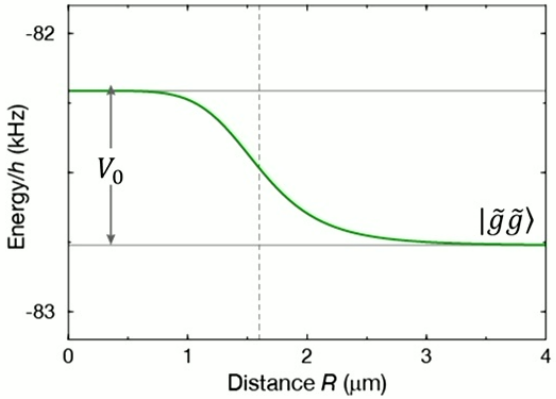
Off-resonant admixture $\Delta \gg \Omega,\ \beta = \frac{\Omega}{2\Delta} \ll 1$

$|\tilde{g}\rangle$ „inherits“ (a little bit of)

☺ Rydberg – Rydberg interaction

☹ Rydberg lifetime

Lightshift modified by blockade



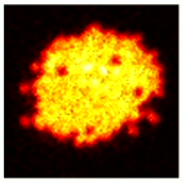
- ✓ Switchable light-induced interaction $V_0 = \frac{\Omega^4}{8\Delta^3} = \beta^3\Omega$
- ✓ Extended range $R_c = \left(\frac{C_6}{2\Delta}\right)^{1/6}$
- ✓ Increased effective lifetime $\tau_{\text{eff}} = \tau\left(\frac{2\Delta}{\Omega}\right)^2 = \frac{\tau}{\beta^2}$

Santos, ... Lewenstein, PRL **85**, 1791 (2000)
Bouchoule, ... Molmer, PRA **65**, 041803 (2002)
Jau, ..., Biedermann, Nat. Phys. **12**, 71 (2016)

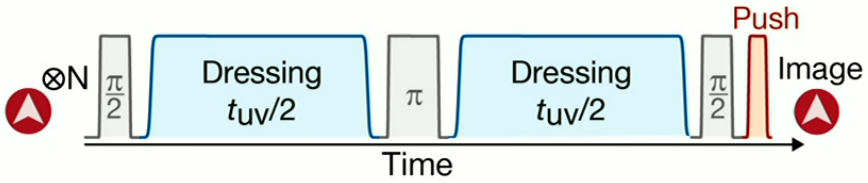
Zeiher, ..., Gross, Nat. Phys. **12**, 1095 (2016)
Borish, ... Schleier-Smith, PRL **124**, 063601 (2020)
Guardado-Sanchez, ... Bakr, PRX **11**, 021036 (2021)

Johannes Zeiher

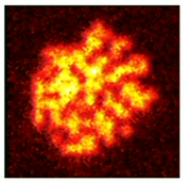
MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK



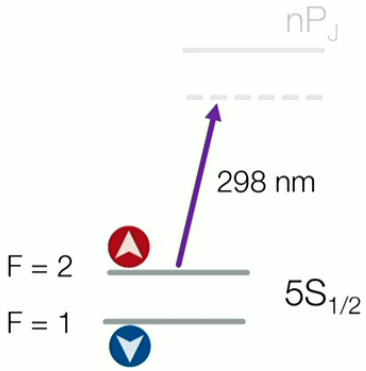
Initial state



Ramsey sequence



Detected atoms



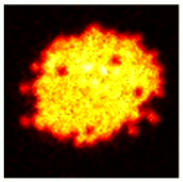
Idea: Interaction energy shift leads to correlated phase evolution

→ Use Ramsey interferometry combined with quantum gas microscopy to measure this

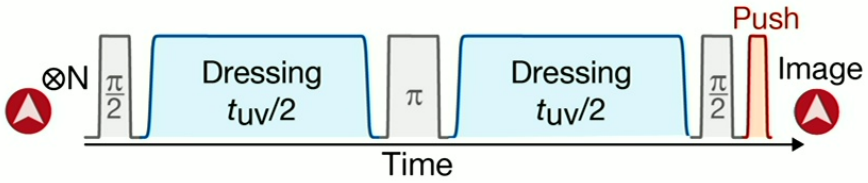
Zeiher, ..., Gross, Nat. Phys. **12**, 1095 (2016)
Zeiher, ..., Gross, PRX **7**, 041063 (2017)
Borish, ... Schleier-Smith, PRL **124**, 063601 (2020)
Steinert, ..., Gross, PRL **130**, 243001 (2023)
Eckner, ... Kaufman, Nature **621**, 734 (2023)

Johannes Zeiher

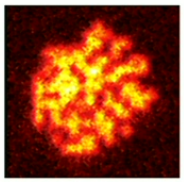
MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK



Initial state



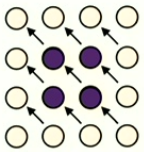
Ramsey sequence

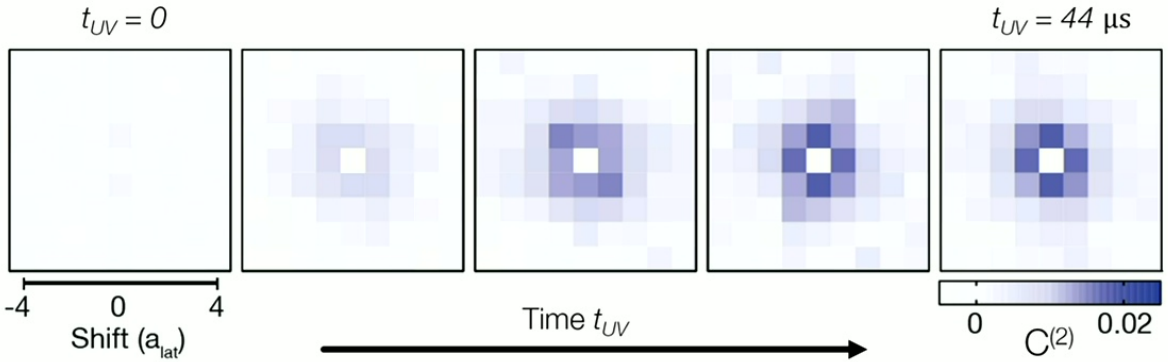


Detected atoms

Extended-range correlations between distant spins

$C^{(2)}$ correlation





① Extended range

Zeiher, ..., Gross, Nat. Phys. **12**, 1095 (2016)
Zeiher, ..., Gross, PRX **7**, 041063 (2017)
Borish, ... Schleier-Smith, PRL **124**, 063601 (2020)
Steinert, ..., Gross, PRL **130**, 243001 (2023)
Eckner, ... Kaufman, Nature **621**, 734 (2023)

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

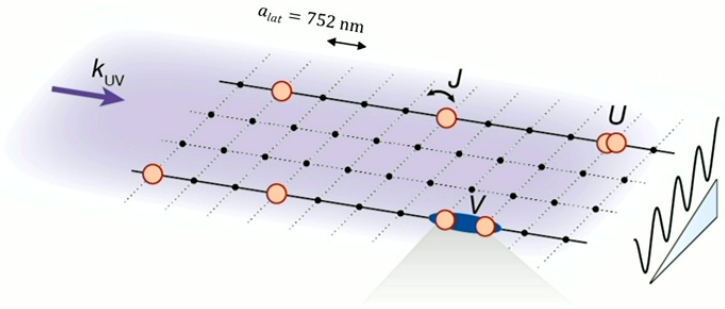
Extended Hubbard model

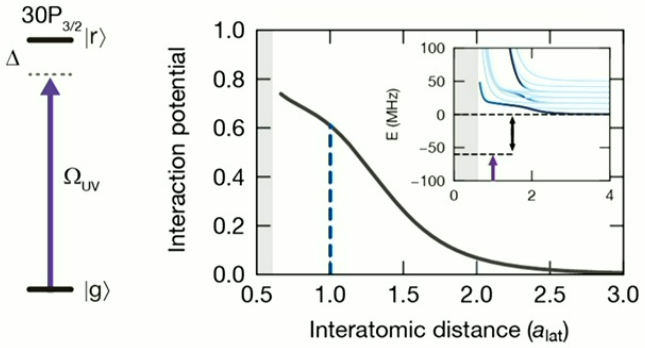
Extended Hubbard model $\hat{H} = -J \sum_i \left(\hat{a}_{i+1}^\dagger \hat{a}_i + \hat{a}_{i+1}\hat{a}_i^\dagger\right) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + V \sum_i \hat{n}_i \hat{n}_{i+1}$

$J/h = 17$ Hz

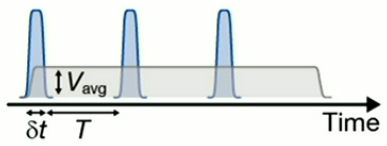
$U/J = 14$

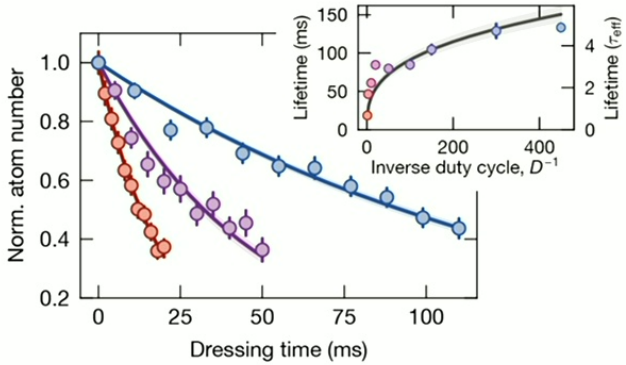
$V = [0, \ldots, 6J]$





Pulsed stroboscopic dressing: Improved lifetime





Santos, ... Lewenstein, PRL **85**, 1791 (2000)
Hines, ... Schleier-Smith, PRL **131**, 063401 (2023)
Guardado-Sanchez, ... Bakr, PRX **11**, 021036 (2021)
Weckesser, ... Zeiher, arXiv:2405.20128 (2024)

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

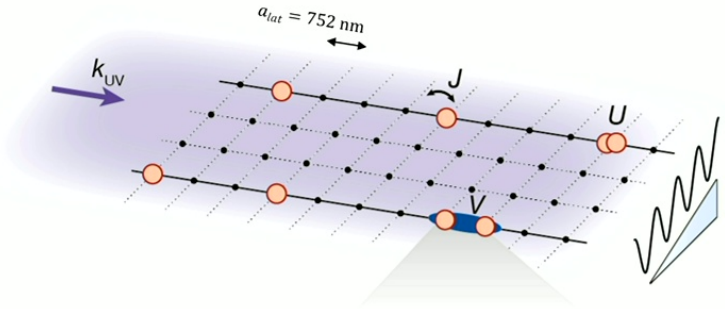
Extended Hubbard model

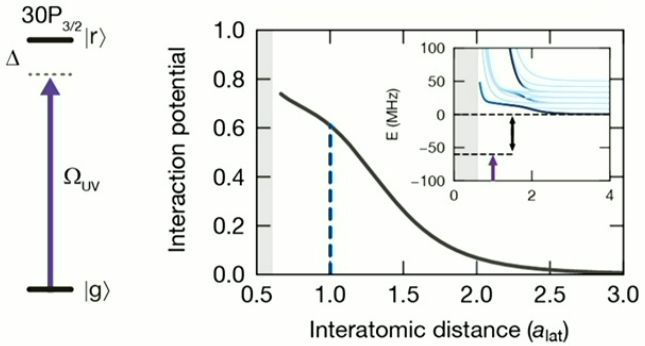
Extended Hubbard model $\hat{H} = -J \sum_i \left(\hat{a}_{i+1}^\dagger \hat{a}_i + \hat{a}_{i+1}\hat{a}_i^\dagger\right) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + V \sum_i \hat{n}_i \hat{n}_{i+1}$

$J/h = 17$ Hz

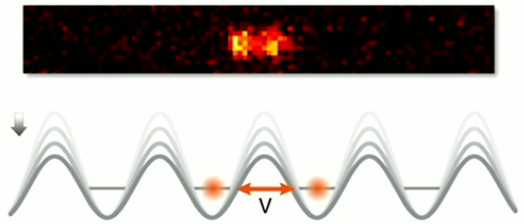
$U/J = 14$

$V = [0, \ldots, 6J]$

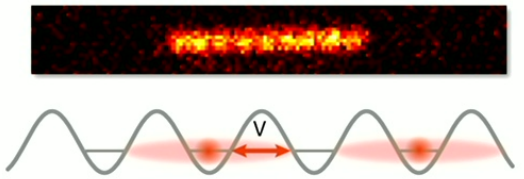




① Quenches from initial states



② Quasi-adiabatic preparation of near ground states



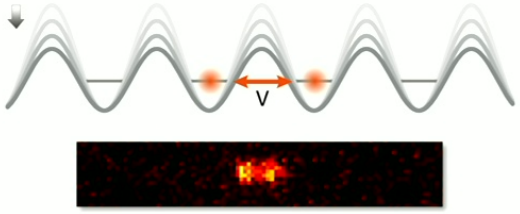
Johannes Zeiher

Guardado-Sanchez, ... Bakr, PRX **11**, 021036 (2021)
Weckesser, ... Zeiher, arXiv:2405.20128 (2024)

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

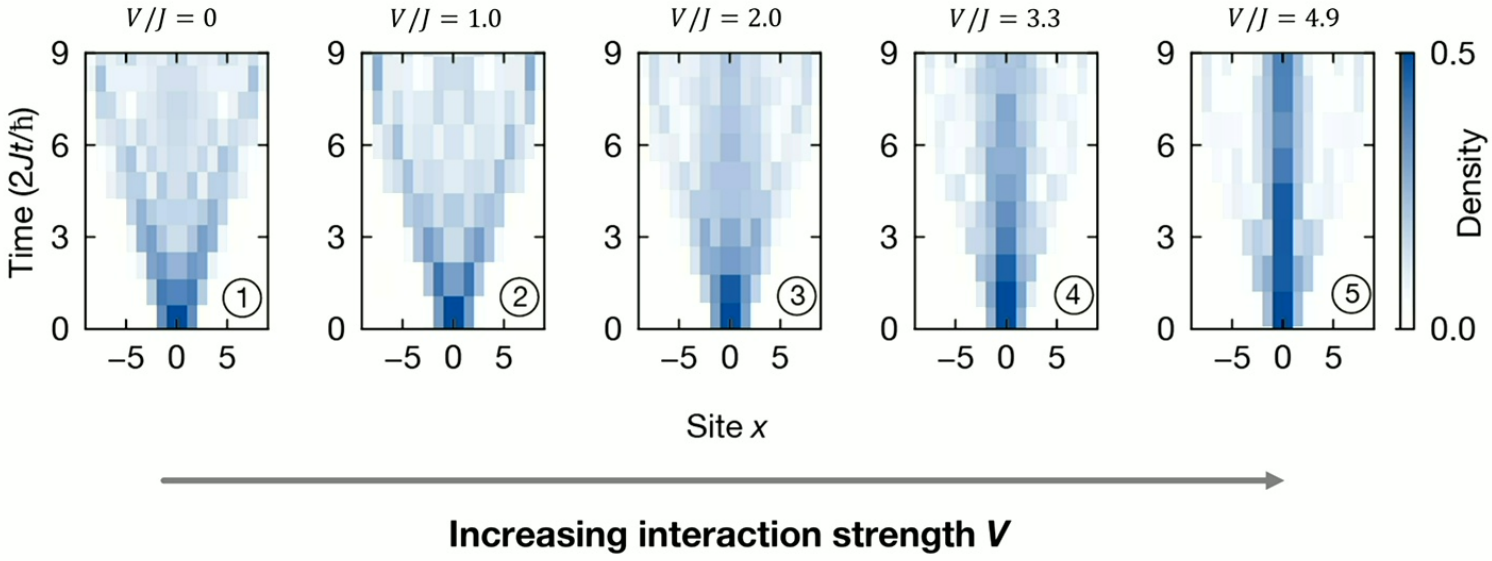
Bound states

Initial state



$$\hat{H} = -J \sum_i (\hat{a}_{i+1}^\dagger \hat{a}_i + \hat{a}_{i+1} \hat{a}_i^\dagger) + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1) + V \sum_i \hat{n}_i \hat{n}_{i+1}$$

$U/J \sim 14$

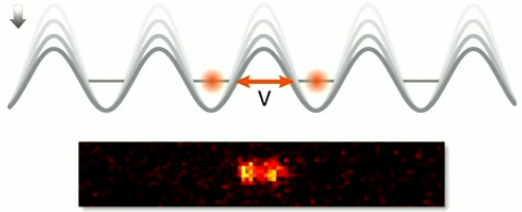


Increasing interaction strength *V*

Valiente, Petrosyan, PRB **42**, 121001 (2009)
Fukuhara, ... Bloch, Nature **502**, 76 (2013)
Morvan, ... Roushan, Nature **612**, 240 (2022)

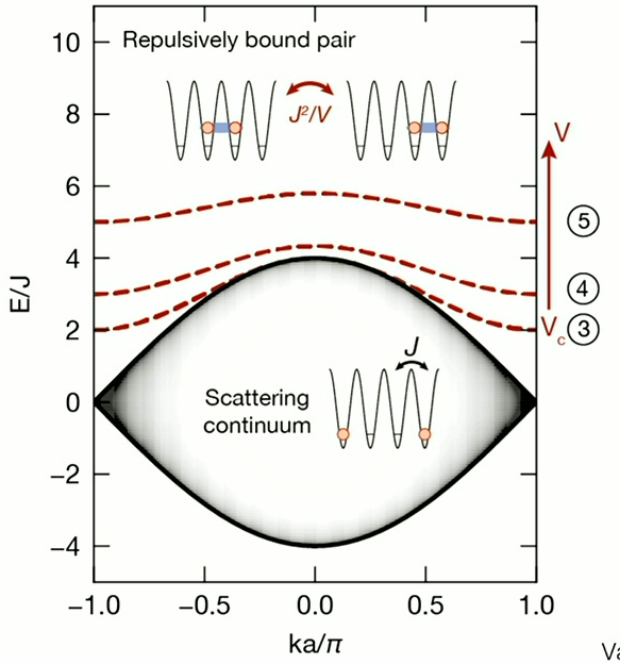
Bound states

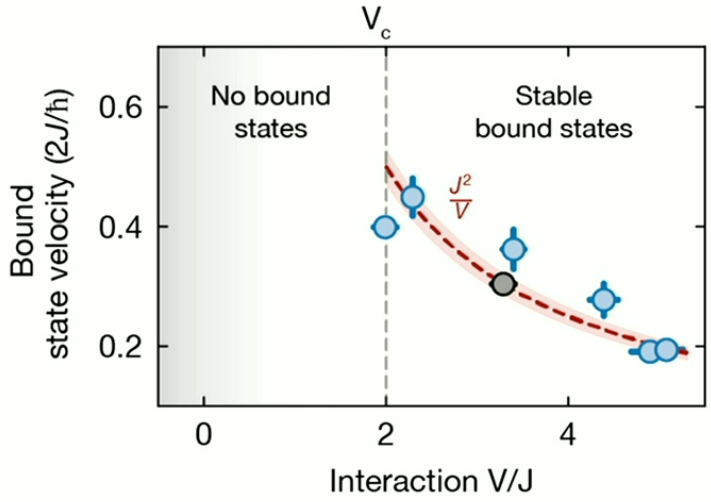
Initial state



$$\hat{H} = -J \sum_i (\hat{a}_{i+1}^\dagger \hat{a}_i + \hat{a}_{i+1} \hat{a}_i^\dagger) + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1) + V \sum_i \hat{n}_i \hat{n}_{i+1}$$

$U/J \sim 14$





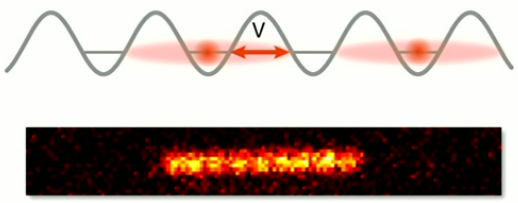
Valiente, Petrosyan, PRB **42**, 121001 (2009)
Fukuhara, ... Bloch, Nature **502**, 76 (2013)
Morvan, ... Roushan, Nature **612**, 240 (2022)

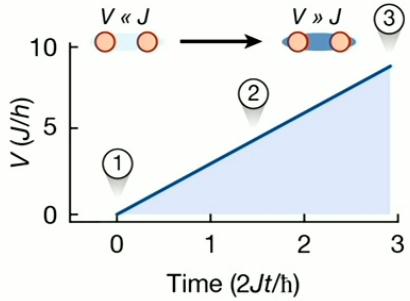
Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Adiabatic preparation

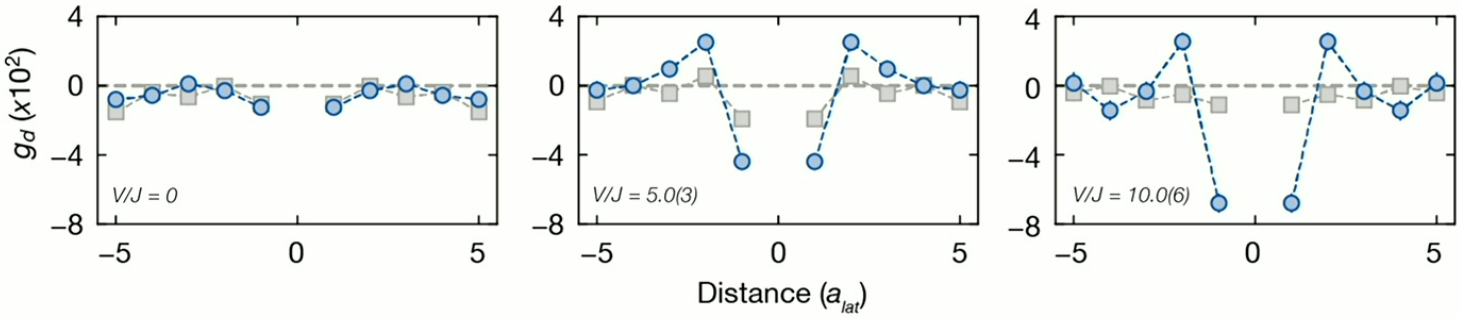
Initial state





Goal: Ramp of extended Hubbard interactions to perform

adiabatic state preparation

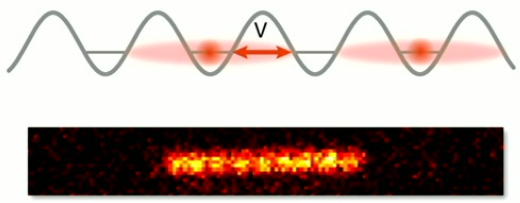


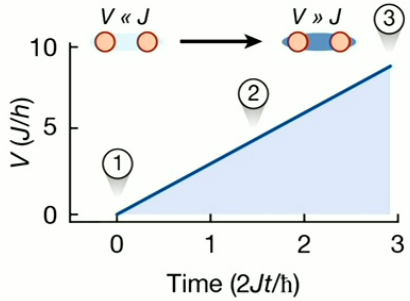
$U/J \sim 14$
$\mathrm{J}/h \sim 17\mathrm{Hz}$
$L = 17$
$N = 9$

Erbium: Su, ... Greiner, Nature **622**, 724 (2023)

Adiabatic preparation

Initial state

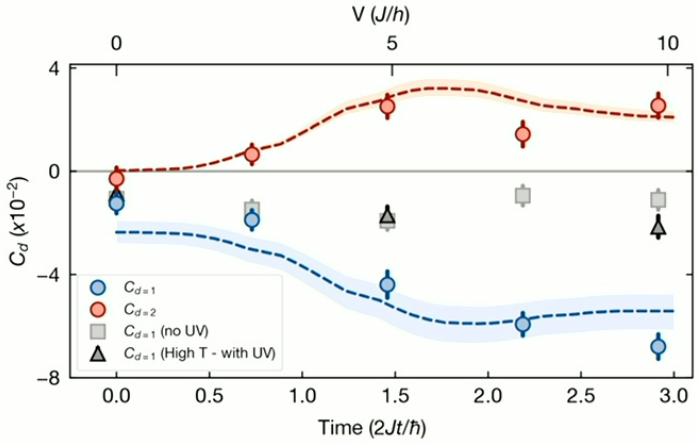


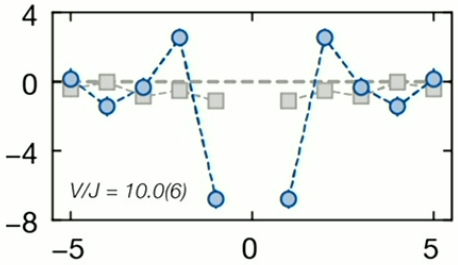


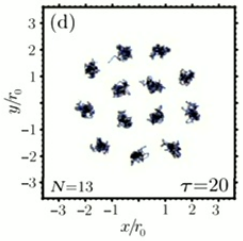
Goal: Ramp of extended Hubbard interactions to perform

adiabatic state preparation

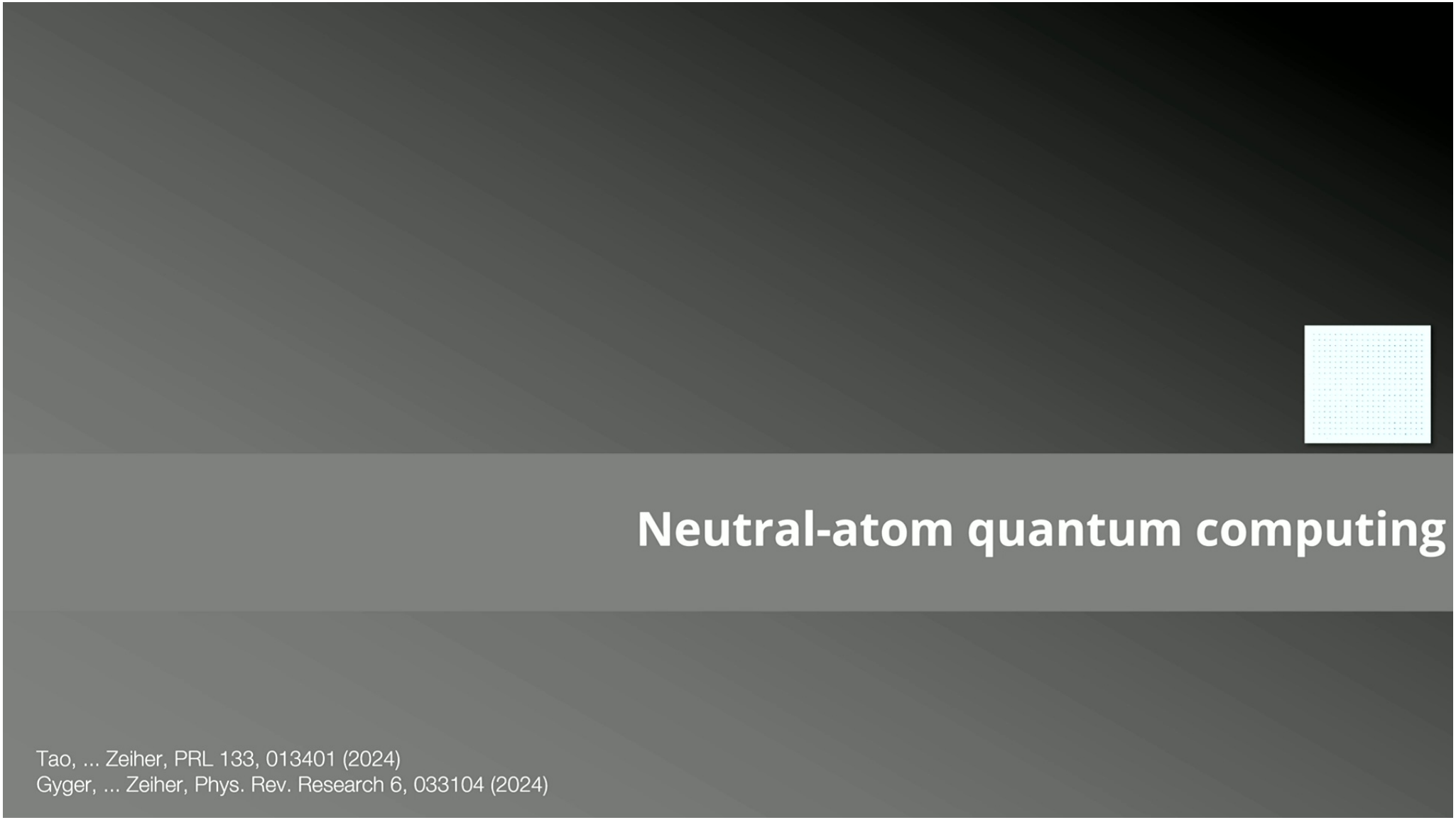
$U/J \sim 14$
$\mathrm{J}/h \sim 17\mathrm{Hz}$
$L = 17$
$N = 9$







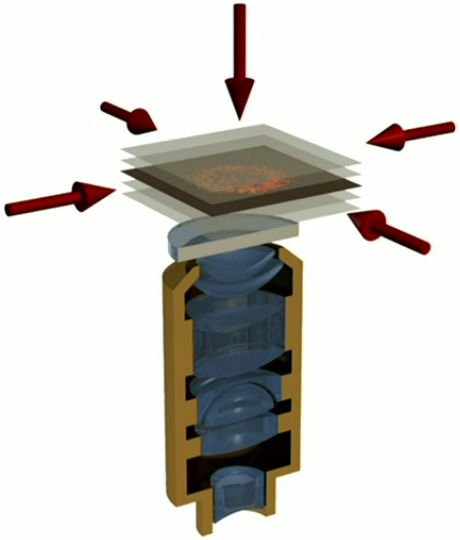
Erbium: Su, ... Greiner, Nature **622**, 724 (2023)

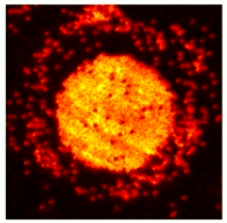

Neutral-atom quantum computing
Tao, ... Zeiher, PRL 133, 013401 (2024)
Gyger, ... Zeiher, Phys. Rev. Research 6, 033104 (2024)

Atomic arrays

Top down

Quantum gas microscope & optical lattices

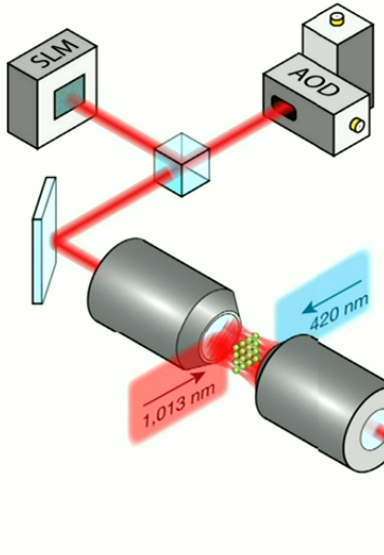


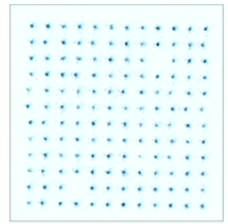


Static traps

Bottom up

Optical microtraps





Dynamic traps

Bakr, ... Greiner, Nature **462**, 74 (2009)
Sherson, ... Bloch, Kuhr, Nature **467**, 68 (2010)
Haller, ... Kuhr, Nat. Phys. **11**, 738 (2015)
Cheuk, ... Zwierlein, PRL **114**, 193001 (2015)
Parsons, ... Greiner, PRL **114**, 213002 (2015)

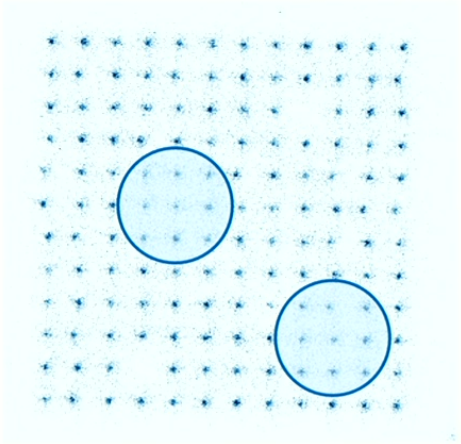
Barredo, ... Browaeys, Science **345**, 1021 (2016)
Endres, ... Lukin, Science **345**, 1024 (2016)
Ebadi, ... Lukin, Nature **595**, 227 (2021)
Scholl, ... Browaeys, Nature **595**, 233 (2021)

Johannes Zeiher

MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Quantum registers

Sortable quantum registers of microscopically controlled atoms



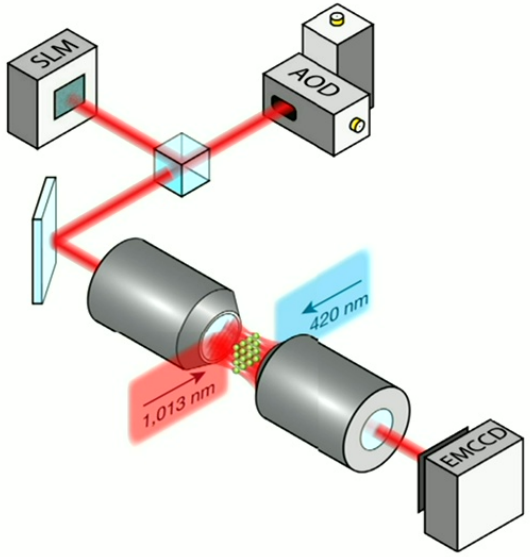
Interaction radius spanning multiple atoms

Rydberg-based entangling gates

Review: Saffman, J. Phys. B, **49**, 202001 (2016)
Levine, ... Lukin, PRL **123**, 170503 (2019)
Ma, ... Thompson, Nature **622**, 279 (2023)

Bottom up

Optical microtraps



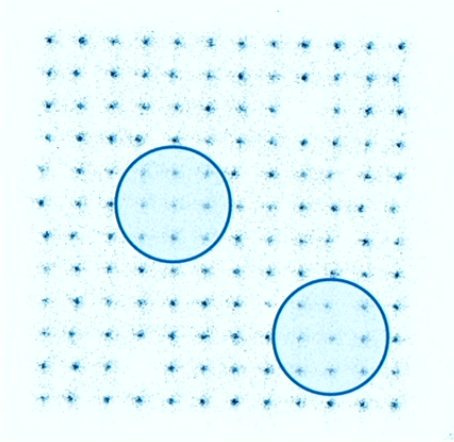
Barredo, ... Browaeys, Science **345**, 1021 (2016)
Endres, ... Lukin, Science **345**, 1024 (2016)
Ebadi, ... Lukin, Nature **595**, 227 (2021)
Scholl, ... Browaeys, Nature **595**, 233 (2021)

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Strontium

Sortable quantum registers of microscopically controlled atoms

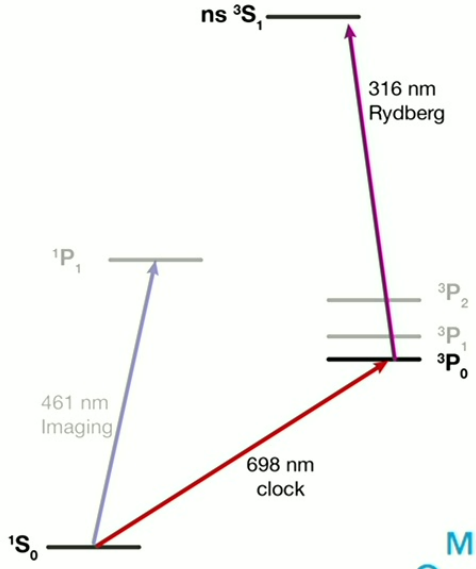


Interaction radius spanning multiple atoms

Rydberg-based entangling gates

^{88}Sr

Use two stable **electronic states & direct optical** coupling for qubits



Munich Quantum Valley

Review: Saffman, J. Phys. B, **49**, 202001 (2016)
Levine, ... Lukin, PRL **123**, 170503 (2019)
Ma, ... Thompson, Nature **622**, 279 (2023)

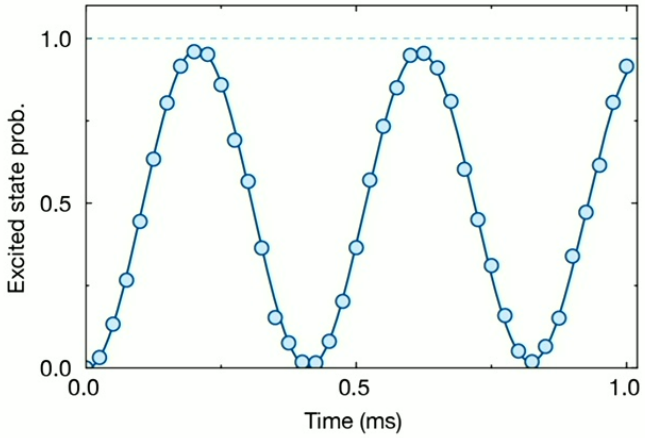
Scholl, ... Endres, Nature **622**, 273 (2023)
Cao, ..., Kaufman, arXiv:2402.16289 (2024)
Tsai, ..., Endres, arXiv:2407.20184 (2024)

Johannes Zeiher

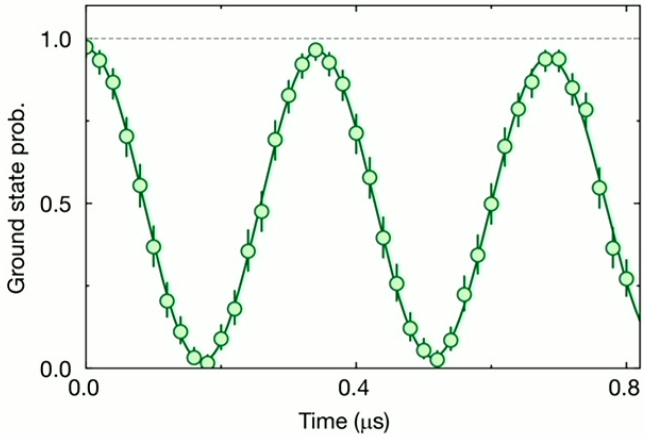
MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Strontium

Clock transition



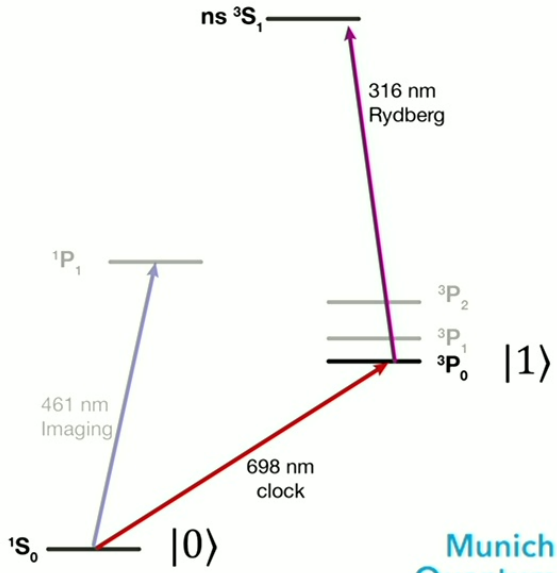
Rydberg transition



Johannes Zeiher

^{88}Sr

Use two stable **electronic states & direct optical** coupling for qubits



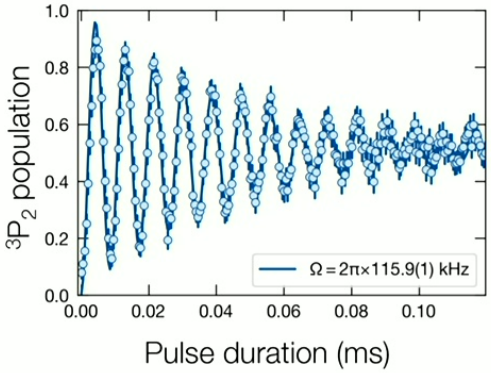
Munich Quantum Valley

Scholl, ... Endres, Nature **622**, 273 (2023)
Cao, ..., Kaufman, arXiv:2402.16289 (2024)
Tsai, ..., Endres, arXiv:2407.20184 (2024)

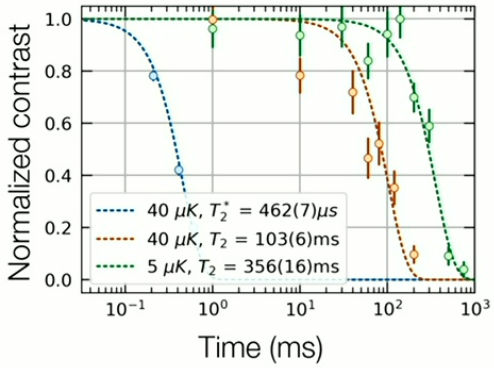
MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Fine-structure qubit

Rabi oscillations via two-photon coupling

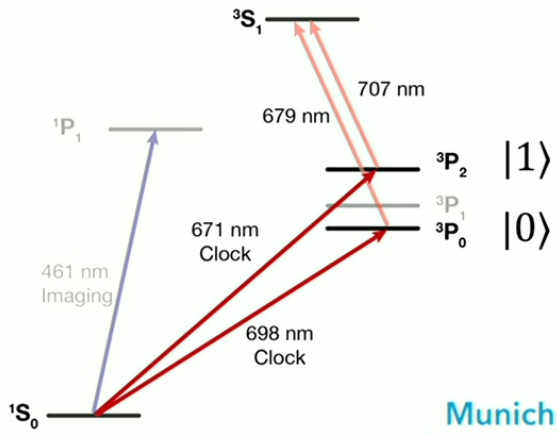


Coherence measurements



^{88}Sr

Two metastable states: Encoding qubit in fine-structure basis $^3P_2$ - $^3P_0$



A fast **and** highly coherent qubit!

(New result: Atom-atom coherence up to **1.4 s**)

Munich Quantum Valley

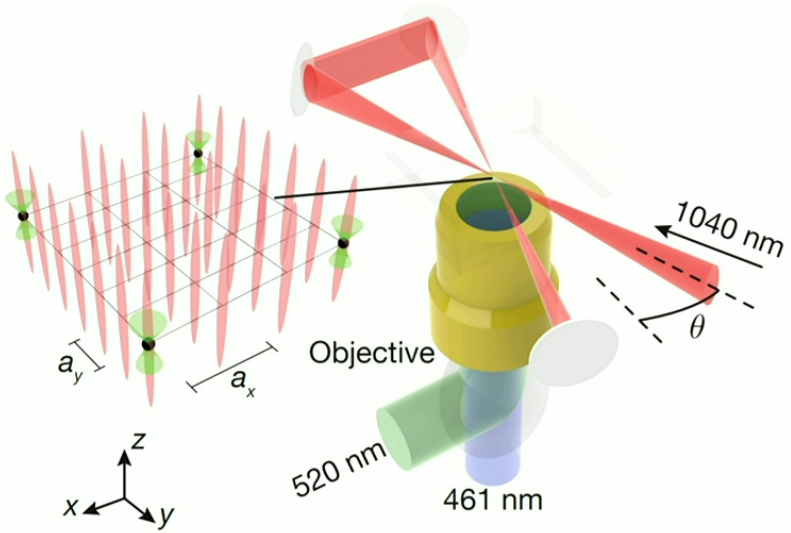
Unnikrishnan, ..., Meinert, PRL **132** 150606 (2024)
Pucher, ..., Blatt, PRL **132** 150605 (2024)
He, ..., Schreck, arXiv:2406.07530 (2024)
Carman, ..., Hogan, arXiv:2406.07902 (2024)

Johannes Zeiher

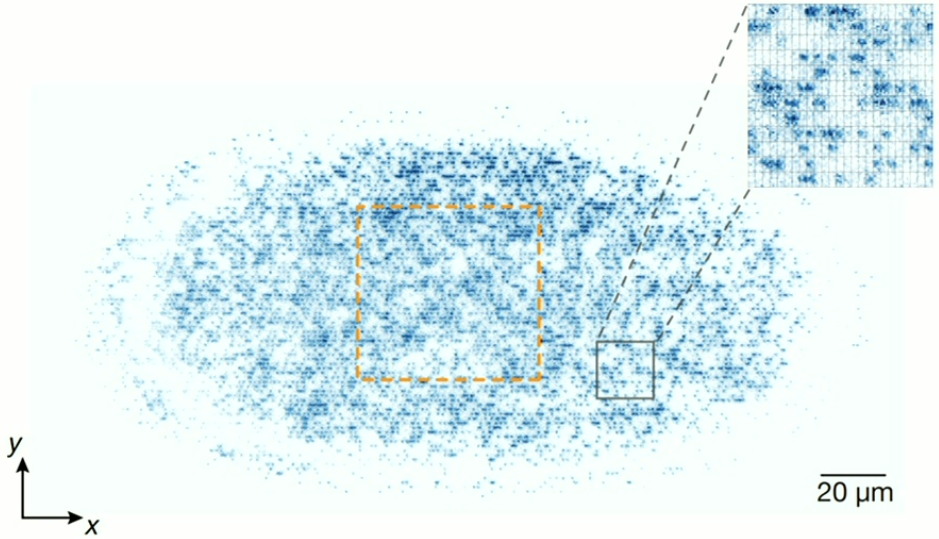
MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Tweezer lattice hybrid

Scaling system sizes: Sr-88 hybrid lattice-tweezer array



Optical lattice at 1040 nm + Optical tweezers at 520 nm and 813 nm



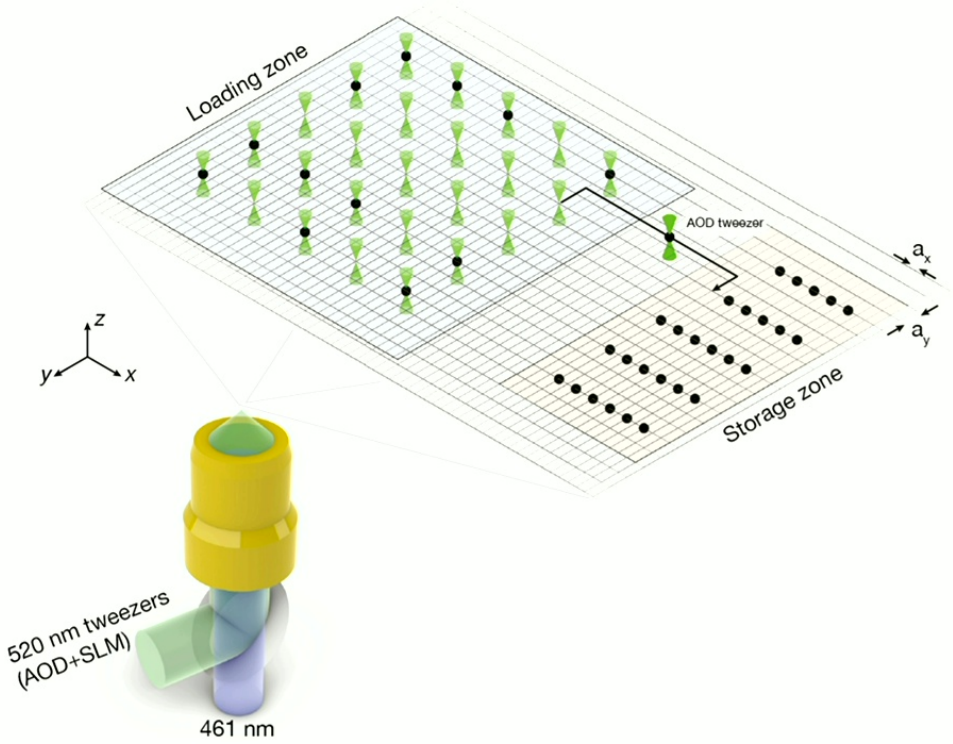
Direct single plane loading from MOT in strongly anisotropic potential!

Tao, ... Zeiher, PRL **133**, 013401 (2024)
See also: Buob, ..., Tarruell, PRX Quantum **5**, 020316 (2024)
Kaufman lab @ JILA
Scaling: Manetsch, ..., Endres, arXiv:2403.12021 (2024)

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Idea: Use optical lattice as storage zone to enable continuous reloading of atoms in loading zone



Paradigm shift:

From repeated single-shot measurements to iteratively assembled and continuously operated arrays

Johannes Zeiher

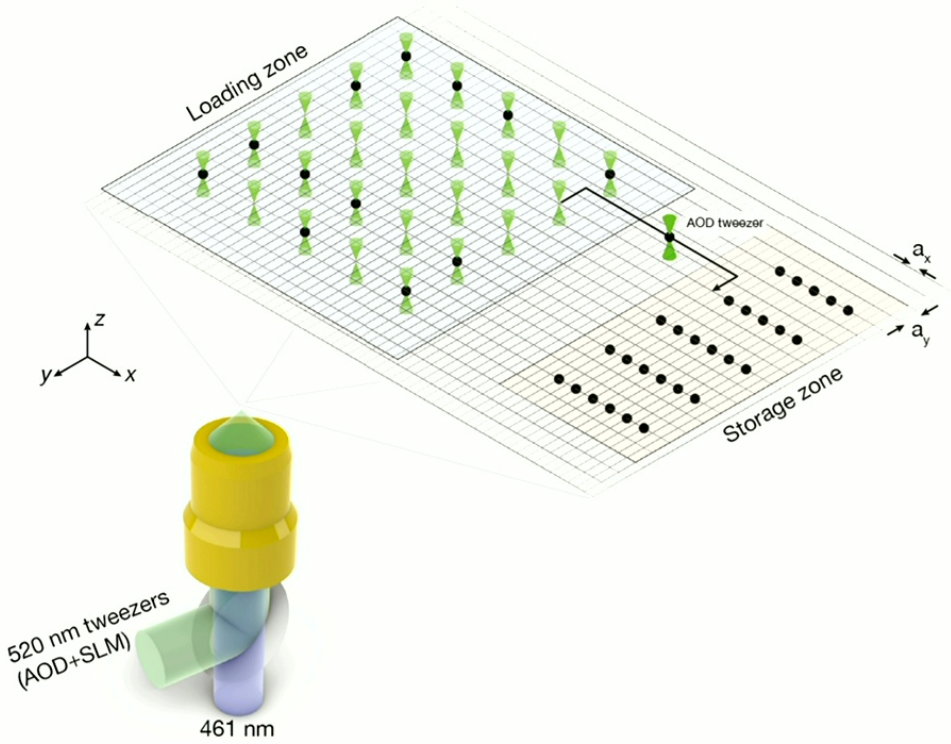
Gyger, ... Zeiher, Phys. Rev. Research **6**, 033104 (2024)
Norcia, ... Bloom, PRX Quantum **5**, 030316 (2024)

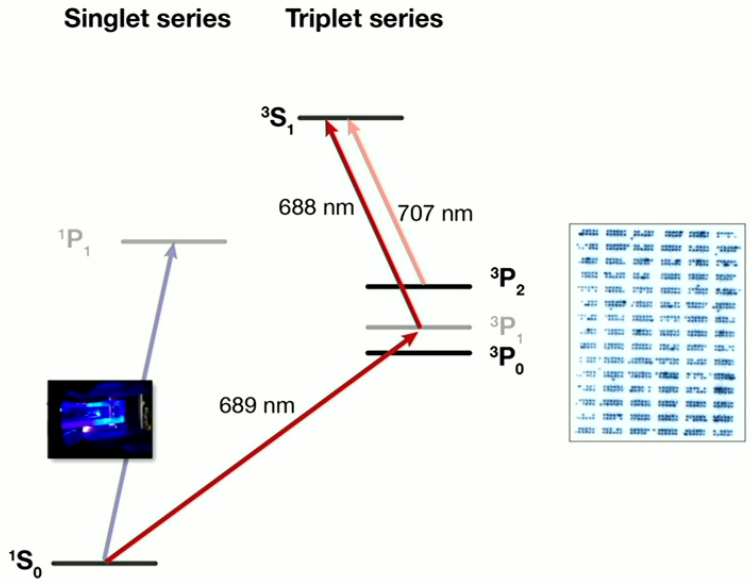
Related: Shaw, ..., Endres, PRL 130, 193402 (2023)
Singh, ... Bernien, PRX **12**, 011040 (2022)

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Requirements

Idea: Use optical lattice as storage zone to enable continuous reloading of atoms in loading zone





Hide the stored atoms in the metastable states!

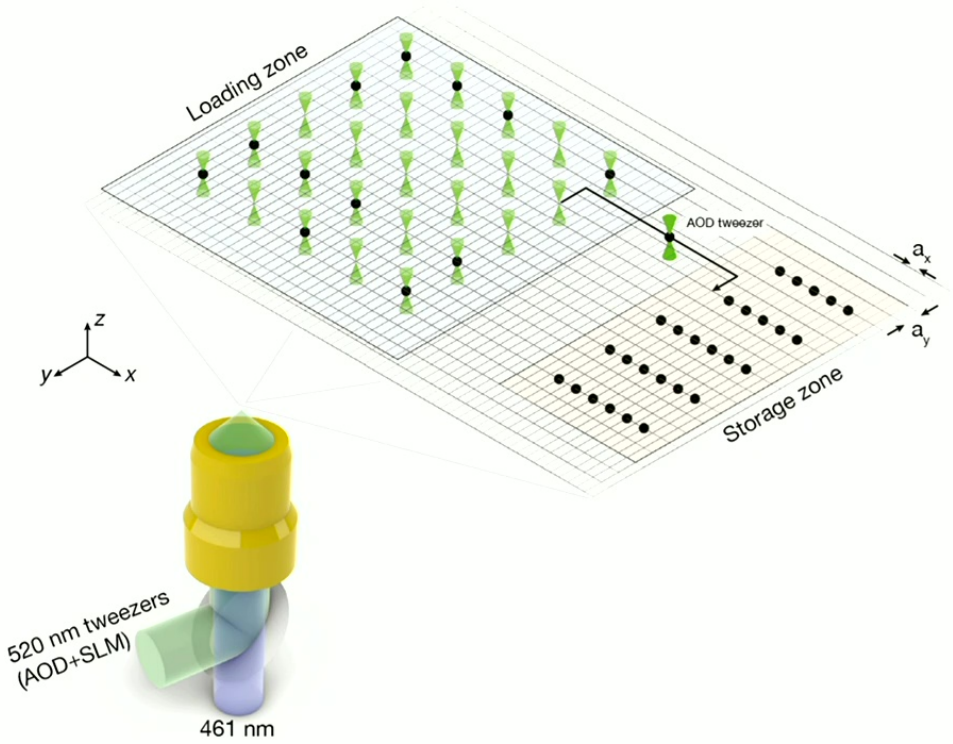
Johannes Zeiher

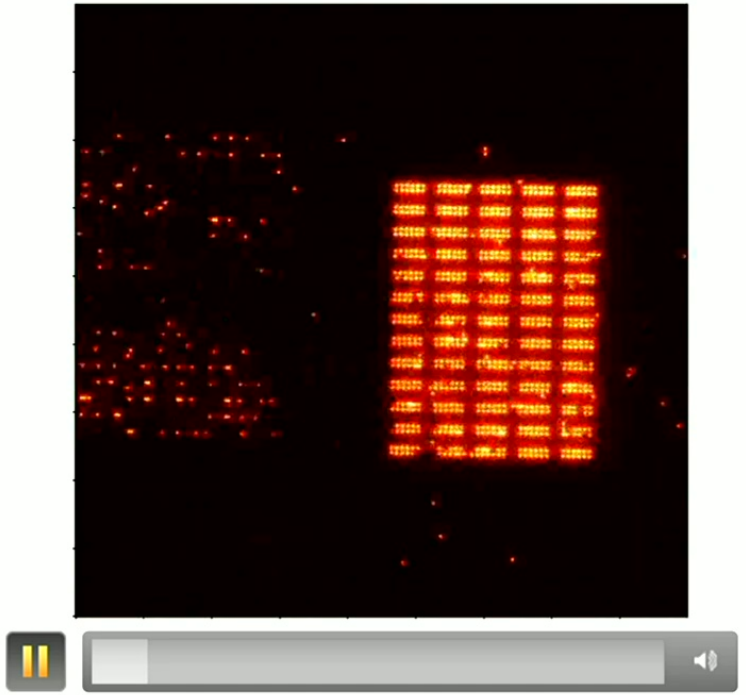
Gyger, ... Zeiher, Phys. Rev. Research **6**, 033104 (2024)
Norcia, ... Bloom, PRX Quantum **5**, 030316 (2024)

Related: Shaw, ..., Endres, PRL 130, 193402 (2023)
Singh, ... Bernien, PRX **12**, 011040 (2022)

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Idea: Use optical lattice as storage zone to enable continuous reloading of atoms in loading zone





Johannes Zeiher

Gyger, ... Zeiher, Phys. Rev. Research **6**, 033104 (2024)
Norcia, ... Bloom, PRX Quantum **5**, 030316 (2024)

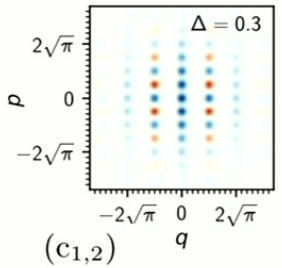
Related: Shaw, ..., Endres, PRL 130, 193402 (2023)
Singh, ... Bernien, PRX **12**, 011040 (2022)

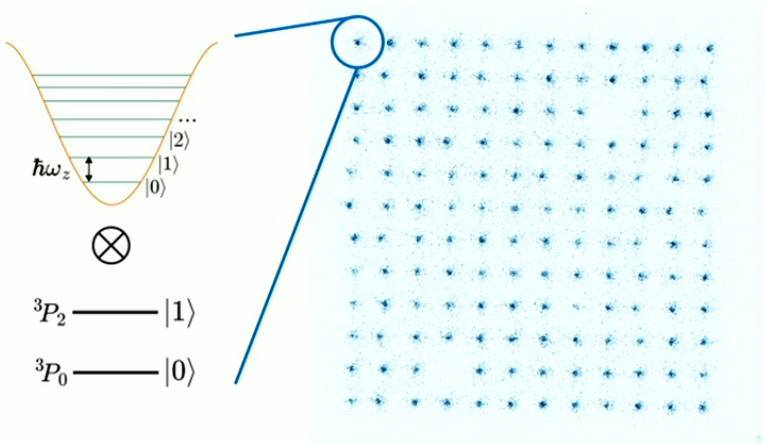
MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

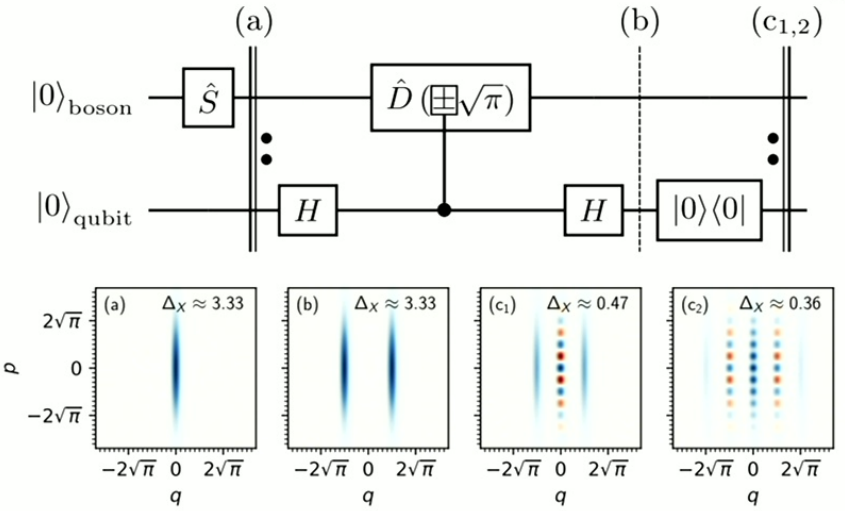
GKP codes

Idea: Combine internal and external degrees of freedom for encoding a logical qubit

Bohnmann, ..., Zeiher, Mueller, arXiv:2408.14251 (2024)







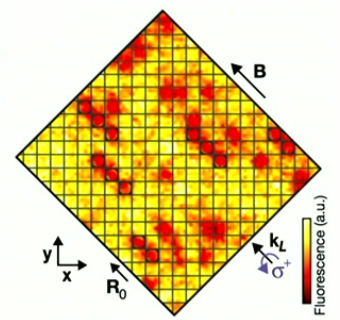
Johannes Zeiher

Ofek, ..., Schoelkopf, Nature **536**, 441 (2016)
Fluehmann, ..., Home, Nature **566**, 513 (2019)

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

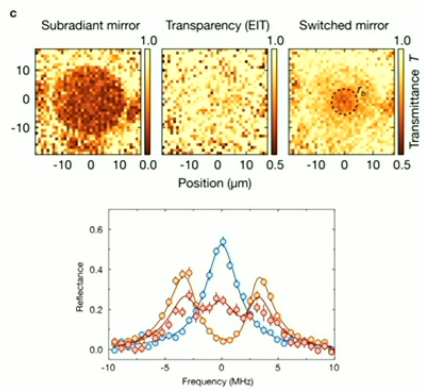
Quantum matter interfaces

Macrodimerons: Rydberg molecules bound by light



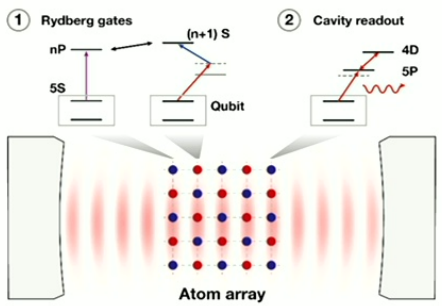
Hollerith,... Zeiher, arXiv:2401.05129 (2024)

Quantum optics with atom arrays

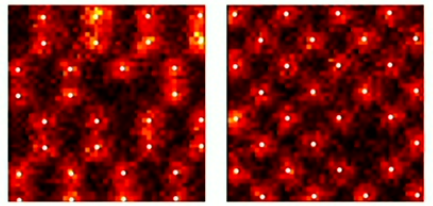


Srakaew,... Zeiher, Nat. Phys. **19**, 714 (2023)

Cavity-enabled readout & error correction in Rydberg atom arrays



Quantum simulation of many-body systems far from equilibrium



Adler,... Zeiher, arXiv:2401.14896 (2024)

Poster:
Jacopo
De Santis

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK

Summary

✓ **Extended Hubbard models with Rydberg dressing**

- Stroboscopic sequence for extended coherece times
- Observation of bound states & low-energy state preparation

✓ **Strontium as a QC platform**

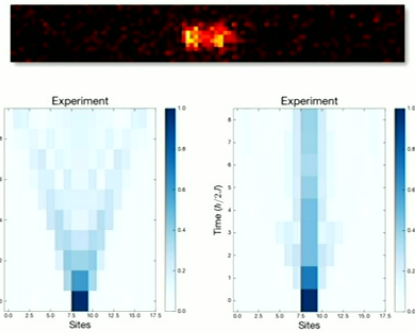
- Highly coherent Rydberg dynamics
- Fast and highly coherent qubits

✓ **Continuous loading**

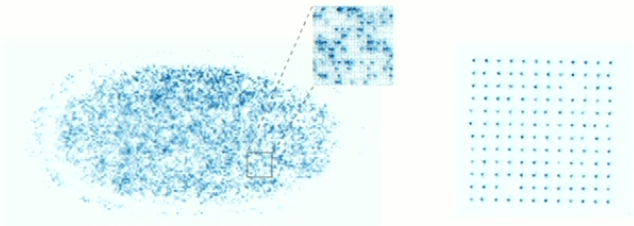
- Iterative assembly of large-scale arrays
- Continuous operation of large-scale arrays

Outlook

- Quantum optics in subwavelength optical arrays
- Fast cavity-based readout of Rydberg atom arrays



Weckesser, ... Zeiher, arXiv:2405.20128 (2024)



Tao, ... Zeiher, PRL **133**, 013401 (2024)
Gyger, ... Zeiher, PRR **6**, 033104 (2024)

Rui, ..., Bloch, Nature **583**, 369 (2020)
Srakaew, ..., Zeiher, Nat. Phys. **19**, 714 (2023)

Johannes Zeiher

MAX-PLANCK-INSTITUT
FÜR QUANTENOPTIK