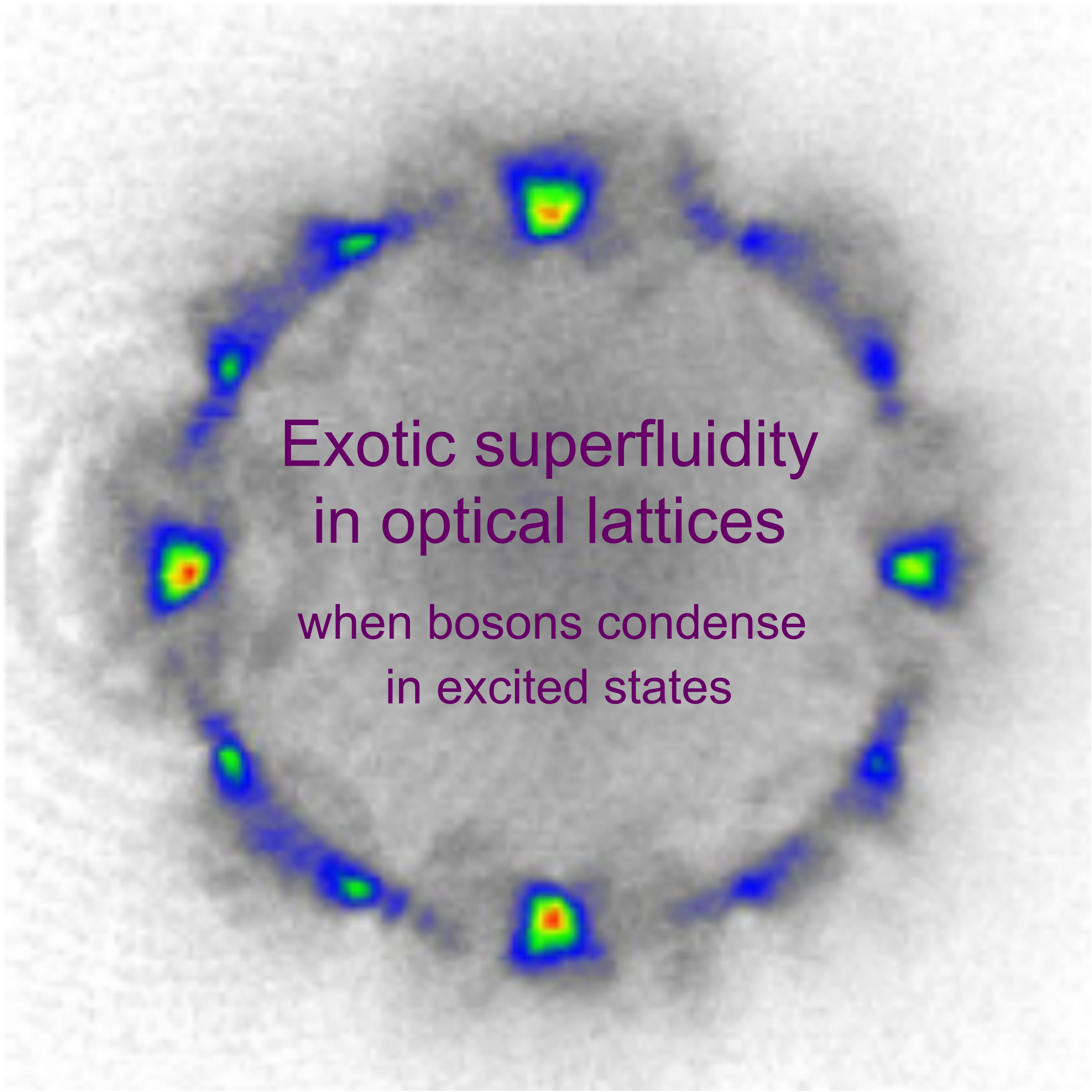
Universität Hamburg

INSTITUT FÜR LASERPHYSIK

Zentrum für Optische Quantentechnologien

Andreas Hemmerich

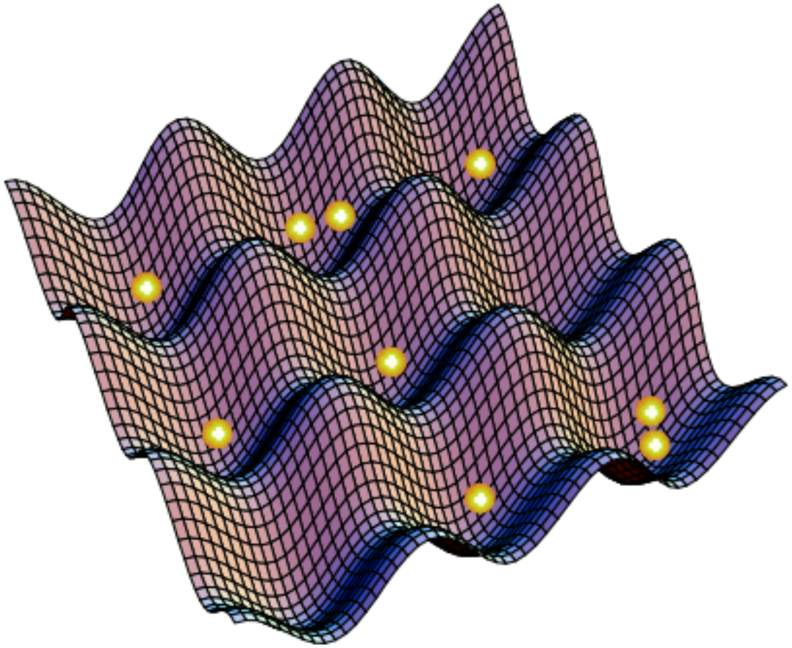


Exotic superfluidity in optical lattices

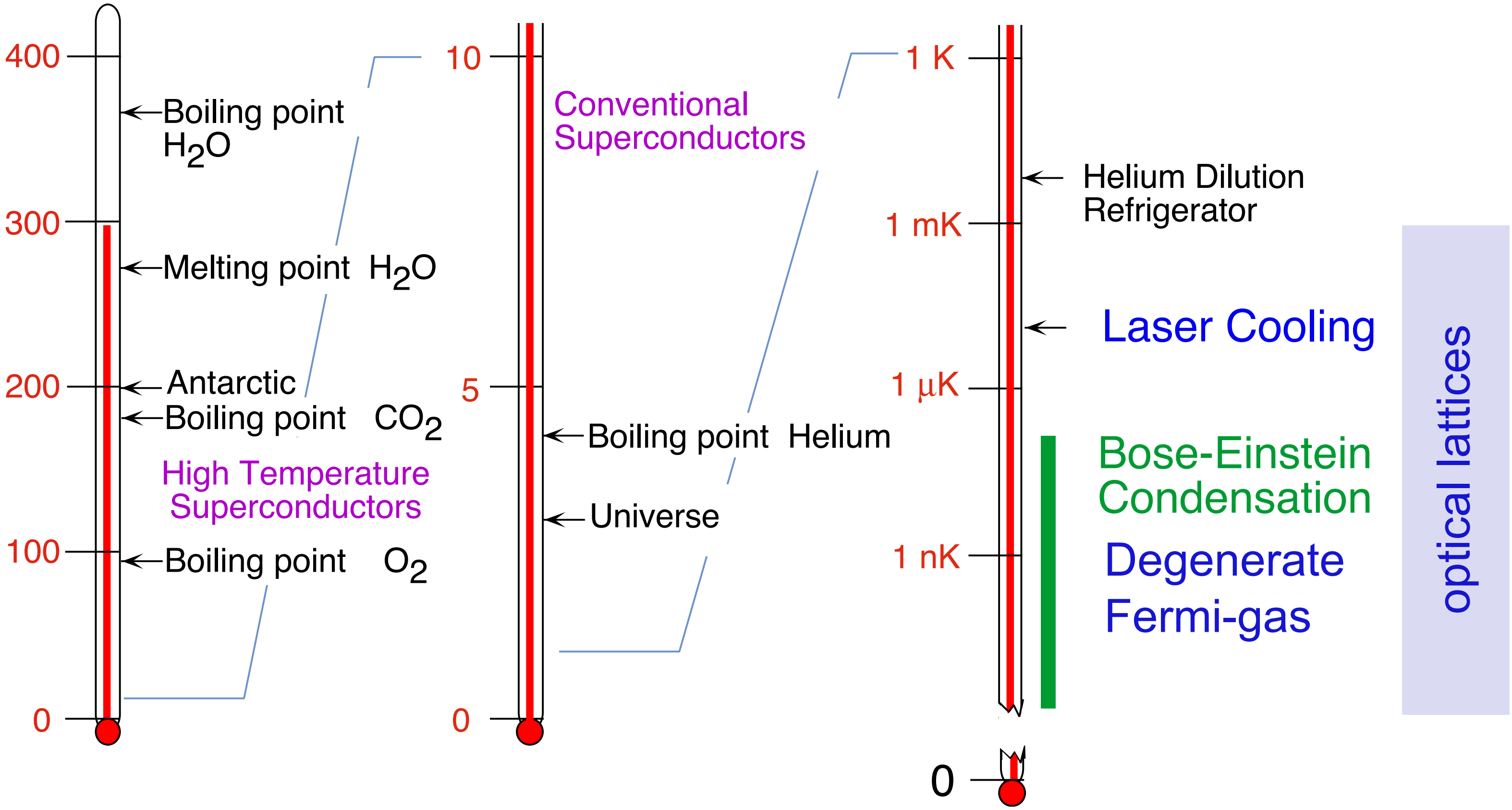
when bosons condense in excited states

Optical lattice =

Ultracold atoms in a lattice made of light



How cold is cold?



400

300

200

100

0

Boiling point H_2O

Melting point H_2O

Antarctic

Boiling point CO_2

High Temperature Superconductors

Boiling point O_2

10

5

0

Conventional Superconductors

Boiling point Helium

Universe

1 K

1 mK

1 μK

1 nK

0

Helium Dilution Refrigerator

Laser Cooling

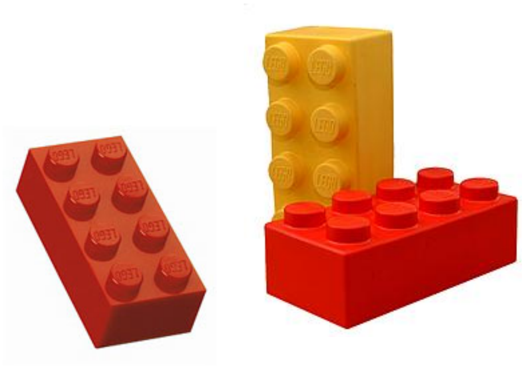
Bose-Einstein Condensation

Degenerate Fermi-gas

optical lattices

Optical lattices, why bother ?

Study many-body phenomena at ultralow temperatures in synthetic lattices with



extreme purity
no impurities or disorder unless designed
bottom-up design of lattice systems

extreme control
quantum statistic of particles: fermions, bosons, mixtures
interaction: attractive, repulsive, short range, long range
dimensionality: 1D, 2D, 3D
lattice geometry: any crystallographic class & quasiperiodic & disordered
unit cell: monopartite, multipartite
band structure: custom-tailored topology, orbital physics in higher bands
artificial gauge potentials: abelian and non-abelian

Light shift potentials ...

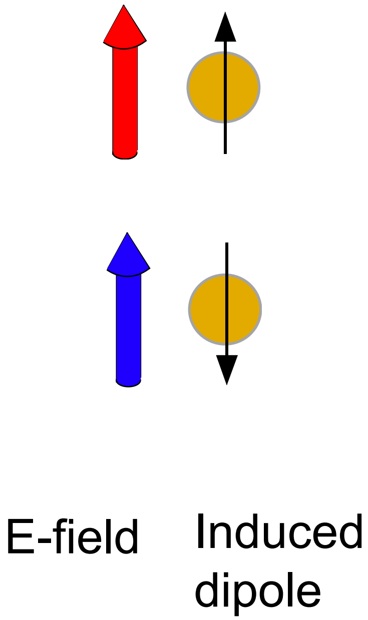
1968 Vladilen Lethokov: lattices of neutral atoms confined in the interference patterns of superimposed laser beams

sub-wavelength confinement → eliminate Doppler-effect

well depths only a few 100 μK → need extremely efficient cooling

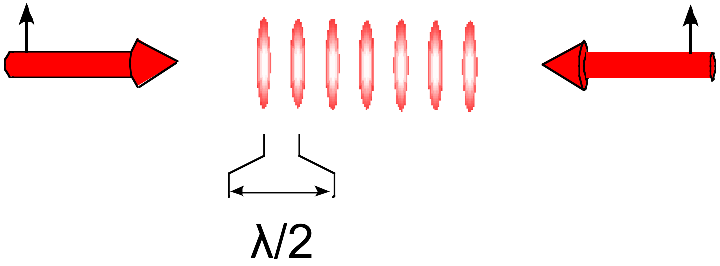
red detuned light → atoms are trapped in antinodes

blue detuned light → atoms are trapped in nodes

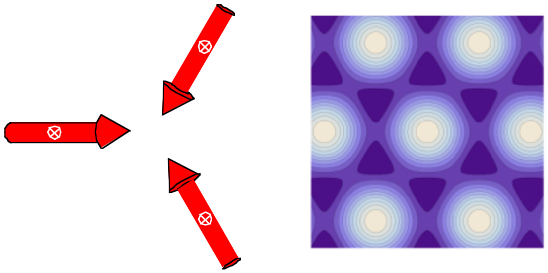


A. Ashkin, Phys. Rev. Lett. 40, 729, (1978)

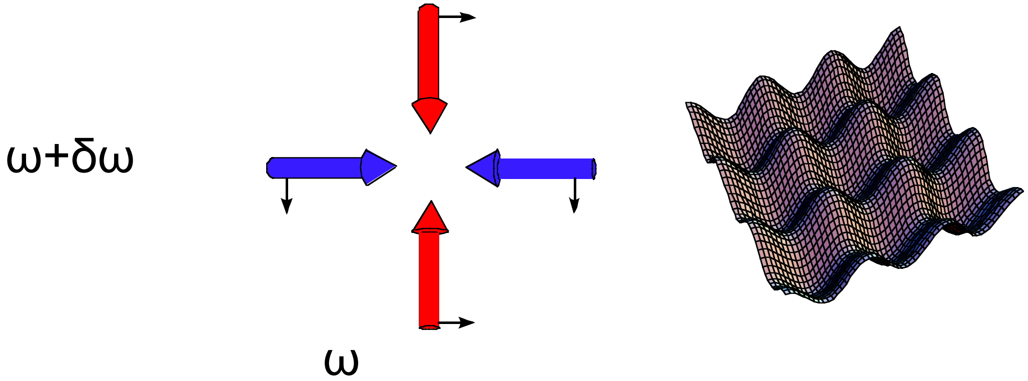
G.P. Gordon & A. Ashkin, Phys. Rev. A 21, 1606, (1980) 2 Beams → 1D lattice of disks



3 Beams → 2D triangular or hexagonal (cf. Graphene) lattice



4 Beams → 2D square lattice of tubes

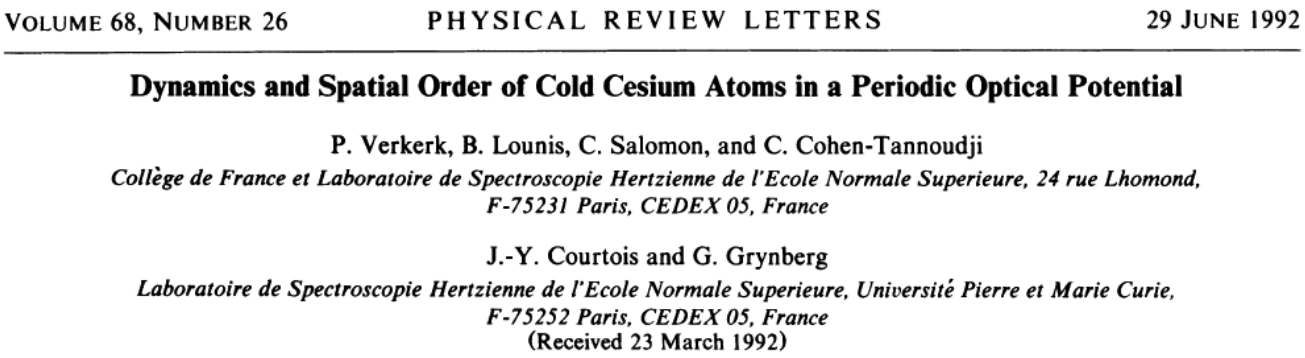


Also: 3D, multipartite, quasi-periodic, disorder potentials, ...

Lethokovs vision becomes reality ...

1980 - 1990: Development of laser cooling, Nobelprize 1997

1992: First 1D optical lattice of laser-cooled atoms



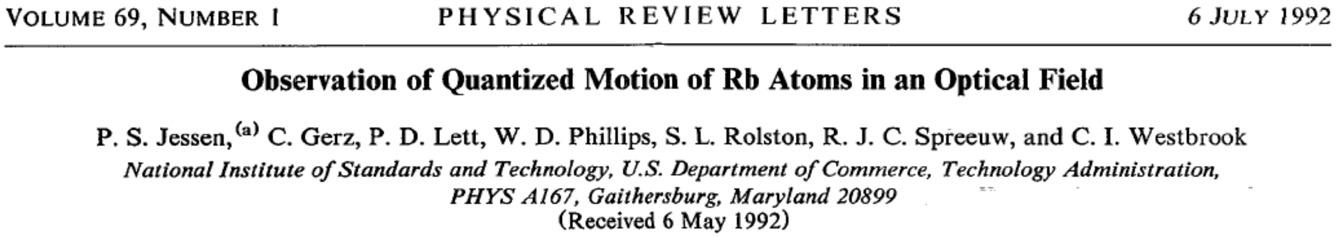
VOLUME 68, NUMBER 26 PHYSICAL REVIEW LETTERS 29 JUNE 1992

Dynamics and Spatial Order of Cold Cesium Atoms in a Periodic Optical Potential

P. Verkerk, B. Lounis, C. Salomon, and C. Cohen-Tannoudji
Collège de France et Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Superieure, 24 rue Lhomond, F-75231 Paris, CEDEX 05, France

J.-Y. Courtois and G. Grynberg
Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Superieure, Université Pierre et Marie Curie, F-75252 Paris, CEDEX 05, France

(Received 23 March 1992)



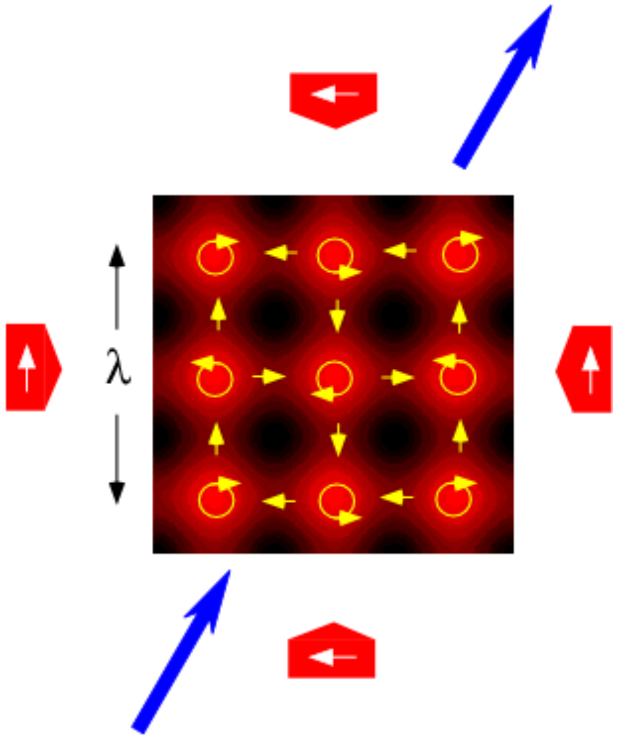
VOLUME 69, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1992

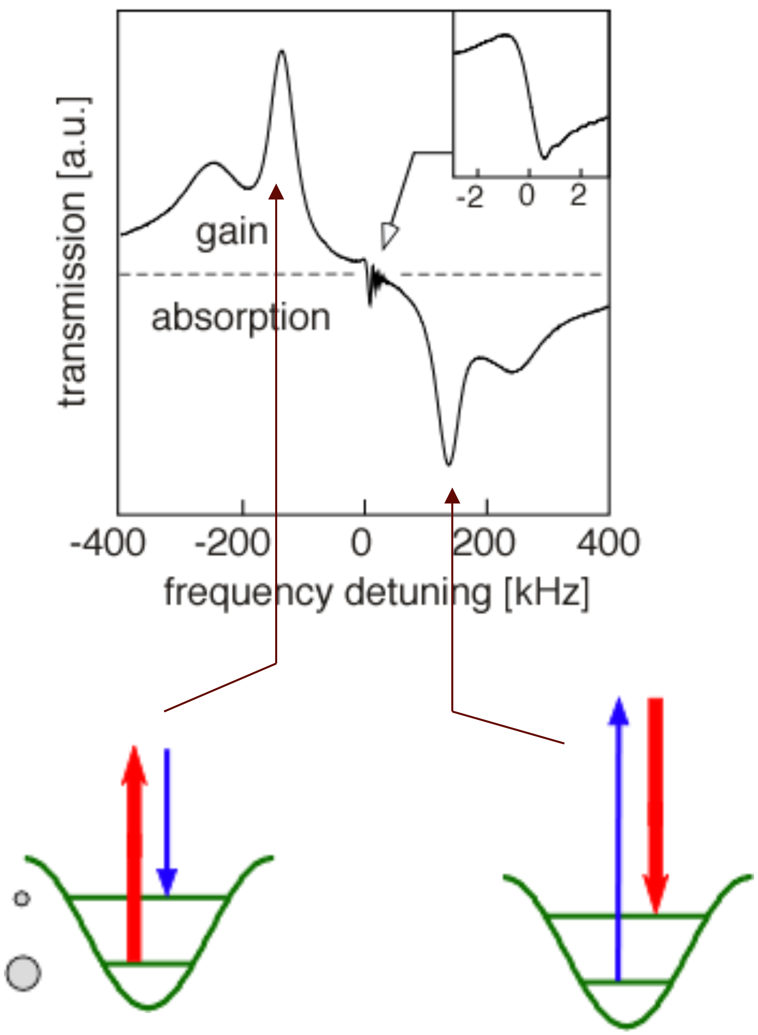
Observation of Quantized Motion of Rb Atoms in an Optical Field

P. S. Jessen,(a) C. Gerz, P. D. Lett, W. D. Phillips, S. L. Rolston, R. J. C. Spreeuw, and C. I. Westbrook
National Institute of Standards and Technology, U.S. Department of Commerce, Technology Administration, PHYS A167, Gaithersburg, Maryland 20899

(Received 6 May 1992)

1993: First 2D and 3D optical lattices with laser-cooled atoms





Occupation < 5% → interaction negligible

Deep wells → tunneling negligible

Array of isolated quantum oscillators

with few vibrational levels occupied

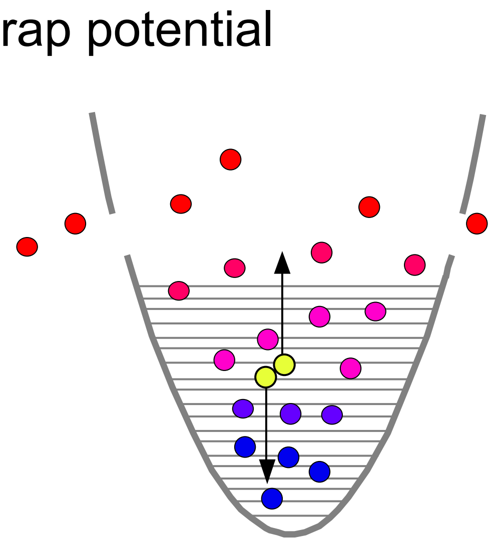
Temperature = few μK

A. Hemmerich & T. Hänsch, PRL 70, 410 (1993)

Cooling beyond the limits of laser cooling

Cooling by evaporation:

H. Hess, Phys. Rev. B, 34, 3476 (1986).



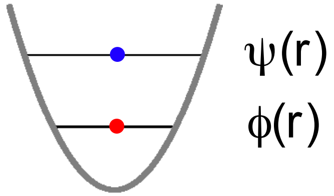
Below critical temperature: quantum degeneracy

bosons or fermions ?

Bosons & Fermions

In quantum mechanics, particles are described by wave functions

Distinguishable particles $\chi(r_1,r_2)=\phi(r_1)\psi(r_2)$



No individualism for quantum particles of same sort

Indistinguishable particles $\chi(r_1,r_2)=\phi(r_1)\psi(r_2) \pm \psi(r_1)\phi(r_2) \Rightarrow \chi(r_1,r_2)=\pm\chi(r_2,r_1)$

\+ Bosons $\phi = \psi \Rightarrow \chi(r_1,r_2) \propto \phi(r_1)\phi(r_2)$

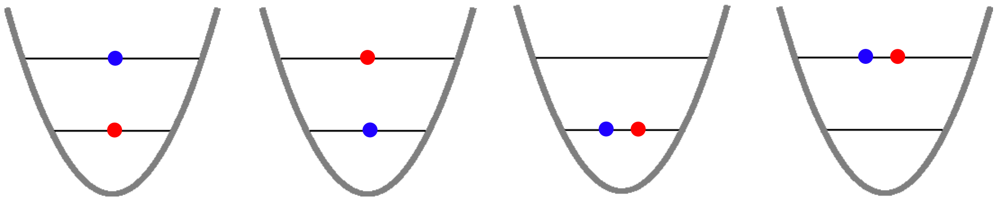
\- Fermions $\phi = \psi \Rightarrow \chi(r_1,r_2) = 0$

Pauli principle:

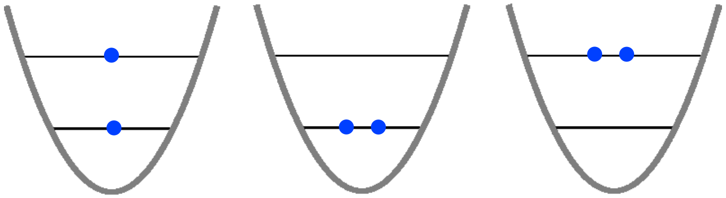
Fermions cannot share the same single particle state

Fermions avoid each other but bosons like to be together

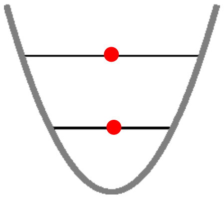
Distinguishable particles



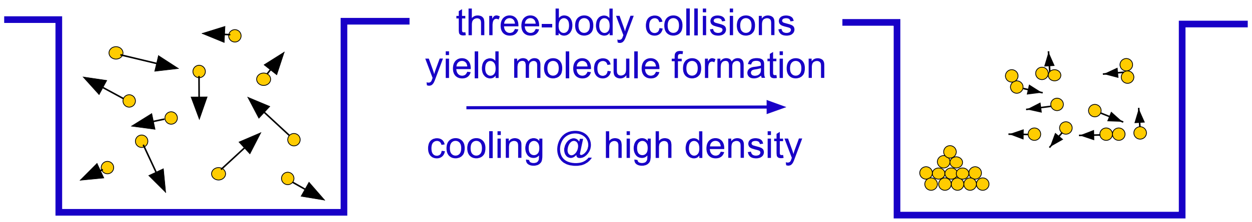
Bosons



Fermions

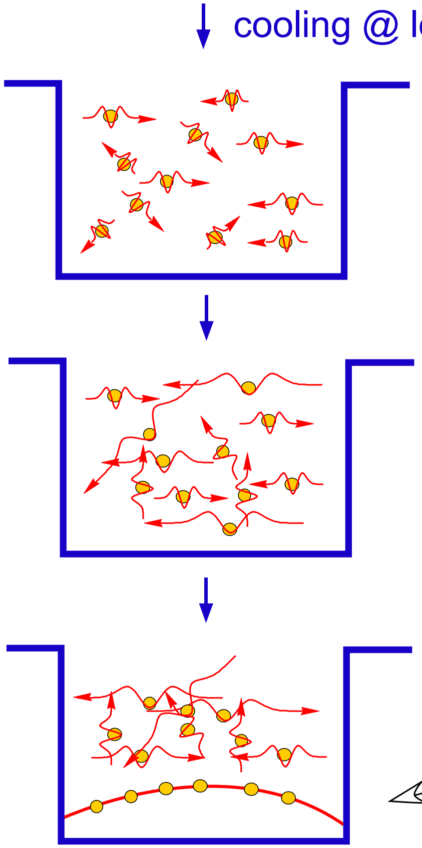


Bosons condense in the ground state



three-body collisions
yield molecule formation

cooling @ high density



cooling @ low density

$$k_BT = \frac{1}{2} m\bar{V}^2$$

$$m\bar{V} = \hbar \frac{2\pi}{\Lambda}$$

$\Rightarrow$ Thermal de Broglie Wavelength:

$$\Lambda = \left(\frac{h^2}{2mk_BT}\right)^{1/2}$$

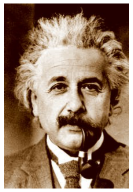
Luis Victor
de Broglie

Critical Temperature:

de Broglie Wavelength Λ $\approx$ mean particle separation d $\approx$ $1/\rho^{1/3}$

$$T = \frac{h^2\,\rho^{2/3}}{2m\,k_B}$$

Satyendra
Nath Bose

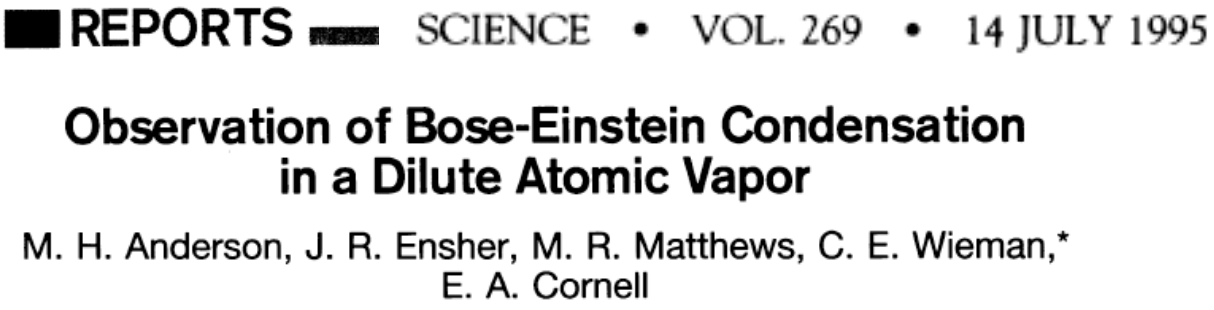


Albert
Einstein

Bose-Einstein-Condensate

1995 Bose-Einstein condensation of ultracold dilute gases

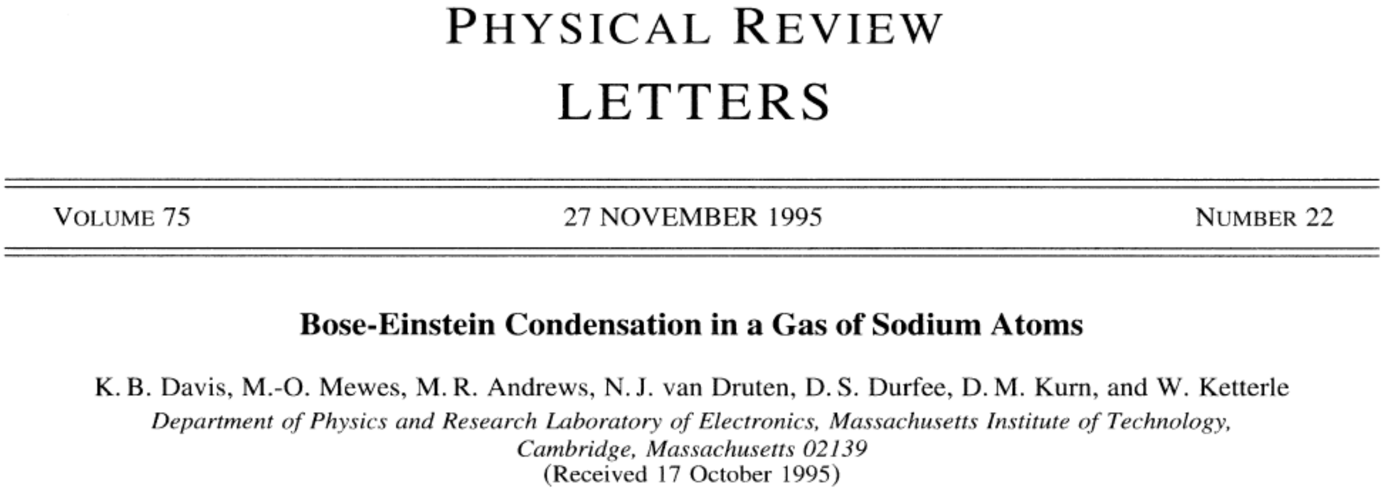
Nobelprize 2001



REPORTS SCIENCE • VOL. 269 • 14 JULY 1995

Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman,*
E. A. Cornell



PHYSICAL REVIEW
LETTERS

VOLUME 75 27 NOVEMBER 1995 NUMBER 22

Bose-Einstein Condensation in a Gas of Sodium Atoms

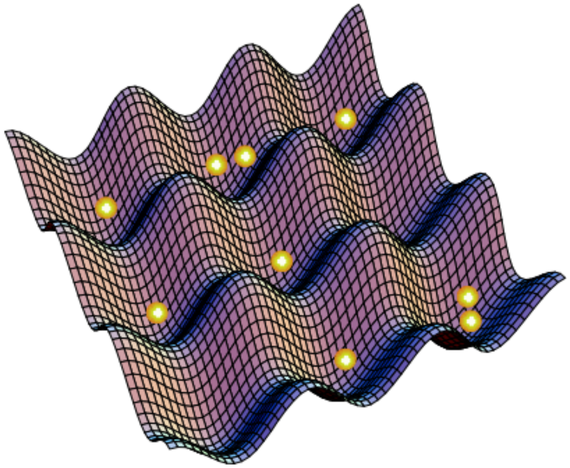
K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139
(Received 17 October 1995)

1999 quantum degenerate Fermi-gases: D. Jin ‘s group, JILA

Quantum gases in optical lattices

load quantum degenerate gas (Bose, Fermi, Mixture)
into periodic light shift potentials

- very low temperatures (< 100 nK)
- multiply occupied lattice sites



relevant physical mechanisms

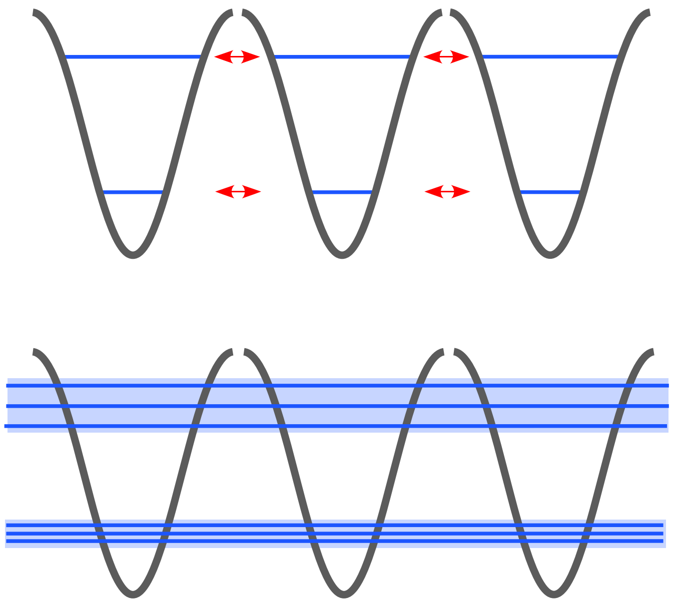
- quantum statistics
- tunneling
- collisional (on-site) interactions

construction kit for synthesising strongly correlated many body systems in perfectly controlled environments

→ study quantum phase transtions

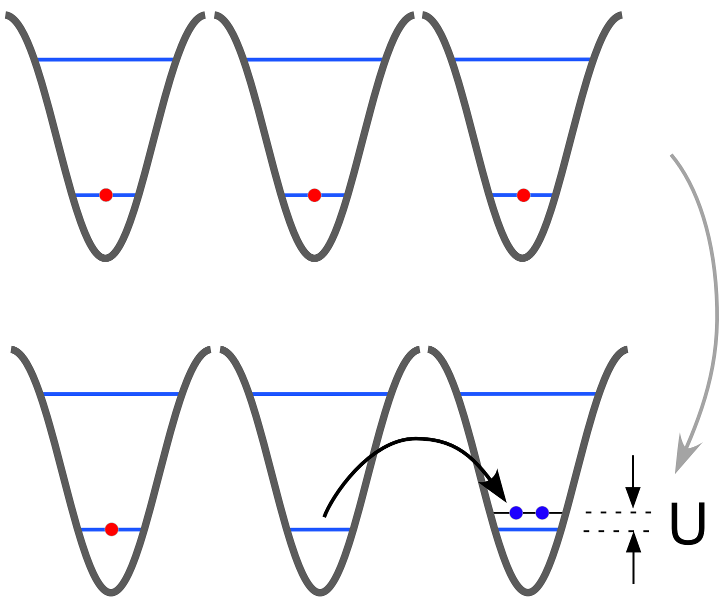
→ study non-equilibrium many-body dynamics

Competition of tunneling and (repulsive, on-site) collisions



Tunneling yields allowed energy bands separated by forbidden gaps

Atoms are delocalized across the entire lattice



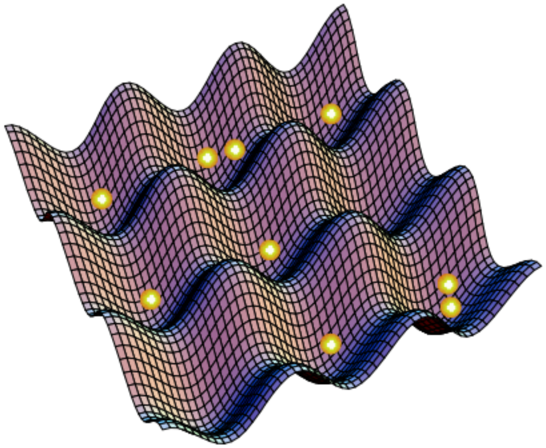
Double occupancy costs Interaction energy U

Optical Lattice with Bosons

in the ground state of the lowest band

Emulation of bosonic Hubbard-model

M. Fisher et al., Phys. Rev. B 40, 546 (1989)

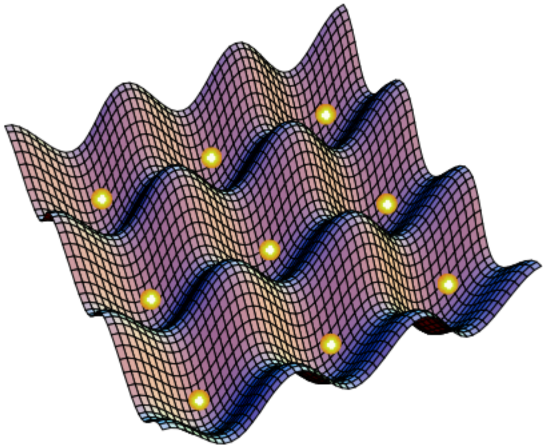


superfluid

Shallow wells
Tunneling dominates
Poissonian particle number fluctuations
Defined relative phases
→ coherence

↔

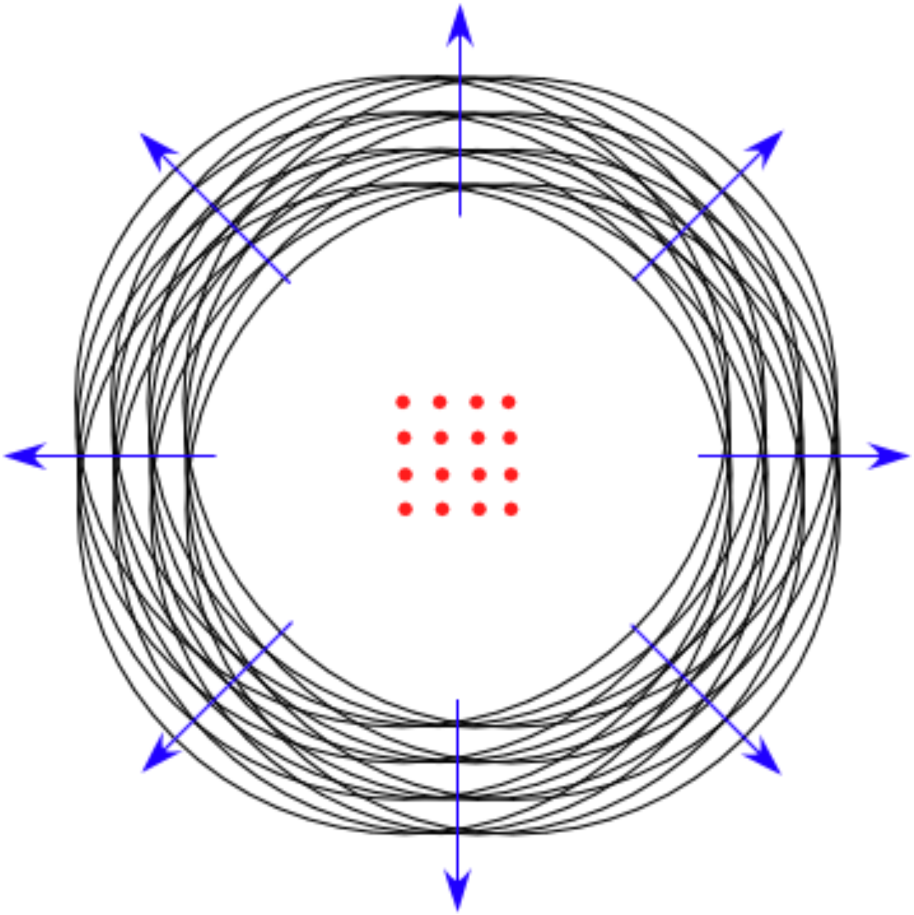
tune well depth to observe quantum phase transition



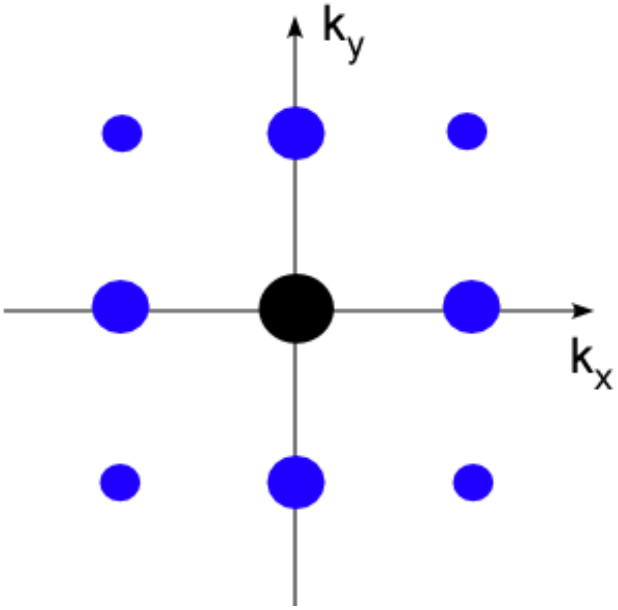
Mott insulator

Deep wells
Collisional repulsion dominates
Fixed local particle number
Relative phases undetermined
→ no coherence

Localized Bragg maxima indicate coherence



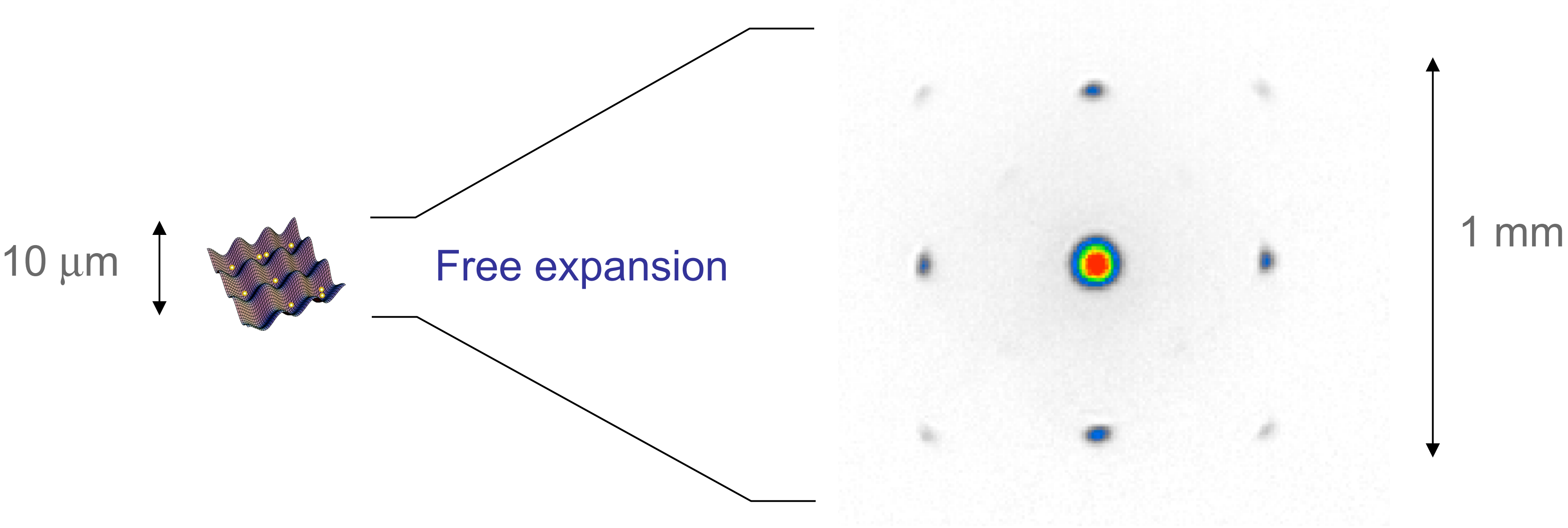
Configuration space



Momentum space

Observation of momentum spectra

- lattice potential rapidly (1 µs) switched off
- free expansion (typically 30 ms)
- absorption image



10 µm

Free expansion

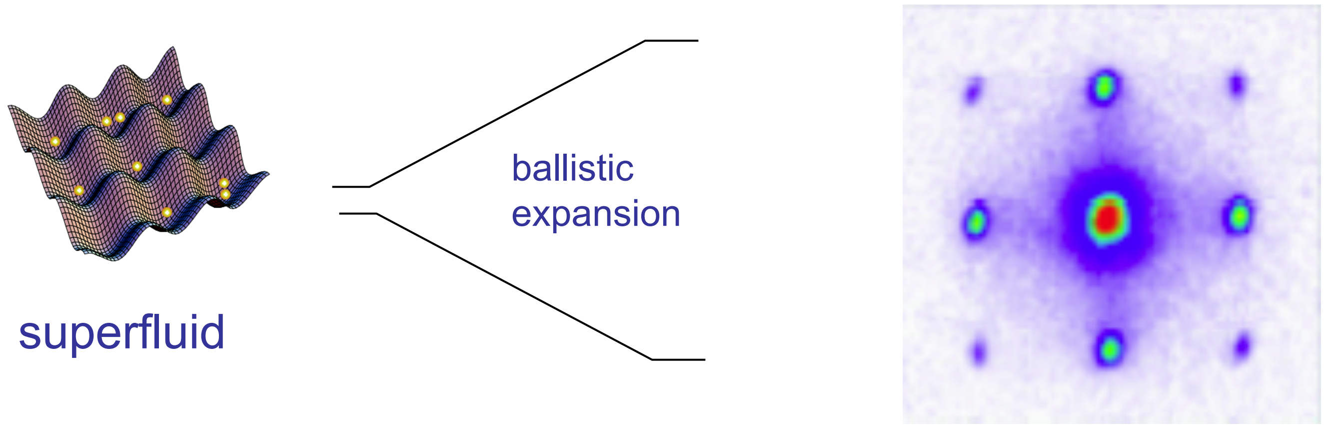
1 mm

Momentum space

localized Bragg maxima indicate coherence

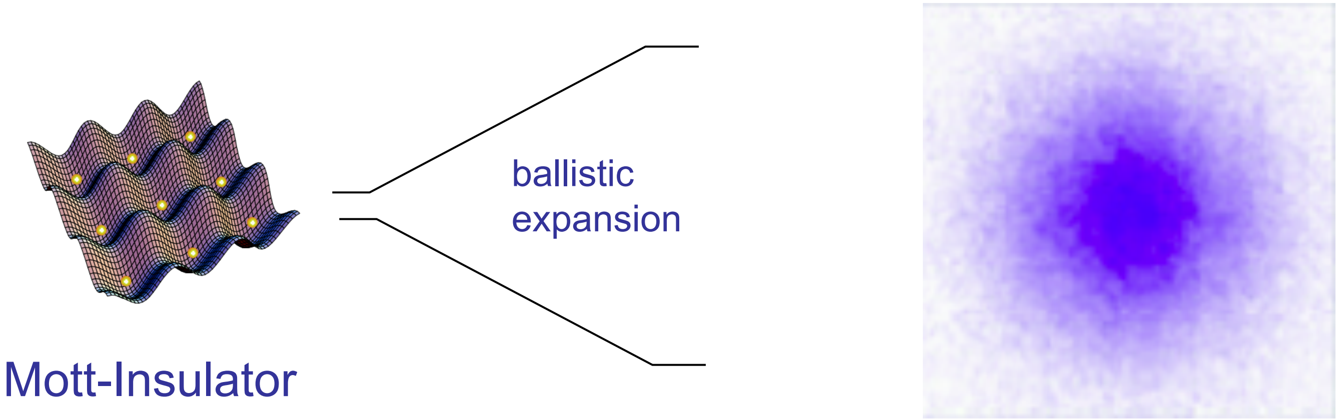
Observation of quantum phase transition

Image momentum space via ballistic expansion experiment



superfluid

ballistic
expansion



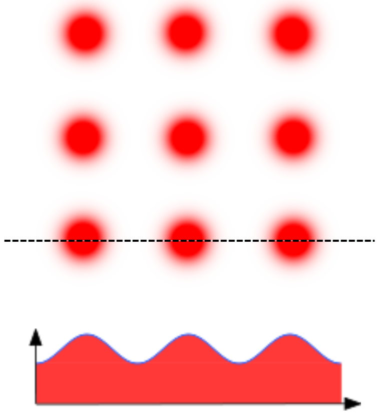
Mott-Insulator

ballistic
expansion

M. Greiner, et al., Nature 415, 39 (2002)

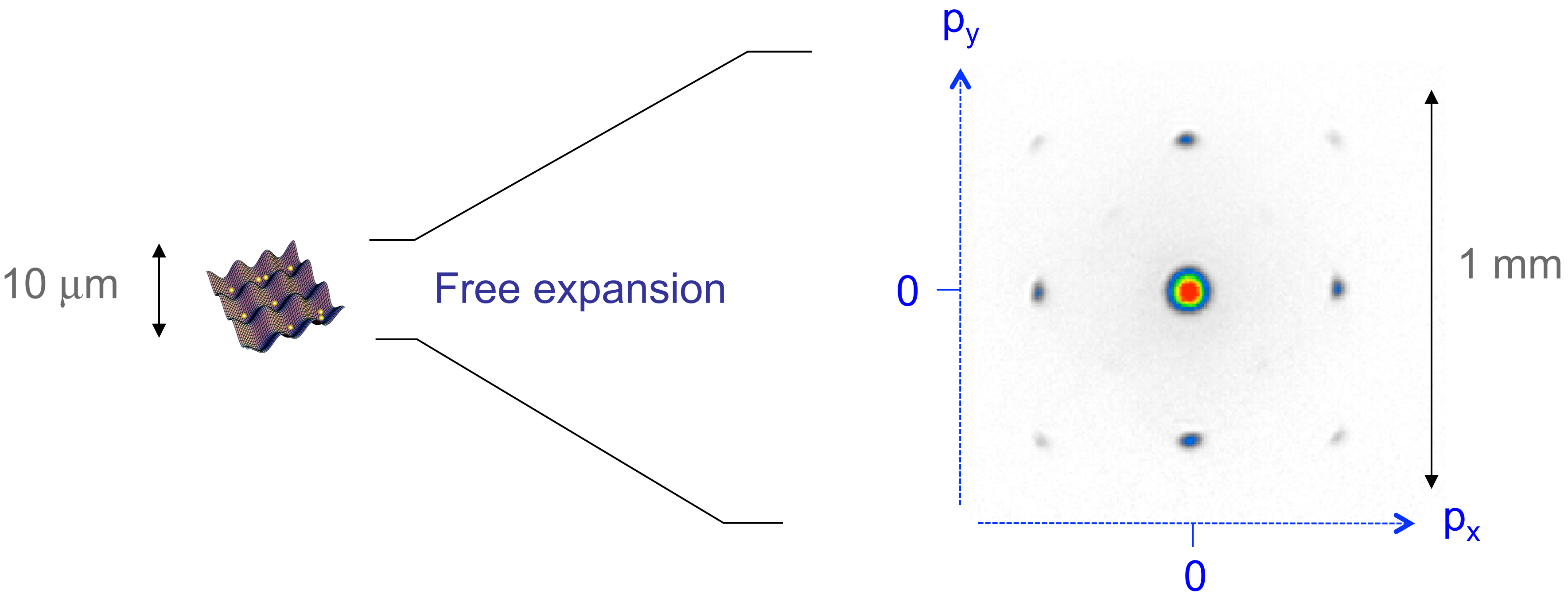
Standard optical lattice with bosons

In standard bosonic optical lattices atoms are condensed in the ground state of lowest band



→ local s-orbital at each site
ground state wave function positive definite
(cf. Feynmans no node theorem for bosons)

Lowest order Bragg peak at zero momentum



More advanced lattices with bosons?

Can we get closer to scenarios of electronic condensed matter?

magnetism & superconductivity in rare earth or transition metal compounds, Kondo-systems, quantum Hall systems, . . .

→ tailored artificial gauge fields for ground state lattices, dynamical lattices

→ orbital degrees of freedom in optical lattices excited to higher bands

Incomplete list of pioneering theory groups

(alphabetic order)

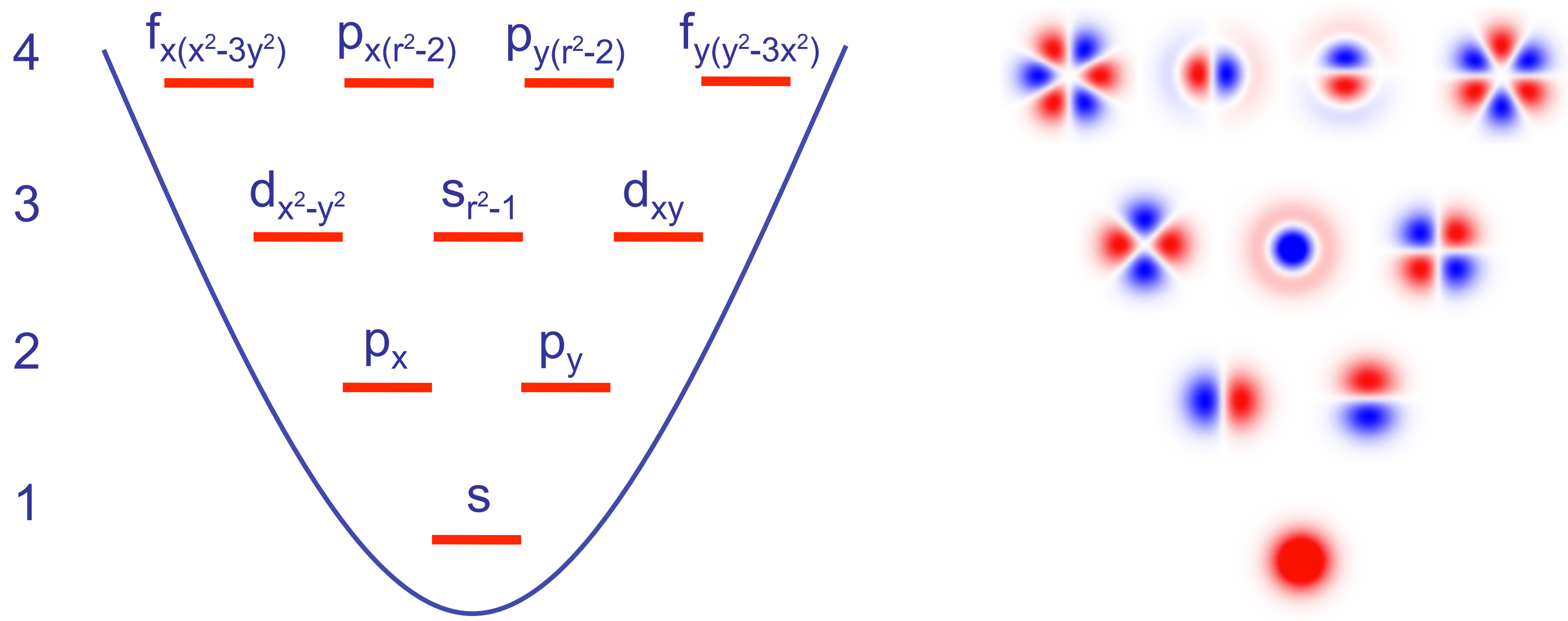
S. Girvin, J. Larson, J.-P. Martikainen, M. Lewenstein,
W. V. Liu, S. Das Sarma, C. Wu, ...

Orbital Optical Lattices

New physics in higher bands

→ anisotropic orbits

→ freedom of orientation



harmonic oscillator orbits (two dimensions)

Challenges

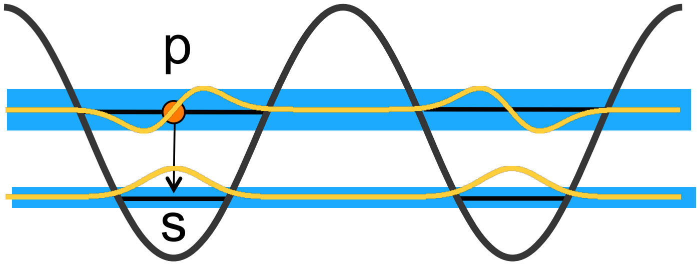
→ exciting higher bands with moderate entropy increase

→ providing cross-dimensional tunneling

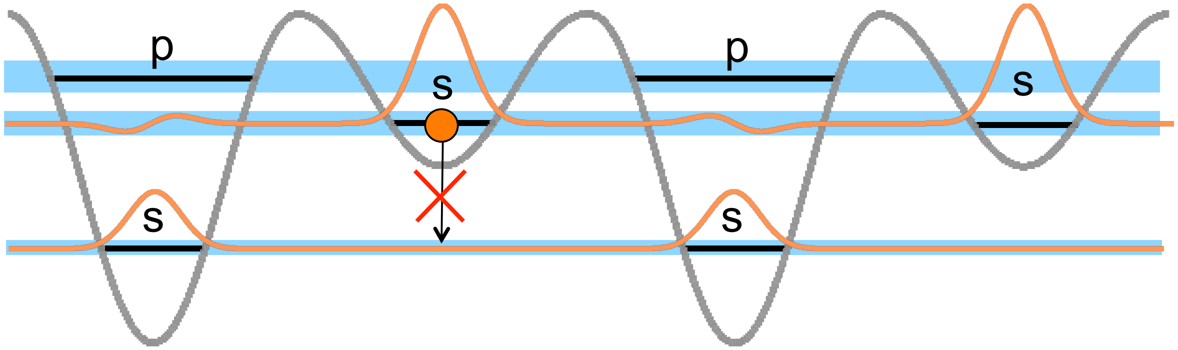
→ control of band relaxation

Control of band relaxation

simple lattice → band life time limited by collisions

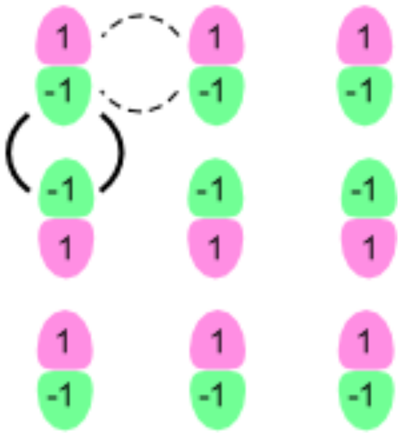


bipartite lattice → band life times up to several 100 ms

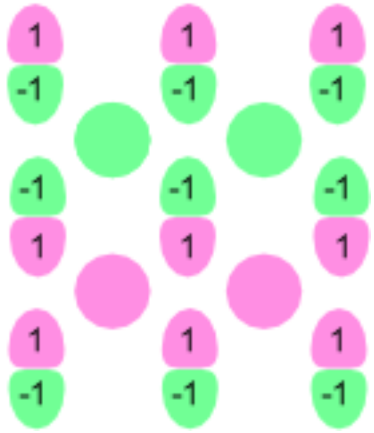


Providing cross-dimensional coherence

monopartite lattice



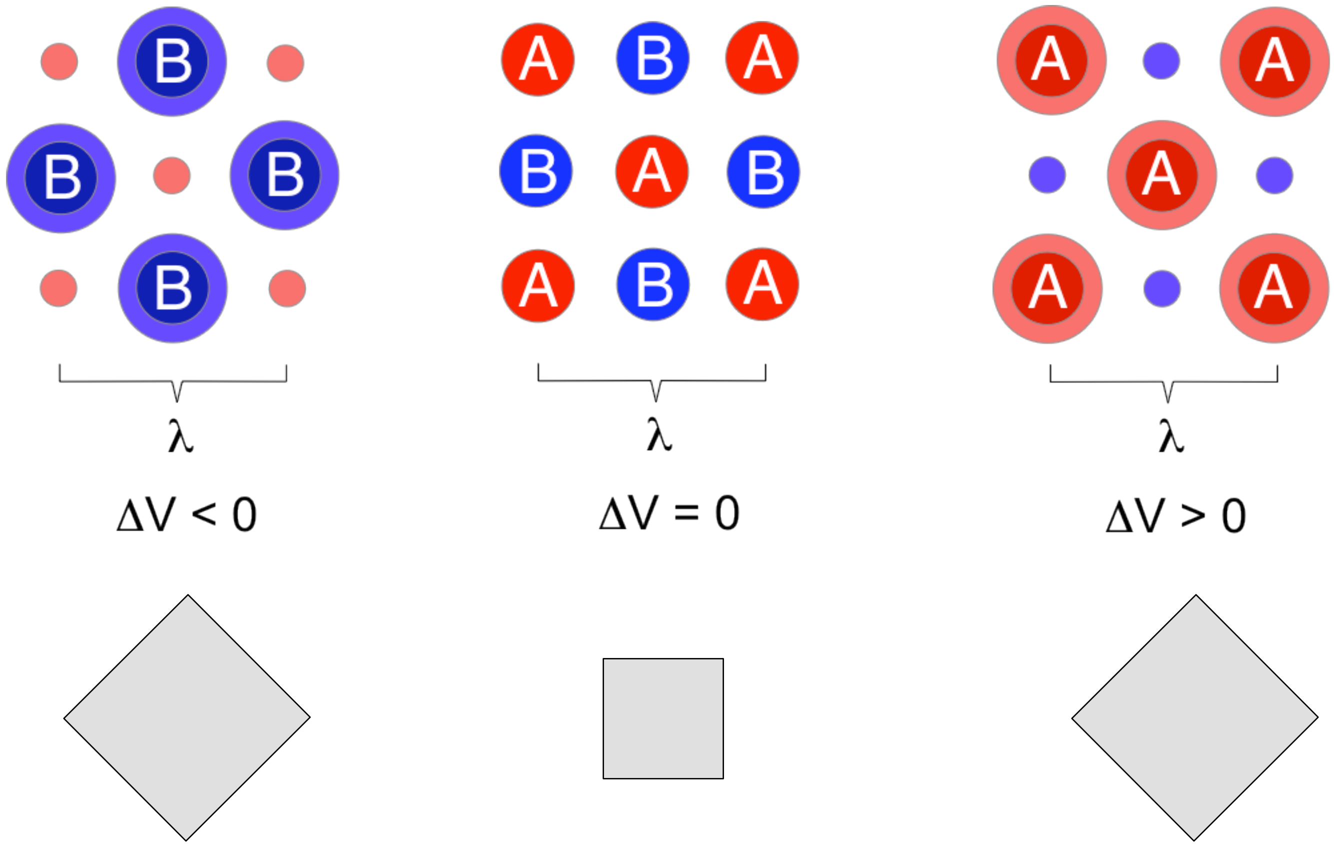
bipartite lattice



A. Isacsson and S. Girvin, Phys. Rev. A 72, 053604 (2005).
W. Vincent Liu and C. Wu, Phys. Rev. A 74, 013607 (2006).

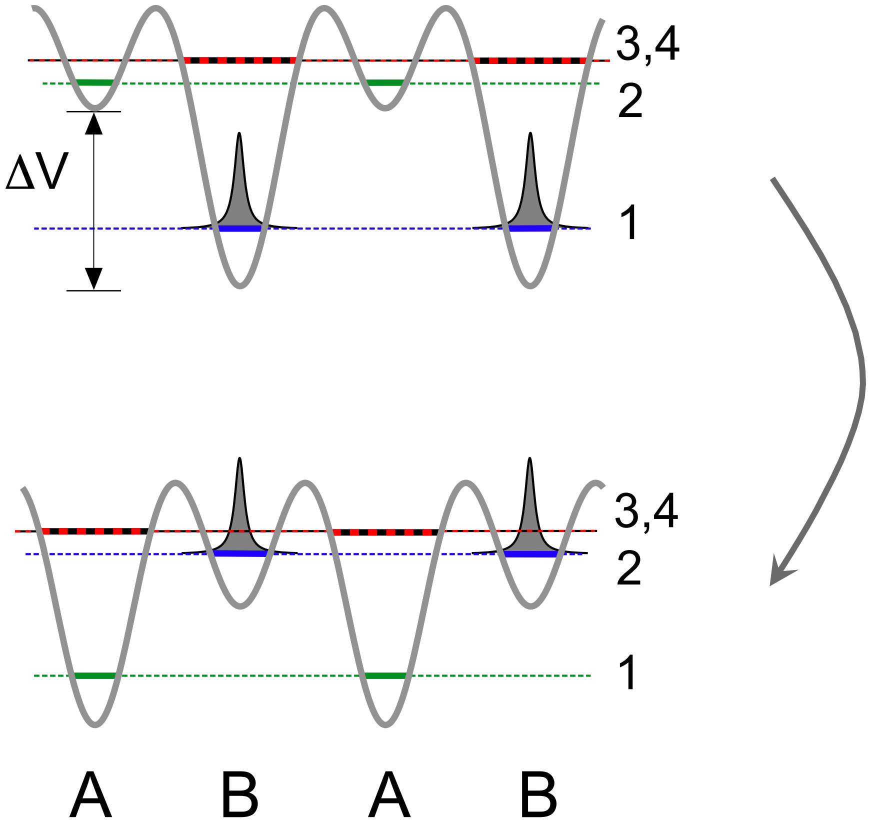
Chequerboard Lattice

Energy difference ΔV between A- and B-sites can be tuned



Wigner-Seitz
unit cells:

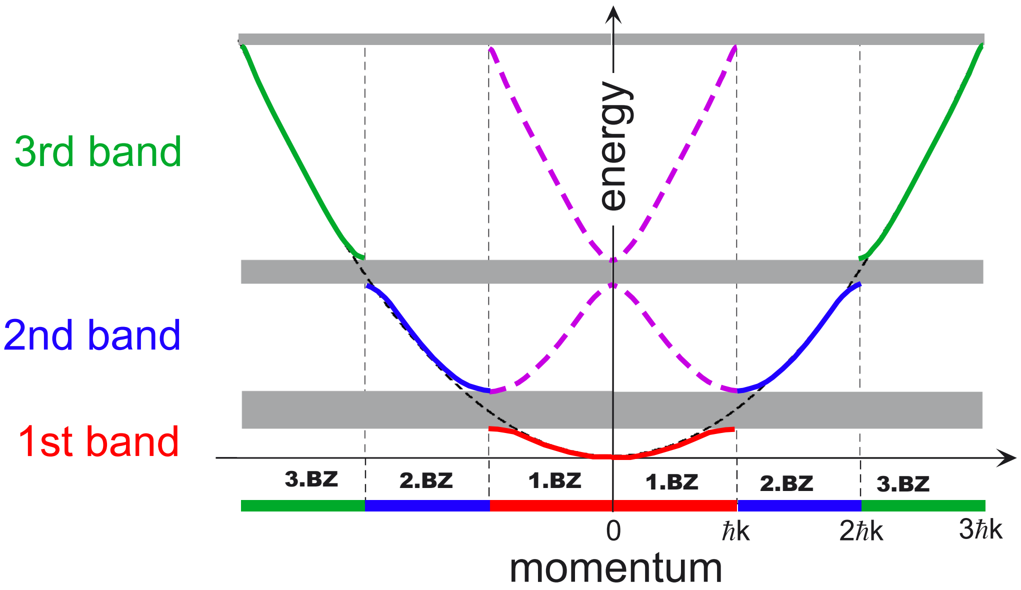
Populating higher bands



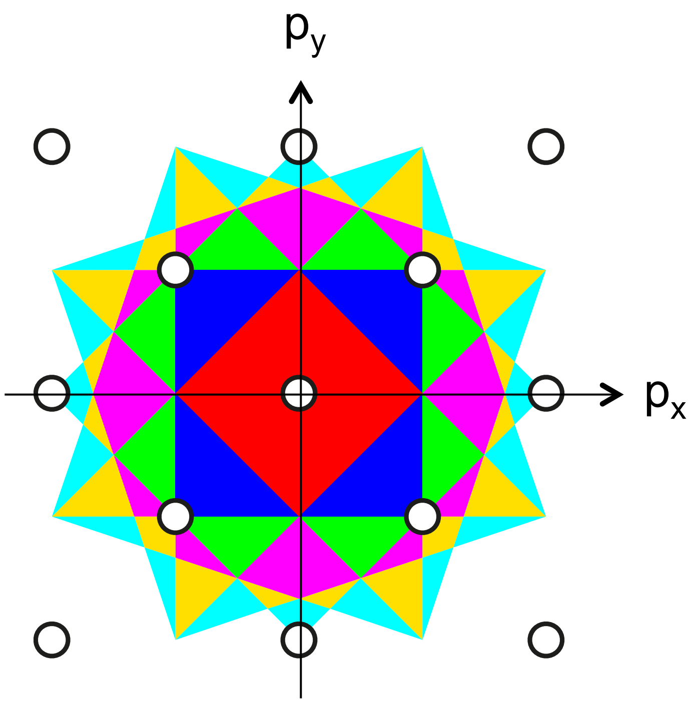
<< tunneling time

\>> on-site oscillation period

Observing atoms in higher bands



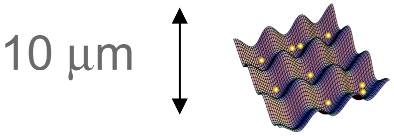
1 dimension



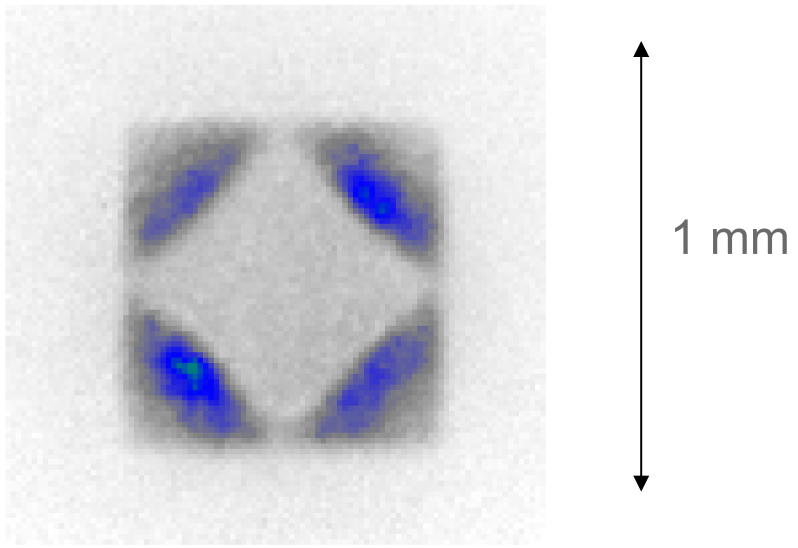
2 dimensions

Band mapping

- lattice potential slowly (> 400 µs) switched off
- free expansion for 30 ms
- absorption image

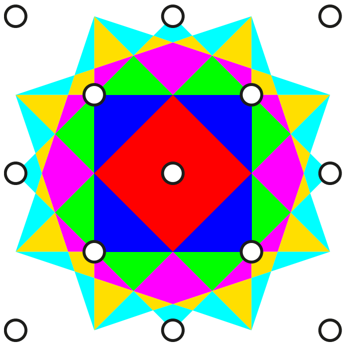


Free expansion



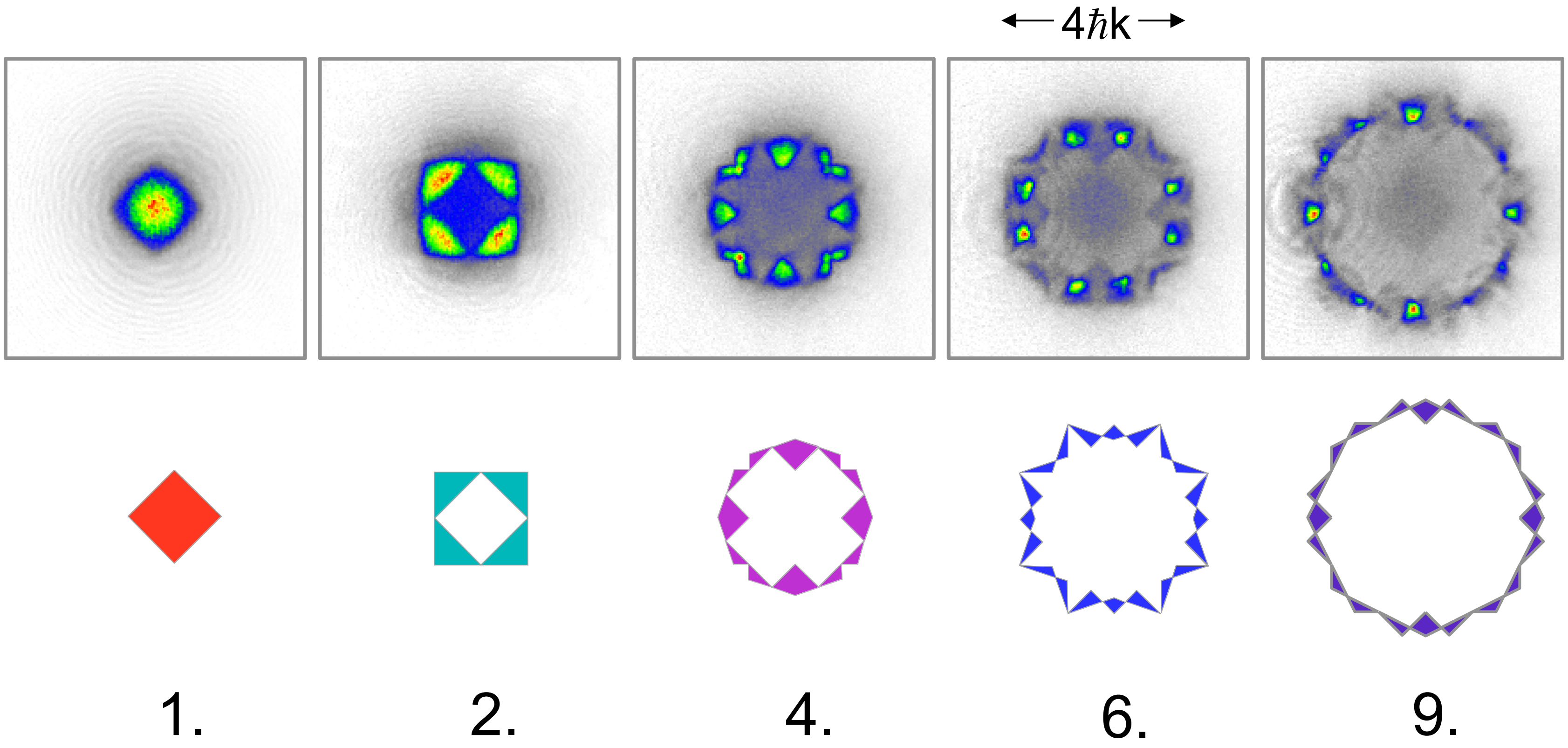
Momentum space

Population of bands preserved



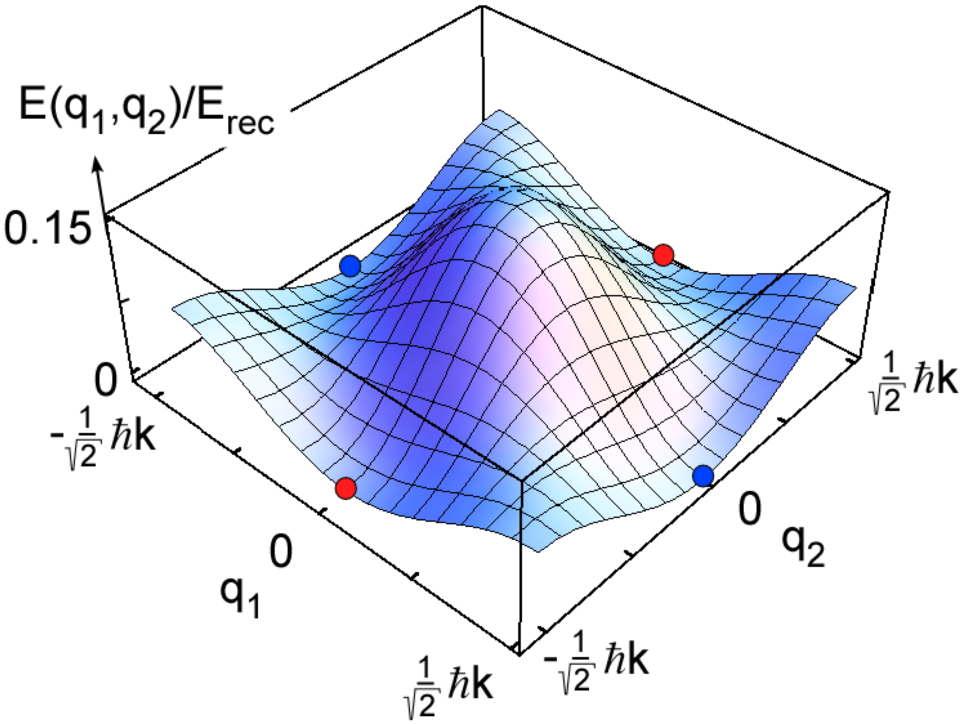
Addressing different bands

G. Wirth, M. Ölschläger, A. Hemmerich, Nature Physics 7, 147 (2011)



2nd band $(2P_x \pm i\, 2P_y)$

2nd band → two inequivalent minima



Lattice with perfect 90° rotation symmetry:

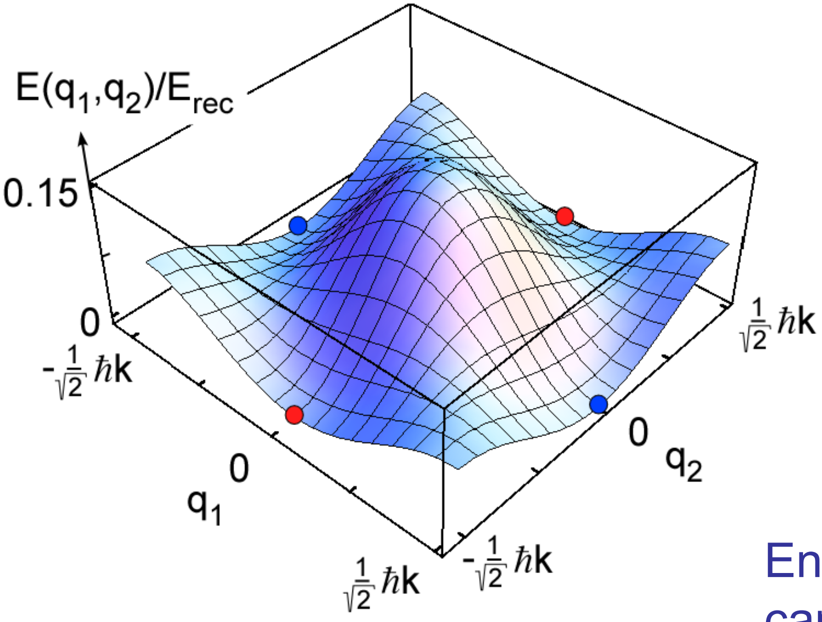
energy difference between band minima $\Delta E = 0$.

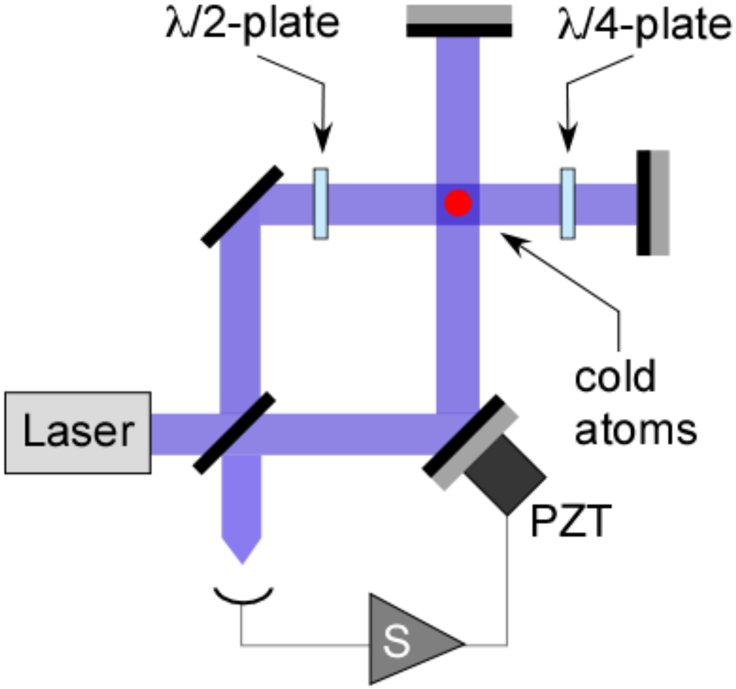
Uniaxial distortion: $\Delta E \neq 0$ → degeneracy lifted

Uniaxial distortion can be controlled in experiment

$$V_{real}(x,y) = -\frac{V_0}{4}\left|\,\eta\left[e^{ikx} + \varepsilon_x e^{-ikx}\right] + e^{i\theta}\left[e^{iky} + \boxed{\varepsilon_y}\, e^{-iky}\right]\right|^2$$

η	unequal intensities coupled to x and y directions
$\varepsilon_x, \varepsilon_y$	imperfect reflection of beams coupled to x and y directions

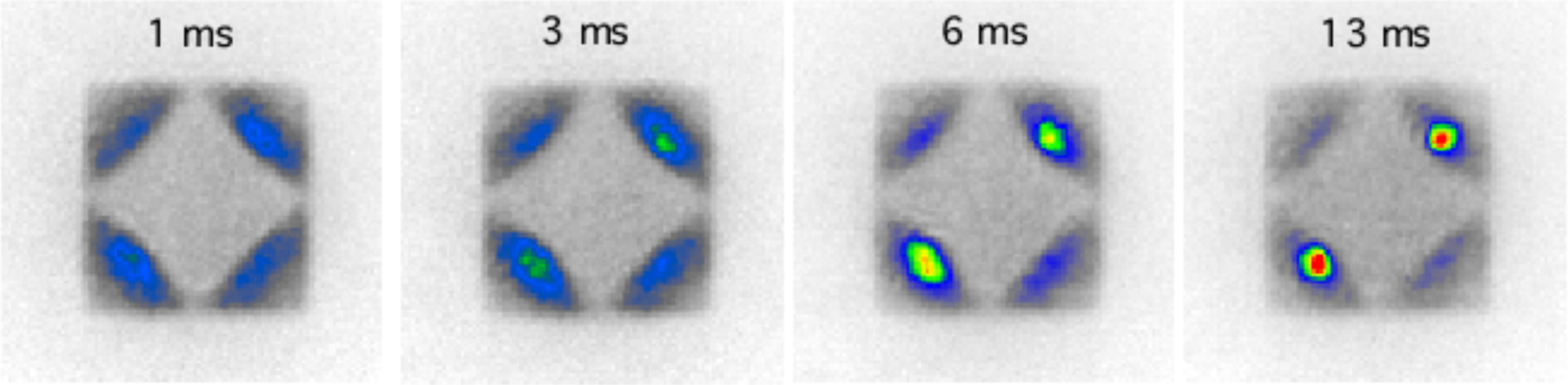




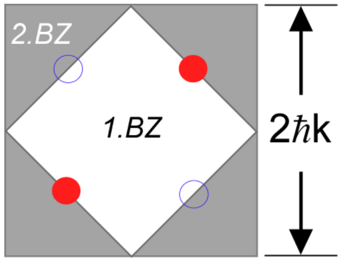
Energy difference ΔE between P-band minima can be tuned via $\boxed{\varepsilon_y}$

Time evolution of band population: $\Delta E \neq 0$

Condensation at lowest band minimum

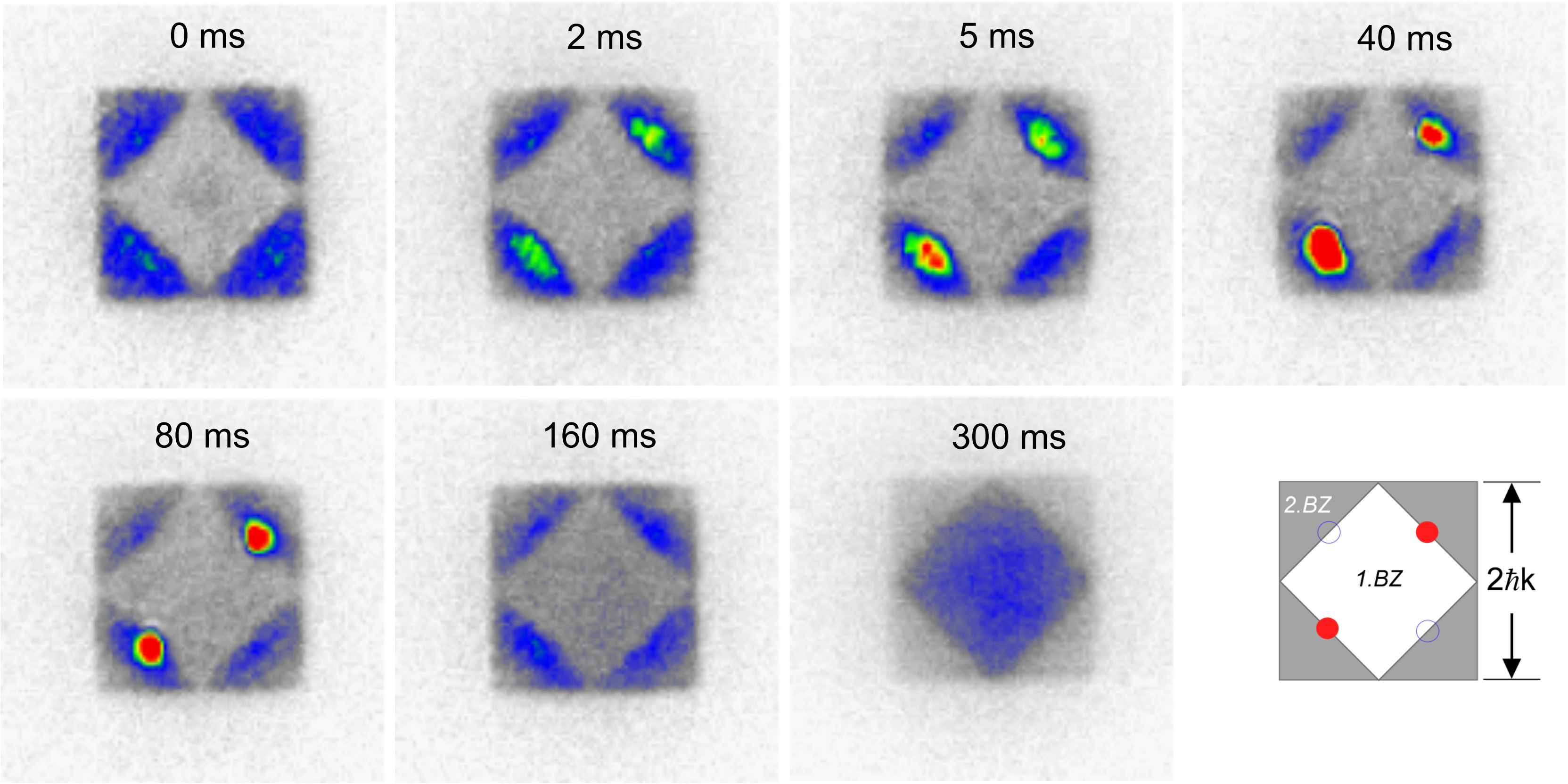


G. Wirth, M. Ölschläger, A. Hemmerich, Nature Physics 7, 147 (2011)

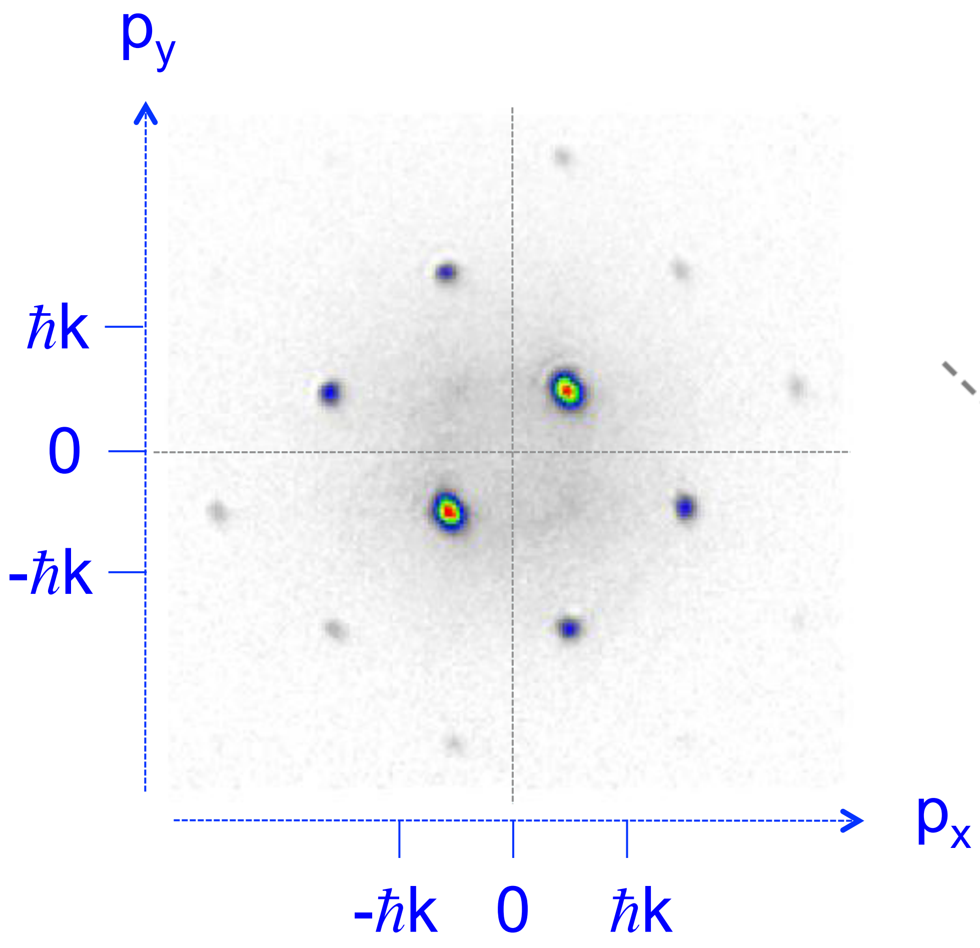


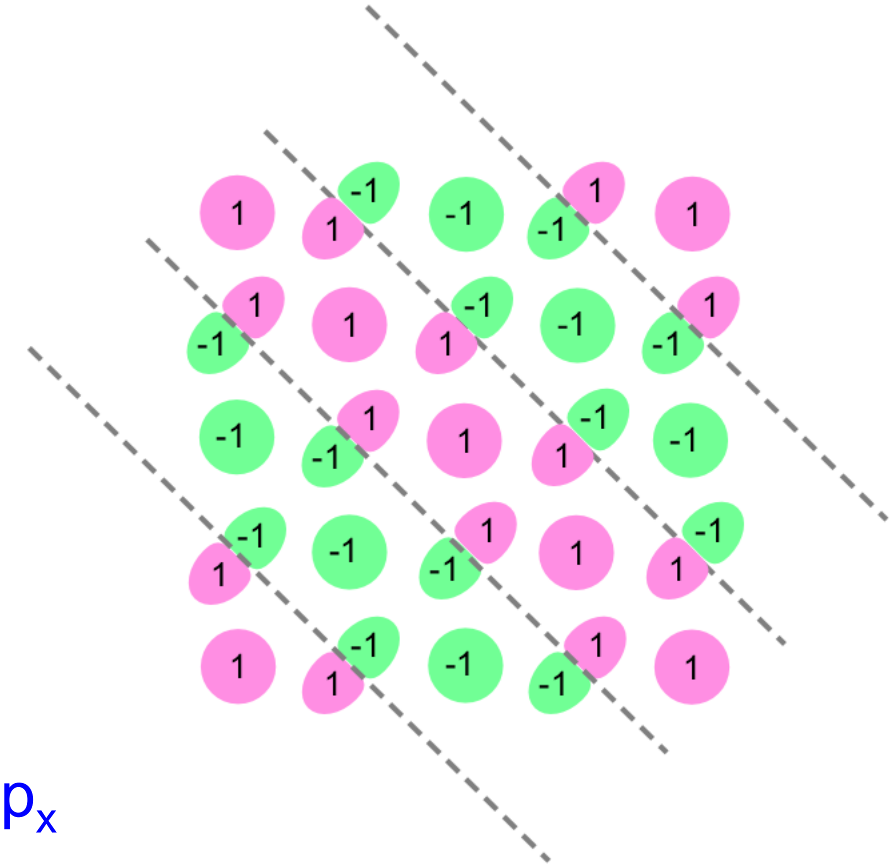
- After 1 ms condensation at finite momenta on the edge between 1st and 2nd Brillouin zone
- Decay after 100 ms
- Distortion selects condensation points

Band relaxation sets in after 100 ms

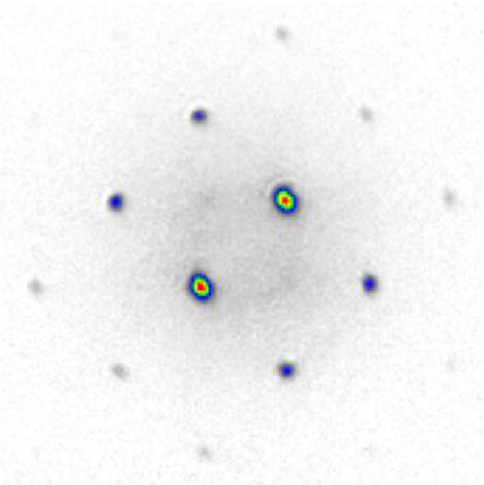


Finite momentum superfluidity



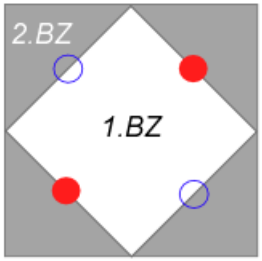


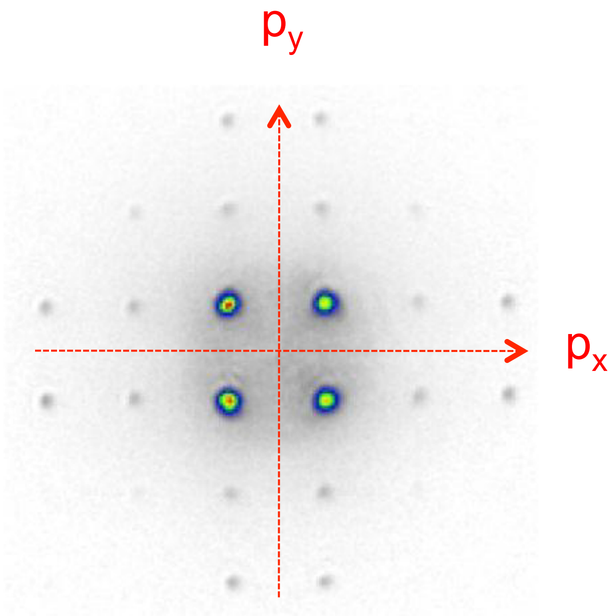
Tuning the distortion ΔE



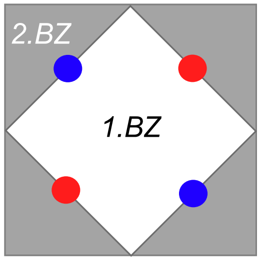
$\Delta E \approx 0.005\, E_{rec} > 0$

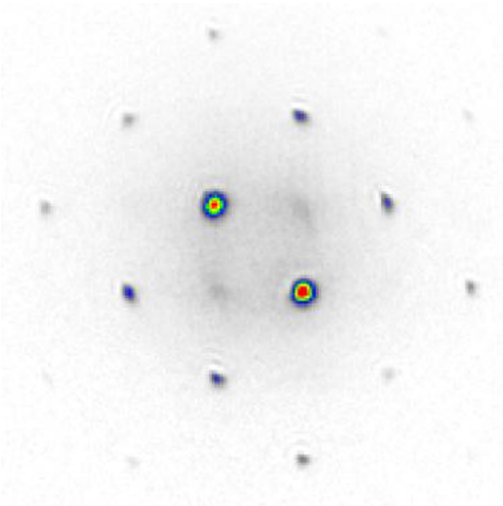
$\rightarrow \Delta T \approx 0.5$ nK



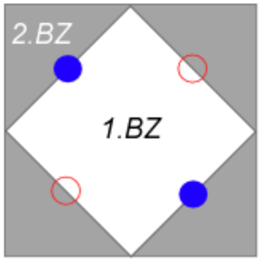


$\Delta E \approx 0$



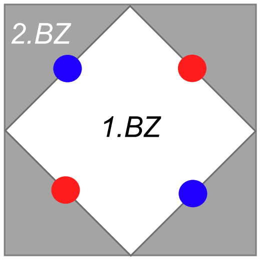


$\Delta E < 0$

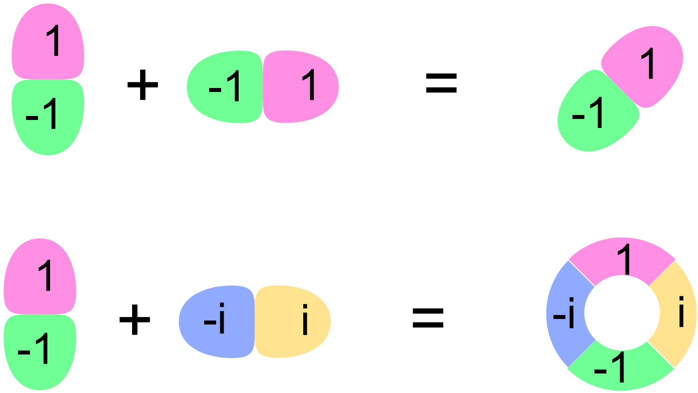


For $\Delta E = 0$

superposition of condensates at both band minima



90° relative phase chosen in order to minimize interaction of atoms in p_x- and p_y-orbitals

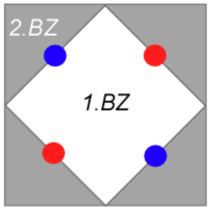


minimizes interaction energy

A. Isacsson and S. Girvin, Phys. Rev. A 72, 053604 (2005).
W. Vincent Liu and C. Wu, Phys. Rev. A 74, 013607 (2006).

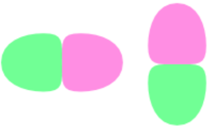
A chiral wave function arises

Atoms condense
at both minima



E🔴 = E🔵

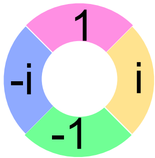
Deep wells support P_x-, P_y-orbitals



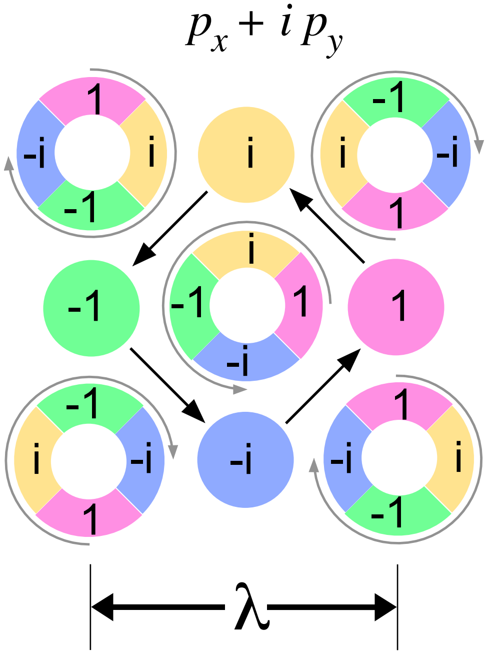
Shallow wells support local S-orbitals

P_x, P_y degenerate with respect
to kinetic energy

$P_x \pm i\, P_y$ minimize local interaction energy



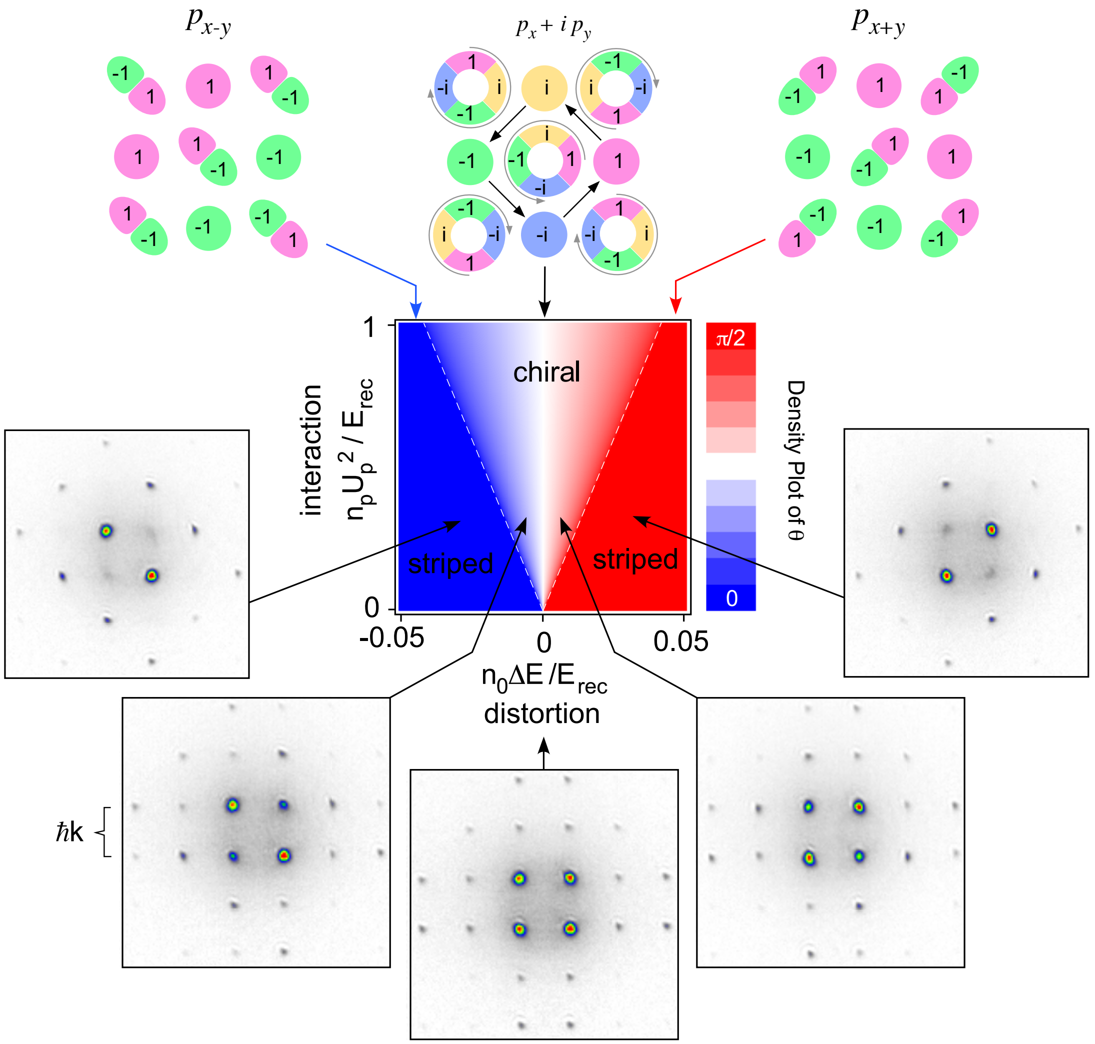
Tunneling maximized by matching
local phases at tunneling junctions



→ broken time reversal symmetry

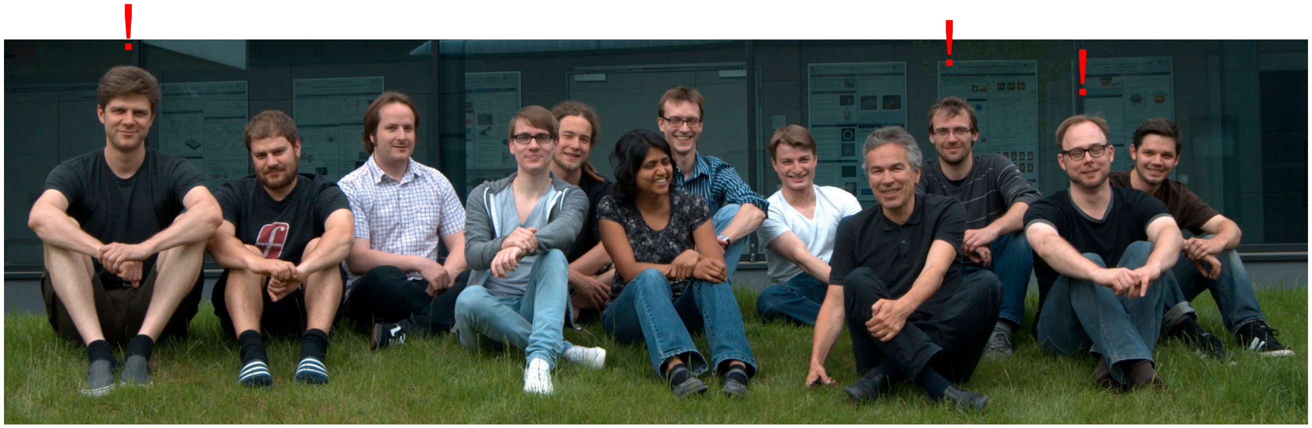
→ interaction induced vortical flow, artificial magnetic field

Observed quantum phases confirmed by Hubbard model



M. Ölschläger, T. Kock, G. Wirth, A. Ewerbeck, C. Morais Smith, A. Hemmerich
New Journal of Physics 15, 083041 (2013)

Atom Optics Group 2013, Hamburg University



Matthias Wolke	Postdoc	Quantum Gases in High Finesse Cavities
Hans Keßler	PhD-stud.	
Jens Klinder	PhD-stud.	
Matthias Ölschläger	Postdoc	Bosons in Optical Lattices
Thorge Kock	PhD-stud.	
Arne Ewerbeck	PhD-stud.	Fermions in Optical Lattices
Robert Büchner	PhD-stud.	
Hannes Winter	PhD-stud.	Ultracold Alkaline Earth Atoms
Thorben Laske	M-stud.	

Present theory collaborations

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Robin Santra, Hamburg
Vincent Liu, Pittsburgh
Arun Paramekanti, Toronto

SFB
SFB 925: Light induced dynamics and control of strongly correlated quantum systems

GRK
GRK 1355: Physik mit neuartigen kohärenten Strahlungsquellen

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