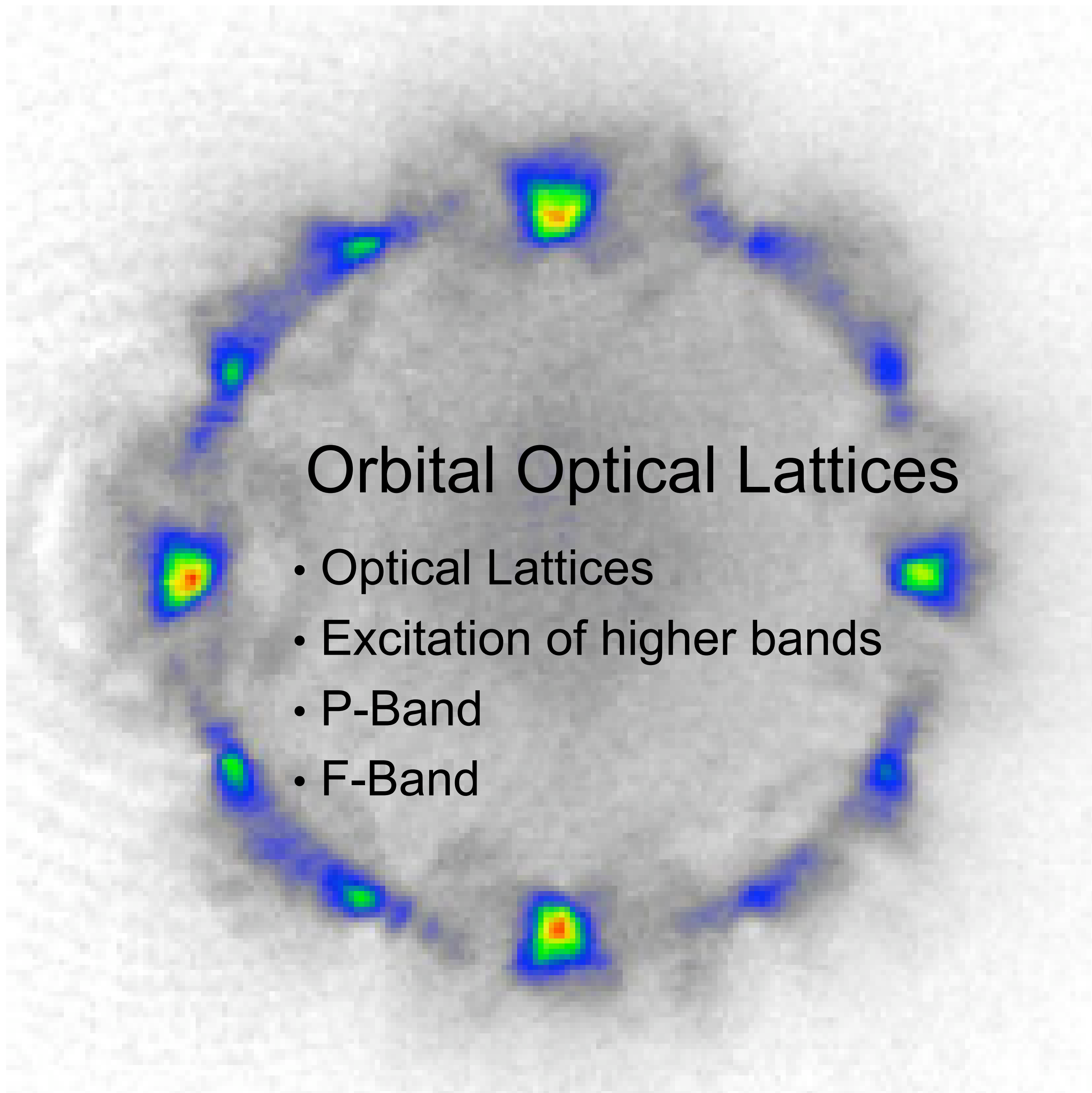
Universität Hamburg
Institut für Laser-Physik

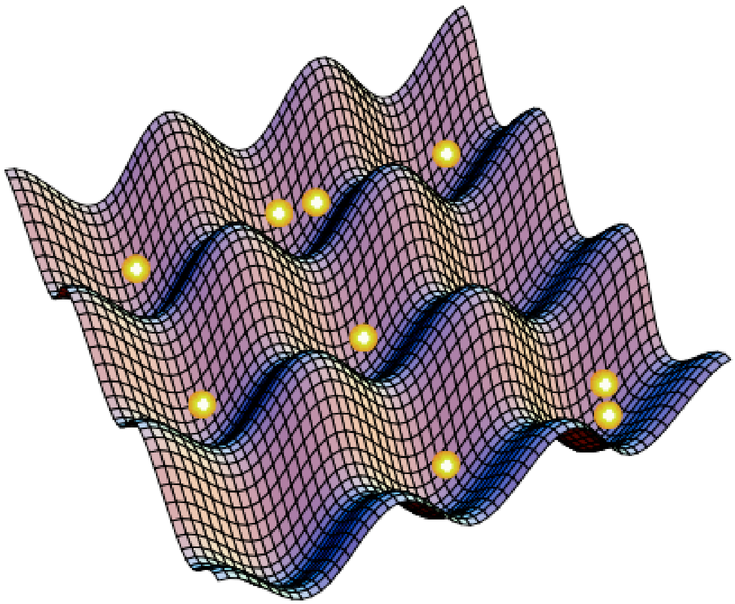
Georg Wirth
Matthias Ölschläger
Andreas Hemmerich



Orbital Optical Lattices

- Optical Lattices
- Excitation of higher bands
- P-Band
- F-Band

Optical Lattice



Cold atoms (fermions, bosons) confined in periodic potentials produced by the interference of laser beams.

Atoms are trapped at intensity maxima

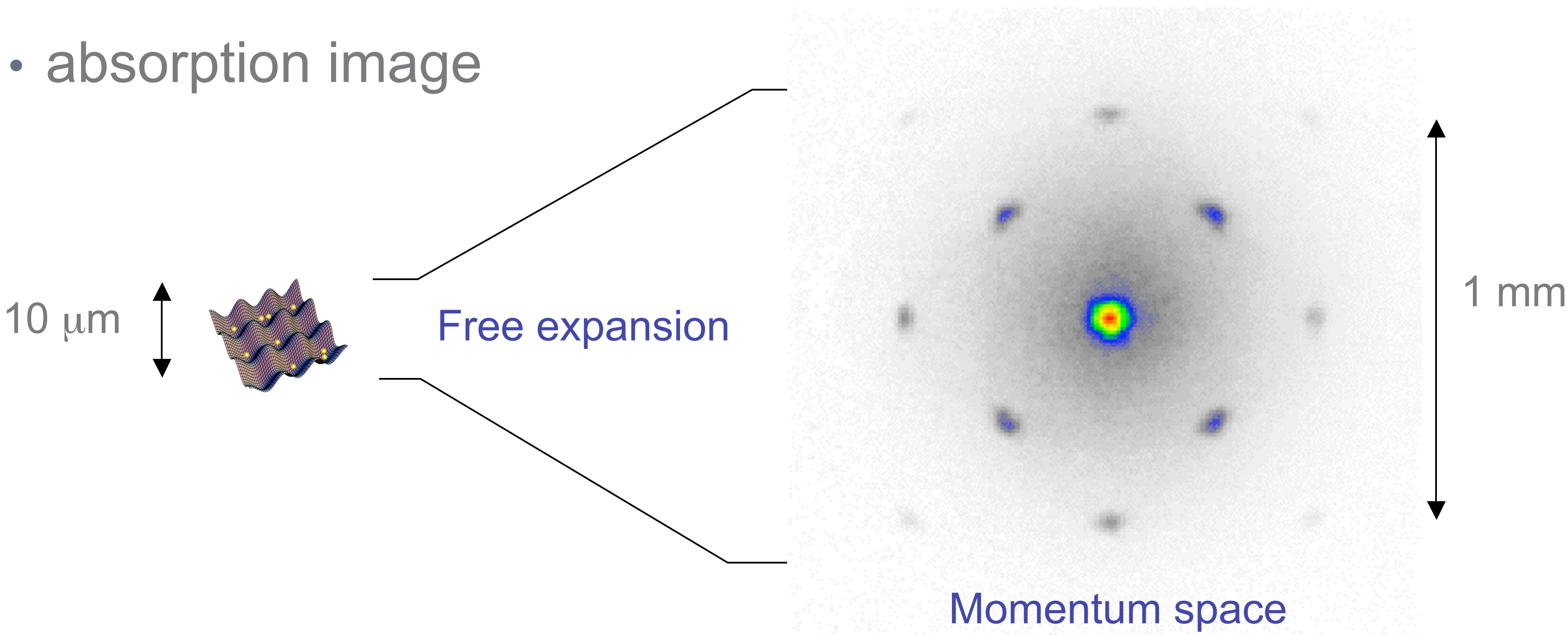
Typical well depths: 1 μK

Typical temperatures: 10 nK

Standard detection procedure

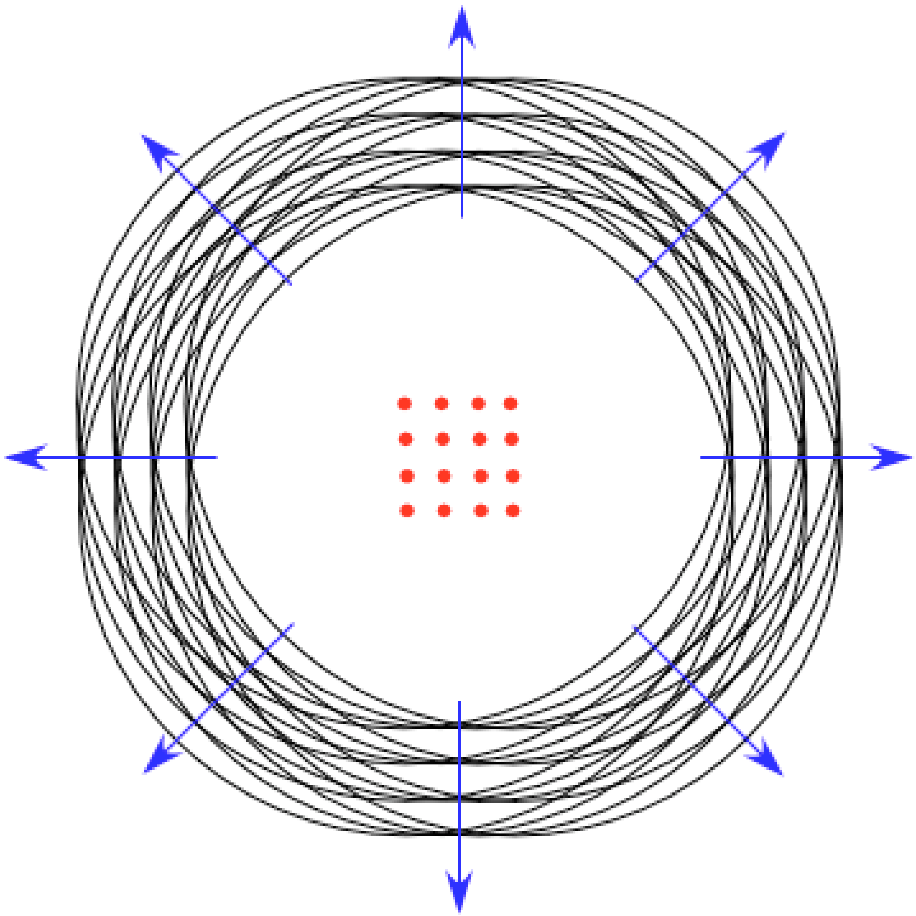
Observation of momentum spectra

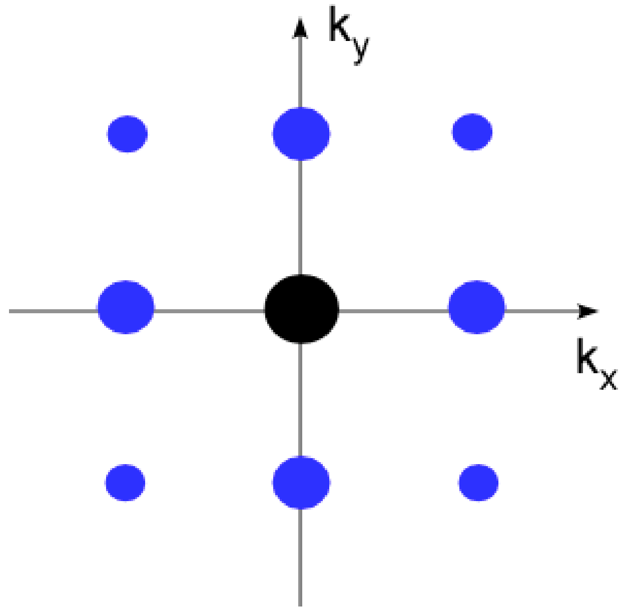
- lattice potential rapidly (< 1 μs) switched off
- free expansion for 30 ms
- absorption image



Localized Bragg maxima indicate coherence

Localized Bragg maxima indicate coherence



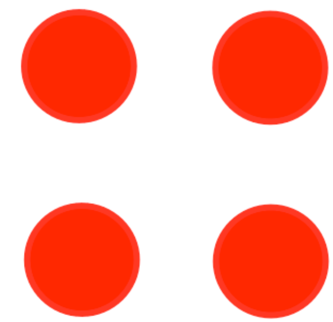


Momentum space

Orbital Optical Lattices

Standard optical lattice: atoms reside in S-band

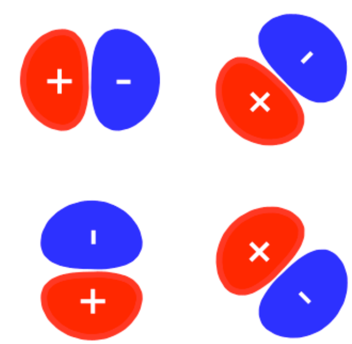
→ local S-orbit at each site



In higher bands of optical lattice

→ anisotropic orbits

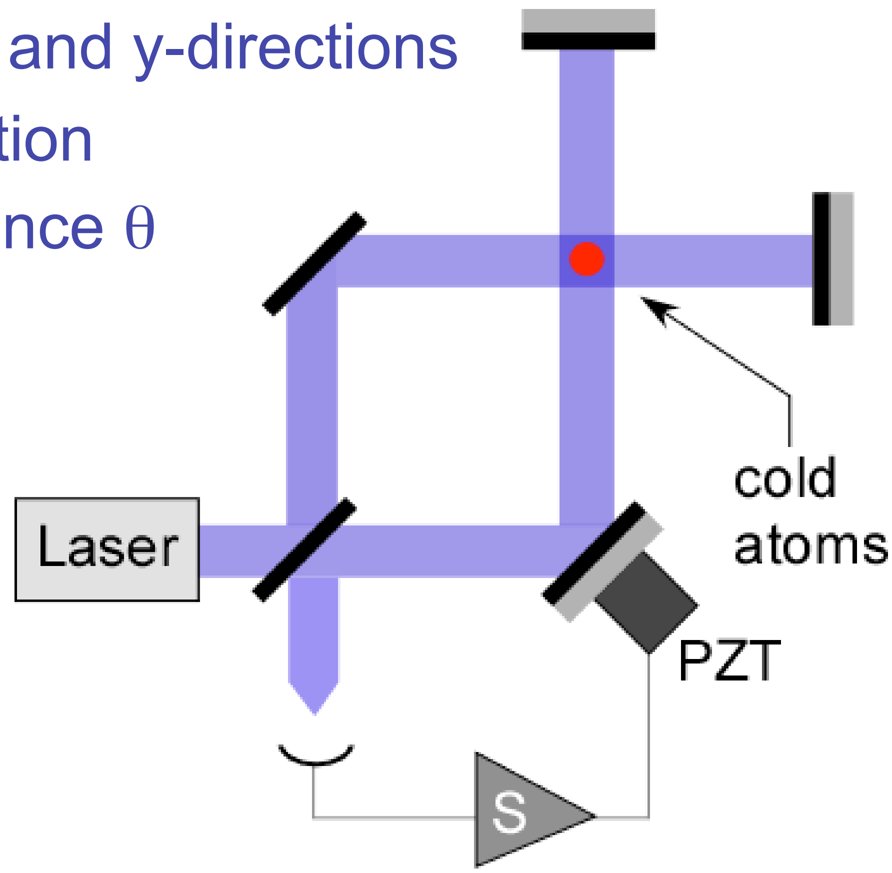
→ freedom of orientation



Important role of orbital physics in material systems:
magnetism & superconductivity in rare earth or transition metal compounds

Optical lattice set-up

- crossed standing waves in x- and y-directions
- linear polarizations in z-direction
- adjustable time-phase difference θ

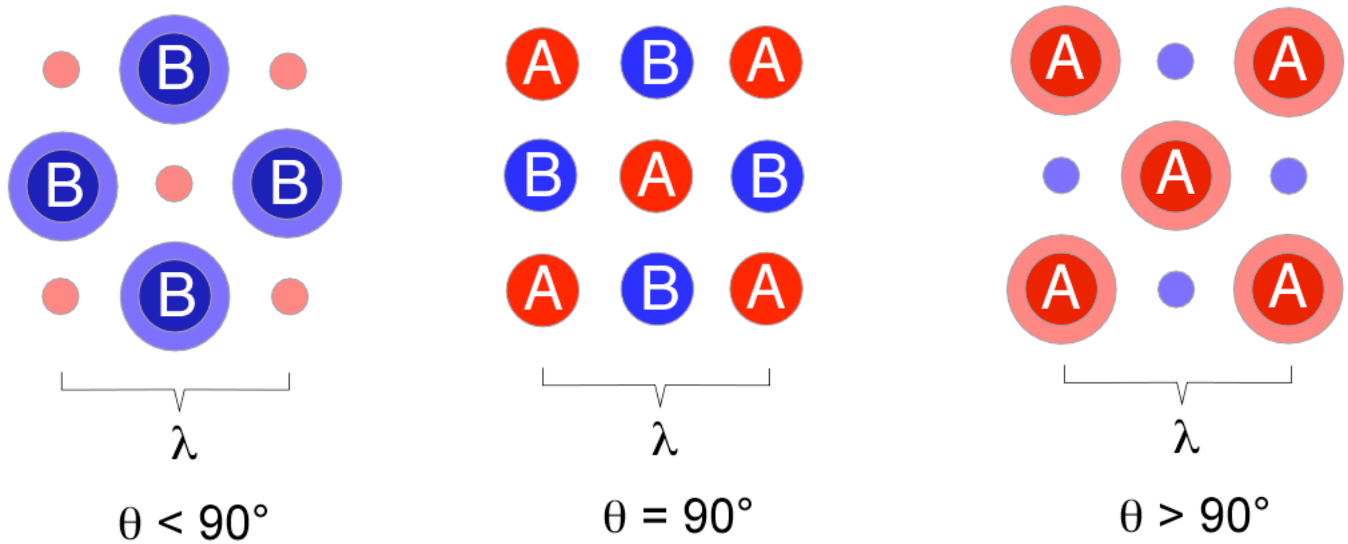


→ Conventional square lattice + interference term

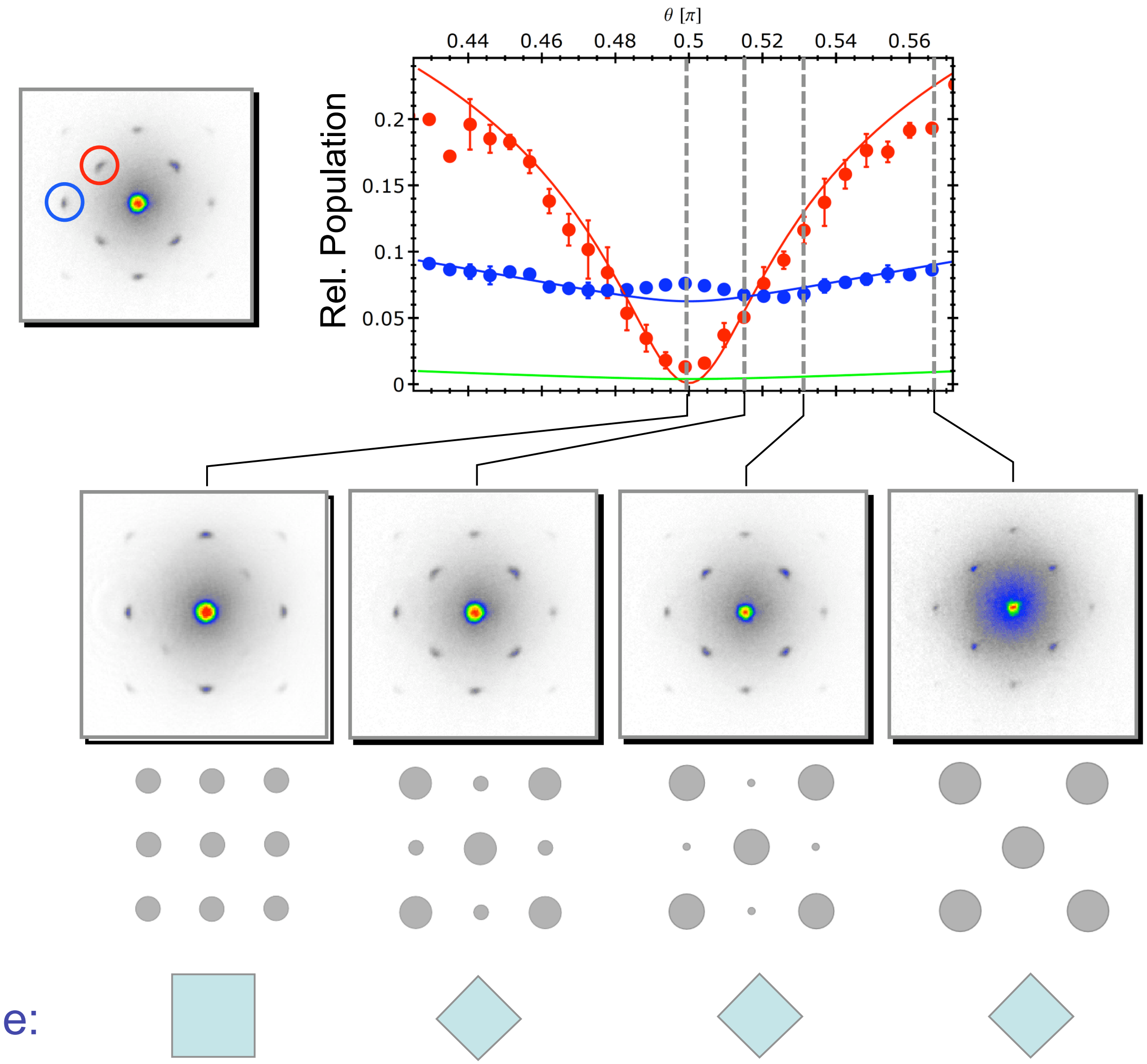
$$V(x,y) = -V_0\left[\sin^2(kx) + \sin^2(ky) + 2\cos(\theta)\sin(kx)\sin(ky)\right]$$

Lattice with adjustable time-phase difference θ

$$V(x,y) = -V_0\left[\sin^2(kx) + \sin^2(ky) + 2\cos(\theta)\sin(kx)\sin(ky)\right]$$



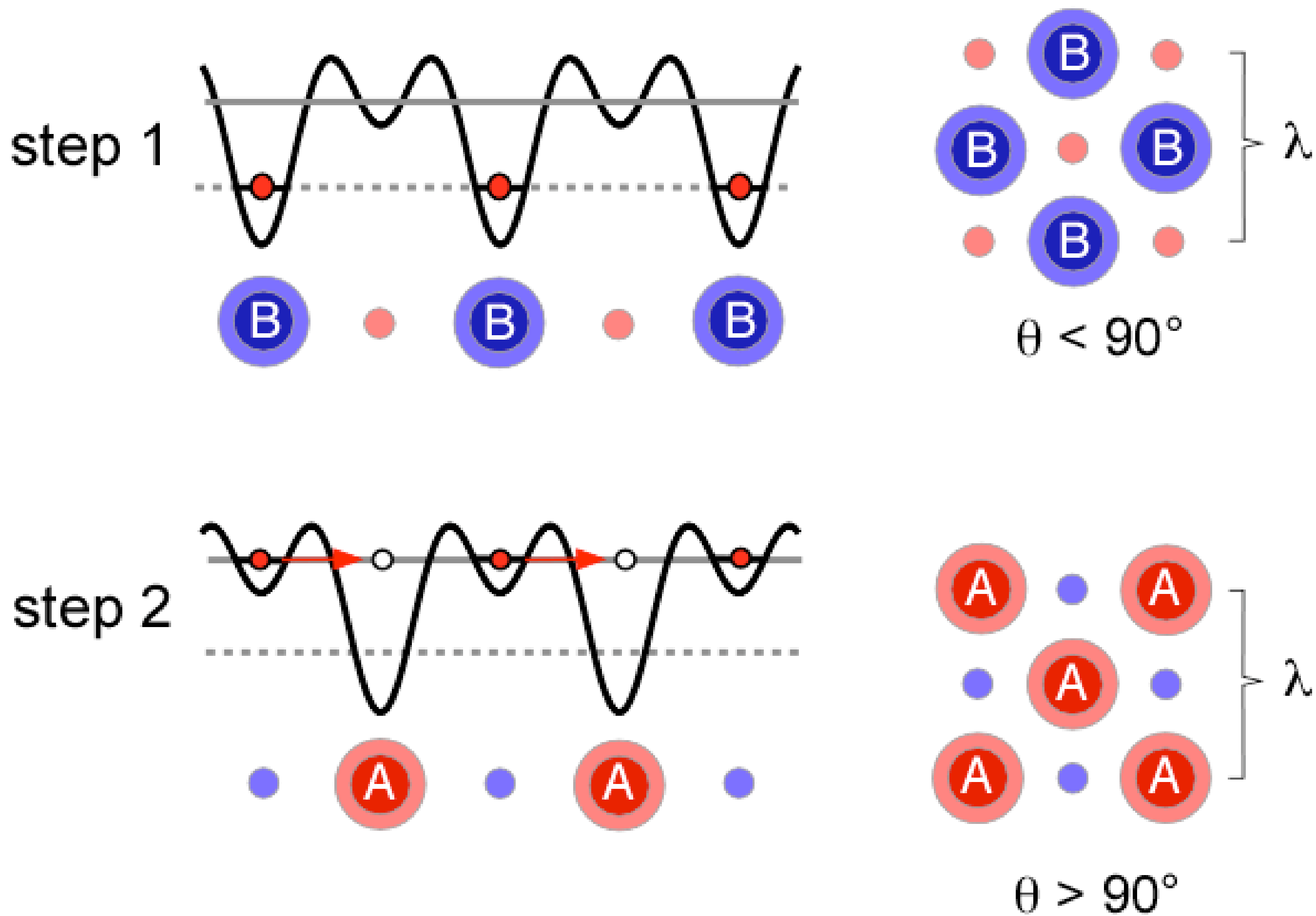
S-band lattice: dependence on θ



Population:

Brillouin zone:

Population Swapping: exciting higher bands



Detailed procedure

→ prepare lattice with $\theta < \pi/2$

→ adiabatically (80 ms) ramp V_0 to 16.5 E_{rec}: tunneling suppressed

→ rapidly (< 0.2 ms) ramp θ to $\theta_f > \pi/2$: θ_f determines band to be populated

→ adiabatically (0.6 ms) decrease V_0 : tunneling enabled

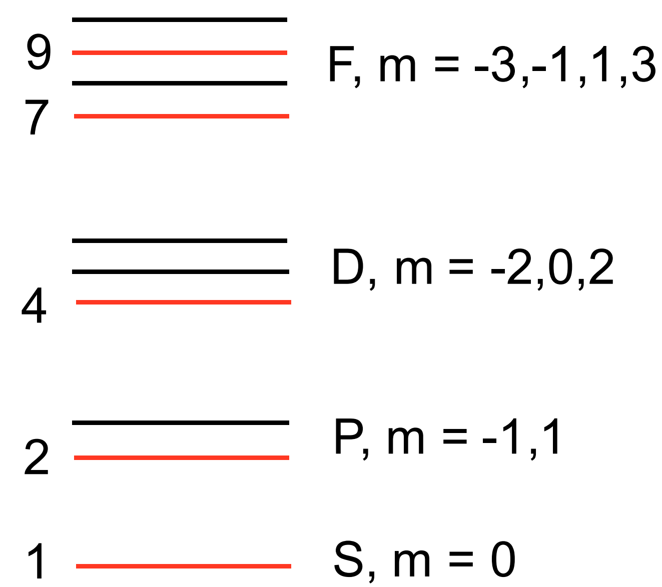
→ adiabatically (< 2 ms) adjust θ

→ hold in lattice

→ detect

Bands that can be accessed

(reason will be discussed later)

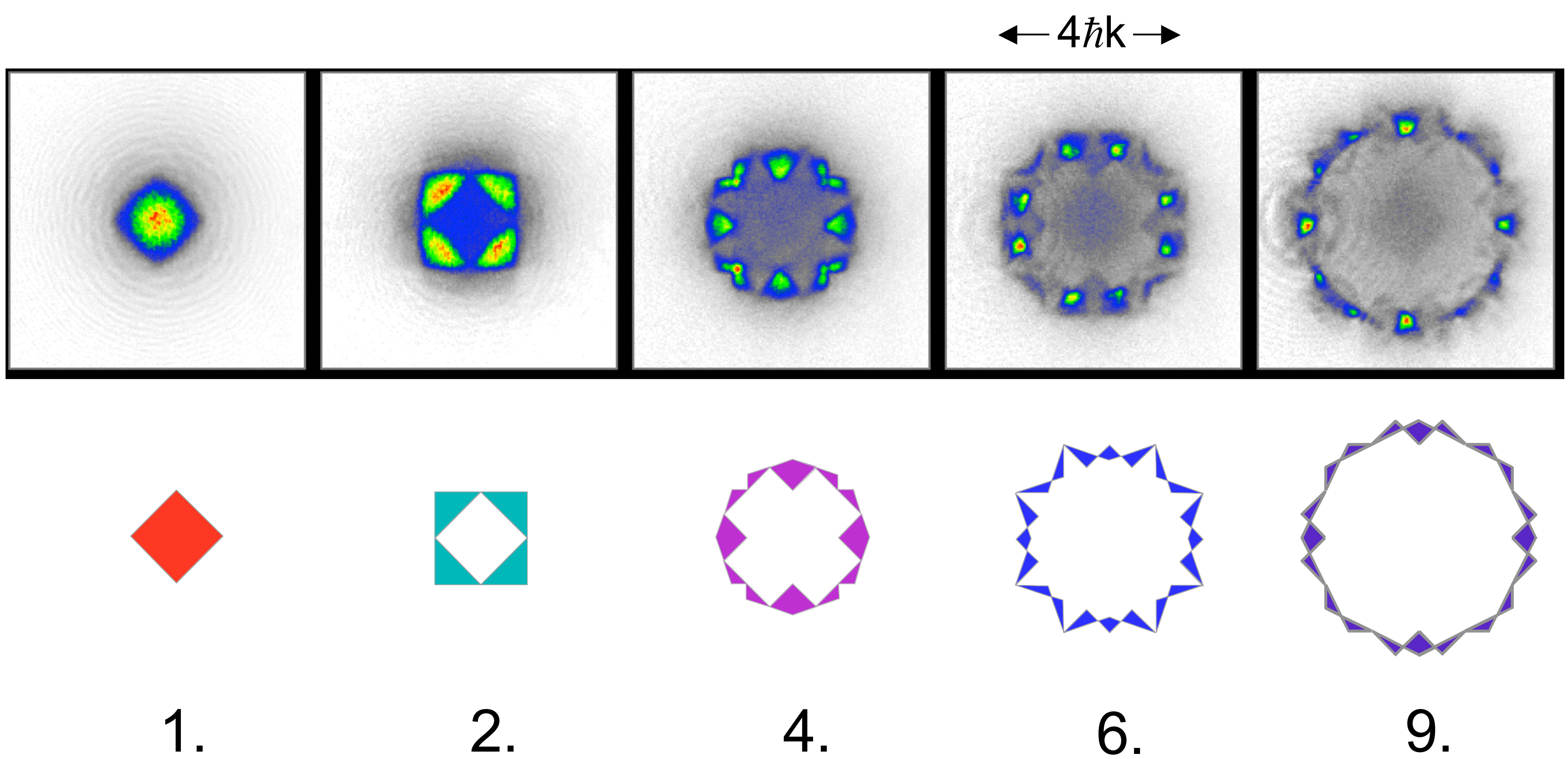


Detecting population of Brillouin zones

Band mapping:

→ adiabatic decrease of potential (0.5 ms)
→ 30 ms ballistic expansion → absorption imaging

maps population of n-th band to n-th Brillouin zone, if no band crossings occur



P-band lattice (2nd band)

More realistic lattice potential accounting for anisotropy

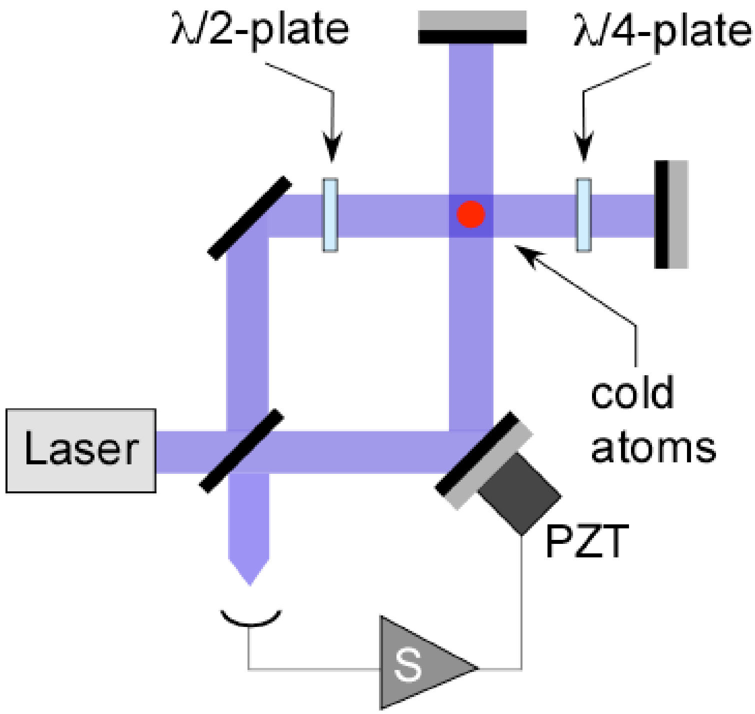
$$V_{real}(x,y) = -\frac{V_0}{4}\left|\eta\left[\left(\cos(\alpha)\,\hat{z} + \sin(\alpha)\,\hat{y}\right) e^{ikx} + \varepsilon\,\hat{z}\,e^{-ikx}\right] + \hat{z}\,e^{i\theta}\left[e^{iky} + \varepsilon\,e^{-iky}\right]\right|^2$$

η unequal intensities coupled to x and y directions

ε imperfect reflection of beams coupled to x and y directions

α compensation of ε via polarization optics

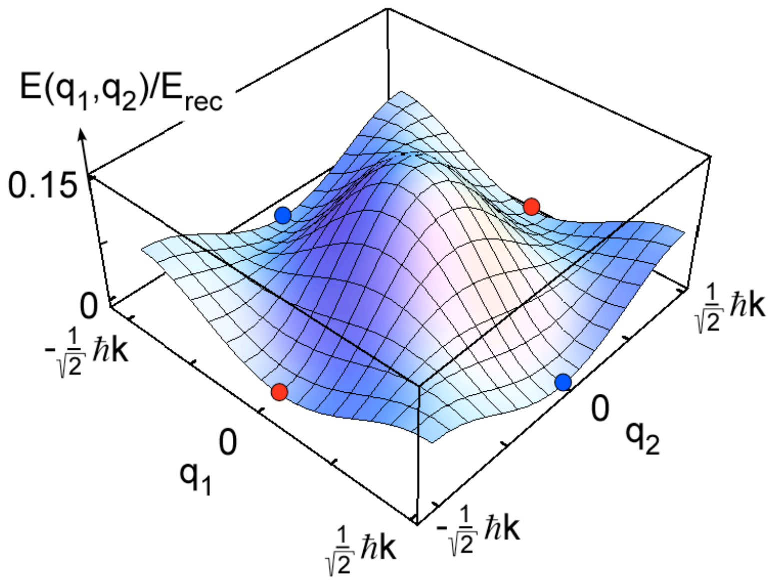
α, η, ε yield anisotropy

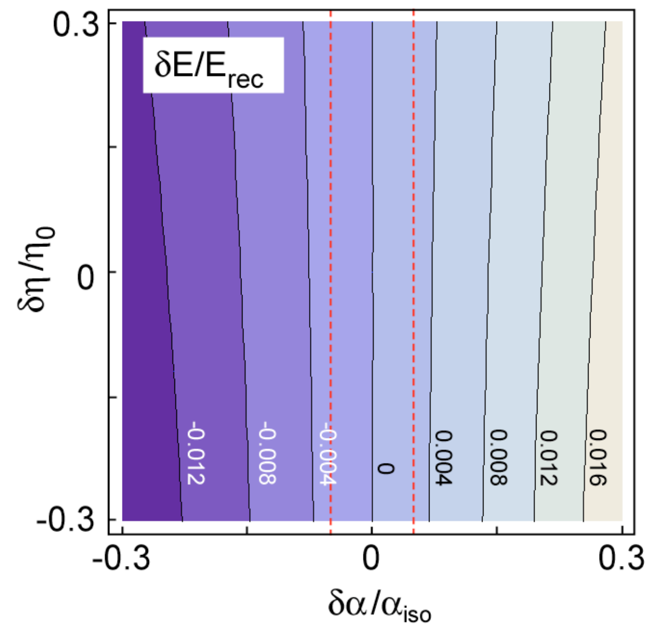


Effect of anisotropy upon P-band (2nd band)

→ energy difference δE between P-band minima can be tuned via α

→ energy minima of P-band are degenerate ($\delta E = 0$) if α adjusted such that the incomplete reflection is perfectly compensated on x-axis: $\cos(\alpha_{iso}) = \varepsilon$

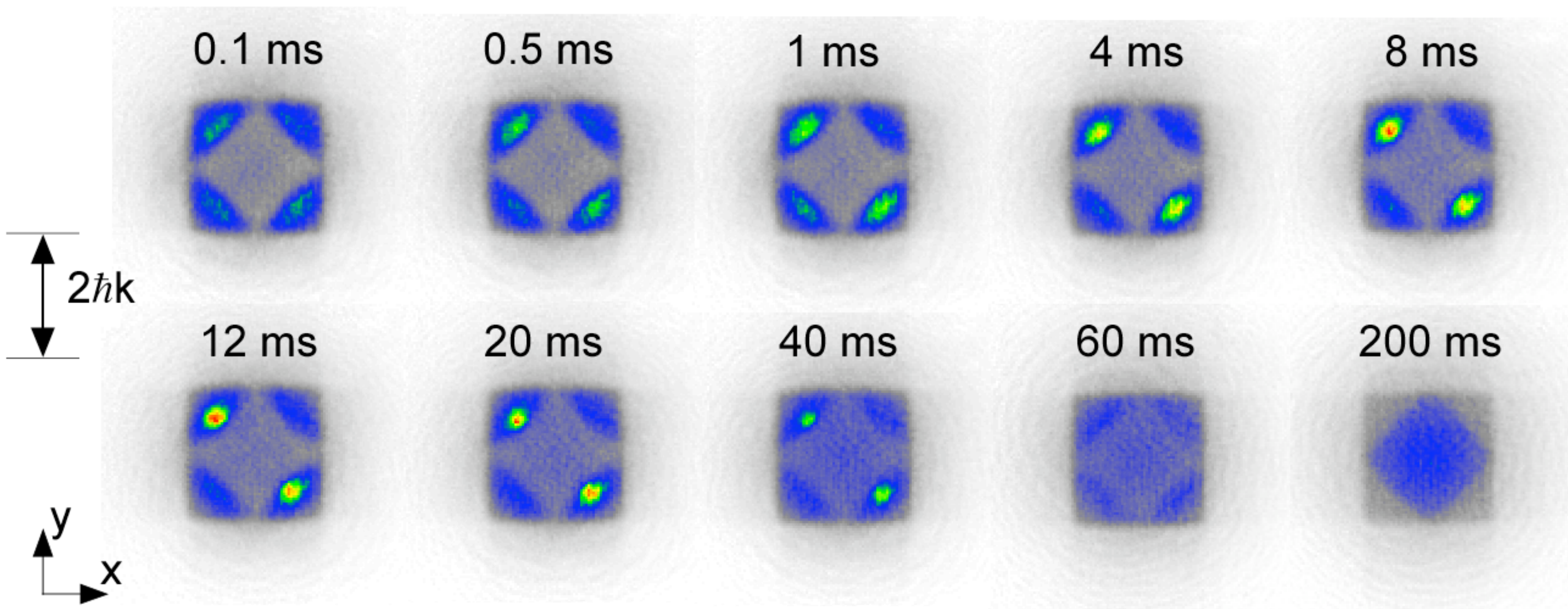


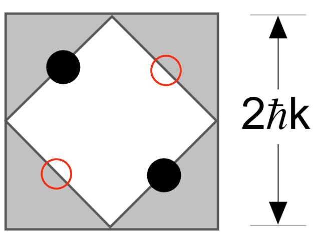


→ if $\alpha = \alpha_{iso}$, a change of η does not lift degeneracy of P-band energy minima

→ local imbalance of standing wave intensities due to finite size beams irrelevant

Time evolution of band population: $\alpha < \alpha_{iso}$

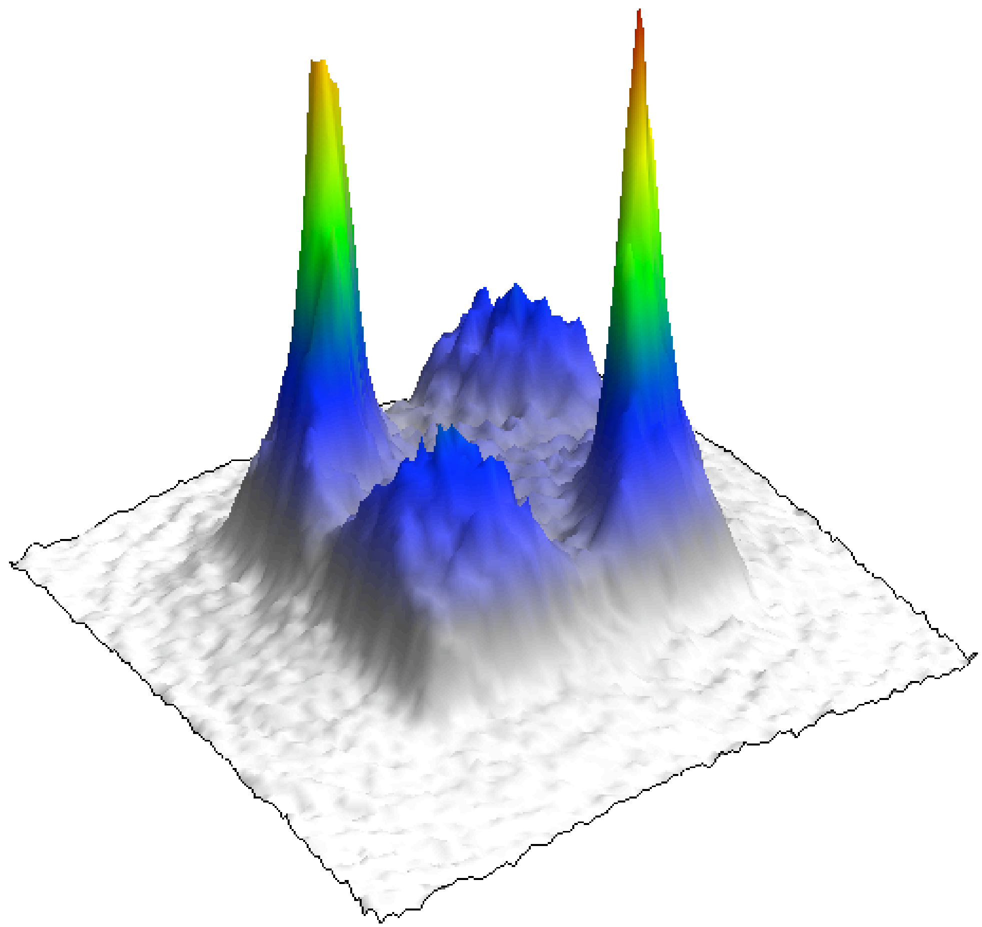




→ After 1 ms condensation at finite momenta on the edge between 1st and 2nd Brillouin zone

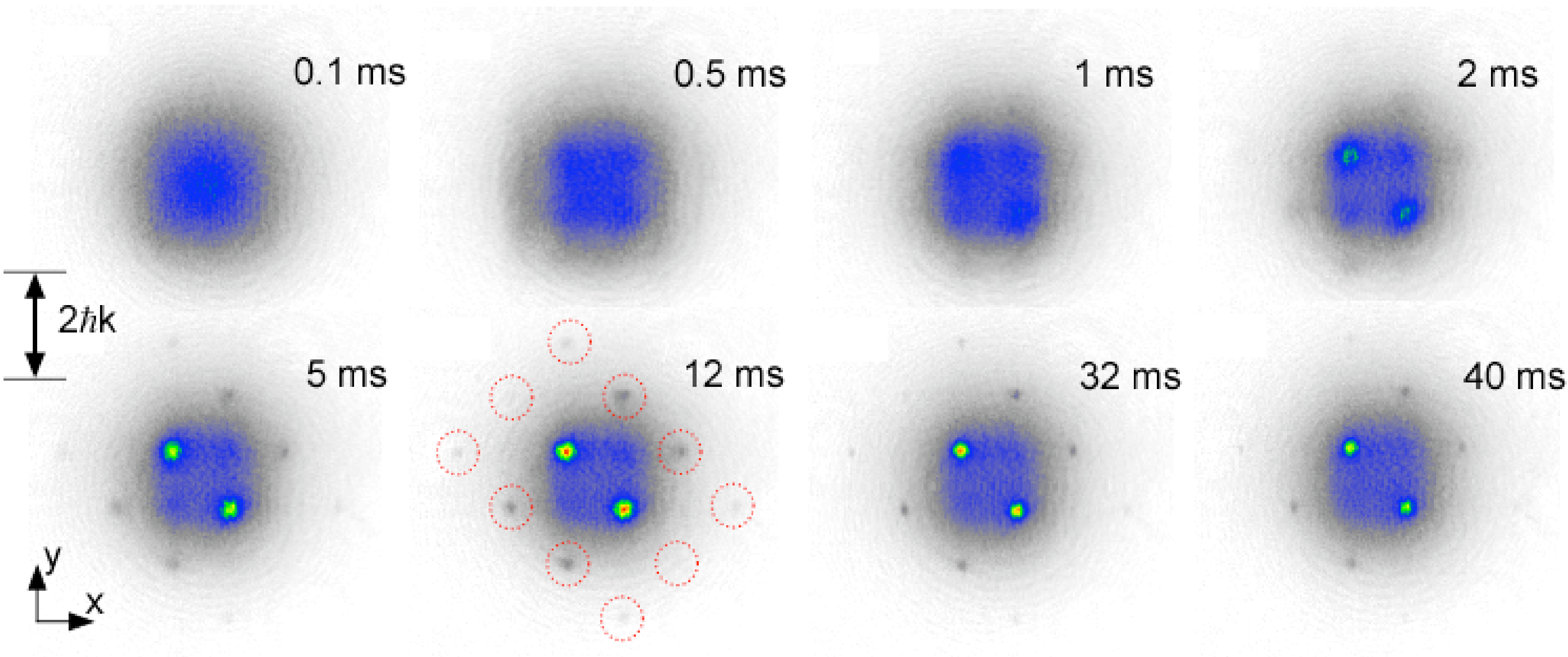
→ Anisotropy selects condensation points

→ Decay after several 10 ms



Significant population at condensation points

Time evolution of momentum spectrum



→ Condensation after few ms, no zero momentum component

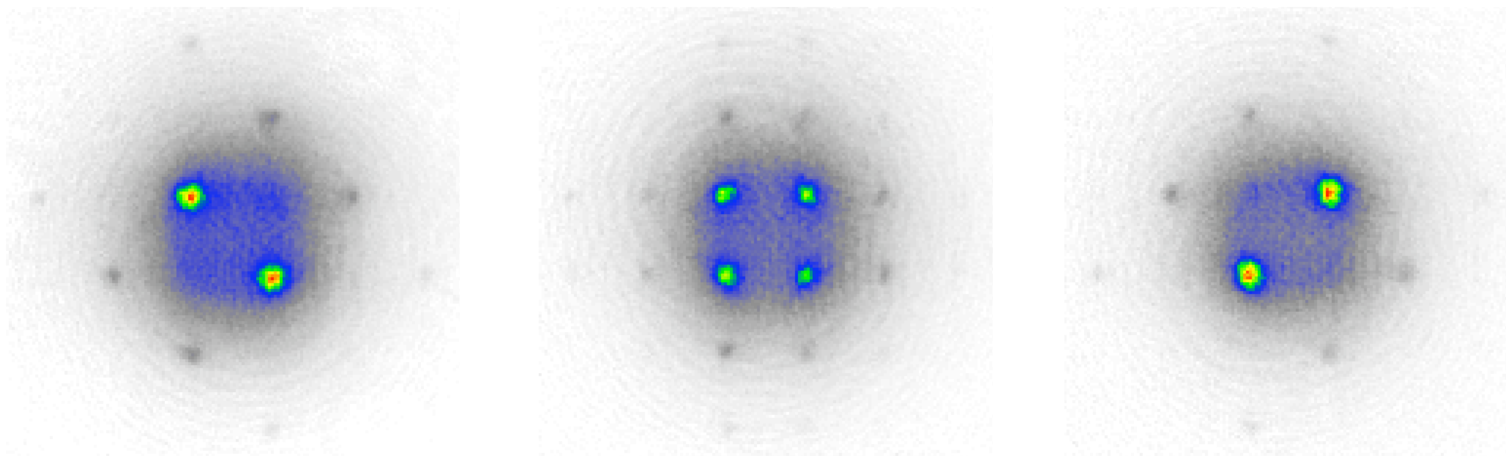
→ Decay after several 10 ms

→ Sharp Bragg peaks show cross-dimensional coherence

Tuning the anisotropy

$\alpha_{iso} \approx \pi/5$, $\eta \approx 0.95$, $\varepsilon \approx 0.81$

Well depth: A-wells 7.5 E_{rec} , B-wells 5 E_{rec}



$\alpha < \alpha_{iso}$	$\alpha \approx \alpha_{iso}$	$\alpha > \alpha_{iso}$
$\delta E \approx 0.005\ E_{rec}$ ≈ 0.03 band width	$\delta E \approx 0$	
$\rightarrow \delta T \approx 0.5$ nK		

→ thermal sample at temperature T would only permit selection of different condensation points by tuning of α , if $T \ll 0.5$ nK

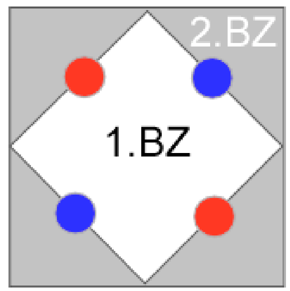
Nature of order parameter

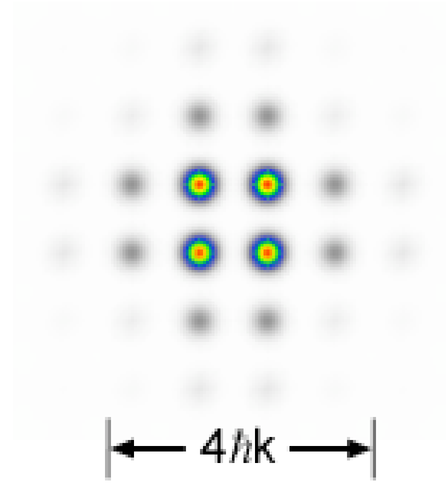
Two inequivalent condensation points

$K_{(1,1)} = K_{(-1,-1)}$

$K_{(-1,1)} = K_{(1,-1)}$

$$K_{(\pm1,\pm1)} \equiv \frac{1}{2}\left(\pm\hbar k, \pm\hbar k\right)$$





$\alpha = \alpha_{iso}$

For weak interactions, order parameter is approximated by coherent superposition or incoherent mixture of real-valued Bloch-functions $\phi_{K_{(1,1)}}$, $\phi_{K_{(1,-1)}}$

Assume: coherent superposition: $\psi = a\,\phi_{K_{(1,1)}} + b\,\phi_{K_{(1,-1)}}$

Observed momentum spectra are only reproduced for

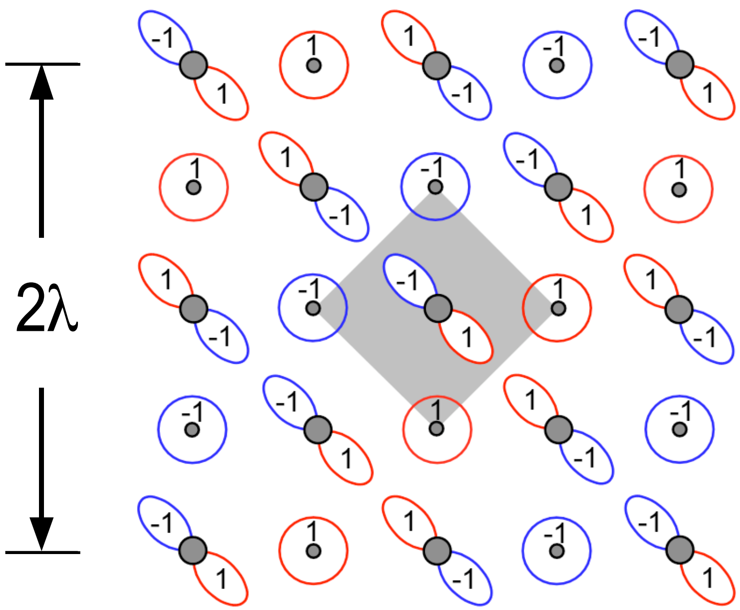
$$\begin{cases} b = i\,a & \text{if } \alpha = \alpha_{iso} \\ a = 0 & \text{if } \alpha < \alpha_{iso} \\ b = 0 & \text{if } \alpha > \alpha_{iso} \end{cases}$$

Striped order $\psi = \phi_{K_{(1,-1)}}$

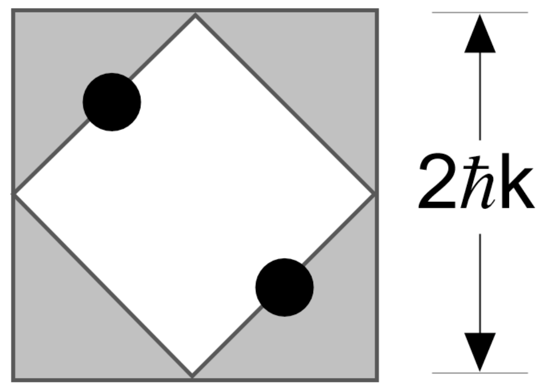
Shallow B-sites: local S-orbits

Deep A-sites: local $(P_x - P_y)$ -orbits preferred because of anisotropy $\alpha < \alpha_{iso}$

Local phases arranged in order to maximize intersite hopping



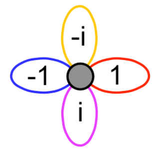
configuration space



momentum space

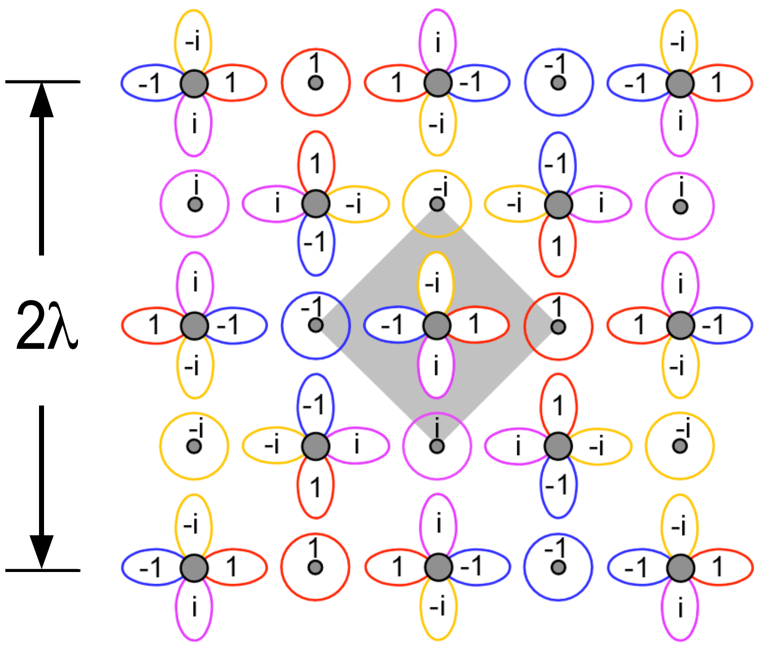
Complex order $\psi = \phi_{K_{(1,1)}} + i\,\phi_{K_{(1,-1)}}$

Shallow B-sites: local S-orbits 

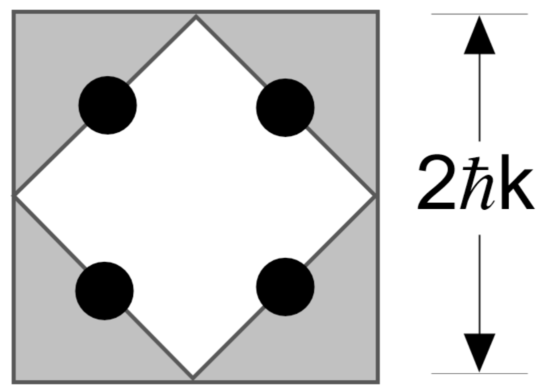
Deep A-sites: local $(P_x \pm iP_y)$-orbits 

minimize single site mean field energy → finite local angular momentum

Local phases arranged in order to maximize intersite hopping



configuration space



momentum space

Properties of $\psi = \phi_{K_{(1,1)}} + i\,\phi_{K_{(1,-1)}}$

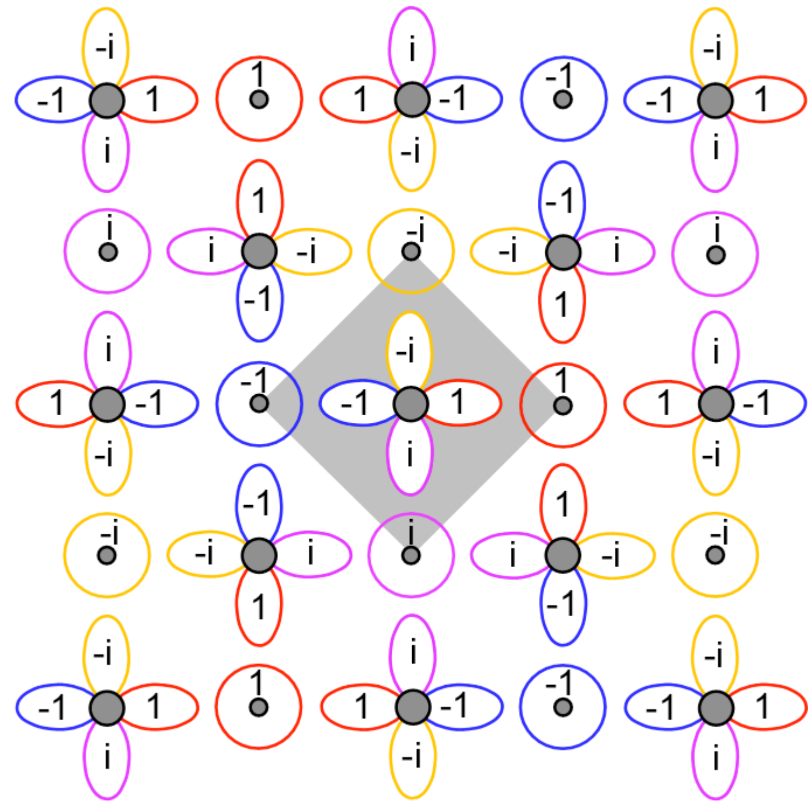
→ breaks translation symmetry of lattice

→ breaks time-reversal symmetry

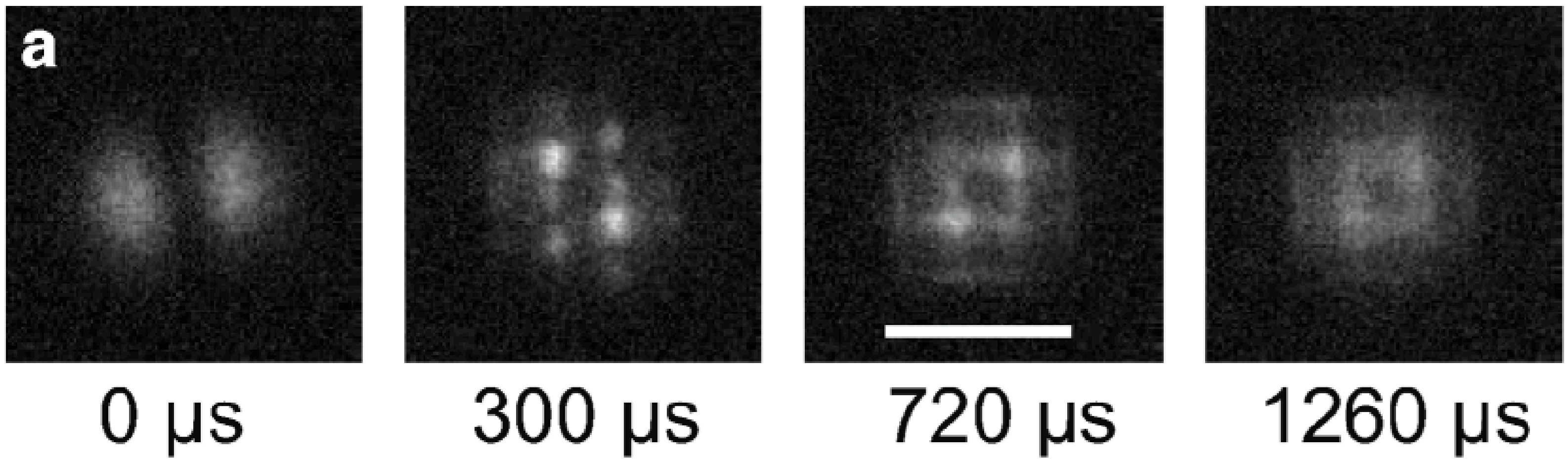
→ staggered local angular momenta

→ ground state of P-band

→ local S-orbits provide cross-dimensional tunneling junctions: important for fast formation of cross-dimensional coherence



Earlier experiment by MPQ group: Mueller et al., PRL 2007



without S-orbits: cross-dimensional coherence hard to obtain because of small transverse tunneling rate between P-orbits

Theoretical discussion

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

Alternative scenarios possible?

A) Degeneracy of P-band minima locally lifted due to „unknown“ local anisotropy

Striped states with orthogonal orientations $\phi_{K_{(1,1)}}$, $\phi_{K_{(1,-1)}}$ arise in different areas of the lattice

→ Not compatible with observed sharp α-dependence

B) P-band minima degenerate, but incoherent mixture of striped states with orthogonal orientations $\phi_{K_{(1,1)}}$, $\phi_{K_{(1,-1)}}$

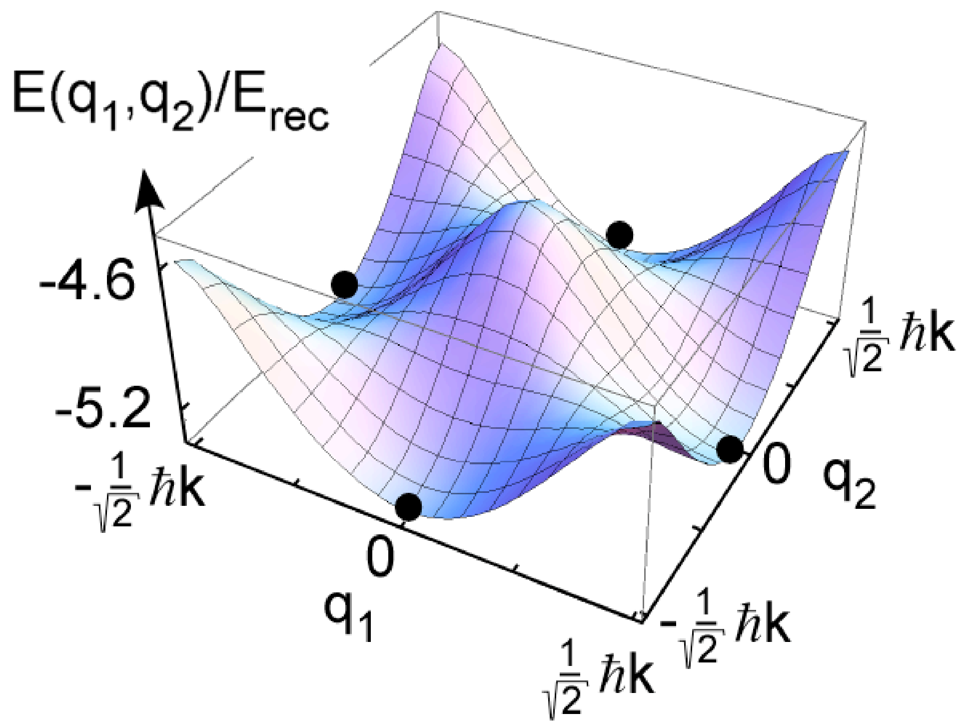
Coherent $(P_x \pm iP_y)$-orbits have lowest energy but collisions for „some reason“ can not populate this state

Both striped states coexist everywhere in lattice with indetermined relative phase → number of particles in each striped state precisely determined. However, striped states share common S-orbits.

Both striped states separated in different locations → costs additional kinetic energy at the phase boundaries

F-band lattice (7th band)

7. Band, condensation points



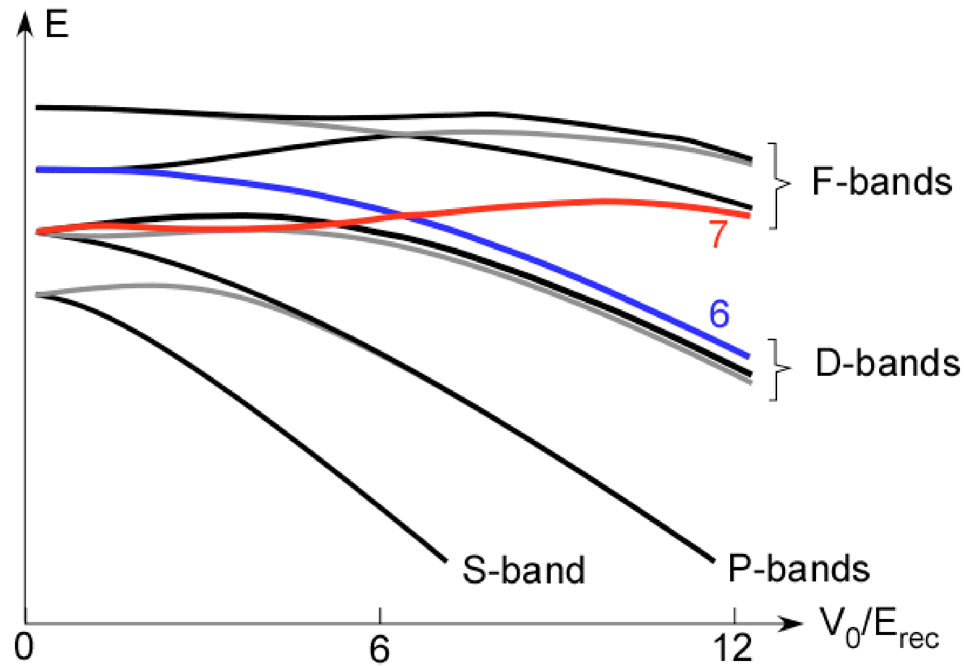
two inequivalent condensation points

$$K_{(1,1)} = K_{(-1,-1)}$$

$$K_{(-1,1)} = K_{(1,-1)}$$

Band crossing

For quasi-momenta q in the vicinity of the condensation points the 6. and 7. band cross, if well depth is decreased to zero



Condensation points of 7. band are mapped onto 6. BZ

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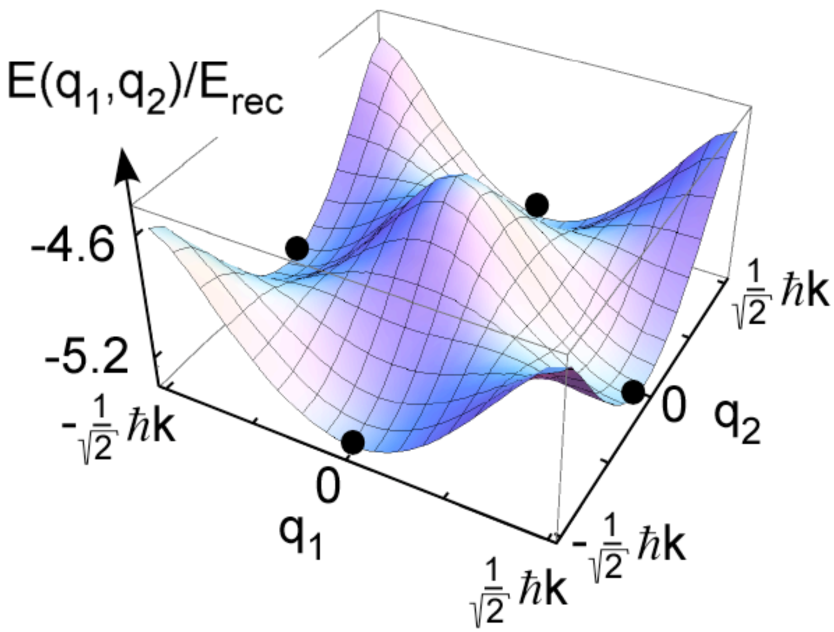
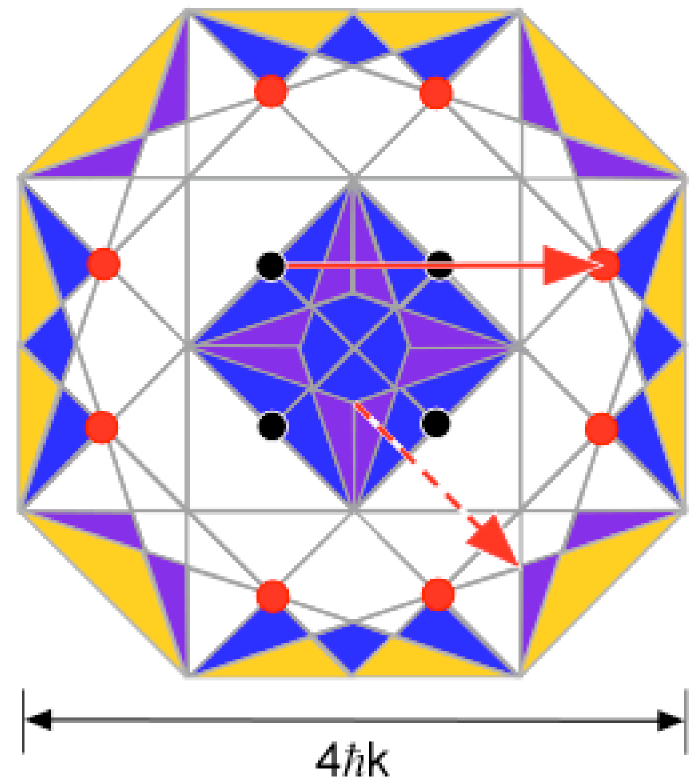
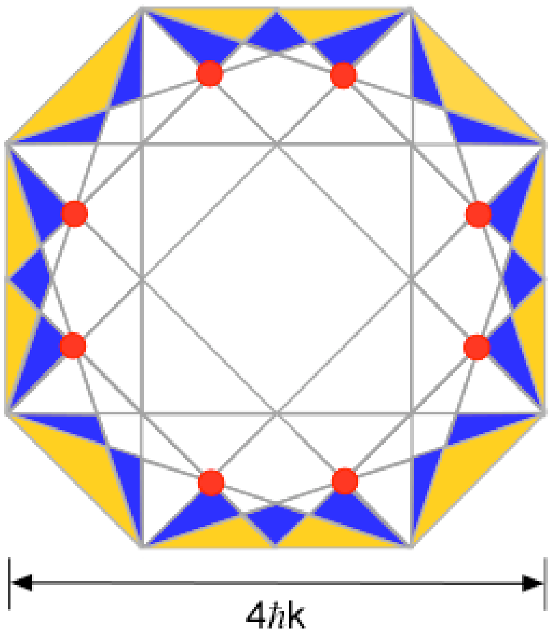
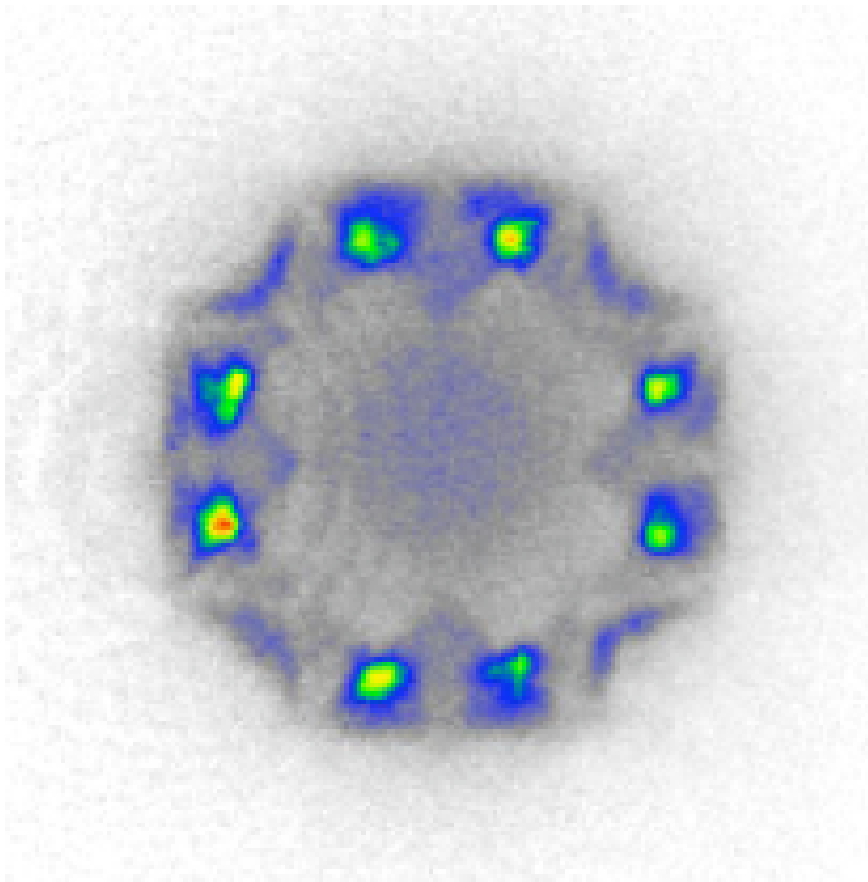


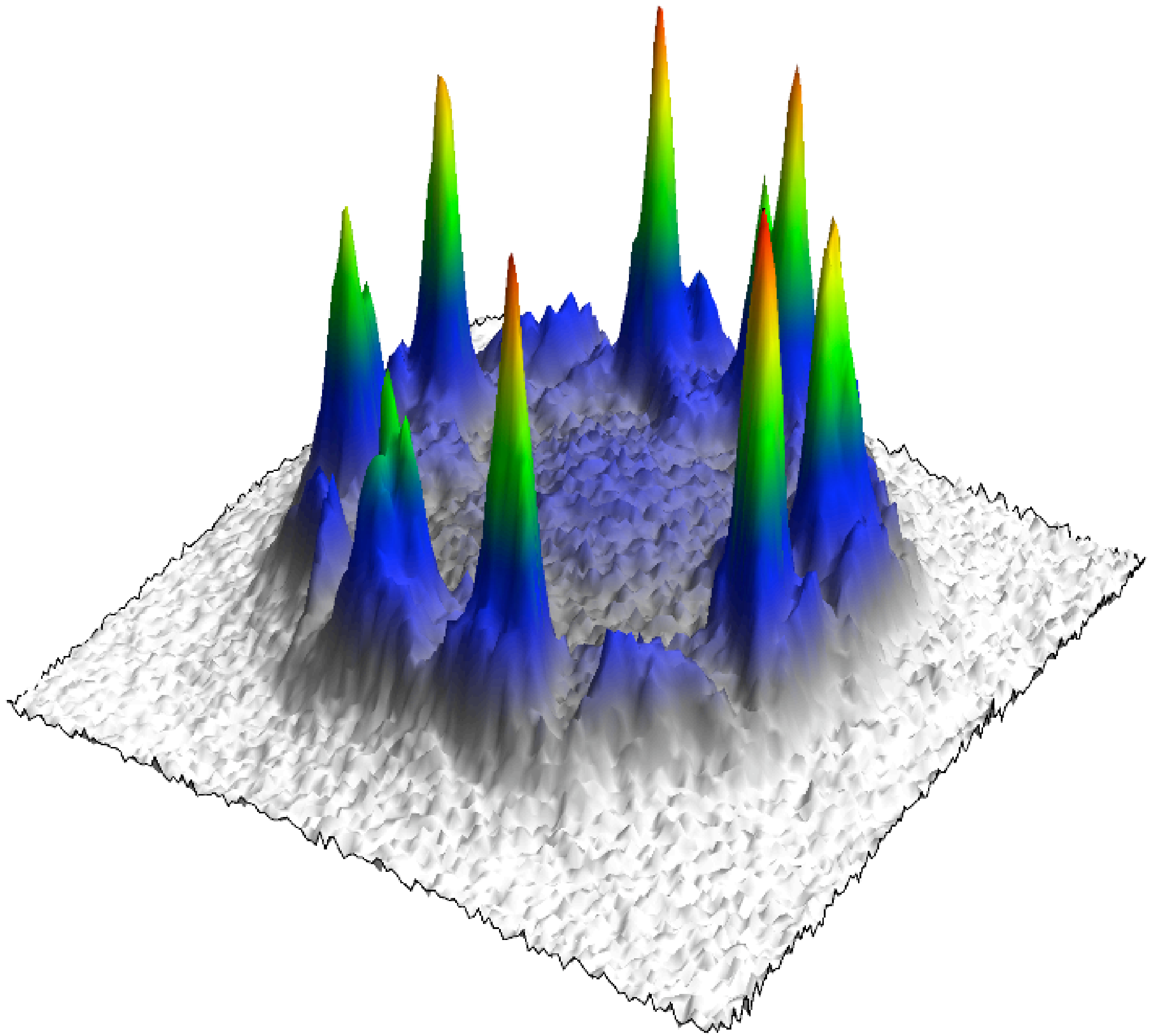


Band mapping



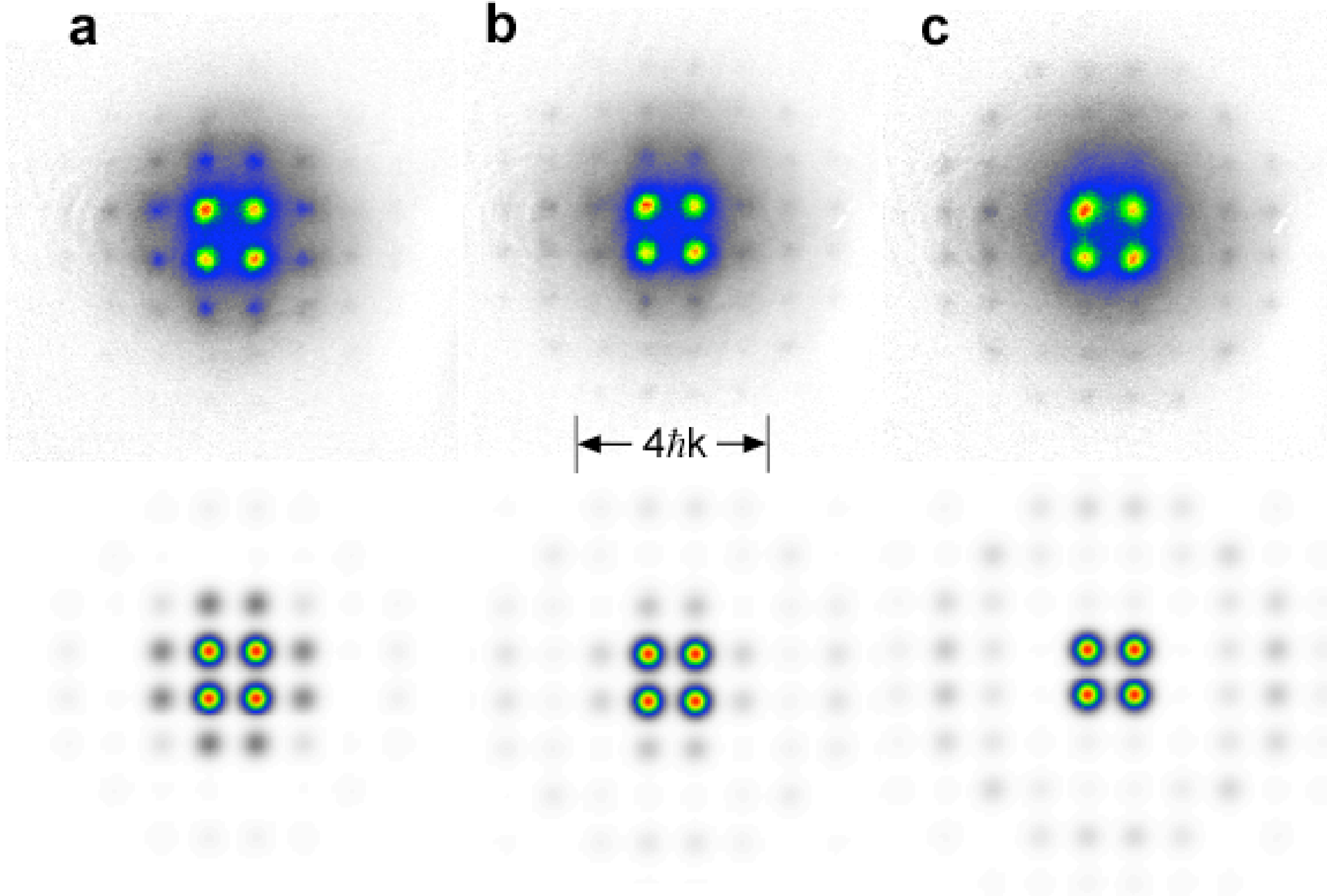


6. & 7. Brillouin zone



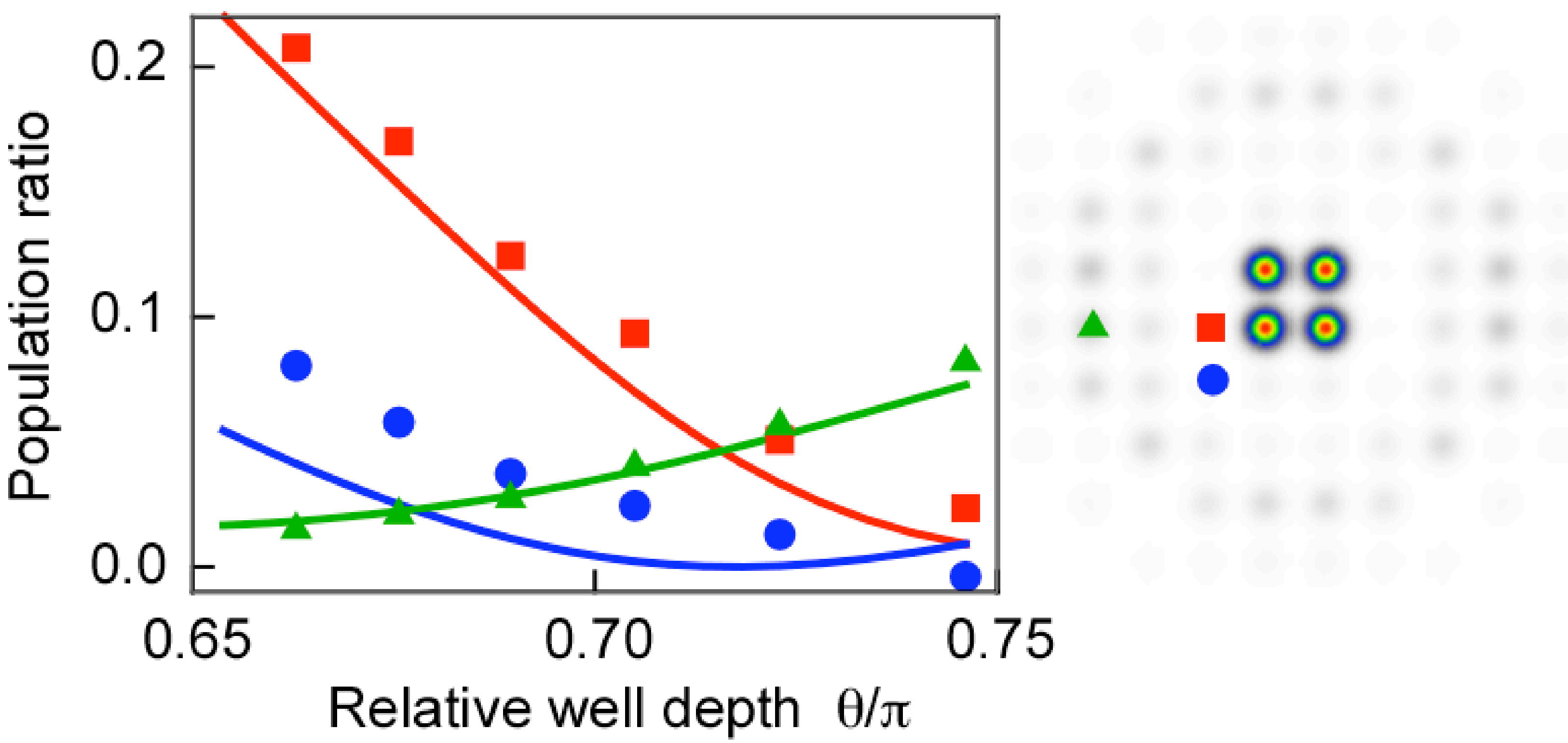
Significant population at condensation points

Momentum spectra: dependence on θ

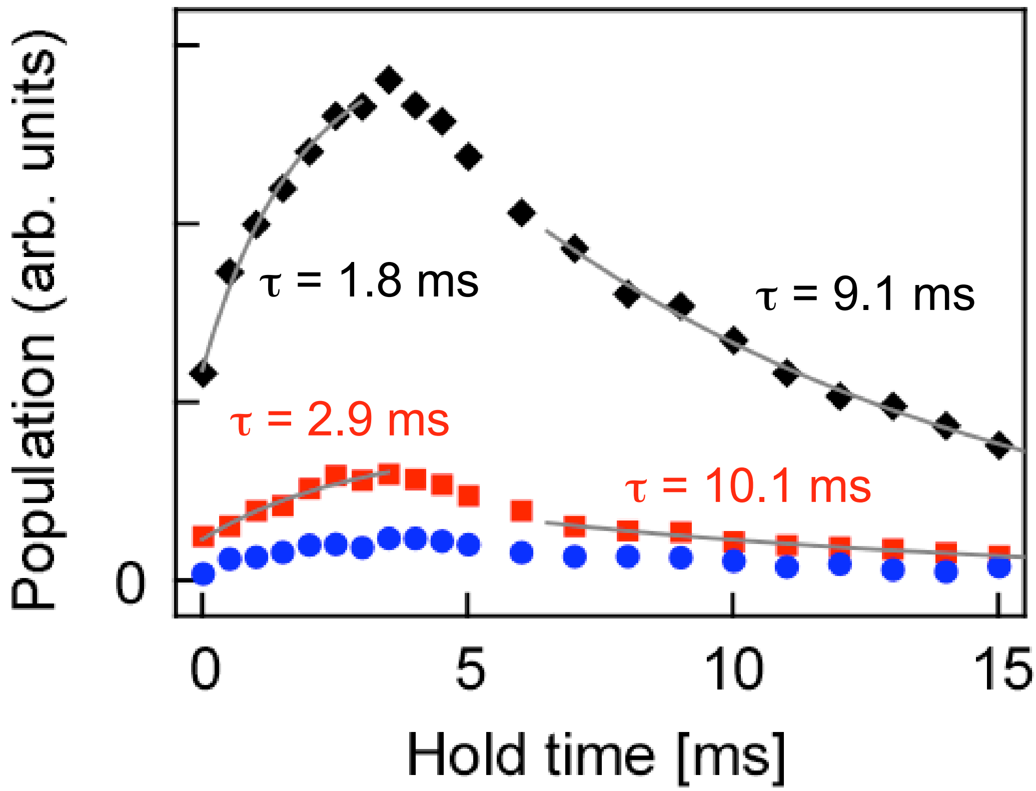


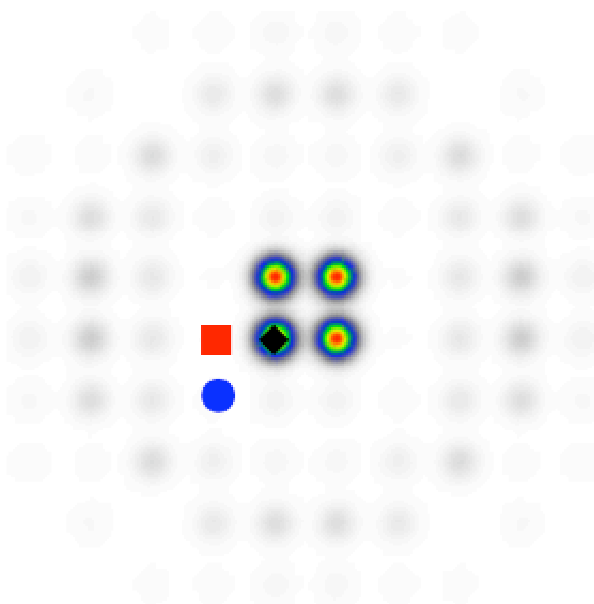
$\theta/\pi = 0.66$ $\theta/\pi = 0.7$ $\theta/\pi = 0.75$

Momentum spectra: dependence on θ



Formation and decay of coherence





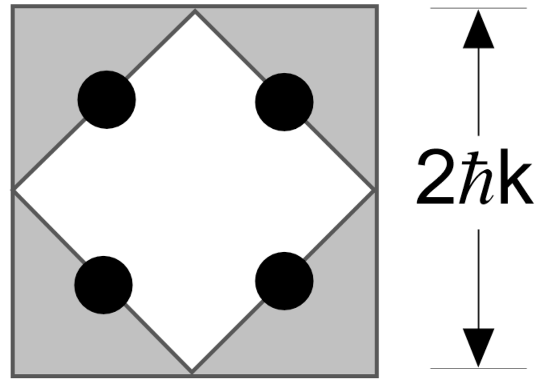
Nature of order parameter

Two inequivalent condensation points

$$K_{(1,1)} = K_{(-1,-1)}$$

$$K_{(-1,1)} = K_{(1,-1)}$$

$$K_{(\pm 1,\pm 1)} \equiv \frac{1}{2}\left(\pm\hbar k, \pm\hbar k\right)$$



For weak interactions, order parameter is approximated by coherent superposition

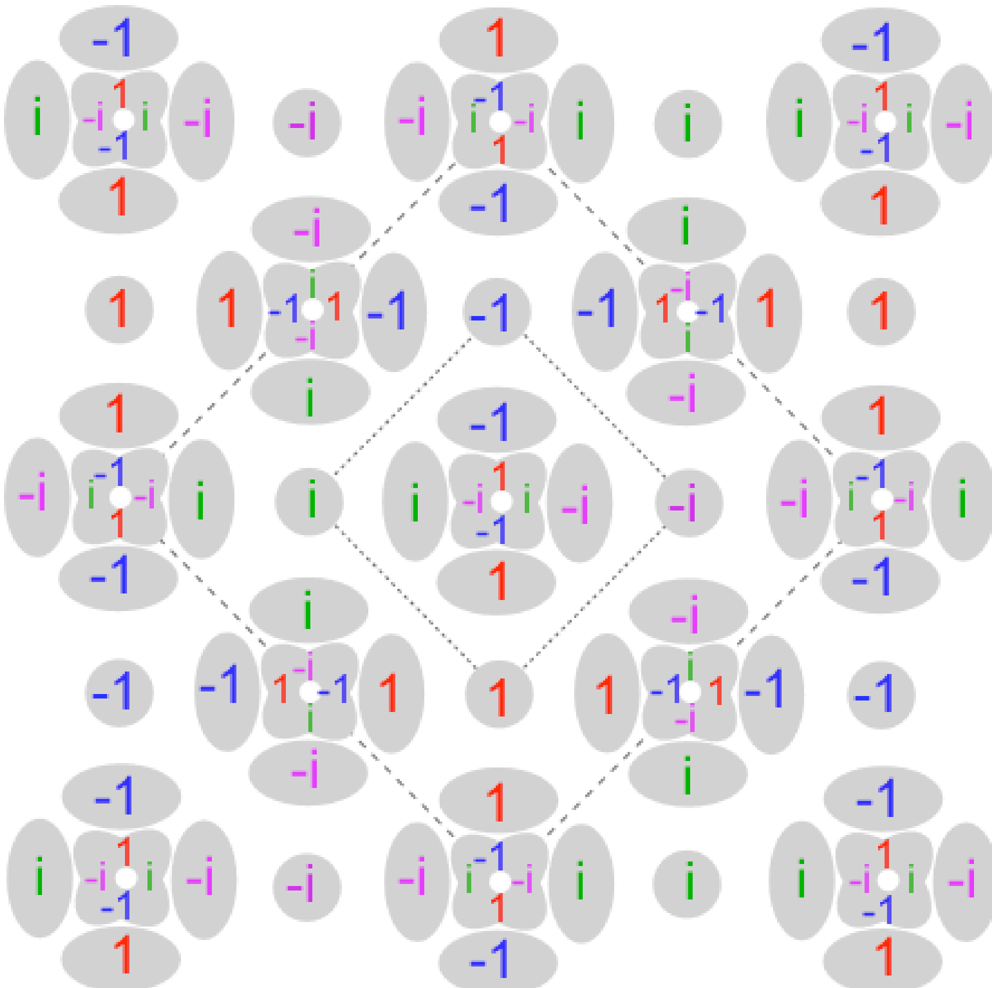
or incoherent mixture of real-valued Bloch-functions $\phi_{K_{(1,1)}}$, $\phi_{K_{(1,-1)}}$

Assume: coherent superposition: $\psi = a\,\phi_{K_{(1,1)}} + b\,\phi_{K_{(1,-1)}}$

Observed momentum spectra are only reproduced for b = i a

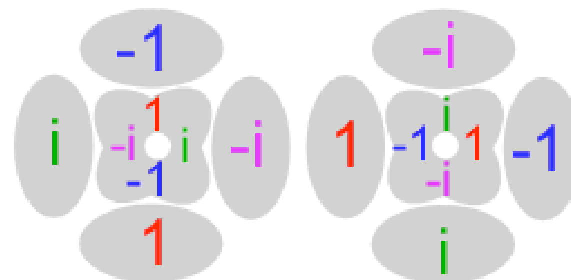
Previous calculations used $\psi = \phi_{K_{(1,1)}} + i\,\phi_{K_{(1,-1)}}$

Shape of order parameter $\psi = \phi_{K_{(1,1)}} + i\,\phi_{K_{(1,-1)}}$



Deep wells:

F-orbits: $\phi_{[3,0]} \pm i\,\phi_{[0,3]}$

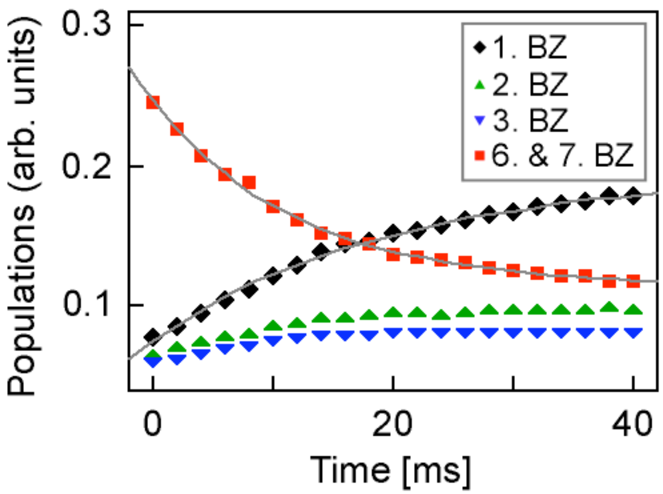


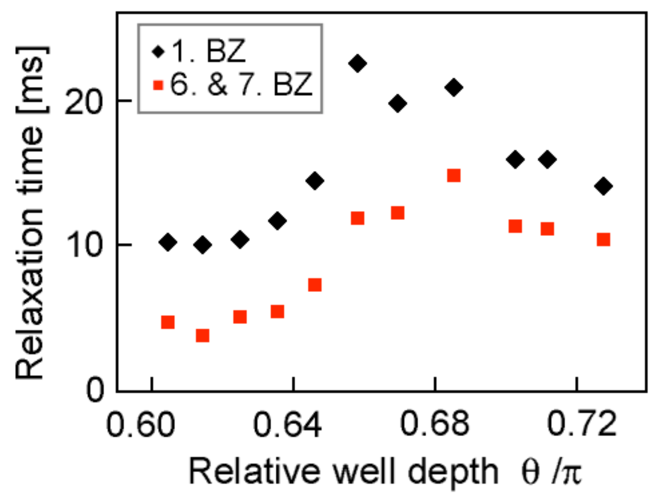
$F_{2x^3-3x} \pm i\,F_{2y^3-3y}$

Shallow wells

S-orbits: $\phi_{[0,0]}$

Collisional relaxation of bands





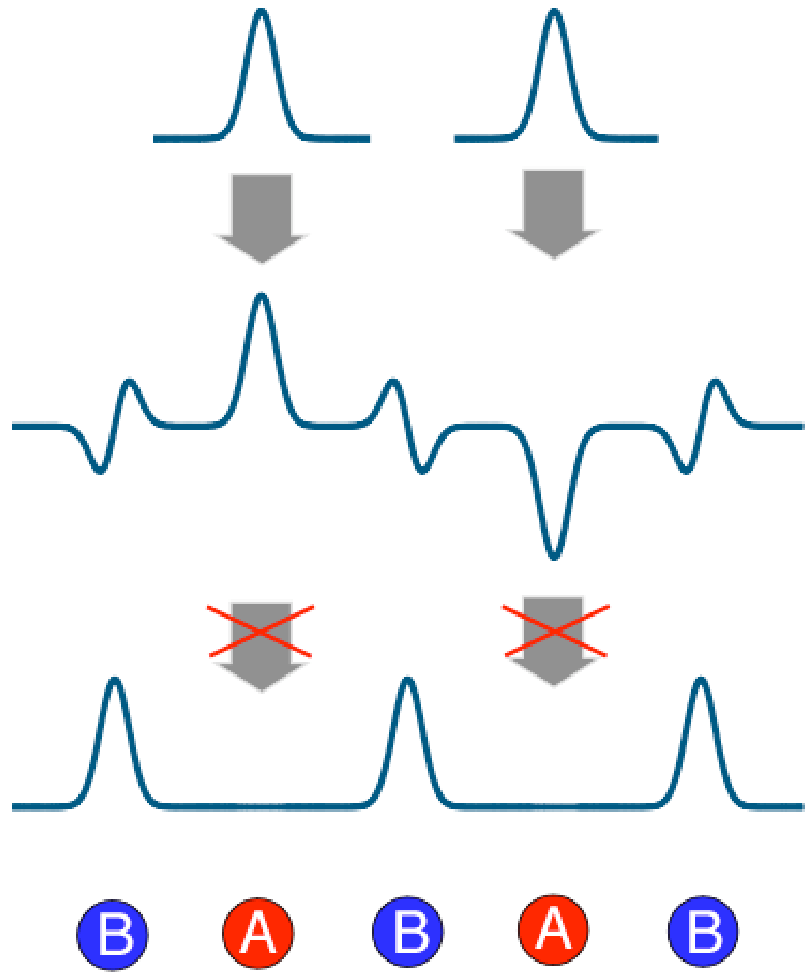
large population
of local S-orbits
increases lifetime

Which bands can be accessed?

Swapping procedure produces incoherent population of local S-orbits in the A-sites

Bloch states providing local S-orbits can be selectively populated with good efficiency

These states are protected from collisional decay, because in the S-band the A-sites are practically empty

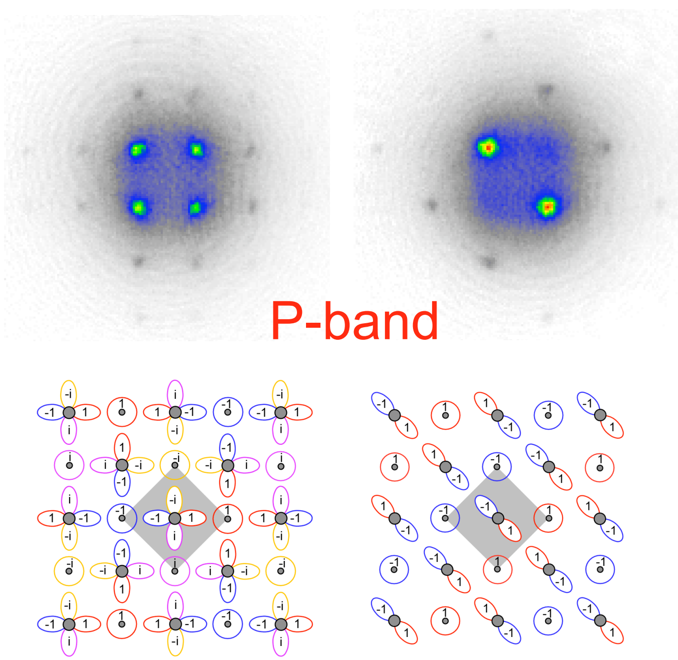


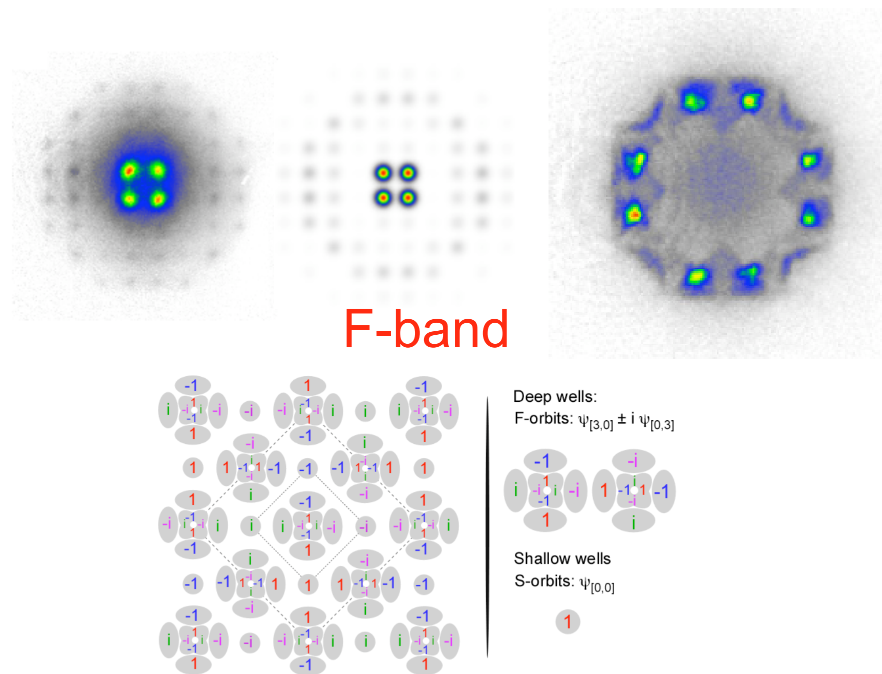
Appropriate Bloch states exist in 2nd, 4th, 7th, 9th,... band

Summary

Bipartite lattices provide an excellent context for exploring orbital physics in optical lattices because of three important features:

- Selective population of higher bands possible
- local S-orbits enable cross-dimensional coherence
- local S-orbits protect against collisional relaxation





PhD-students

Matthias Ölschläger
Georg Wirth

Support

JOACHIM HERZ STIFTUNG

DFG Deutsche Forschungsgemeinschaft

References

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