Quantum Simulations with Laser Assisted Tunneling

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Brussels
Solvay Workshop on "Quantum Simulation with Cold Matter and Photons"

Massachusetts Institute of Technology

in magnetic fields, we have TWO momenta

$$\vec{p}_{mech} = \vec{p}_{can} - q\vec{A}$$

Similar, in spin-orbit coupling

$$p_{mech,i} = p_{can,i} - \vec{\sigma} \cdot \vec{\alpha}$$

$$\vec{p}_{mech}^{\,2} \longrightarrow p_i \sigma_j \text{ terms}$$

⇒ Spin-orbit coupling is equivalent to a spin-dependent vector potential in magnetic fields, we have TWO momenta

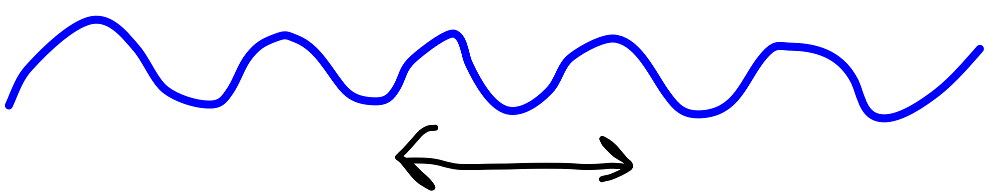
$$\vec{P}_{mech} = \vec{P}_{can} - \underbrace{q\vec{A}}_{n\hbar k}$$

photon momentum

Used in Raman coupling schemes and laser assisted tunneling

Photon $\rightarrow$ e^{ikx}

Shaking the Lattice



$$t \longrightarrow e^{i\phi}\, t$$

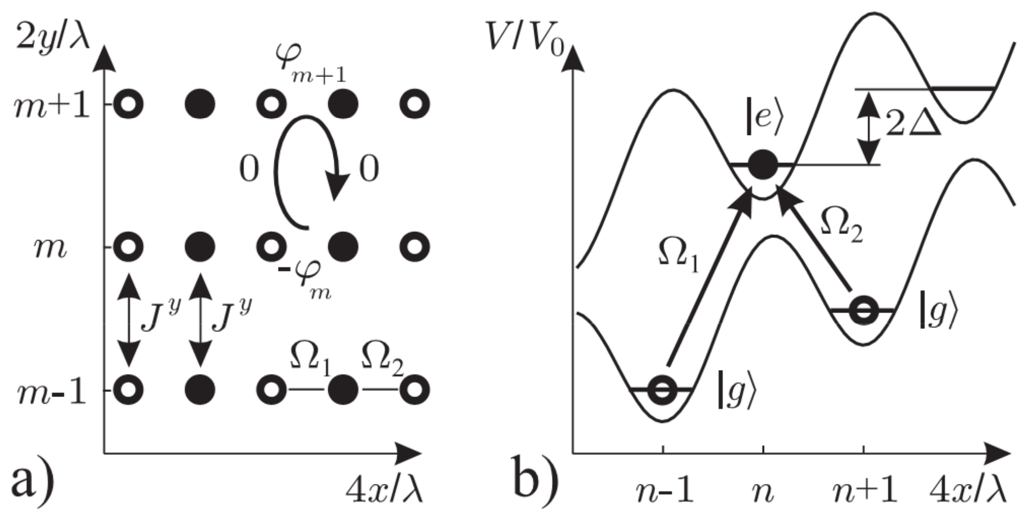
$$\phi(x) \hat{=} \vec{A}$$

Peierl's Substitution

Creation of effective magnetic fields in optical lattices: the Hofstadter butterfly for cold neutral atoms

D Jaksch[1,2] **and P Zoller**[2]
[1] Clarendon Laboratory, Department of Physics, University of Oxford, Oxford OX1 3PU, UK
[2] Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria
E-mail: dieter.jaksch@physics.oxford.ac.uk

New Journal of Physics **5** (2003) 56.1–56.11 (http://www.njp.org/)



How to engineer these phases?

Concept:

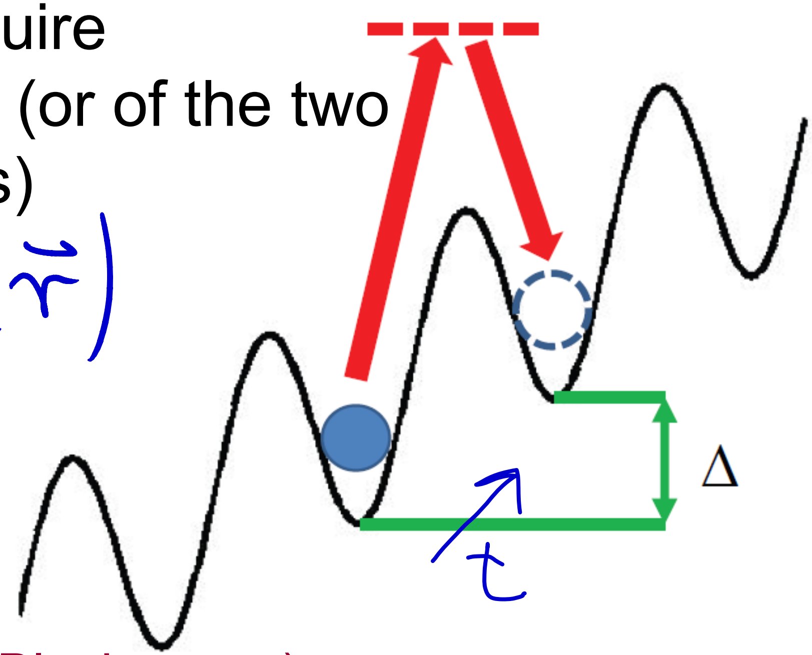
Create a situation where motion (tunneling) is only possible with the help of laser beams

Result:

Tunneling matrix element will acquire the local phase of the laser beam (or of the two photon field for Raman processes)

$$t \rightarrow t\, e^{i\varphi_{Laser}(\vec{r})}$$

$$\varphi_{Laser} = \overrightarrow{\Delta K}\, \vec{r}$$



Realized: 2013 (MIT, Ketterle group; Munich, Bloch group)
(without lattice: JQI 2009)

Miyake H, Siviloglou G A, Kennedy C J, Burton W C and Ketterle W, Phys. Rev. Lett. 111, 185302 (2013): Realizing the Harper Hamiltonian with Laser-Assisted Tunneling in Optical Lattices

Constant magnetic field $\vec{B} = B_0 \hat{z}$

Vector potential MUST break translational invariance in x and y

Different gauges have different symmetries:

For $\vec{B} = B\hat{z}$ $\quad \alpha = \frac{p}{q}$, flux per unit cell

Landau gauge

$$\vec{A} = -By\hat{x}$$

$$\vec{A} = Bx\hat{y}$$

Different gauges have different symmetries:

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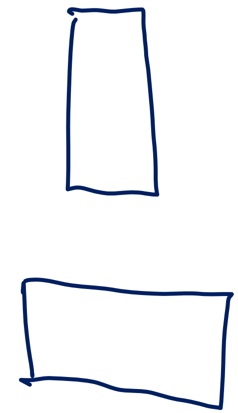
Landau gauge

$\vec{A} = -By\hat{x}$ $\qquad 1 \times q$

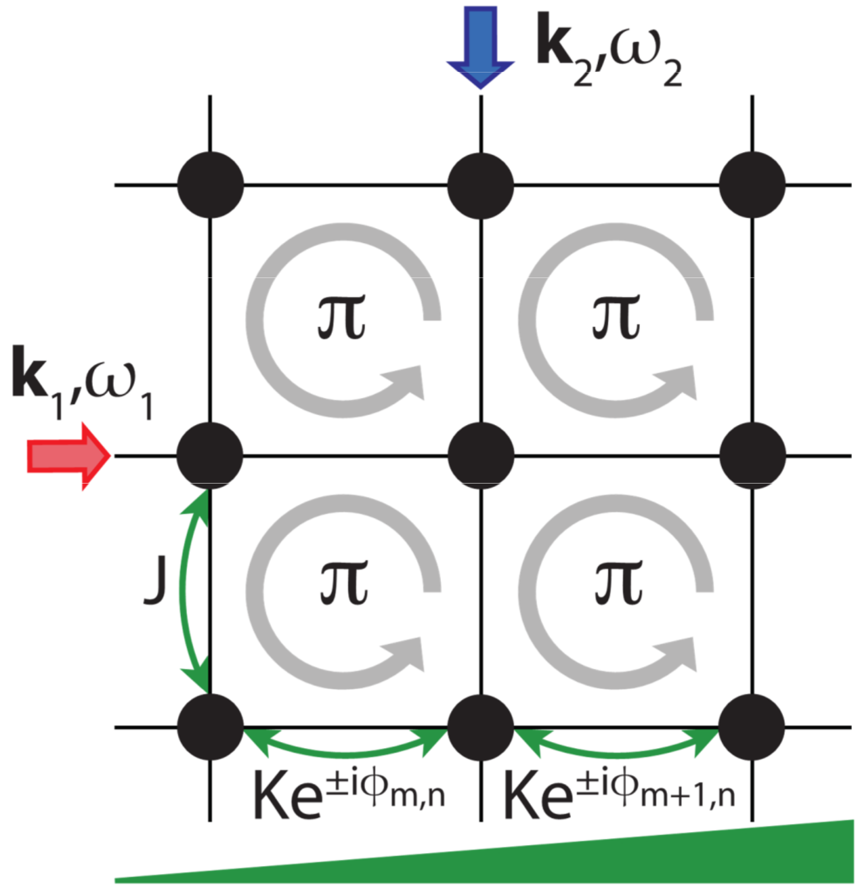
$\vec{A} = Bx\hat{y}$ $\qquad q \times 1$



unit cell of Hamiltonian

Wavefunction has different periodicity!

Experimental Setup for $\alpha = 1/2$



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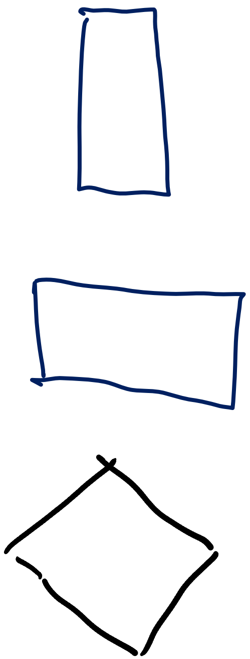
Our implementation

$\vec{A} = -B(y+x)\hat{x}$



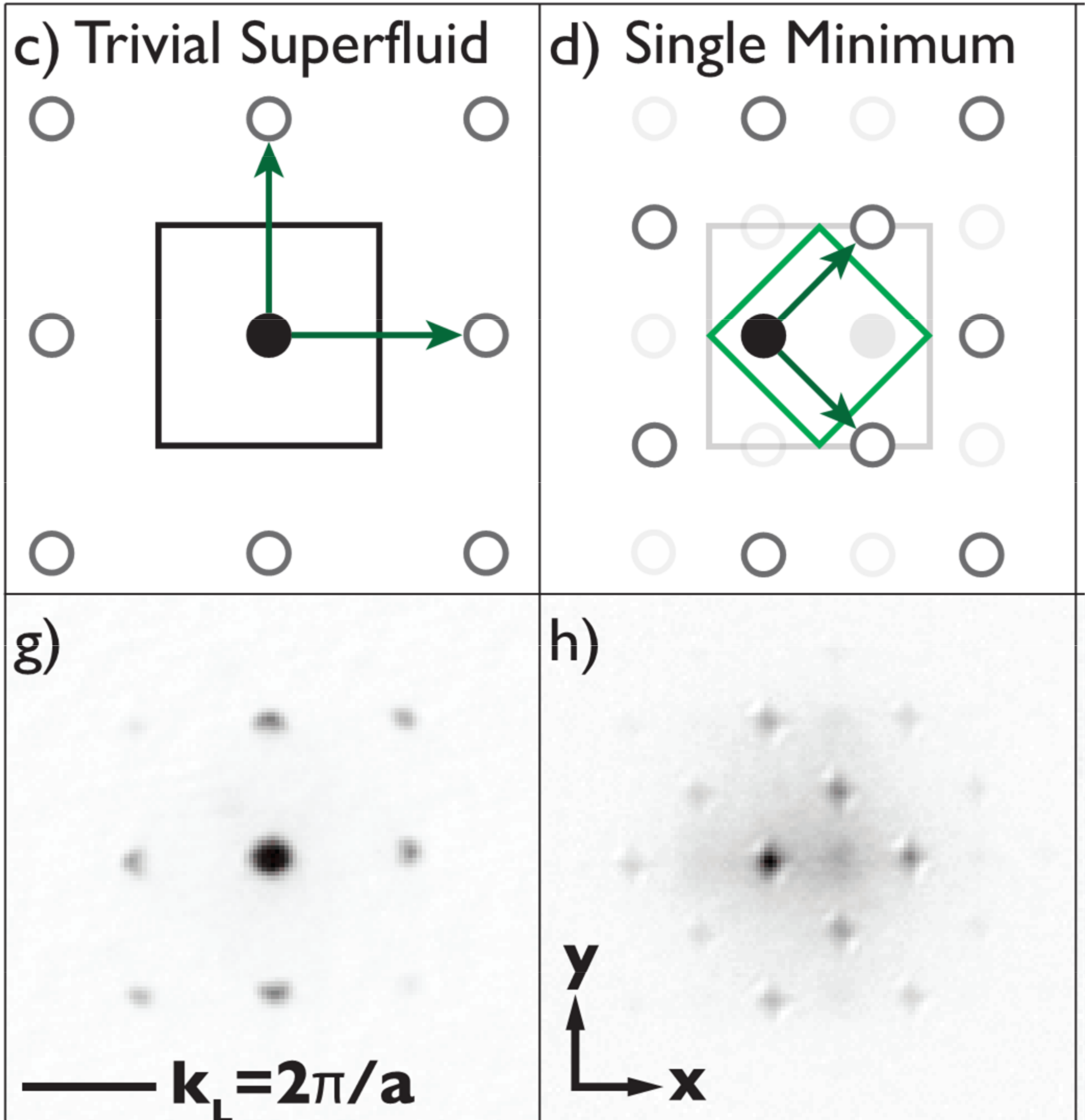
unit cell of Hamiltonian

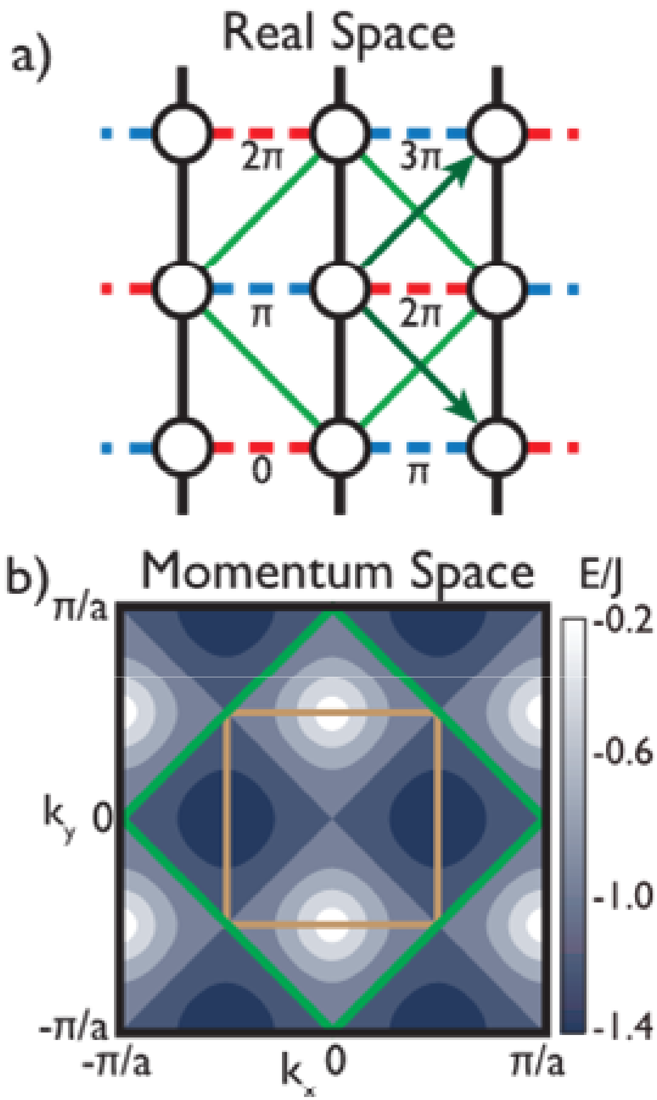
Wavefunction has different periodicity!

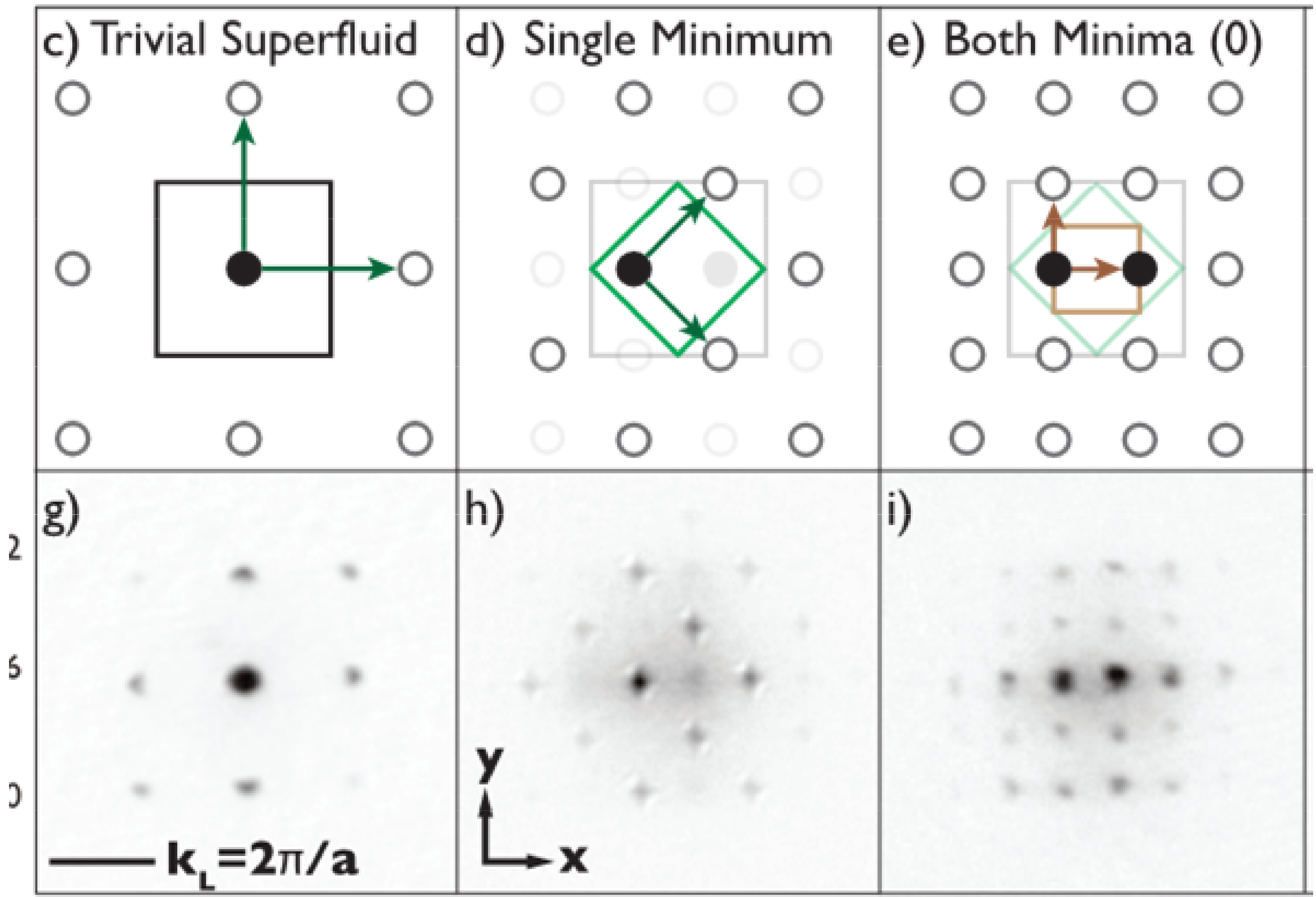
Switch off lattice – wavefunction is not changed.
“Self diffraction of coherent matter wave”

Canonical momentum becomes mechanical momentum.
Observed after ballistic expansion.

Time-of-flight images show the momentum distribution of the wavefunction (which is NOT gauge invariant).

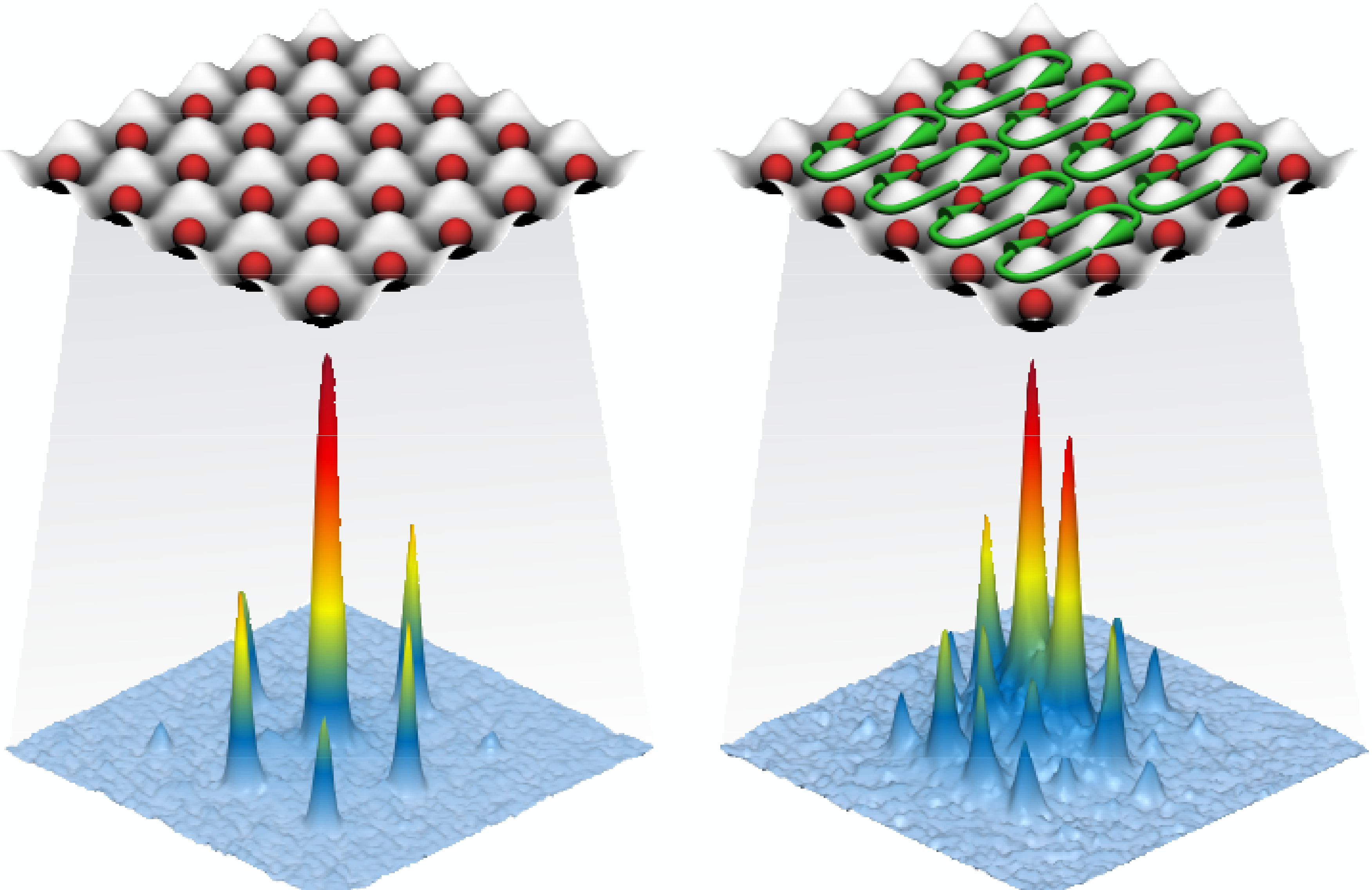

c) Trivial Superfluid
d) Single Minimum
g)
h)
$k_L = 2\pi/a$
y
x


a)
Real Space
2π
3π
π
2π
0
π
b)
Momentum Space
E/J
π/a
-0.2
-0.6
k_y 0
-1.0
-π/a
-1.4
-π/a
k_x 0
π/a



c) Trivial Superfluid
d) Single Minimum
e) Both Minima (0)
g)
h)
i)
y
x
k_L=2π/a

C.J. Kennedy, W.C. Burton, W.C. Chung, and W. Ketterle, *Observation of Bose-Einstein Condensation in a Strong Synthetic Magnetic Field*, Nature Physics **11**, 859–864 (2015).



Simplest explanation for time of flight pictures:

The wavefunction is unchanged, TOF pictures show momentum distribution (i.e. $\langle \psi | -i\hbar\nabla | \psi \rangle$)

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However, this cannot be done with electrons and real magnetic fields since the wavefunction is NOT gauge invariant.

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Alternative description:

Canonical momentum $\hat{p}=-i\hbar\nabla$ becomes mechanical momentum

Mechanical momentum changes from p – A to p

Momentum change by A can be described by synthetic electric field

$$E = -\partial_t A$$

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This is not gauge invariant!

For (real) electromagnetic fields:

$$E = -\partial_t A - \nabla\phi$$

and momentum distributions after switch-off (time-of-flight images) are independent of gauge

(but in general, don't show the momentum distribution of the wavefunction)

Now: Spin degree of freedom

How to engineer spin-orbit coupling for neutral atoms?

Raman spinflip scheme

Flip the spin in a momentum-dependent way
(using the Doppler shift)

Our scheme

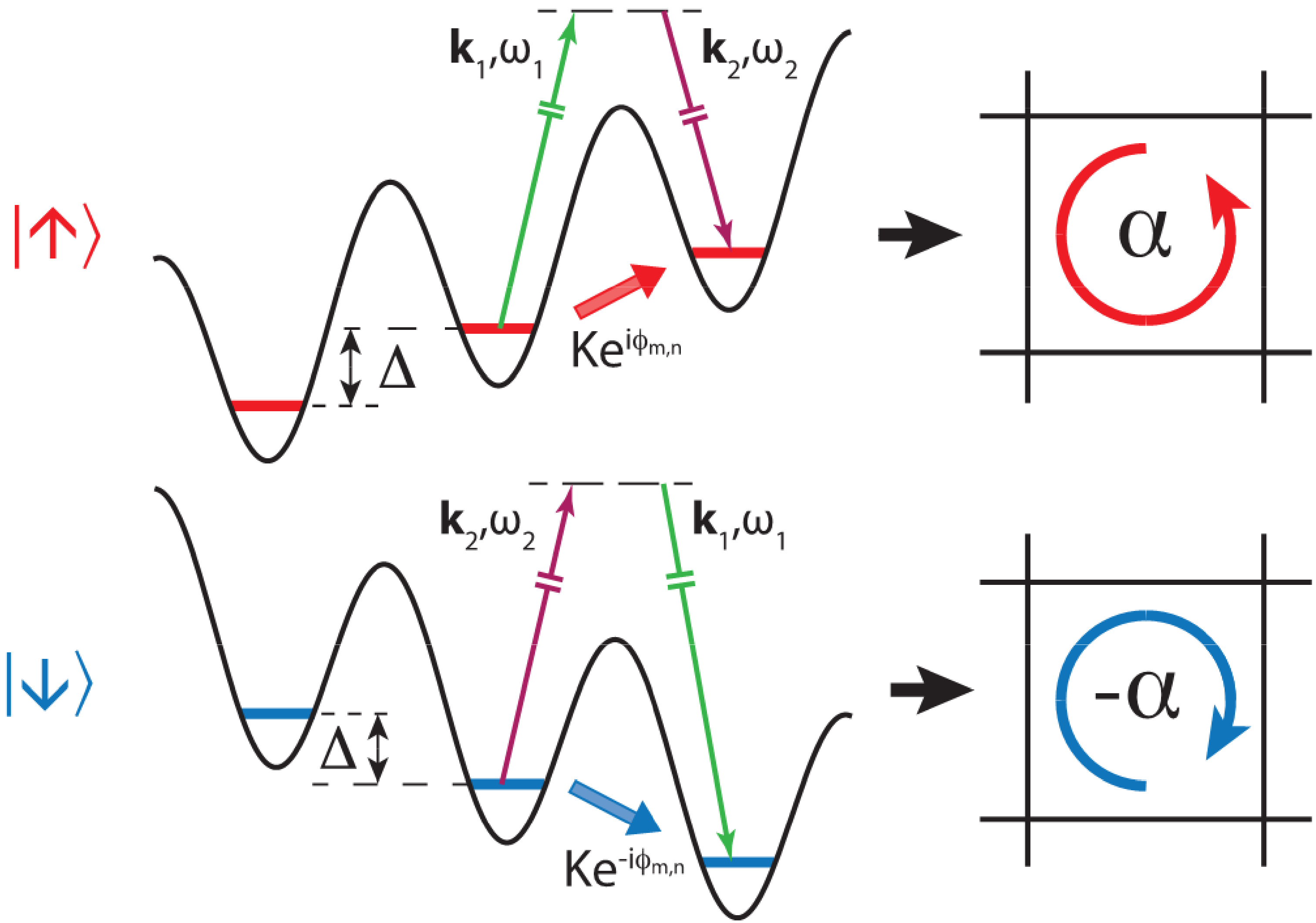
Affect the motion of spin up and down differently
WITHOUT flipping the spin
(using Zeeman shifts to address spin up and down differently)

Kennedy C J, Siviloglou G A, Miyake H, Burton W C and Ketterle W, Phys. Rev. Lett. **111**, 225301 (2013). Spin-orbit coupling and spin Hall effect for neutral atoms without spin-flips

In our scheme:

signs of B, A, phase of tunneling matrix elements reflect the momentum transfer by Raman beams

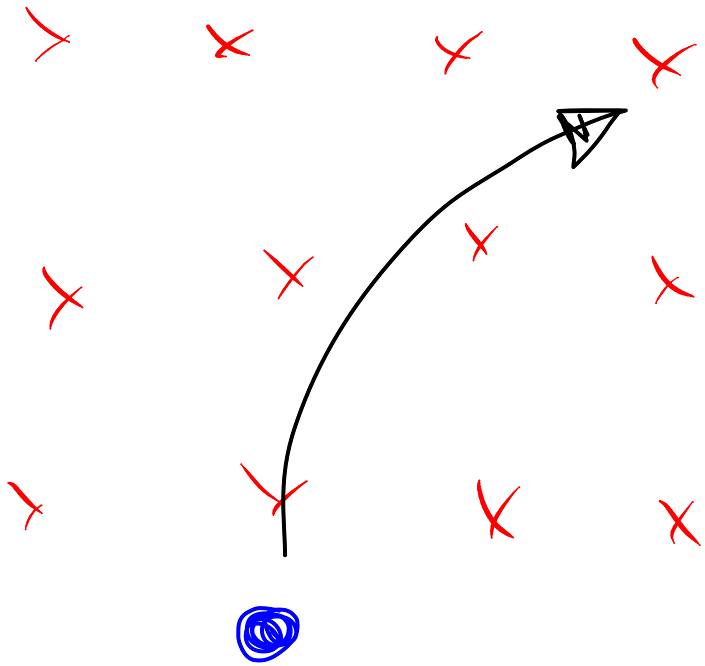
also: Munich



$$\phi_{m,n} = (mk_x a + nk_y a)\,\sigma_z \quad \mathbf{A} = \frac{\hbar}{a}(k_x x + k_y y)\,\hat{\mathbf{x}}\,\sigma_z$$

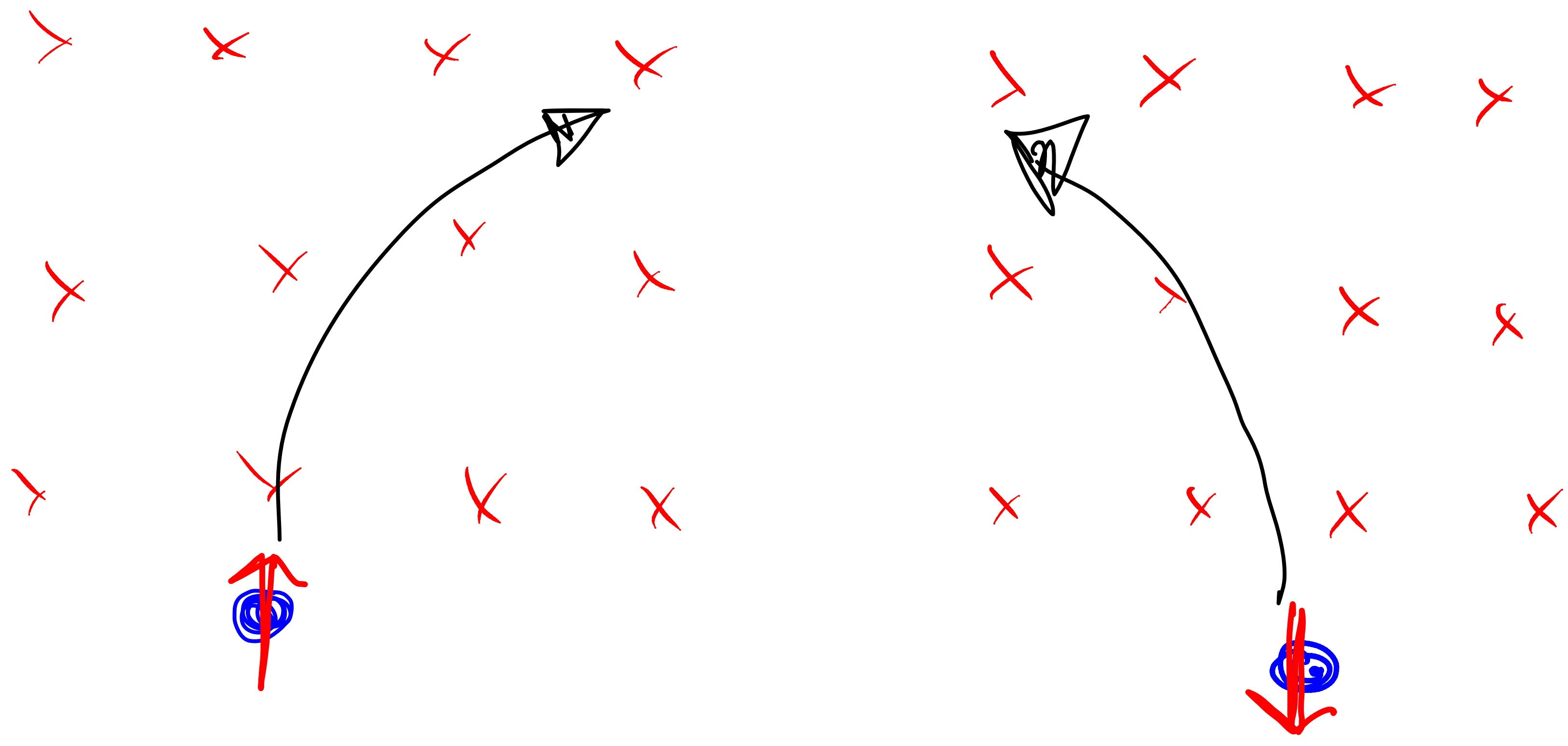
Hall effect

B field separates charge



Spin Hall effect

B field separates spin



Means that effective B field is different for two spins

Time reversal symmetry

- Quantized spin Hall effect (two opposite quantum Hall phases)
- Z topological index (due to conservation of σ_z)
- Topological insulator

PRL **96,** 106802 (2006) PHYSICAL REVIEW LETTERS week ending 17 MARCH 2006

Quantum Spin Hall Effect

B. Andrei Bernevig and Shou-Cheng Zhang

Department of Physics, Stanford University, Stanford, California 94305, USA

Exact realization of this idealized proposal

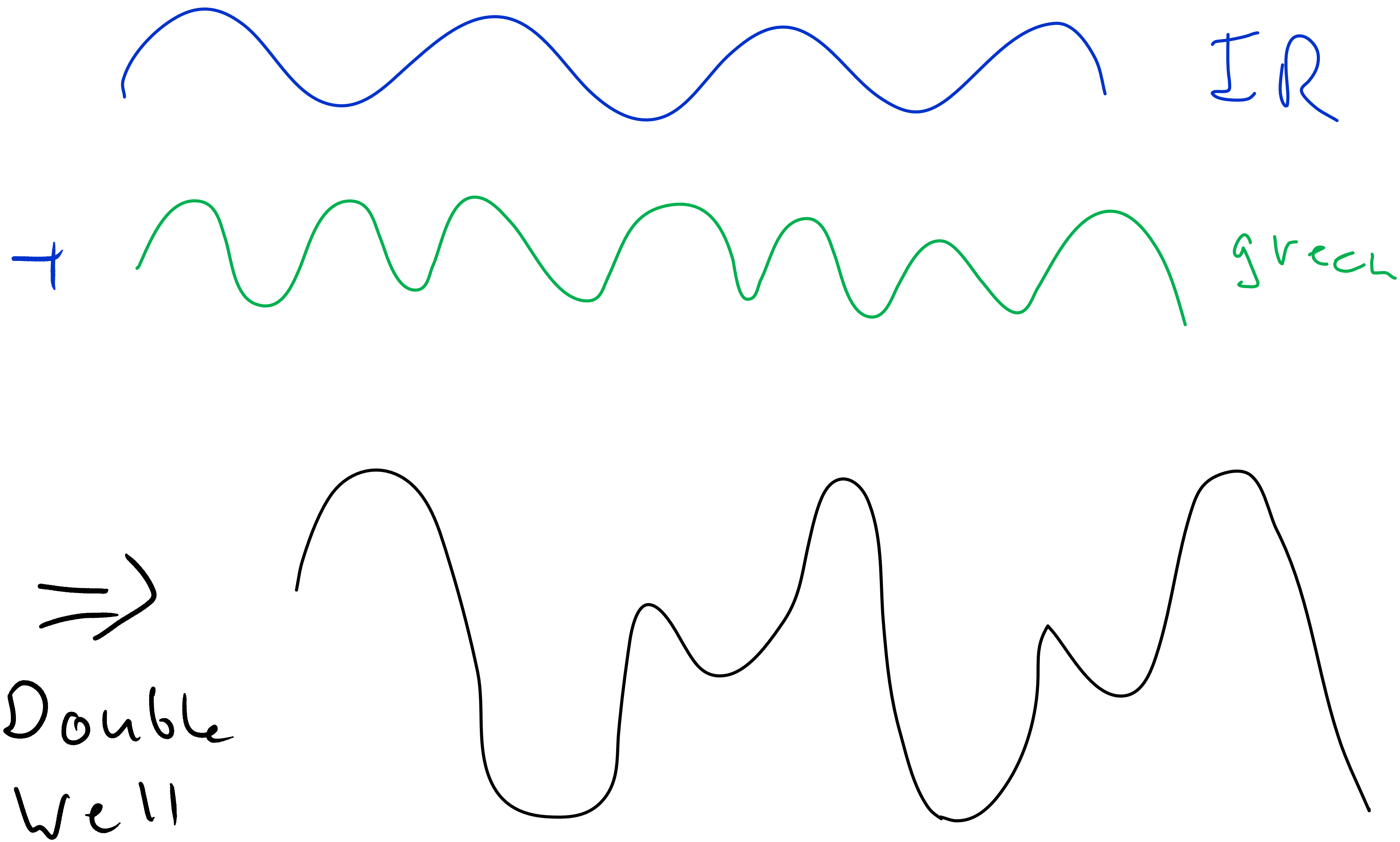
Diagonal in σ_z
Abelian SU(2) gauge field

How to do spinflips without transitions between spin states?

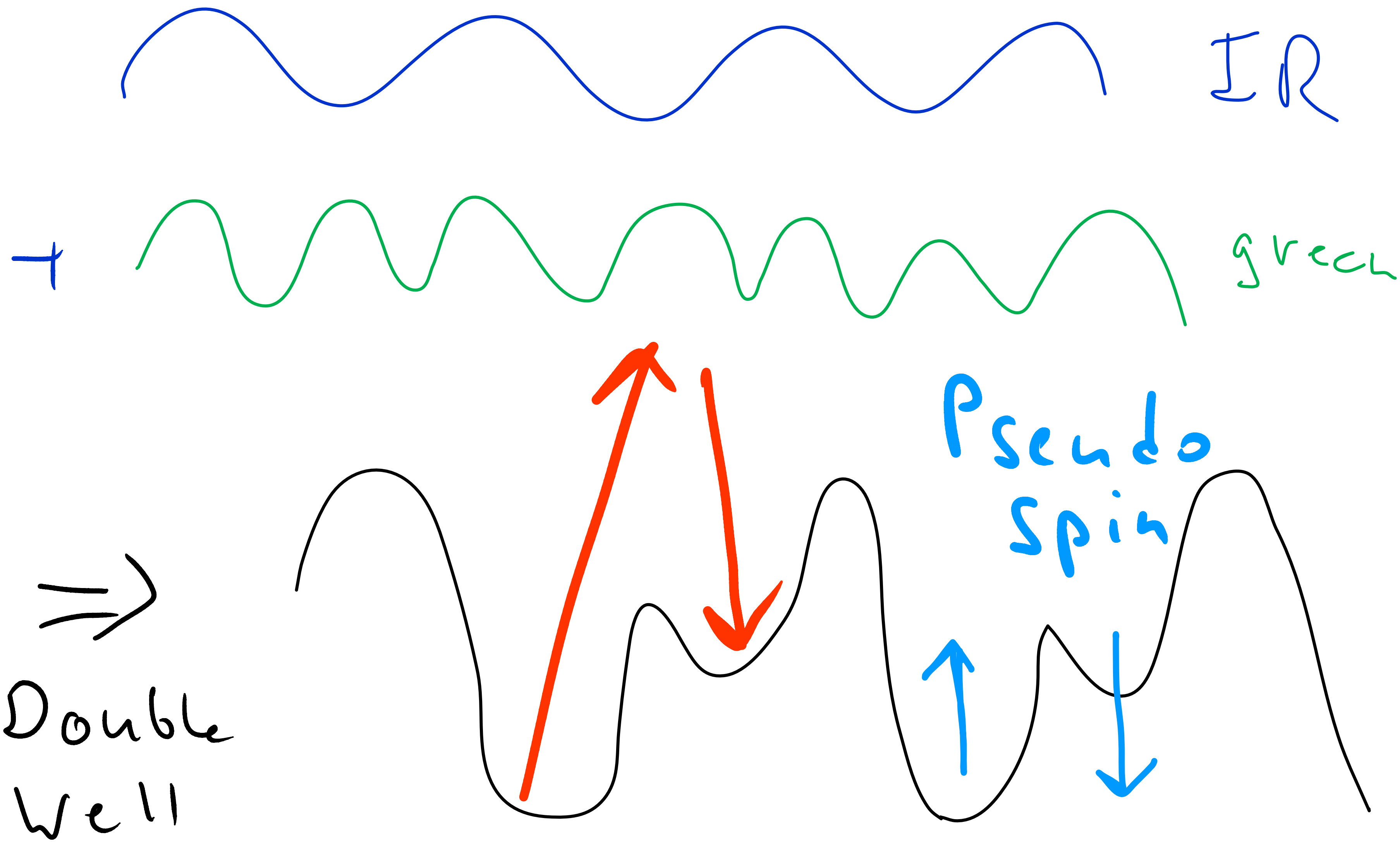
σ^+, σ^- terms

A new spin-orbit coupling scheme

Superlattice



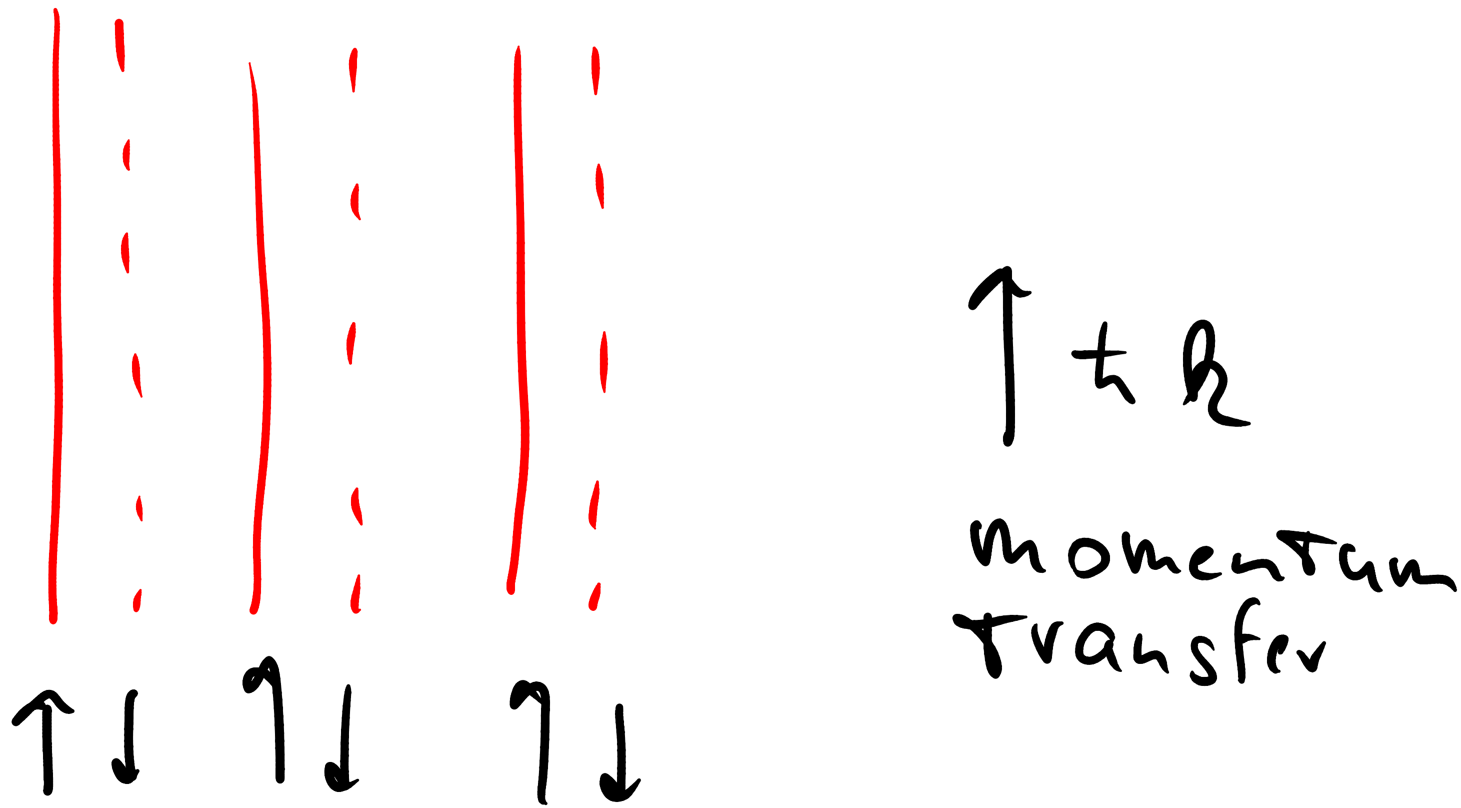
Superlattice

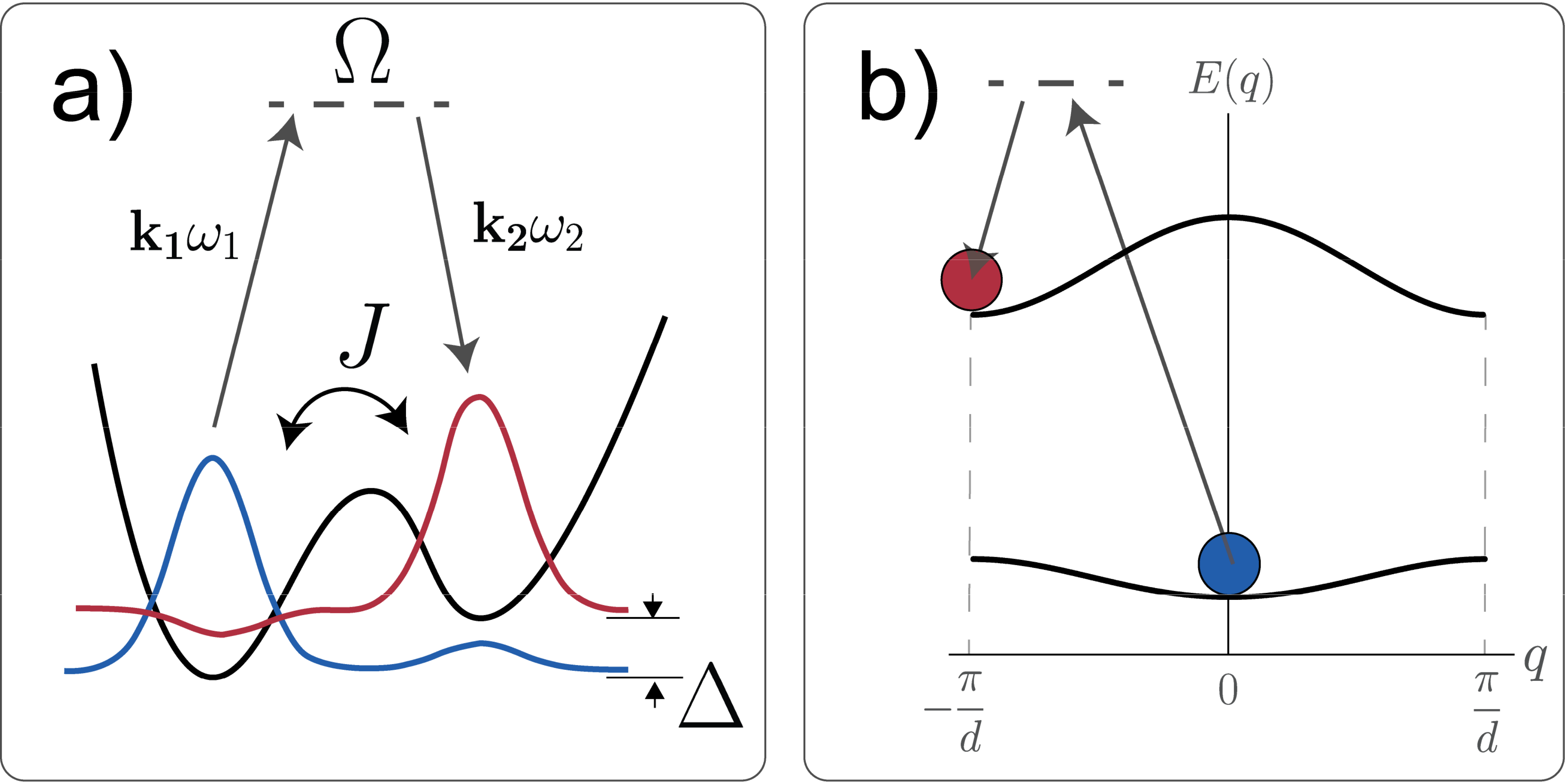


- Use orbital degree of freedom (lowest and first excited band) as pseudo-spin

- Double-well potential leads to long lifetimes (see also: Hemmerich) and adjustable interactions between the two spin states

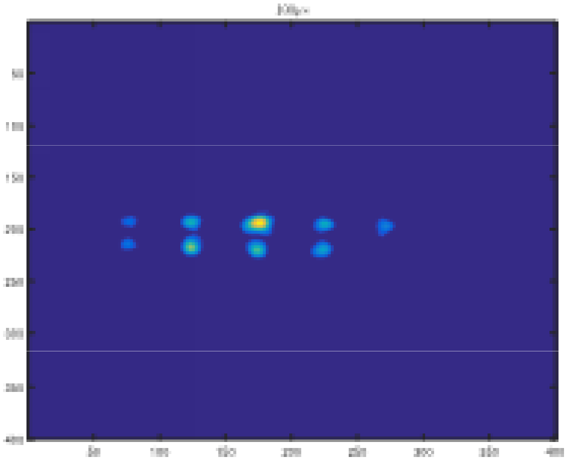
Stack of double pancakes



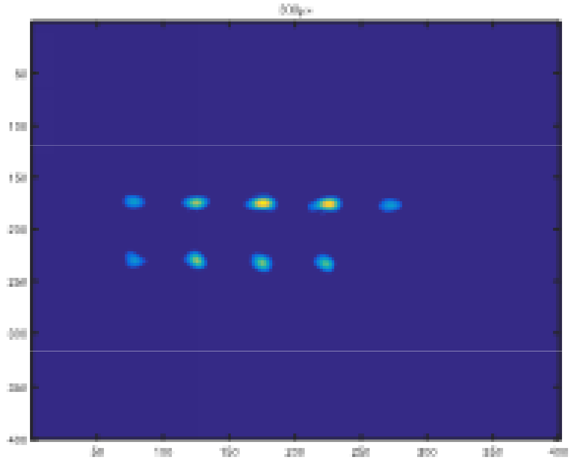


tunneling for ↓ and ↑ is positive / negative
band minimum at k=0 / k=±π

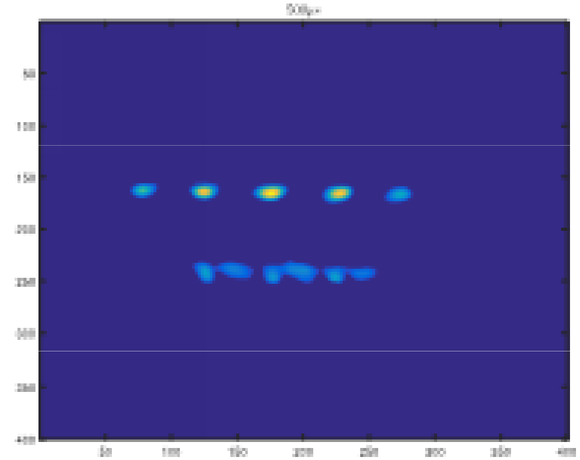
separate pseudo-spins by optical “Stern Gerlach” effect



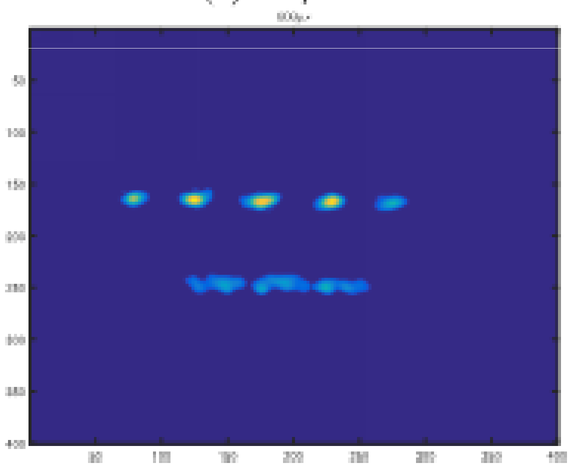
(a) $100\mu s$



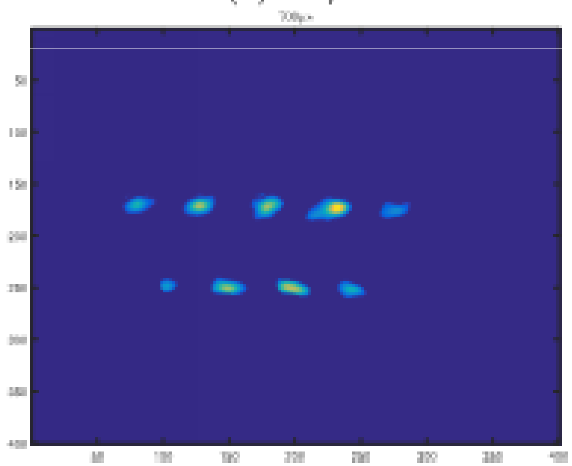
(b) $300\mu s$



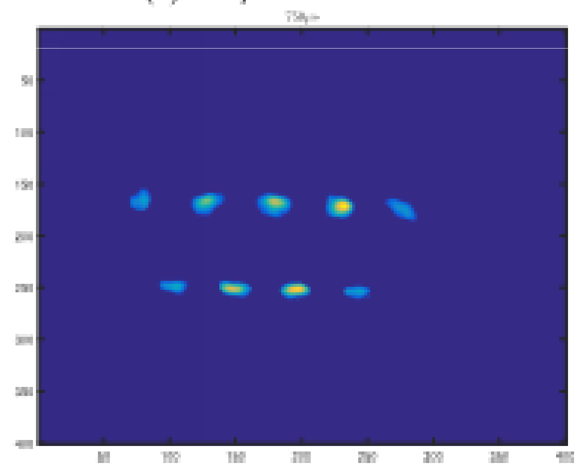
(c) $500\mu s$



(d) $600\mu s$

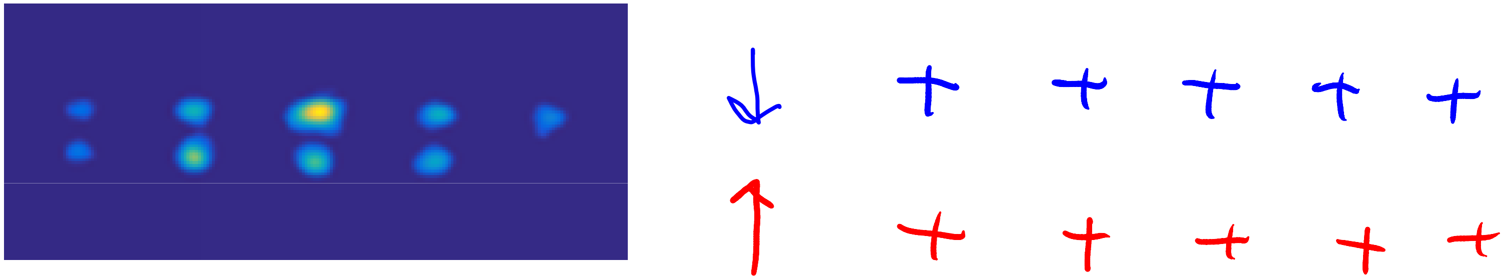


(e) $700\mu s$

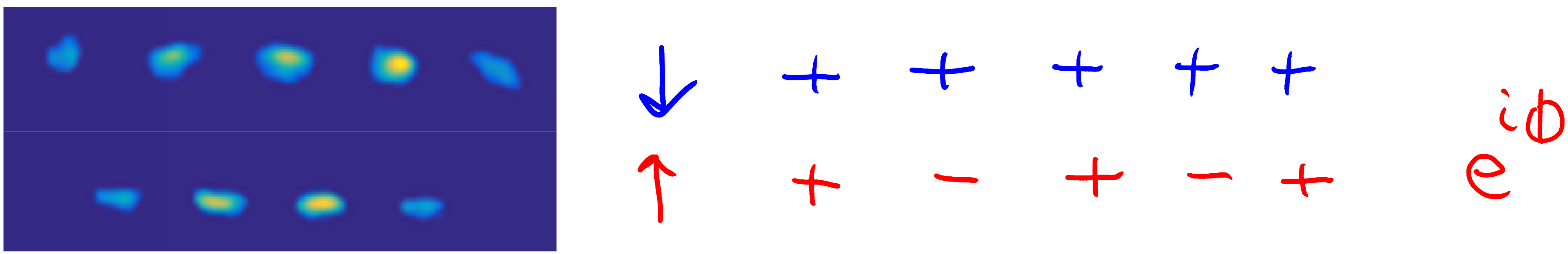


(f) $750\mu s$

Spontaneous formation of xy anti-ferromagnetic spin texture



xy ferromagnetic



xy anti-ferromagnetic

Spontaneous breaking of lattice symmetry (doubling of unit cell)
Spontaneous U(1) phase for angle of spin texture

trivial example for supersolid !! (?)

Notes:

…. a simple way to create spin dependent lattices for engineering new Hamiltonians ….

PRL 115, 073002 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

see also:

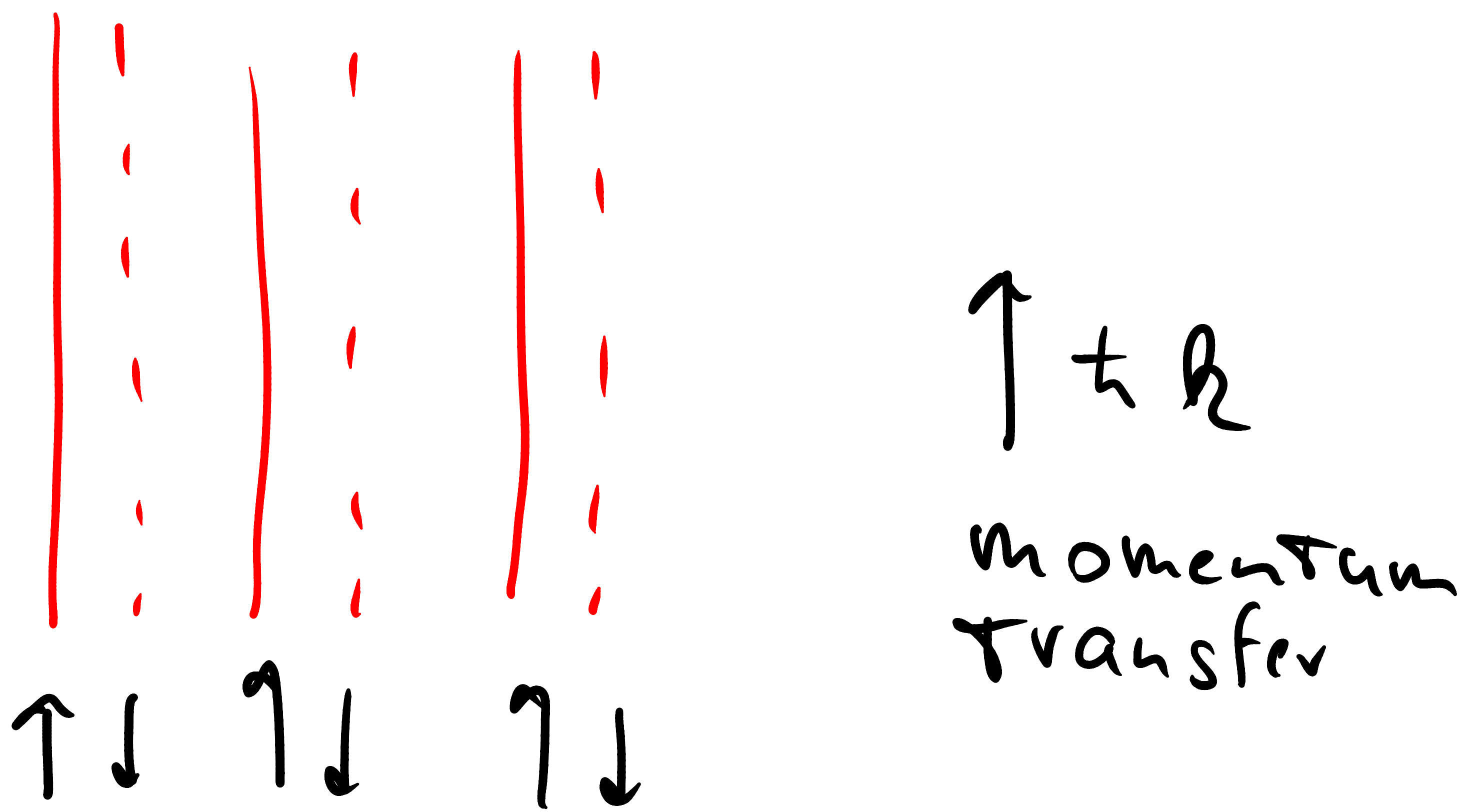
Creating State-Dependent Lattices for Ultracold Fermions by Magnetic Gradient Modulation

Gregor Jotzu, Michael Messer, Frederik Görg, Daniel Greif, Rémi Desbuquois, and Tilman Esslinger
Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland

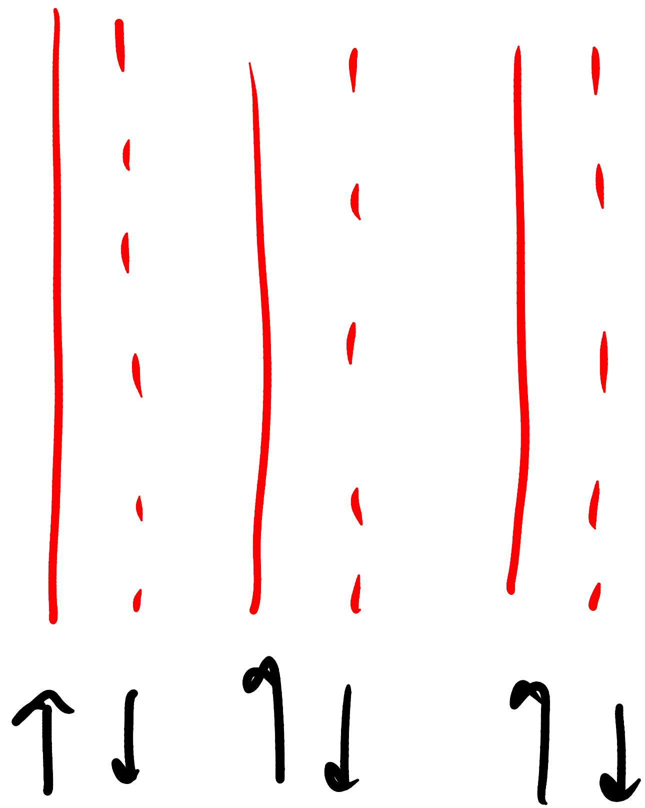
(Received 21 April 2015; published 13 August 2015)

…. see population in left/right well without band mapping ….

Stack of double pancakes



Stack of double pancakes

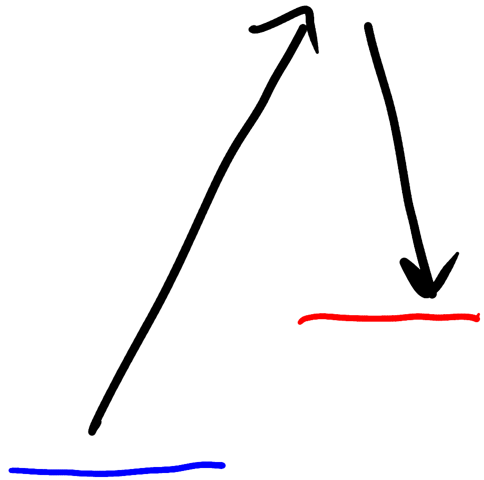


↑ $\hbar k$

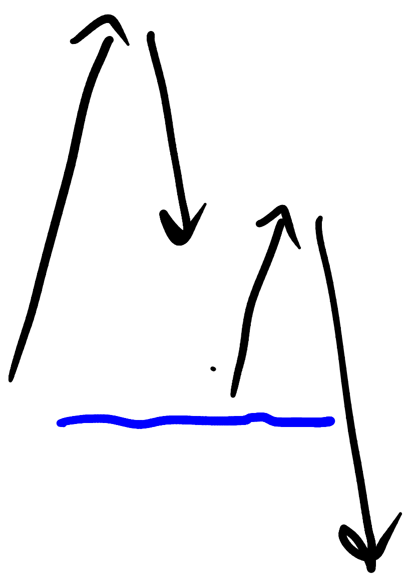
momentum transfer

For SO coupling

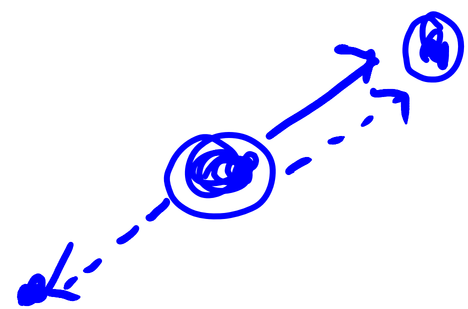
$\longrightarrow$ $\hbar k$ For coupling Wannier functions

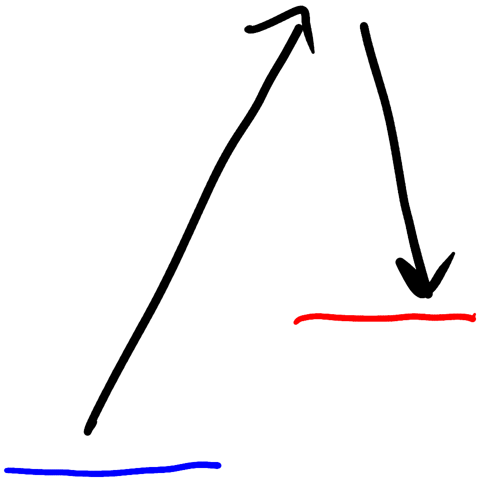


SO coupling
resonant



"on site" coupling
non-resonant





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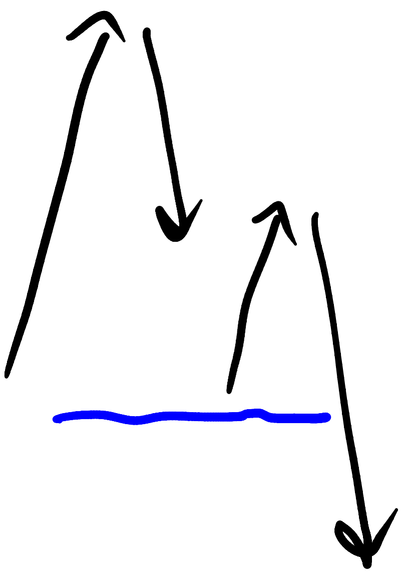

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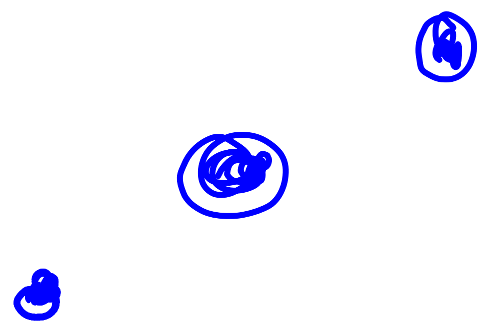
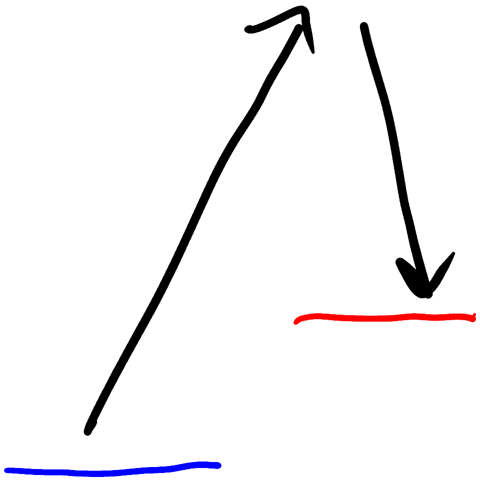
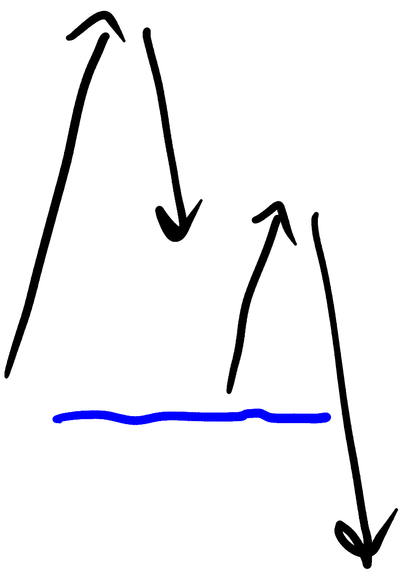
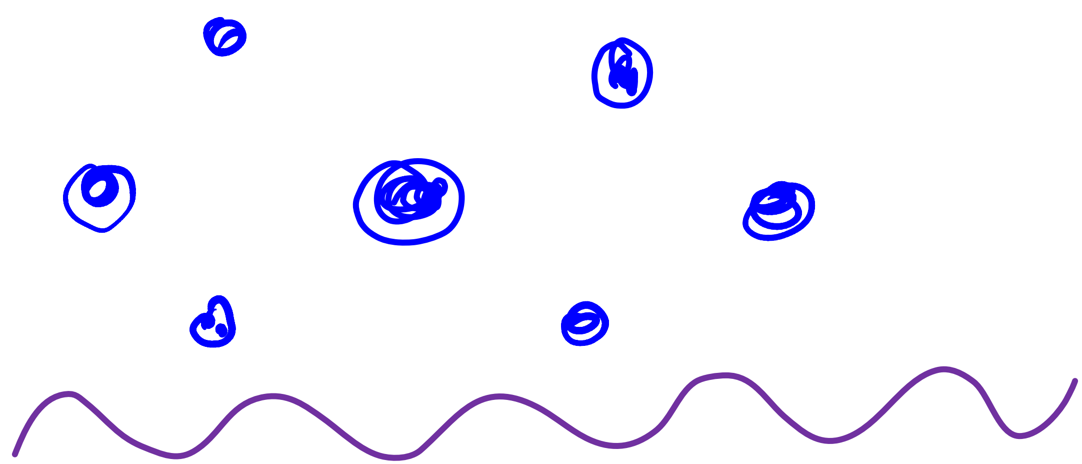


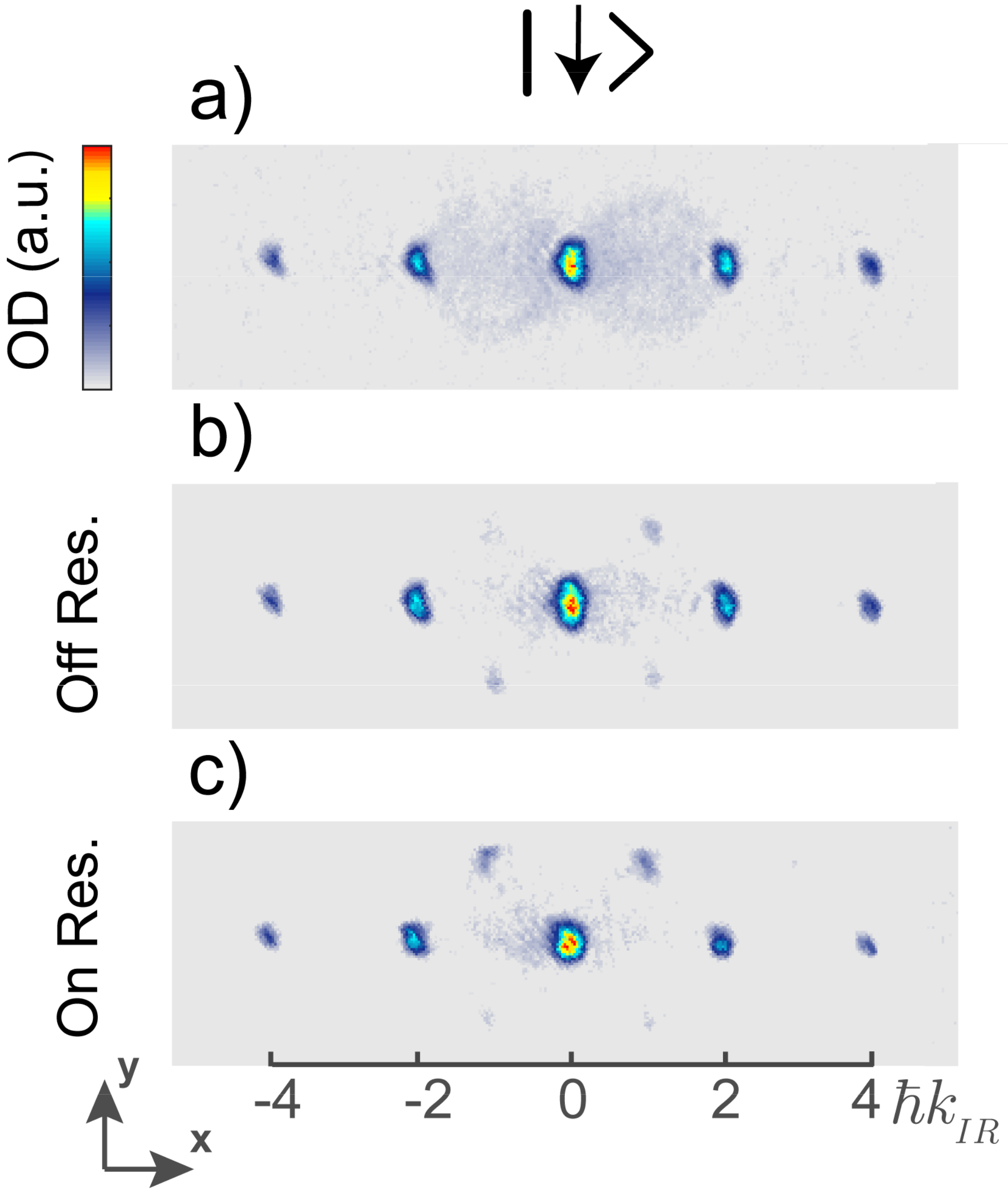


SO coupling
resonant

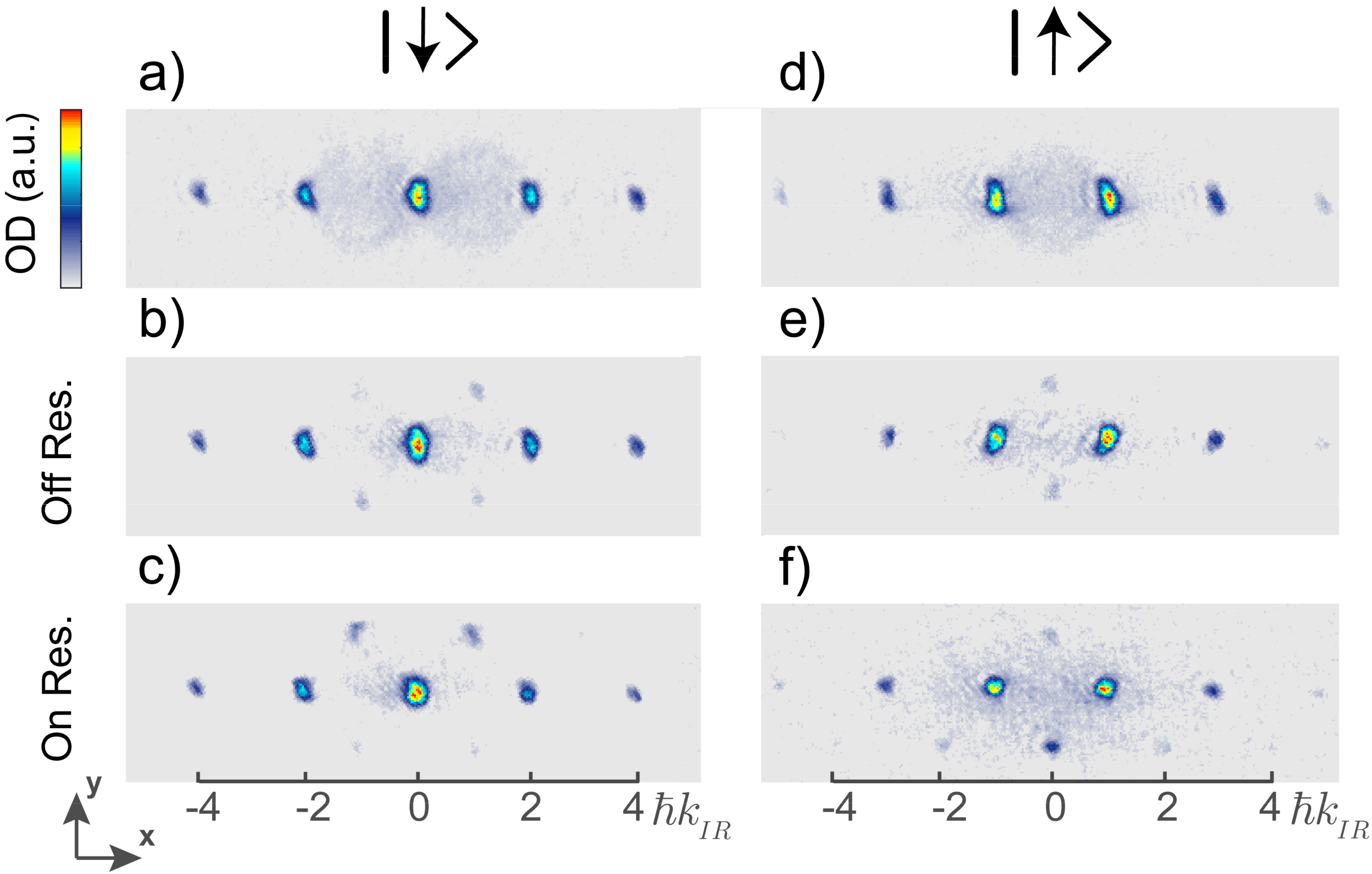


"on site" coupling
non-resonant

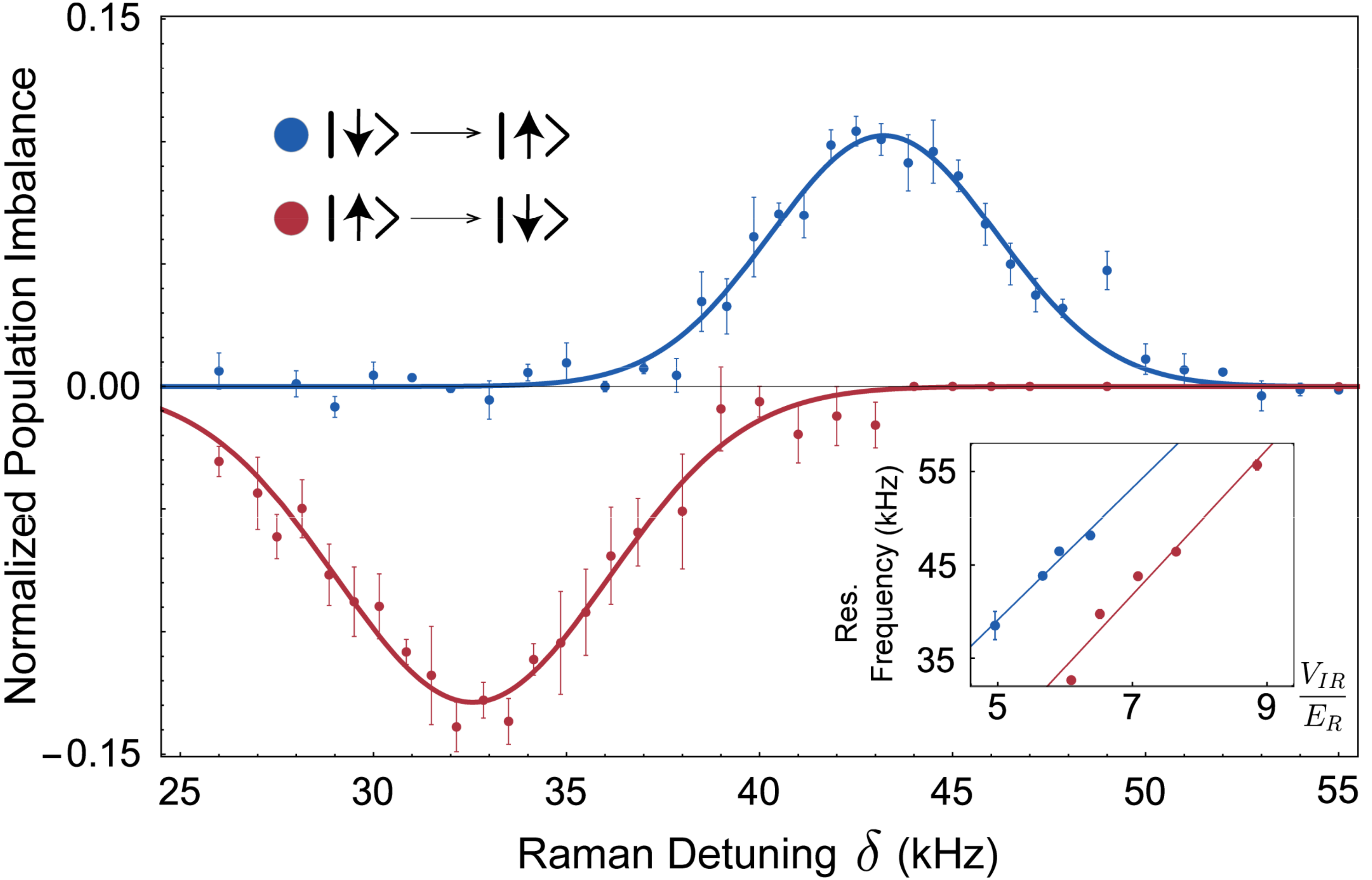




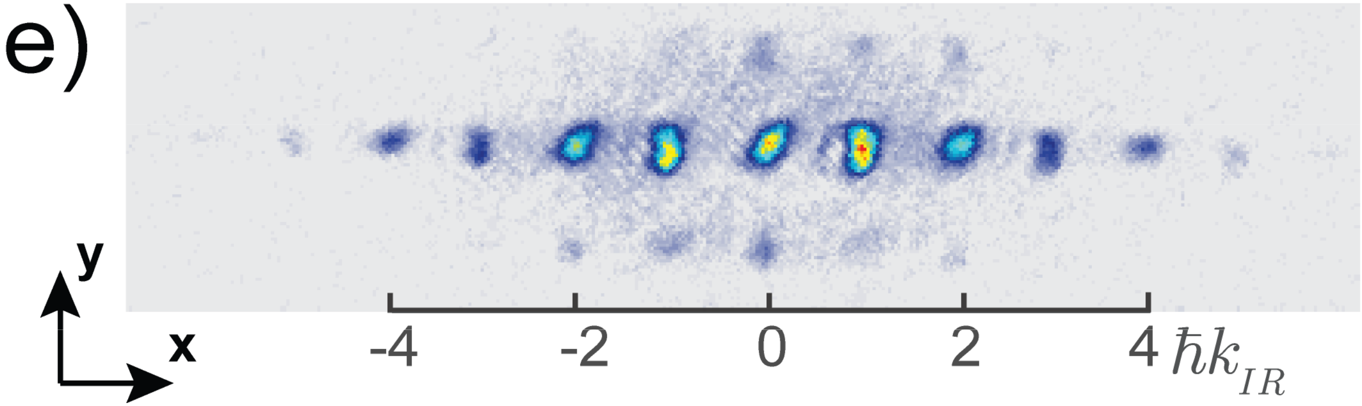
|↓⟩
a)
OD (a.u.)
b)
Off Res.
c)
On Res.
y
x
-4
-2
0
2
4
$\hbar k_{IR}$



|↓⟩
|↑⟩
a)
b)
c)
d)
e)
f)
OD (a.u.)
Off Res.
On Res.
-4
-2
0
2
4
$\hbar k_{IR}$
y
x



0.15
0.00
−0.15
Normalized Population Imbalance
|↓> ⟶ |↑>
|↑> ⟶ |↓>
25
30
35
40
45
50
55
Raman Detuning δ (kHz)
Res. Frequency (kHz)
55
45
35
5
7
9
V_IR / E_R



50/50 mixture with spin-orbit coupling

Should be BEC with stripe phase (density modulation)
breaks two continuous symmetries (gauge and translation)
(Zhai, Ho, Stringari, Baym, Santos, Liu, Paramekanti and more)

see:

PHYSICAL REVIEW A **90**, 041604(R) (2014)

Approach for making visible and stable stripes in a spin-orbit-coupled Bose-Einstein superfluid

Giovanni I. Martone,[1] Yun Li,[1,2] and Sandro Stringari[1]

our scheme was inspired by their suggestion to use spin-dependent lattices

Credits:

BEC 4

Colin Kennedy
Cody Burton
Woo Chang Chung

former members:
Hiro Miyake
Georgios Siviloglou

Rb BEC in optical lattices
synthetic magnetic fields

BEC 2

Wujie Huang
Junru Li
Boris Shteynas
Furkan Top
Sean Burchensky
Alan Jamison

Superlattices
Spin orbit coupling

$$
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