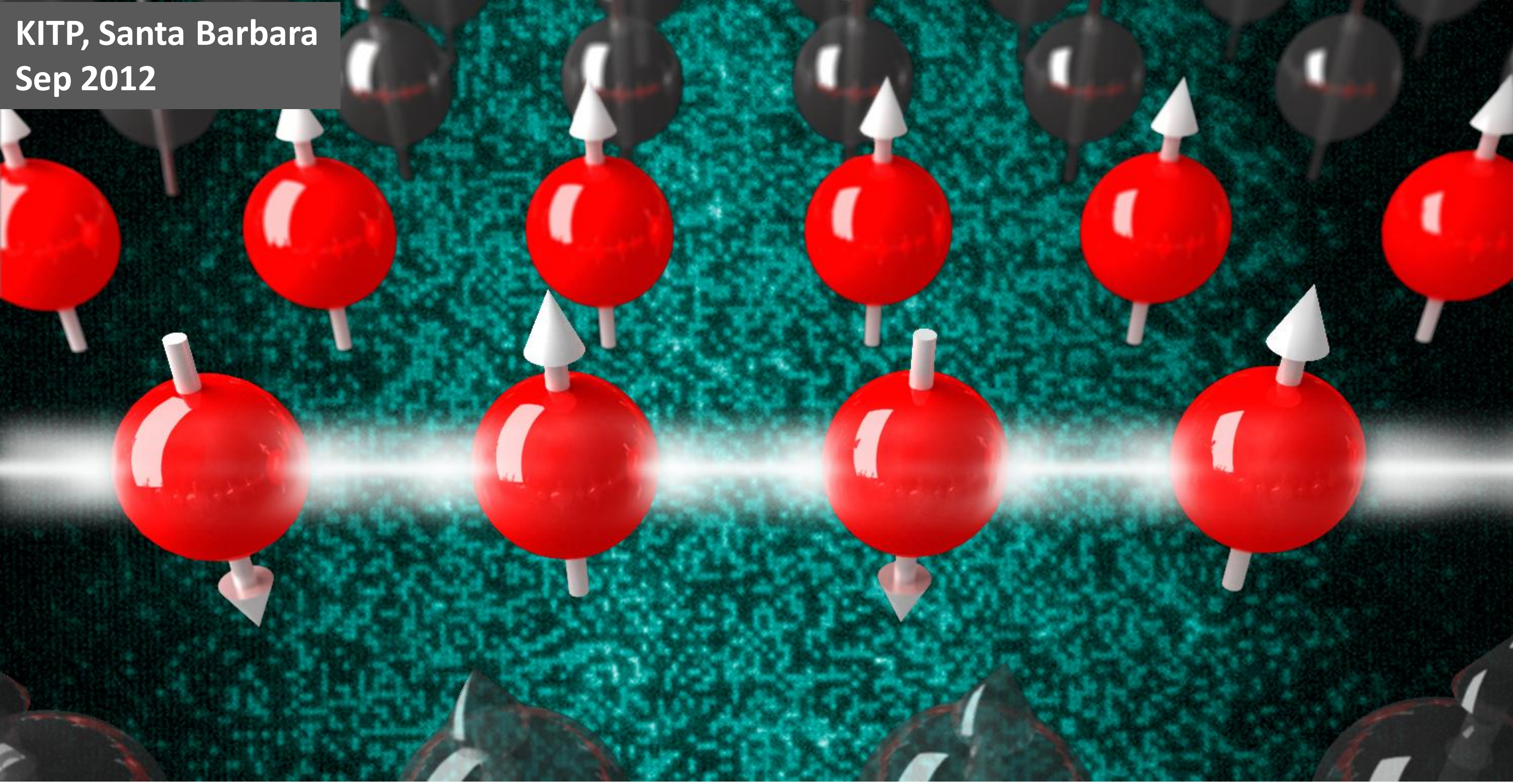


KITP, Santa Barbara
Sep 2012

Lower dimensional and spin-orbit coupled Fermi gases

Towards simulating topological matter with ultracold atoms

Waseem Bakr, MIT

Topological phases of matter

A little bit of History

- Last century : classification of quantum states in terms of spontaneous symmetry breaking [Anderson 1997]

- In 1980 : Quantum Hall state. First topological state characterized by a topological invariant [von Klitzing *et al.* 1980]

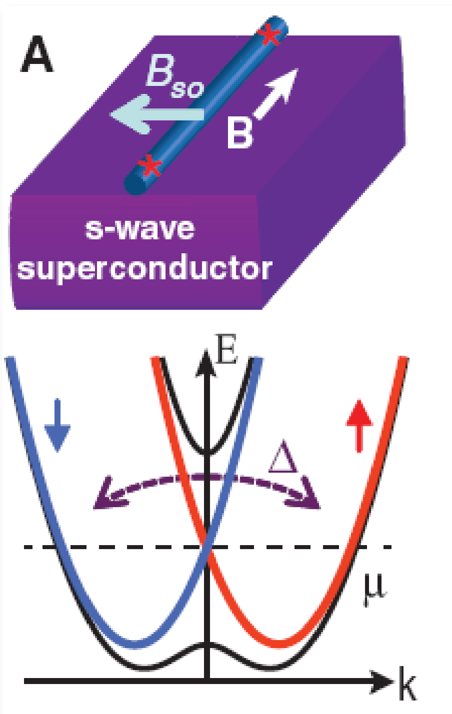
- 2008-2010 : a new topological class predicted and discovered, where time-reversal symmetry is preserved. Spin-Orbit coupling plays a crucial role [M.Z. Hasan and C.L. Kane, RMP , 2010]

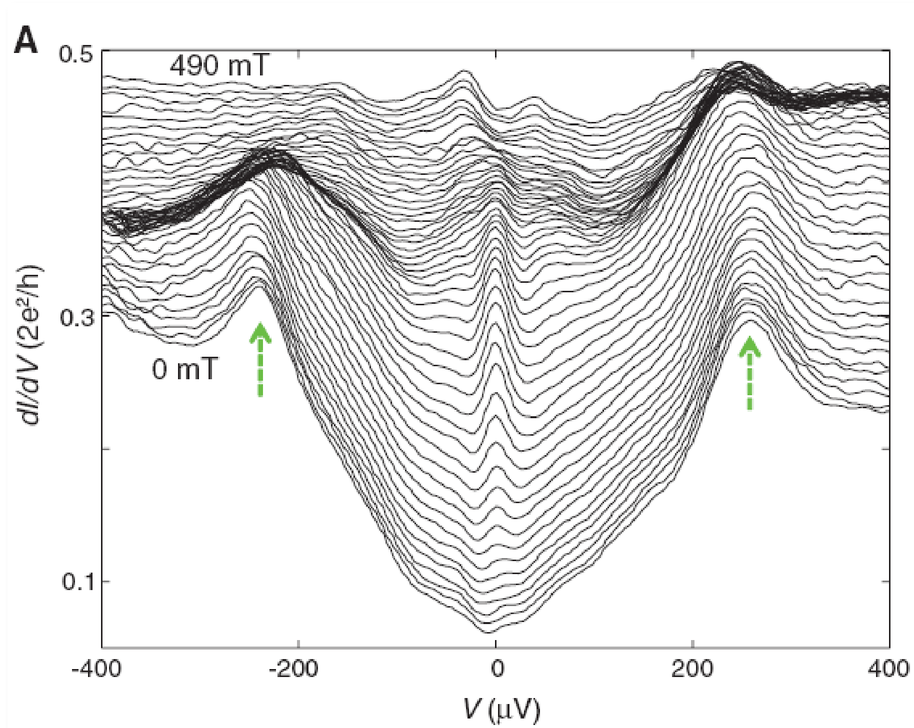
Also : Modified interactions, unconventional pairing, Majorana fermions

Topological phases of matter

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1*] K. Zuo,[1*] S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†

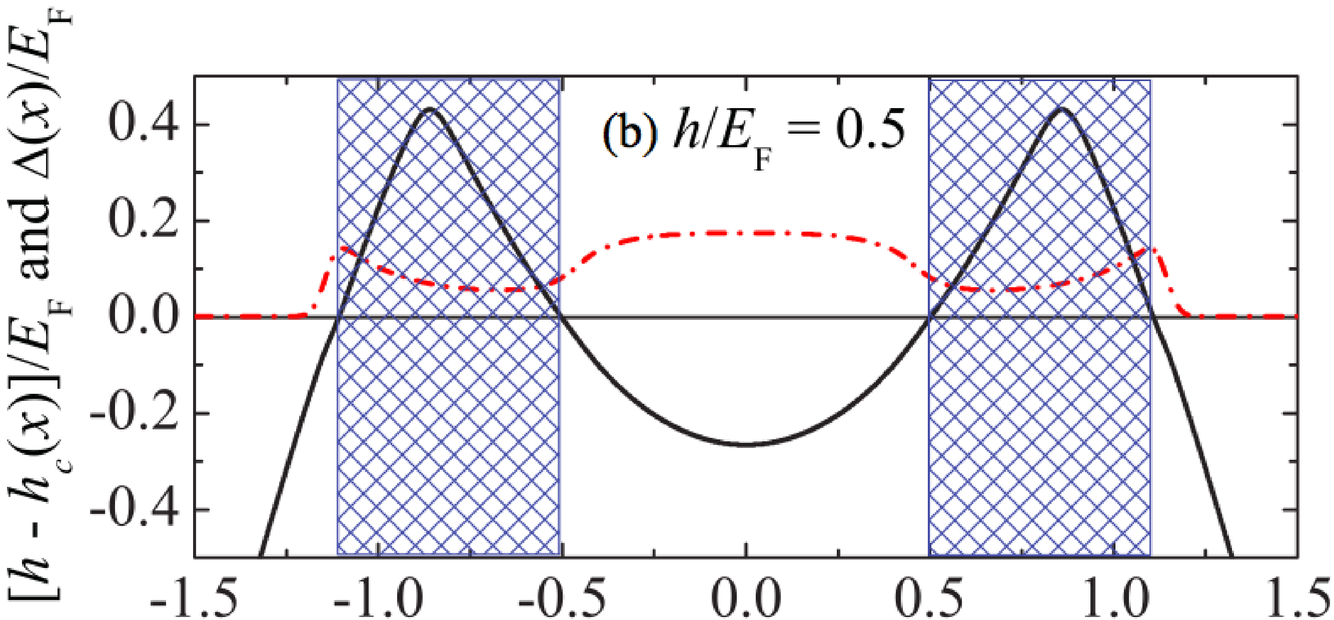




Topological superfluids

Required Hamiltonian (Liu et al, PRA 85, 033622)

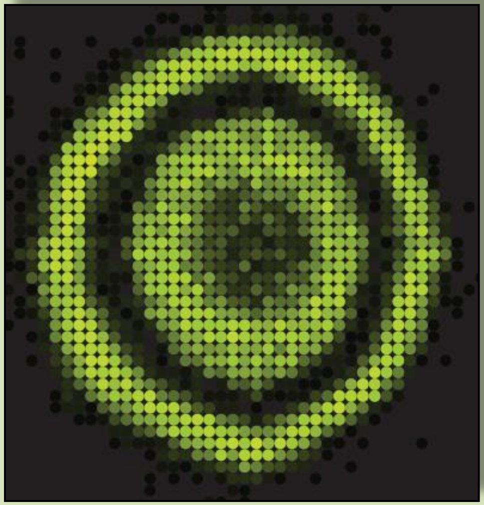
$$\mathcal{H} = \int dx \psi^{\dagger}(x)\left[\mathcal{H}_0^S(x) - h\sigma_z + \lambda k \sigma_y\right]\psi(x) + g_{1D}\int dx \psi_{\uparrow}^{\dagger}(x)\psi_{\downarrow}^{\dagger}(x)\psi_{\downarrow}(x)\psi_{\uparrow}(x)$$



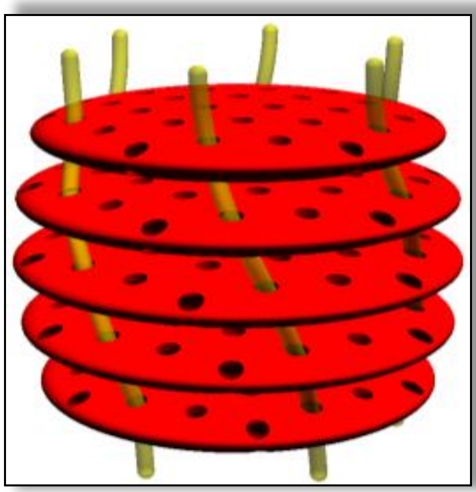
In harmonic trap: Topological and conventional superfluids regions

Majorana fermions at interface

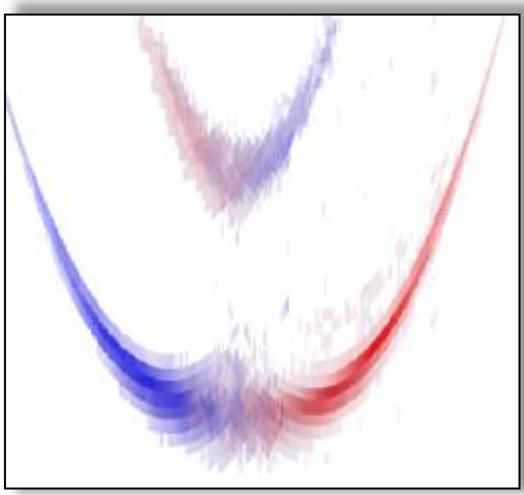
Outline of this talk



Quantum gas microscopy

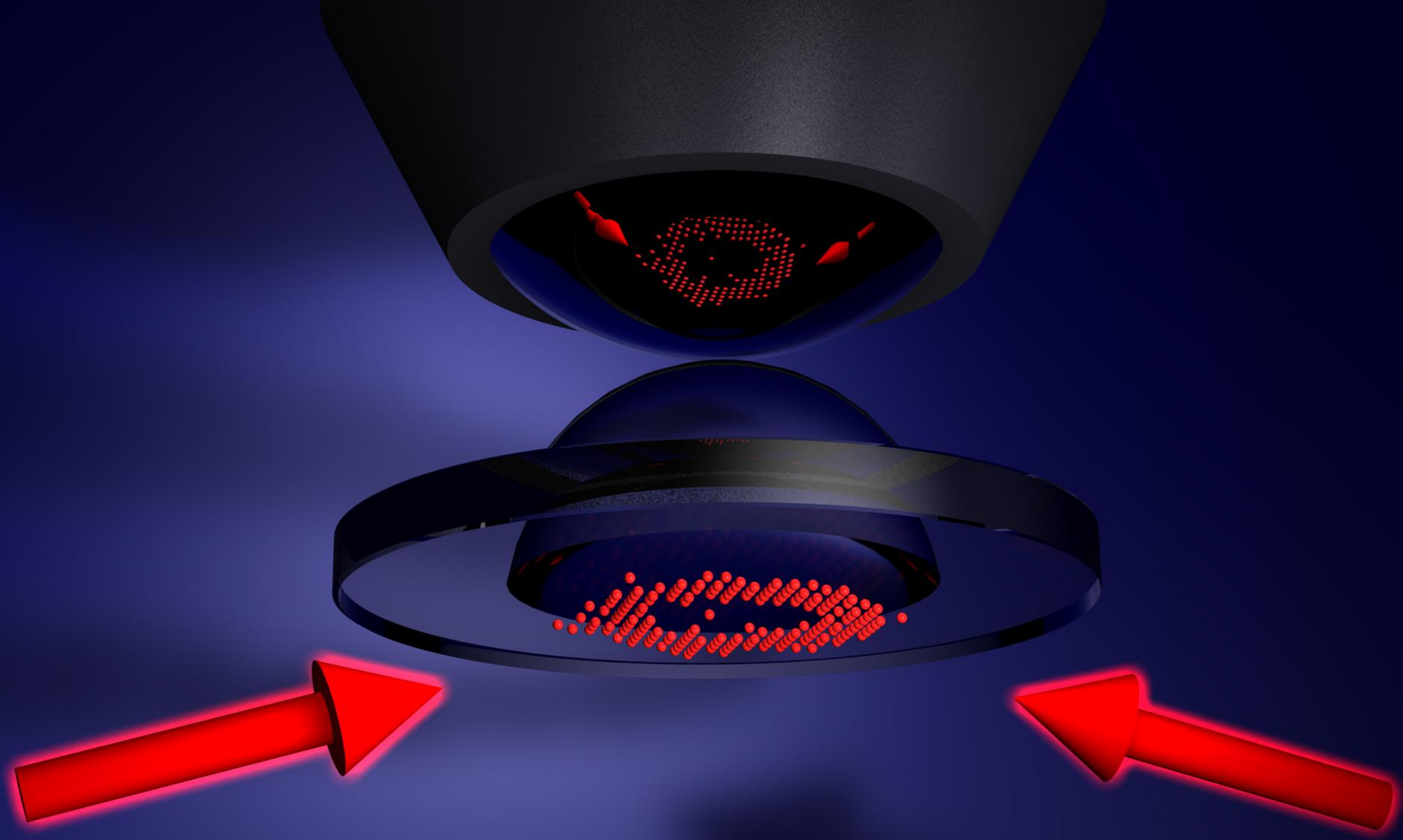


Pairing in 2D Fermi gases



Spin-orbit coupling in Fermi gases

Quantum gas microscope



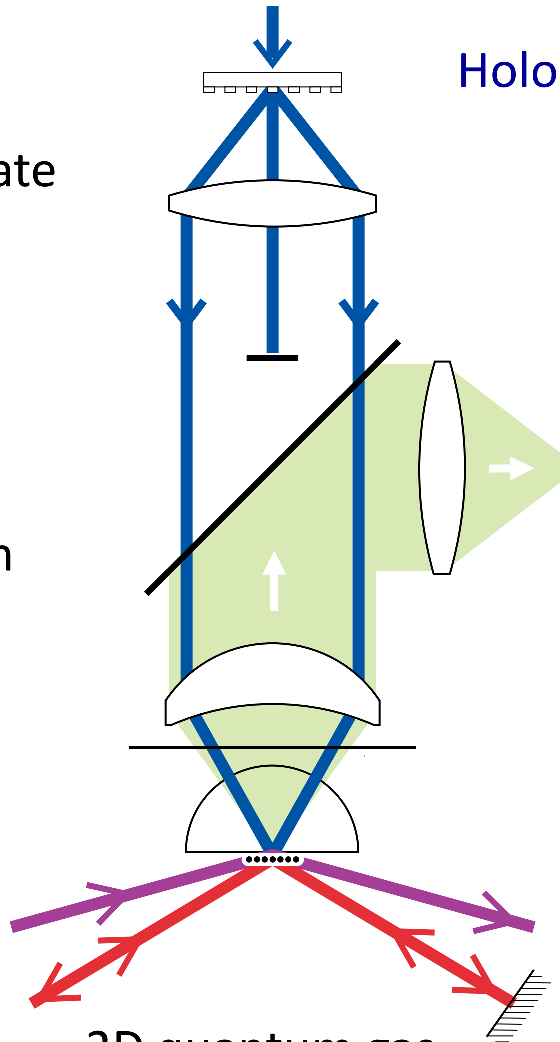
Previous work:

Large spacing lattices (D. Weiss) , 1D standing waves (D. Meschede), electron microscope (H. Ott), few site resolution (C. Chin)

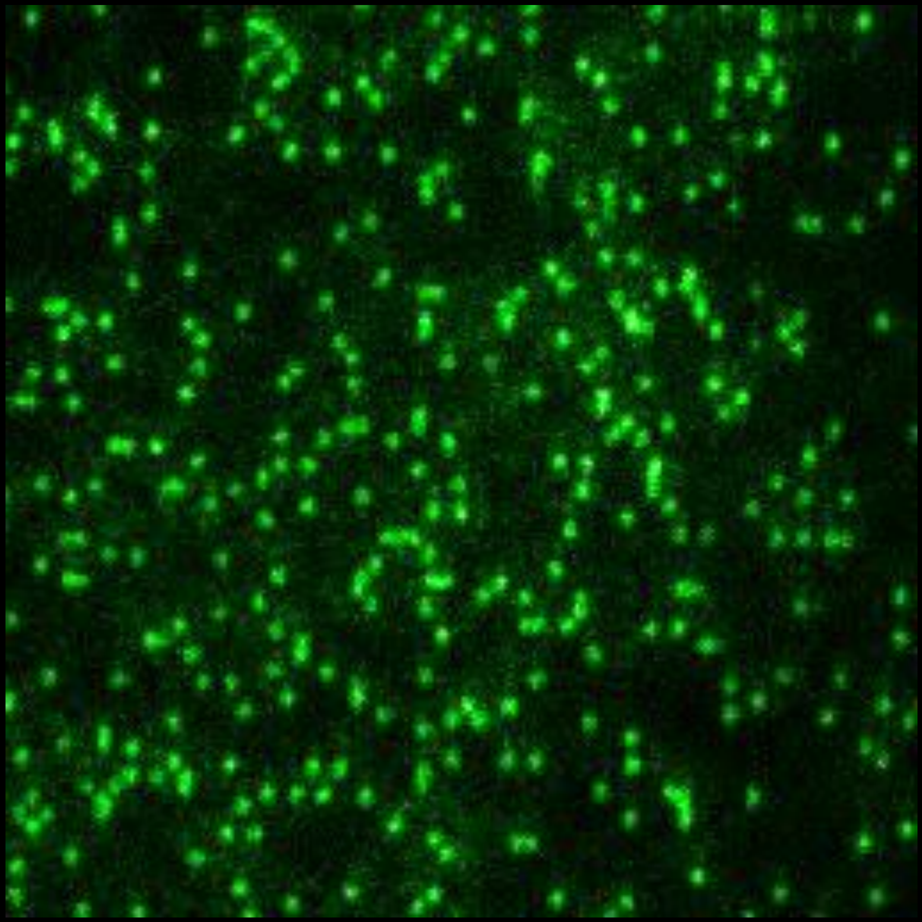
Quantum gas microscope

Experimental sequence:

1. Preparation of condensate in magnetic trap
2. Creation of single 2D pancake cloud
3. Projection of lattice potential in plane
4. Increase potential depth several hundred fold by reducing laser detuning
5. Imaging with molasses

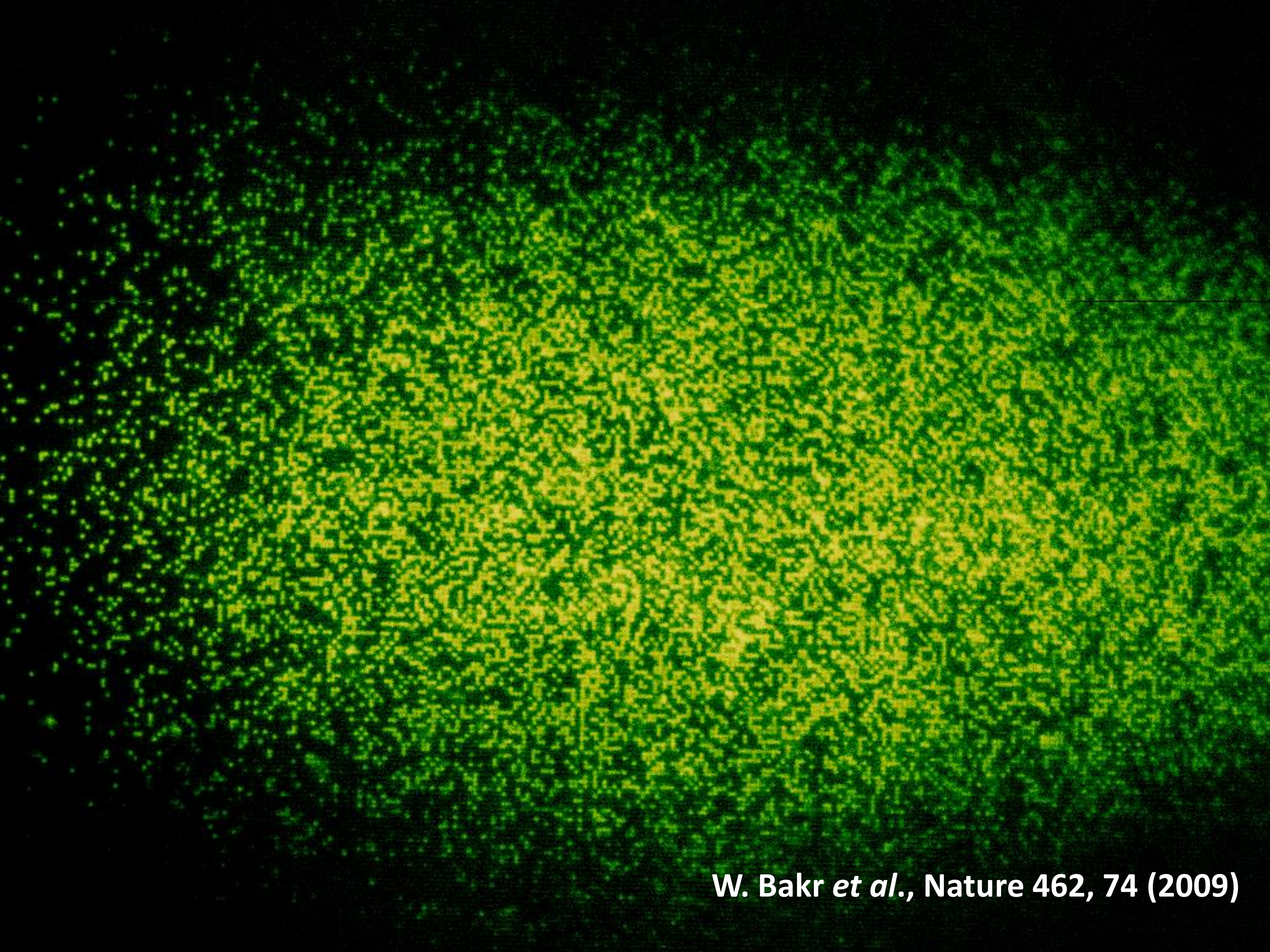


Atoms hopping in the lattice



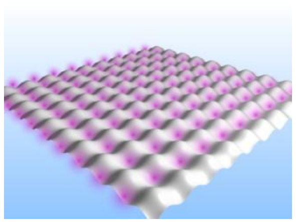
Real time movie of single atoms in lattice

Here vertical lattice reduced to observe thermal hopping of atoms



W. Bakr *et al.*, Nature 462, 74 (2009)

Bose-Hubbard Hamiltonian

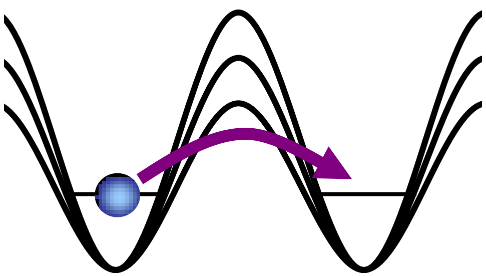


$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Tunneling term:

J: tunneling matrix element

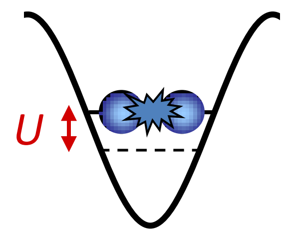
$\hat{a}_i^\dagger \hat{a}_j$:tunneling from site j to site i



Interaction term:

U : on-site interaction matrix element

$\hat{n}_i (\hat{n}_i - 1)$: n atoms collide with n-1 atoms on same site



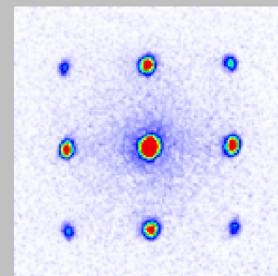
Ratio between tunneling J and interaction U can be widely varied by changing depth of 3D lattice potential!

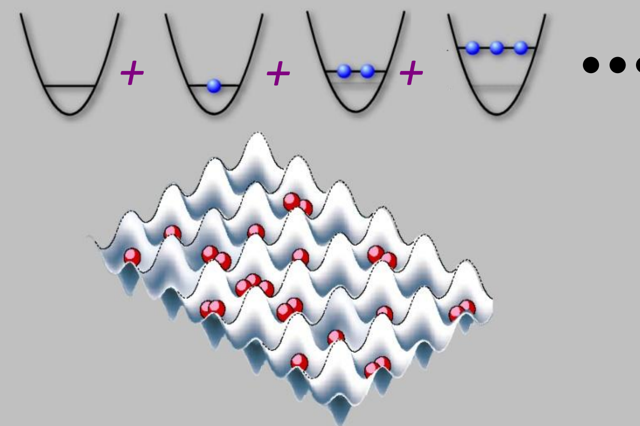
M.P.A. Fisher et al, PRB 40, 546 (1989), D. Jaksch et al., PRL 81, 3108 (1998)

Superfluid – Mott insulator phase transition

Superfluid:

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

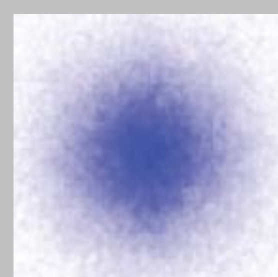


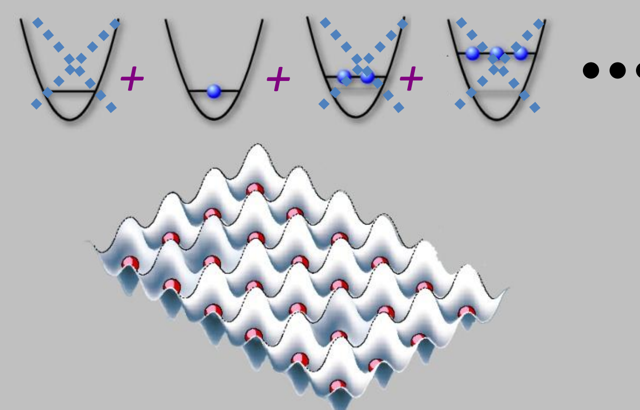


Atoms are delocalized over the entire lattice !

Mott Insulator:

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

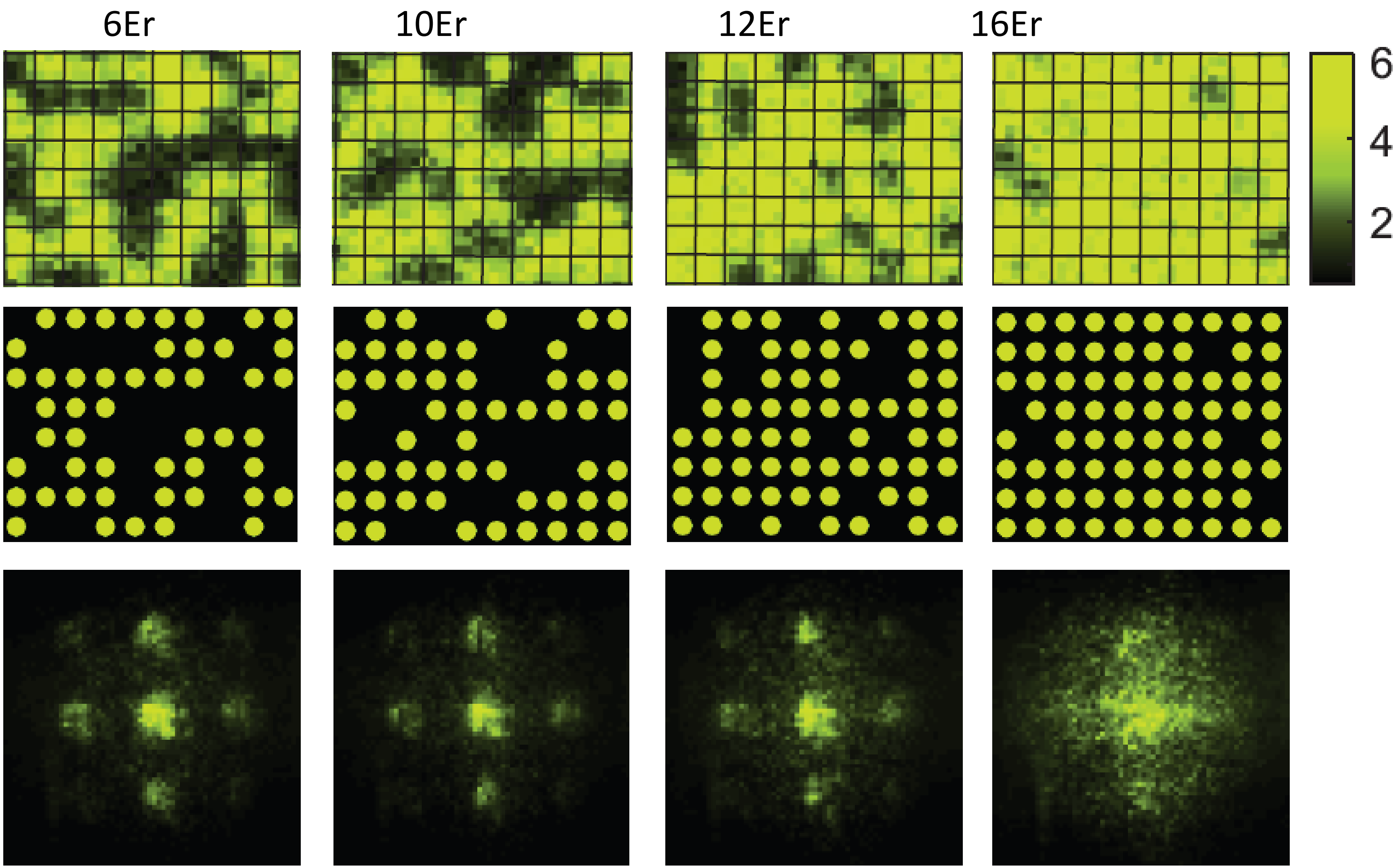




Atoms are localized to lattice sites !

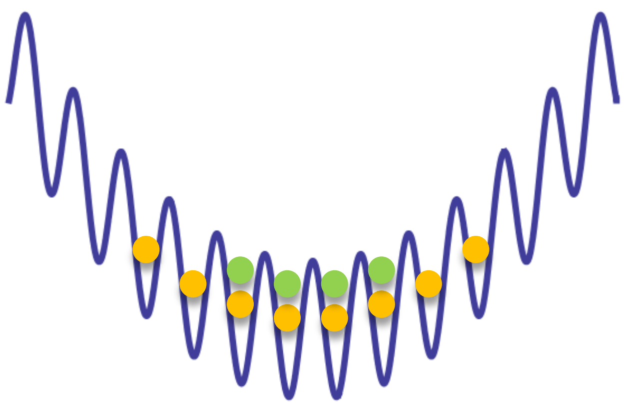
Greiner et al., Nature 415 (2002)

Atom number squeezing across the transition



W. Bakr *et al.*, **Science** 329, 547-550 (2010)

Shell structure in a harmonic trap



Shell structure with MI
of 3 – 2 – 1 atoms/site

Expected population
on lattice sites

Detection as
1 – 0 – 1 atoms/site

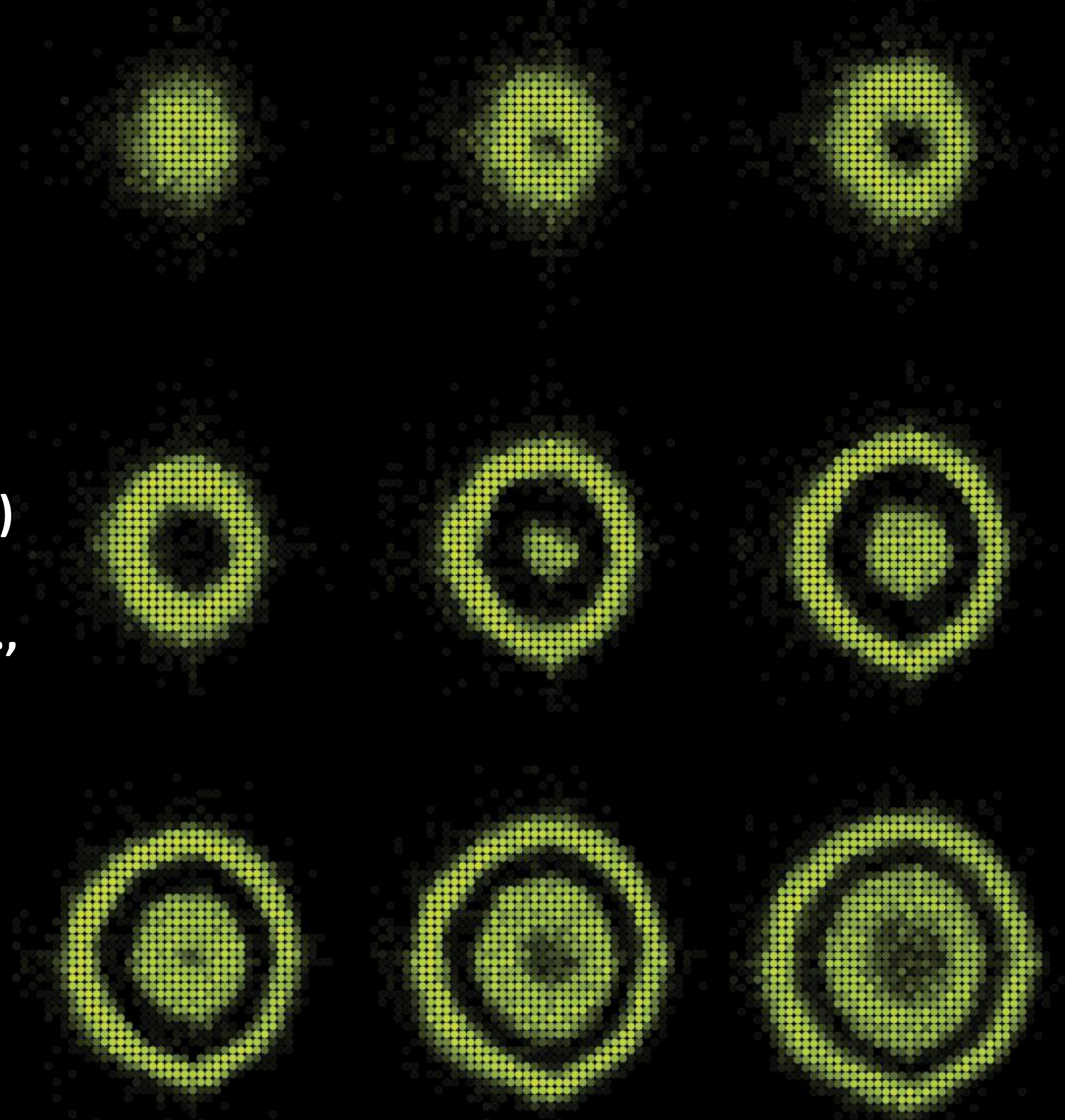
Odd/Even detection
(N mod 2)

Shells detected in density (Bloch, Ketterle, Chin)

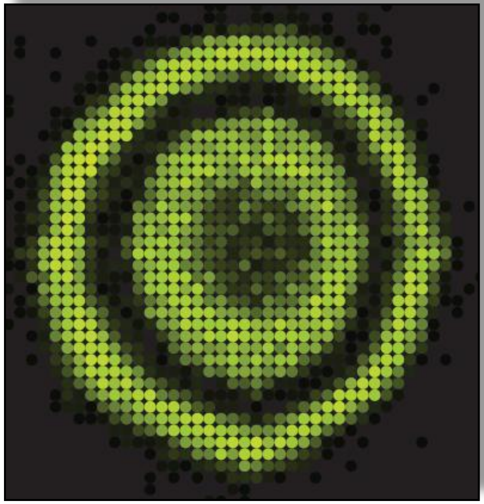
Single site imaging of shell structure

W. Bakr *et al.*,
Science 329, 547 (2010)

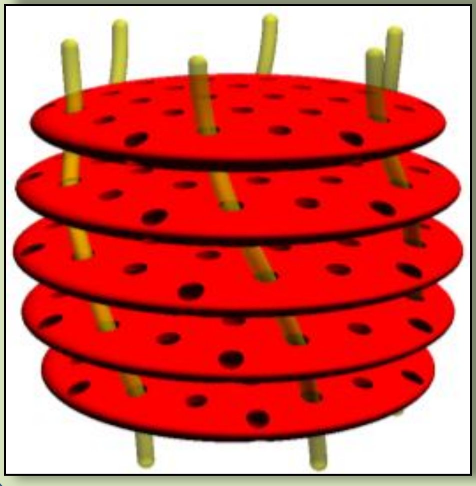
See also: Sherson *et al.*,
Nature 467, 68 (2010)



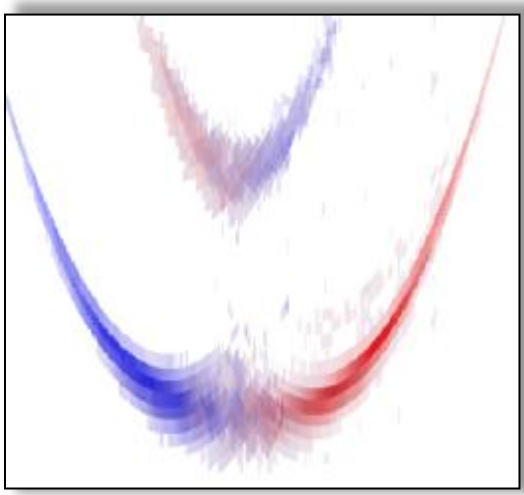
Outline of this talk



Quantum gas microscopy

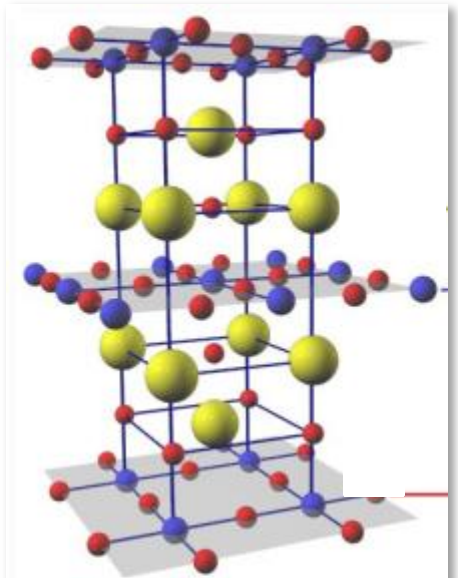


Pairing in 2D Fermi gases

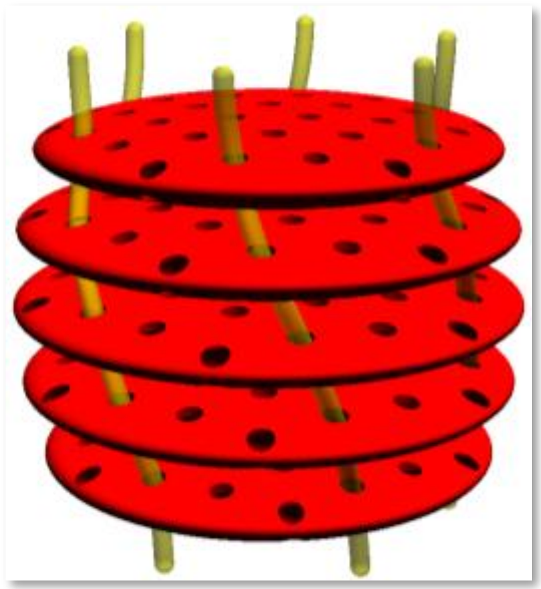


Spin-orbit coupling in Fermi gases

Fermions entering Flatland



High-T_c Superconductor with stacks of CuO planes



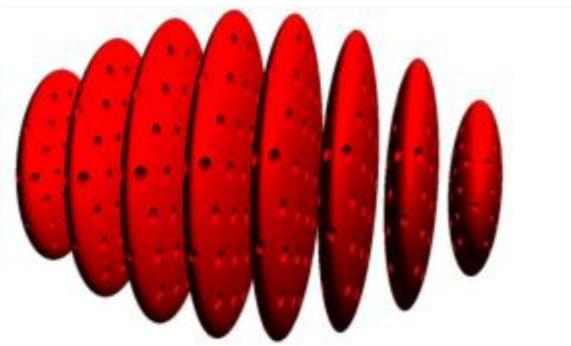
Stacks of 2D coupled fermionic superfluids

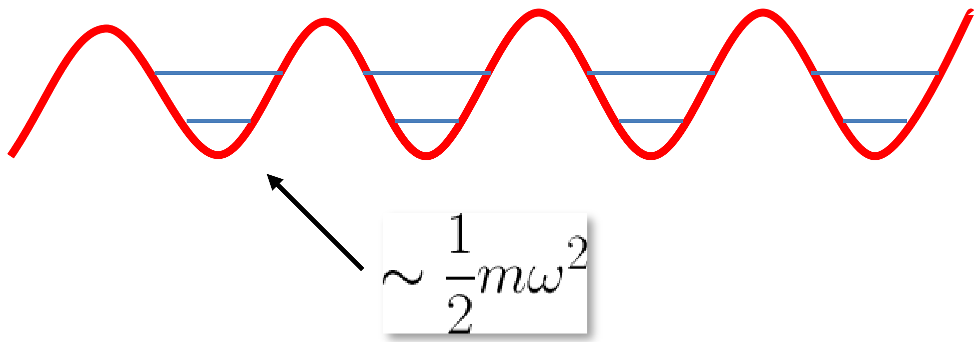
- 2D Fermi Gases: A paradigm of condensed matter physics
- Access physics of layered superconductors
- Evolution of Fermion Pairing from 3D to 2D
- Study superfluidity in lower dimensions

Expts on 2D Bose gases: Ketterle, Dalibard, Cornell, Phillipps, Chin
Other expts on 2D Fermi gases: Turlapov, Koehl, Thomas, Vale

Making quasi-2D Fermi gases

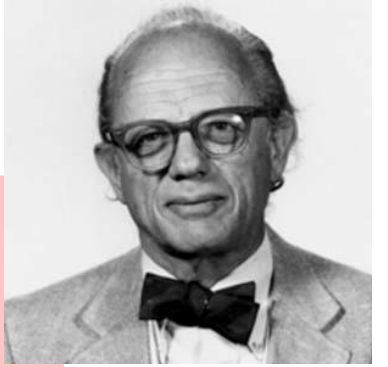
- Confine atoms tightly in one direction until only the ground state is occupied
- Our setup: 1D lattice (retro-reflected laser beam)
- 2D-ness tuned by lattice depth
- Deep lattice: $\frac{\varepsilon_F}{\hbar\omega} \sim 0.1$, aspect ratio of ~1:1000

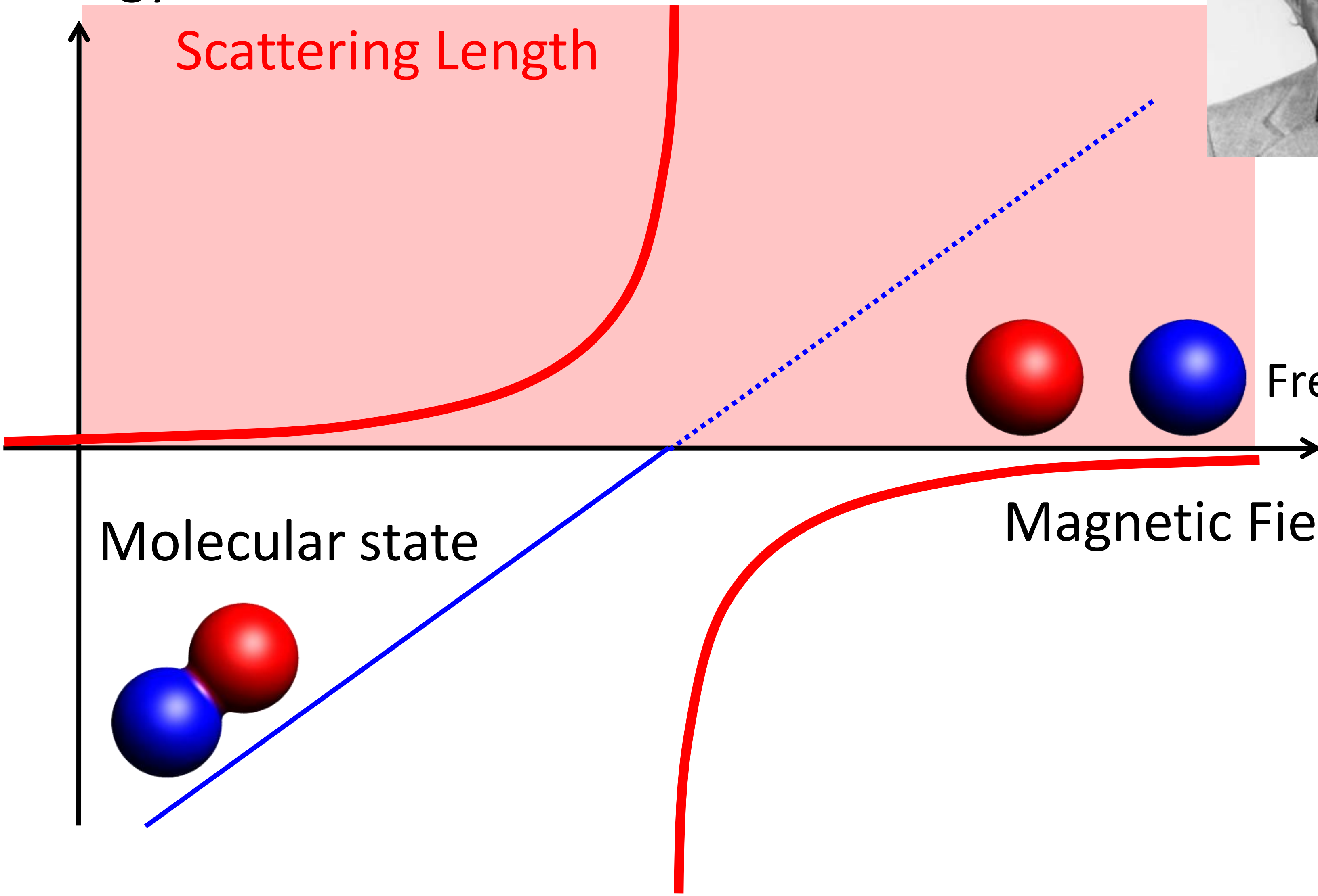




Feshbach resonances: Tuning the interactions

Herman Feshbach

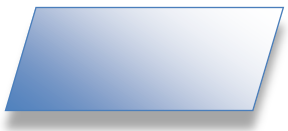




Pairing in 1D, 2D, 3D

- In 1D 

Two particles bind for the slightest attraction

- In 2D 

Two particles bind for the slightest attraction
... but binding is exponentially weak

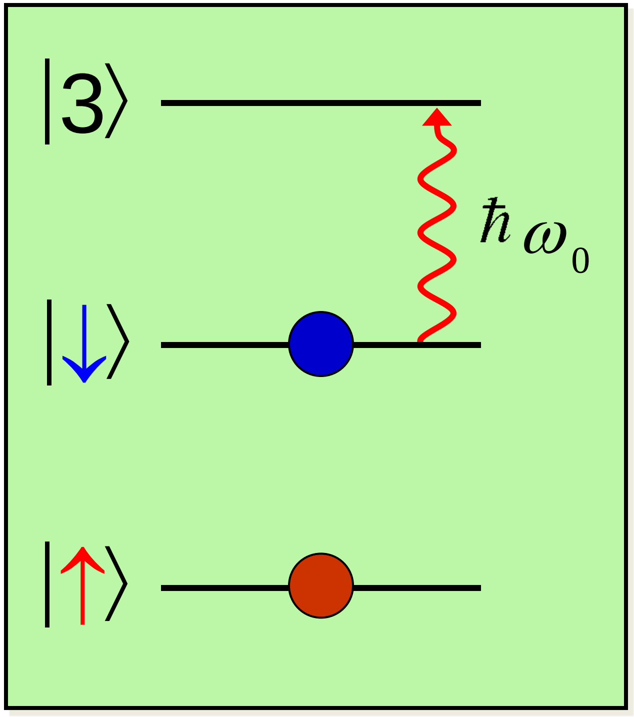
- In 3D 

Pairing requires strong attraction, or many-body physics:
The presence of a Fermi sea (Cooper pairing)

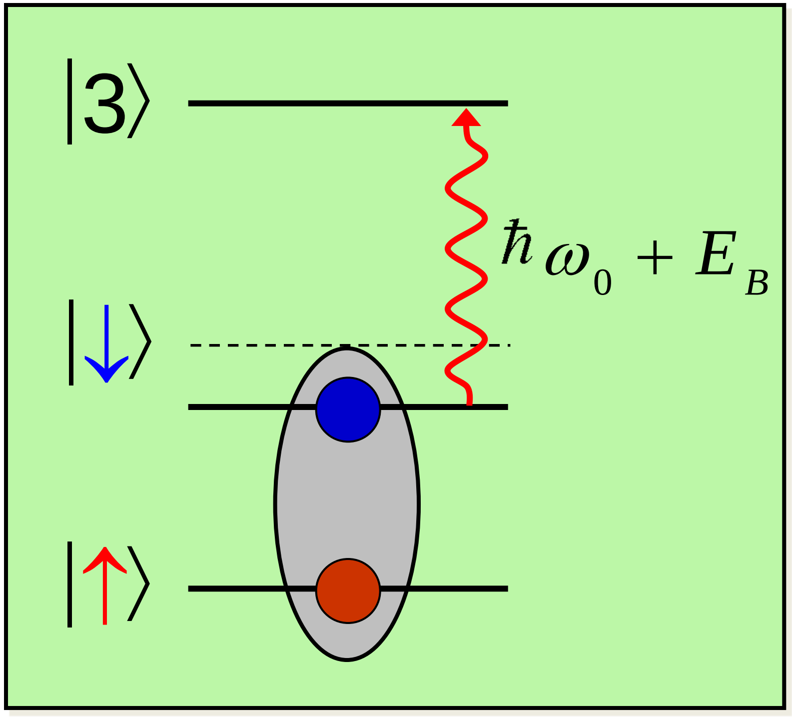
How to measure the binding energy?

Radiofrequency spectroscopy
= "Tunneling" to another internal state

No interactions



Some form of binding

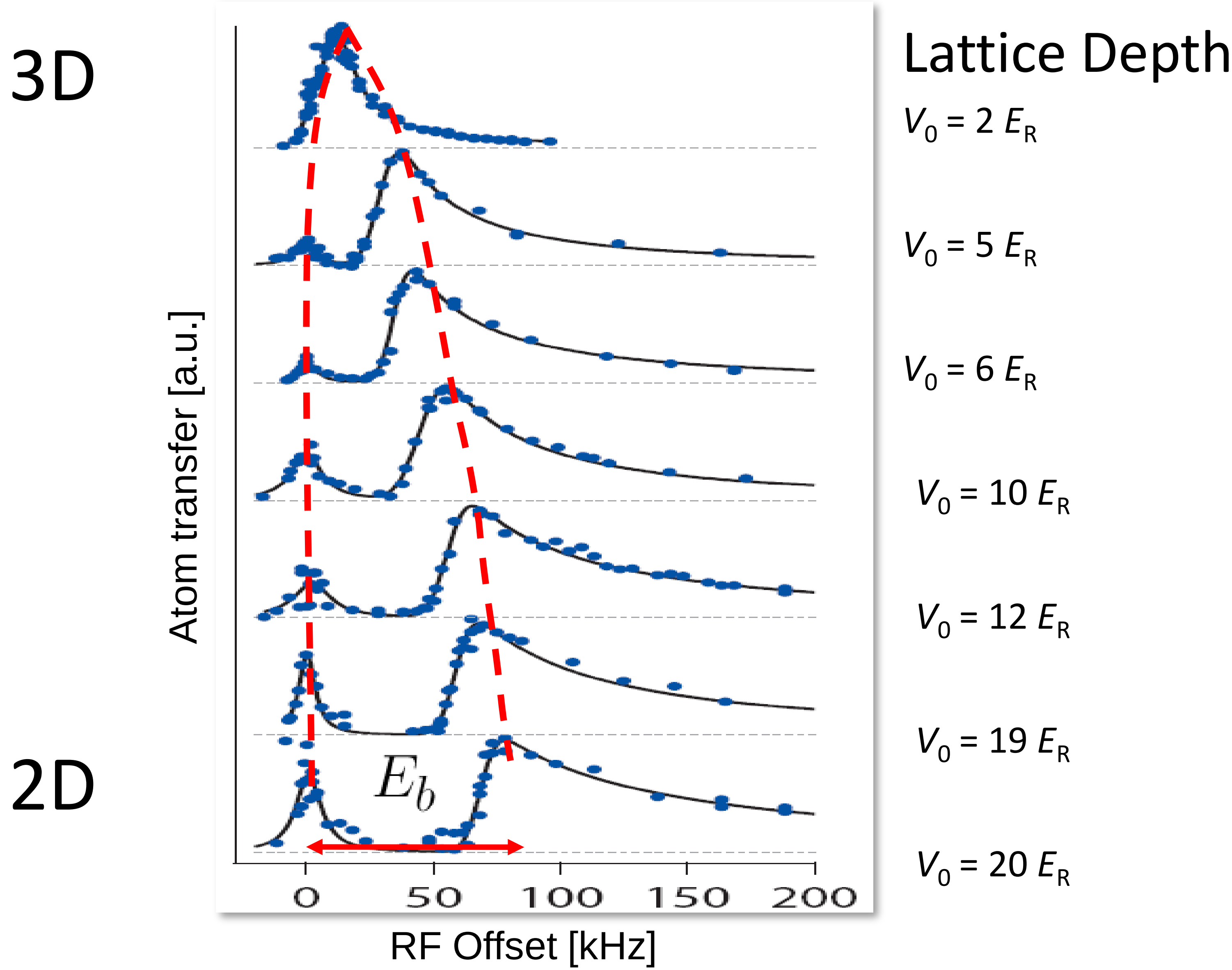


Photon energy = Zeeman + Binding + Kinetic energy

$$\hbar\omega = \hbar\omega_0 + E_B + 2\varepsilon_k$$

RF spectroscopy of Fermi gases: Jin, Ketterle, Grimm,... many

Evolution of Fermion Pairing from 3D to 2D

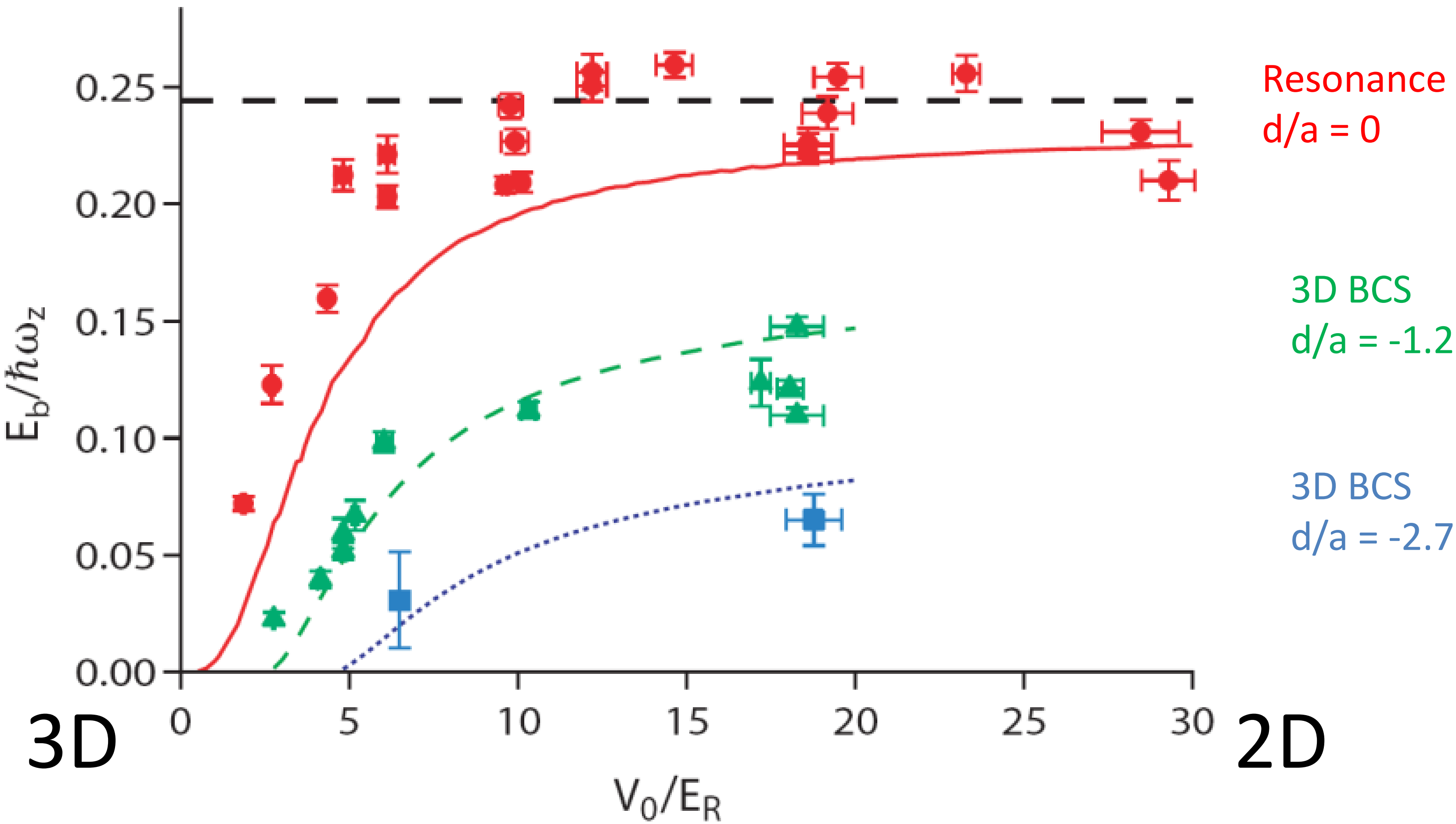


A. T. Sommer, L. W. Cheuk, M. J.-H. Ku, W. S. Bakr, M. W. Zwierlein

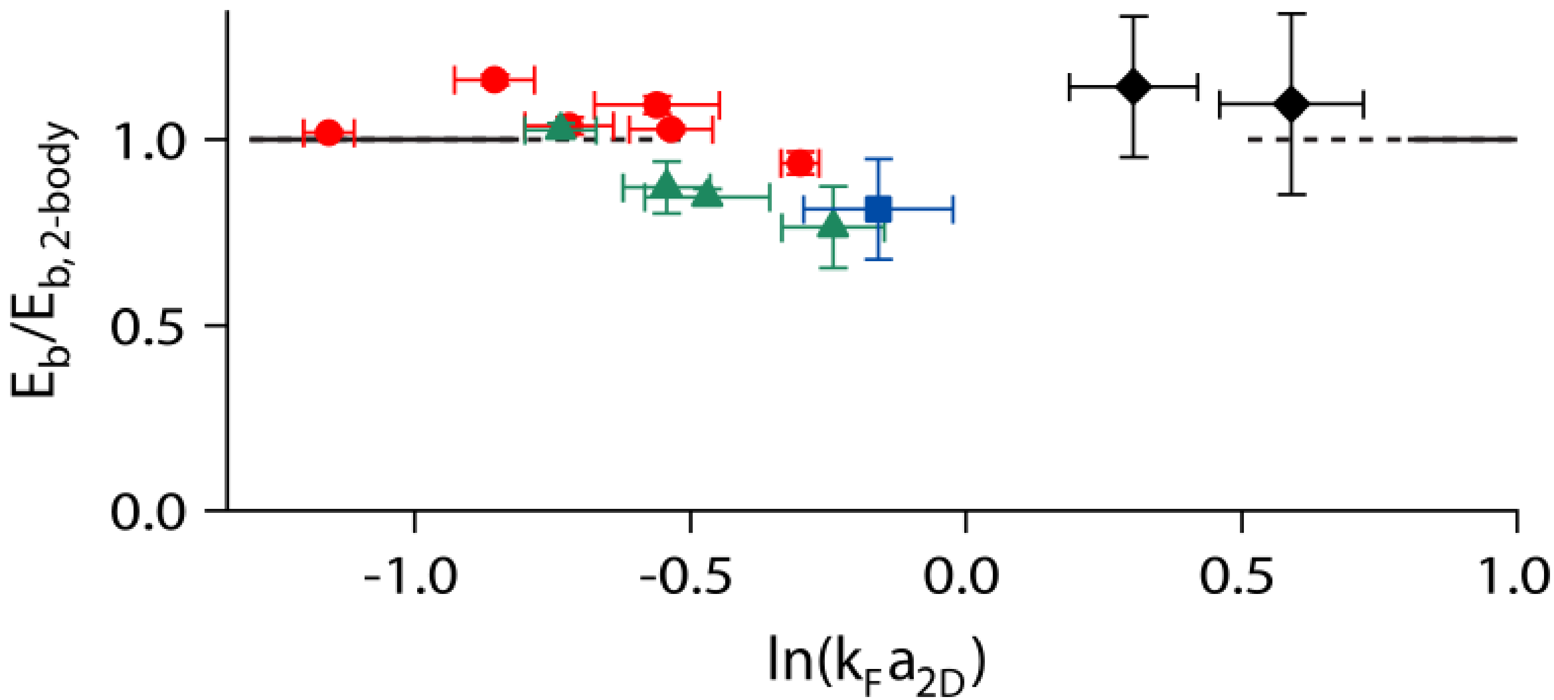
PRL **108**, 045302 (2012) Selected for Viewpoint in Physics, Jan '12

Evolution of Fermion Pairing from 3D to 2D

On resonance in 2D: $E_{B,th} = 0.244\,\hbar\omega_z$



Evolution of Fermion Pairing from 3D to 2D

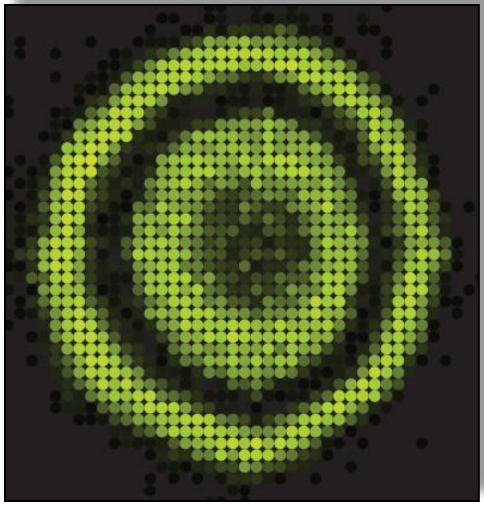


Binding energy increases from 3D to 2D

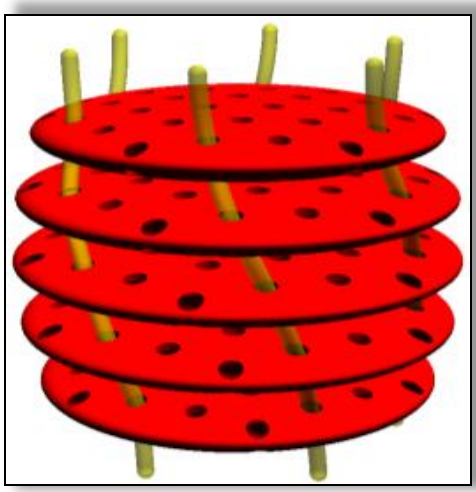
How about superfluidity? More fragile (phase fluctuations)

BKT physics on BCS side?

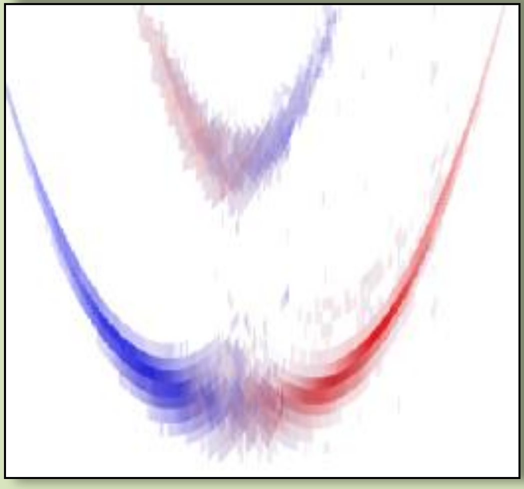
Outline of this talk



Quantum gas microscopy



Pairing in 2D Fermi gases



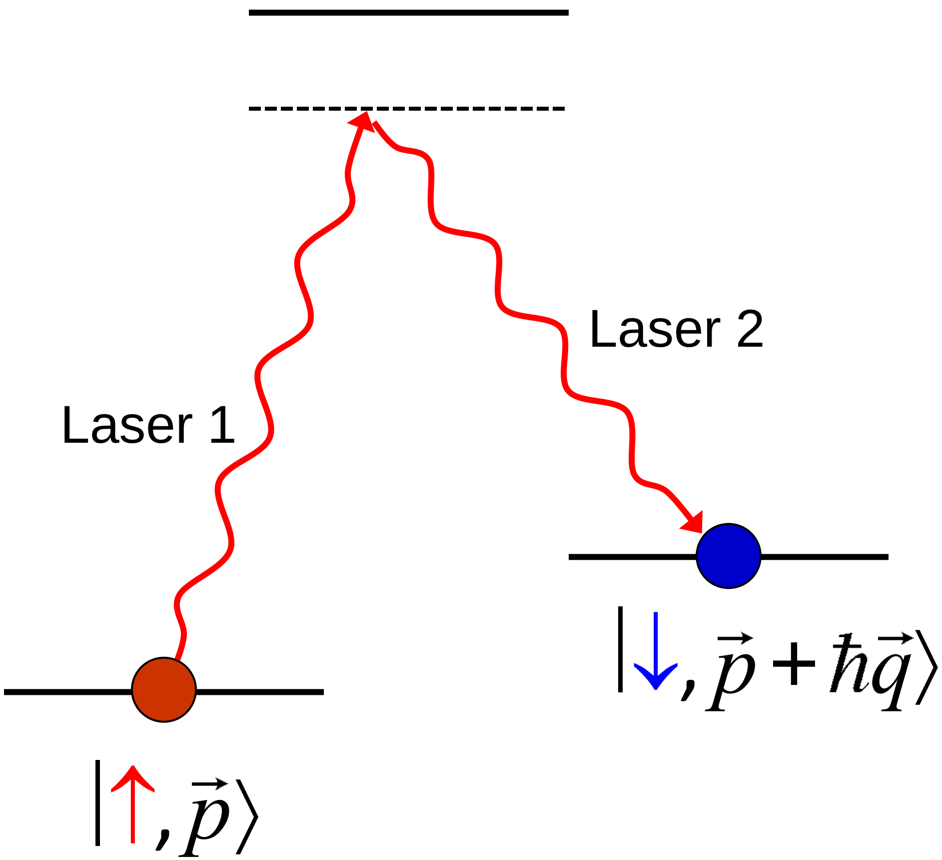
Spin-orbit coupling in Fermi gases

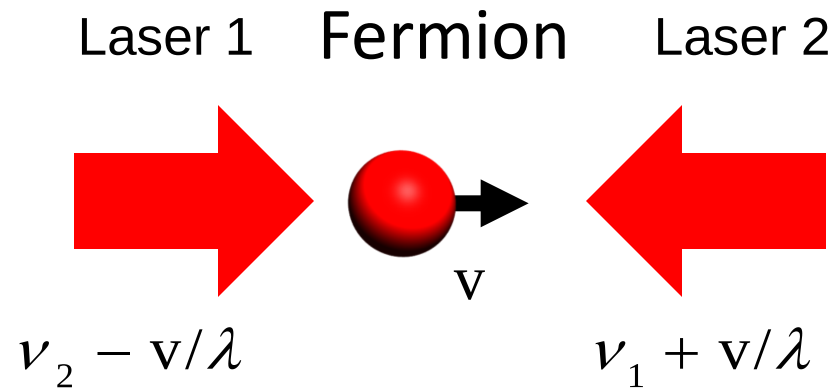
Spin-Orbit Coupling

Raman transition:

Couple different spin (hyperfine) states

Doppler effect causes momentum-dependent coupling





Pioneering work with bosons:

Ian Spielman, NIST

Y. J. Lin et al. Nature 471, 83 (2011)

R. A. Williams et al. Science 335, 314 (2011)

Y. J. Lin et al Nature 462, 628 (2009)

Spin-Orbit Coupling of Fermions:

P. Wang et al. PRL 109, 095301 (2012)

L. Cheuk, A. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, MWZ, PRL 109, 095302 (2012)

The spin-orbit Hamiltonian

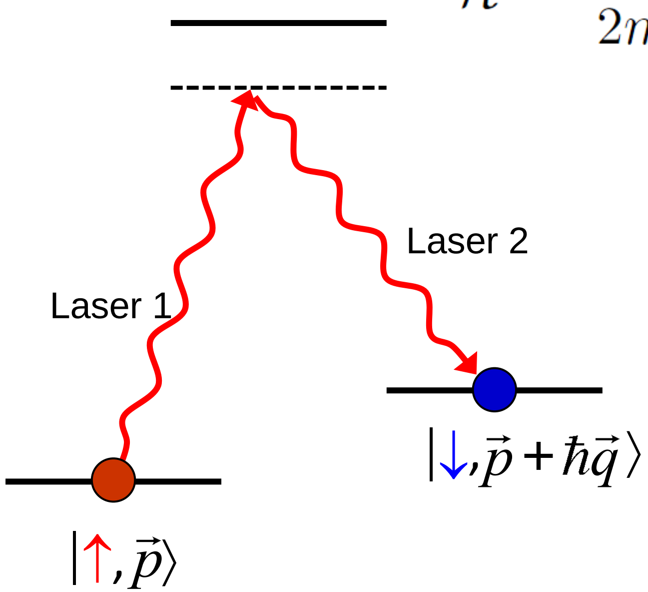
- The SO Hamiltonian

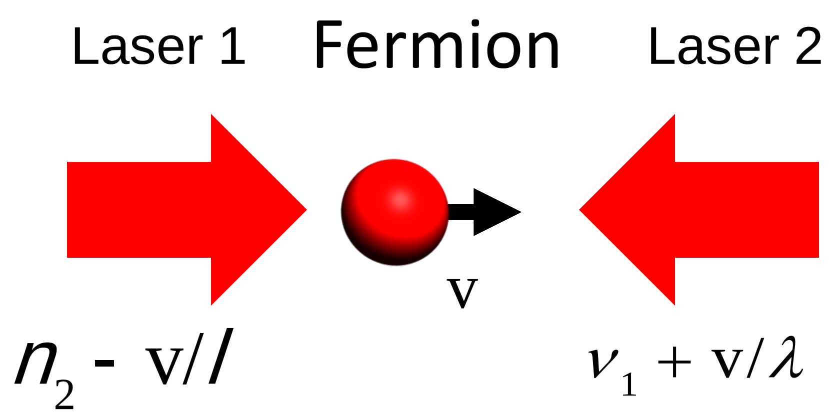
$$\mathcal{H} = \frac{\hbar^2 k^2}{2m} - \frac{g\mu_B}{\hbar}\mathbf{S}\cdot(\mathbf{B}^{(D)} + \mathbf{B}^{(R)} + \mathbf{B}^{(Z)})$$

$$\mathbf{B}^{(R)} = \alpha(k_y, -k_x, 0) \qquad \mathbf{B}^{(D)} = \beta(k_y, k_x, 0)$$

- 1D SO Hamiltonian

$$\mathcal{H} = \frac{\hbar^2 k^2}{2m} + 2\alpha k \sigma_z + \frac{\delta}{2}\sigma_z + \frac{\hbar\Omega_R}{2}\sigma_x$$

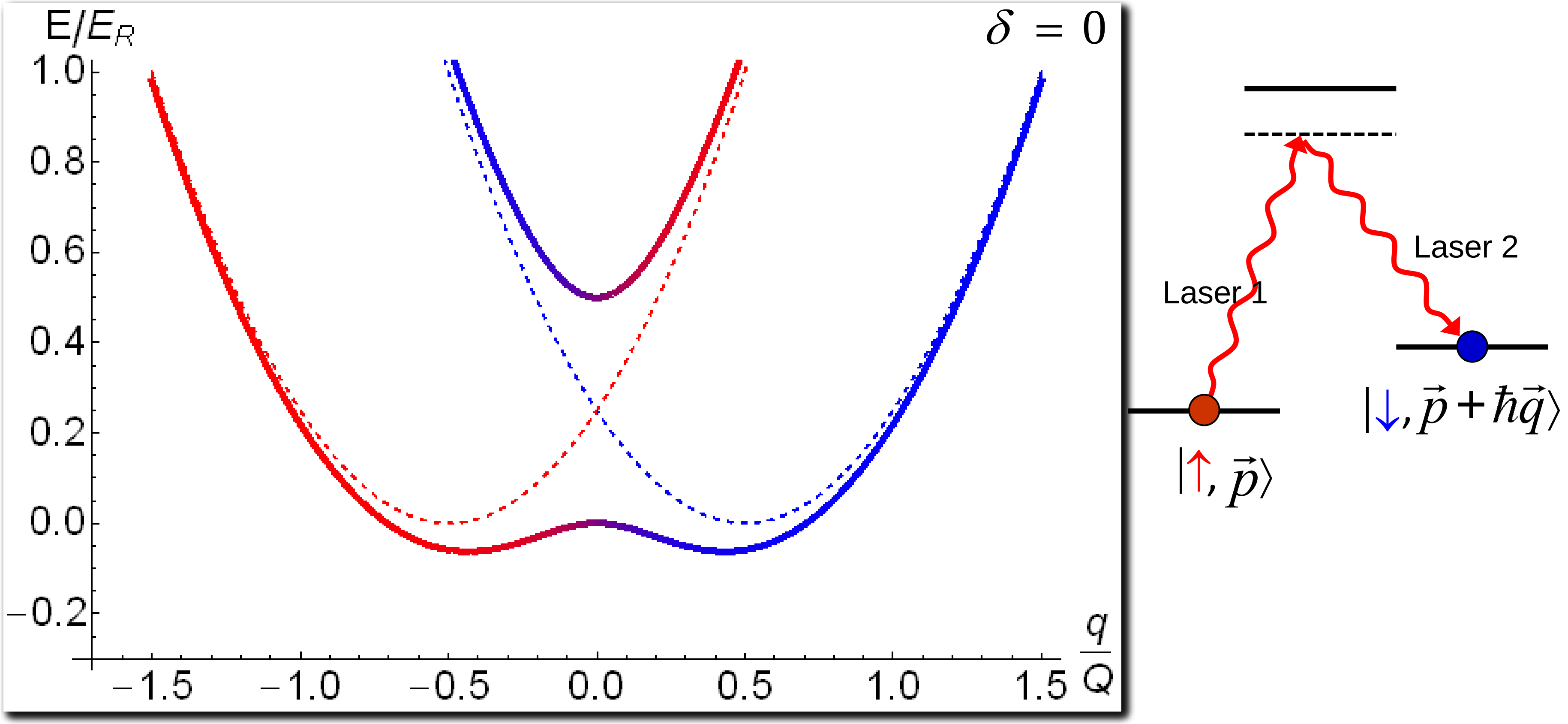




L. Cheuk, A. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, MWZ, PRL 109, 095302 (2012)

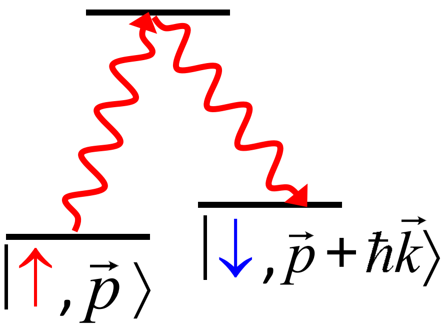
The spin-orbit gap

$$\mathcal{H} = \frac{\hbar^2 k^2}{2m} + 2\alpha k \sigma_z + \frac{\delta}{2}\sigma_z + \frac{\hbar\Omega_R}{2}\sigma_x$$

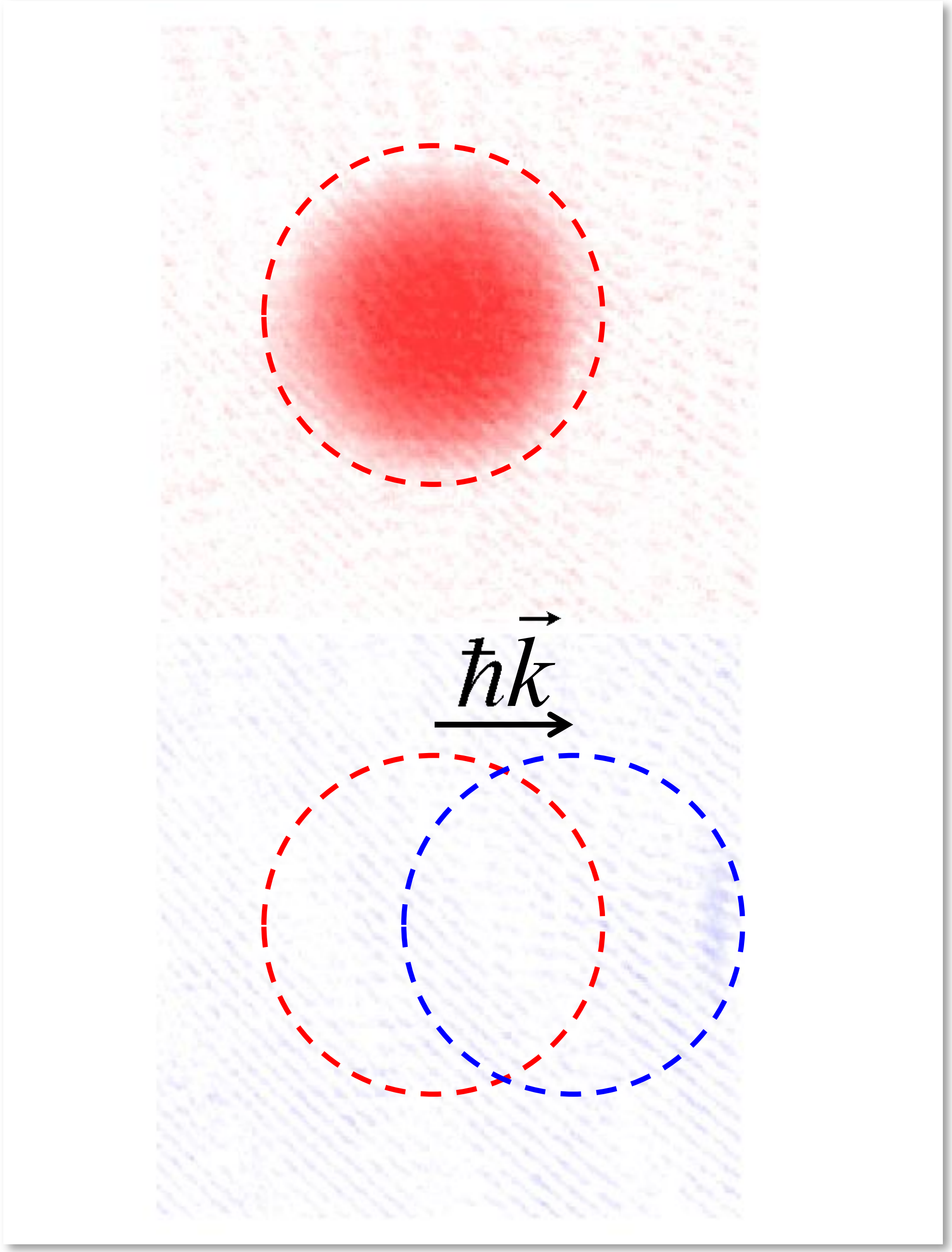


L. Cheuk, A. Sommer, Z. Hadzibabic, T. Yefsah, W. Bakr, MWZ, PRL 109, 095302 (2012)

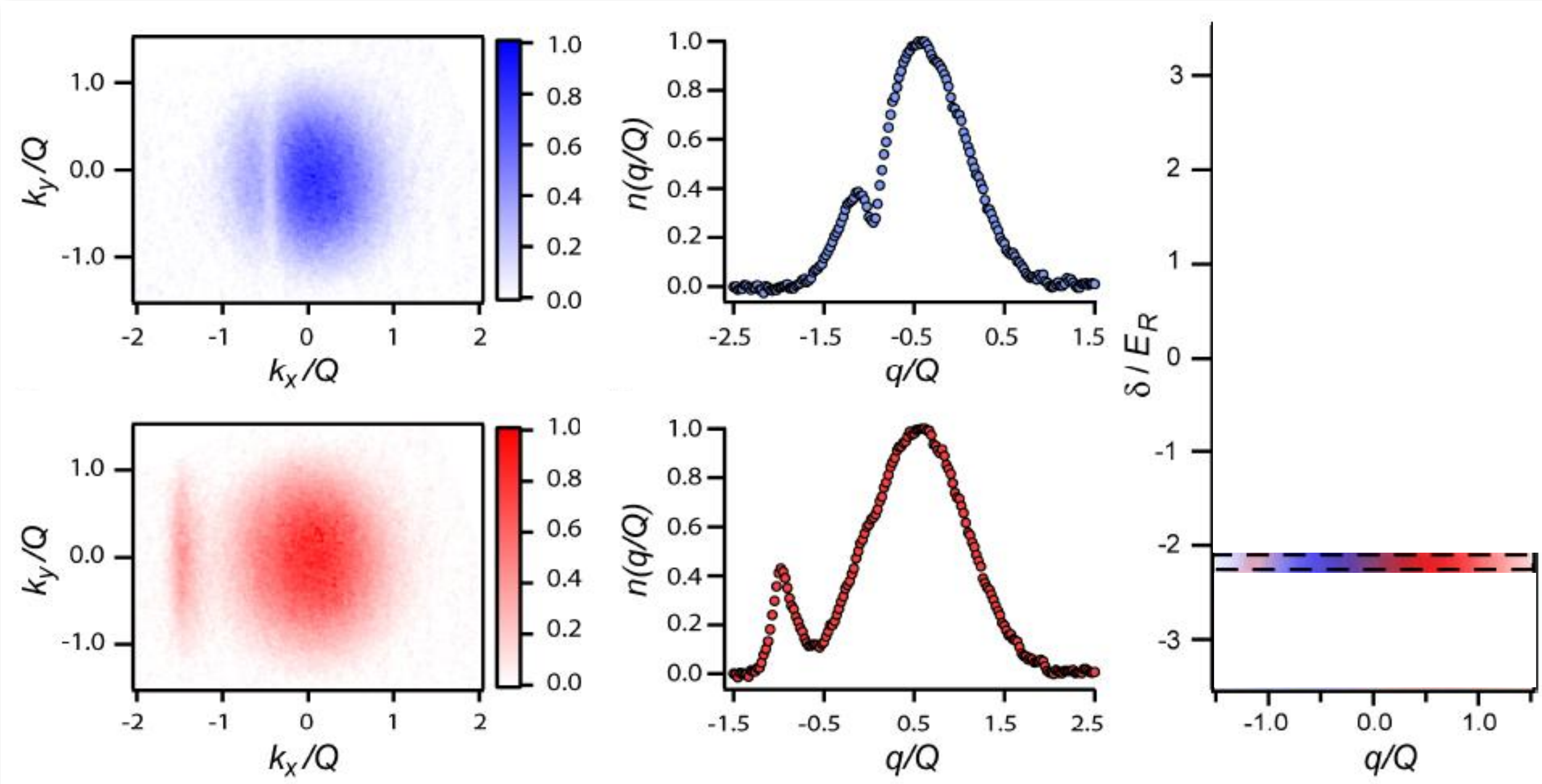
Spin-orbit Coupling of a Fermi sea



Vary detuning



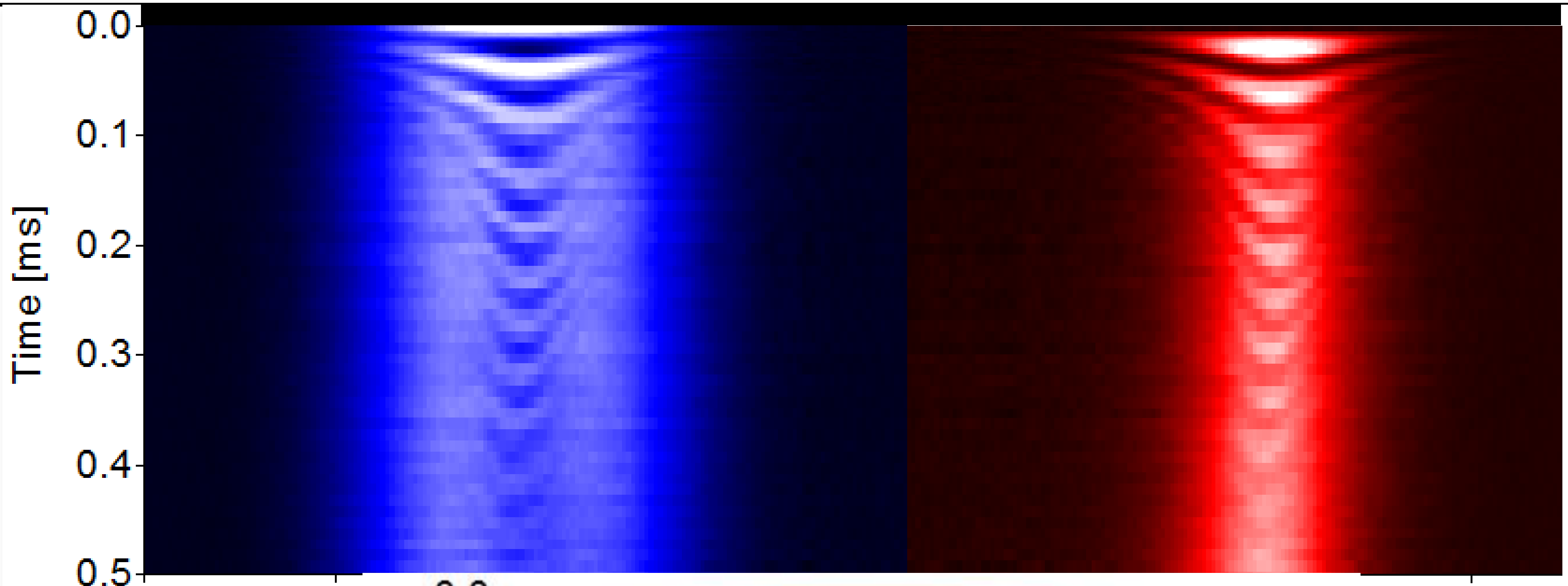
Coupling Spin and Momentum via Raman

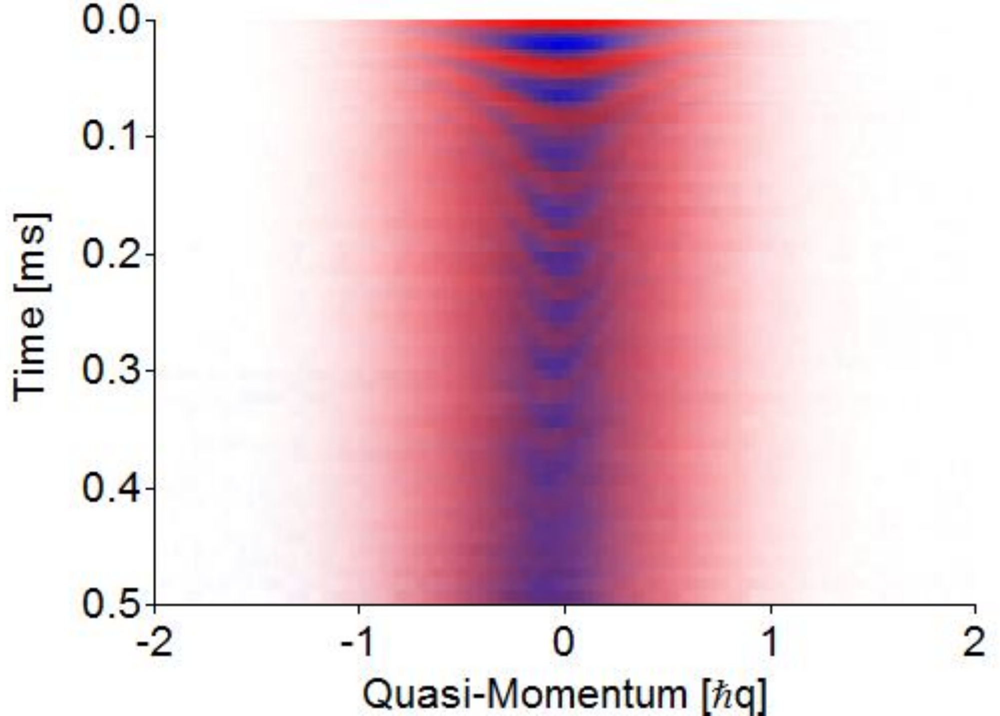


$$\left|\tilde{k}\right\rangle = a_k \left|k,\downarrow\right\rangle + b_k \left|k+q,\uparrow\right\rangle$$

L. Cheuk, A. Sommer, Z. Hadzibabic,
T. Yefsah, W. Bakr, MWZ, PRL 109, 095302 (2012)

Rabi Oscillations of Spin-Momentum Coupled States





Spin-injection spectroscopy

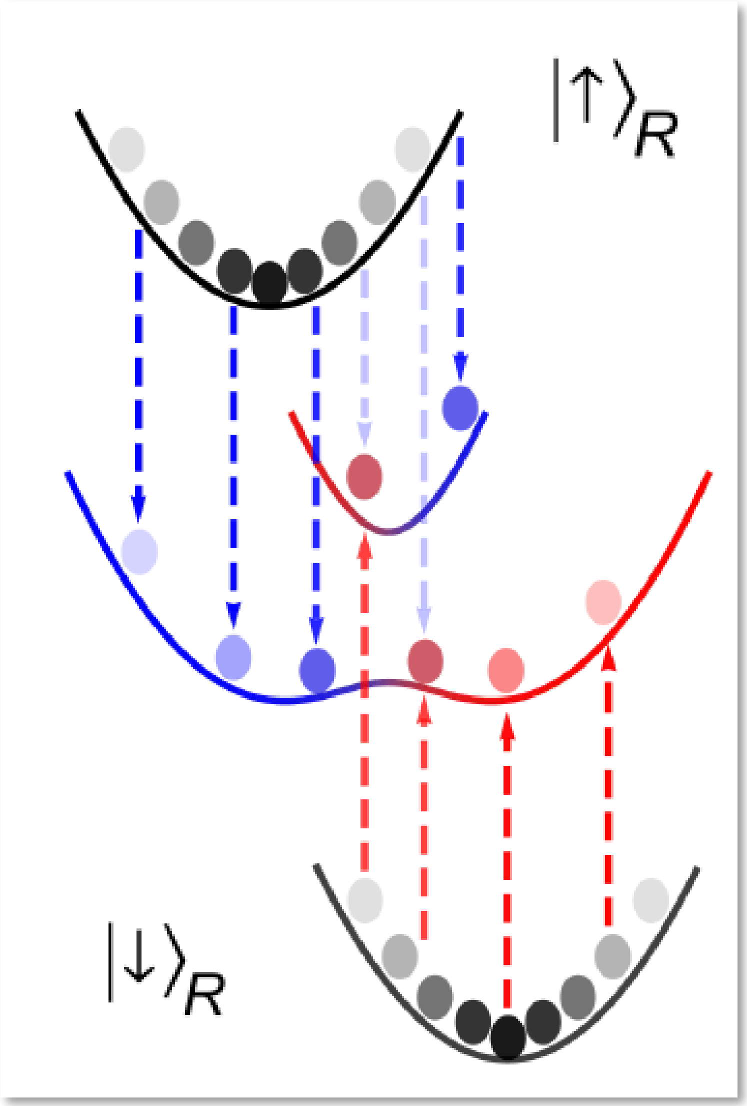
Can Topology be measured?

Spin-injection spectroscopy:

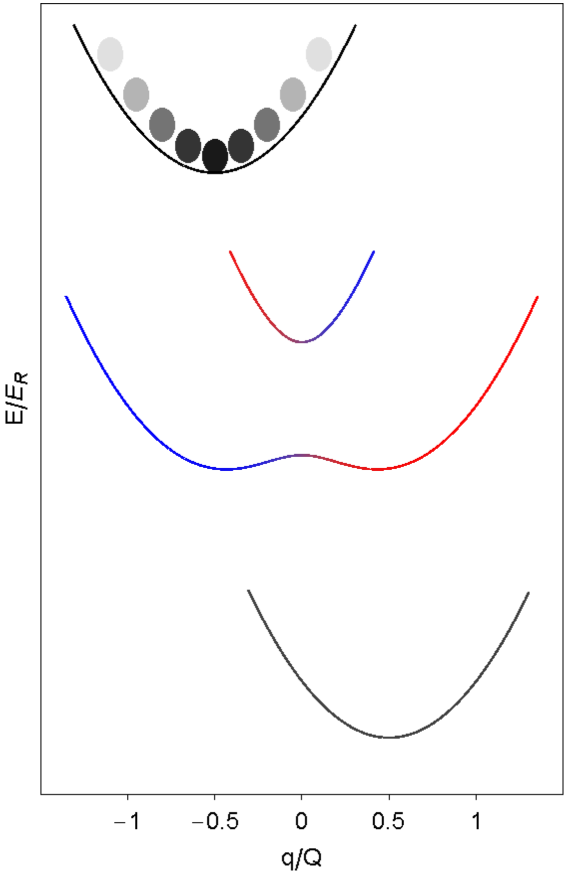
Measures spin, energy, momentum

1. Inject atoms from "reservoir"
2. Project into free space
3. Spin-selective imaging

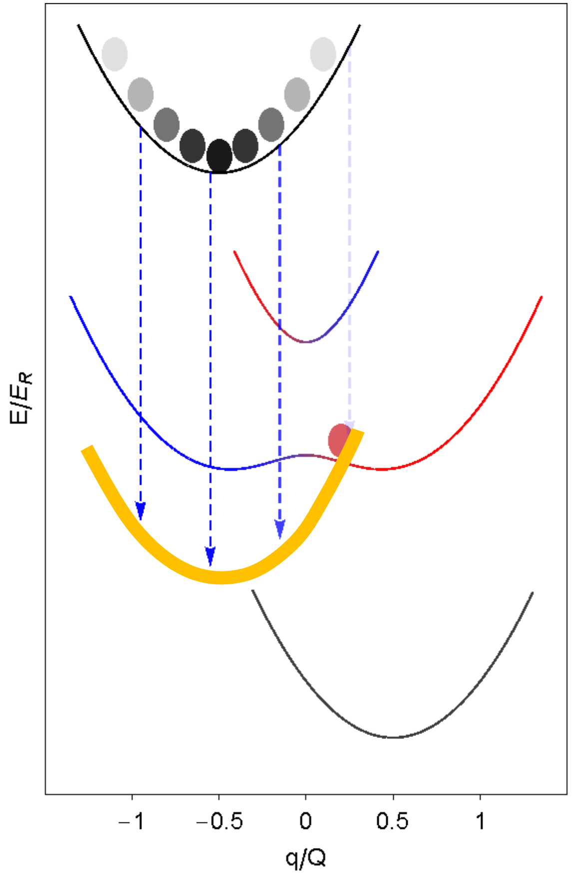
→ Reconstruct *E(k)* along with "color" of band

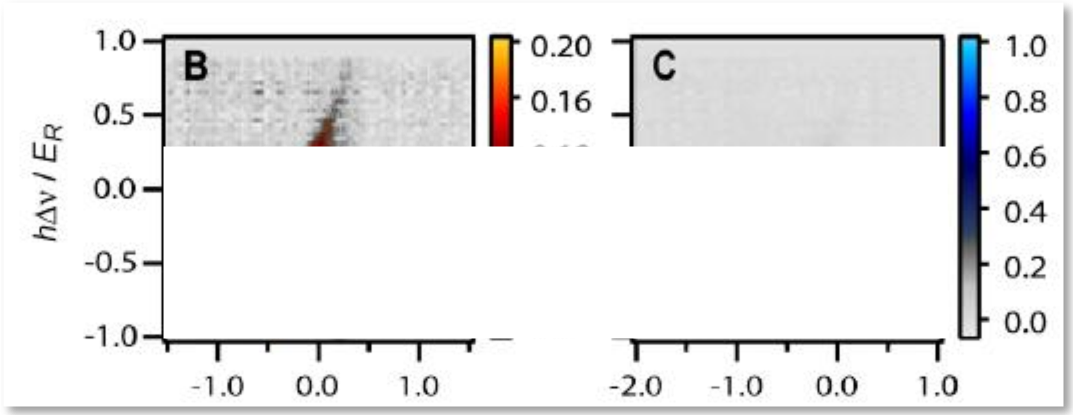


Spin-injection spectroscopy

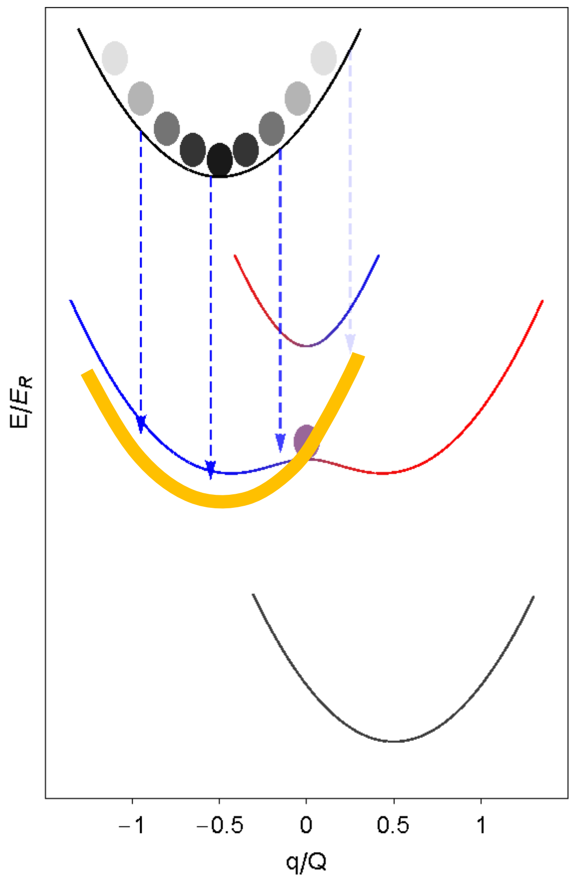


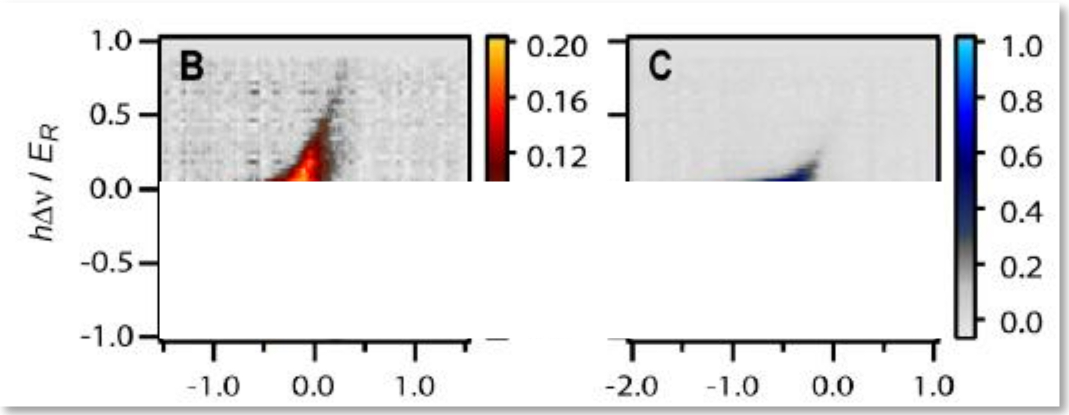
Spin-injection spectroscopy



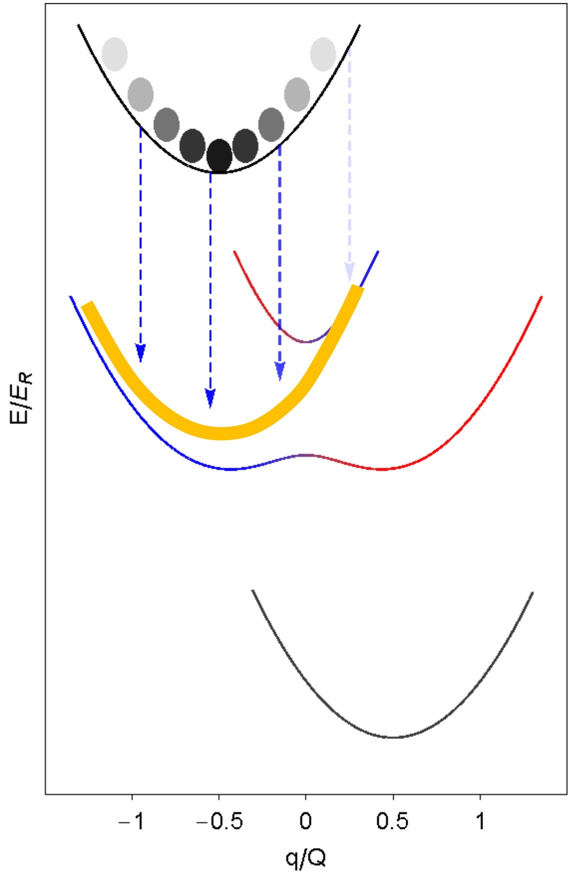


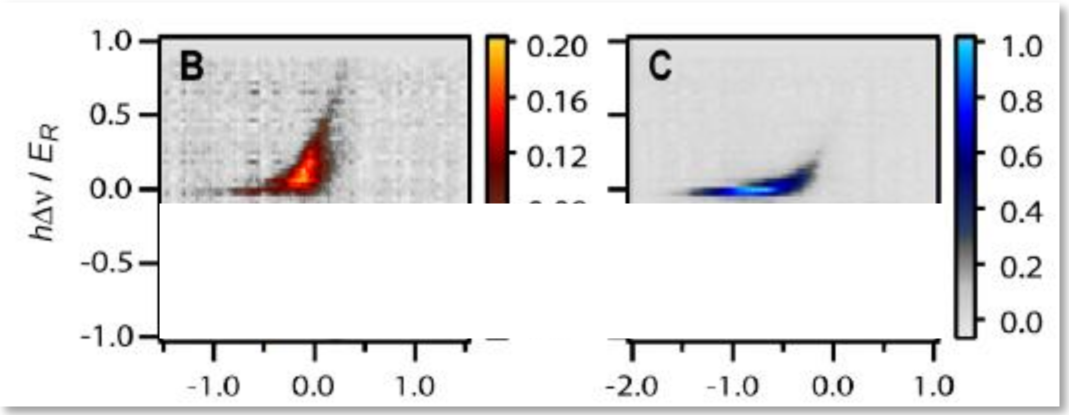
Spin-injection spectroscopy



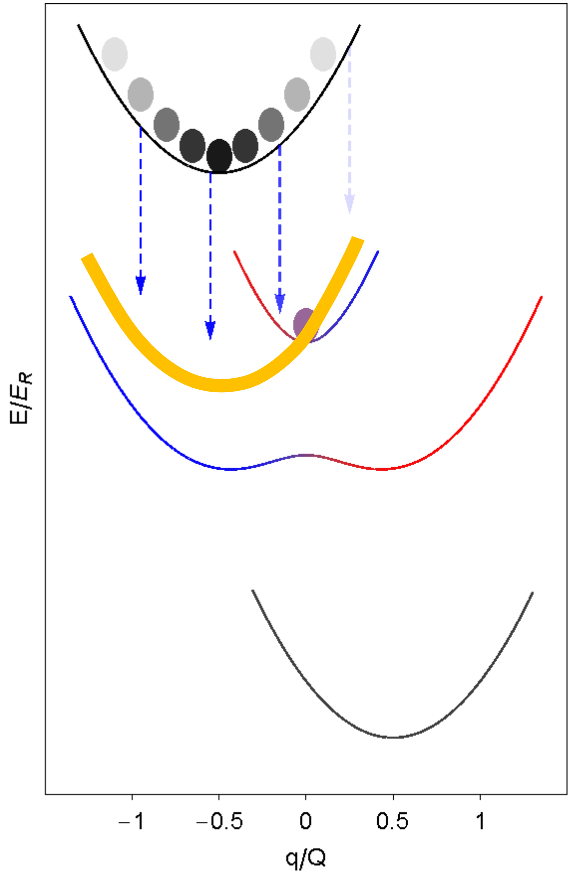


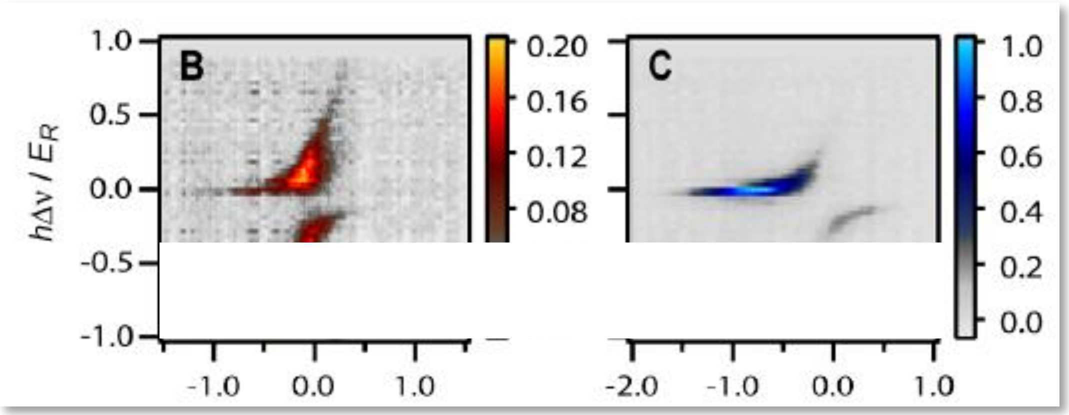
Spin-injection spectroscopy



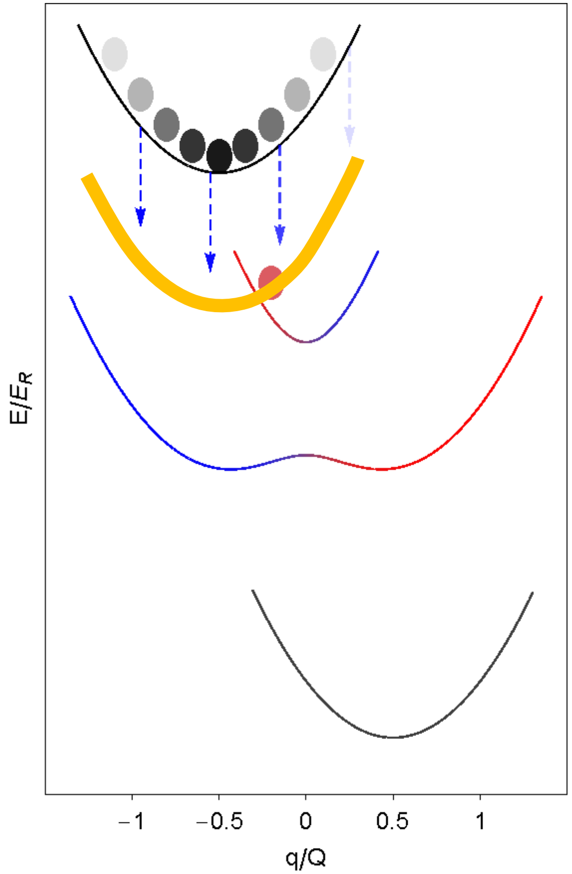


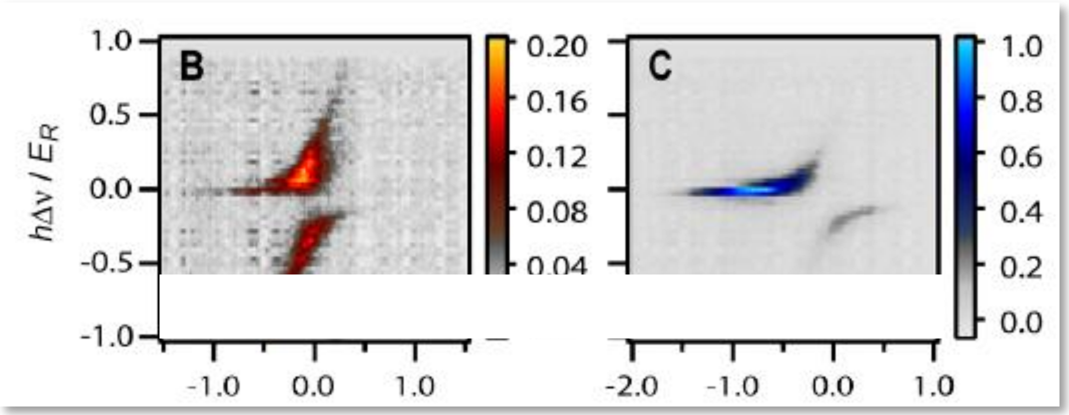
Spin-injection spectroscopy



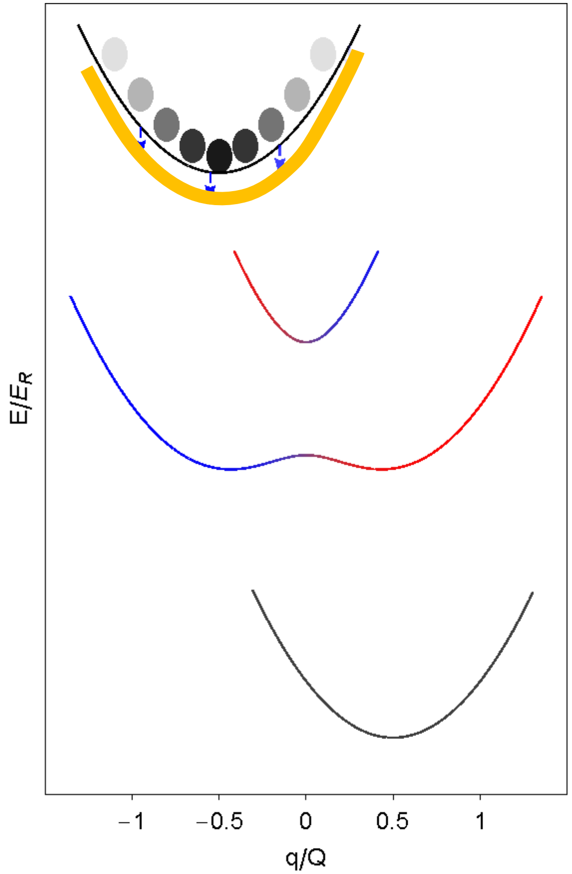


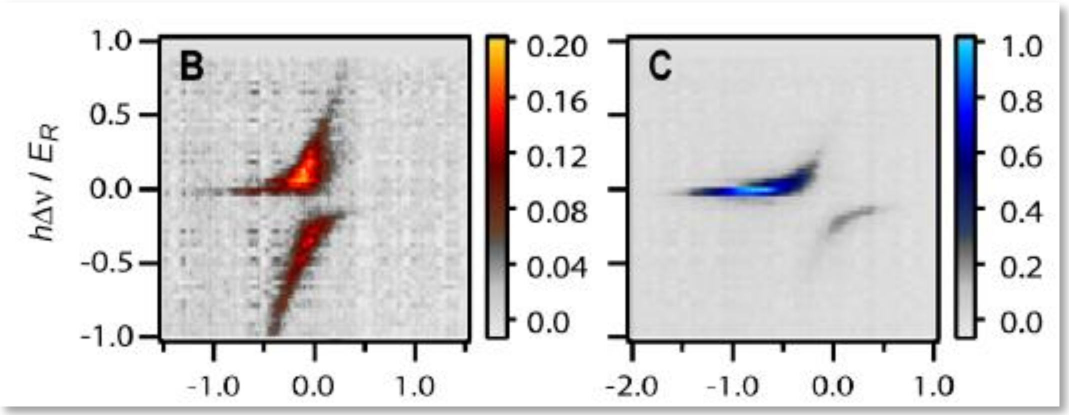
Spin-injection spectroscopy



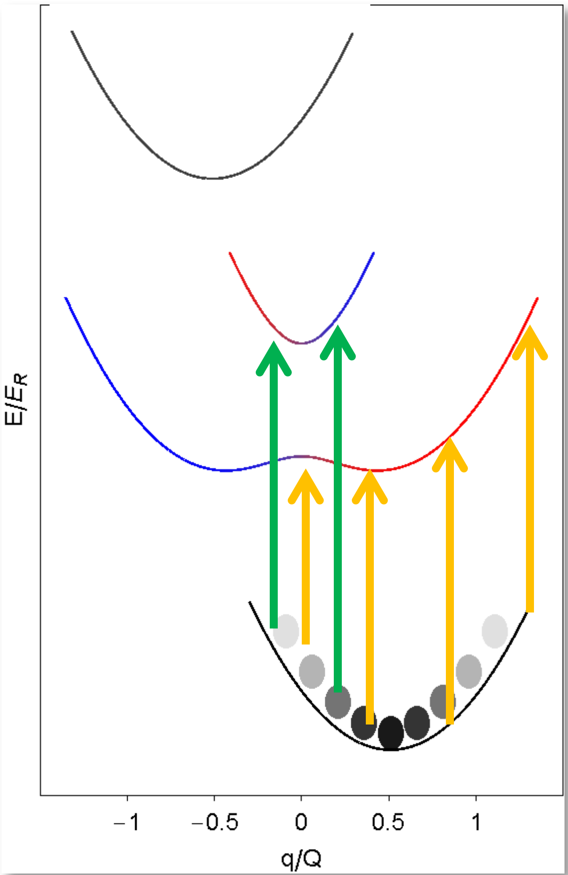


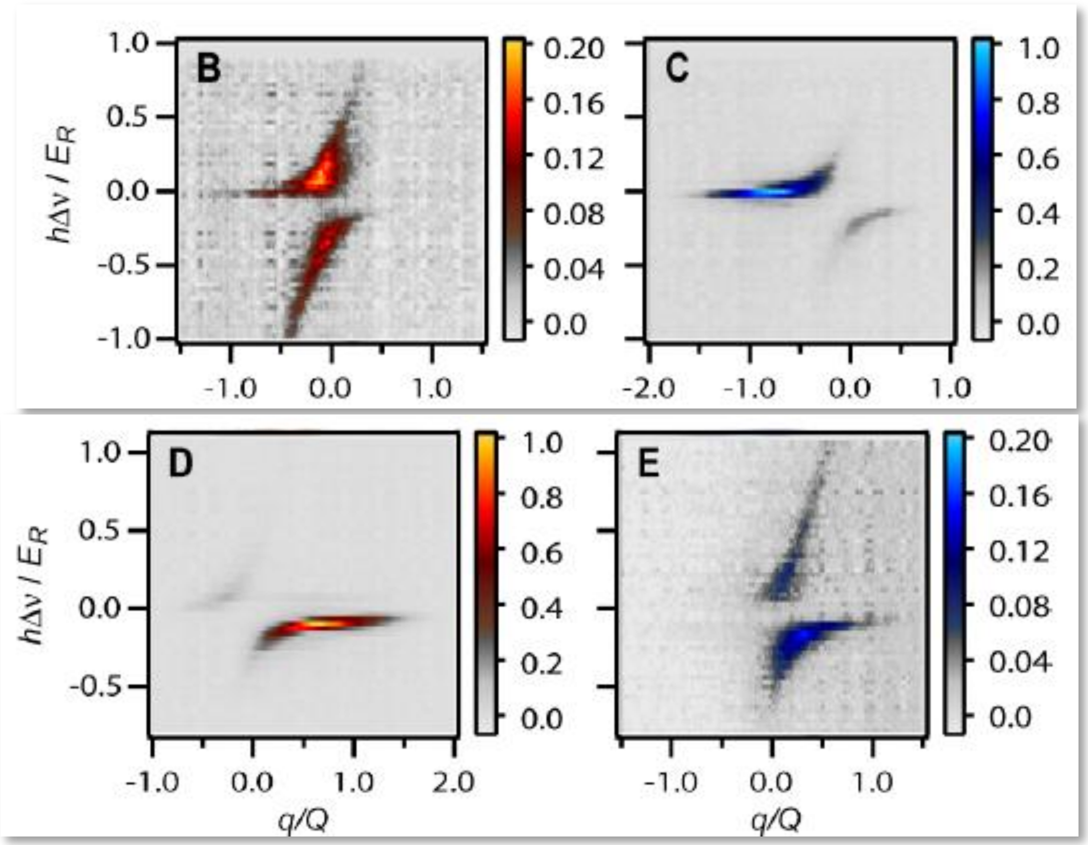
Spin-injection spectroscopy



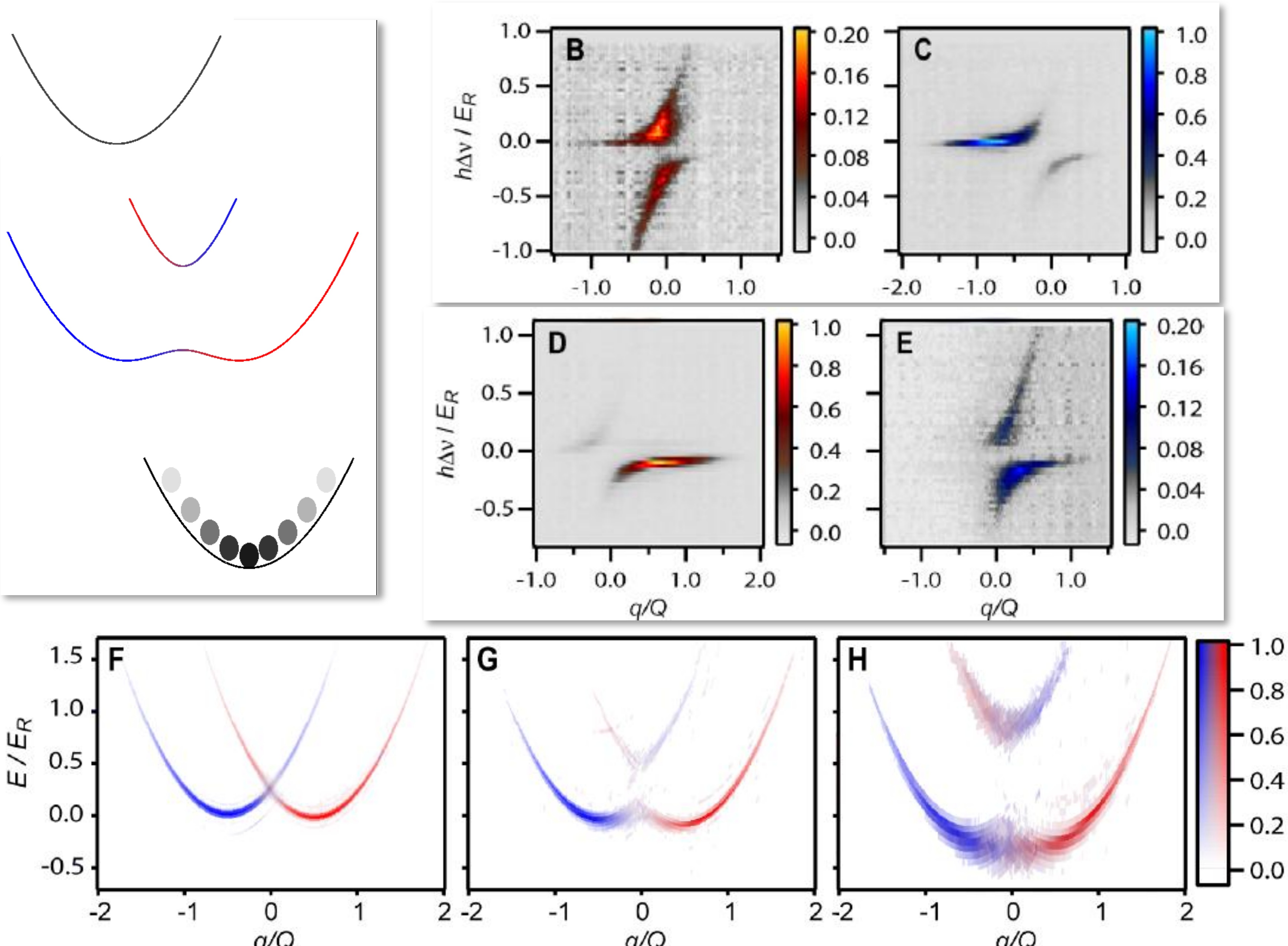


Spin-injection spectroscopy





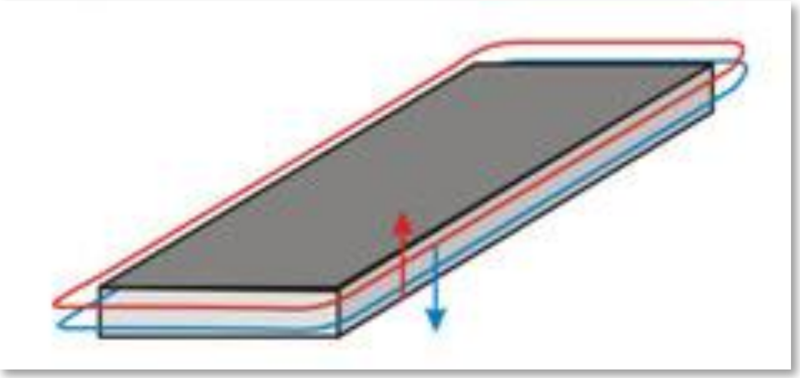
Direct Observation of the Spin-Orbit Gap



Outlook: Topological insulators

Without interactions

With Rashba type coupling
(two pairs of Raman beams)



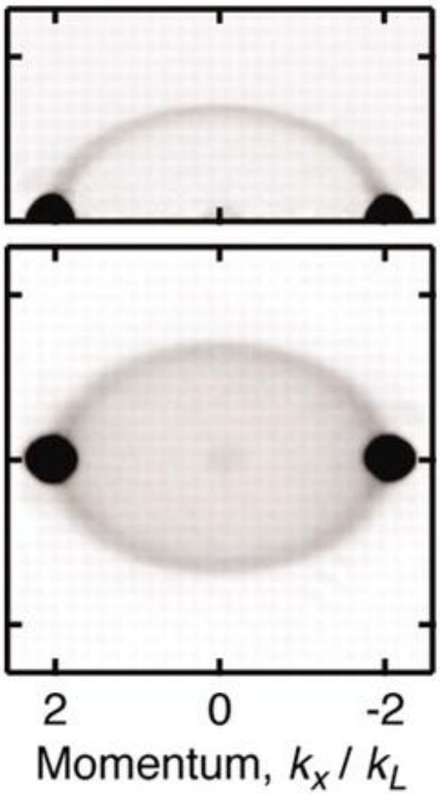
Reach quantum spin hall regime
in 2D system

Proposal by Zhu et al, PRL 97, 240401 (2006)

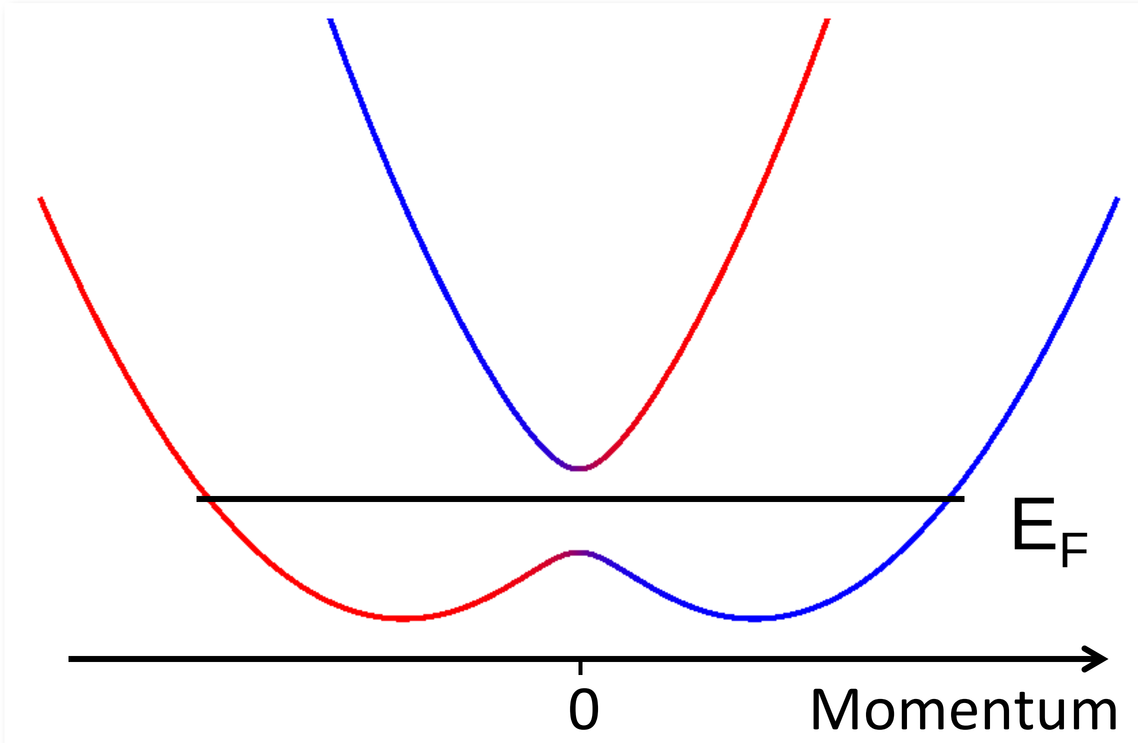
Topological insulators, edge states

Outlook: Topological superfluids

With interactions

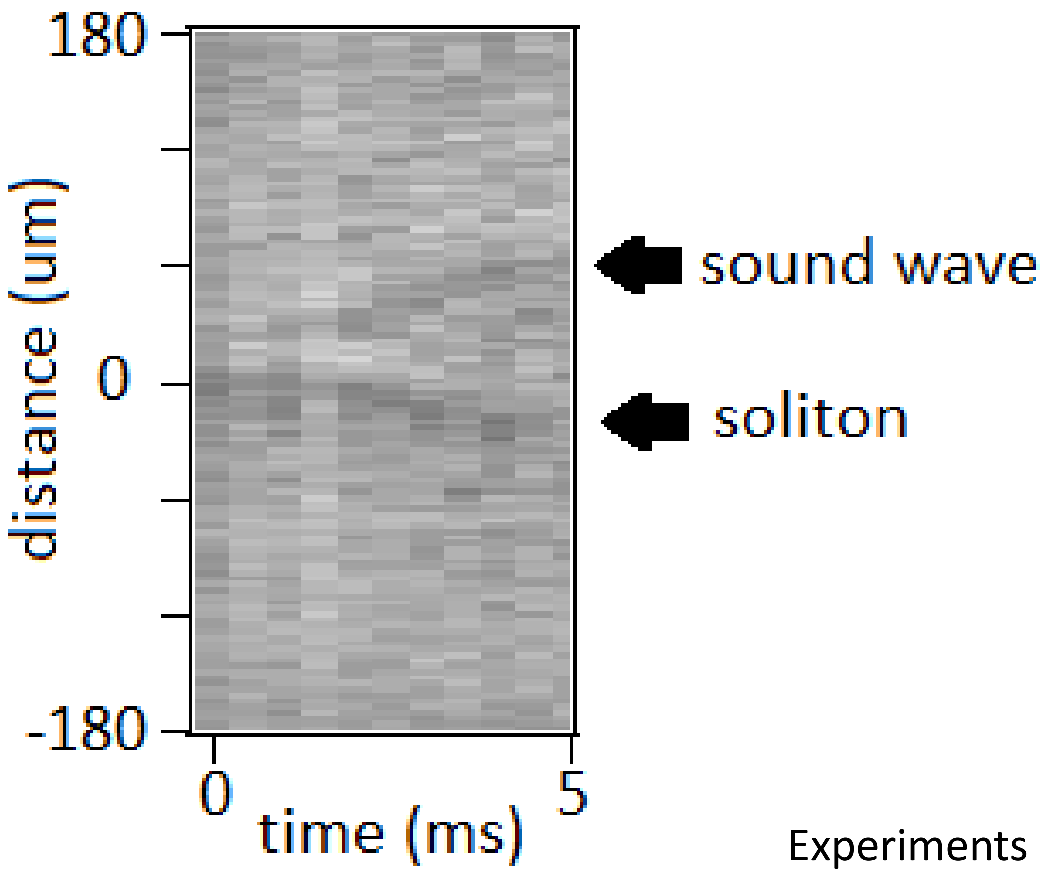


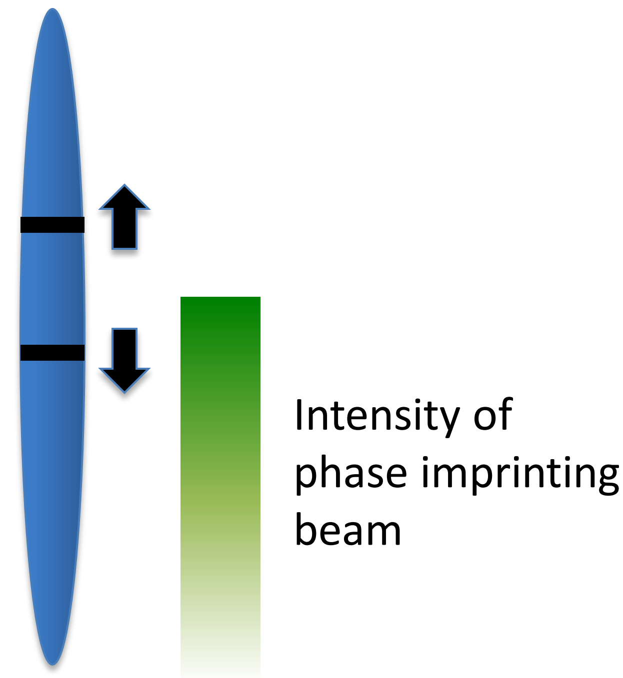
Higher partial wave
Interactions in SOC bosons
Williams et al, Science 335, 314 (2011)



With fermions: Expect p-wave pairing

Soliton dynamics in fermionic superfluids





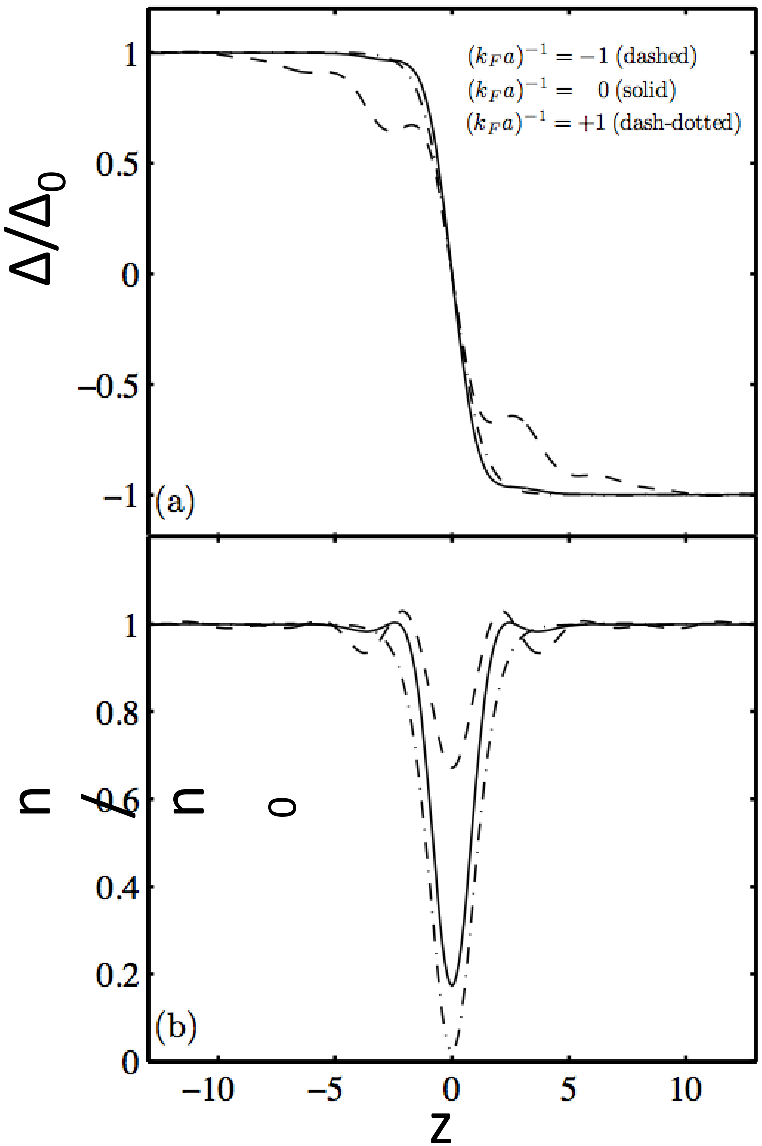
Experiments on solitons in BECs:
Burger et al, PRL 83, 5198 (1999)
Denschlag et al, Science 287, 97 (2000)

Andreev bound states in a soliton

What's different in a fermionic superfluid?

- Density dip at nodal plane decreases across BEC-BCS crossover.
- Soliton gets "heavier", increased oscillation period.
- Andreev bound states localized at the nodal plane, could be spectroscopically resolvable.

Theory on solitons in fermionic superfluids:
Antezza et al, PRA 76, 043610 (2007)
Scott et al, PRL 106, 185301 (2011)



Thanks

Thank you

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Fermion microscope
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