Spin-injection Spectroscopy of a Spin-orbit coupled Fermi Gas

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Why spin-orbit coupling ?

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

Cold atoms : (very often) constitute optimal system thanks to purity and controle

Spin-orbit Hamiltonian

- Electron moving in an electric field creates a momentum-dependent magnetic fields in the moving frame

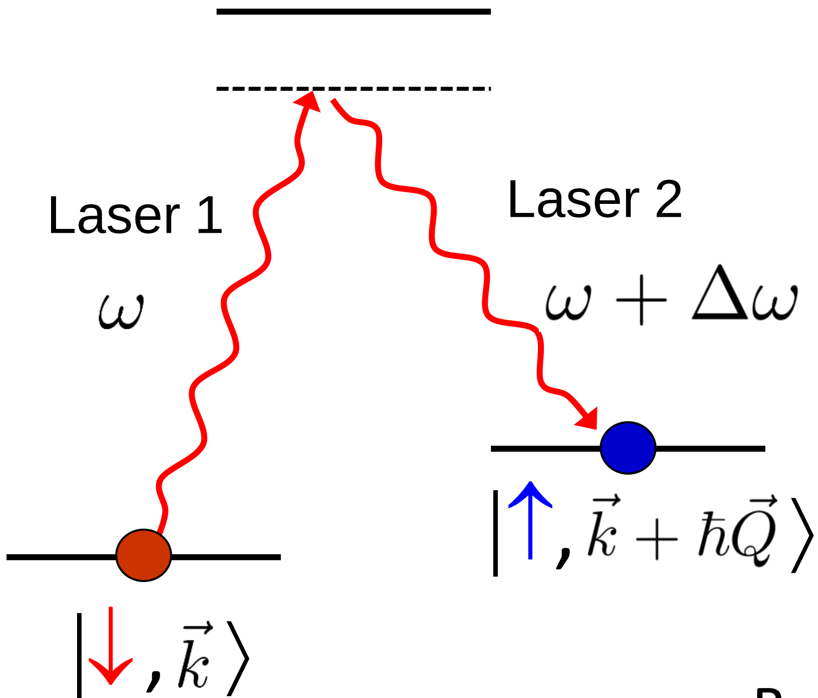
- In 2D semiconductor electric field can arises from structure

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} - \mu \cdot [\mathbf{B} + \mathbf{B}_{\mathrm{SO}}(\mathbf{k})]$$

$$-\mu \cdot \mathbf{B}_{\mathrm{SO}}(\mathbf{k}) \propto= \begin{cases} \sigma_x k_y - \sigma_y k_x & \text{Rashba} \\ -\sigma_x k_y - \sigma_y k_x & \text{Dresselhaus} \end{cases}$$

Provides a good description of 2D SOC in solids

Engineering SO coupling



Raman Beams

↓

Flip spin + imparts momentum

How does the Hamiltonian look like ?

Reminder

2-level system + electric field

e

g

$$\vec{E} = E_0 \vec{\epsilon} \cos(\omega t + \phi)$$

RWA approx. :

$$-\vec{d} \cdot \vec{E} = \frac{\hbar\Omega}{2} (\sigma_x \cos\phi - \sigma_y \sin\phi)$$

By adiabatic elimination of the excited state the Raman process can be described as the interaction of a 2-level system with a field $E_0 \vec{\epsilon} \cos(\Delta\omega t + Qx)$

$$\longrightarrow \quad -\vec{d} \cdot \vec{E} = \frac{\hbar\Omega_R}{2} (\sigma_x \cos Qx - \sigma_y \sin Qx)$$

Engineering SO coupling

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \frac{\hbar\Omega_R}{2}(\sigma_x \cos Qx - \sigma_y \sin Qx) + \frac{\delta}{2}\sigma_z$$

Local pseudo-spin rotation of angle Qx around the *z*-axis

$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \frac{\hbar^2 Q}{2m}\sigma_z k_x + \frac{\hbar\Omega_R}{2}\sigma_x + \frac{\delta}{2}\sigma_z + \frac{E_R}{4}\mathbb{I}$$

Global rotation $\sigma_z \to \sigma_y, \sigma_y \to \sigma_x, \sigma_x \to \sigma_z$

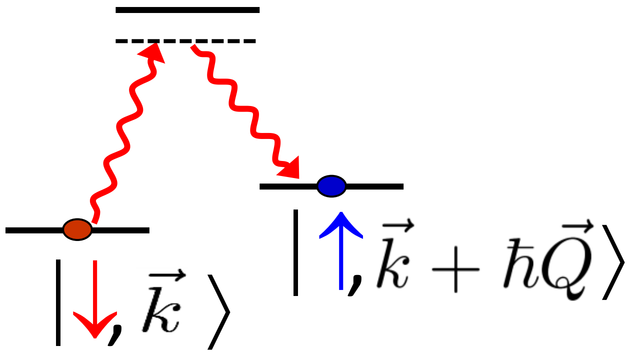
$$\mathcal{H} = \frac{\hbar^2 \mathbf{k}^2}{2m}\mathbb{I} + \underbrace{\frac{\hbar^2 Q}{2m}\sigma_y k_x}_{-\mu \cdot \mathbf{B}_{\mathrm{SO}}(\mathbf{k})} + \underbrace{\frac{\hbar\Omega_R}{2}\sigma_z + \frac{\delta}{2}\sigma_y}_{-\mu \cdot \mathbf{B}} + \frac{E_R}{4}\mathbb{I}$$

Momentum dependent Zeeman field

"equal Rashba and Dresselhaus contributions"

Y. J. Lin *et al.* *Nature* **471,** 83-86 (2011)

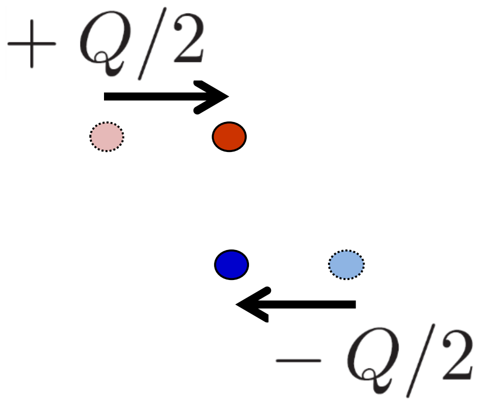
Engineering SO coupling



Define quasi-momentum q

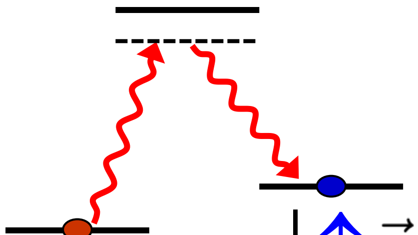
$$|\downarrow\rangle \quad q = k + Q/2$$

$$|\uparrow\rangle \quad q = k - Q/2$$



quasi-momentum space

Engineering SO coupling



$|\downarrow,\vec{k}\,\rangle \qquad |\uparrow,\vec{k}+\hbar\vec{Q}\rangle$

$$\mathcal{H}_{SO} = \begin{pmatrix} \frac{\hbar^2(q-Q/2)^2}{2m} + \frac{d}{2} & \\ & \frac{\hbar^2(q+Q/2)^2}{2m} - \frac{d}{2} \end{pmatrix}$$

Define quasi-momentum q

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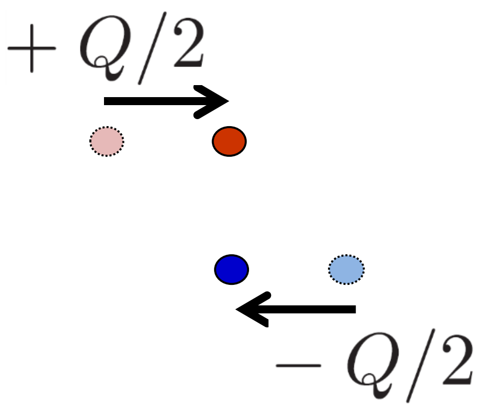
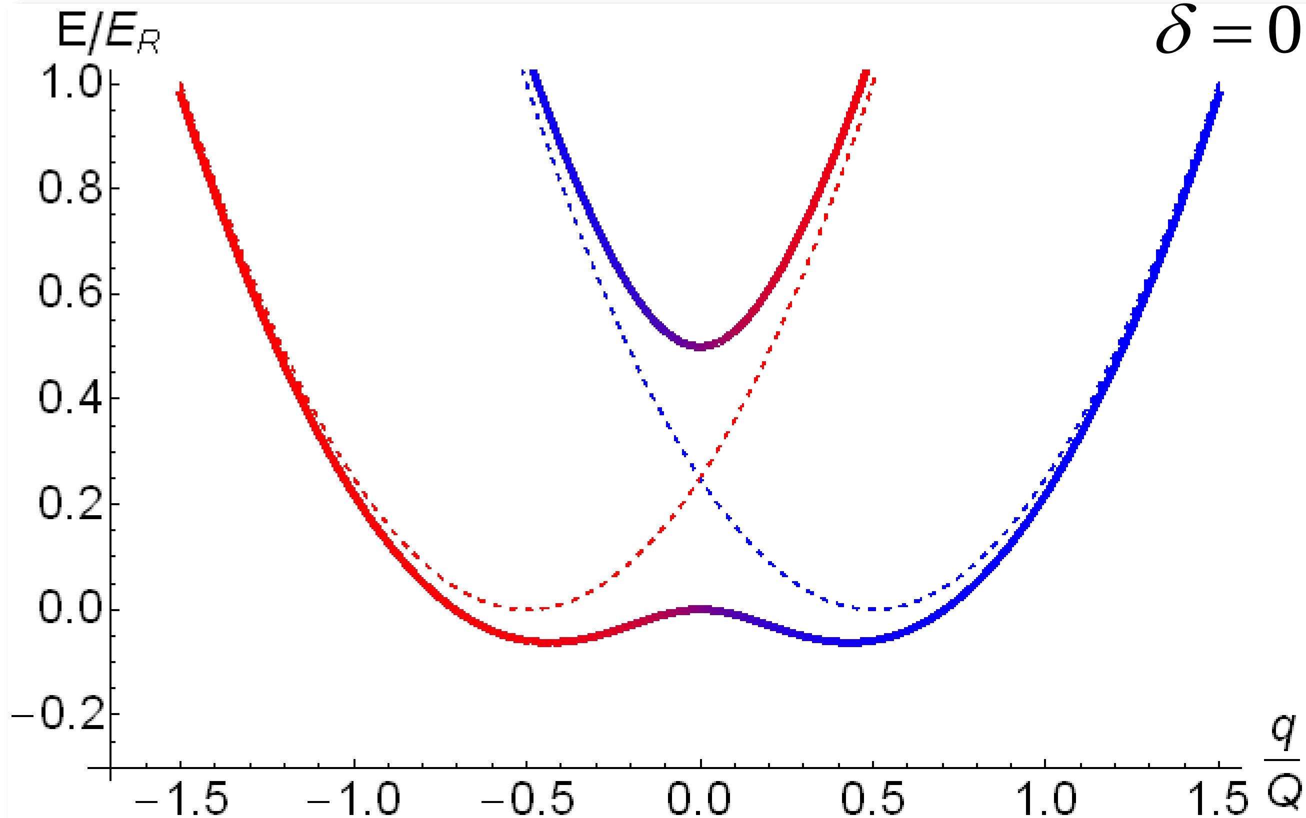
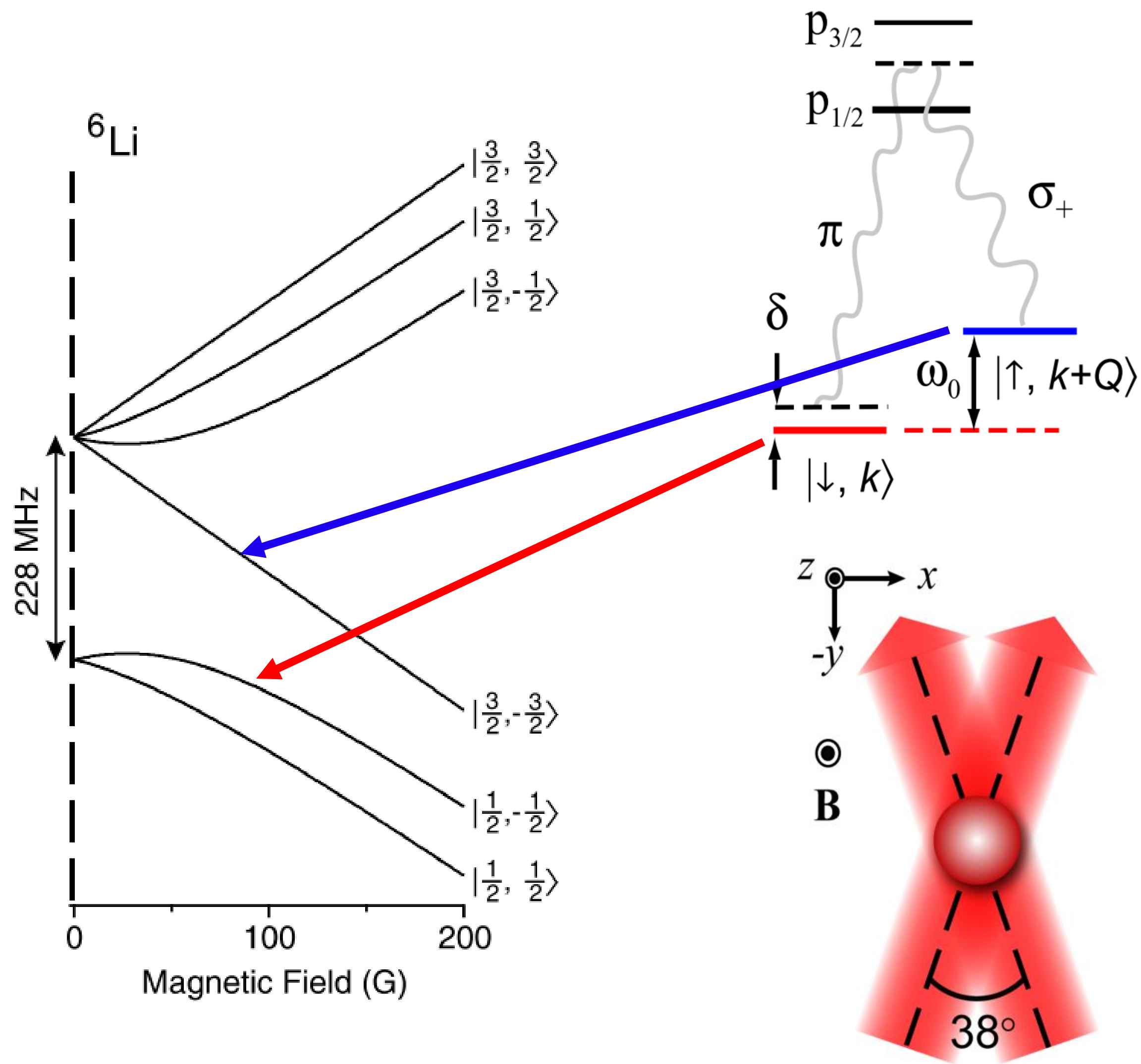


quasi-momentum space

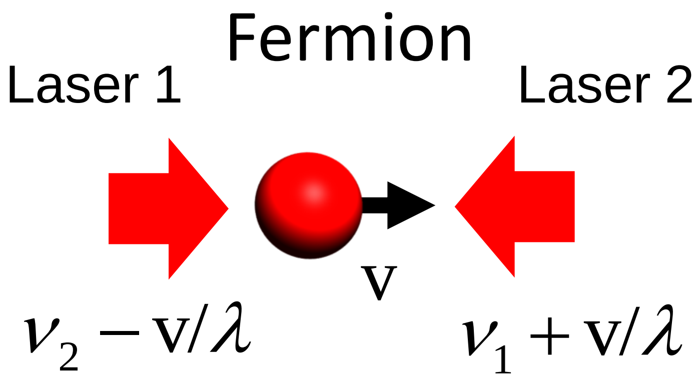


Experimental Setup

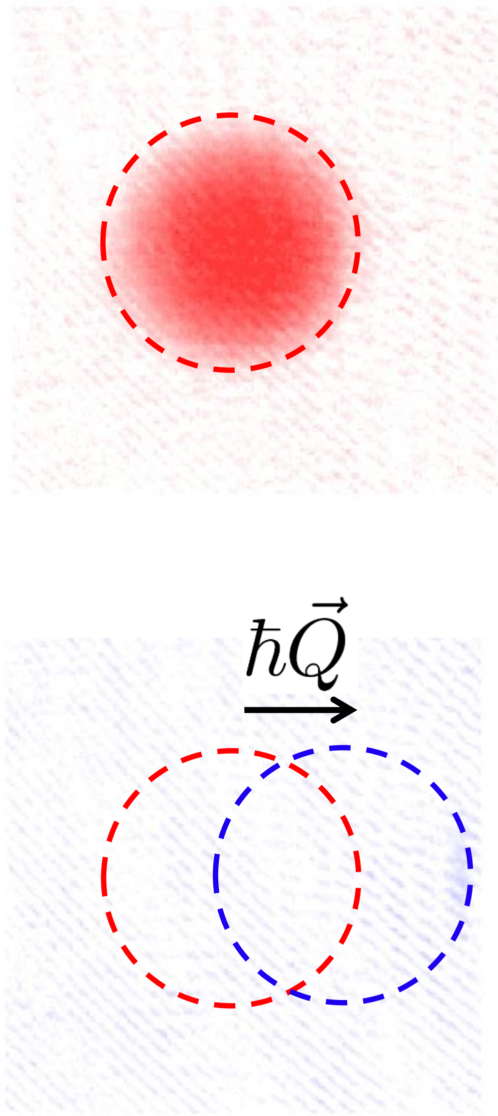
- Fermionic ^{6}Li atoms sympathetically cooled by ^{23}Na
- Relevant states are 2nd and 3rd lowest states at 11G
- Interactions are negligible ($20a_0$)



Coupling spin and momentum via Raman



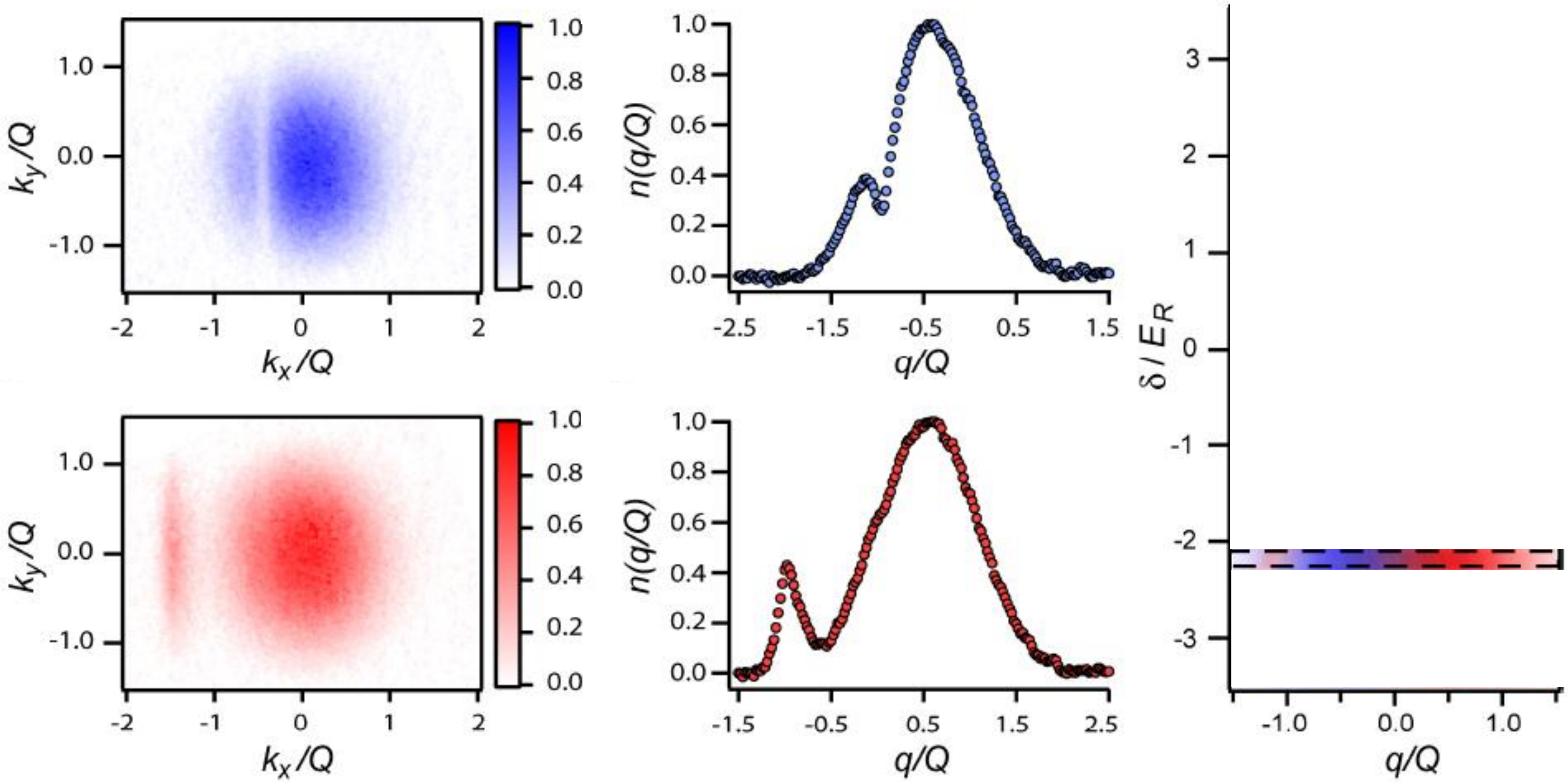
Vary detuning
Short pulse



State-selective imaging after TOF provides
spin and momentum information

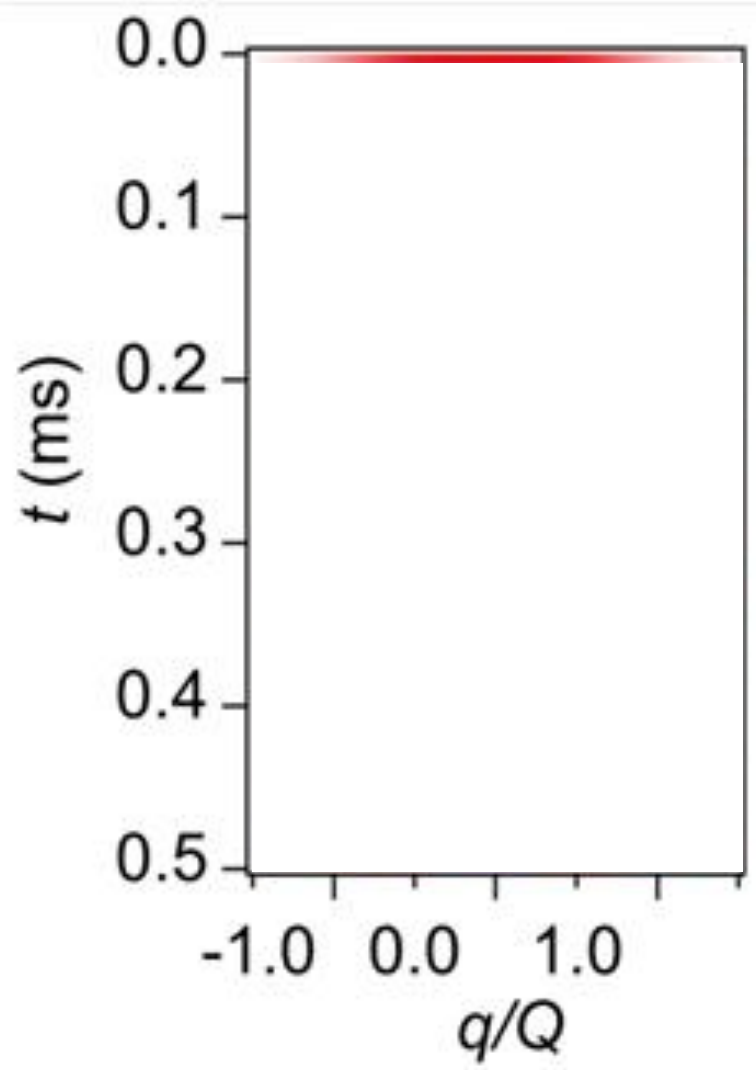
Image analysis

- Start with a mixture of $|\downarrow\rangle$ and $|\uparrow\rangle$, and apply a Raman pulse for a given δ



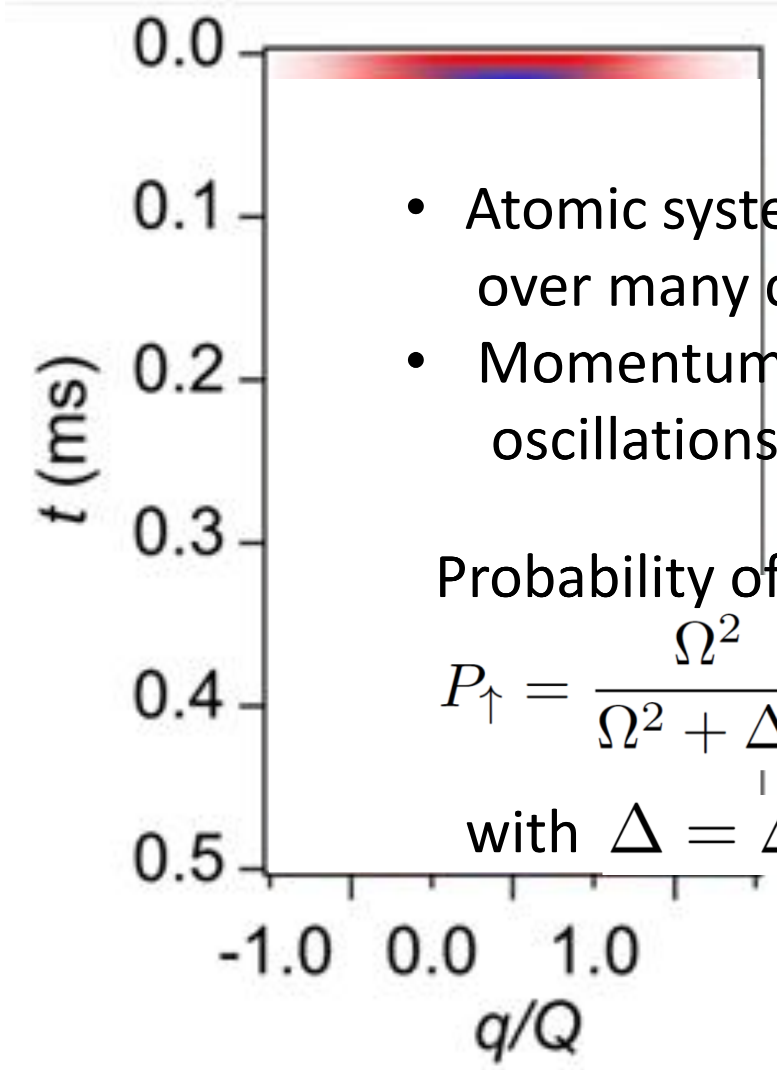
Check for the linear dependence of the transfer with momentum *q*
(Doppler shift $\propto k_x Q$)

Pulsing on Raman Beams



Start with state $|\downarrow\rangle$

Pulsing on Raman Beams



Start with state $|\downarrow\rangle$

- Atomic system is coherent over many cycles
- Momentum-dependent Rabi oscillations

Probability of transfer :

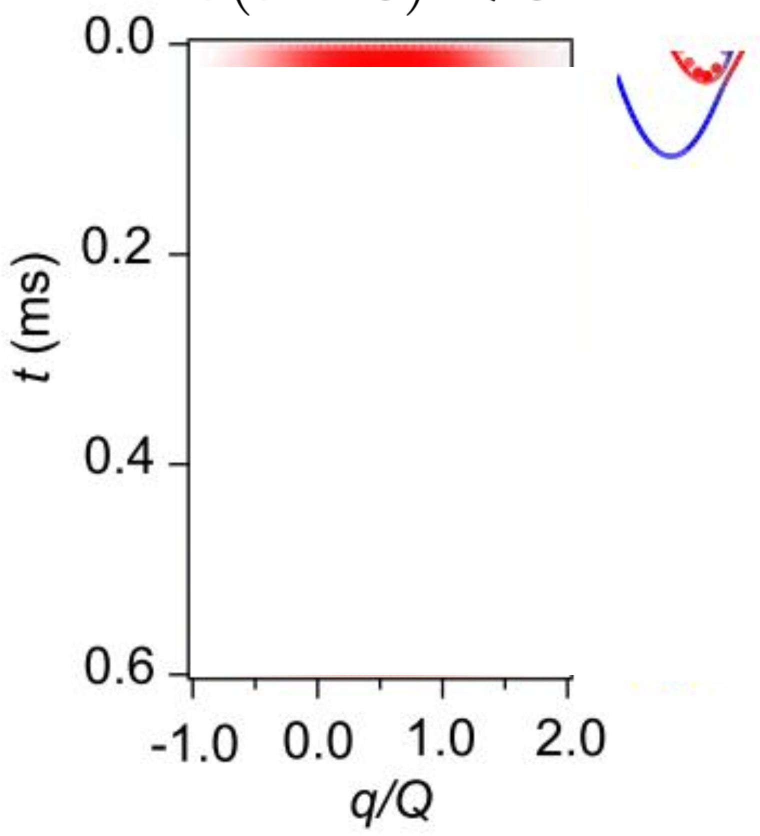
$$P_\uparrow = \frac{\Omega^2}{\Omega^2+\Delta^2}\sin^2\left(\frac{1}{2}\sqrt{\Omega^2+\Delta^2}t\right)$$

with $\Delta = \Delta(q)$

Adiabatic Sweep

- Start with state $|\downarrow\rangle$
- Set large initial detuning ($|\delta| \gg E_R$) and then sweep

$\delta(t=0) < 0$



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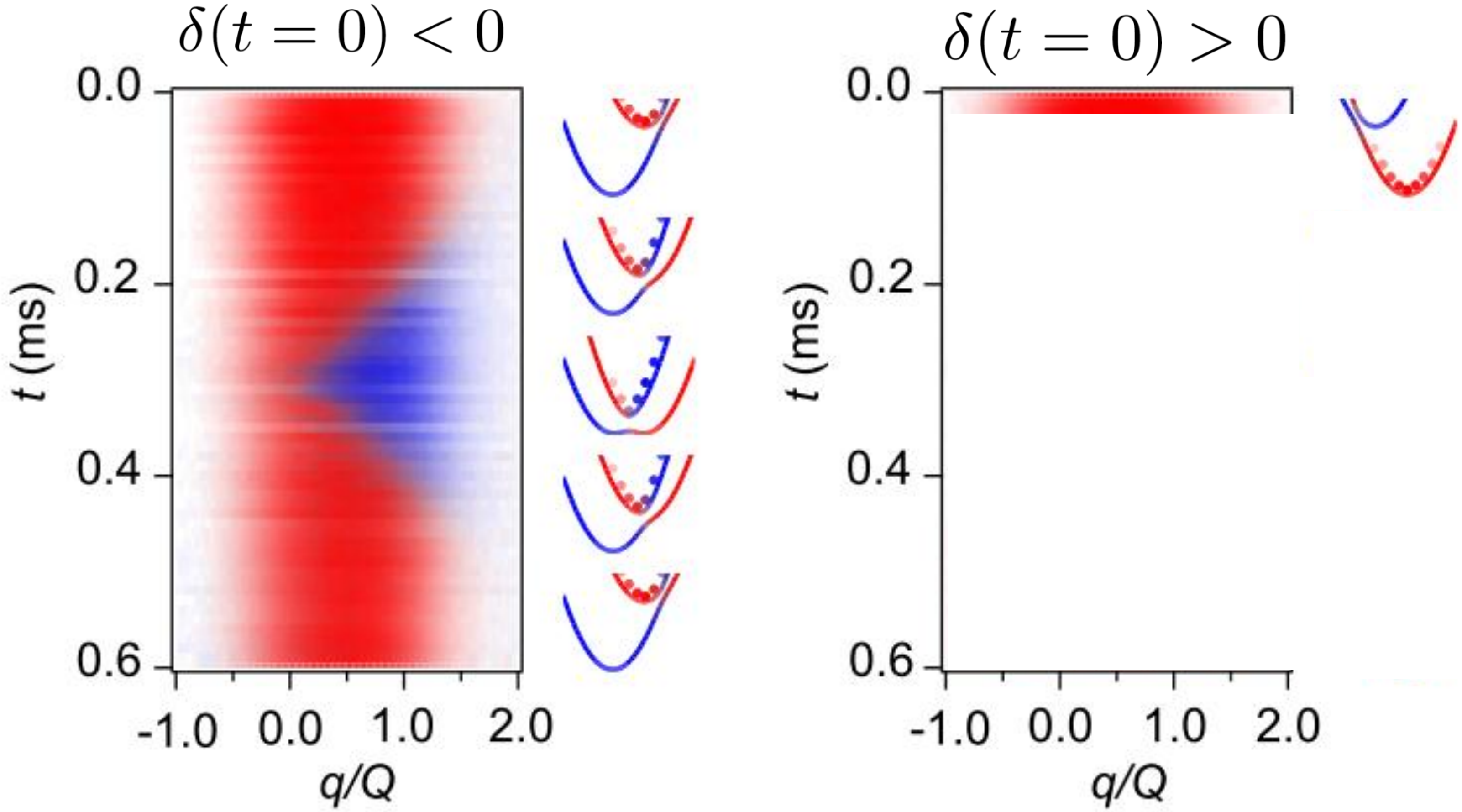
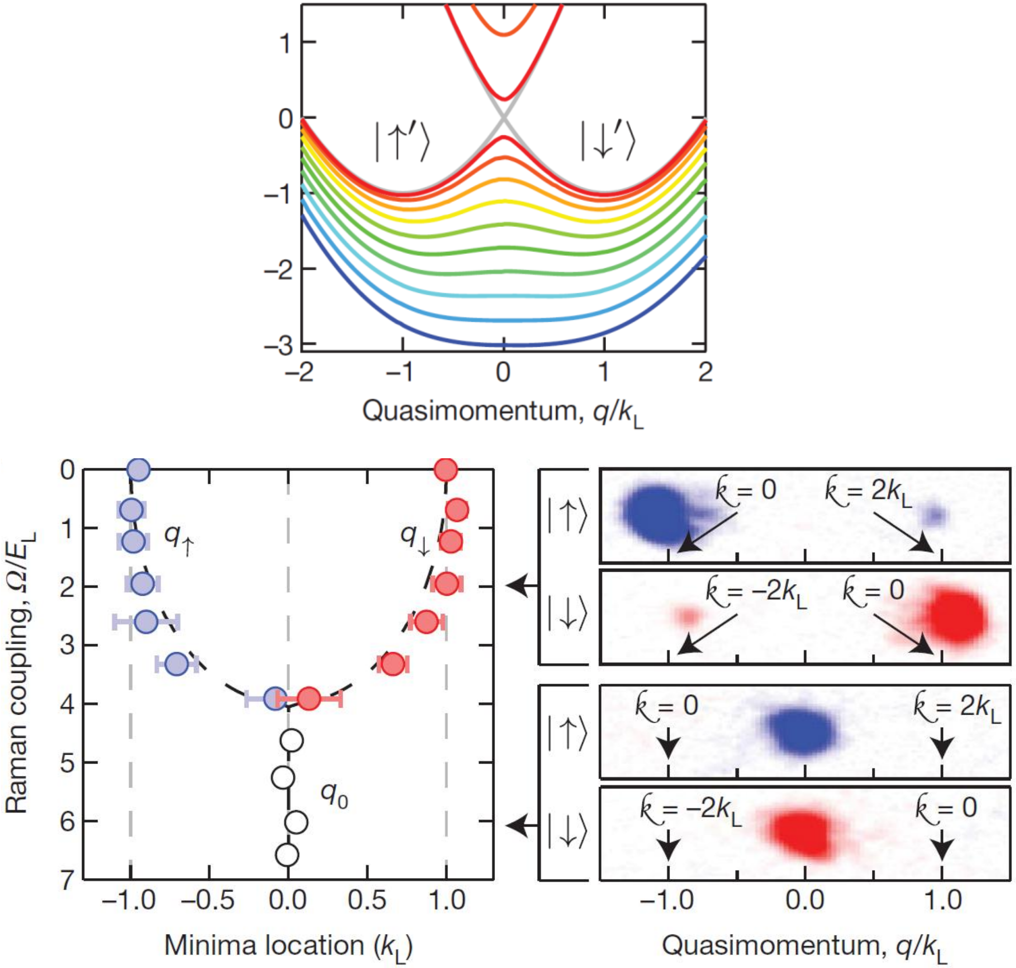


Spin-injection spectroscopy

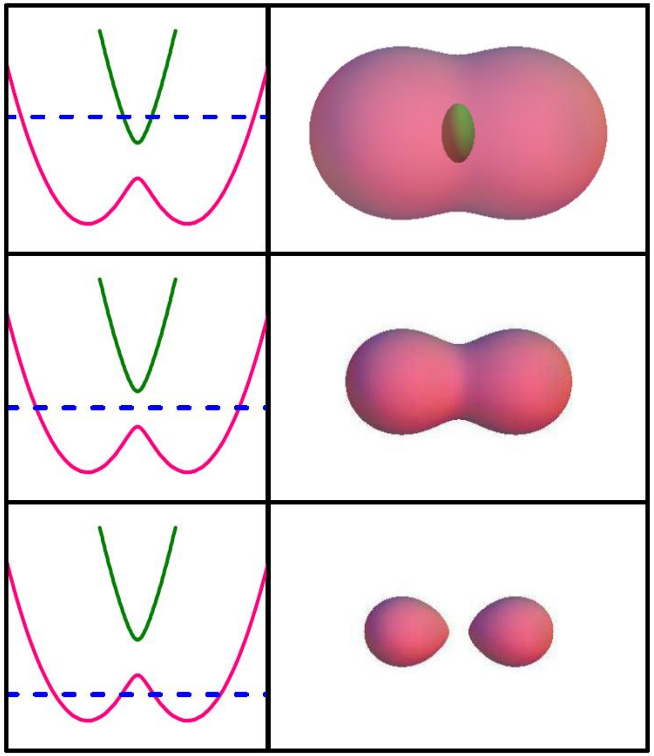
- How to characterize Hamiltonian?
  - Can topology be measured?
- Condensed matter: transport, (spin-)ARPES, STM …
- Cold atom analog:
  momentum resolved RF (Jin, Koehl)
  (=photoemission spectroscopy)
- Photoemission Spectroscopy probes dispersion *E(k)*

What has been done so far

Y. J. Lin *et al.* *Nature* **471,** 83-86 (2011)
Ian Spielman's group



P. Wang *et al* **arXiv:1204.1887**
(Jing Zhang's group)



Spin-injection spectroscopy

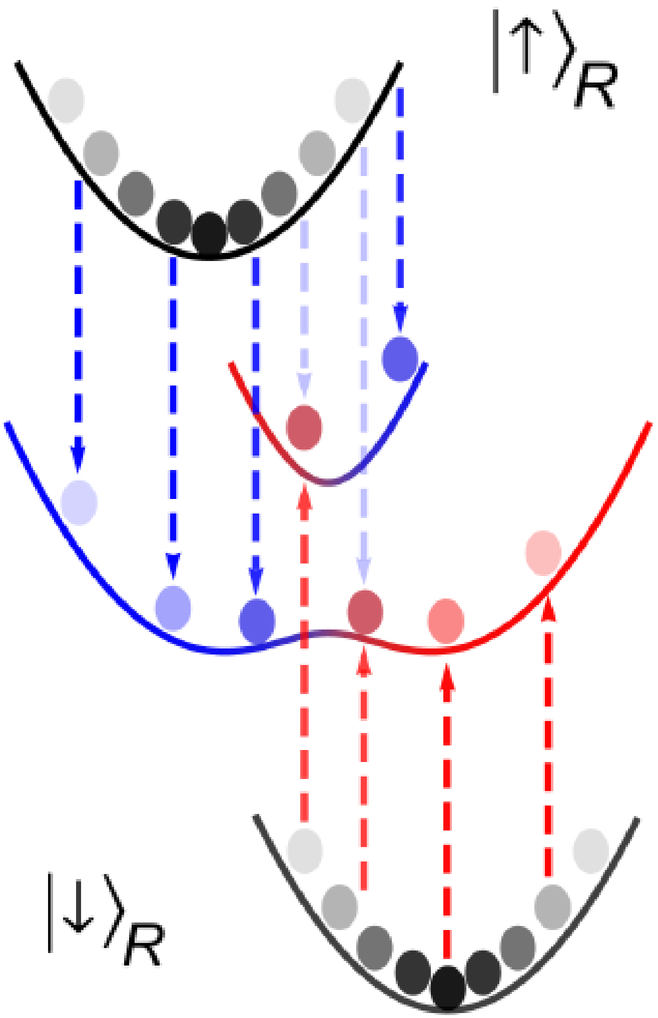
Can Topology be measured?

Spin-injection spectroscopy:

Measures spin, energy, momentum

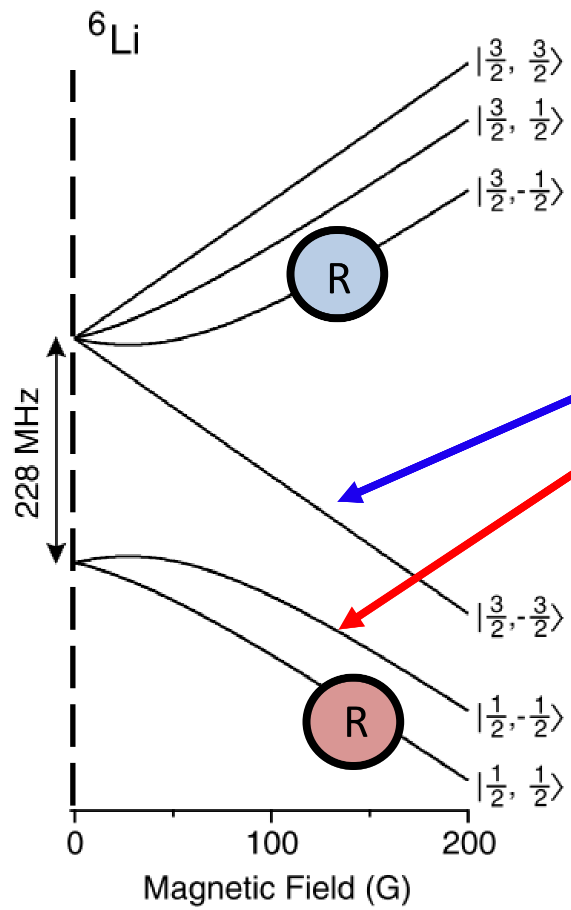
1. Inject atoms from “reservoir”
2. Project into free space
3. Spin-selective imaging

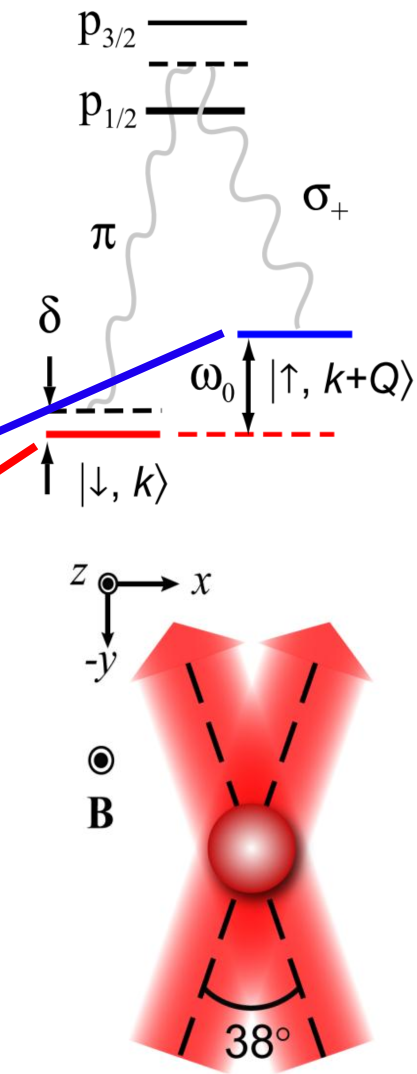
→ Reconstruct *E(k)* along with “color” of band



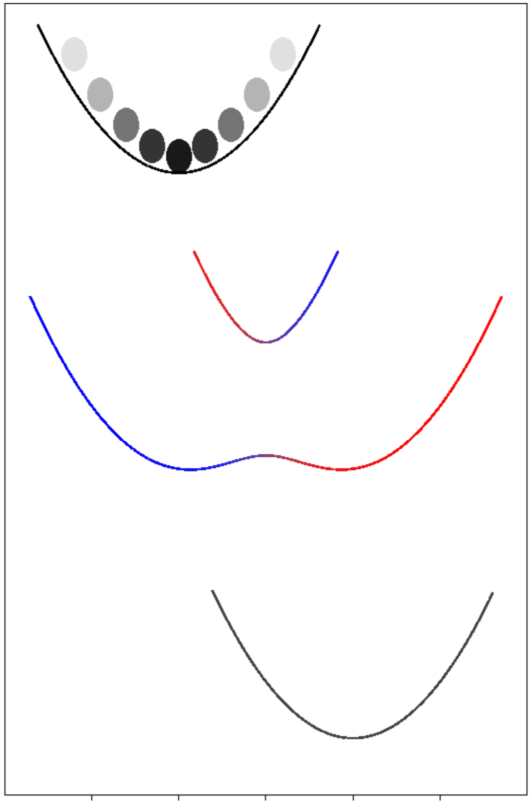
Experimental Setup

- 1^{st} and 4^{th} states used as reservoir states





Spin-injection spectroscopy



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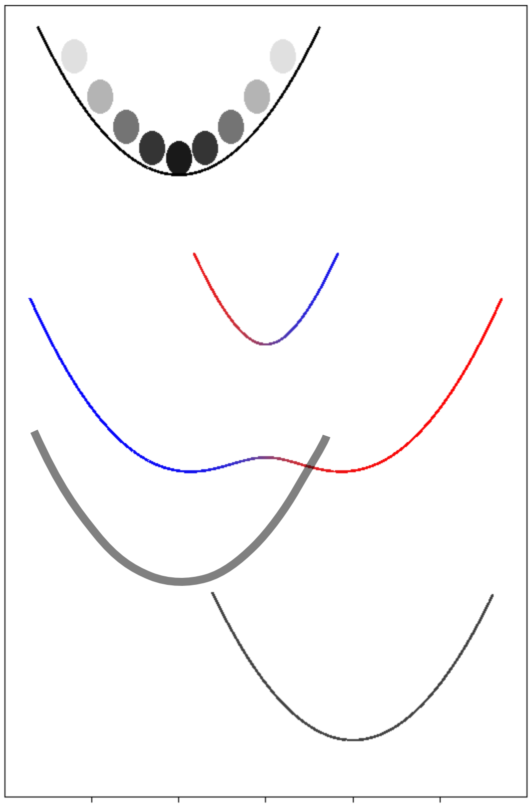

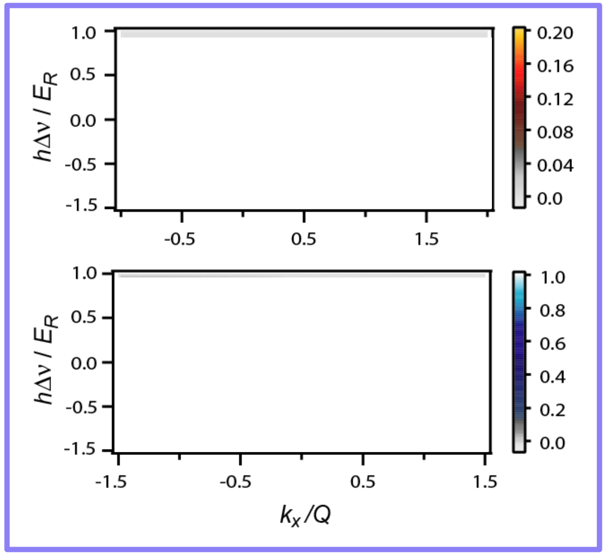

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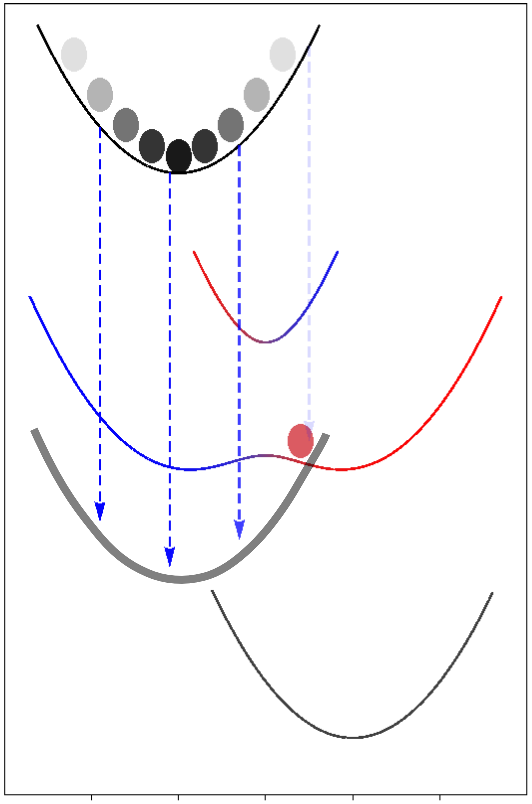

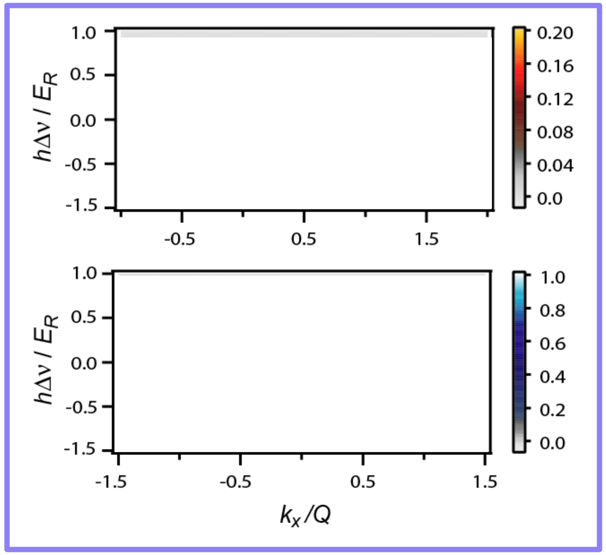

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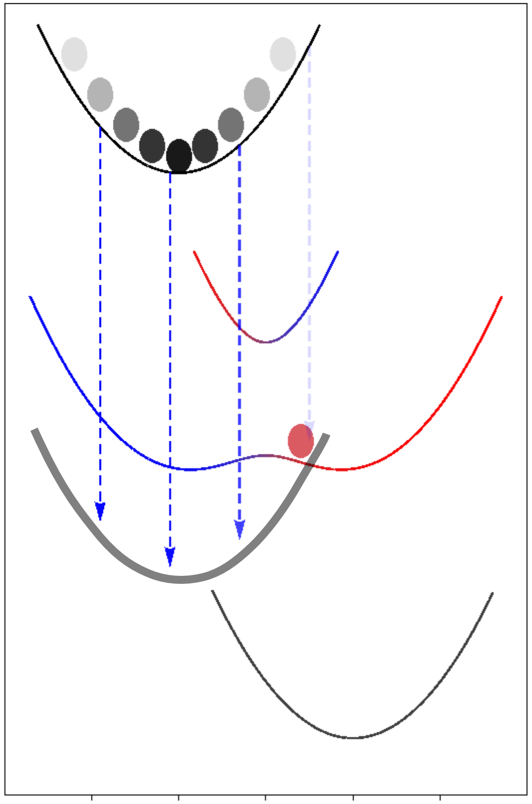

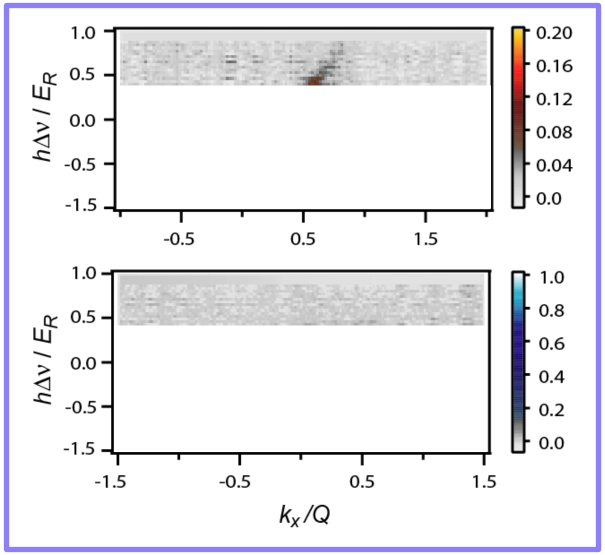

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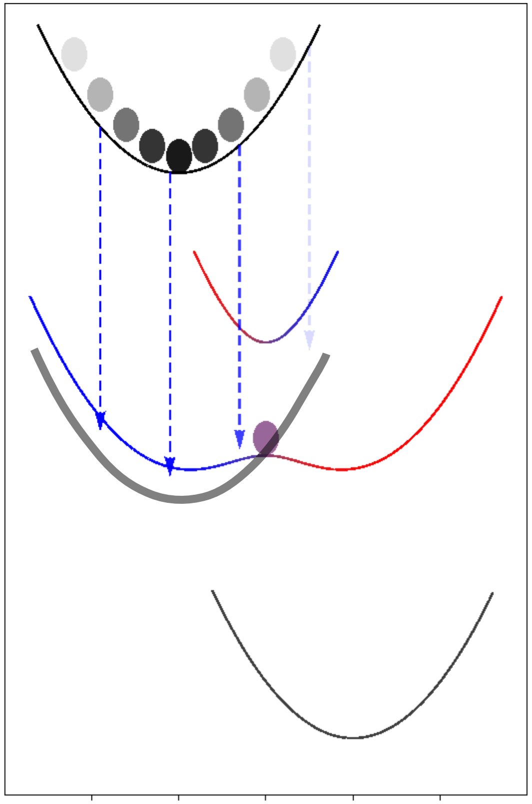

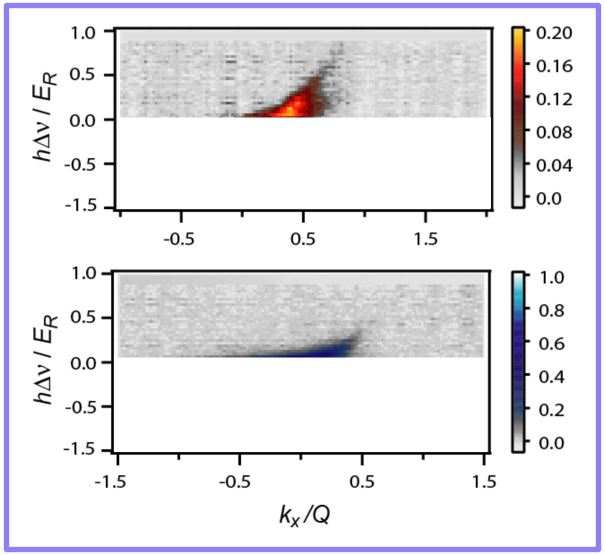

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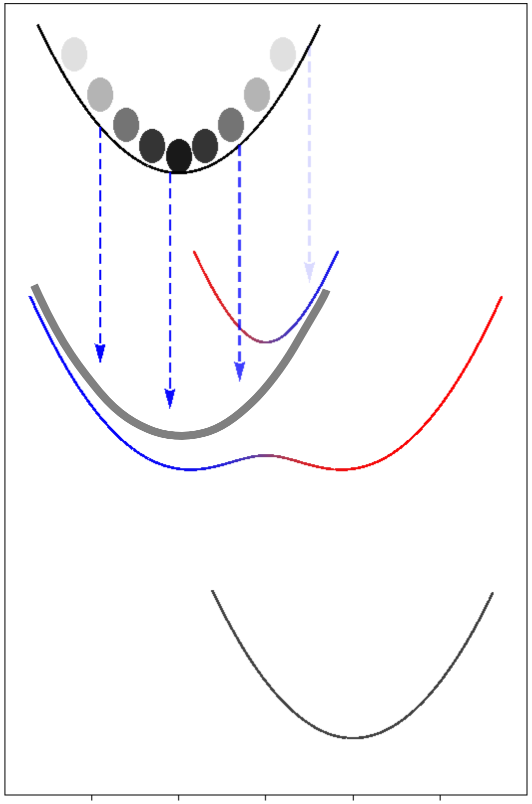

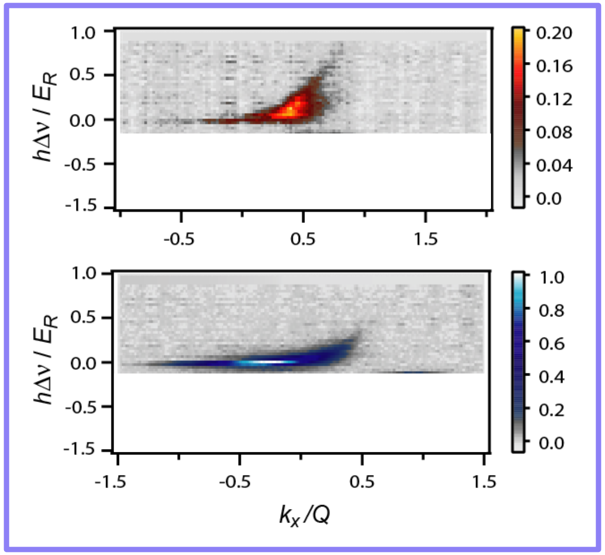

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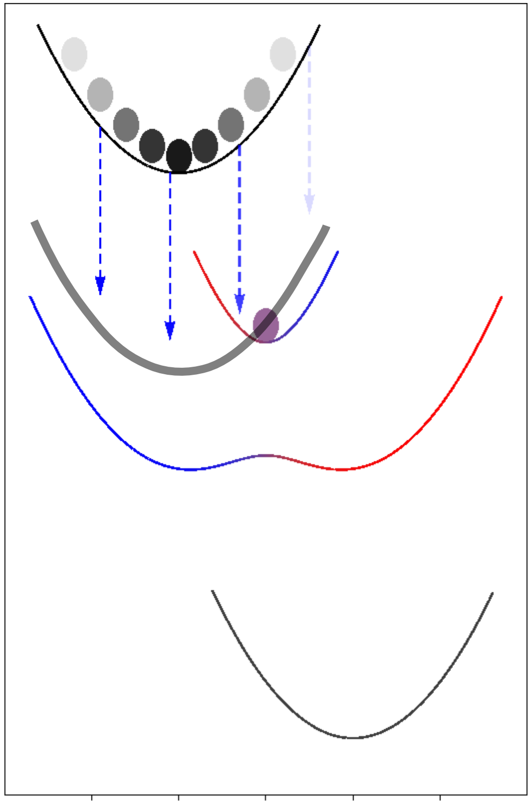

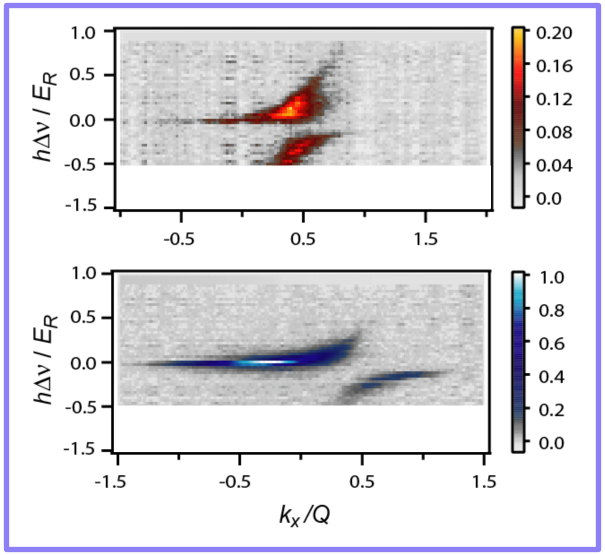

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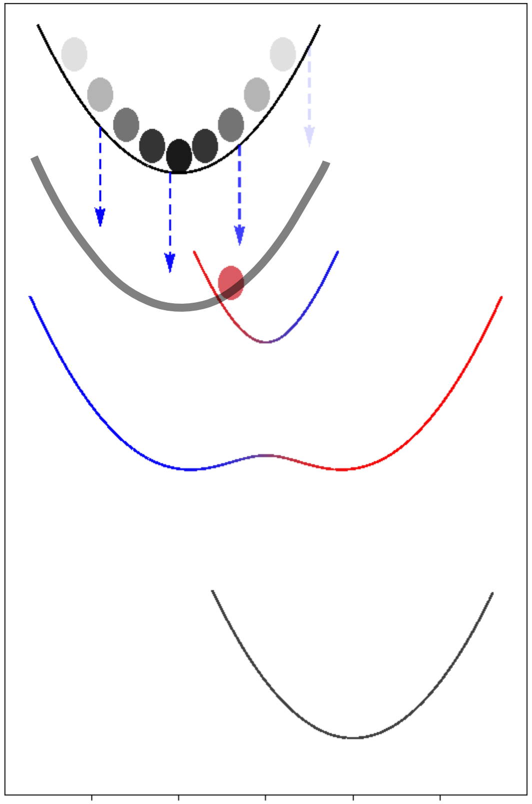

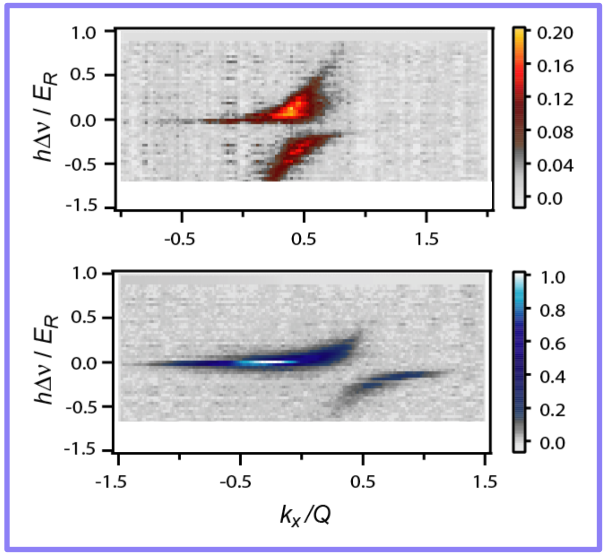

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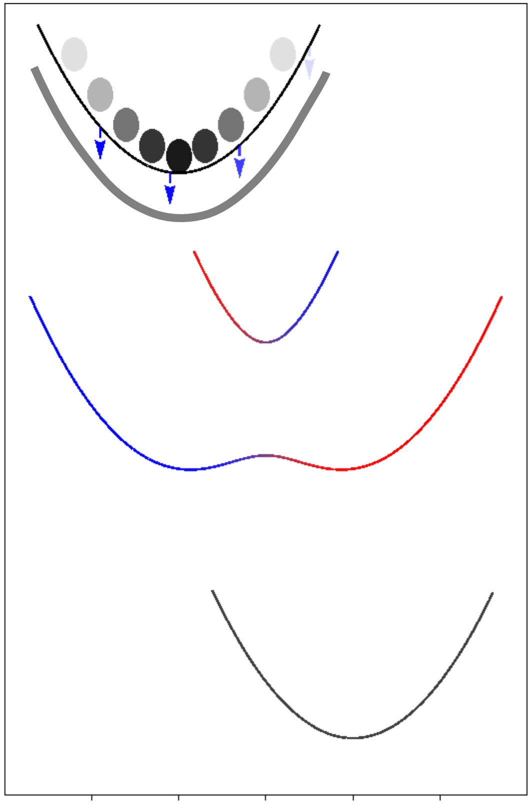

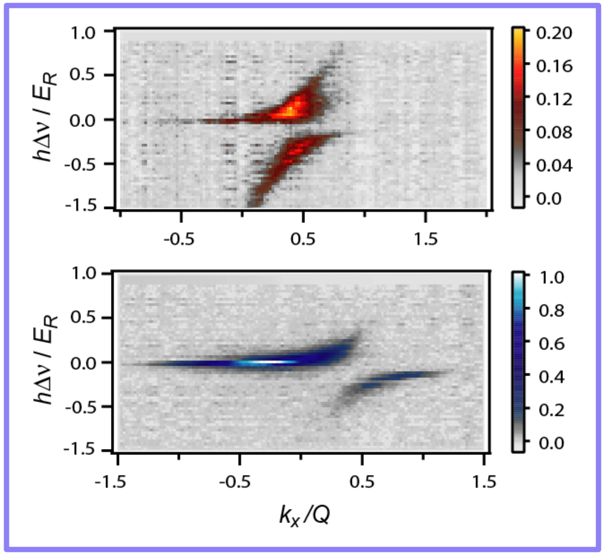

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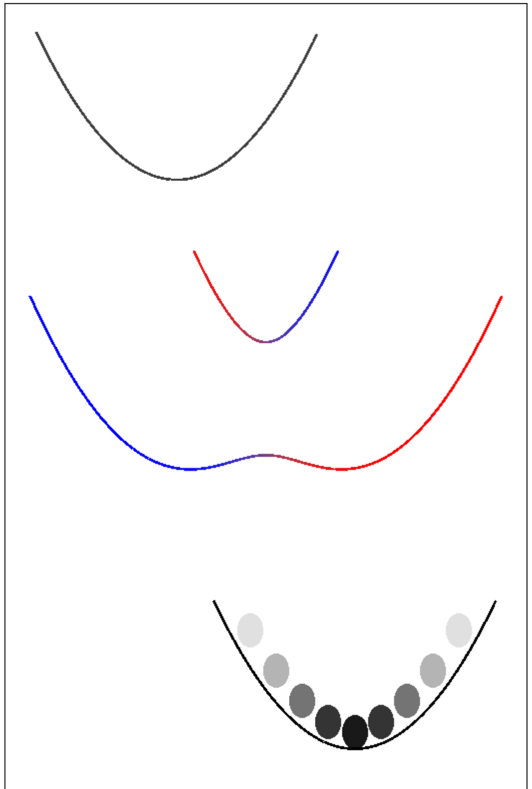

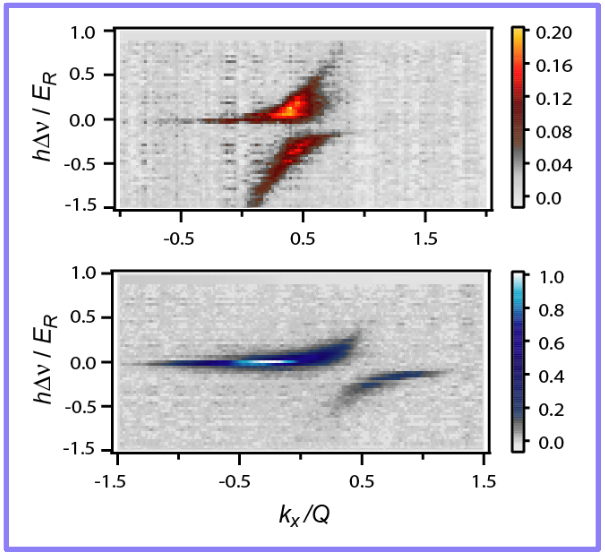

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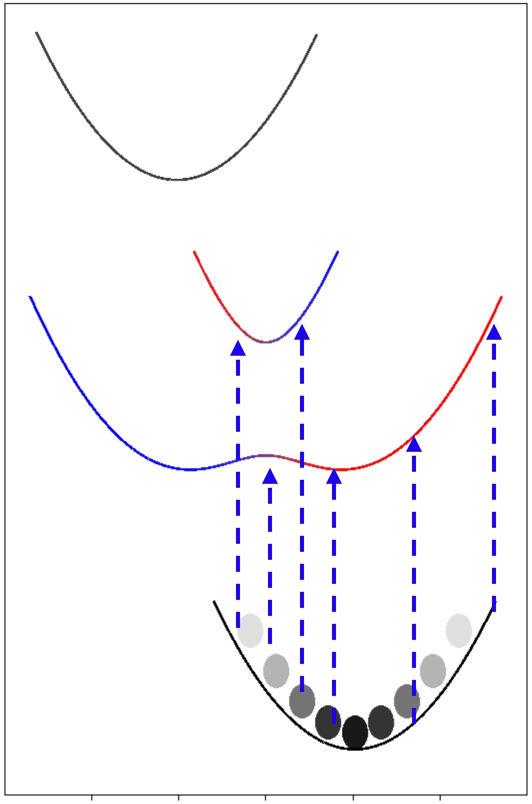

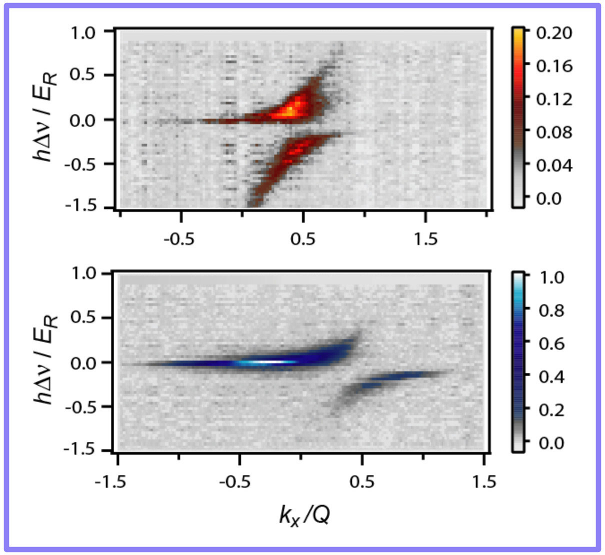

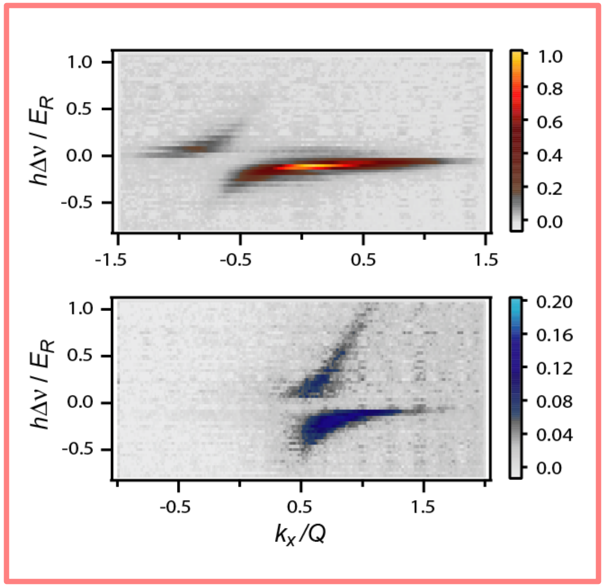

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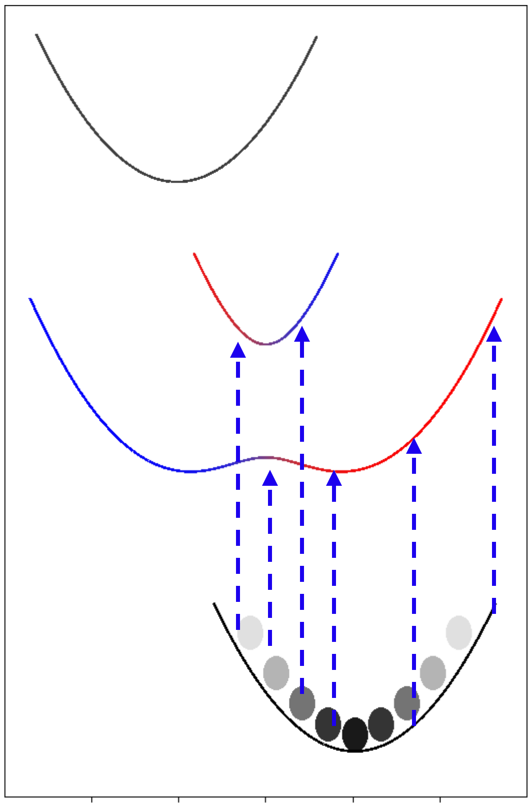

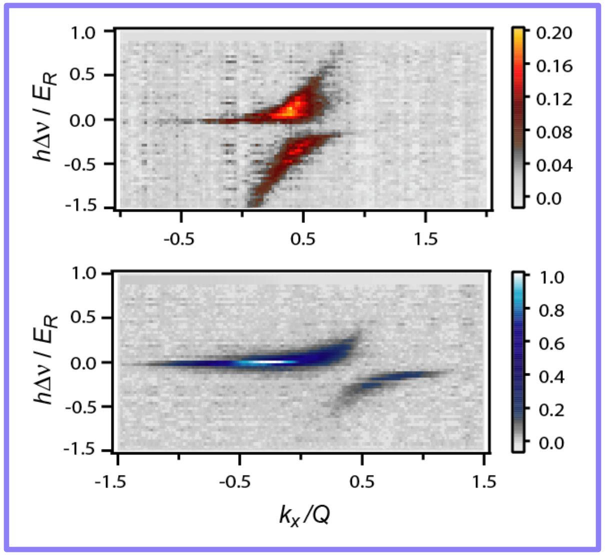

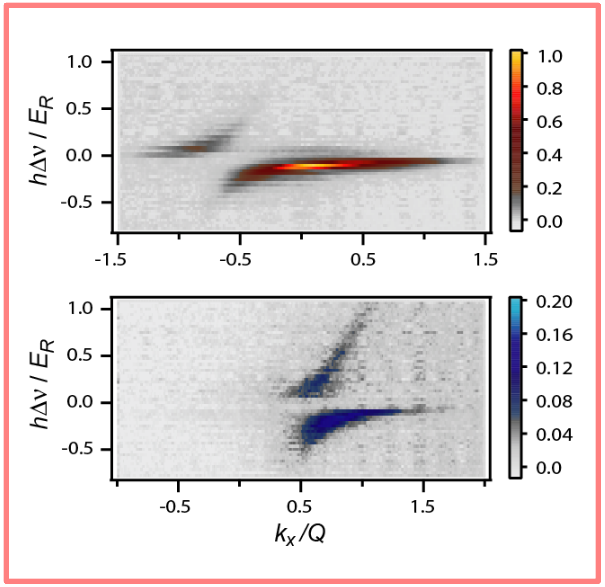

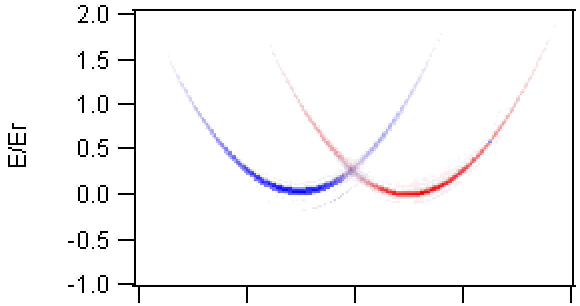

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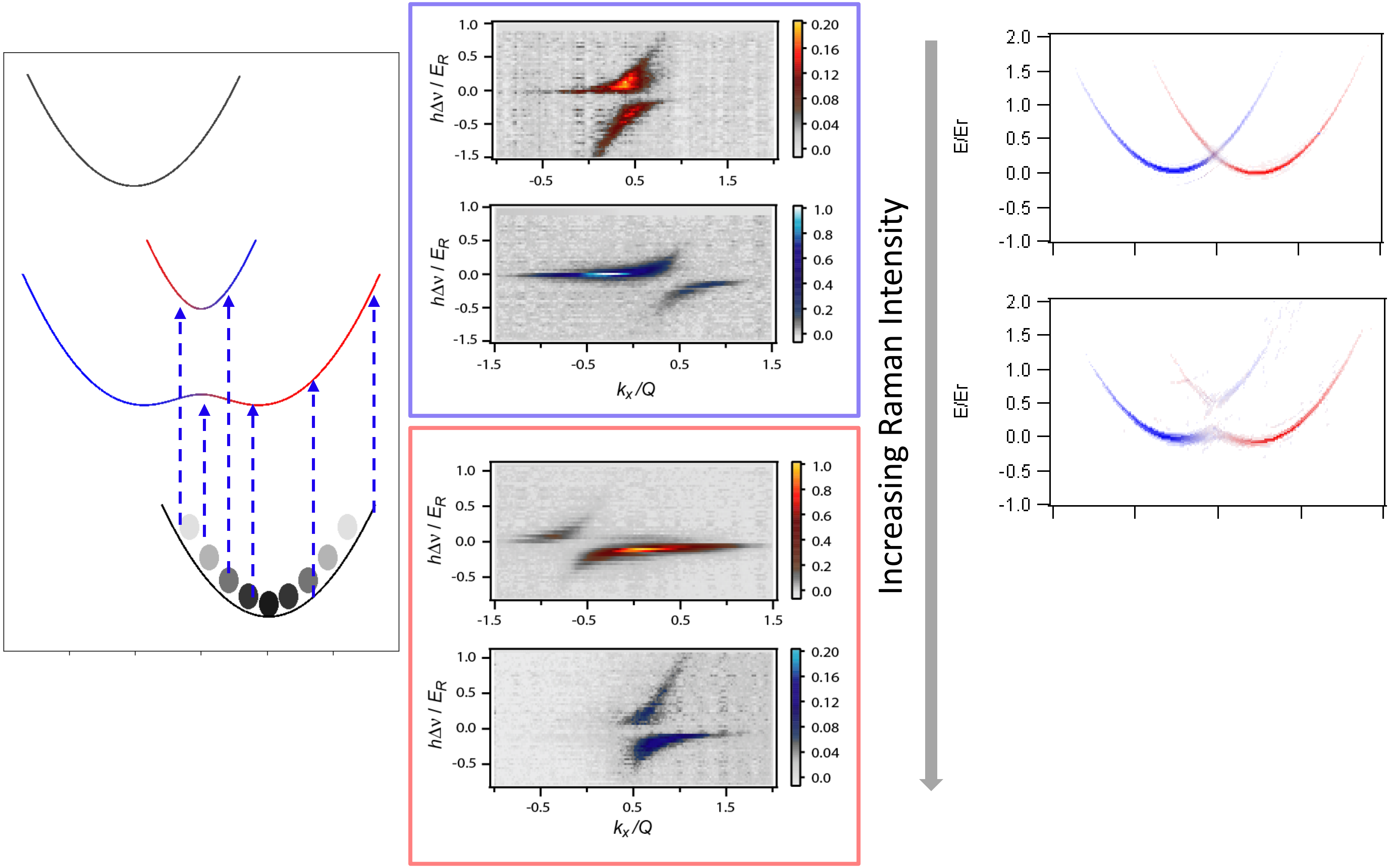

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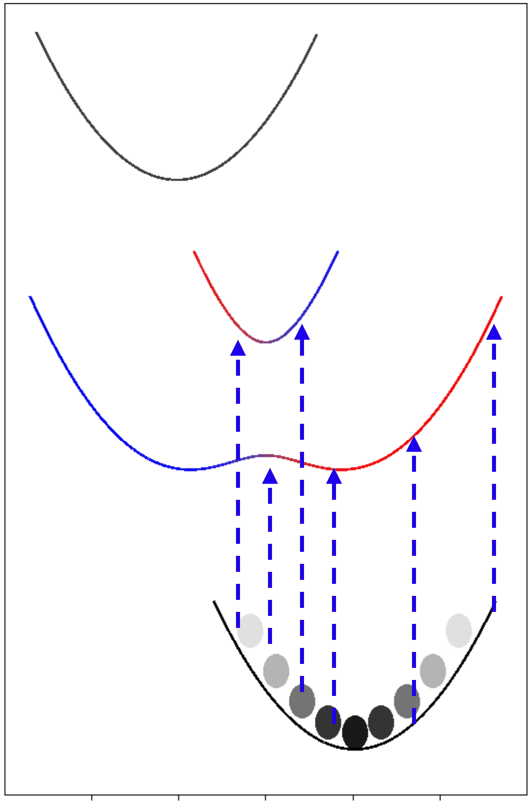
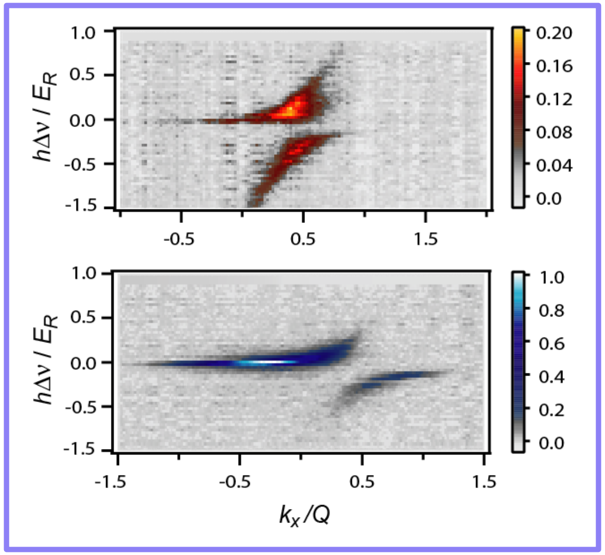
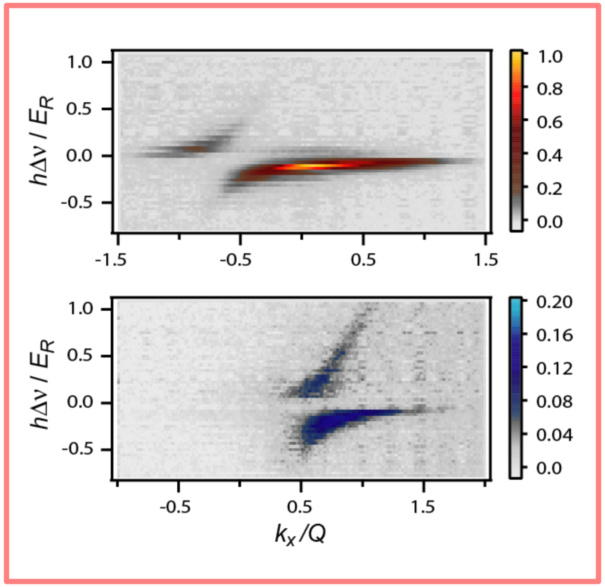
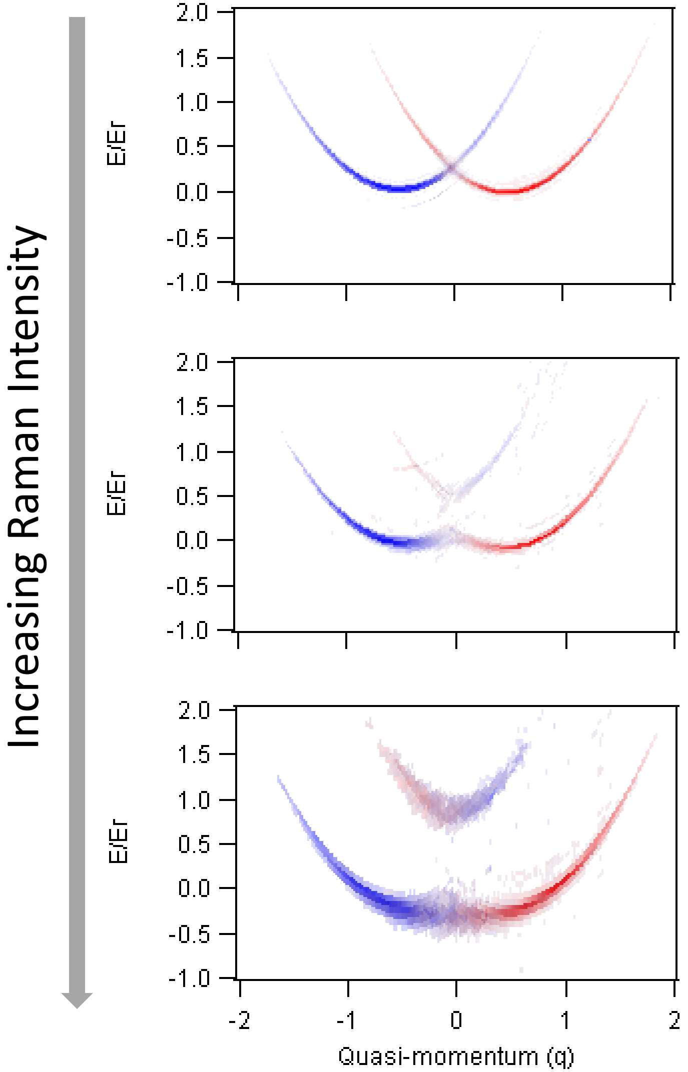


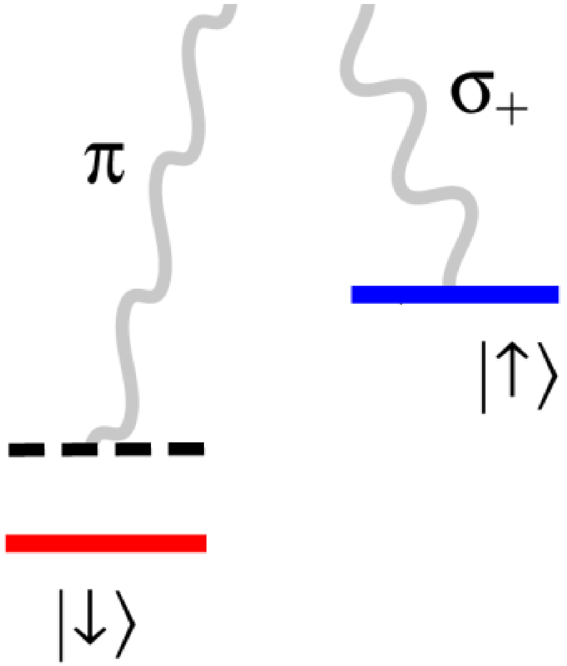


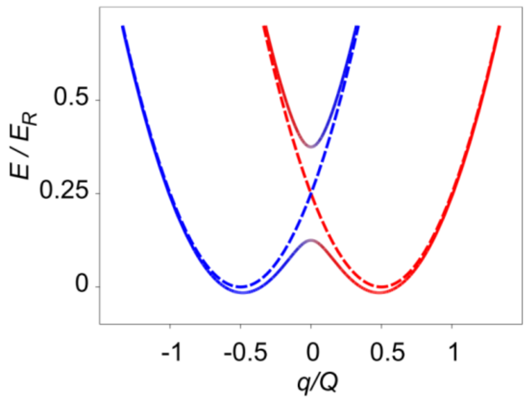




Creating a Spinful Lattice

- Add RF coupling -> lattice system with full bandgaps and spinful bands





K. Jimenez-Garcia et al **PRL 108,** 225303 (2012)

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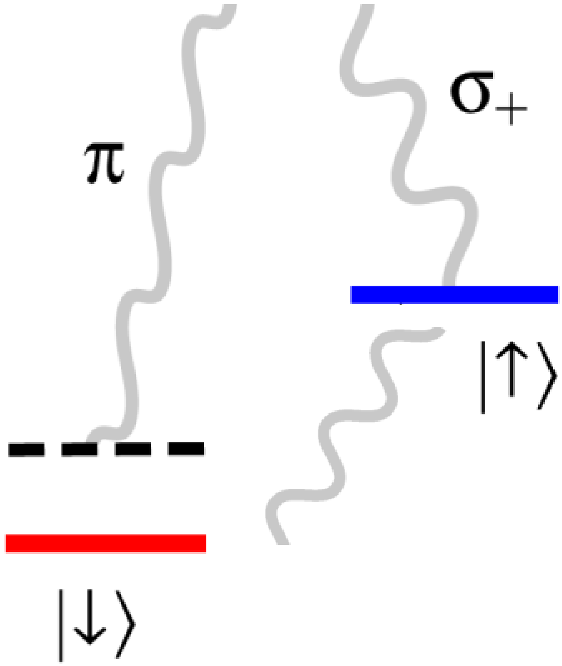
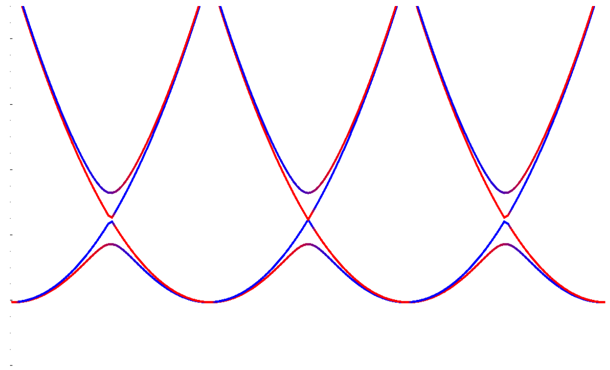


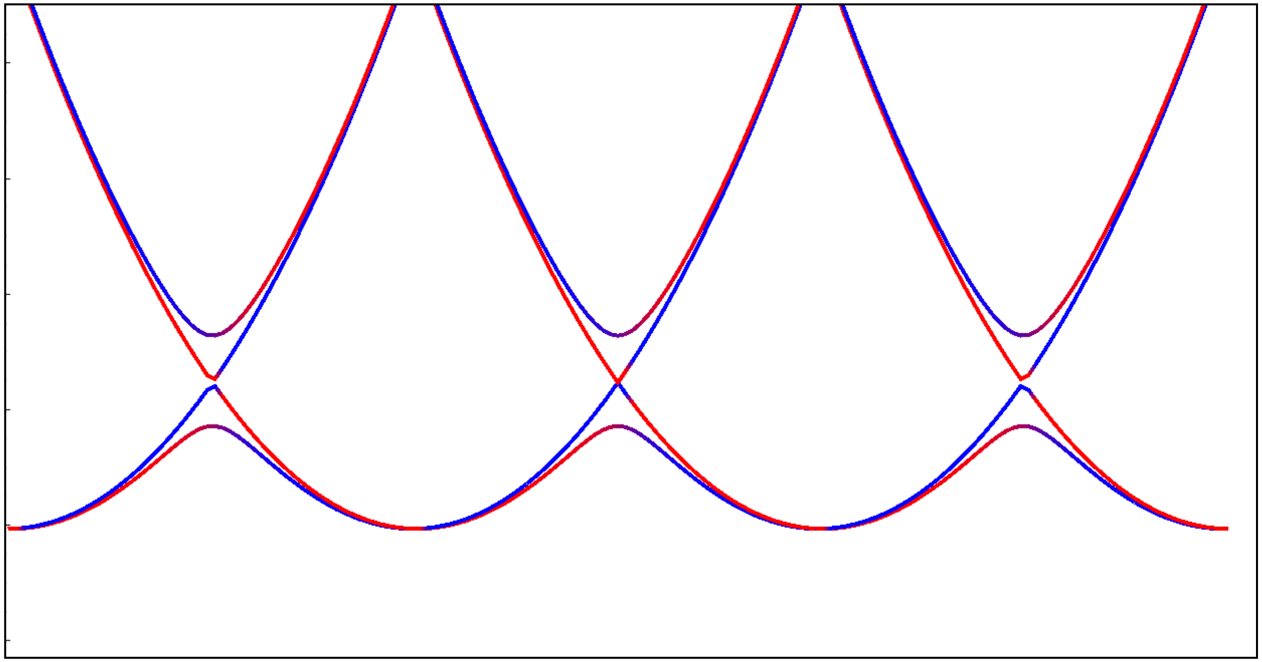


The Spin-Orbit band structure is periodically repeated

K. Jimenez-Garcia et al **PRL 108,** 225303 (2012)

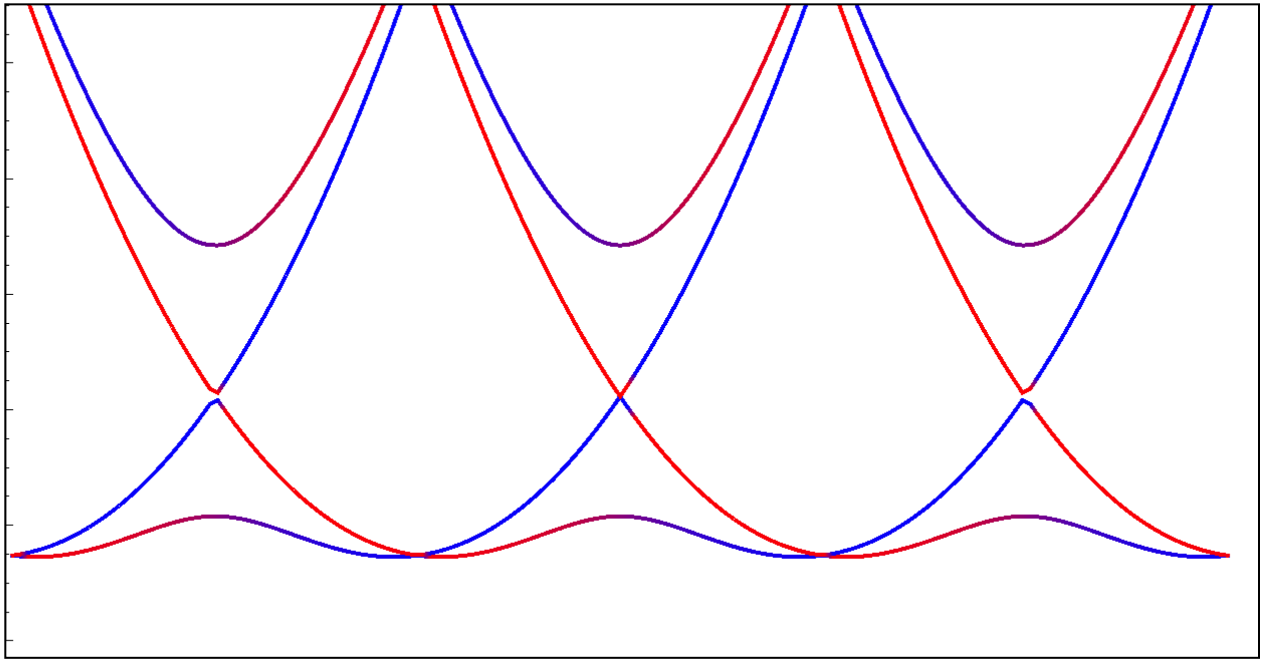
Bandstructure of Raman + RF lattice

- In repeated scheme



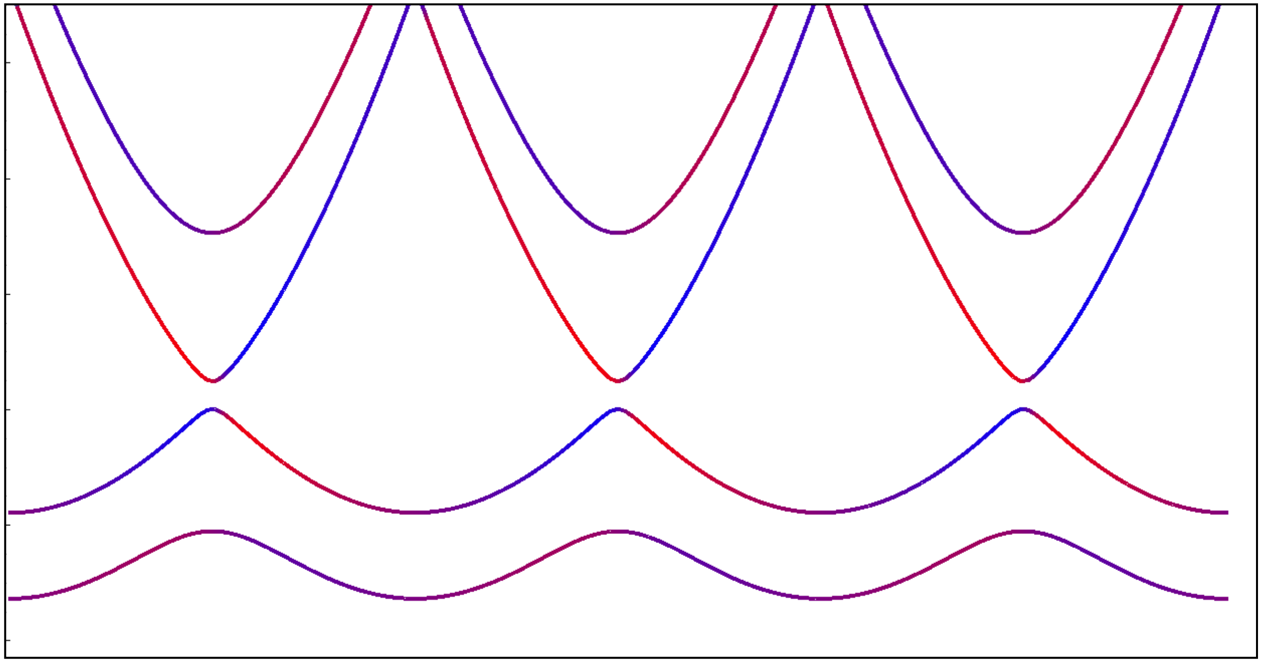
Bandstructure of Raman + RF lattice

- Degenerate point inside spin orbit gap



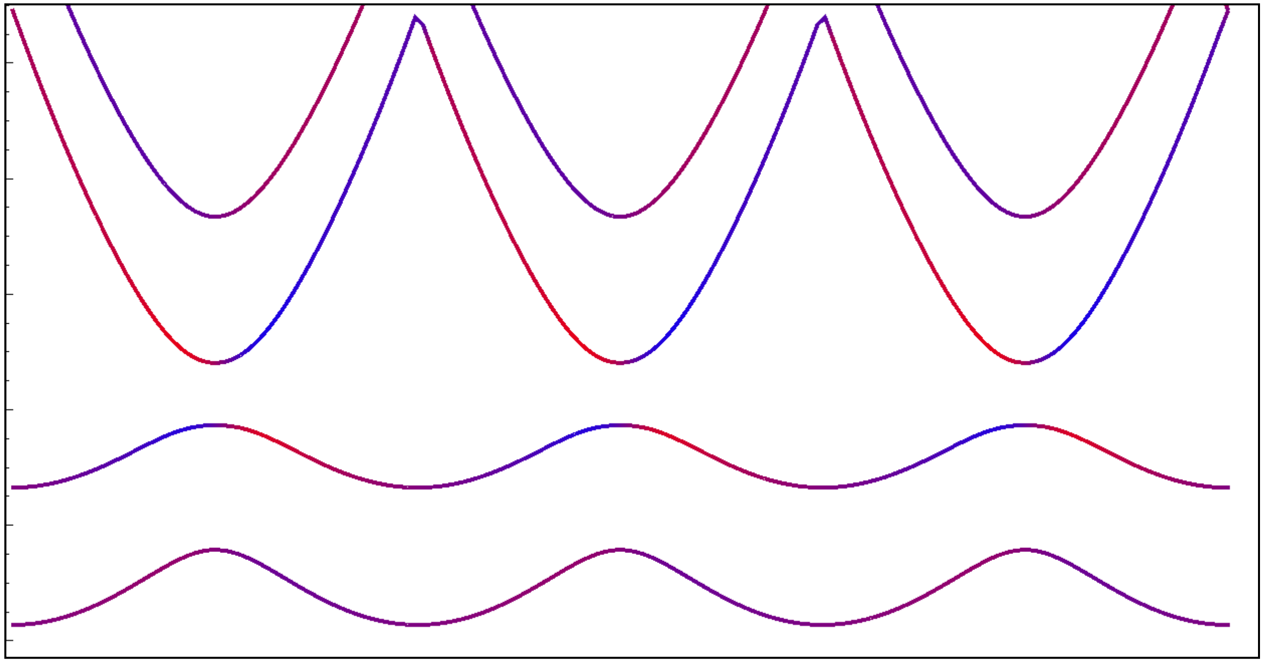
Bandstructure of Raman + RF lattice

- Bandgap opens between 2nd and 3rd band



Bandstructure of Raman + RF lattice

- Larger RF, gap between lowest bands



Spin-injection Spectra

Increasing Raman Intensity

$\hbar\Omega_R/E_R$

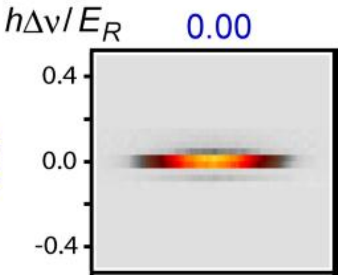
Increasing RF Intensity

$\hbar\Omega_{RF}/E_R$

0.00

0.11

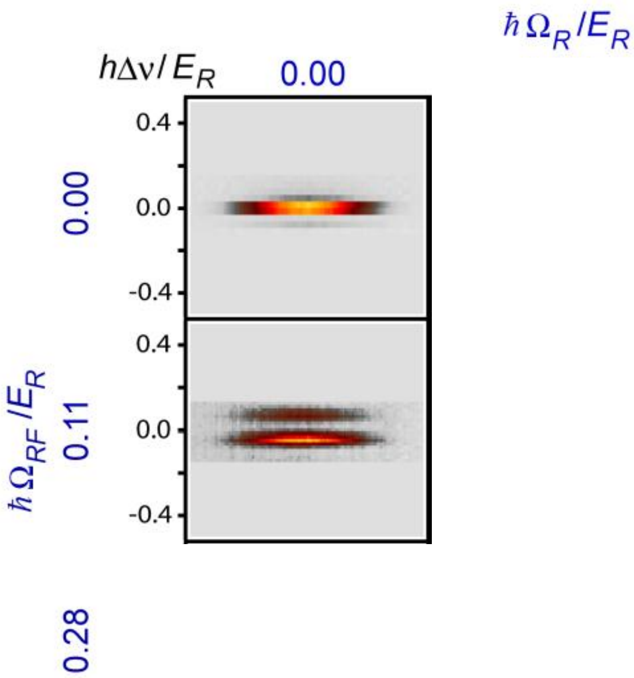
0.28



Spin-injection Spectra

Increasing Raman Intensity

Increasing RF Intensity



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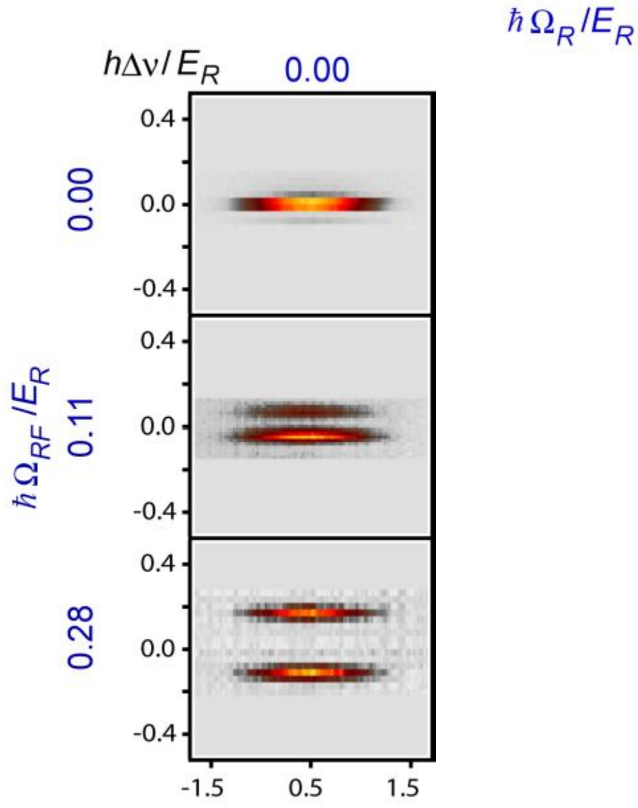

Spin-injection Spectra

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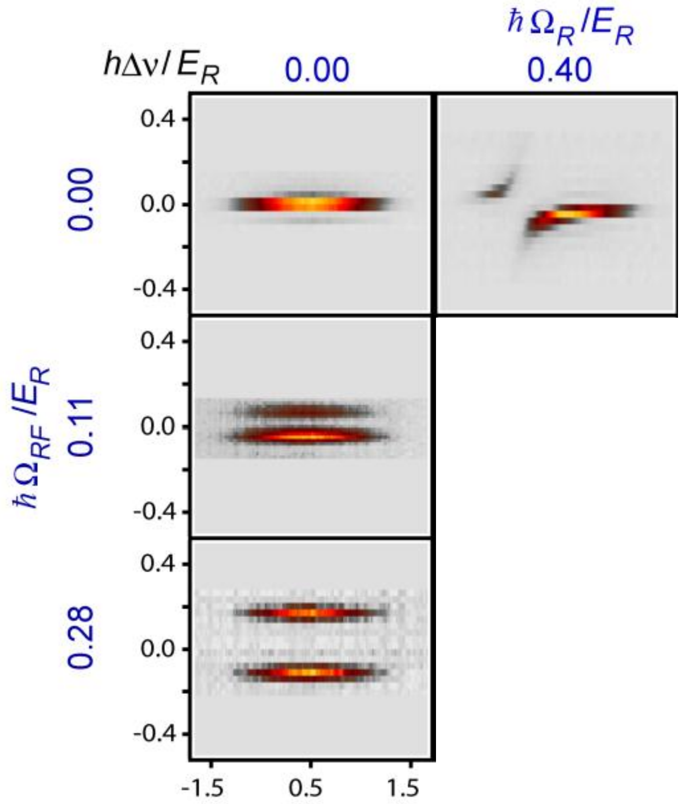

Spin-injection Spectra

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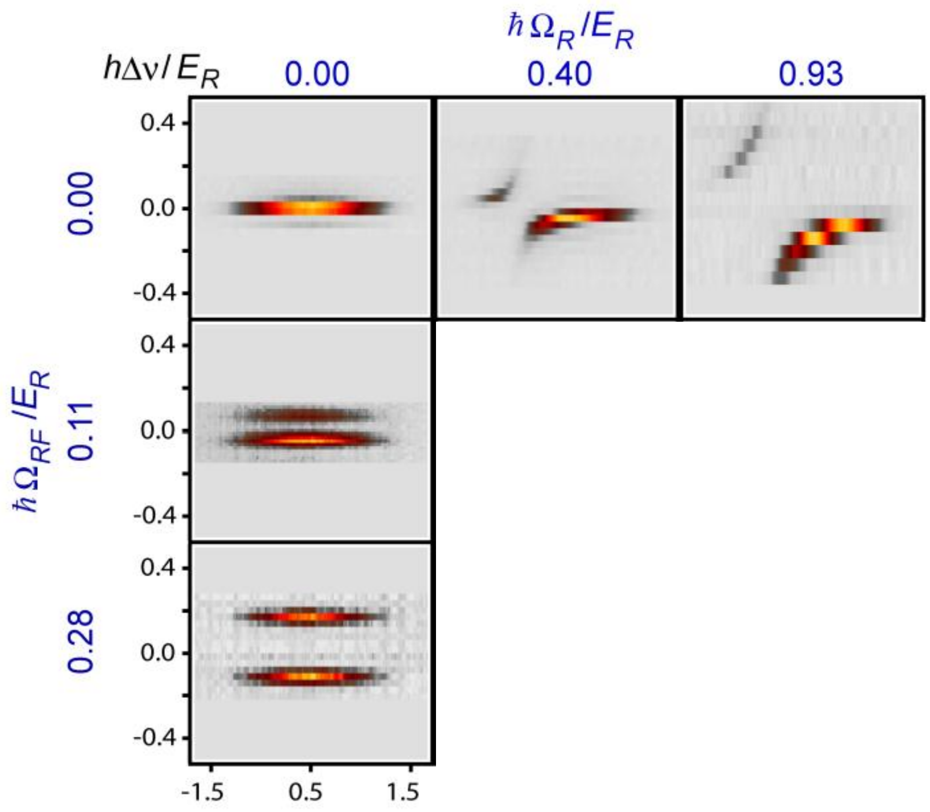

Spin-injection Spectra

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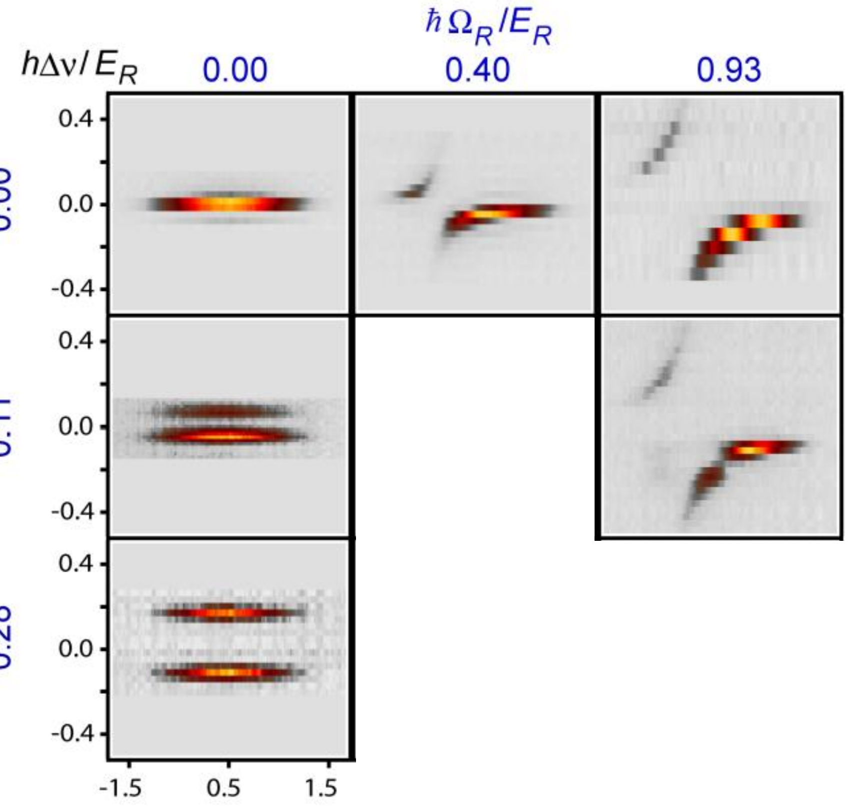
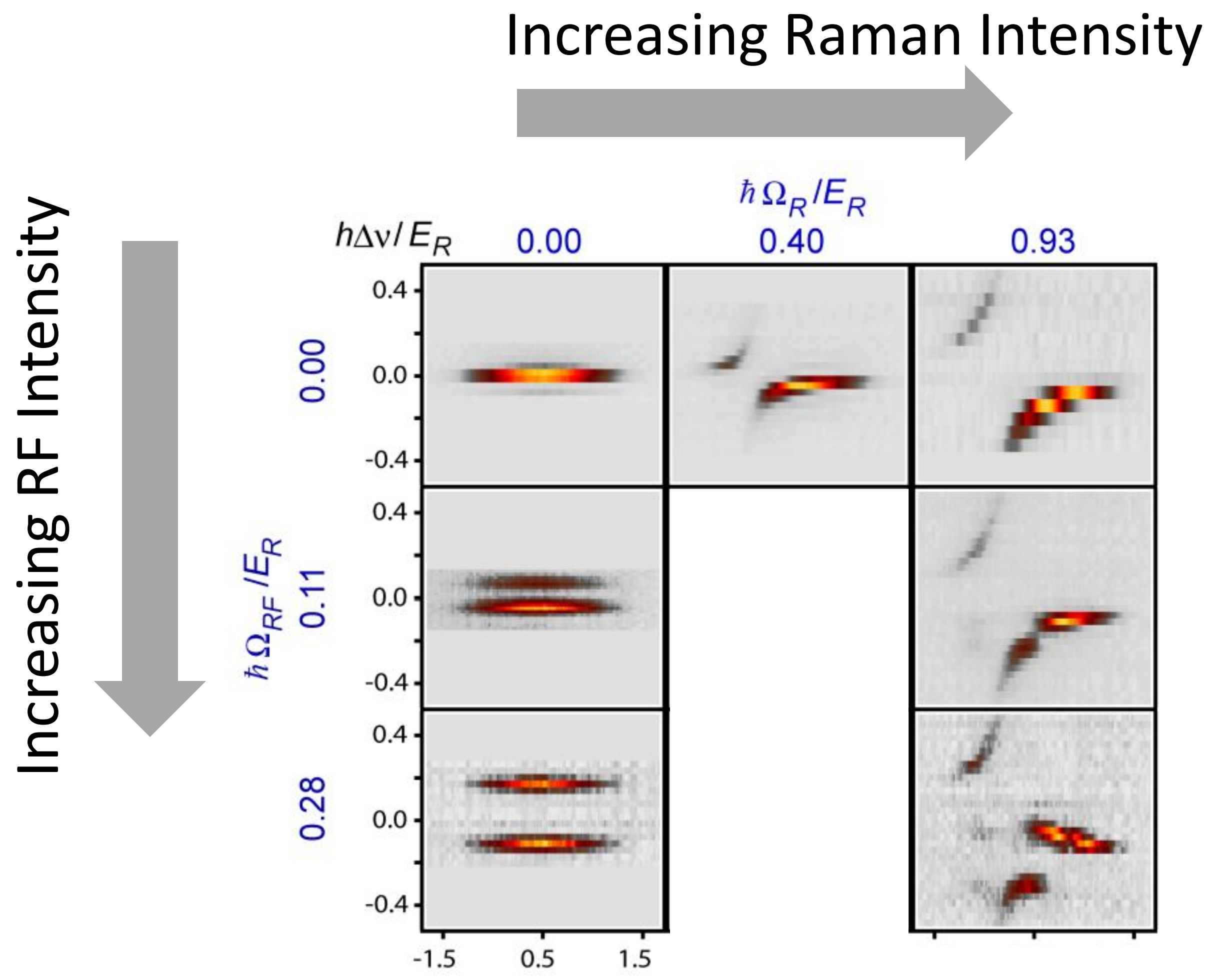


Spin-injection Spectra



Spin-injection Spectra

Increasing Raman Intensity

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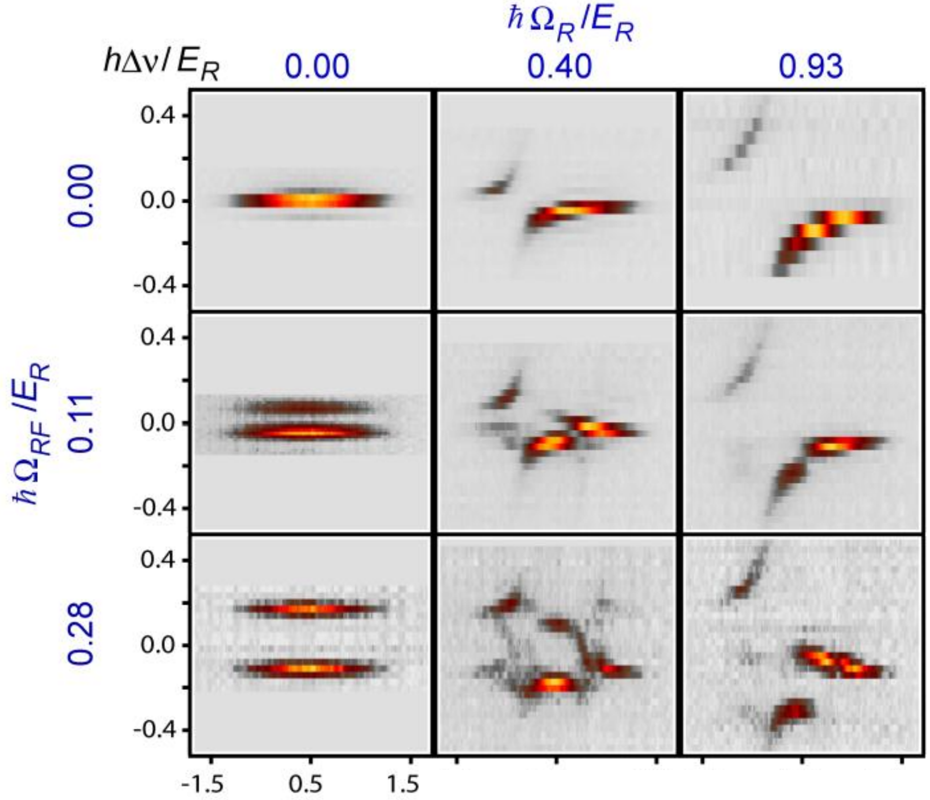
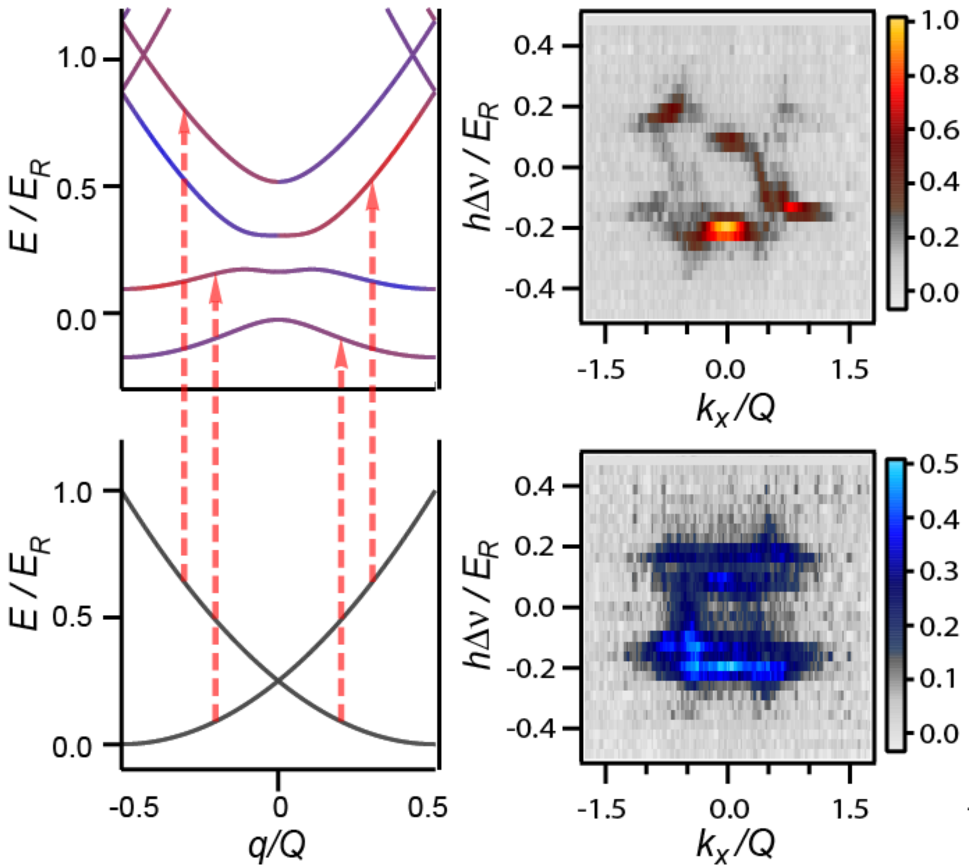
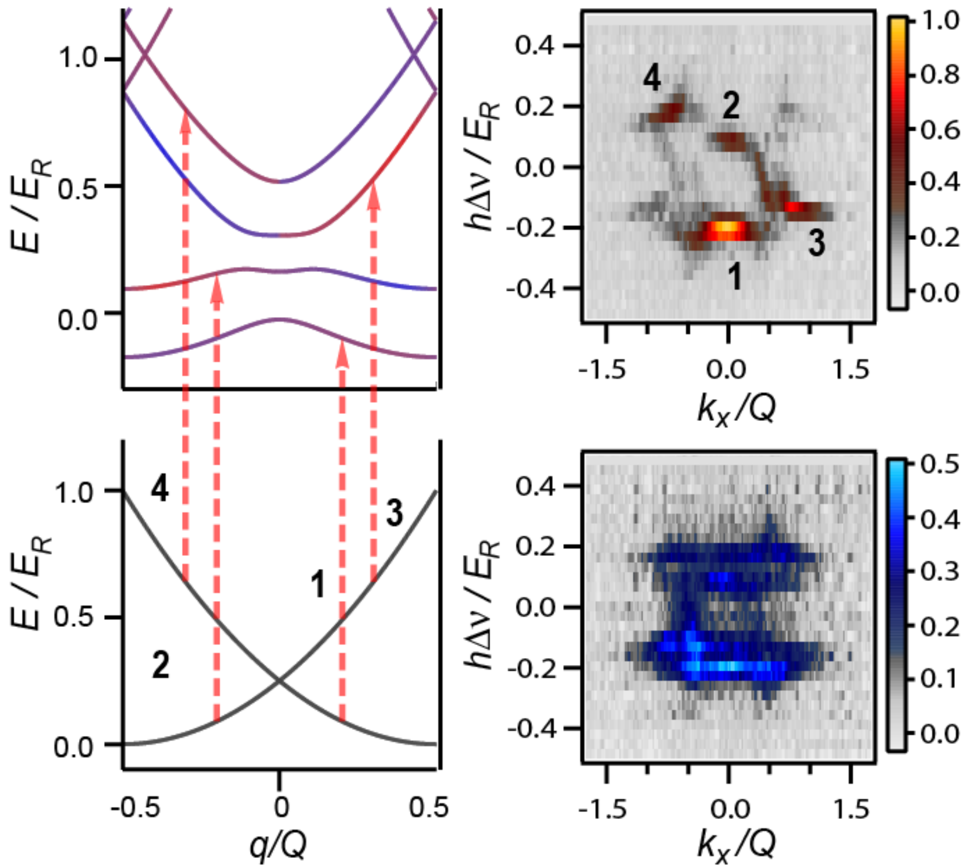


Spin-injection Spectra

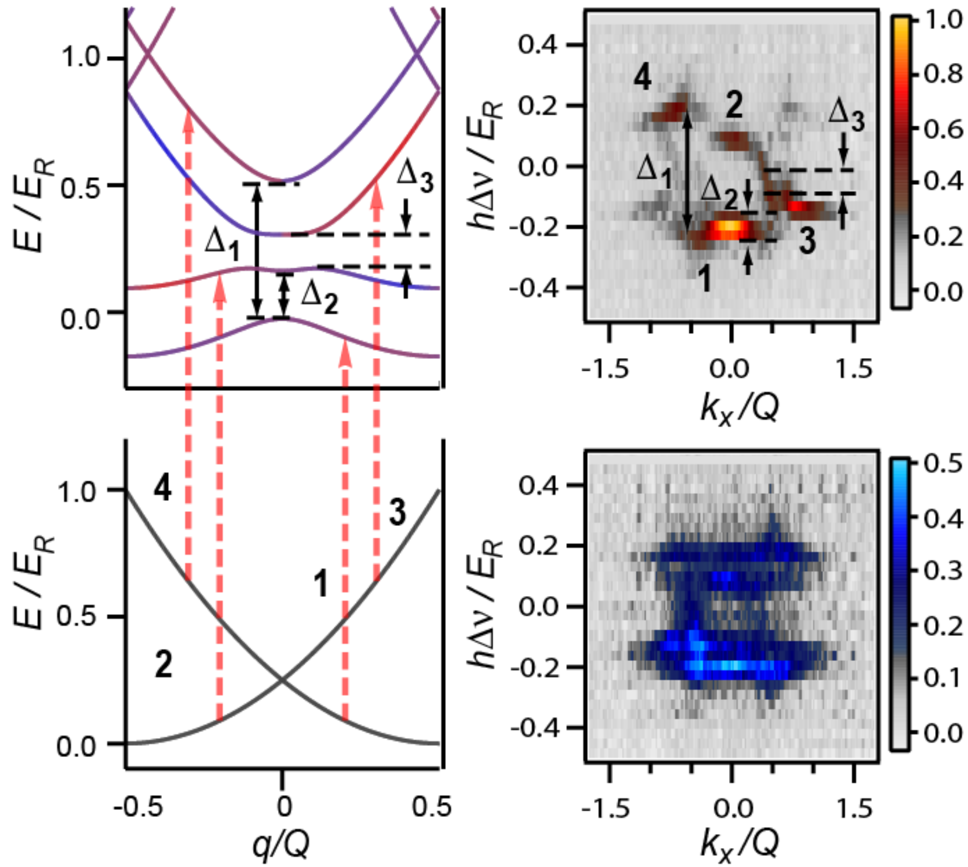


Spin-injection Spectra



Tarik Yefsah, Ens, July 20, 2012

Spin-injection Spectra



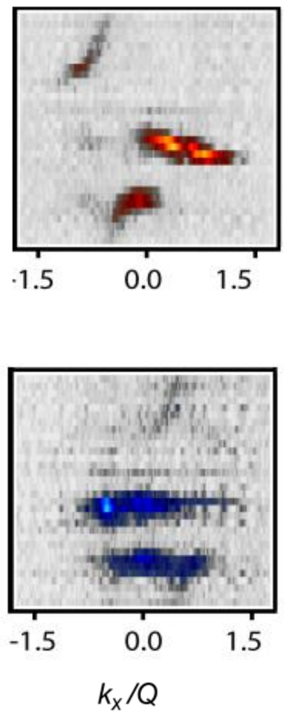
Δ_1 → Raman gap

Δ_2 → RF gap

Δ_3 → Raman + RF gap

Reconstructing the Bandstructure

- In addition to dispersion, can reconstruct eigenstates
- TOF gives eigenstate in the basis of free space spin/momentum states



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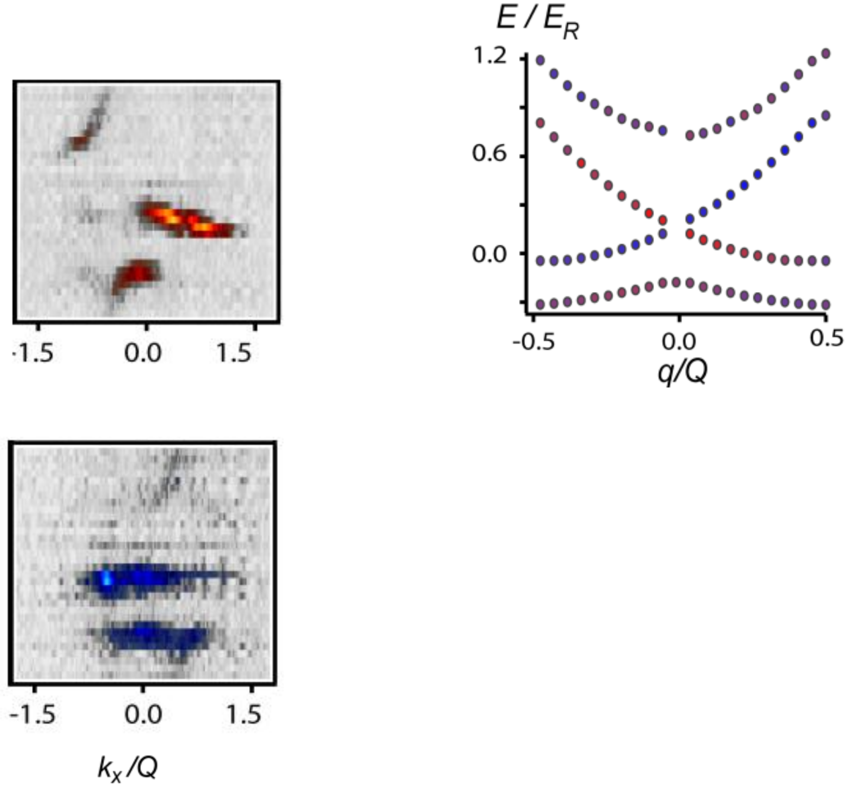

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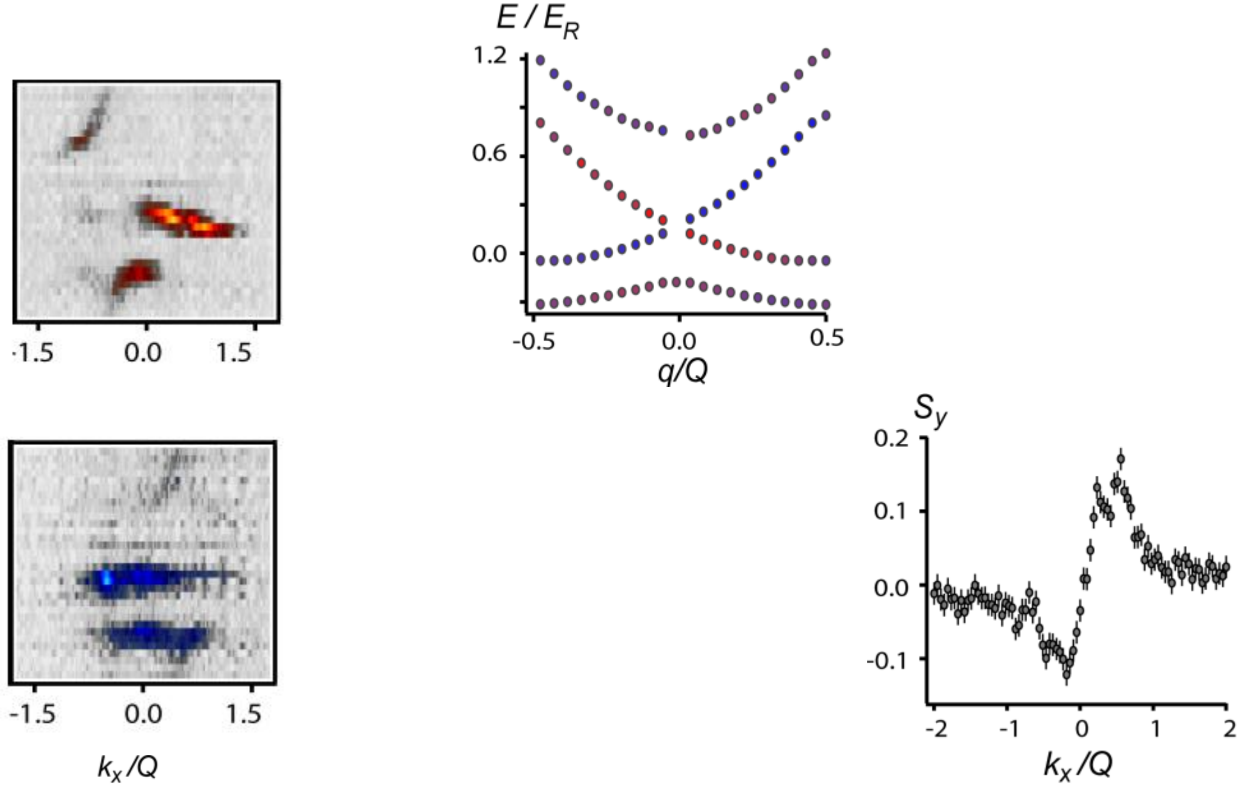

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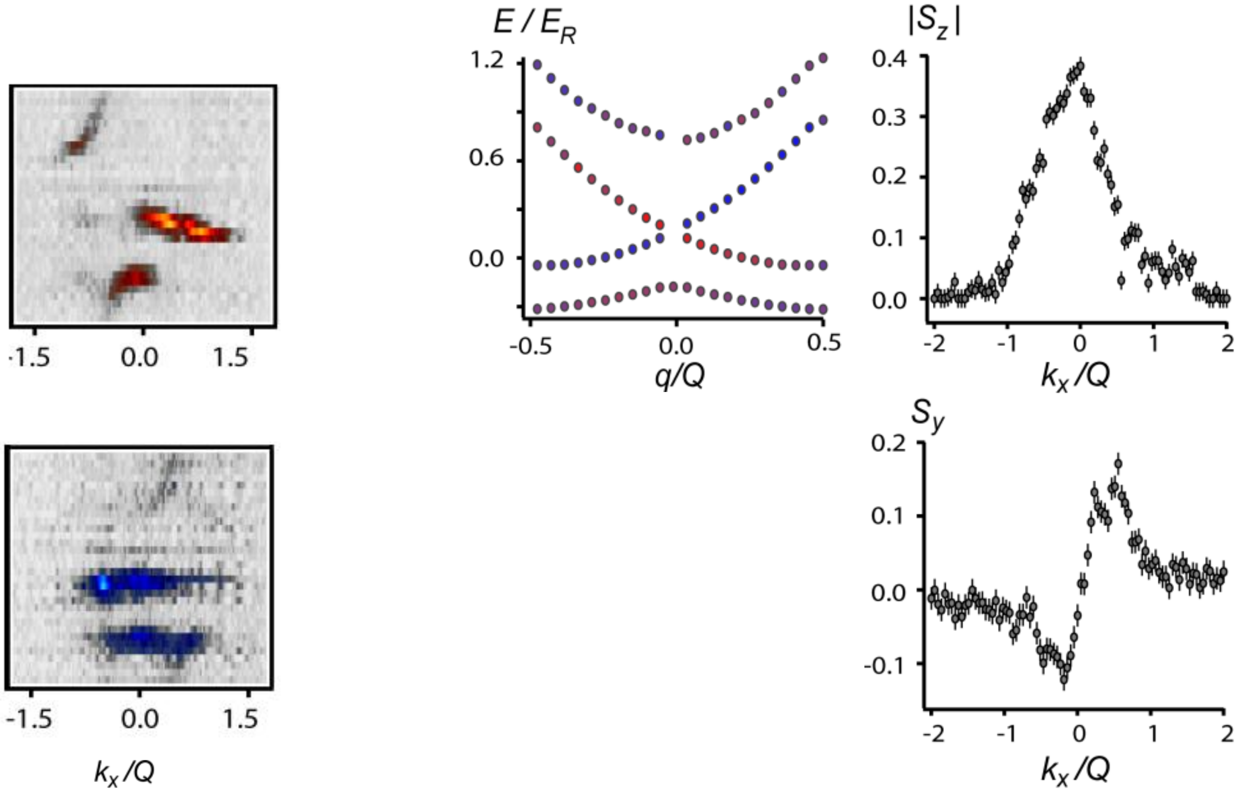

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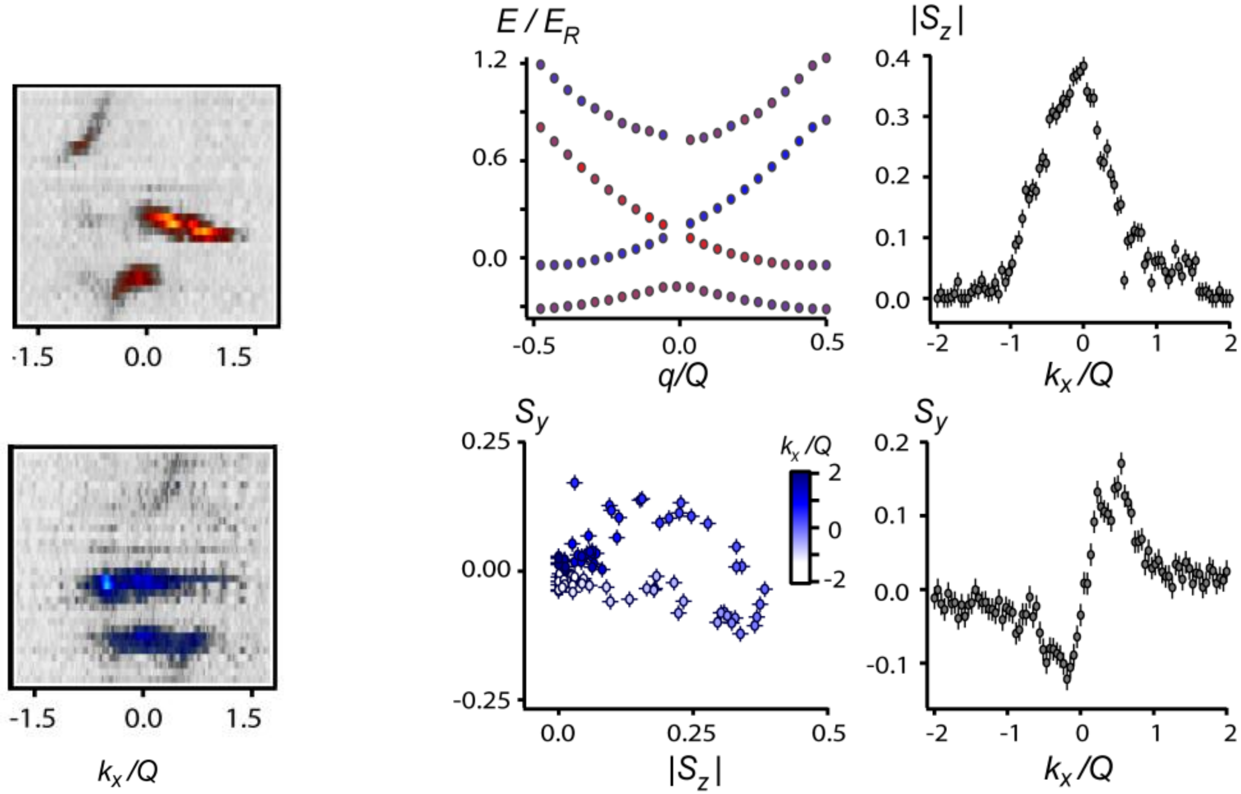
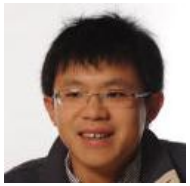


Summary and Outlook

- Summary:
  - SO-coupled Fermi gas
  - Spinful lattice
  - Spin-injection spectroscopy
  - Band and eigenstate reconstruction
- Future:
  - Interactions : p-wave
  - Pairing in 1D tubes : Majorana edge mode ?

For details see:
L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Y, W. Bakr, M. W. Zwierlein, **arXiv:1205.3483**

Collaborators



Lawrence Cheuk

Ariel Sommer

Zoran Hadzibabic

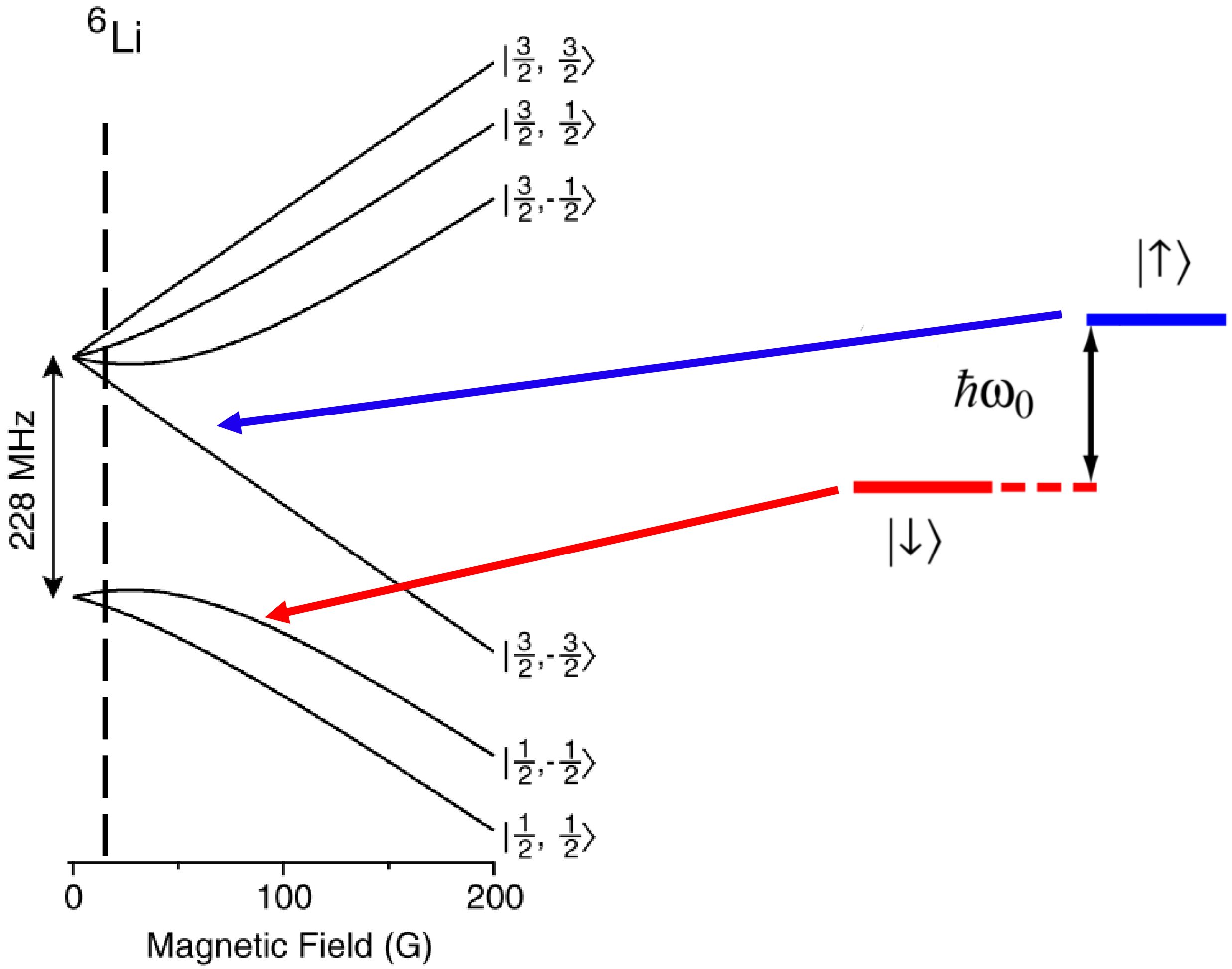
Waseem Bakr

Martin Zwierlein

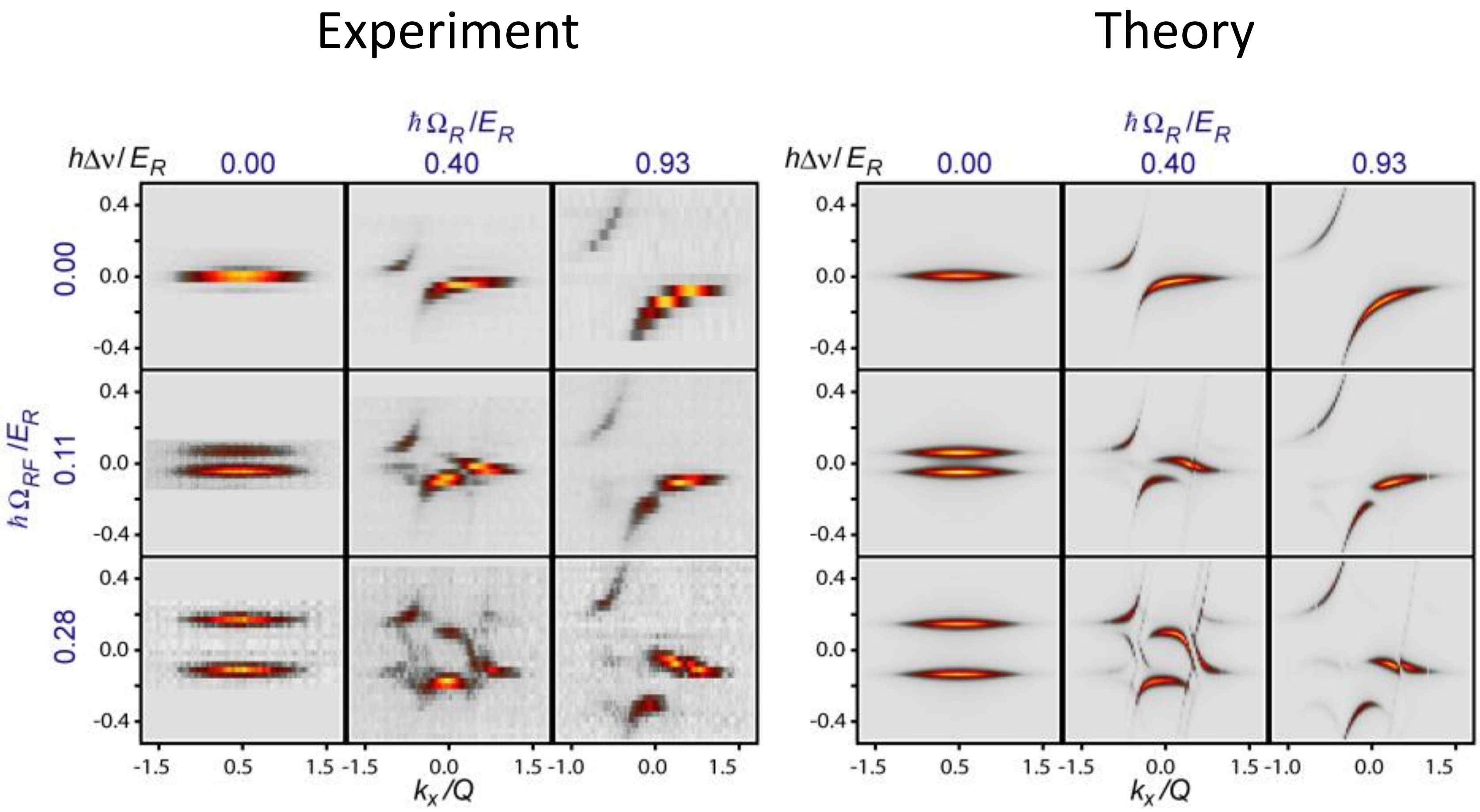
We thank these organizations for their support: DARPA, NSF, ONR, AFOSR, Sloan Foundation

Experimental Setup

- Fermionic ^{6}Li atoms sympathetically cooled by ^{23}Na
- Relevant states are 2nd and 3rd lowest states at 11G



Spin-injection spectroscopy



SO-coupling in a Fermi gas

- Direct demonstration of SO-coupling through Rabi oscillations
- Controlled adiabatic loading of SO-coupled bands.
- Reversibility of loading shows adiabaticity.

The spin-orbit Hamiltonian

- The SO Hamiltonian

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

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

- Raman Coupling Hamiltonian

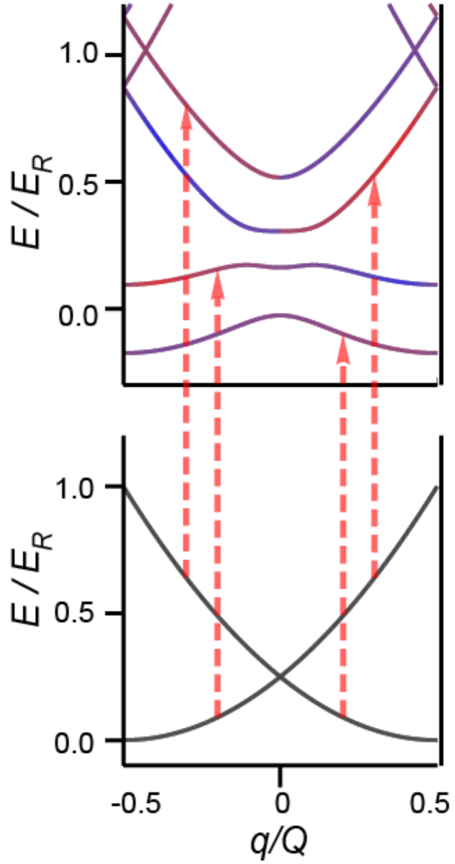
$$\mathcal{H}_{SO} = \begin{pmatrix} \frac{\hbar^2 k^2}{2m} + \frac{\delta}{2} & \frac{\hbar\Omega_R}{2} \\ \frac{\hbar\Omega_R}{2} & \frac{\hbar^2 (k+Q)^2}{2m} - \frac{\delta}{2} \end{pmatrix}$$

maps to 1D spin-orbit Hamiltonian with

$$\alpha = \beta = \frac{\hbar^2 Q}{2mg\mu_B} \qquad B_z^{(Z)} = \hbar\Omega_R / g\mu_B \qquad B_y^{(Z)} = \hbar\delta / g\mu_B$$

Spin-injection spectroscopy

- Spin-injection spectroscopy on a spinful lattice



The spin-orbit Hamiltonian

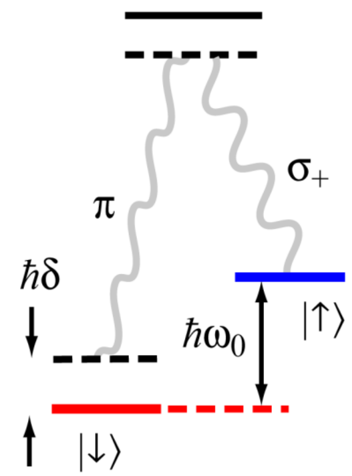
- Raman coupled atomic system maps to SO Hamiltonian.
- Rotating-Frame approximation:

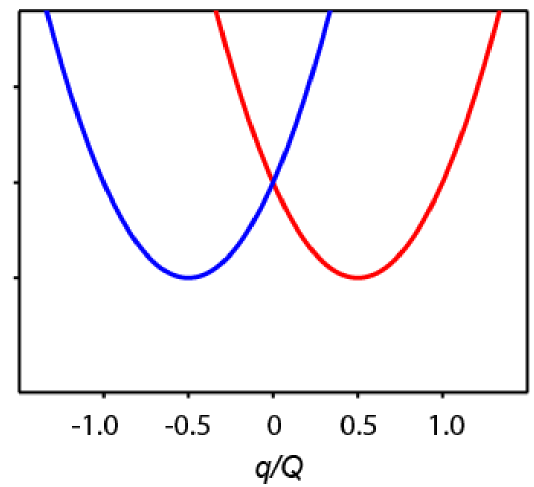
$$\mathcal{H}_{SO} = \begin{pmatrix} \frac{\hbar^2 k^2}{2m} + \frac{\delta}{2} & \frac{\hbar\Omega_R}{2} \\ \frac{\hbar\Omega_R}{2} & \frac{\hbar^2 (k+Q)^2}{2m} - \frac{\delta}{2} \end{pmatrix}$$

- Write in terms of COM momentum q (spin-dependent transformation):

$$\uparrow \qquad q = k + Q/2$$

$$\downarrow \qquad q = k - Q/2$$





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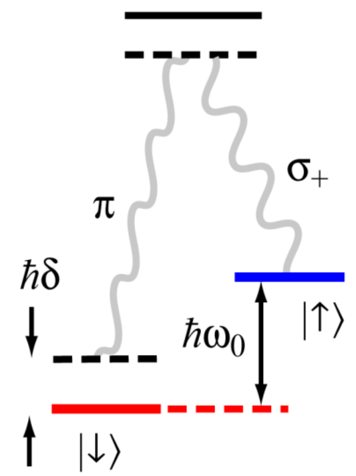

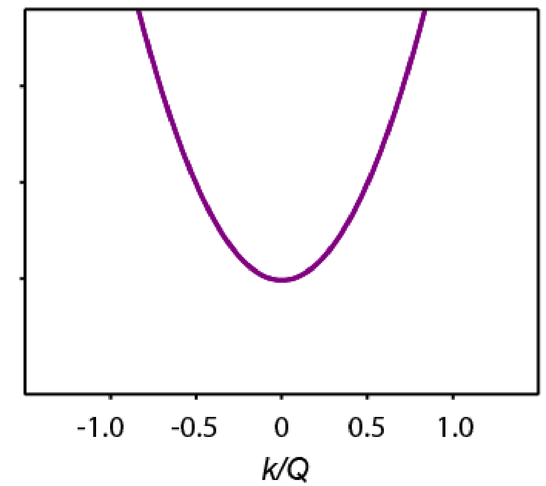

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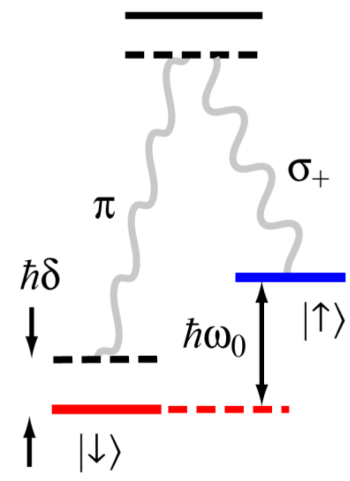
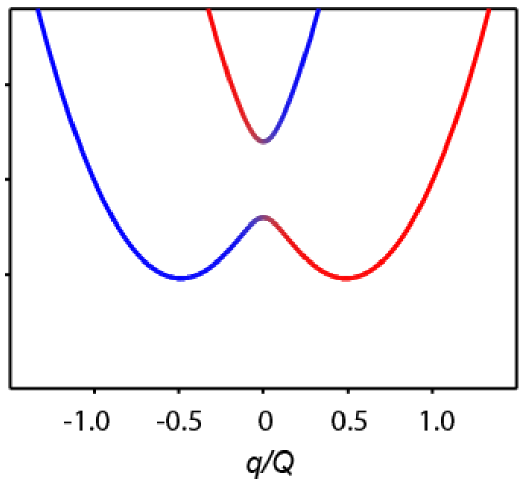
- Amplitude of Raman beams give splitting
- Detuning imbalances the two wells





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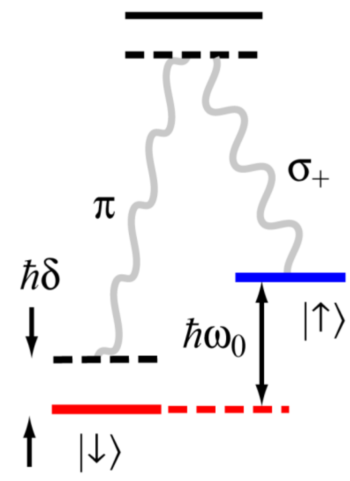
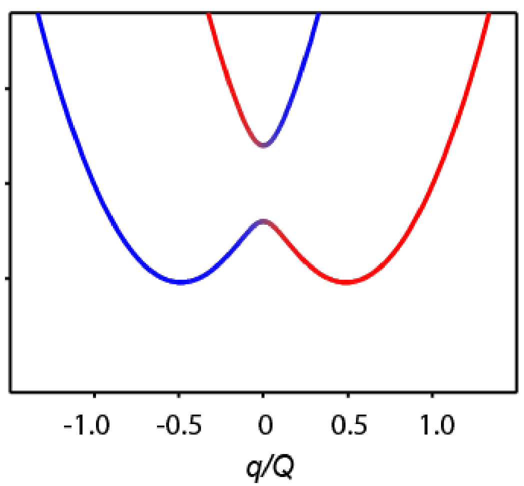




SO-coupling in a Fermi gas

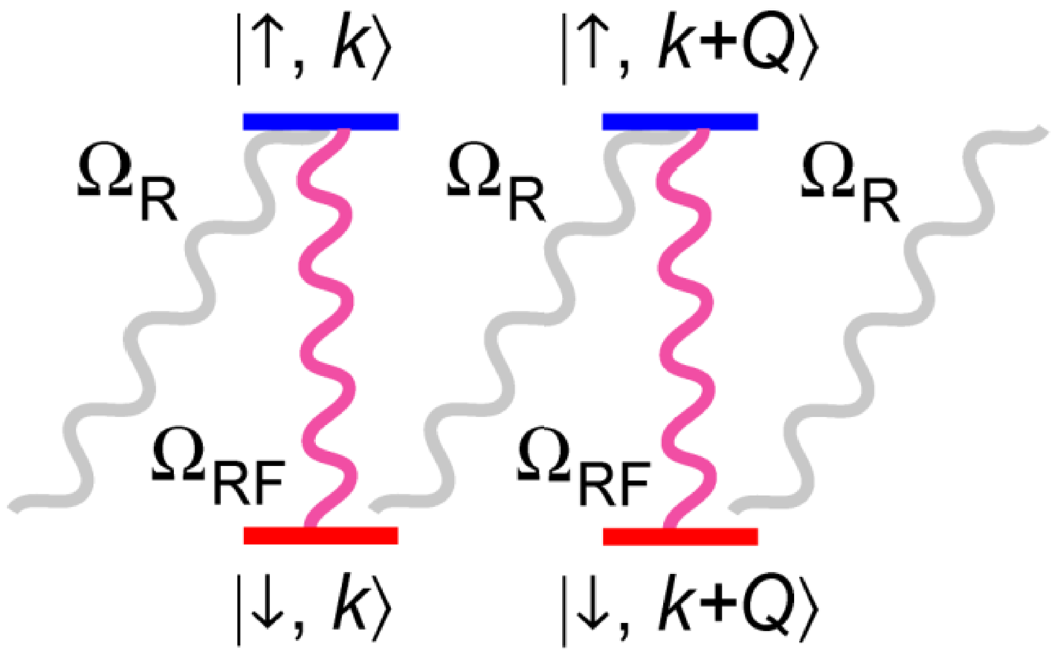
- When SO coupling is ramped slowly:
  - Spin composition follows effective magnetic field
  - Process is reversible
  - By changing detuning, either upper band or lower band

Spin-injection spectroscopy

- How to characterize Hamiltonian?
  - Can we measure topology?
- Condensed matter: transport, ARPES, STM …
- Cold atom analog: photoemission spectroscopy (PES) has been
- PES probes *E(k)*
  - Transfer to hyperfine states outside system with RF
  - Measure momentum in TOF
  - Use RF frequency, free particle dispersion and momentum to reconstruct E(k)

Creating a Spinful Lattice

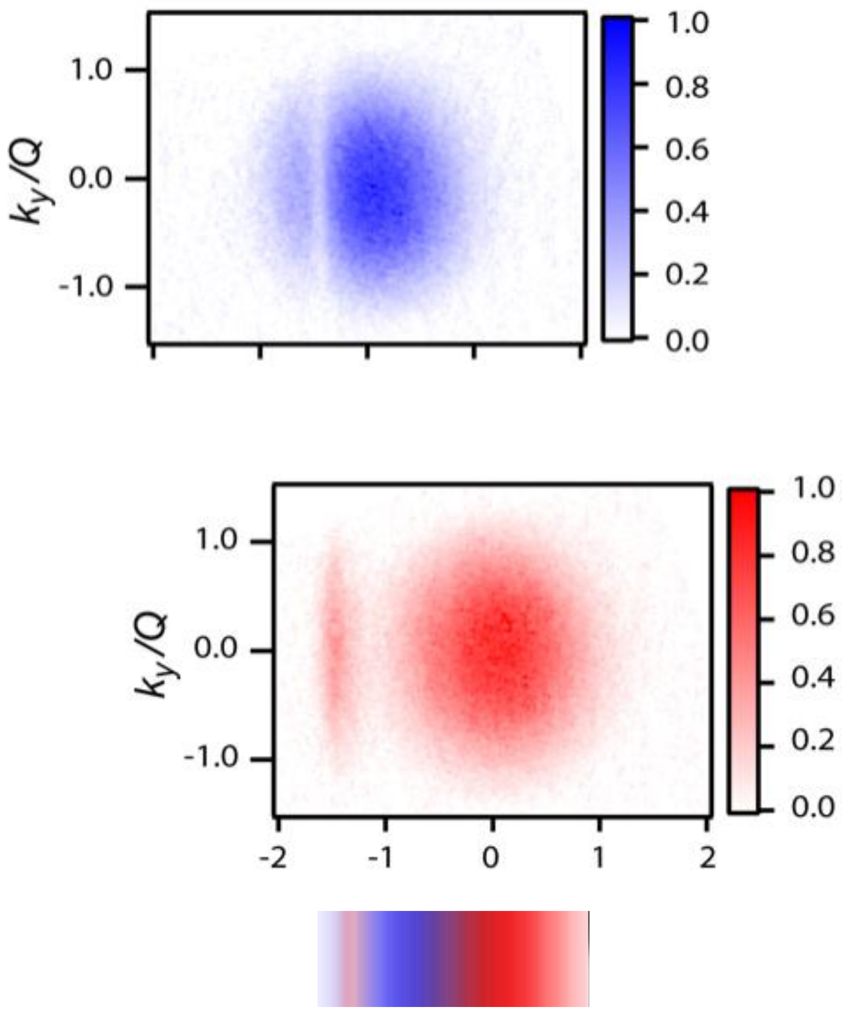
- Add RF coupling -> lattice system with full bandgaps and spinful bands



K. Jimenez-Garcia et al **PRL 108,** 225303 (2012)

Detecting Spin Texture

- Image Sequence: TOF + state-selective imaging



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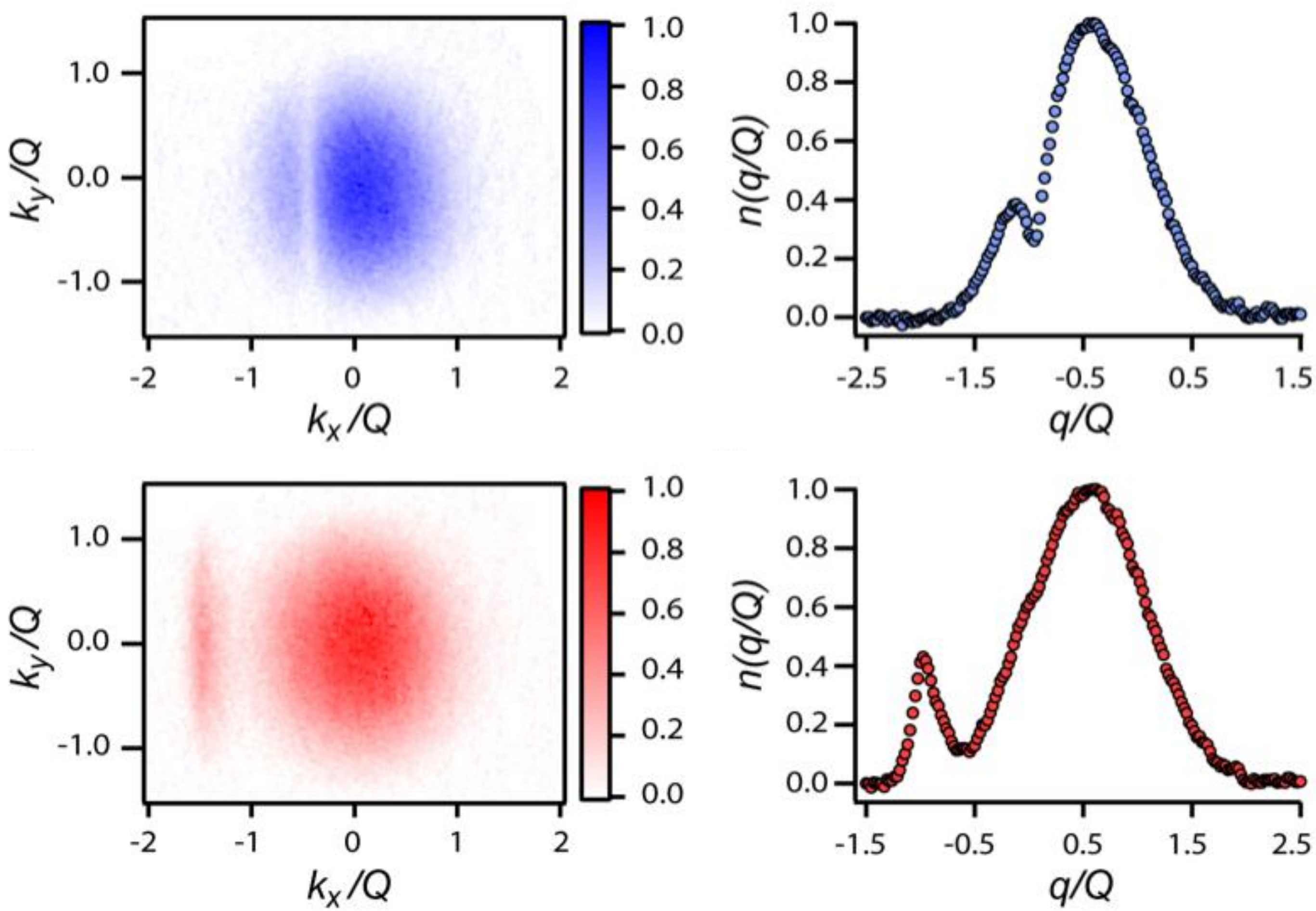

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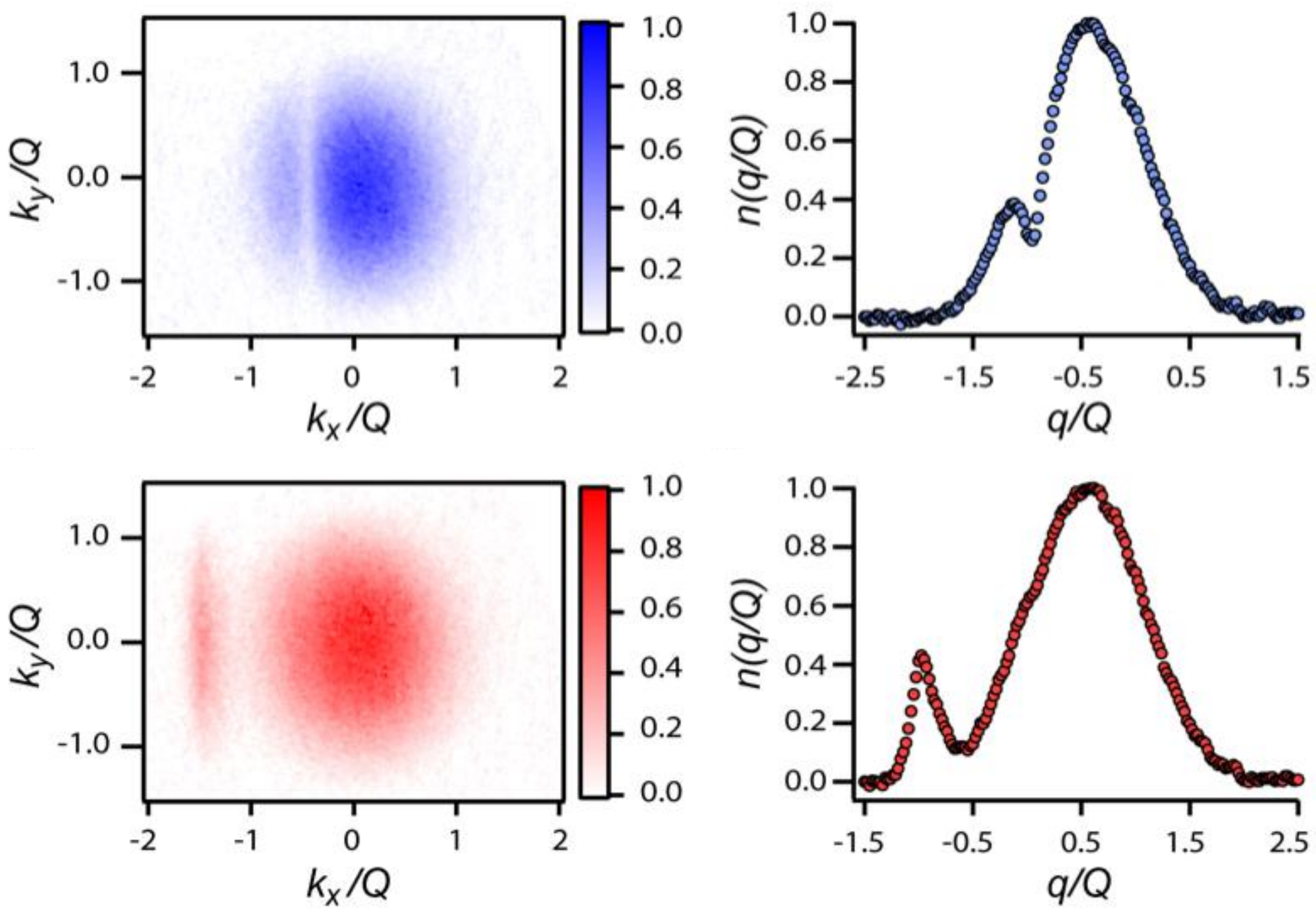
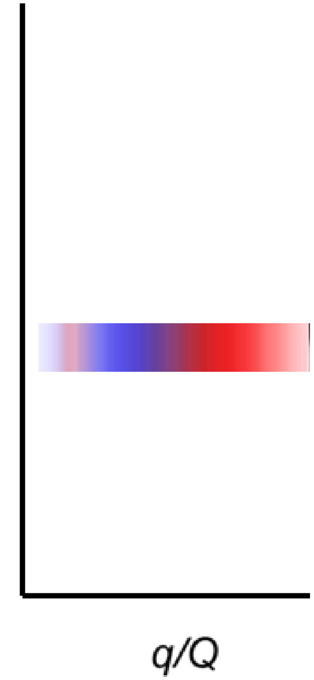
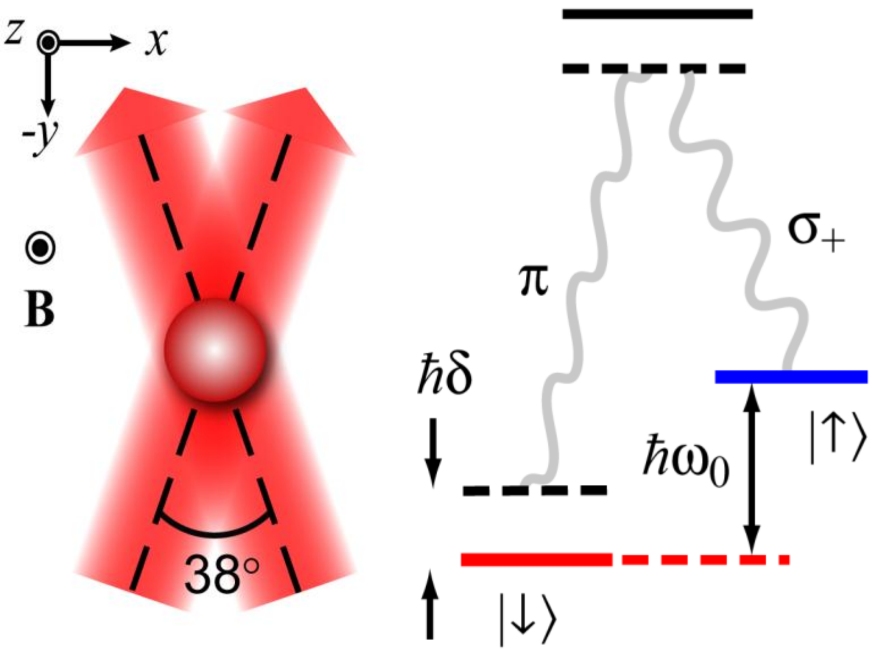


Some parameter



Engineering SO coupling

- Raman Beams couple two hyperfine states
- SO coupling along one direction
- Recoil momentum: Q
- Recoil energy : $E_R = \frac{\hbar^2 Q^2}{2m}$



SO-coupling in Ultracold Atoms

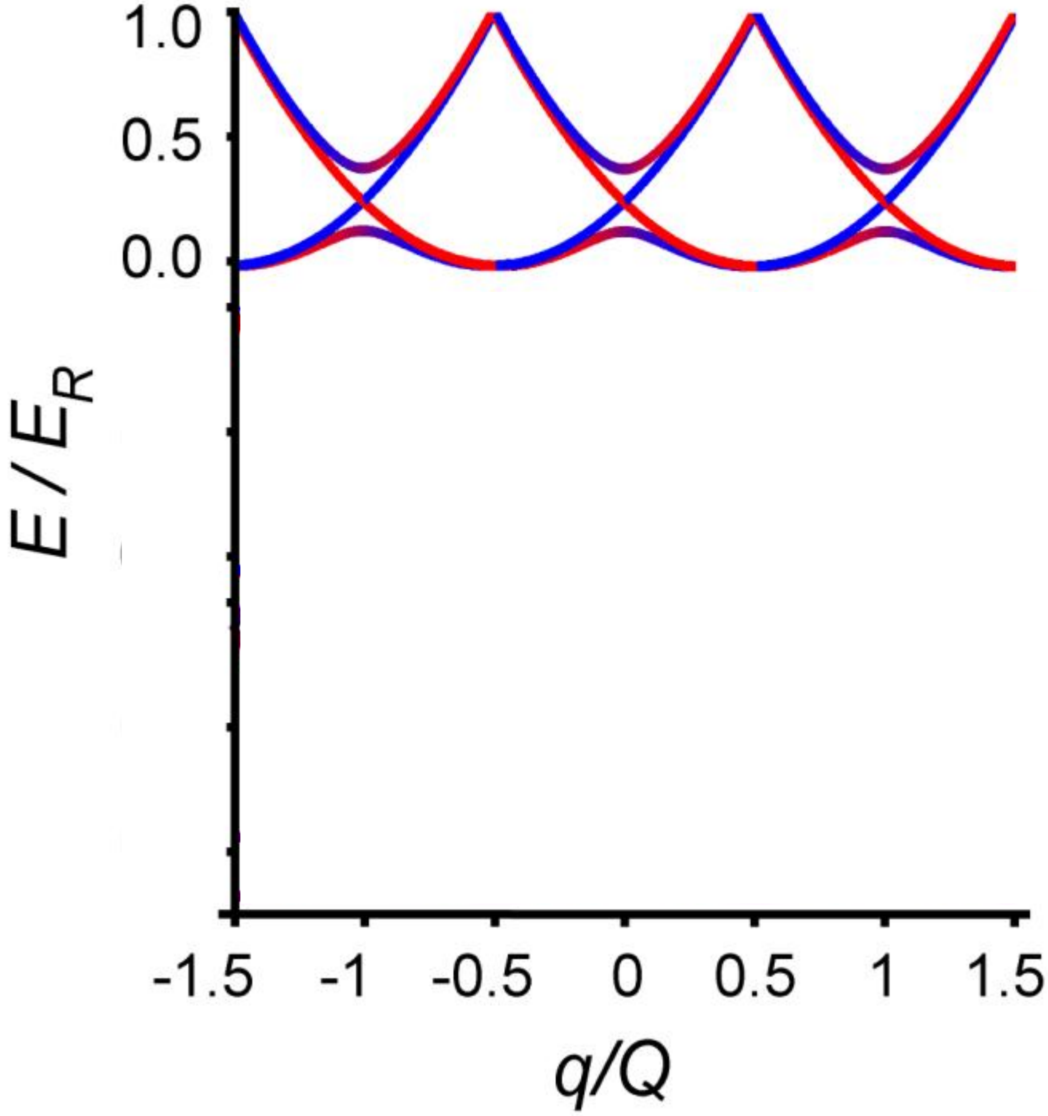
- Realized in bosons:
  - Modified dispersion
  - Synthetic higher-order partial waves
  - Synthetic magnetic field

Y. J. Lin *et al.* *Nature* **471,** 83-86 (2011)
R. A. Williams *et al.* *Science* **335,** 314-317 (2011)
Y. J. Lin *et al* *Nature* **462** 628-632 (2009).

- Recently realized in fermions

P. Wang et al **arXiv:1204.1887**
L. W. Cheuk at el **arXiv:1205.3483**

Bandstructure of Raman + RF lattice



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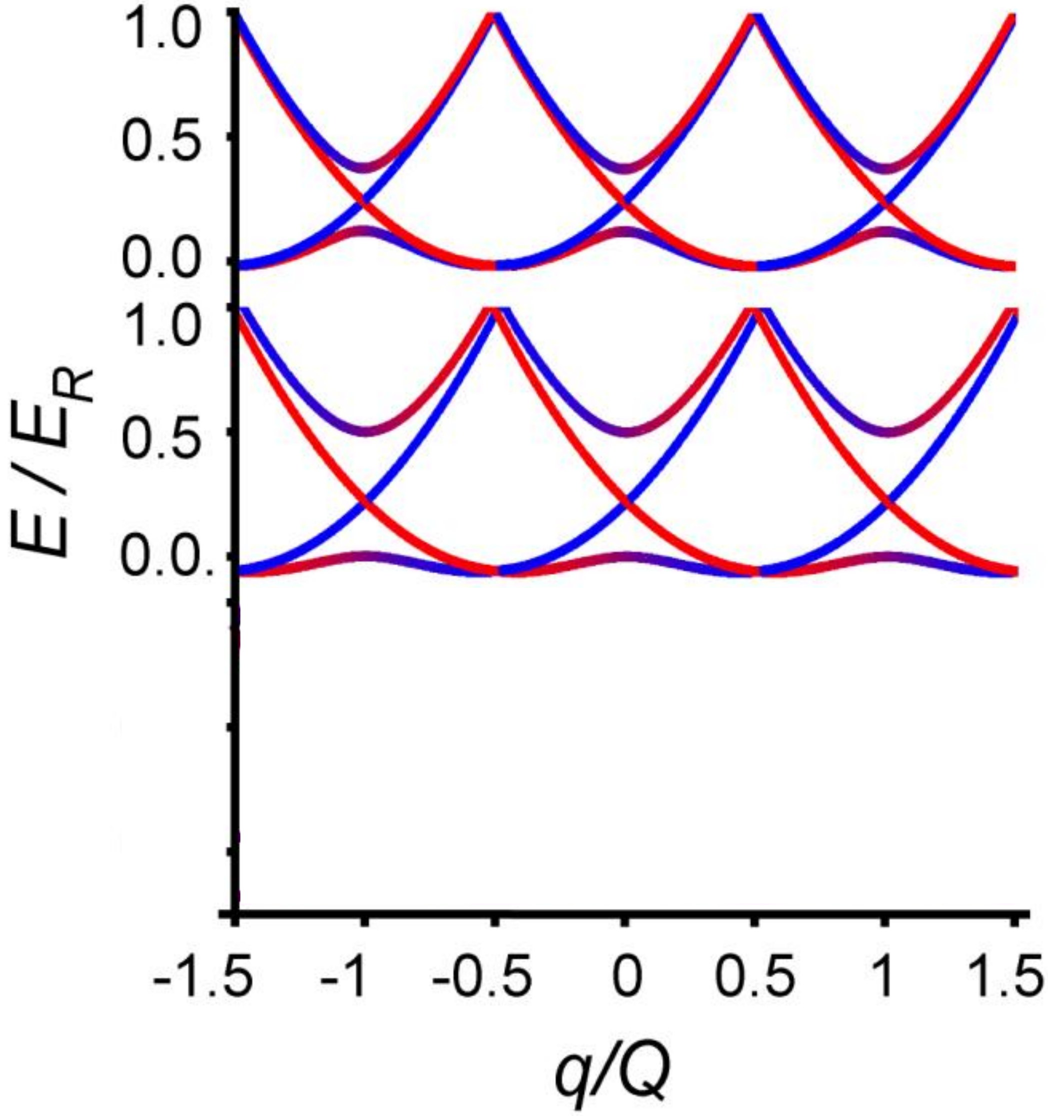

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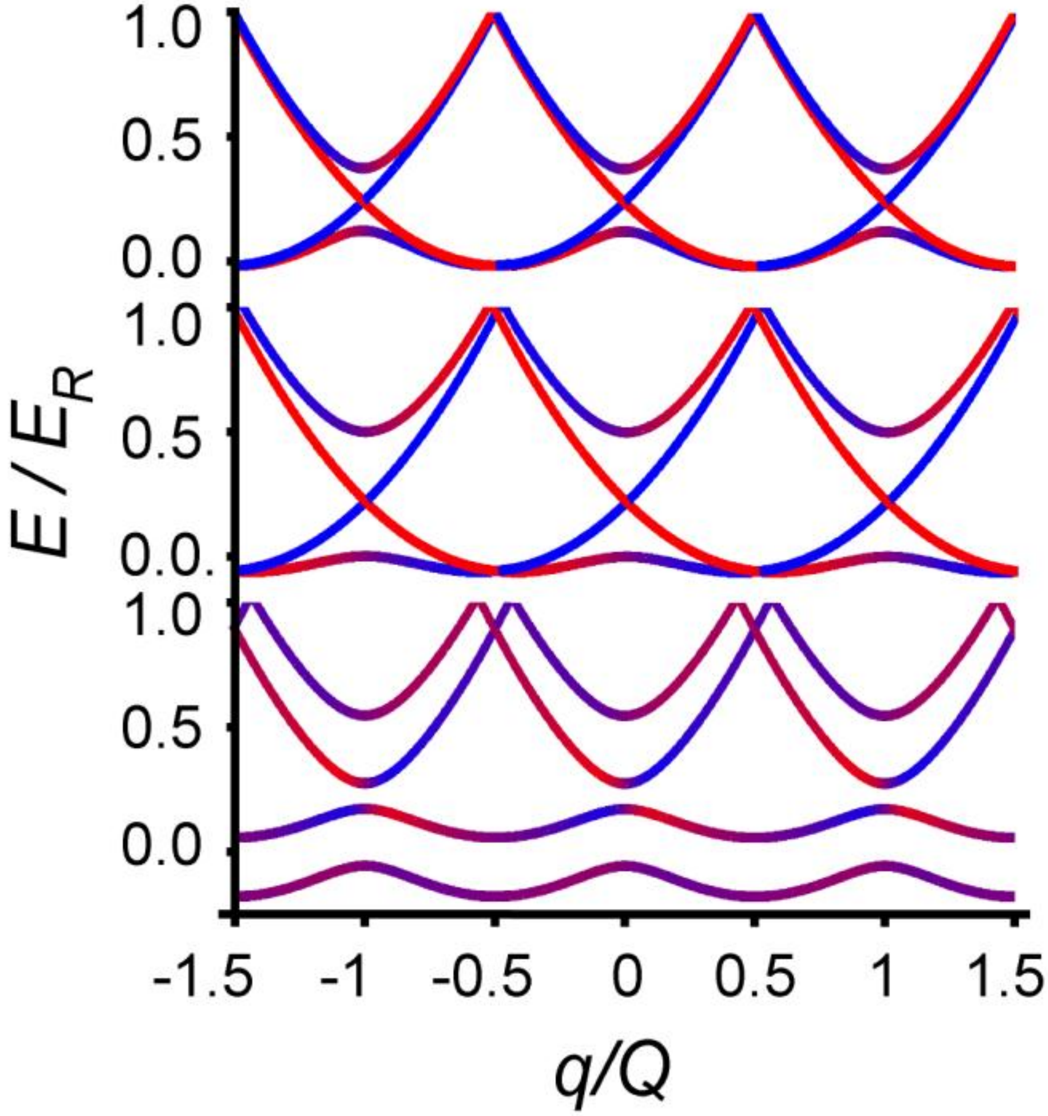
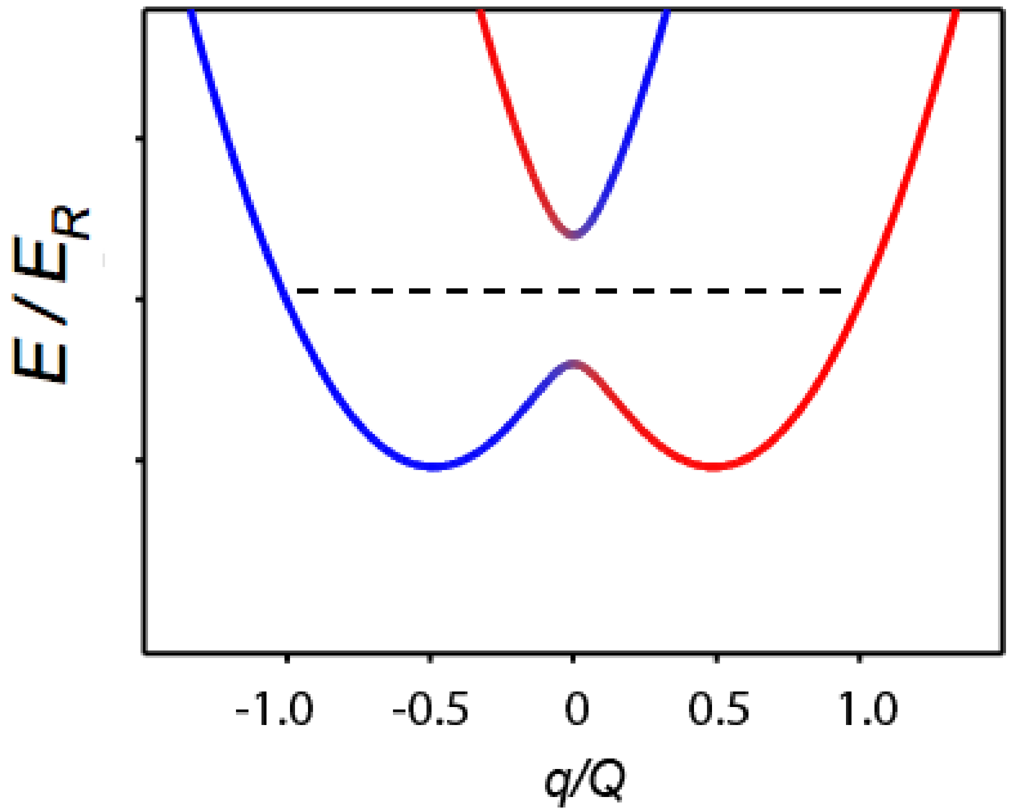
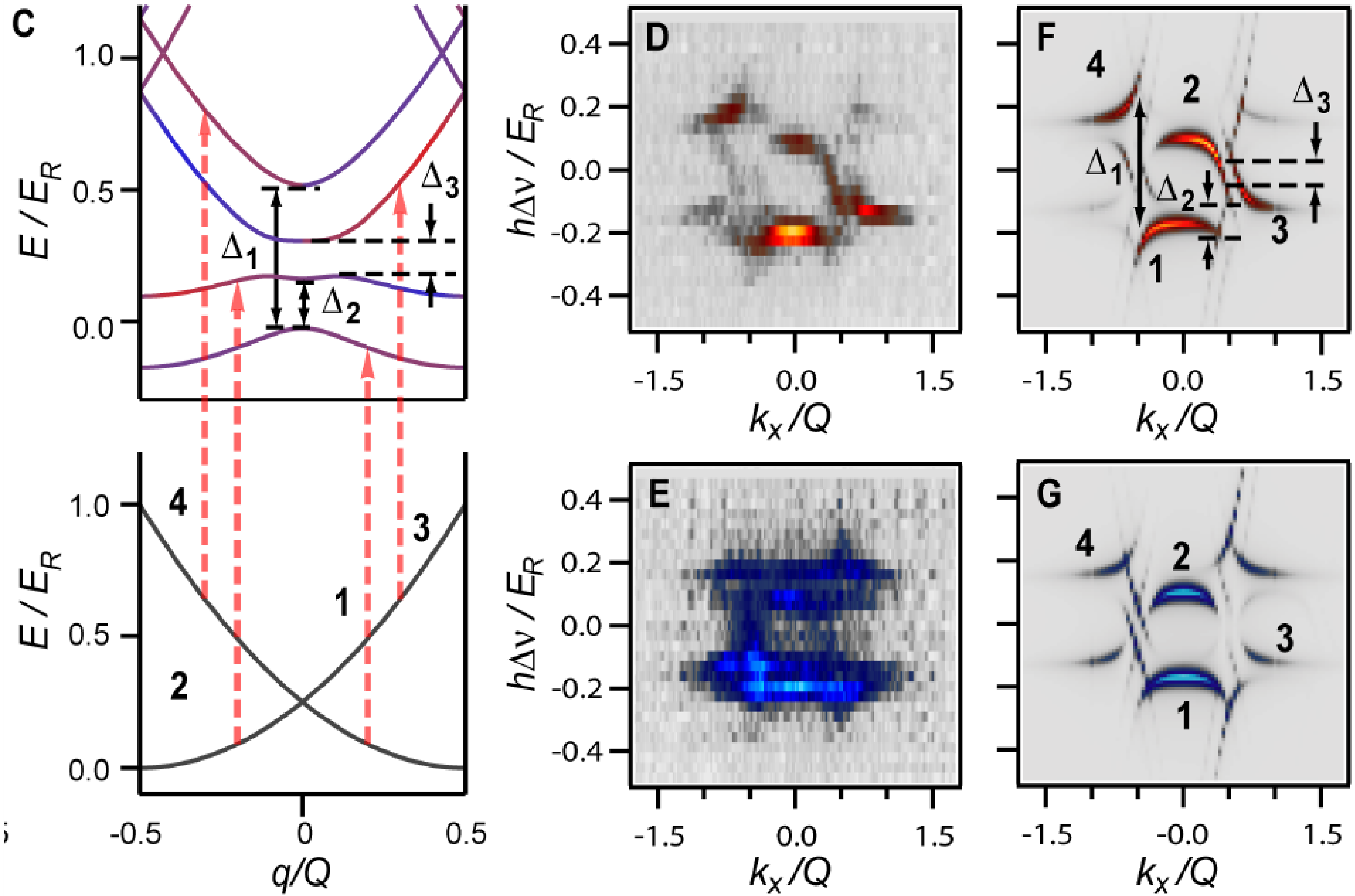


A Spin Diode

- Spin diode when the Fermi level is inside the spin gap



Experiment vs Simulation



Why spin-orbit coupling?

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]†