



# PHYS 596 - JOURNAL CLUB PRESENTATION

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Team 10

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November 30 2012

# Structure of the Presentation

- Introduction
- A Summary of the Article
- Comparison with Previous Literature
- Analysis on Results
- Summary of Conclusions and Citation Evaluation

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# The Topic

A pioneering work on realizing  
**Spin-Orbit Coupling in Ultracold Fermi Gas**

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Phys. Rev. Lett. 109, 095302 (2012) [5 pages]

## Spin-Injection Spectroscopy of a Spin-Orbit Coupled Fermi Gas

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Abstract

References

**Citing Articles (10)**

Supplemen

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# Why is this study interesting?

- Spin-Orbit Coupling (SOC) is responsible for a variety of phenomena: fine structure of atomic spectra, topological edge states, and topological superconductivity.
- Once SOC is included in the cold-atom toolbox, by using the optical lattices, it is possible to design and measure exotic states, such as topological edge states, which are difficult to create and analyze experimentally in condensed matter physics.

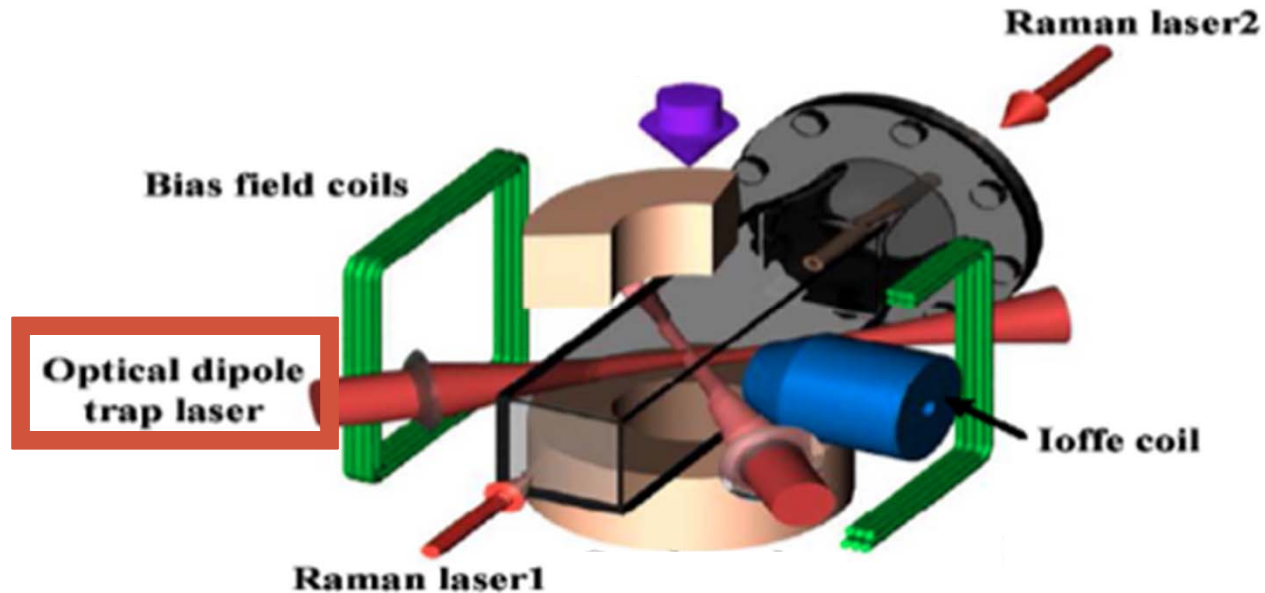
## Why is this study pioneering?

- This experiment is one of the two first realizations of spin-orbit coupling in an ultracold Fermi gas.
- Spin splitting of the atoms is experimentally verified.
- The spin-orbit coupled band structure is mapped out.

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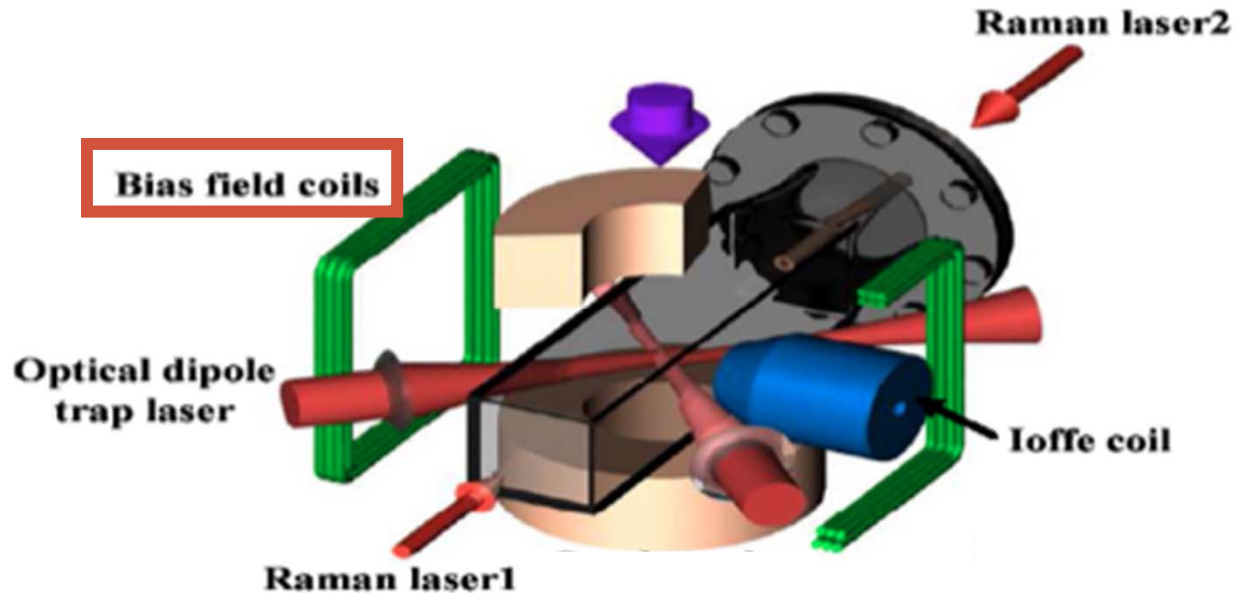
# I. Preparing atoms with spin orbit coupling



- Fermionic  ${}^6\text{Li}$  atoms are cooled down and put into an optical dipole trap.

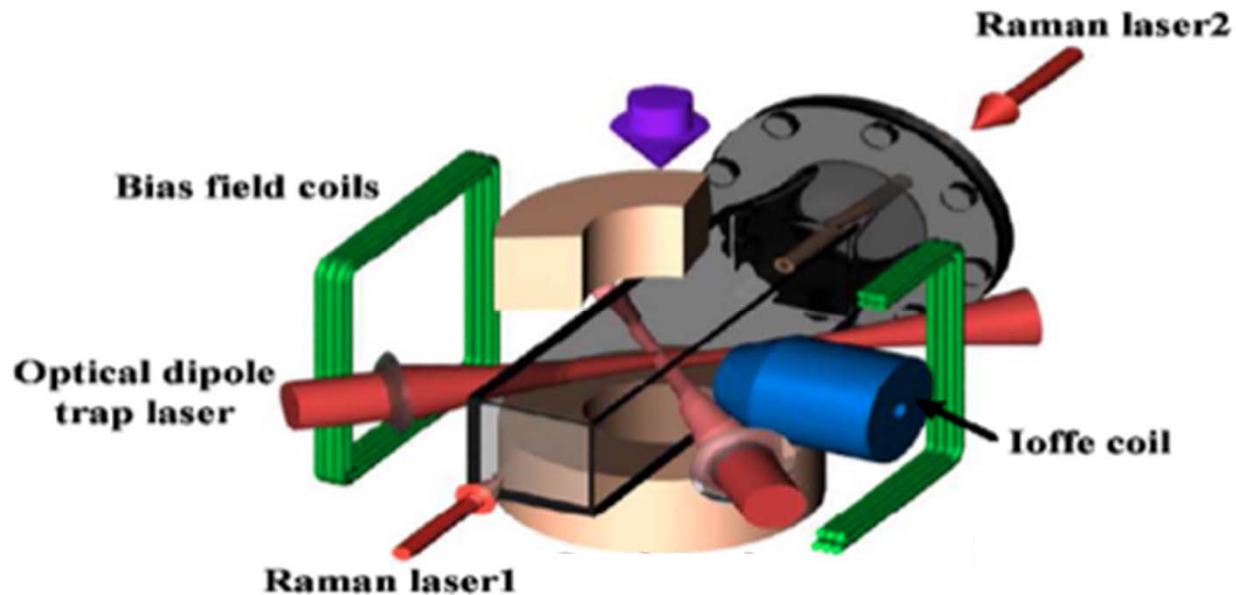


# I. Preparing atoms with spin orbit coupling



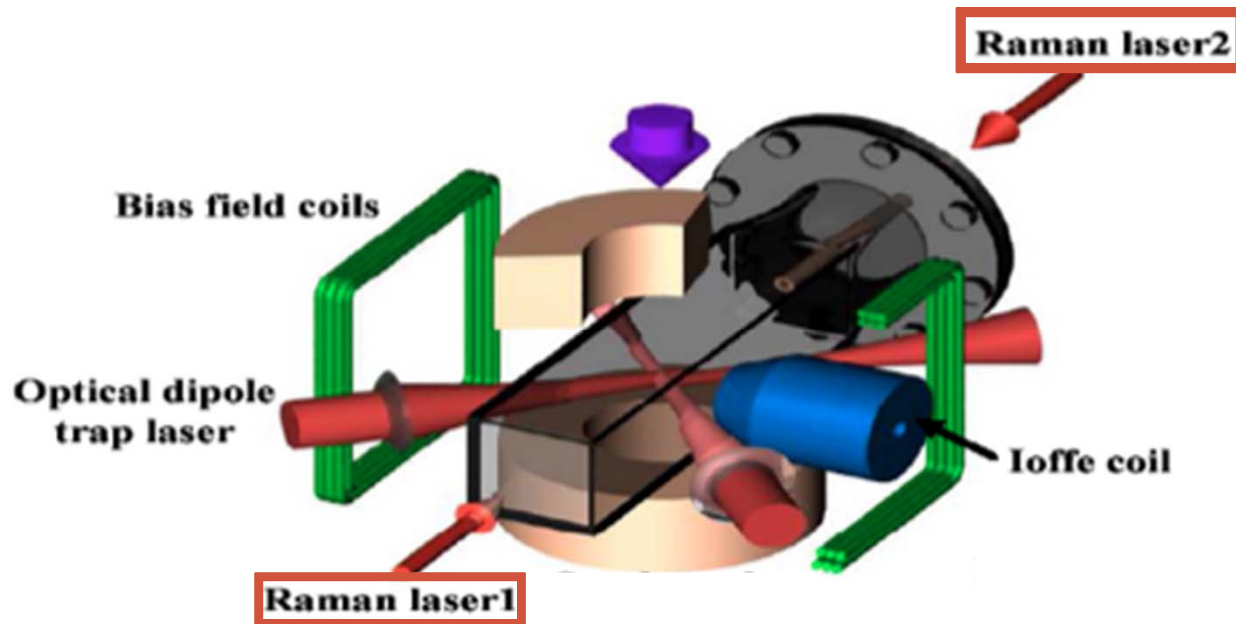
- A magnetic field is applied to separate the hyperfine states.

# I. Preparing atoms with spin orbit coupling



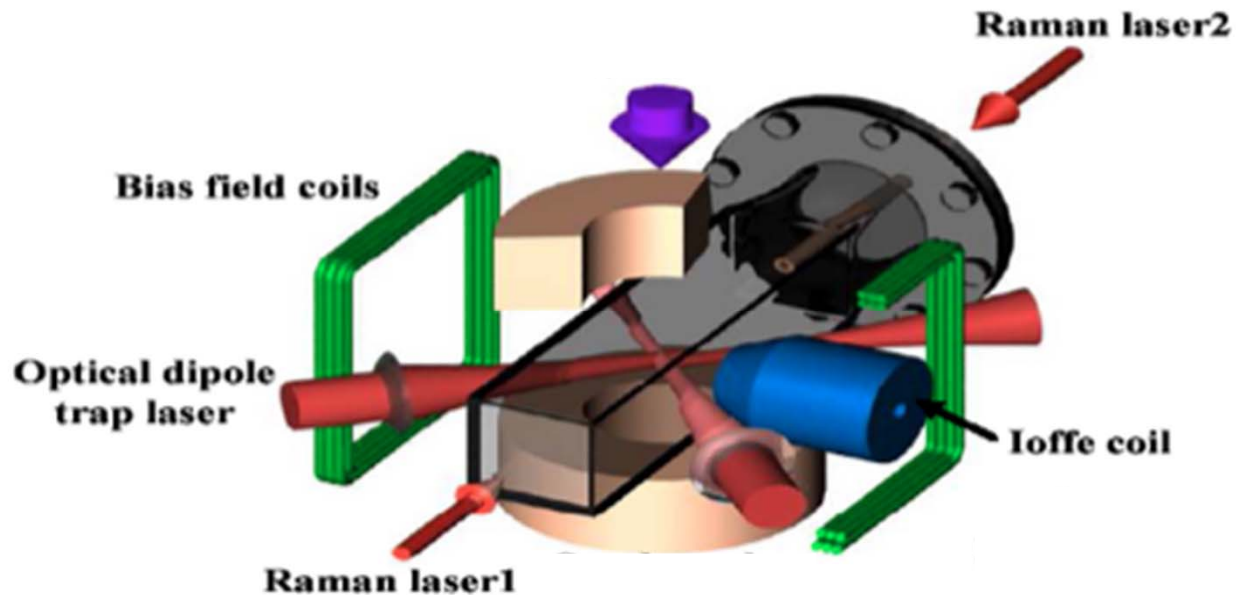
- The atoms are transferred into the lowest four hyperfine states ( $F=3/2$ ) via radiofrequency sweeps.

# I. Preparing atoms with spin orbit coupling



- Spin orbit coupling is created with two Raman lasers.

# I. Preparing atoms with spin orbit coupling



- A theoretical explanation of this process is following.

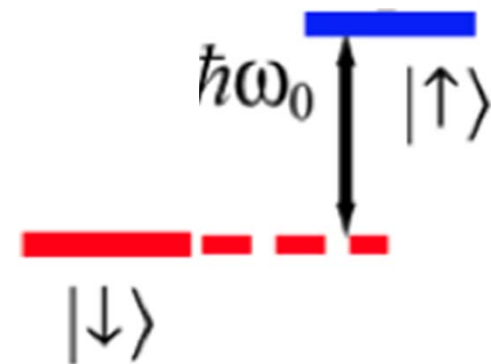
## II. Define atoms' spin "Up" and "Down"

- With the Zeeman field, the degeneracy of the  $F=3/2$  state is removed.
- The two states in the middle are used as spin "up" and spin "down" states.



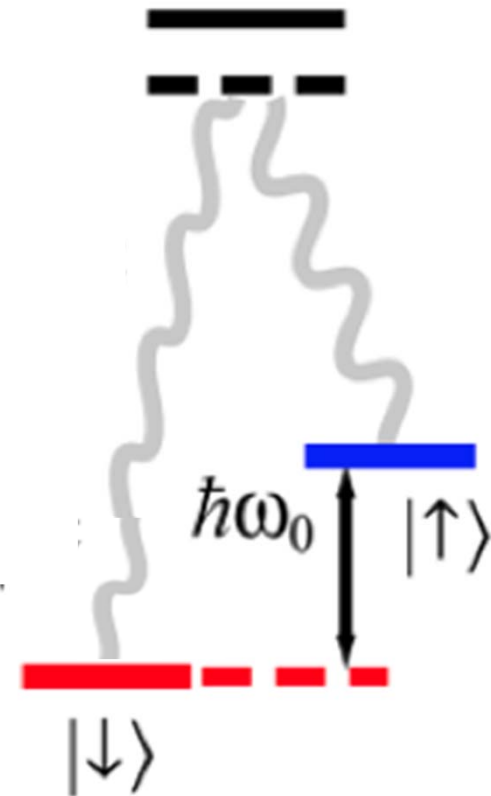
### III. Introducing Two-Photon Raman Process

- One atom is on the spin “up” state (blue).
- A spin “down” state (red) is  $\hbar\omega_0$  lower in energy.



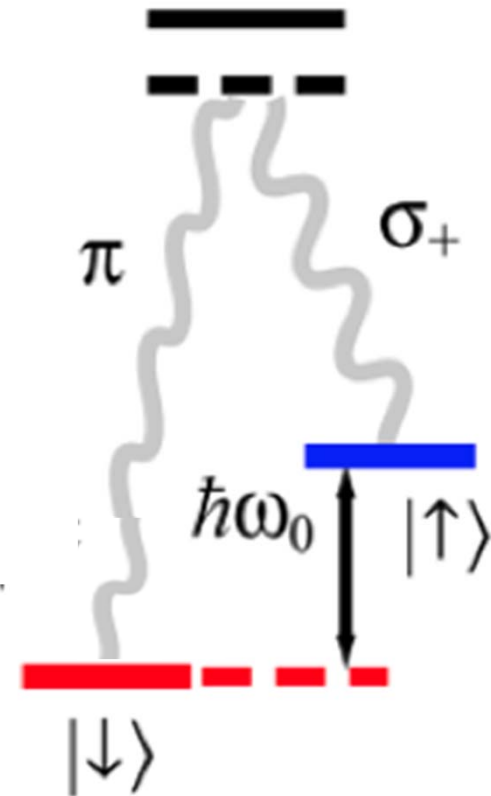
### III. Introducing Two-Photon Raman Process

- Two Raman beams are turned on.



## III. Introducing Two-Photon Raman Process

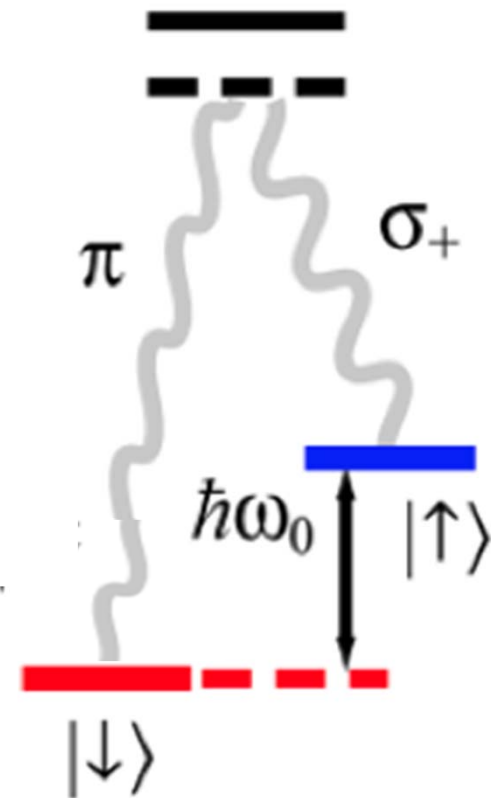
- The transition from spin “up” to spin “down” state is accomplished by absorbing a photon from one laser and emitting a photon to the other laser.
- The momentum of the atom changes at the same time because of the photons.





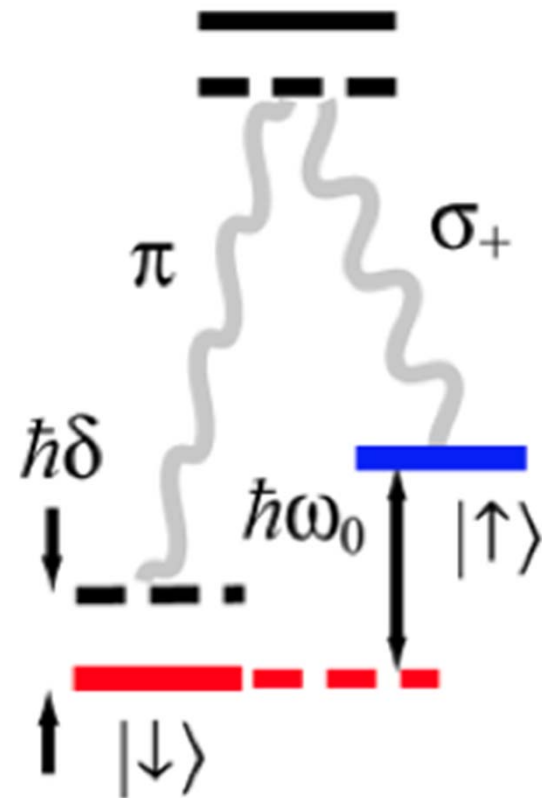
# III. Introducing Two-Photon Raman Process

- The dashed line means a virtual state.
- It is not a real state because the atom does not stay there for any time.



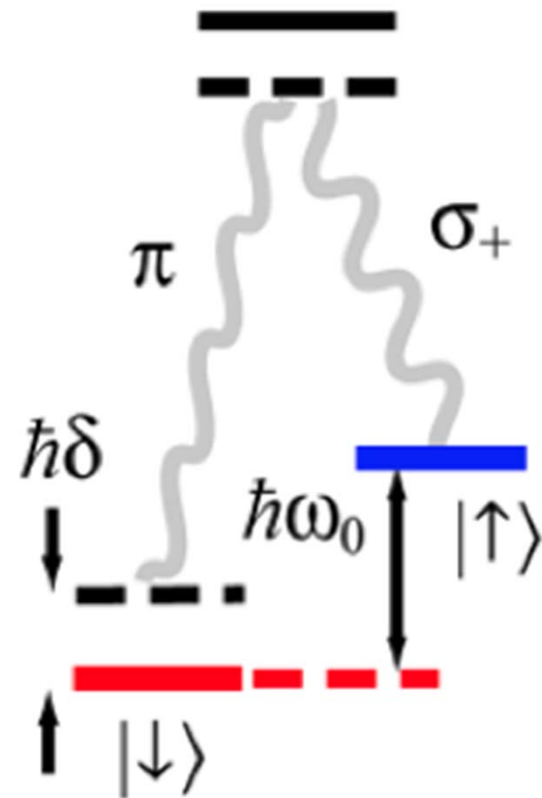
## III. Introducing Two-Photon Raman Process

- The  $\pi$  beam can be tuned away from the the right frequency.  $\hbar\delta$  is called Raman detuning.



## IV. Spin orbit coupling is realized by two-photon Raman process

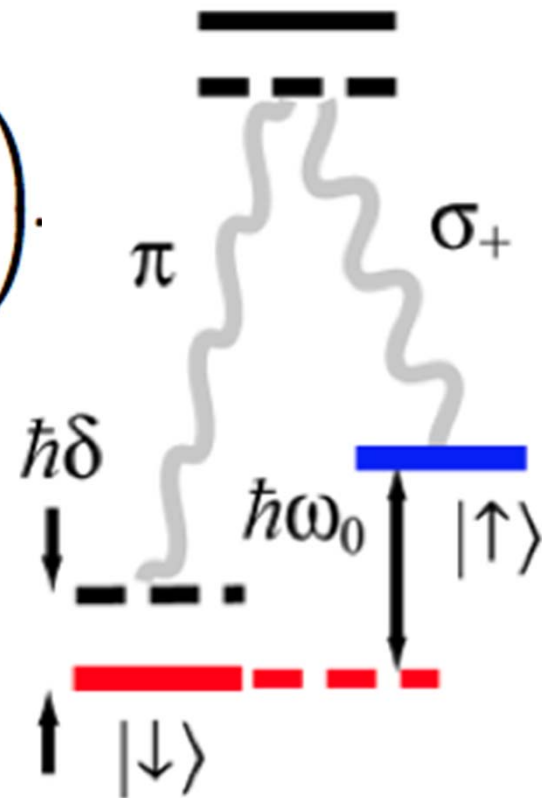
- During a two-photon Raman process, an atom changes its spin orientation and its momentum at the same time.
- Loosely speaking, the spin and the momentum of the atom are coupled.



## V. Hamiltonian for Spin orbit coupling

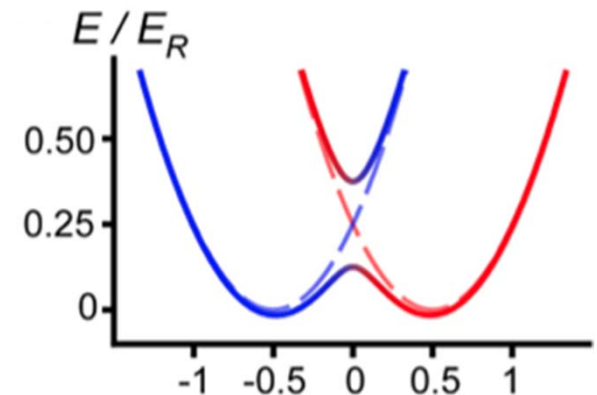
$$\mathcal{H} = \begin{pmatrix} \frac{1}{2m} (\mathbf{p} - k_r \hat{\mathbf{e}}_x)^2 - \frac{\delta}{2} & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{1}{2m} (\mathbf{p} + k_r \hat{\mathbf{e}}_x)^2 + \frac{\delta}{2} \end{pmatrix}.$$

- $k_r$  comes from the coefficient of spin-orbit coupling.
- $\delta$  is Raman detuning ( $\hbar$  set to be 1).
- Zeeman field introduces off-diagonal terms  $\Omega/2$ .



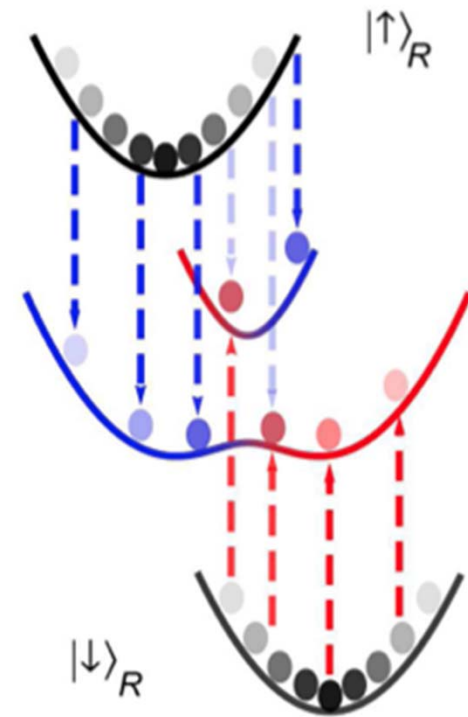
## VI. The band structure with spin-orbit coupling

- In the presence of the spin-orbit coupling, the cold atoms have a dispersion relation shown in the right graph.
- Dashed lines are there if there is no magnetic field.
- A gap appears if there is magnetic field.



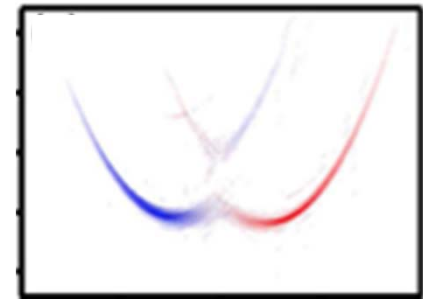
## VII. Inject the atoms to the spin-orbit coupled state

- Atoms on the two bands in the middle are spin-orbit coupled.
- Black dots stand for atoms in the reservoir.
- Transitions of the atoms from the reservoirs are induced by radio wave sweeping.
- **Blue** and **red** dots stand for atoms injected with opposite spin orientations.



## VIII. Introducing spin-injection spectroscopy

- Transition rate of the atoms are measured as a function of the radio frequency
- The dispersion (energy vs. momentum) relation of the spin-orbit coupled states can be mapped out.
- This is taken as the verification of the presence of spin-orbit coupling.



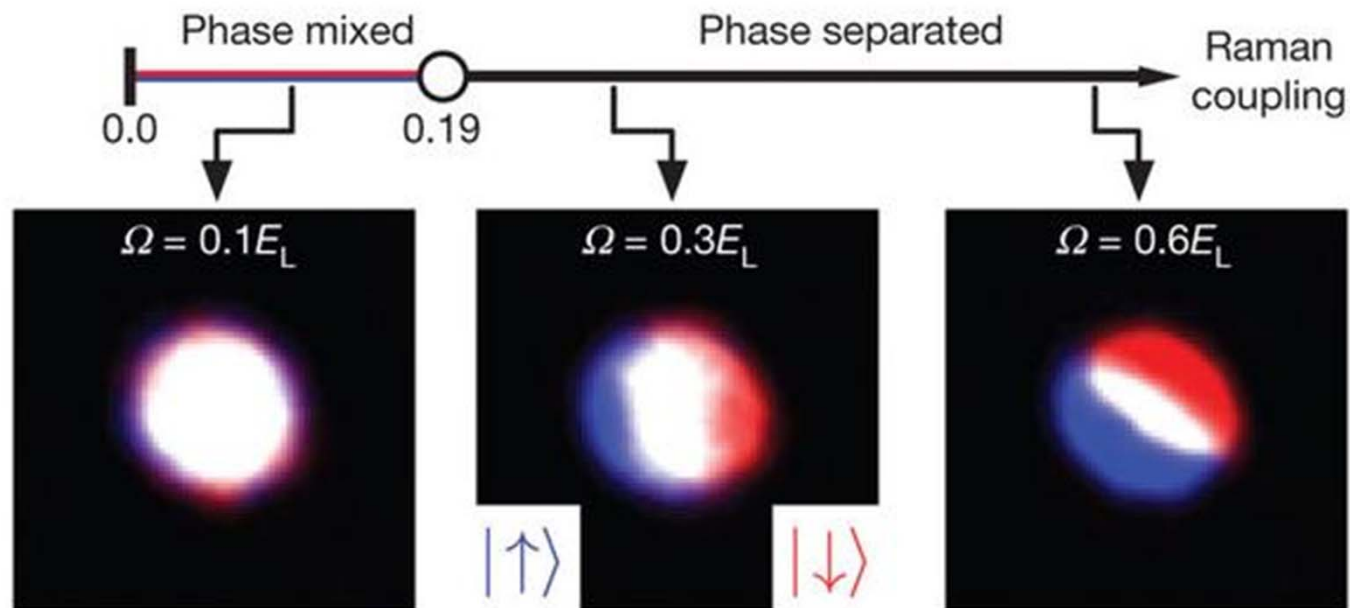
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# Spin Orbit Coupling in Ultracold Bosons

- Spatial ordering phase transition is observed



Lin et. Al, Nature, **471**, 83-86, 2011.

- Why bother with Fermions?
  - Pauli Exclusion Principle means more momentum states are occupied

# Same Experiment, Different Authors

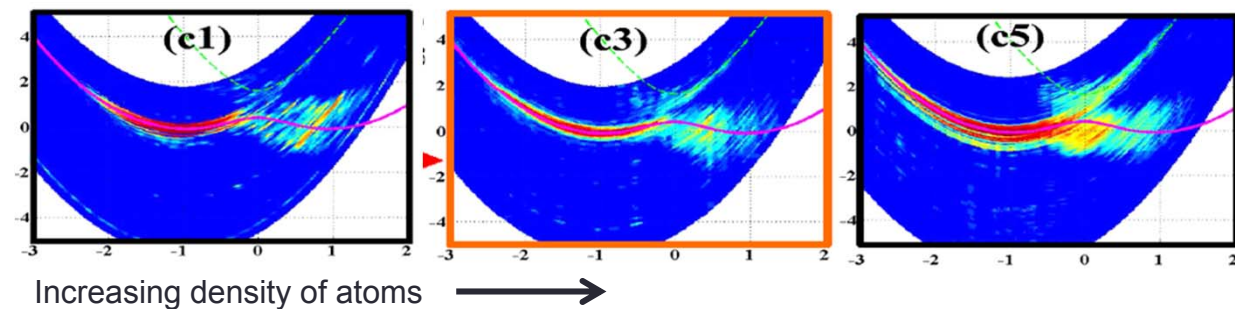
	Cheuk et al.	Wang et al.
Atom	${}^7\text{Li}$	${}^{40}\text{K}$
Detection Technique	Spin-injection spectroscopy <u>into</u> states	Momentum-resolved rf spectroscopy <u>from</u> states
Probes	Spin <u>and</u> Momentum	Momentum
Hallmark of SOC	Time-dependent Rabi oscillations	Time-dependent Rabi oscillations Momentum distribution asymmetry

Wang, et al., PRL, **109**, 095301, 2012.

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Wang Results

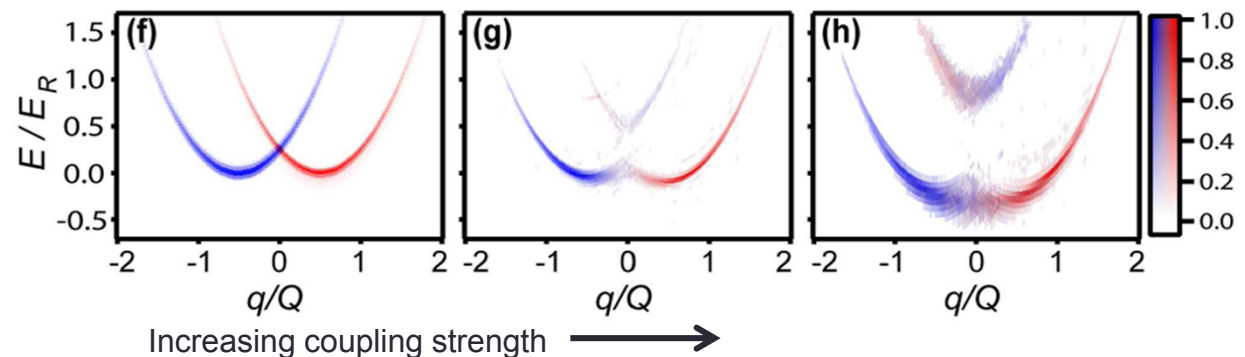


- Only see part of the band structure
- Bad way to see spin orbit coupling develop

# Same Experiment, Different Authors

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## Cheuk Results

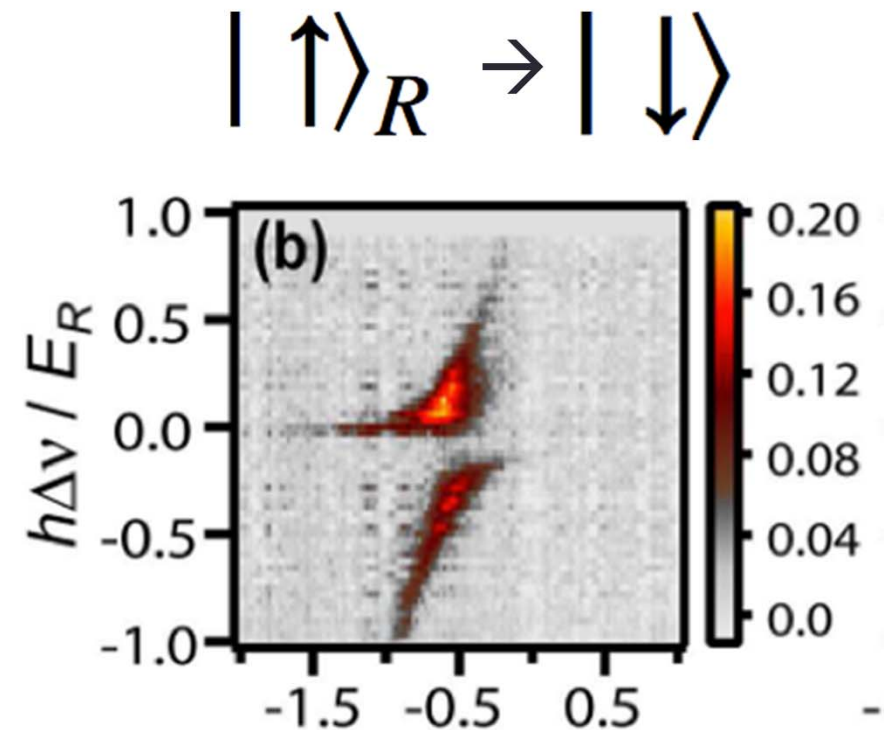
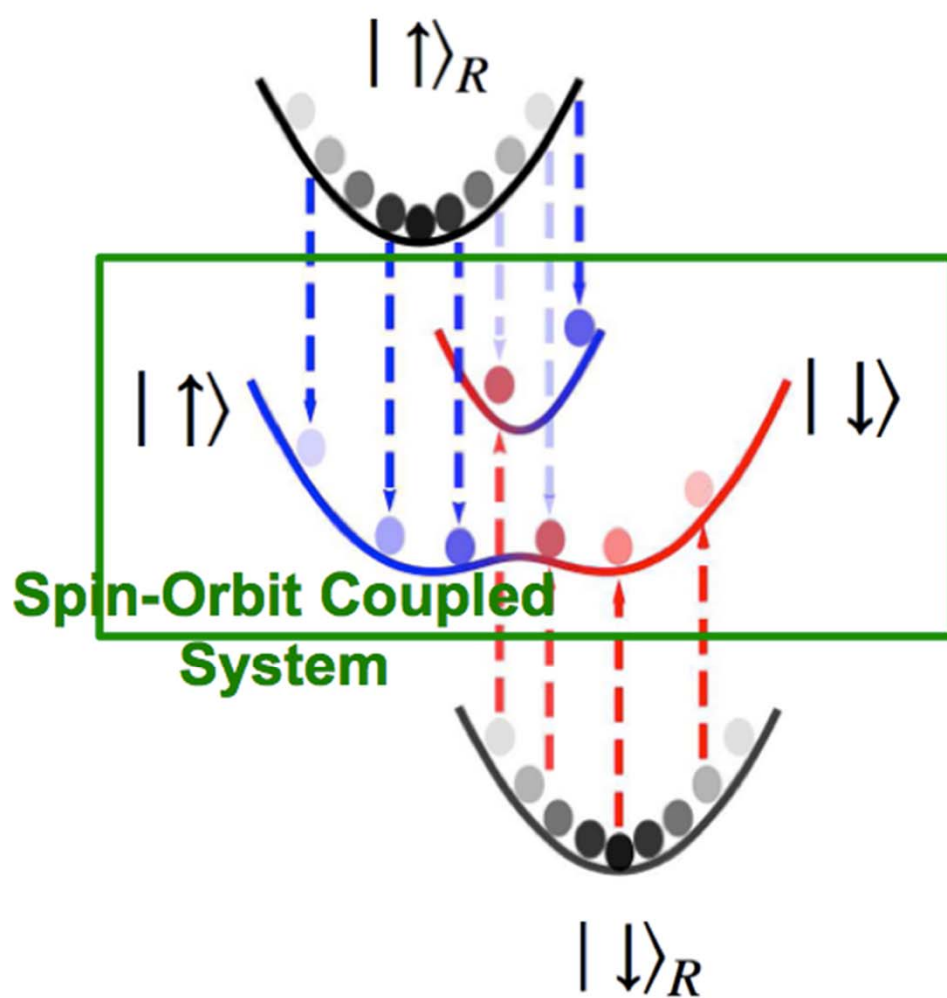


- Full band and spin structure easily seen
- Dynamic view of spin orbit coupling action

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# Result I – Probing the band structure by using Spin-injection Spectroscopy



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# Summary of Conclusions

- The authors created spin-orbit coupling in an ultracold atomic Fermi gas and detected spin-orbit gap via spin-injection spectroscopy, which characterize the energy-momentum dispersion and allow reconstruction of eigenstates in a spinful lattice.
- The cold atom experimental method in this paper can reveal the nontrivial topology of bands in more general spin-orbit coupled systems (such as with interactions), providing a way to probe topological insulators, and Majorana edge states.



# Citation Evaluation

- This article, published on August 27 2012, is cited **9** times (5 PRA + 3 PRL +1 EPL)(by Web of Knowledge, Scopus)

## Evolution in spin-orbit coupled atomic gas research

- Spin-orbit coupled degenerate Fermi gas (PRL 10 times, this study is also published on August 27 2012)
- Collective dipole oscillations of a spin-orbit coupled Bose-Einstein condensate (PRL 4 times)
- Molecule and polaron in a highly polarized two dimensional fermi gas with spin-orbit coupling (PRL 1 time)
- Sum rule, dipole oscillation and spin polarizability of a spin-orbit coupled quantum gas (EPL 1time)
- Manipulating Majorana fermions in one-dimensional spin-orbit coupled atomic Fermi gases (PRA 0 time)
- ...

Thank you for your attention!

We are happy to answer questions