第六届全国冷原子物理与
量子信息青年学者学术讨论会

# Experimental realization of spin-orbit coupling in degenerate Fermi gas


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山西大學光電研究所

# Outline

## Motivation: Quantum simulation with ultracold atoms

## Experimental realization of spin-orbit coupling in degenerate Fermi gas

- Raman Rabi oscillation
- Momentum distribution asymmetry
- Topological change of Fermi surface

## Momentum-resolved RF spectroscopy of spin-orbit coupling degenerate Fermi gas

## Spin-orbit coupling Feshbach molecules

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# Quantum simulation with ultracold atoms

**We can control the Hamiltonian of cold atoms in a number of ways**

$$\hat{H} = \frac{p^2}{2m} + V(x) + U_{interaction}$$

**Kinetic: Synthetic vector potential**

**Potential: Optical lattice**

**Interaction: Feshbach resonance**

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**For a particle with charge q, moving in an electromagnetic field, the Hamiltonian can be expressed as:**

$$\hat{H} = \frac{(p - qA)^2}{2m} + V(x)$$

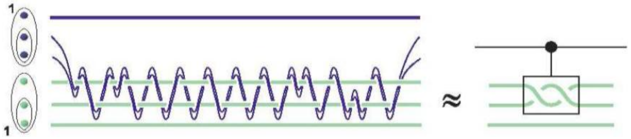
**Vector potential: A**

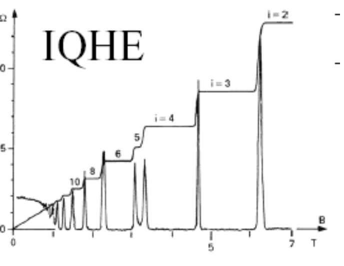
**Magnetic field: B=∇×A**

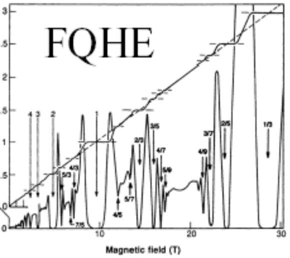
**Once we could construct such a Hamiltonian for the neutral atoms, we can simulate the charged particle with neutral atoms!!**

# Ultracold atoms simulate charged particle


- To simulate Lorenz Force: $\vec{F} = q\vec{v} \times \vec{B}$
- To understand Quantum Hall Effect?
- To form the topological insulator
- Topological Quantum Computing






Klaus von Klitzing

Nobel Prize 1985
Quantum Hall Effect

Robert B. Laughlin

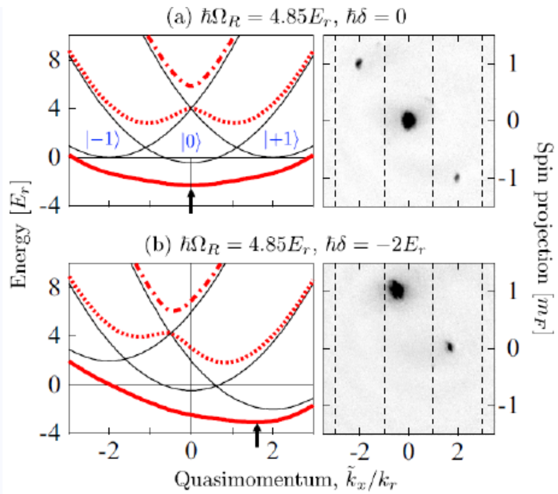
Horst L. Störmer

Daniel C. Tsui

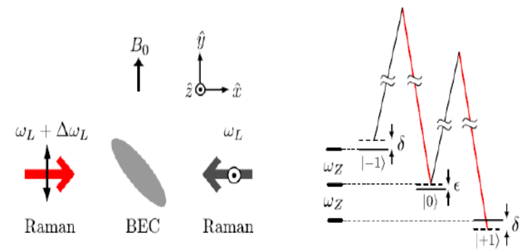
Nobel Prize 1998
Fractional Quantum Hall Effect

# Experimental Progress

## Effective Vector Potential generation:

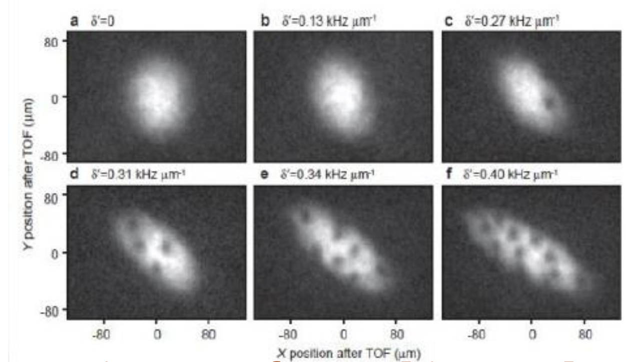



## Raman coupling




**Y.-J. Lin, et.al., PRL 102, 130401 (2009)**

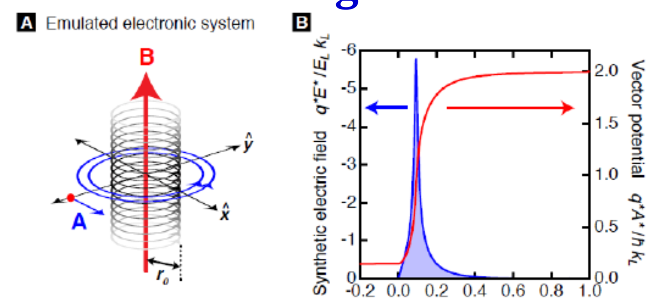
## Synthetic magnetic fields for BEC




## Vortices are formed in condensates

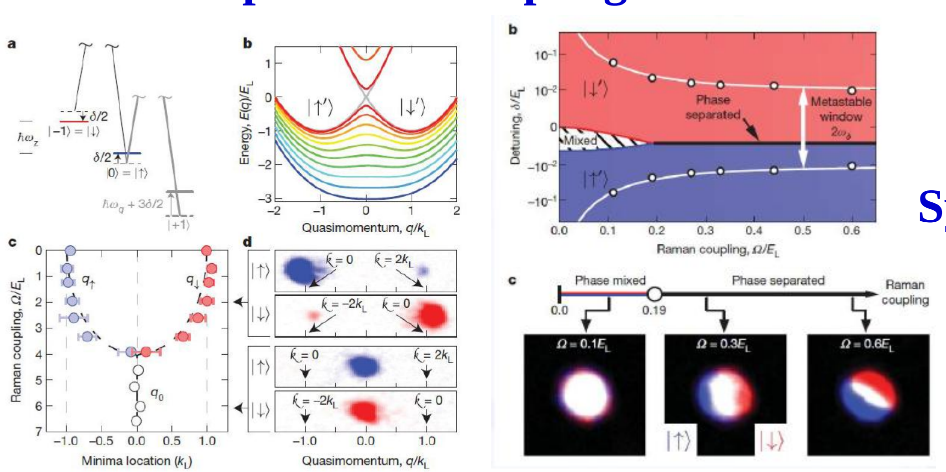
**Y.-J. Lin, et.al., Nature 462, 628 (2009)**

## Electric field generation



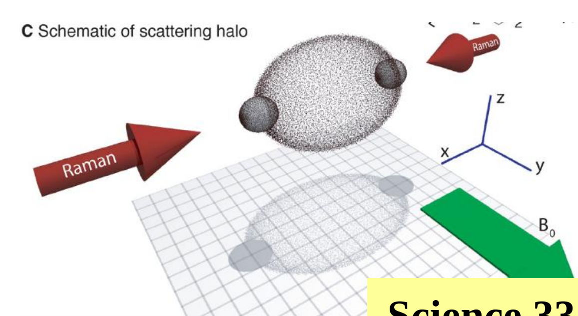

**Y.-J. Lin, et.al., Nature Physics 7, 531 (2011)**

## Spin-Orbit coupling



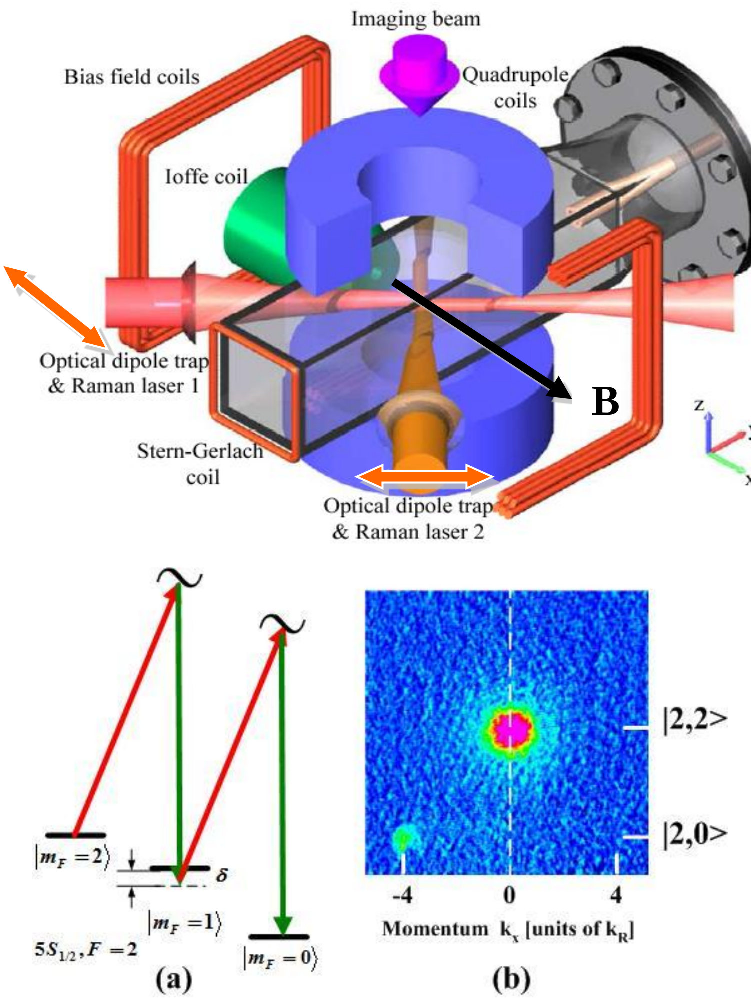

**Y. -J. Lin, et.al., Nature 417, 83 (2011)**

## Synthetic Partial Waves in Atomic Collisions



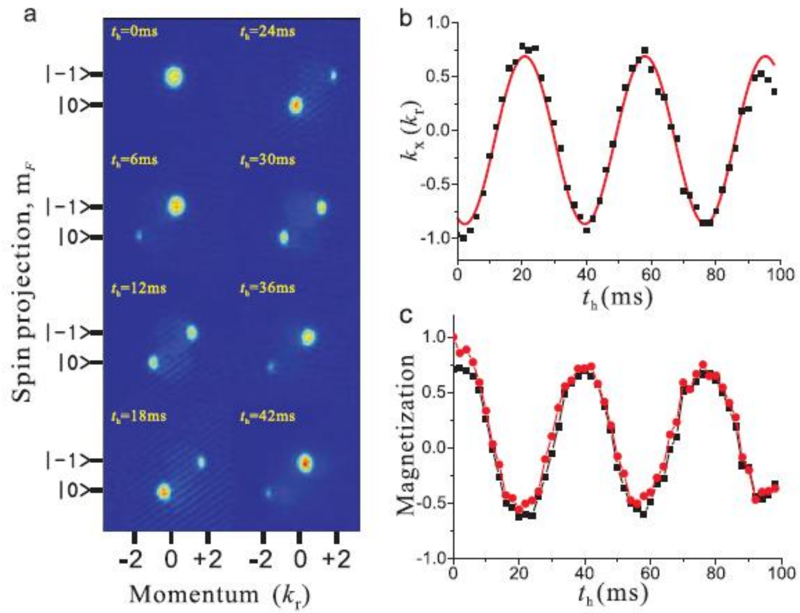

**Science 335, 314 (2012)**

## BEC in light-induced vector gauge potential using the 1064 nm optical dipole trap lasers




**Z. Fu, P. Wang, S. Chai, L. Huang, J. Zhang,** ***Phys. Rev. A*** **84, 043609 (2011)**

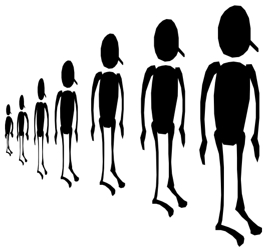
## Collective Dipole Oscillation of spin-orbit coupling BEC

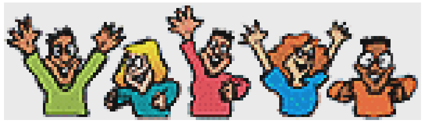



**University of Science and Technology of China, Shuai Chen and Jian-Wei Pan's group**

**S. Chen, J. Y. Zhang, S. C. Ji, Z. Chen, L. Zhang, Z. D. Du, Y. J. Deng, H. Zhai, and J. W. Pan, arXiv:1201.6018.**

# 超冷原子气体中的合成规范场

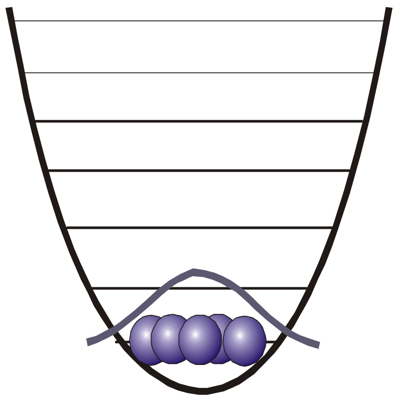




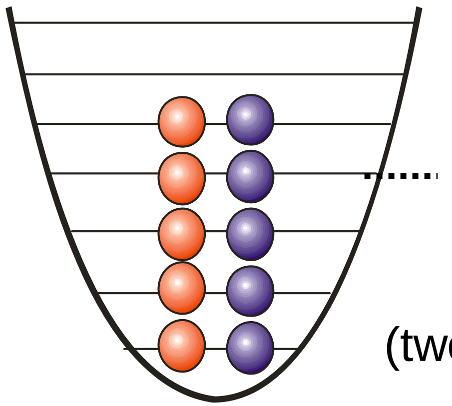
## Bosons and Fermions

- Integer spin
- Half-integer spin

Atoms in a harmonic potential.



T = 0



$E_F = k_b T_F$

(two spin states)

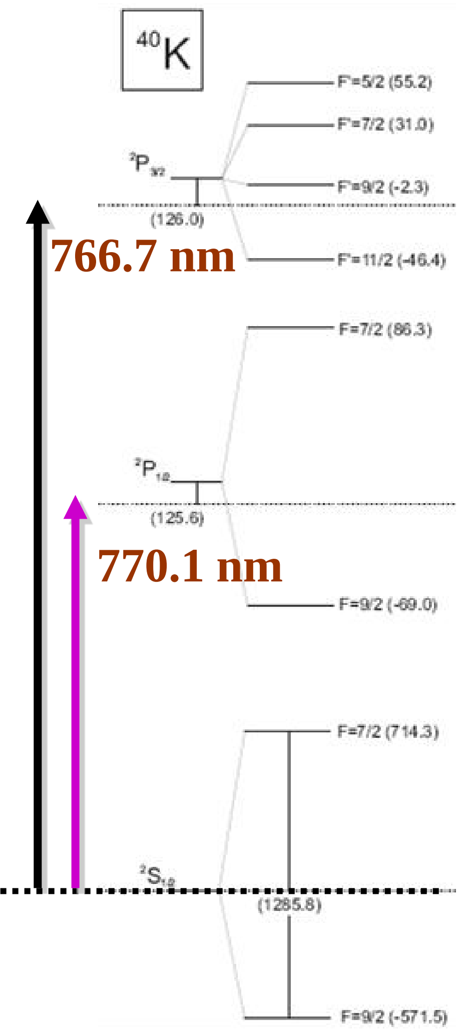
**Bose-Einstein condensation**

**Degenerate Fermi gas**

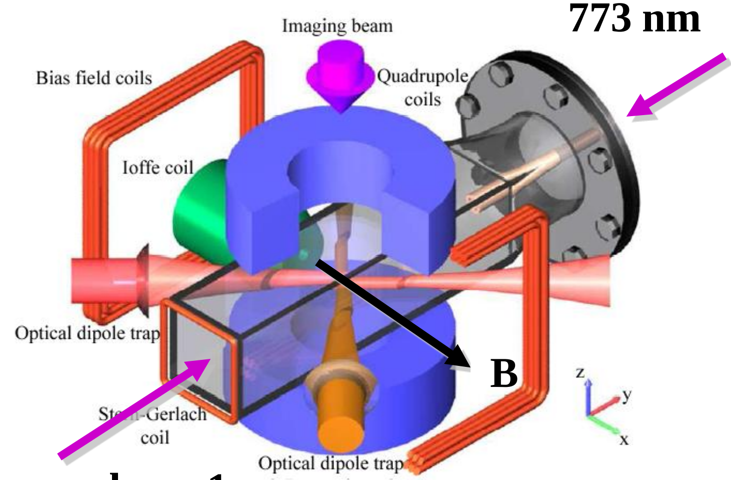
**NIST, 山西大学, 科大**

**山西大学, MIT**

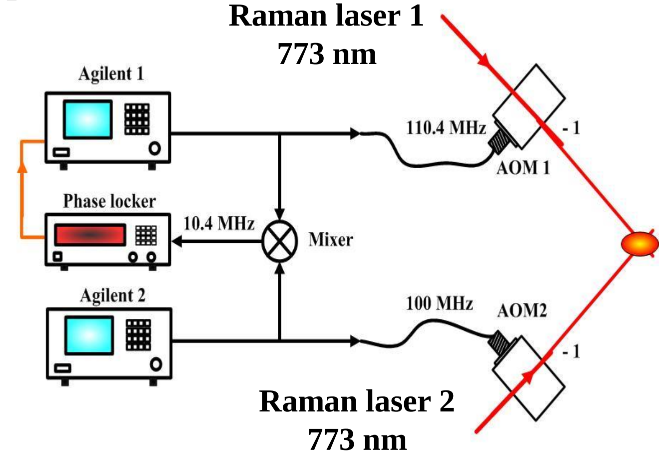
# Experimental realization of spin-orbit coupling in degenerate Fermi gas

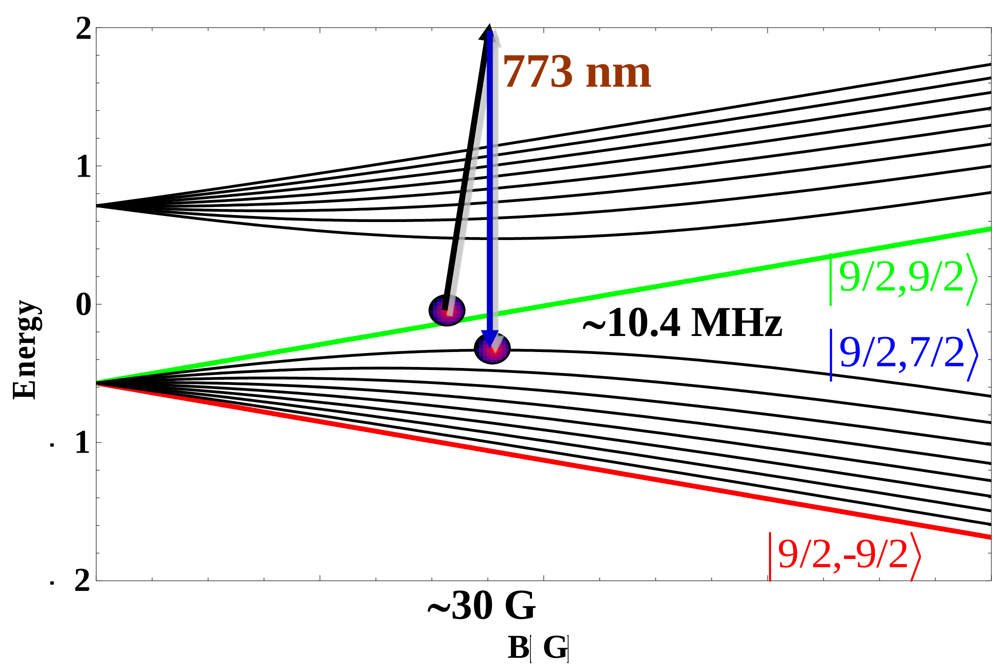


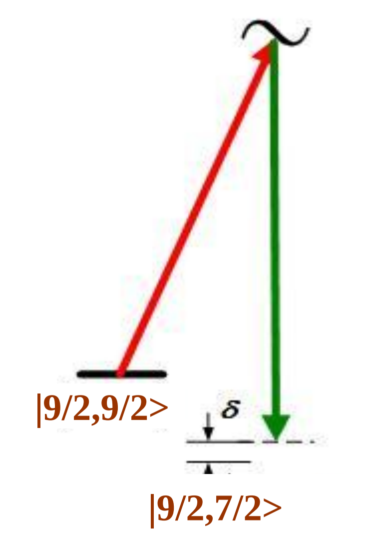

Raman laser 2
773 nm




Raman laser 1
773 nm




|9/2,7/2> → |9/2,5/2>
δ ~ 170 KHz

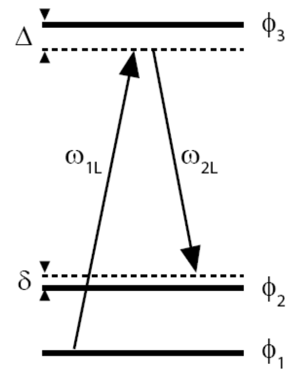
# Theoretical model of two-level system

$$H=\frac{\hbar^2 p^2}{2m}\hat{I}+\frac{\delta}{2}\hat{\sigma}_z+\frac{\Omega}{2}\hat{\sigma}_x\cos(2k_R\hat{x})-\frac{\Omega}{2}\hat{\sigma}_y\sin(2k_R\hat{x})$$

**(NIST group's SO Coupling)**

$$U=\begin{pmatrix} e^{-ik_R x} & 0 \\ 0 & e^{ik_R x}\end{pmatrix}$$

**Translate unitary transformation**

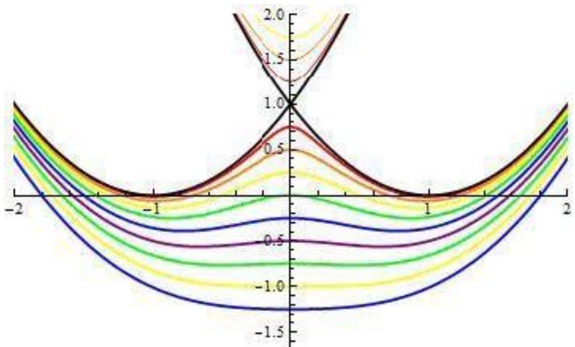



**Base:** $\{|\uparrow, k_x = p + k_R\rangle, |\downarrow, k_x = p - k_R\rangle\}$

$$H_R(k_x)=\hbar\begin{pmatrix}\frac{\hbar}{2m}(p+k_R)^2-\delta/2 & \Omega/2 \\ \Omega/2 & \frac{\hbar}{2m}(p-k_R)^2+\delta/2\end{pmatrix}$$

**two energy eigenvalues:**

$$E_\pm(p)=\hbar[\hbar(p^2+k_R^2)/2m\pm\sqrt{(4\hbar p k_R/2m-\delta)^2+\Omega^2}/2]$$

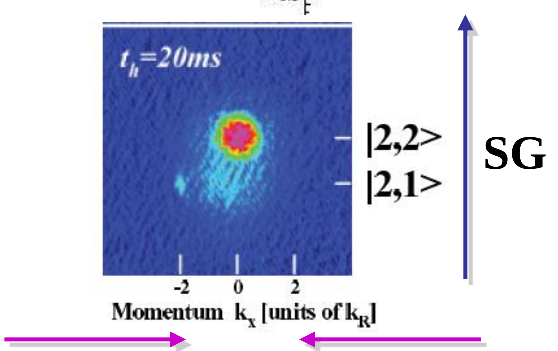



**two dressed eigenstates:**

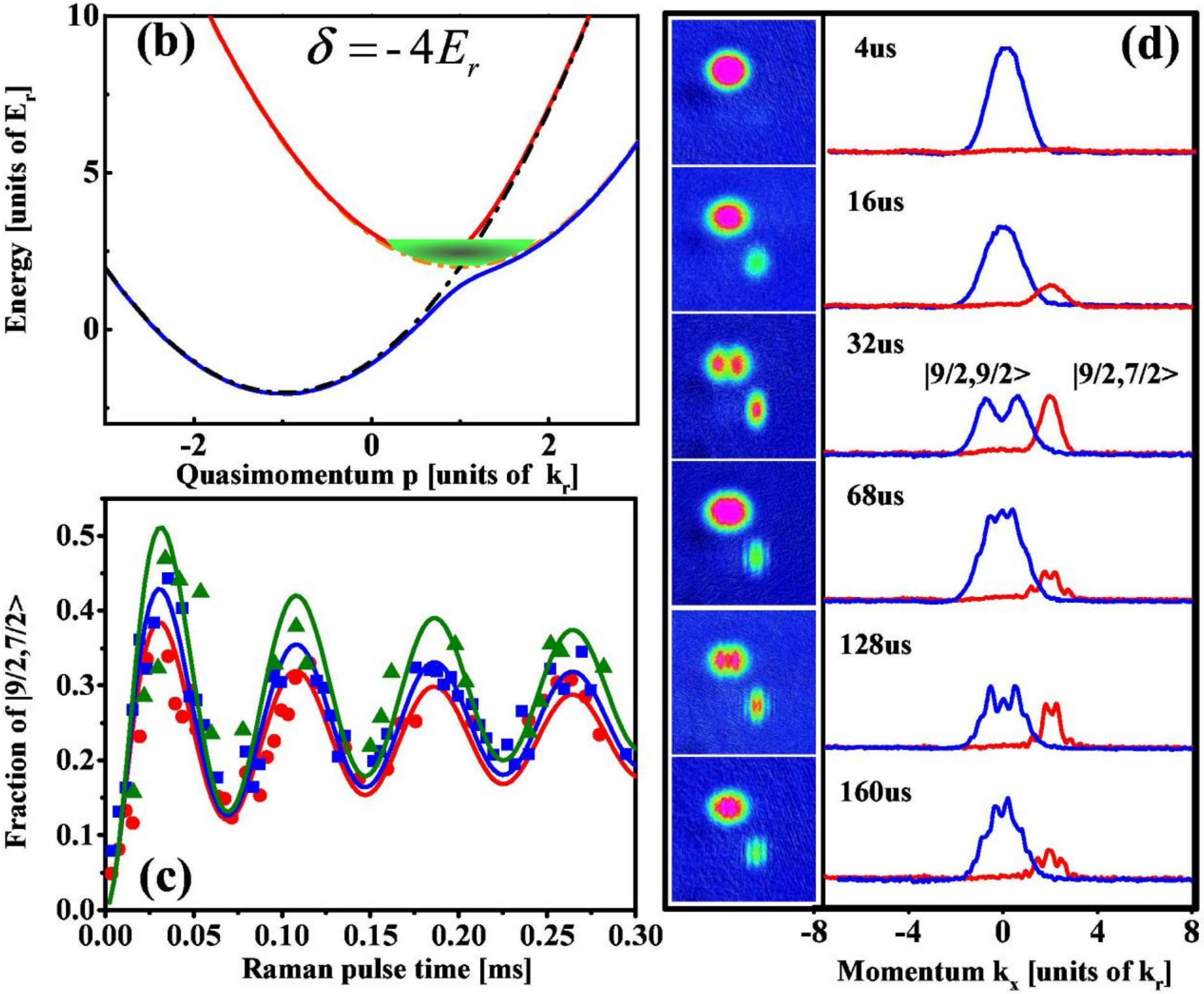
$$|\uparrow', p\rangle = c_1|\uparrow, k_x = p + k_R\rangle + c_2|\downarrow, k_x = p - k_R\rangle$$
$$|\downarrow', p\rangle = c_3|\uparrow, k_x = p + k_R\rangle + c_4|\downarrow, k_x = p - k_R\rangle$$

$$\hat{H}_2=\frac{\hbar^2\hat{k}^2}{2m}\check{1}+\frac{\Omega}{2}\check{\sigma}_z+\frac{\delta}{2}\check{\sigma}_y+2\frac{\hbar^2 k_L\hat{k}_x}{2m}\check{\sigma}_y+E_L\,\check{1}$$

**Spin-orbit coupled form**



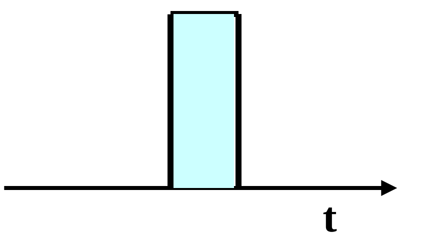
# SO Coupled Fermi Gases: Raman Rabi Oscillation




$$n_{\downarrow}(\mathbf{p}+2\hbar k_r \hat{\mathbf{e}}_z, r, t) = n_{\uparrow}(\mathbf{p}, \mathbf{r}, 0)\frac{1}{1+\left(\frac{2p_x k_r}{\Omega m}\right)^2}\sin^2\sqrt{(p_x k_r/m)^2+\Omega^2/4t}$$

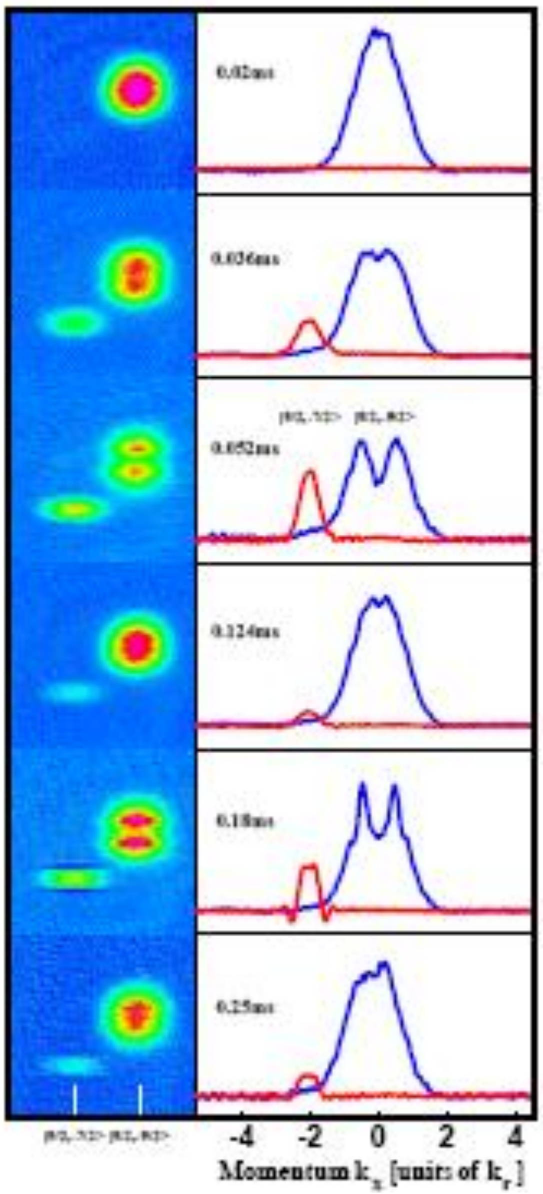
$$\Omega = 1.48(5)E_r.$$

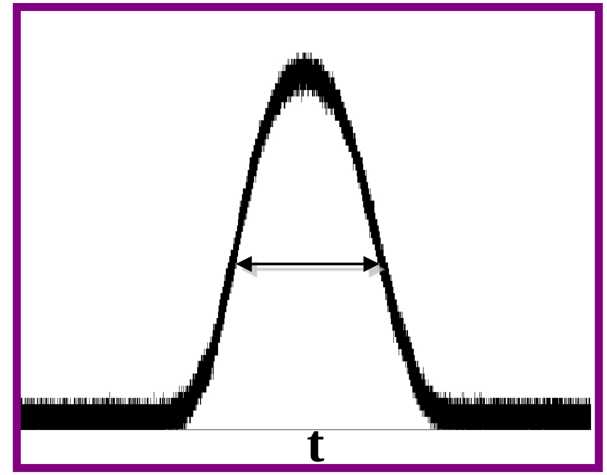
**First prepare fermion in 9/2, and then turn on Raman coupling with square envelop pulse**

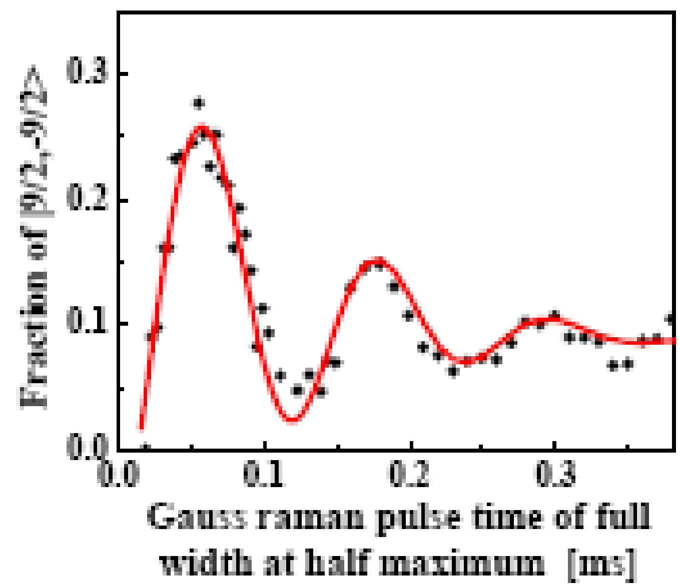



P. Wang, Z. Yu, Z. Fu, J. Miao, L. Huang, S. Chai, H. Zhai, and J. Zhang, arXiv:1204.1887 appear in *Phys. Rev. Lett.*

# Raman coupling with Gaussian envelop pulse



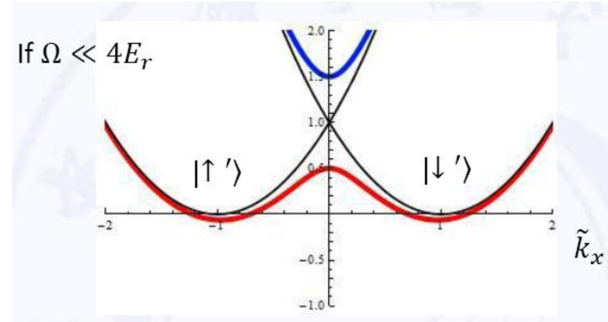



# SO Coupled Fermi Gases: Equilibrium Momentum distribution

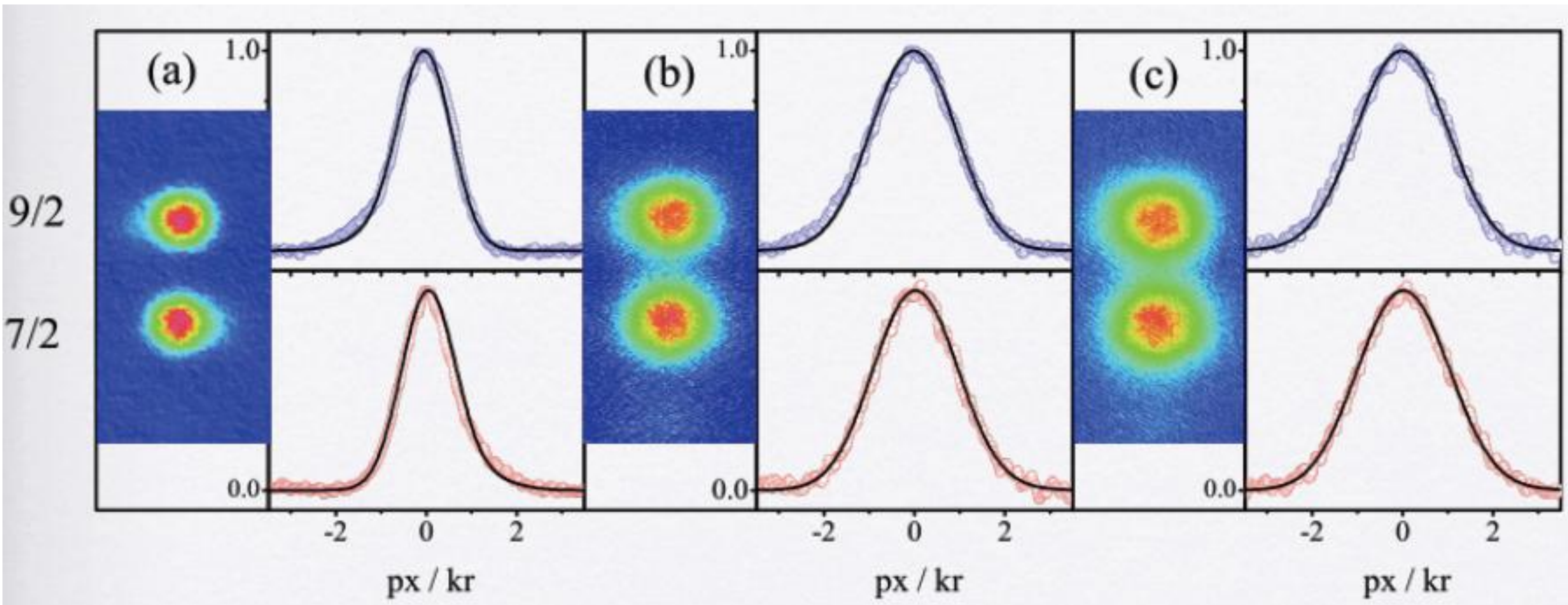
$$H_R(k_x) = \hbar \begin{pmatrix} \frac{\hbar}{2m}(p+k_R)^2 - \delta/2 & \Omega/2 \\ \Omega/2 & \frac{\hbar}{2m}(p-k_R)^2 + \delta/2 \end{pmatrix}$$

$\delta = 0,$




**Break spatial reflectional symmetry:** $n(\mathbf{p}) \neq n(-\mathbf{p})$

**Preserve reversal symmetry:** $n_\uparrow(\mathbf{k}) = n_\downarrow(-\mathbf{k})$




**Time of flight measurement with Stern-Gerlach effect**

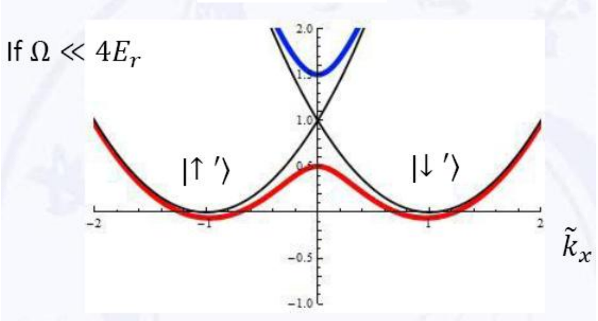
**P. Wang, Z. Yu, Z. Fu, J. Miao, L. Huang, S. Chai, H. Zhai, and J. Zhang, arXiv:1204.1887 appear in *Phys. Rev. Lett.***

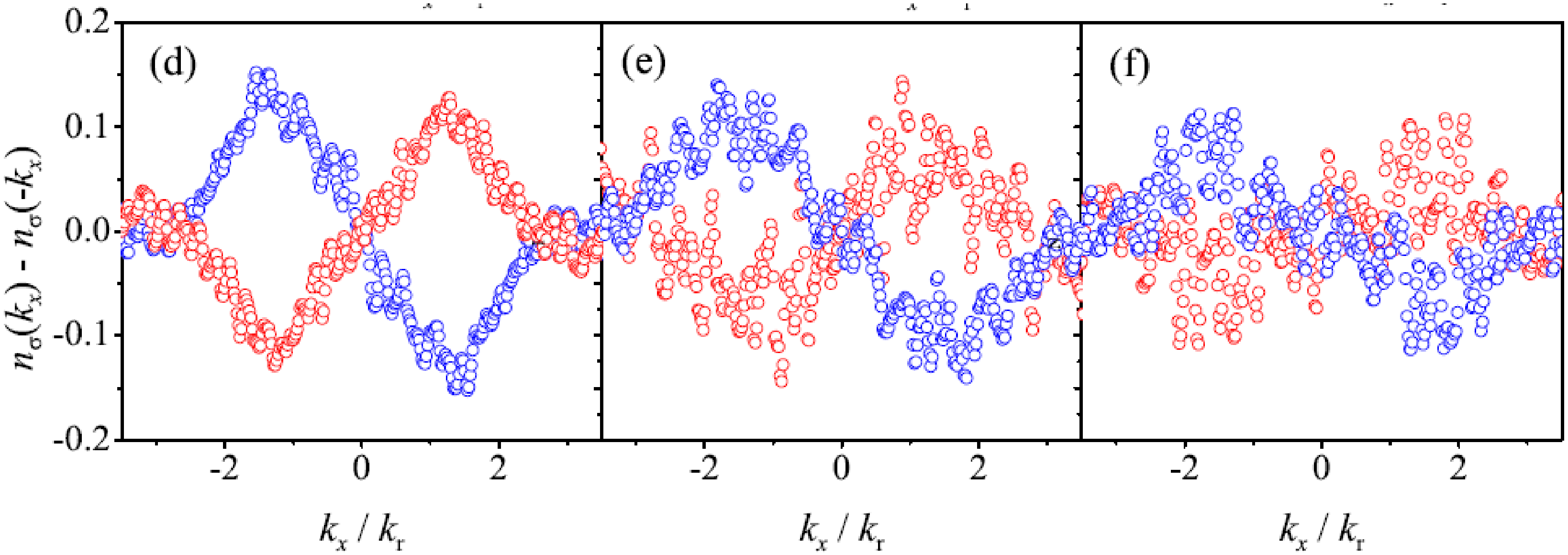
# SO Coupled Fermi Gases: Equilibrium Momentum distribution

$\delta = 0$,

**Break spatial reflectional symmetry:** $n(\mathbf{p}) \neq n(-\mathbf{p})$

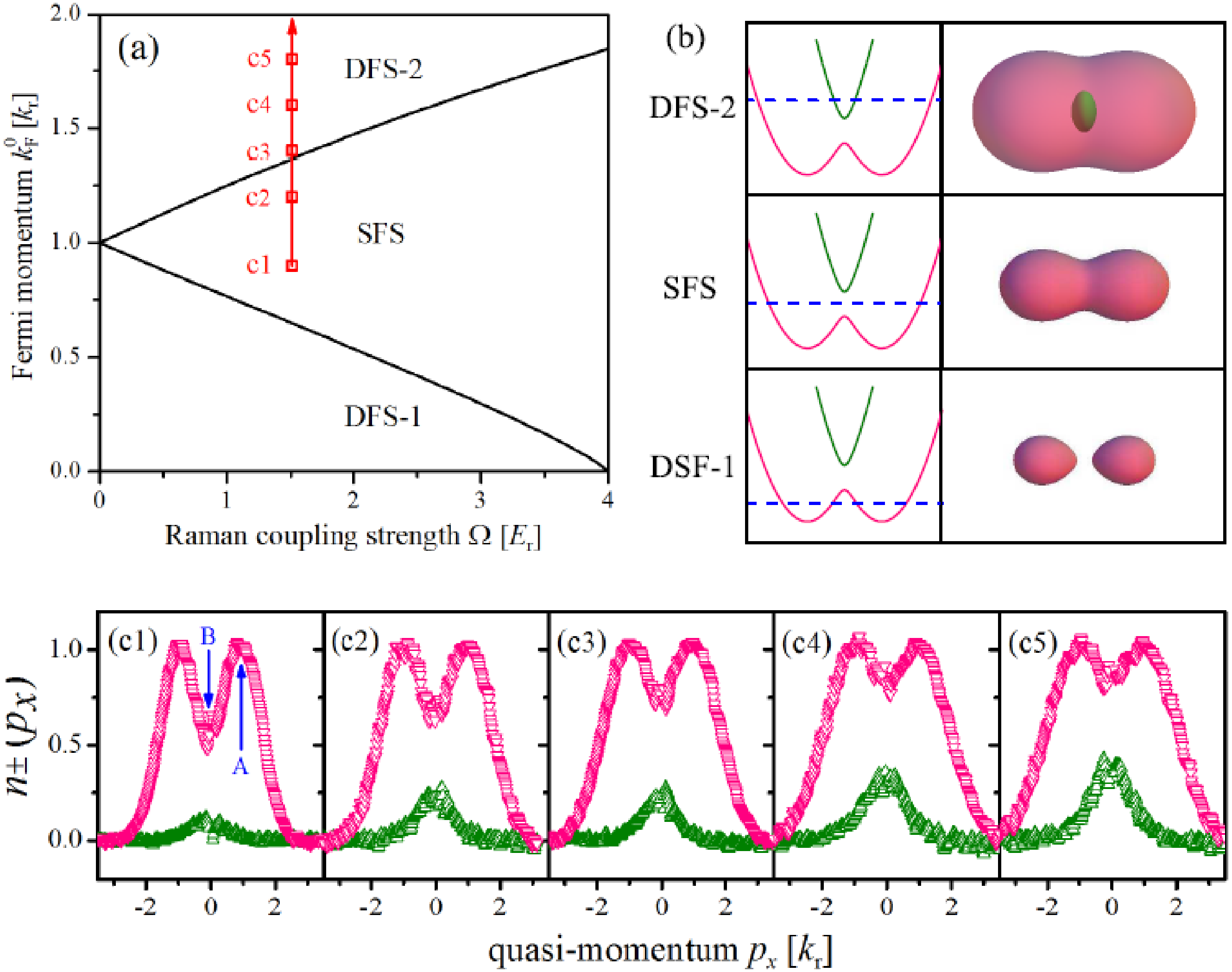
**Preserve time reversal symmetry:** $n_{\uparrow}(\mathbf{k}) = n_{\downarrow}(-\mathbf{k})$




$$n_\sigma(p_x) - n_\sigma(-p_x)$$

# SO Coupled Fermi Gases: Momentum distribution in helical bases



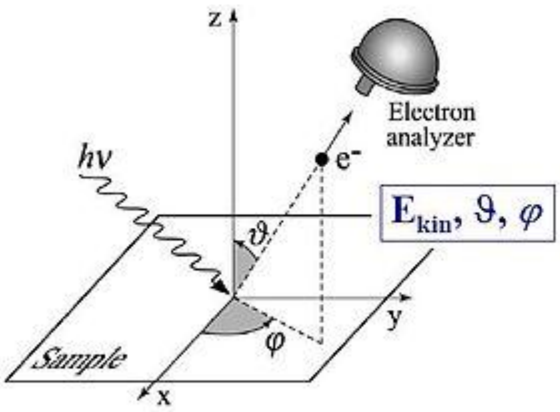

$$n_+(\mathbf{p}) = \frac{u_\mathbf{p}^2 n_\uparrow(\mathbf{p} - \hbar k_r \hat{\mathbf{e}}_x) - v_\mathbf{p}^2 n_\downarrow(\mathbf{p} + \hbar k_r \hat{\mathbf{e}}_x)}{u_\mathbf{p}^2 - v_\mathbf{p}^2}$$

$$n_-(\mathbf{p}) = \frac{v_\mathbf{p}^2 n_\uparrow(\mathbf{p} - \hbar k_r \hat{\mathbf{e}}_x) - u_\mathbf{p}^2 n_\downarrow(\mathbf{p} + \hbar k_r \hat{\mathbf{e}}_x)}{v_\mathbf{p}^2 - u_\mathbf{p}^2}$$

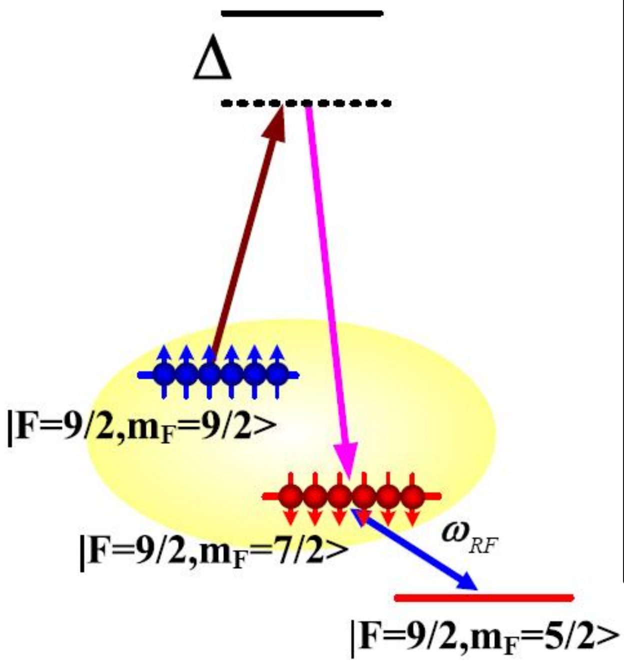
**(A) Double peak structure in lower branch**
**(B) Small population in higher branch**

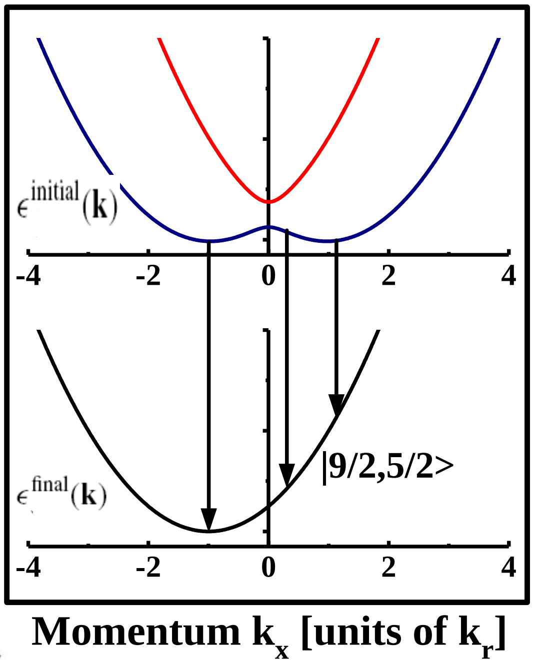
**(A) Double peak structure gradually disappears**
**(B) Significant population in higher branch**

# Momentum-resolved RF spectroscopy of non-interacting SO coupling Fermi gas




角分辨光电子谱(Angle resolved photoemission spectroscopy ARPES)




$$\hbar\omega_{\rm RF} = E_Z + \epsilon^{\rm initial}(\mathbf{k}) - \epsilon^{\rm final}(\mathbf{k})$$

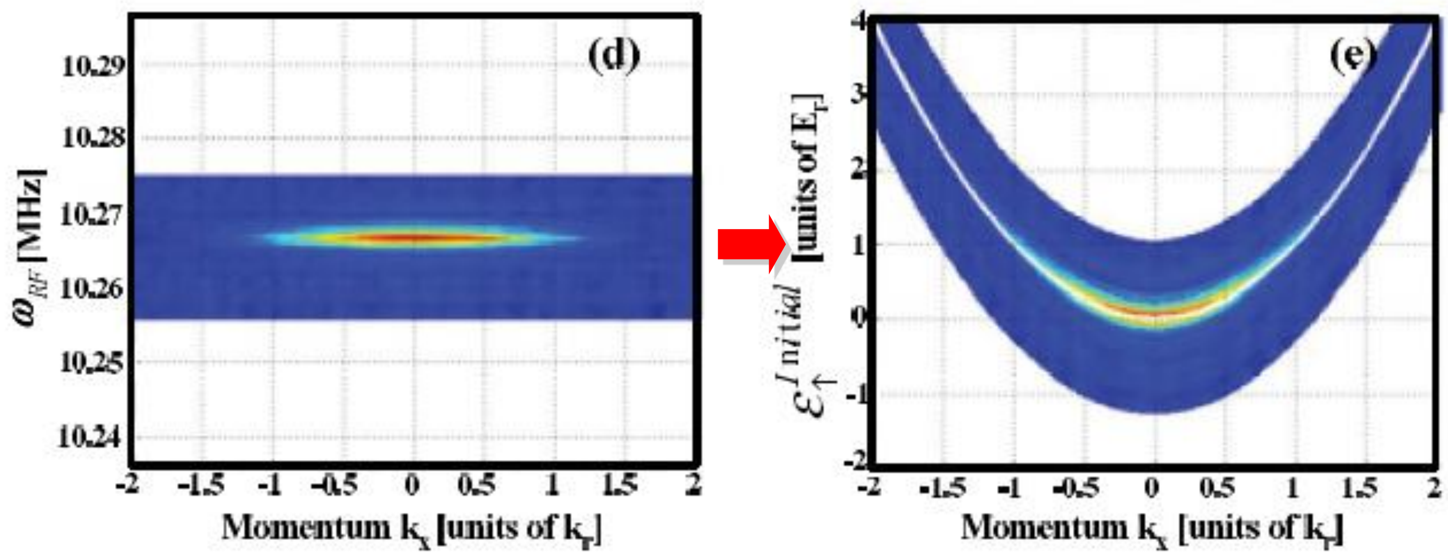
$$\epsilon^{\rm initial}(\mathbf{k}) = \hbar\omega_{\rm RF} - E_Z + \epsilon^{\rm final}(\mathbf{k})$$

***Ez*** **: the energy split of the two Zeeman states**

$\epsilon^{\rm initial}(\mathbf{k})$**: energy-momentum dispersion of the initial state**

$\epsilon^{\rm final}(\mathbf{k})$ **: energy-momentum dispersion of the final state (empty state)**

# Momentum-resolved RF spectroscopy of non-interacting Fermi gas without SO coupling




**When:** $\epsilon^{\text{initial}}(\mathbf{k}) = \epsilon^{\text{final}}(\mathbf{k}) = \hbar^2\mathbf{k}^2/2m$

$$\hbar\omega_{\text{RF}} = E_Z$$

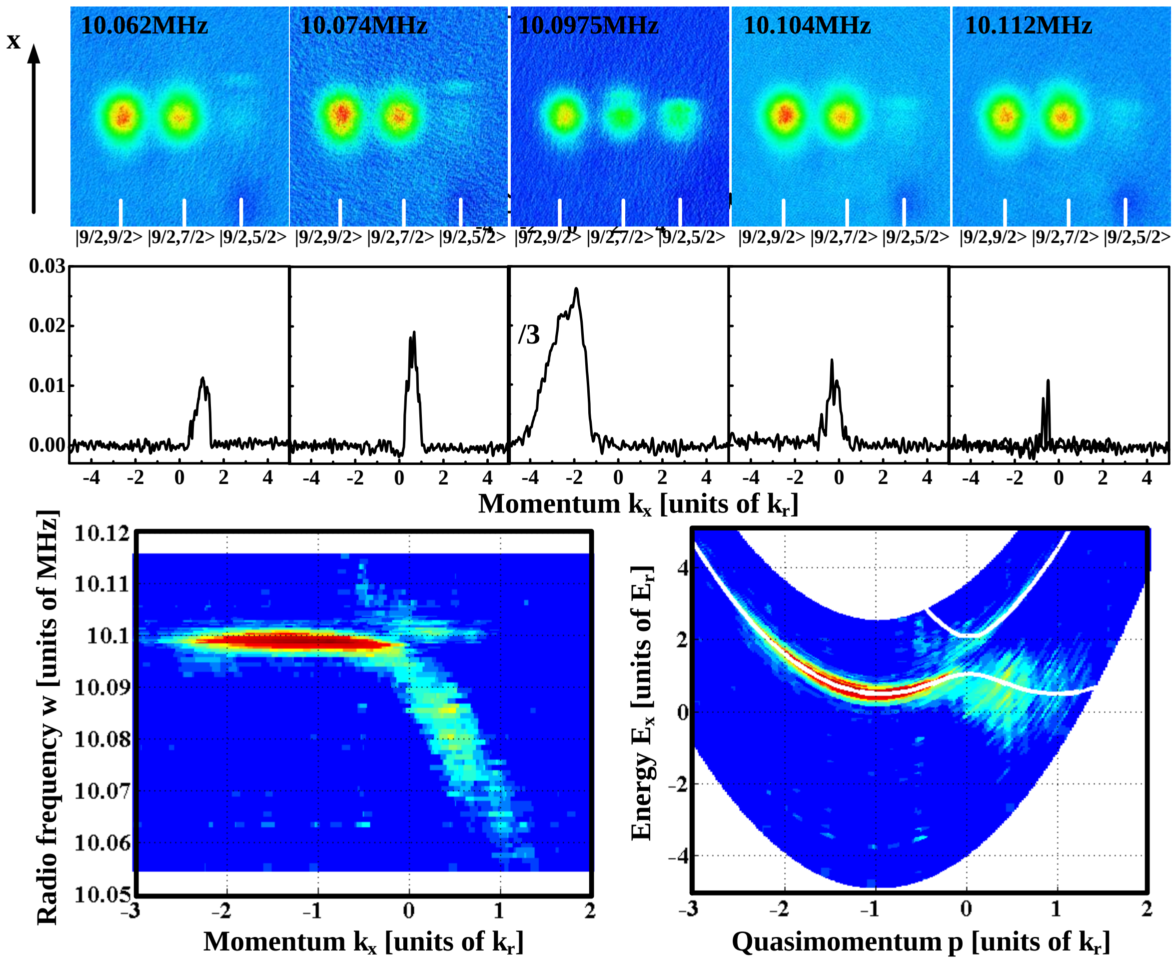
**When we know:**

$$\epsilon^{\text{final}}(\mathbf{k}) = \hbar^2\mathbf{k}^2/2m$$

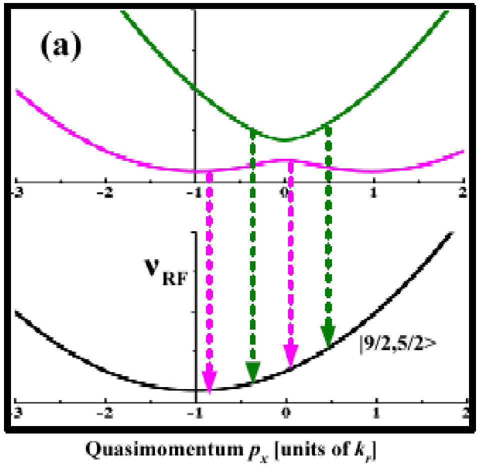
**Then:**

$$\epsilon^{\text{initial}}(\mathbf{k}) = \hbar\omega_{\text{RF}} - E_Z + \epsilon^{\text{final}}(\mathbf{k})$$

# Momentum-resolved RF spectroscopy of non-interacting SO coupling Fermi gas




**δ=0 Ω=1.5Er**




$$\hbar\omega_{\mathrm{RF}} = E_Z + \epsilon_{\uparrow}^{\mathrm{initial}}(\mathbf{k}) - \epsilon_{\downarrow}^{\mathrm{final}}(\mathbf{k})$$

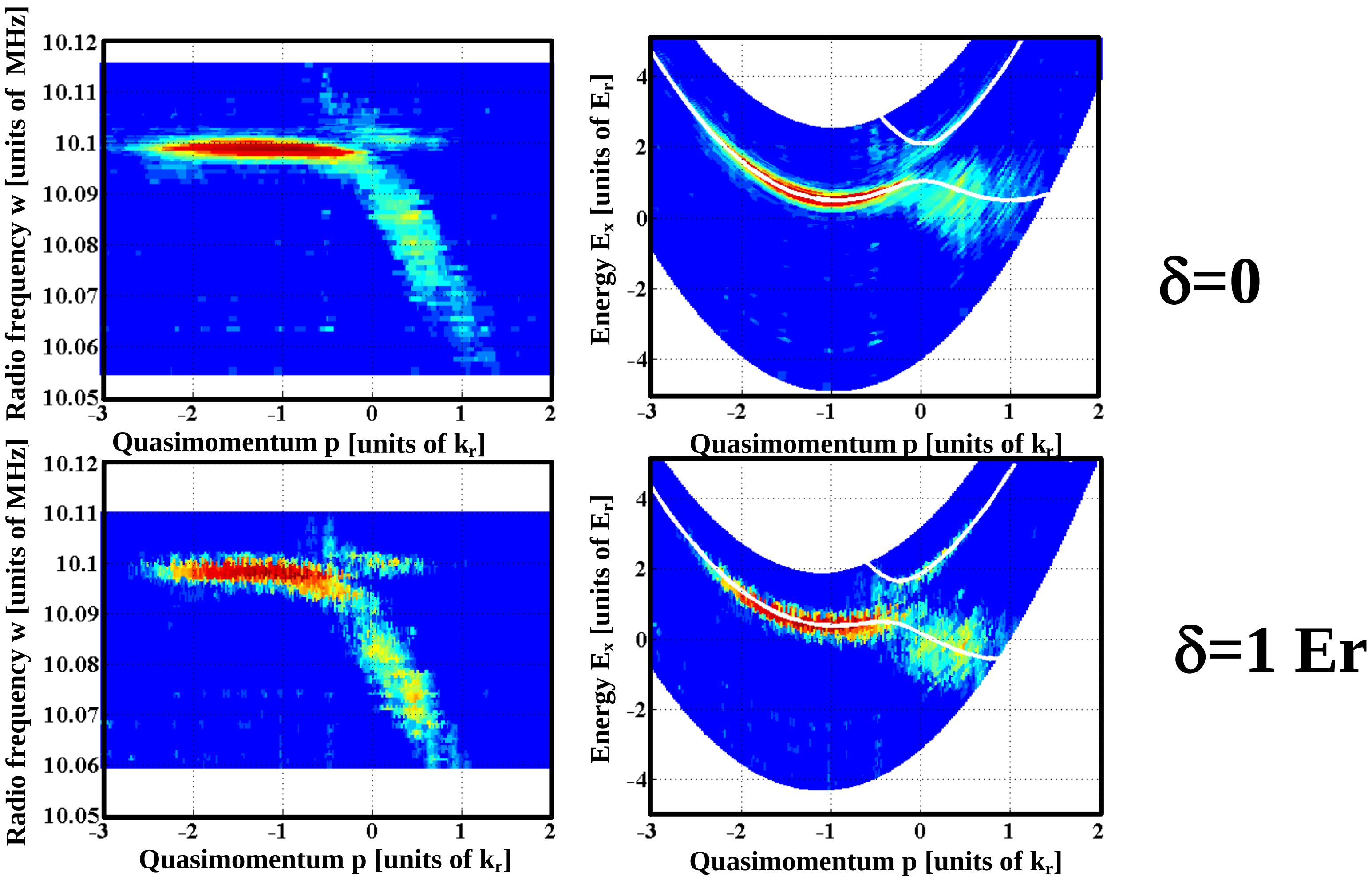
**When we know:**

$$\epsilon^{\mathrm{final}}(\mathbf{k}) = \hbar^2\mathbf{k}^2/2m$$

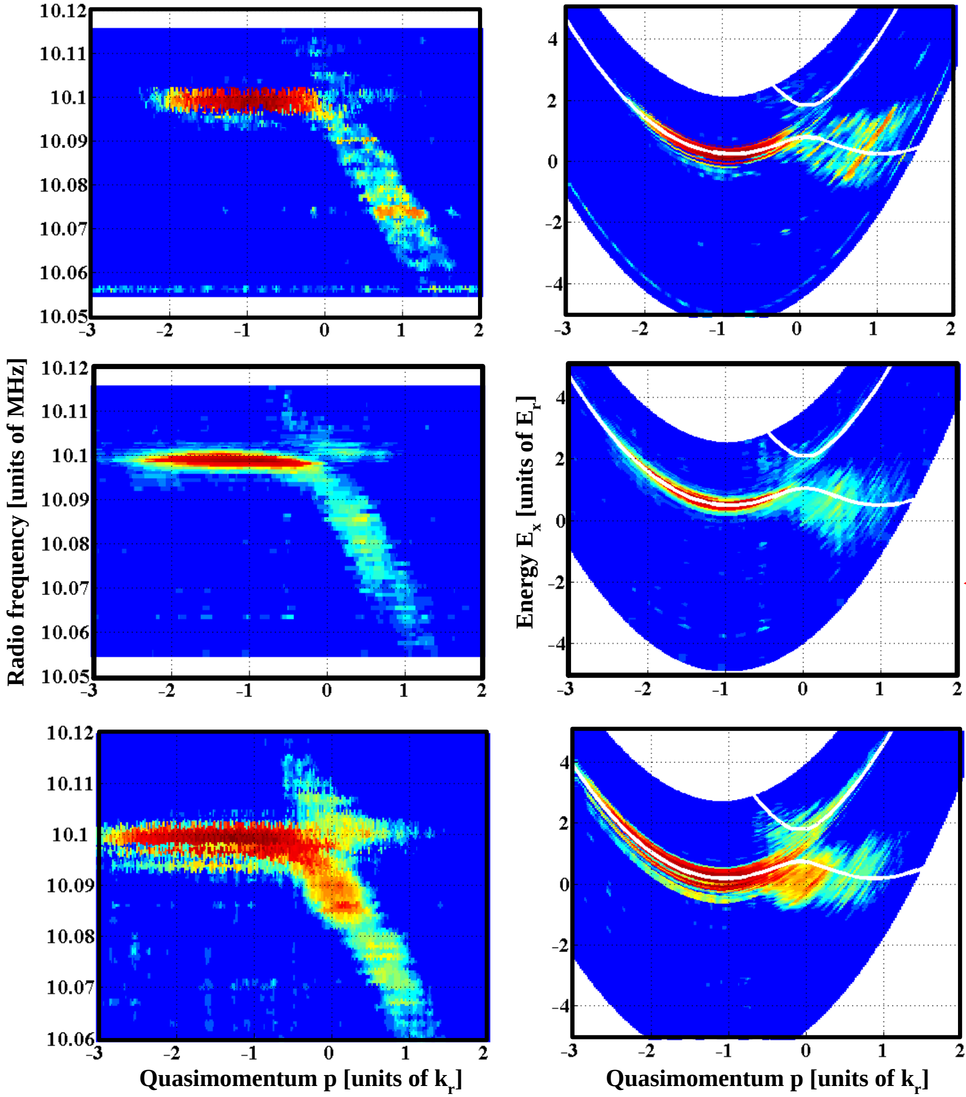
**Then:**

$$\epsilon^{\mathrm{initial}}(\mathbf{k}) = \hbar\omega_{\mathrm{RF}} - E_Z + \epsilon^{\mathrm{final}}(\mathbf{k})$$

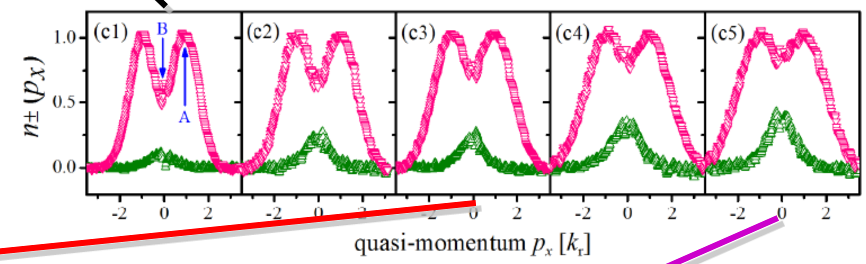
# Momentum-resolved RF spectroscopy of non-interacting SO coupling Fermi gas



# Momentum-resolved RF spectroscopy of non-interacting SO coupling Fermi gas

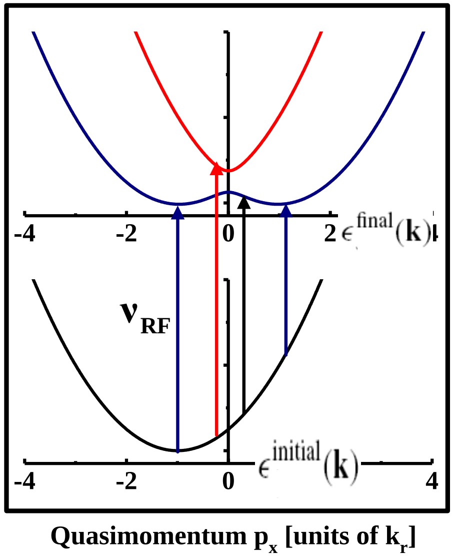


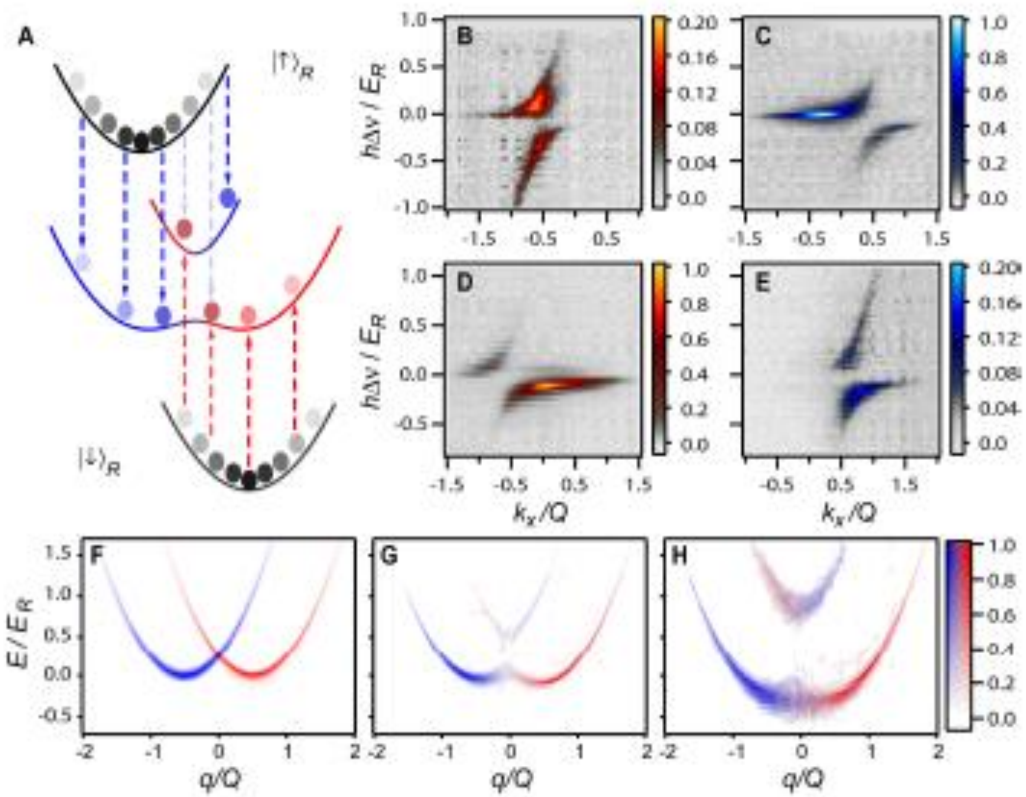

**Adiabatically change the trap frequency**



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

L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. S. Bakr, M. W. Zwierlein, arXiv:1205.3483




**When we know:**

$$\epsilon^{\text{initial}}(\mathbf{k}) = \hbar^2\mathbf{k}^2/2m$$

**Then:**

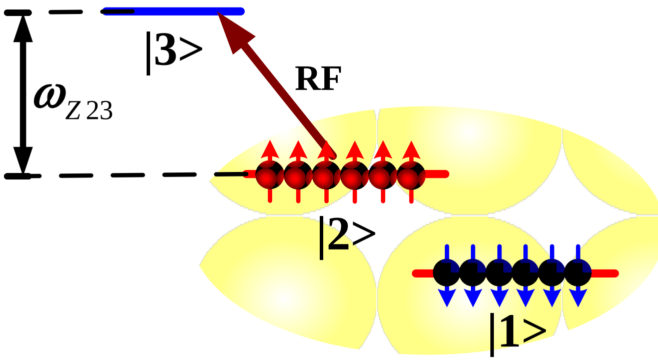
$$\epsilon^{\text{final}}(\mathbf{k}) = \hbar\omega_{\text{RF}} - E_Z + \epsilon^{\text{initial}}(\mathbf{k})$$

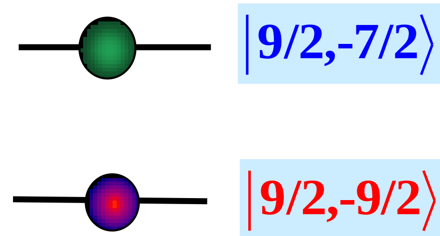
$\epsilon^{\text{final}}(\mathbf{k})$ **:SO coupling**

Raman fields have previously been used to generate spin-orbit coupling and gauge fields in pioneering work on Bose-Einstein condensates [19–21], and recently spin-orbit coupling in Fermi gases [22]. Here, we directly


[22] P. Wang, *et al.* Spin-Orbit Coupled Degenerate Fermi Gases. *arXiv:1204.1887v1 [cond-mat.quant-gas]* (2012).

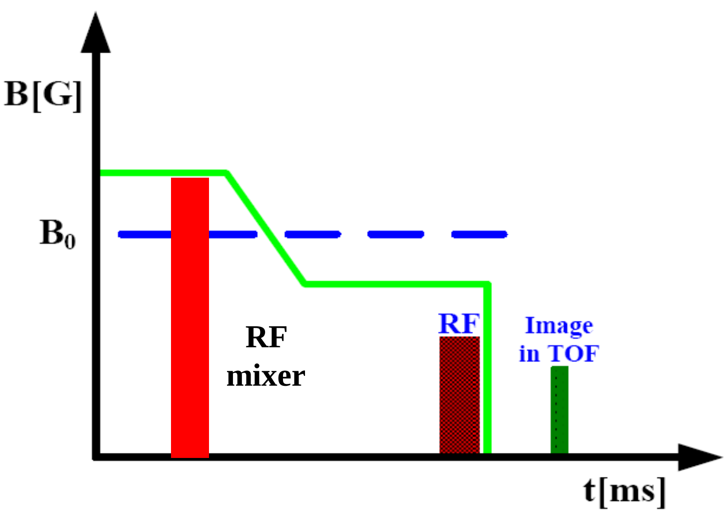
# RF spectroscopy of strongly interacting ultracold Fermi gas




S-wave $B_0$= 202.2 G

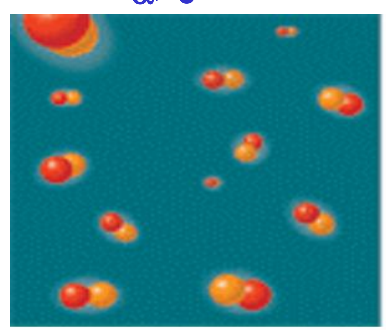
$|9/2,-9/2\rangle + |9/2,-7/2\rangle$




## BEC – BCS Crossover

*molecules*

$\alpha>0$



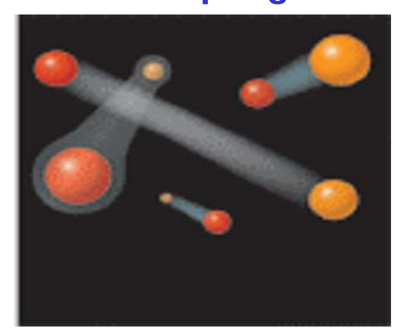
localized pairs

Crossover

Feshbach resonance

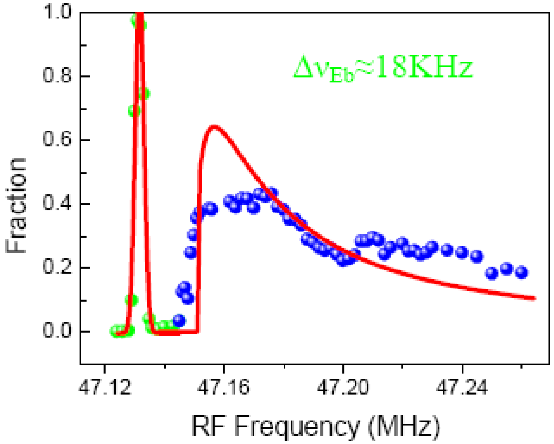
*Cooper pairs*

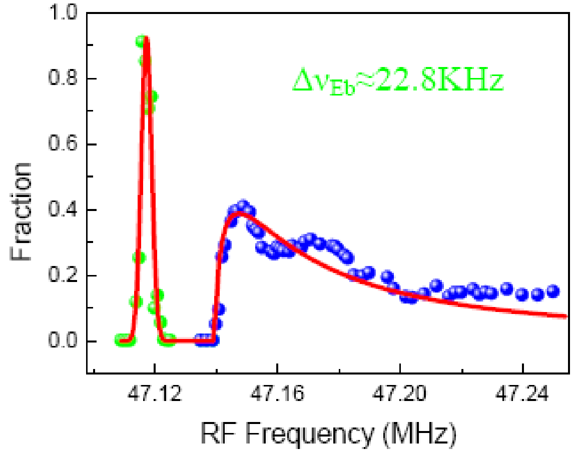
weak coupling $\alpha<0$

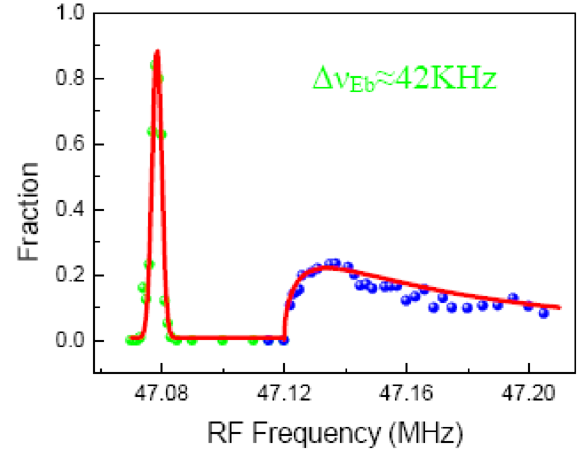


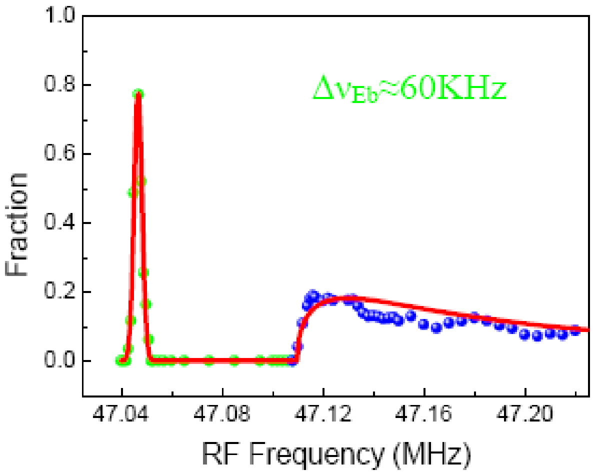
Nonlocalized pairs

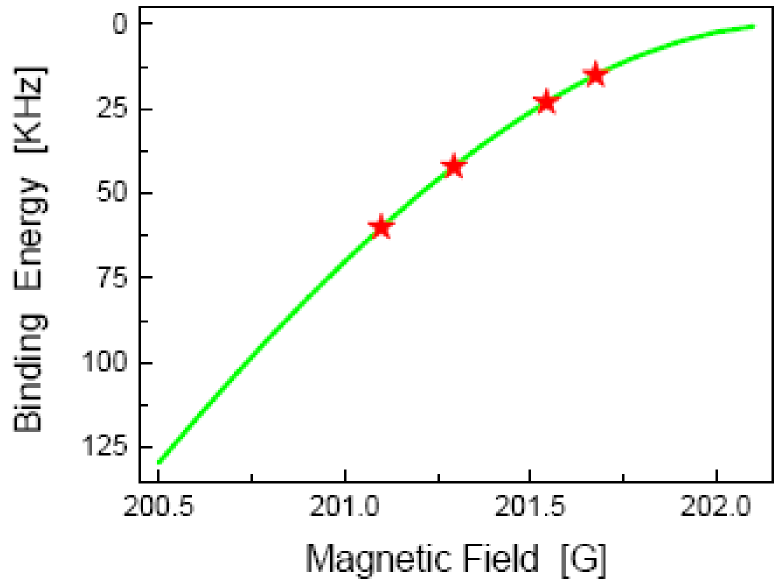
# RF spectroscopy of strongly interacting ultracold Fermi gas



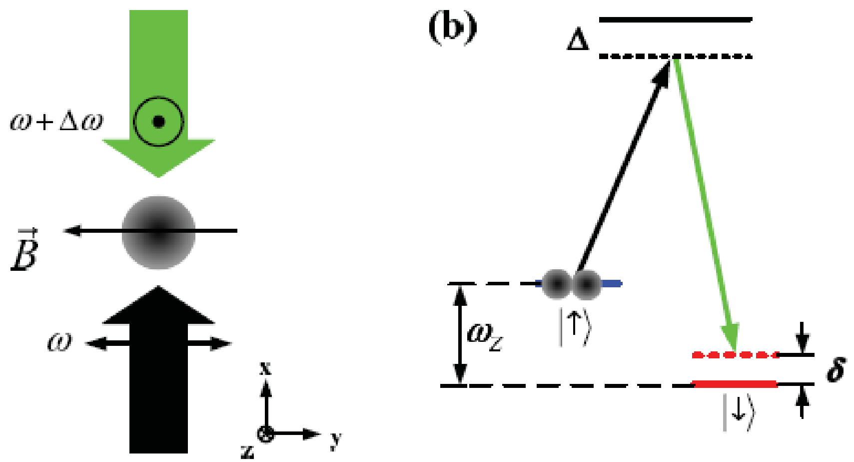




$$E_b = \frac{\hbar^2}{m(a - r_0)^2}$$

$$r_0 \approx 60a_0$$

C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Nature 424, 47 (2003)

# Momentum-resolved Raman spectroscopy of non-interacting ultracold Fermi gas




**T.-L. Dao, I. Carusotto, and A. Georges, Phys. Rev. A 80, 023627 (2009)**

$$\hbar\Delta\omega = E_Z + \epsilon^{\text{initial}}(\mathbf{k}) - \epsilon^{\text{final}}(\mathbf{k}+\mathbf{q}_r)$$

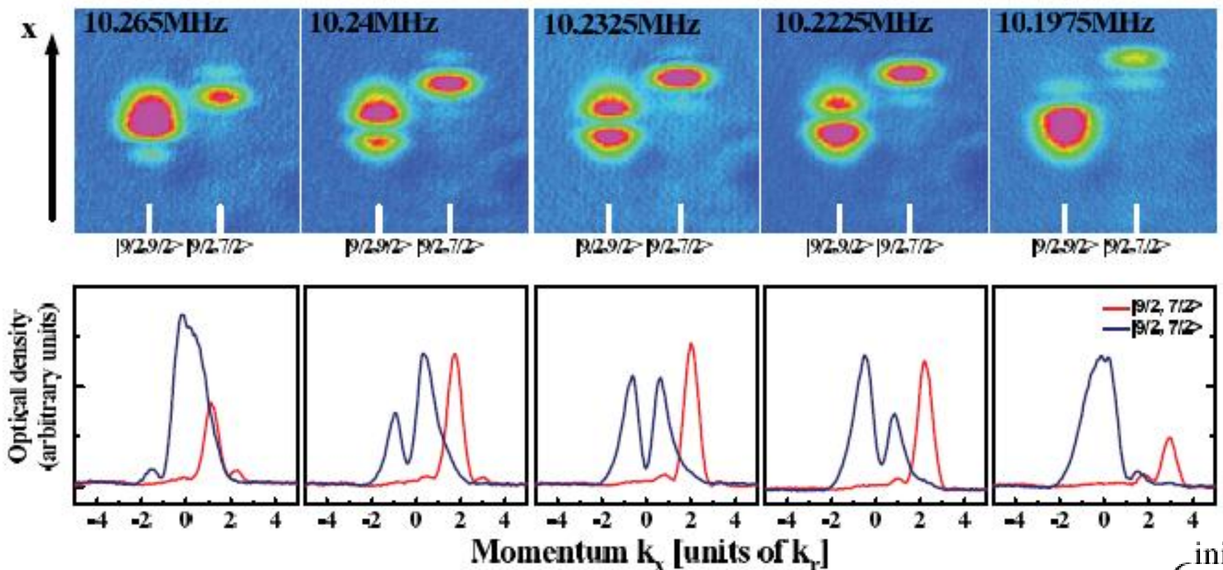
$$|\mathbf{q}_r| = 2k_r \sin(\theta/2)$$

***Ez*** **: the energy split of the two Zeeman states**

$\epsilon^{\text{initial}}(\mathbf{k})$**: energy-momentum dispersion of the initial state**

$\epsilon^{\text{final}}(\mathbf{k}+\mathbf{q}_r)$**: energy-momentum dispersion of the final state**

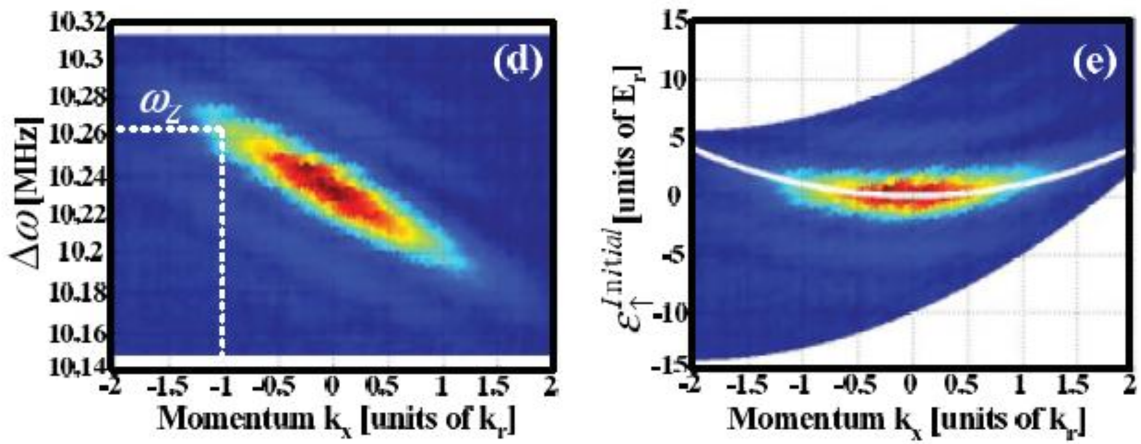
# Momentum-resolved Raman spectroscopy of non-interacting ultracold Fermi gas




First prepare fermion in 9/2, and then turn on Raman coupling pulse.

**When:**

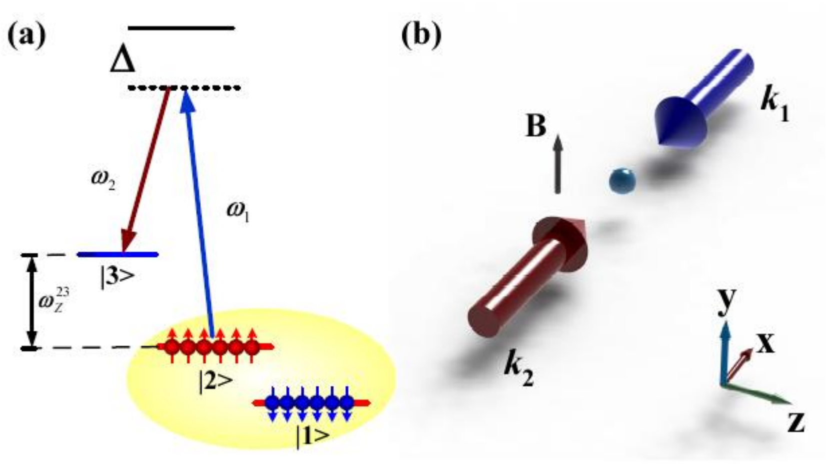
$$\epsilon^{\text{initial}}(\mathbf{k}) = \epsilon^{\text{final}}(\mathbf{k}) = \hbar^2\mathbf{k}^2/2m$$

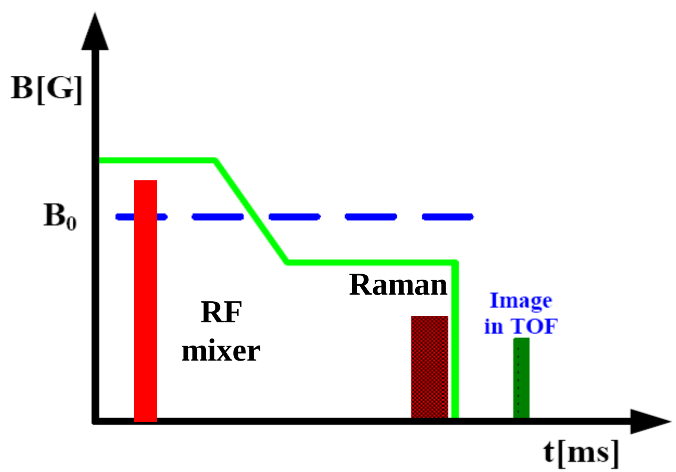


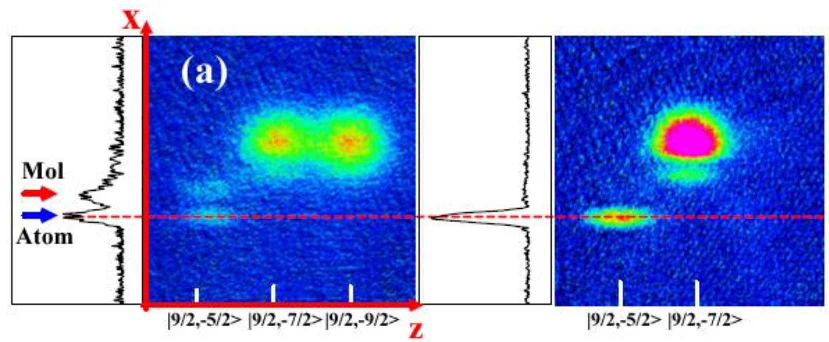

$$\hbar\Delta\omega = E_Z - \frac{\hbar^2\mathbf{q}_r^2}{2m} - \frac{\hbar^2\mathbf{q}_r\cdot\mathbf{k}}{m}$$

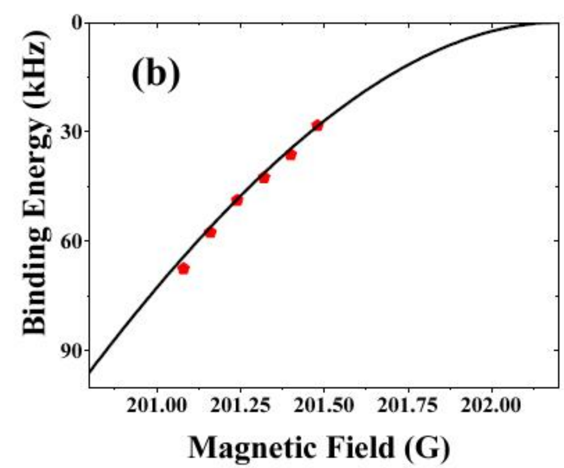
**P. Wang, Z. Fu, L. Huang, and J. Zhang, Phys. Rev. A 85, 053626 (2012); arXiv:1205.1110**

# Momentum-resolved Raman spectroscopy of bound molecules in strongly interacting ultracold Fermi gas



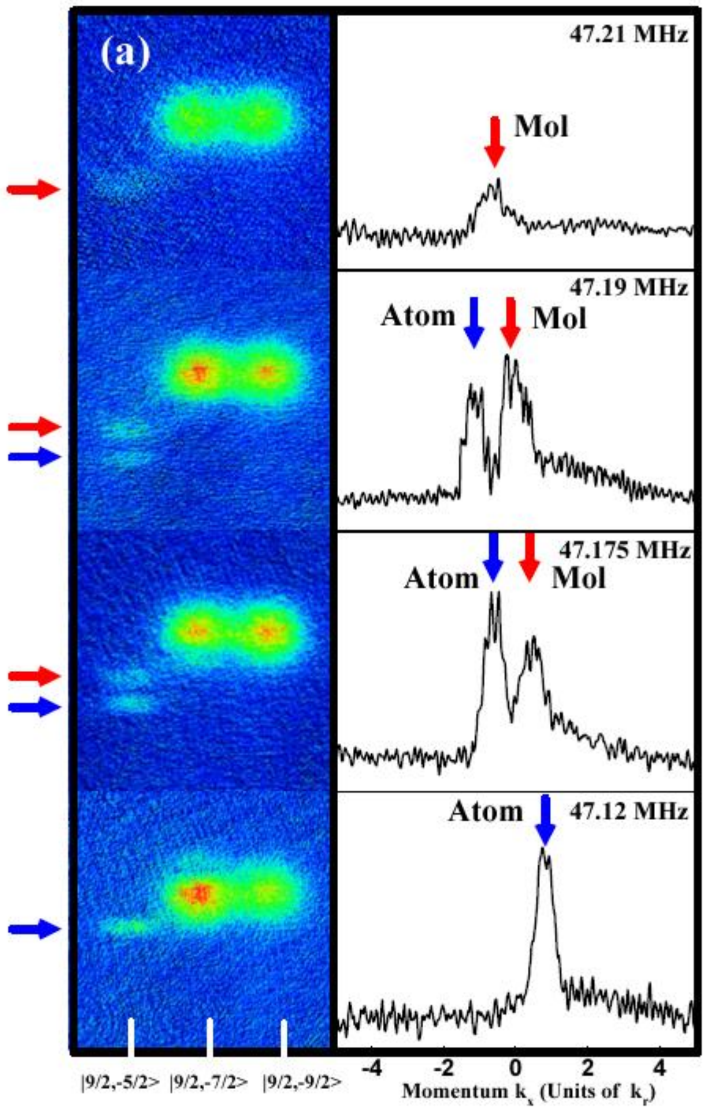



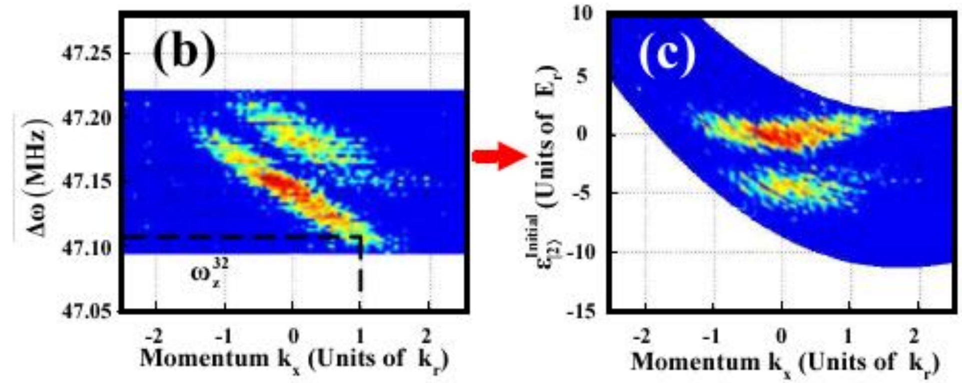




$$\hbar\Delta\omega = E_Z + \epsilon_{\uparrow}^{\text{initial}}(\mathbf{k}) - \epsilon_{\downarrow}^{\text{final}}(\mathbf{k}+\mathbf{q}_r)$$

**First prepare fermion mixture in -9/2 and -7/2, and ramp the magnetic field to generate Feshbach molecules, then turn on Raman coupling pulse with Gaussian envelop.**

# Momentum-resolved Raman spectroscopy of bound molecules in strongly interacting ultracold Fermi gas




$$\epsilon^{\text{initial}}(\mathbf{k}) = \hbar\Delta\omega - E_Z + \epsilon^{\text{final}}(\mathbf{k} + \mathbf{q}_r)$$

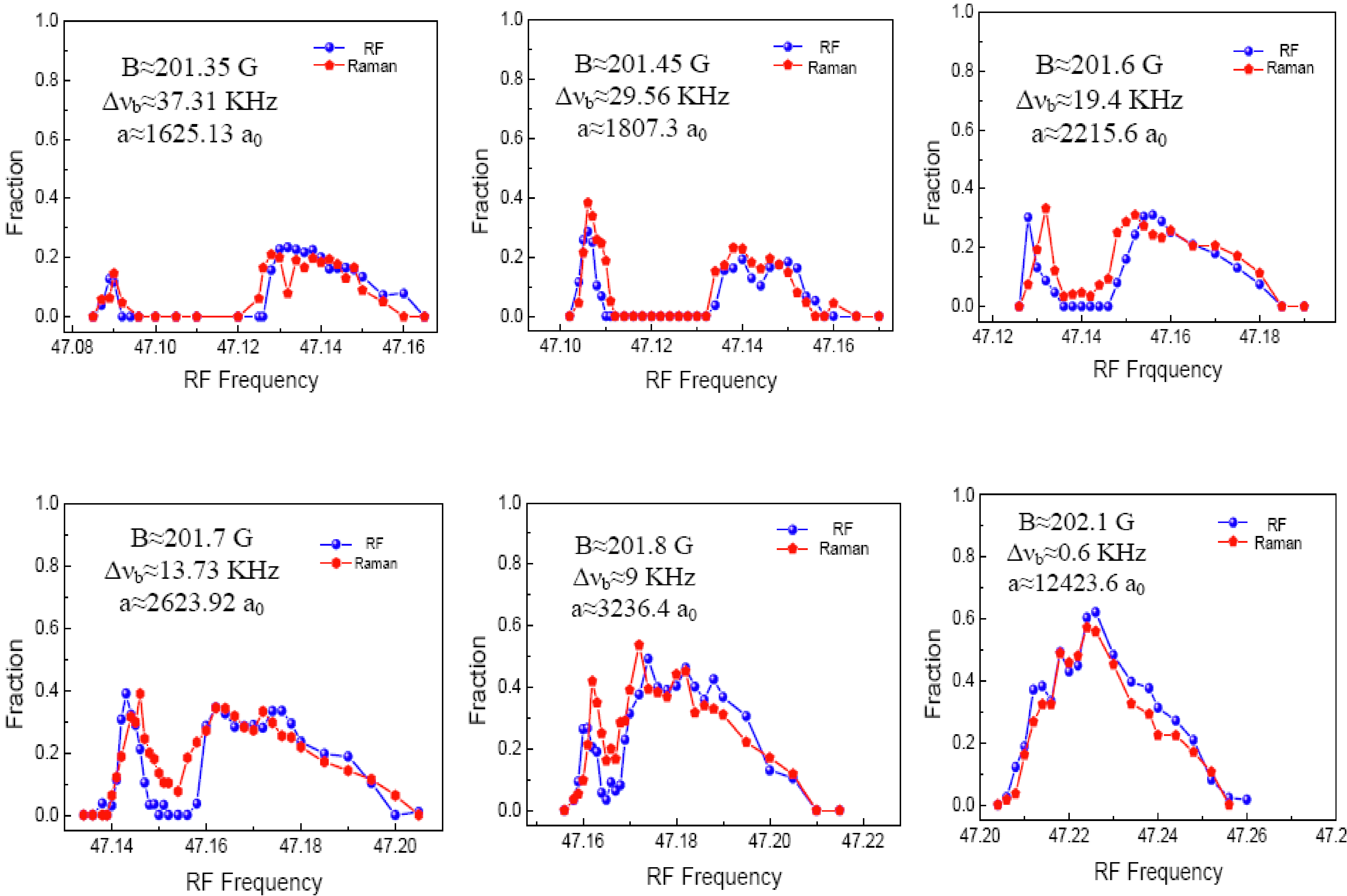
***Ez*** **: the energy split of the two Zeeman states**

$\epsilon^{\text{initial}}(\mathbf{k})$ **: dispersion of the initial state**

$\epsilon^{\text{final}}(\mathbf{k} + \mathbf{q}_r)$ **: dispersion of the final state**

**Z. Fu, P. Wang, L. Huang, Z. Meng, and J. Zhang, submitted (2012)**

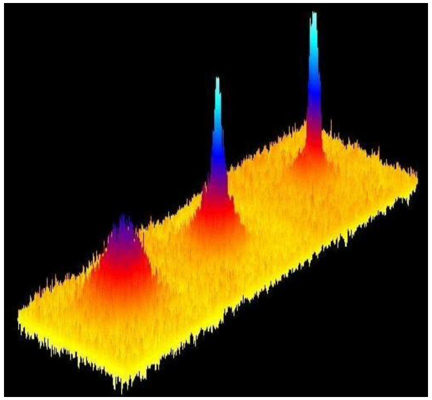
# Spin-orbit coupling Feshbach molecules



# Ultracold $^{87}$Rb-$^{40}$K Bose-Fermi mixture gases

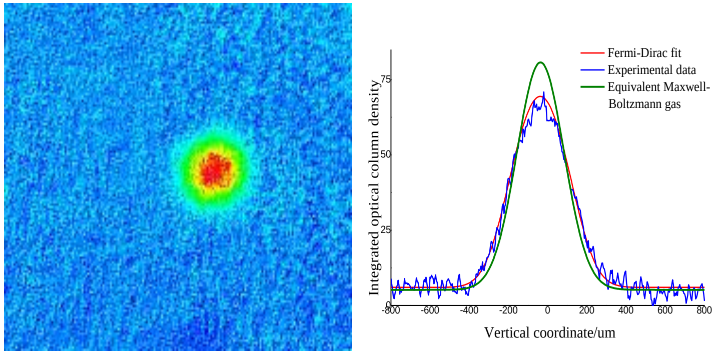
**2004. 9 Began to establish**

**2007.7.7 pm7:00, achieve $^{87}$Rb BEC**



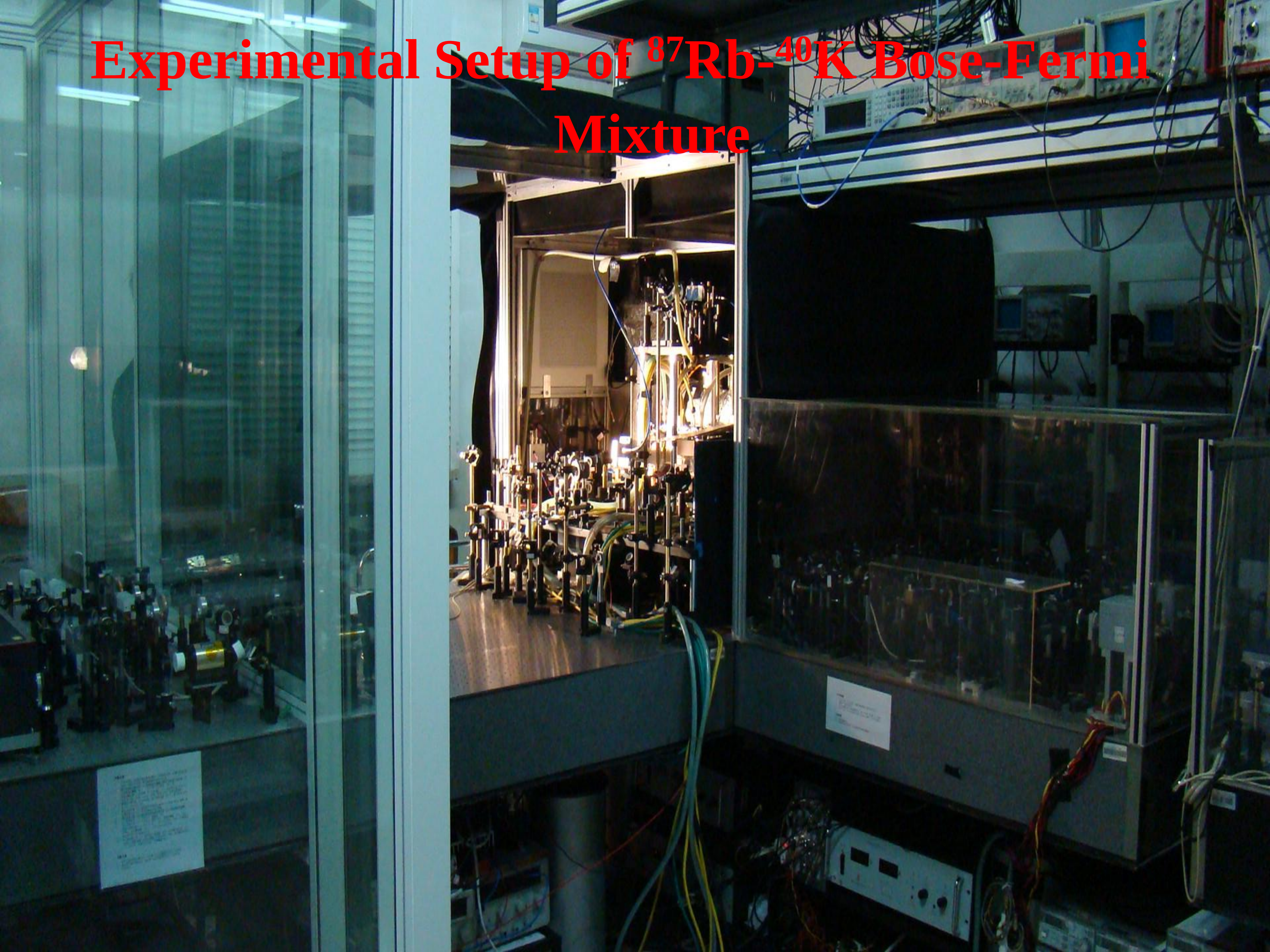
$^{87}$Rb BEC

**2007.8.30 pm11:00, using sympathetic cooling technology to achieve quantum degenerate of $^{40}$K Fermi gas**

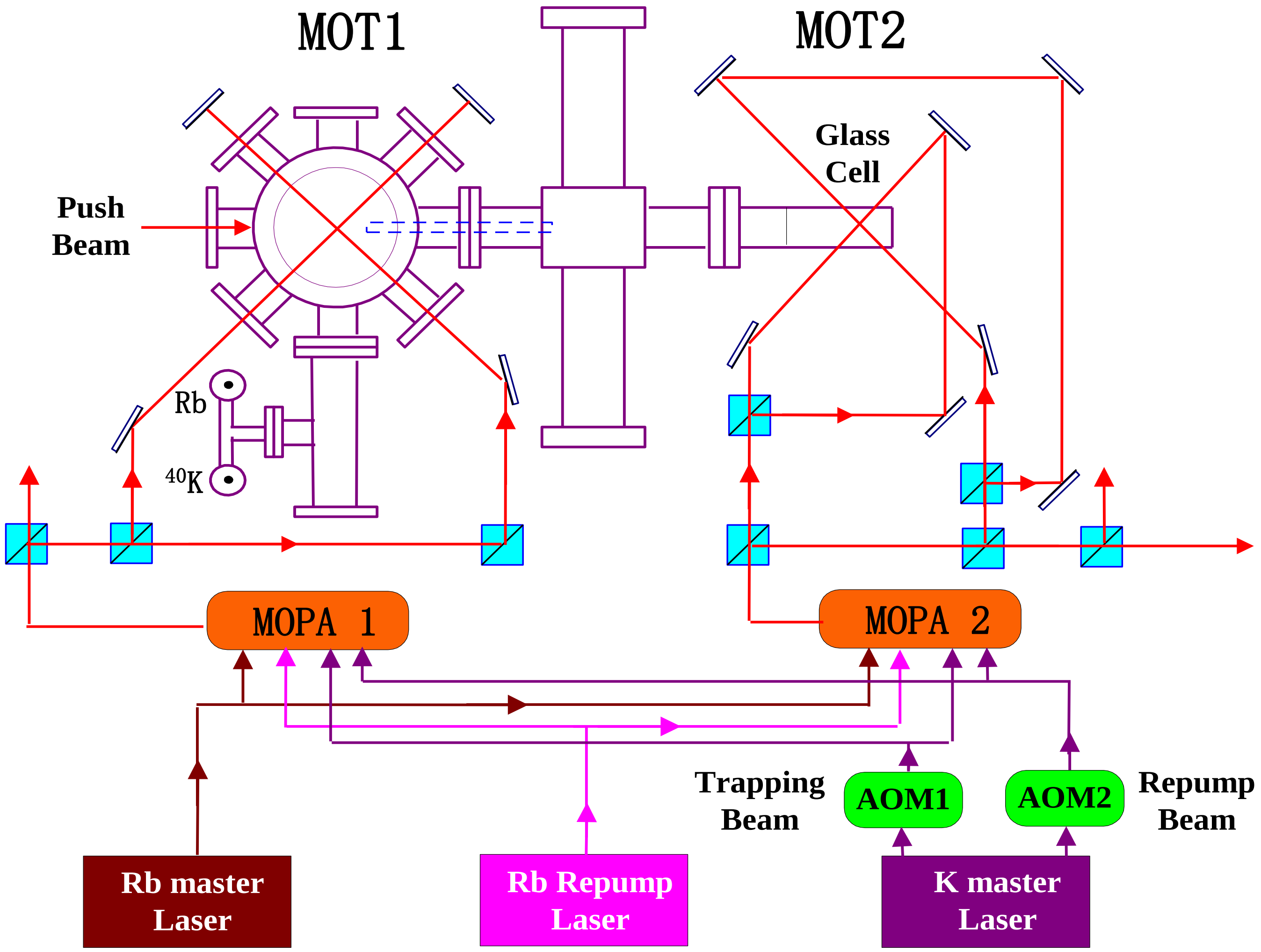



$^{40}$K DFG

# Experimental Setup of $^{87}$Rb-$^{40}$K Bose-Fermi Mixture



# Schematic of experimental setup



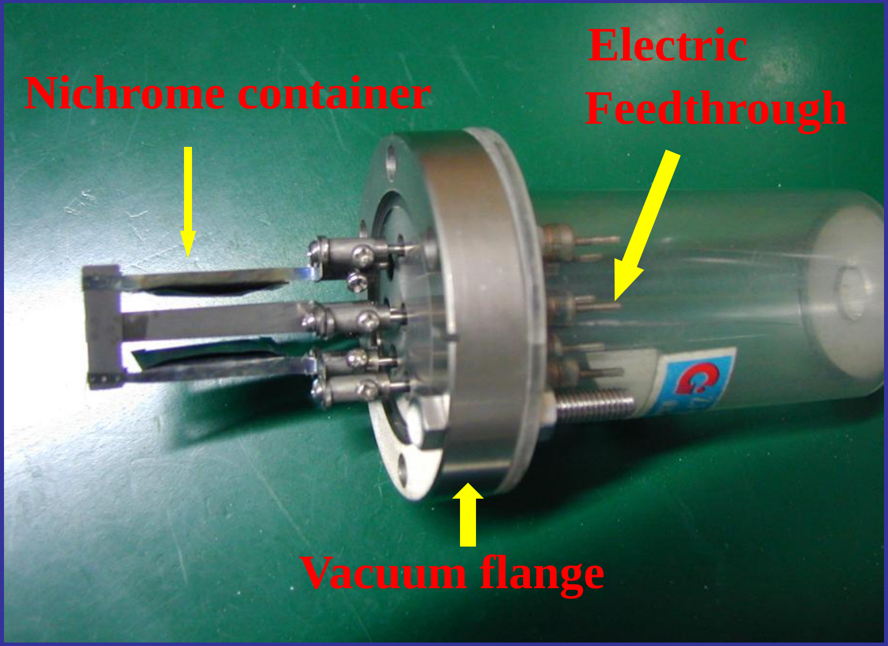
# Potassium 40 Dispenser

$$2KCl + Ca \xrightarrow{\text{加热}} 2K + CaCl_2$$

B. DeMarco, H. Rohner, and D. S. Jin, Rev. Sci. Instrum. 70, 1967 (1999).

0.0012% $^{40}K$ naturally

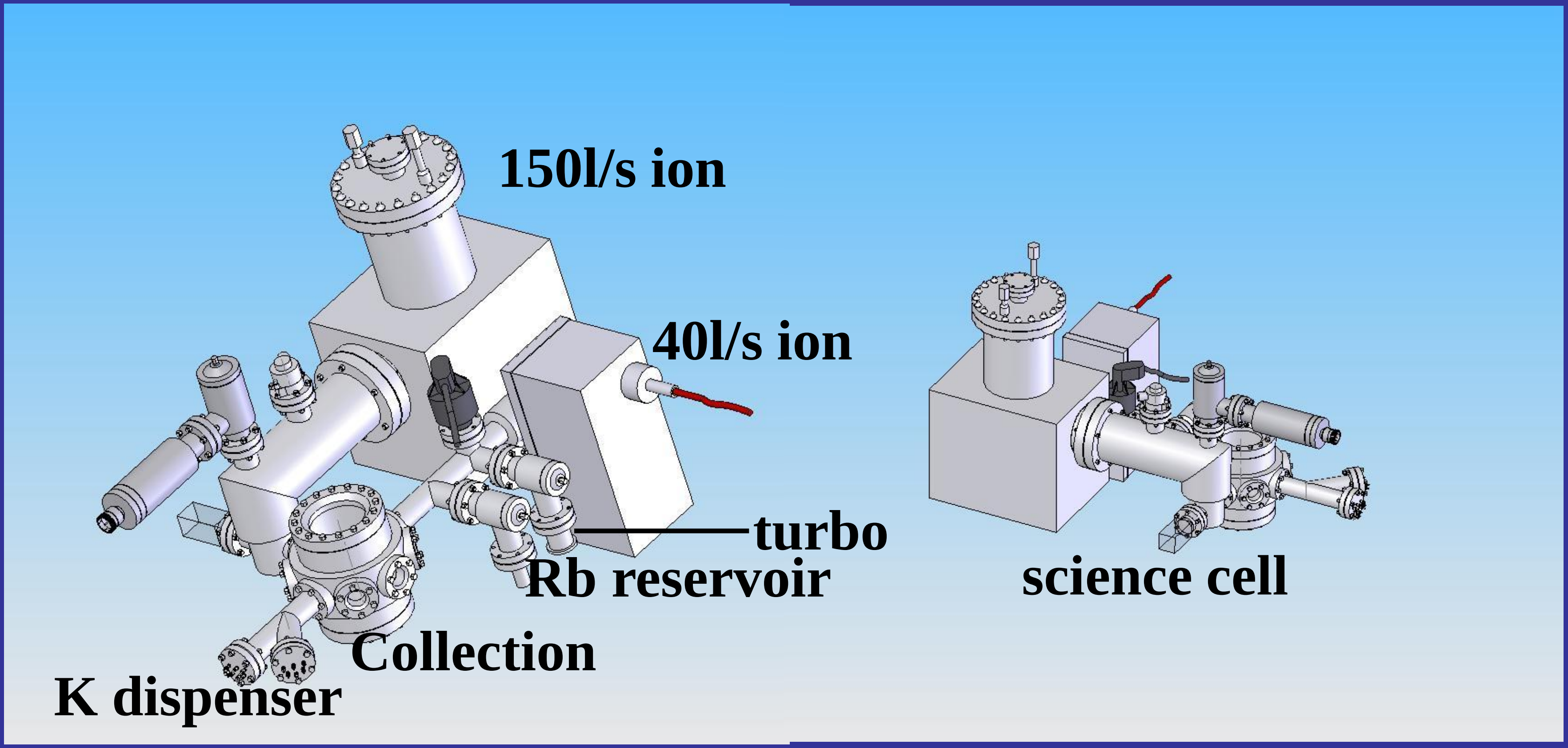
Enriched 6% $^{40}K$



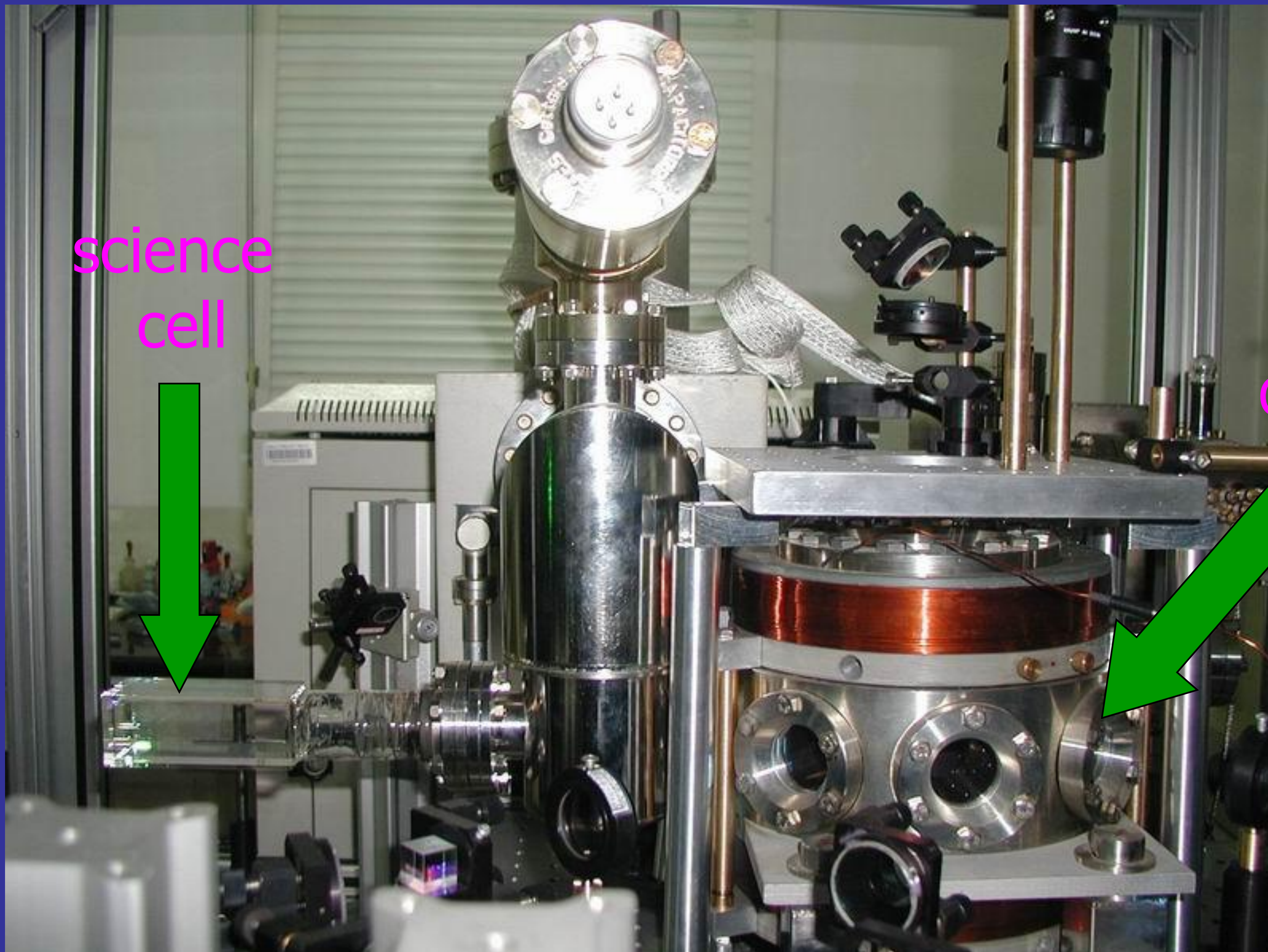

Dispenser

Glove Box

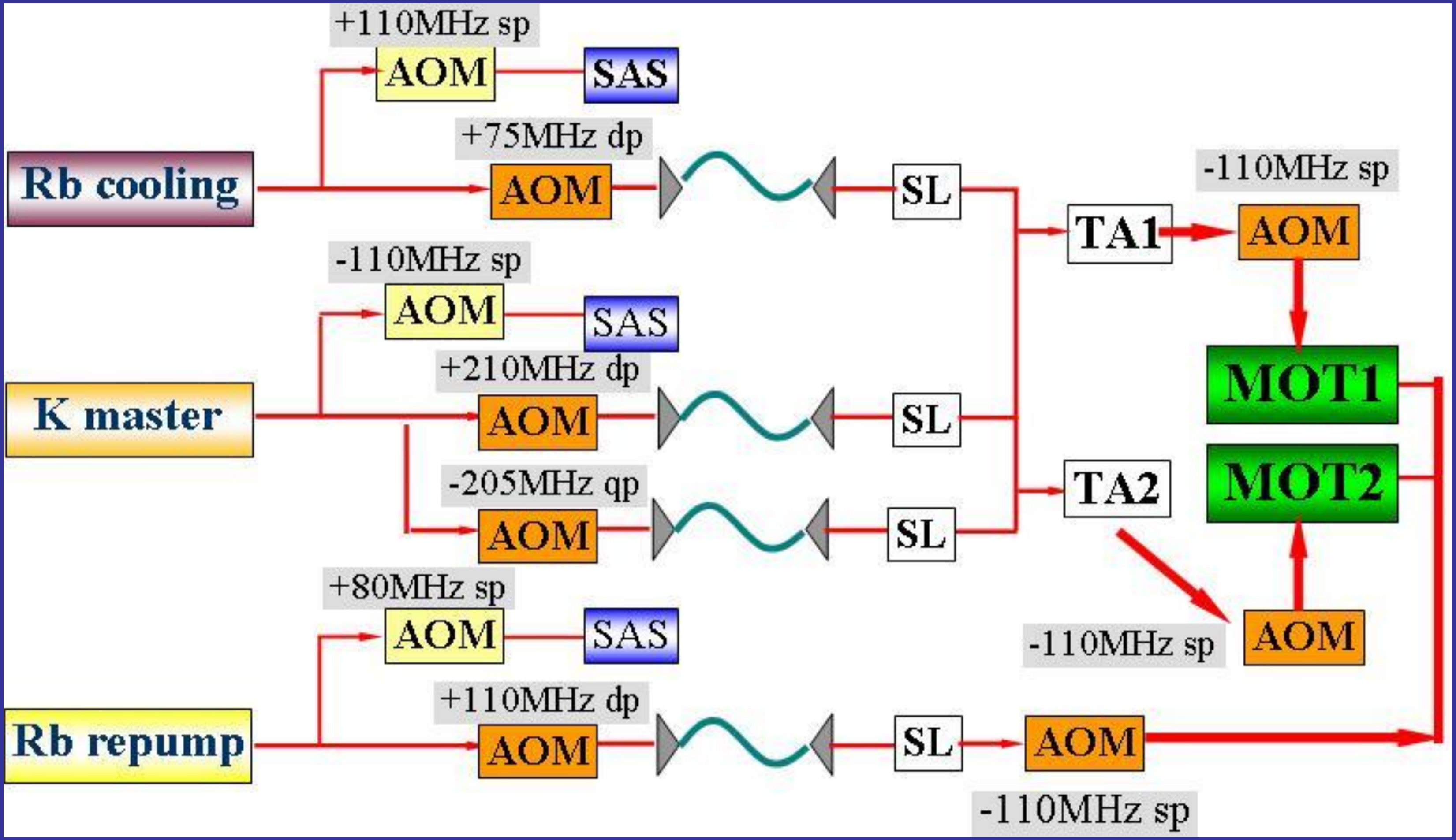
# Vacuum system

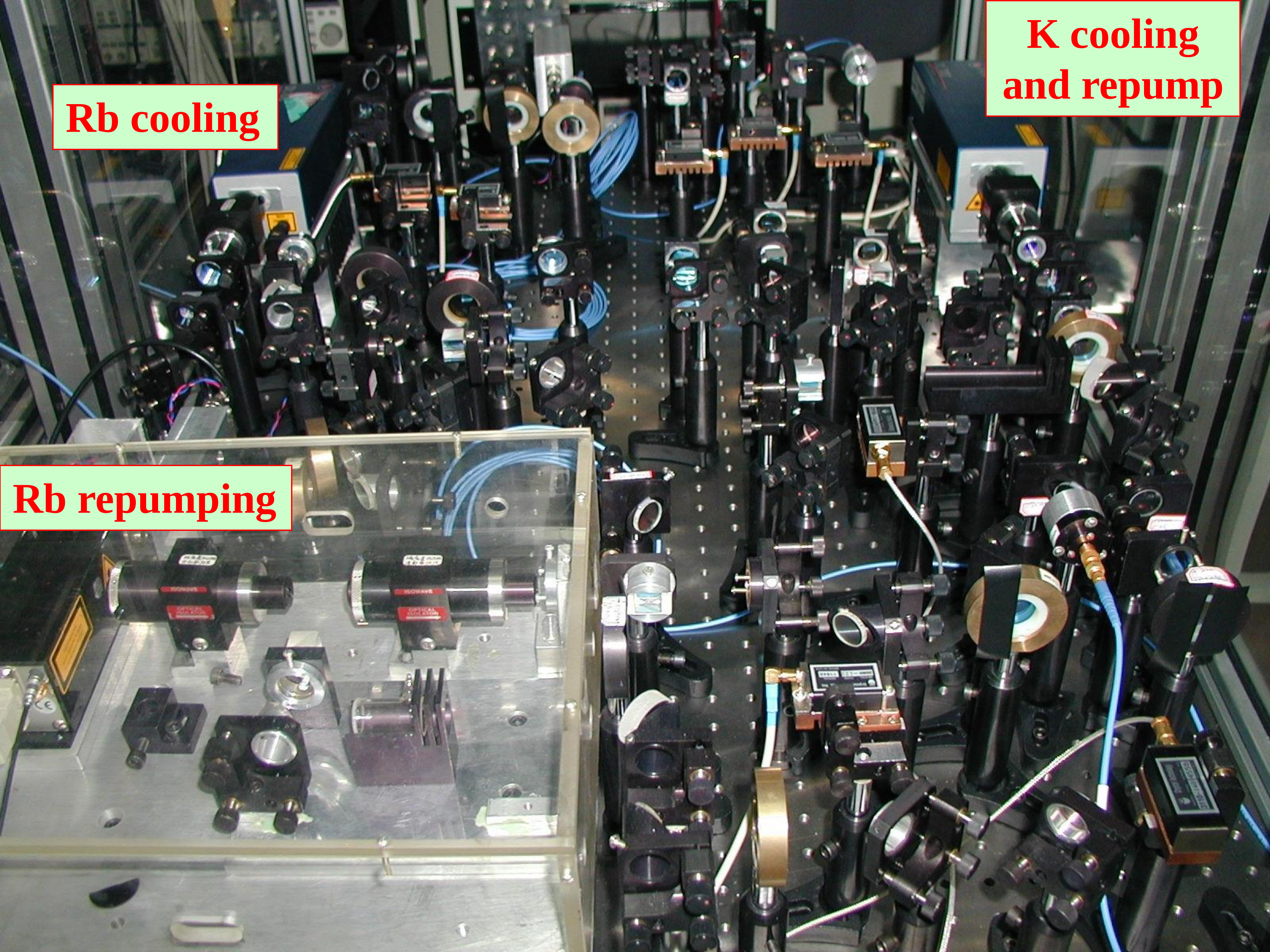


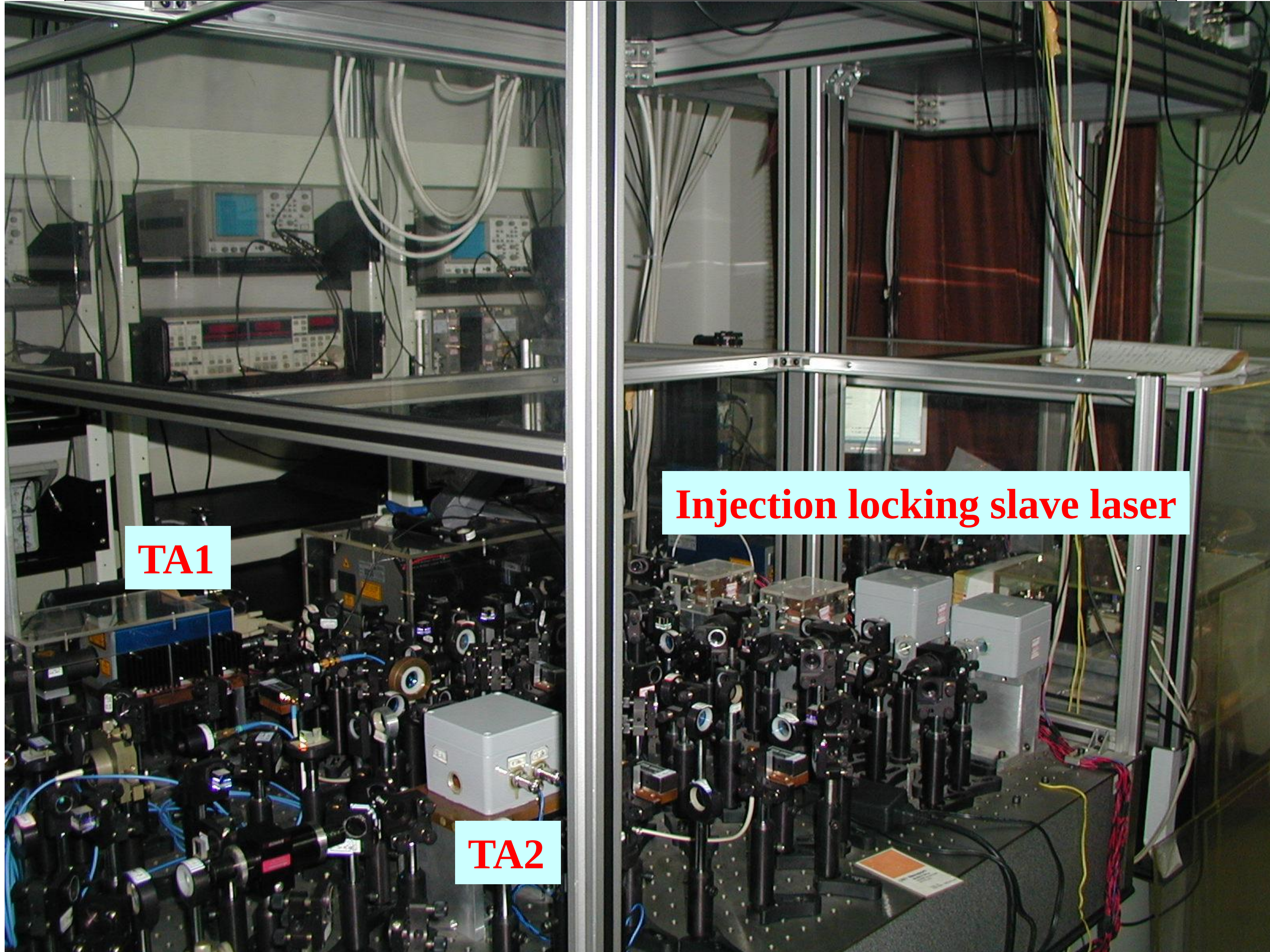

First Chamber: 1.2*10-7Pa
Second Chamber: 2.9*10-9Pa


science cell
Collection cell

# Laser System

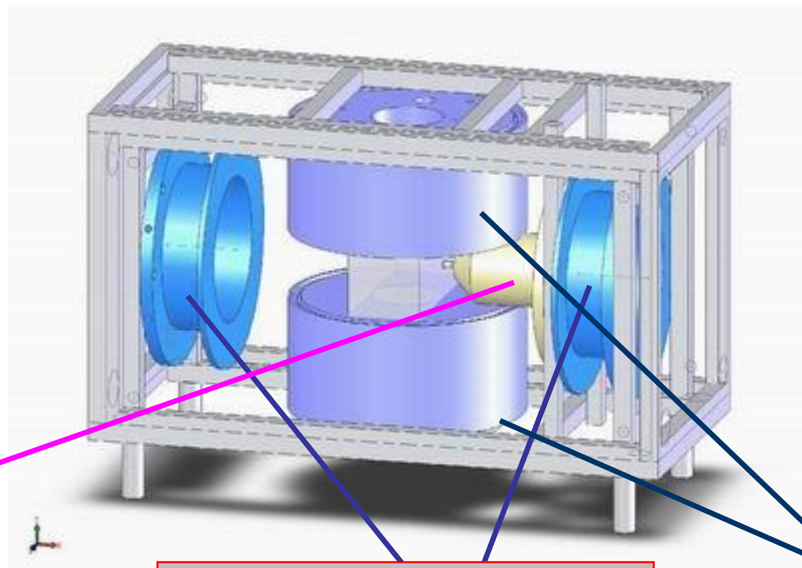


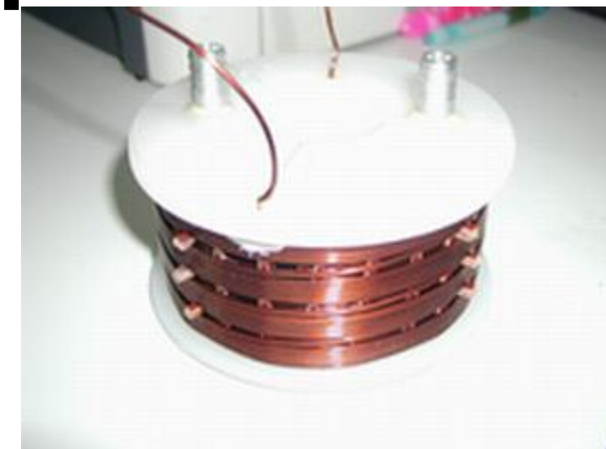

Rb cooling
K cooling
and repump
Rb repumping



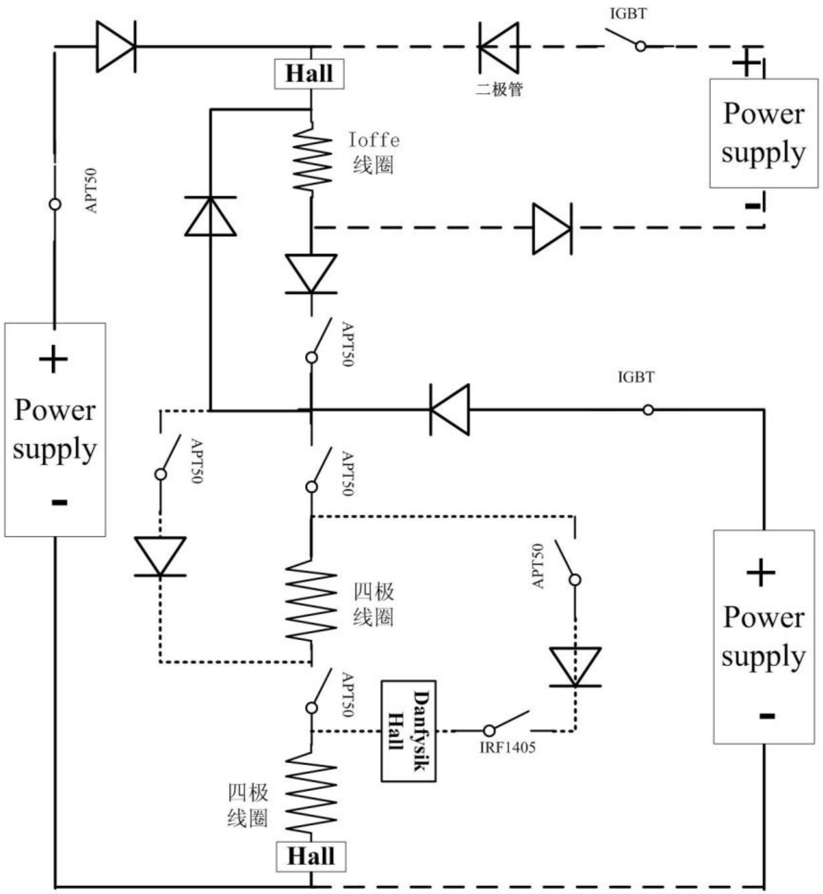
TA1
Injection locking slave laser
TA2

# Magnetic trap: Quadrupole-Ioffe configuration (Quic) trap



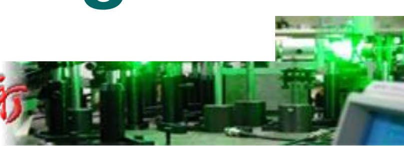
# Control magnetic field current




- **MOT2**
- **QUIC trap**
- **Feshbach resonance**

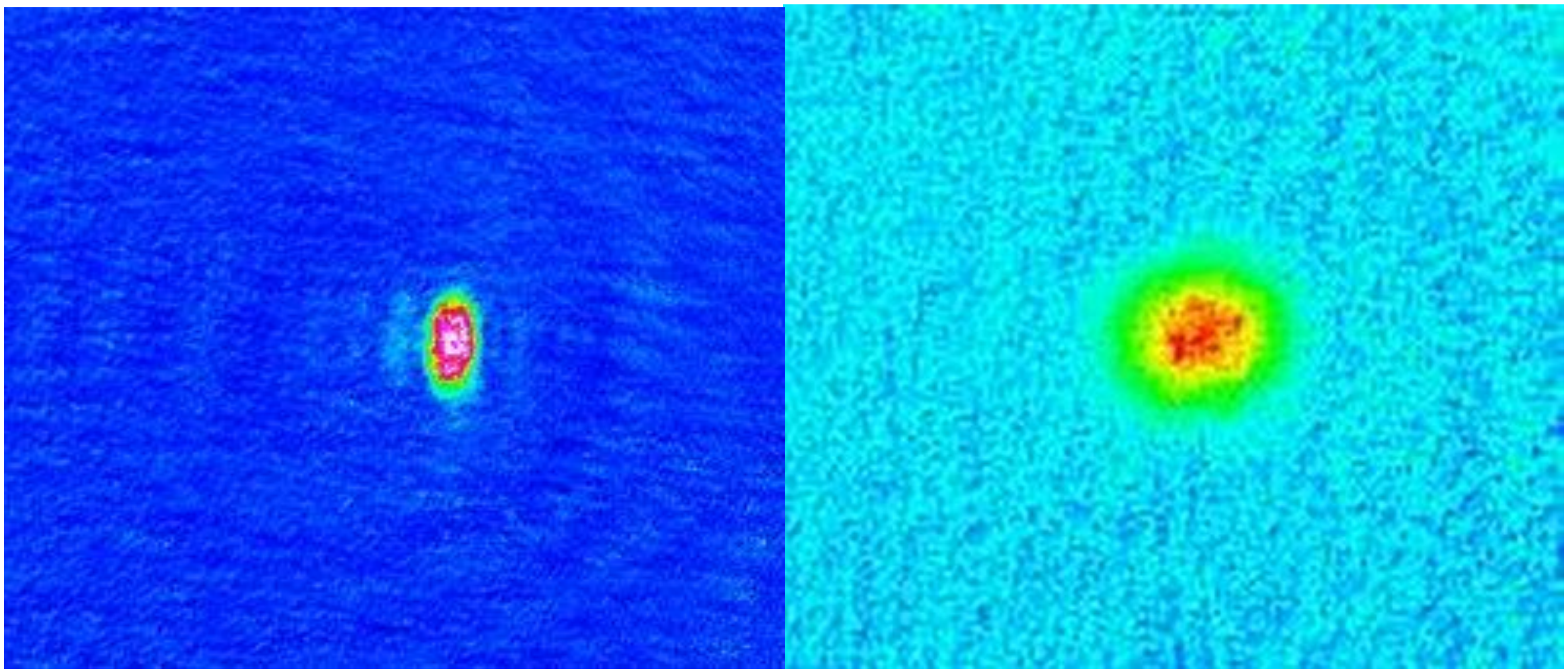
# Experimental Sequence

- **Transfer MOT1 to MOT2**
- **Optical molasses and Optical pump**
- **Loading atoms into QUIC**
  **( Quadrupole Ioffe Configuration)**
- **RF evaporation**
- **Time of flight and absorption image**



# Generation of quantum degenerate gases

**$^{87}$Rb BEC** | **$^{40}$K DFG**

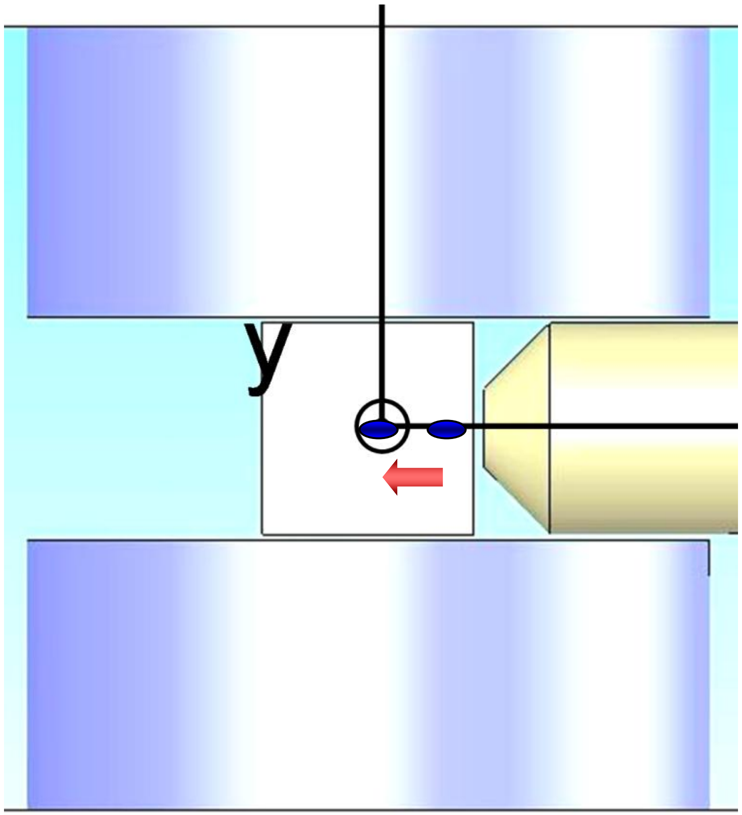


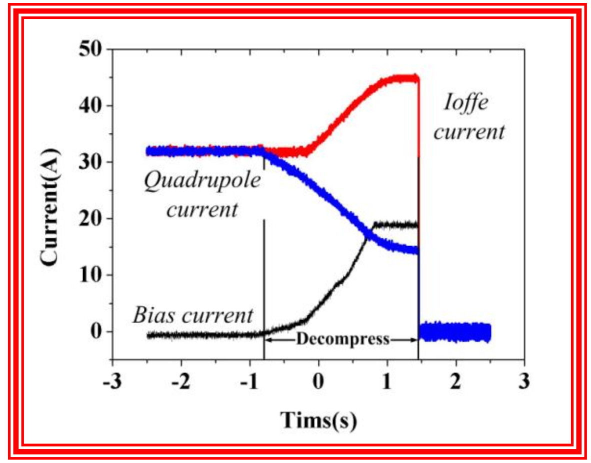
$N=1.8*10^5$
$t_f=25ms$

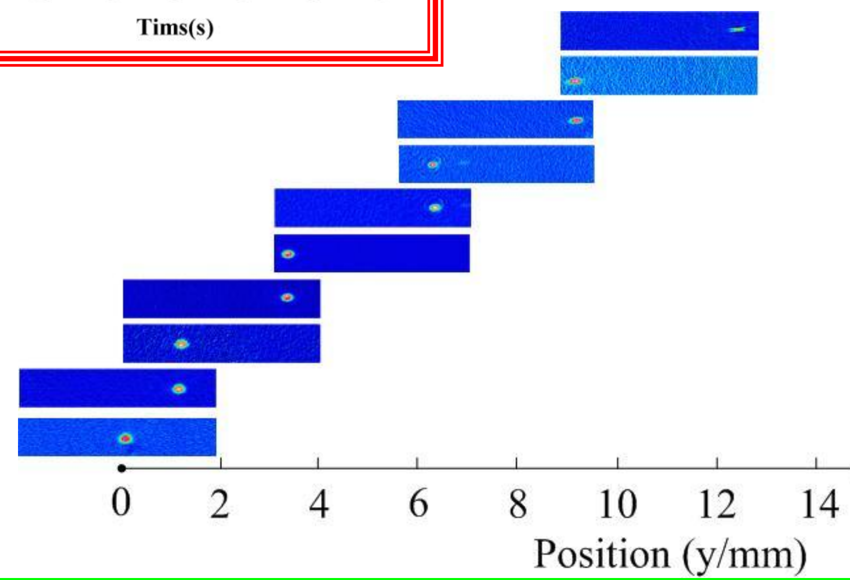
$T/T_F=0.56$
$N=5.5*10^5$
$t_f=12ms$

**Dezhi Xiong, Haixia Chen, Pengjun Wang, Xudong Yu, Feng Gao, Jing Zhang, *Chin. Phys. Lett.* 25, 843 (2008).**

# Transfer ultracold atoms from QUIC to the center of glass cell



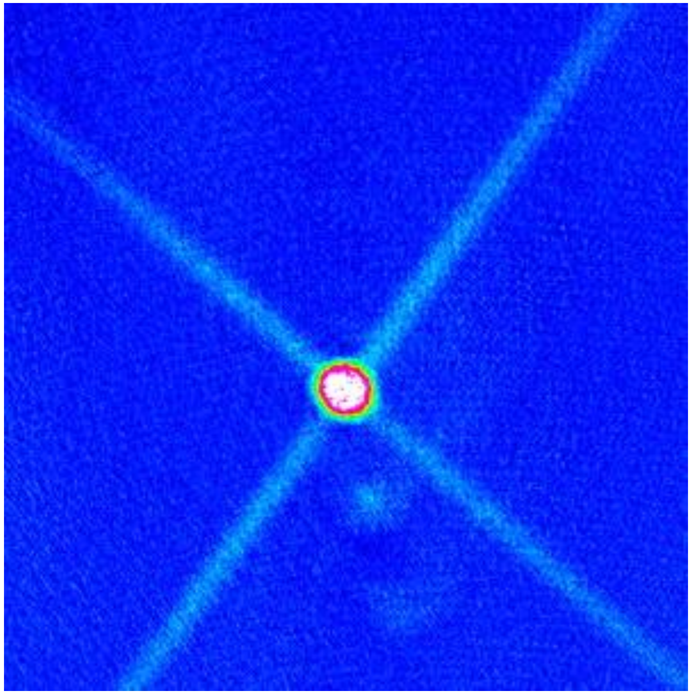



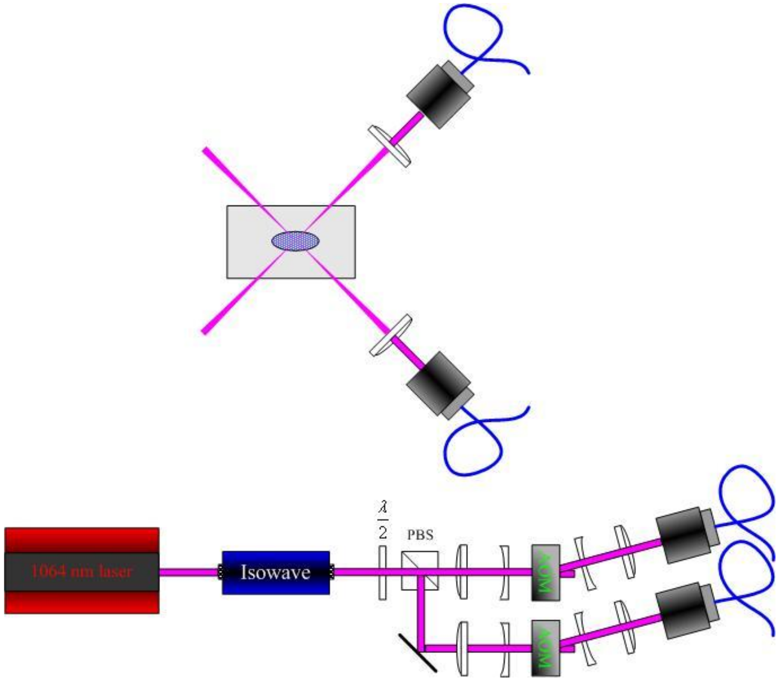




**Distance: 11.8 mm**

**Dezhi Xiong, Haixia Chen, Pengjun Wang, Zhengkun Fu, Jing Zhang, *Opt. Express* 18, 1649 (2010)**

# Loading of a crossed dipole trap

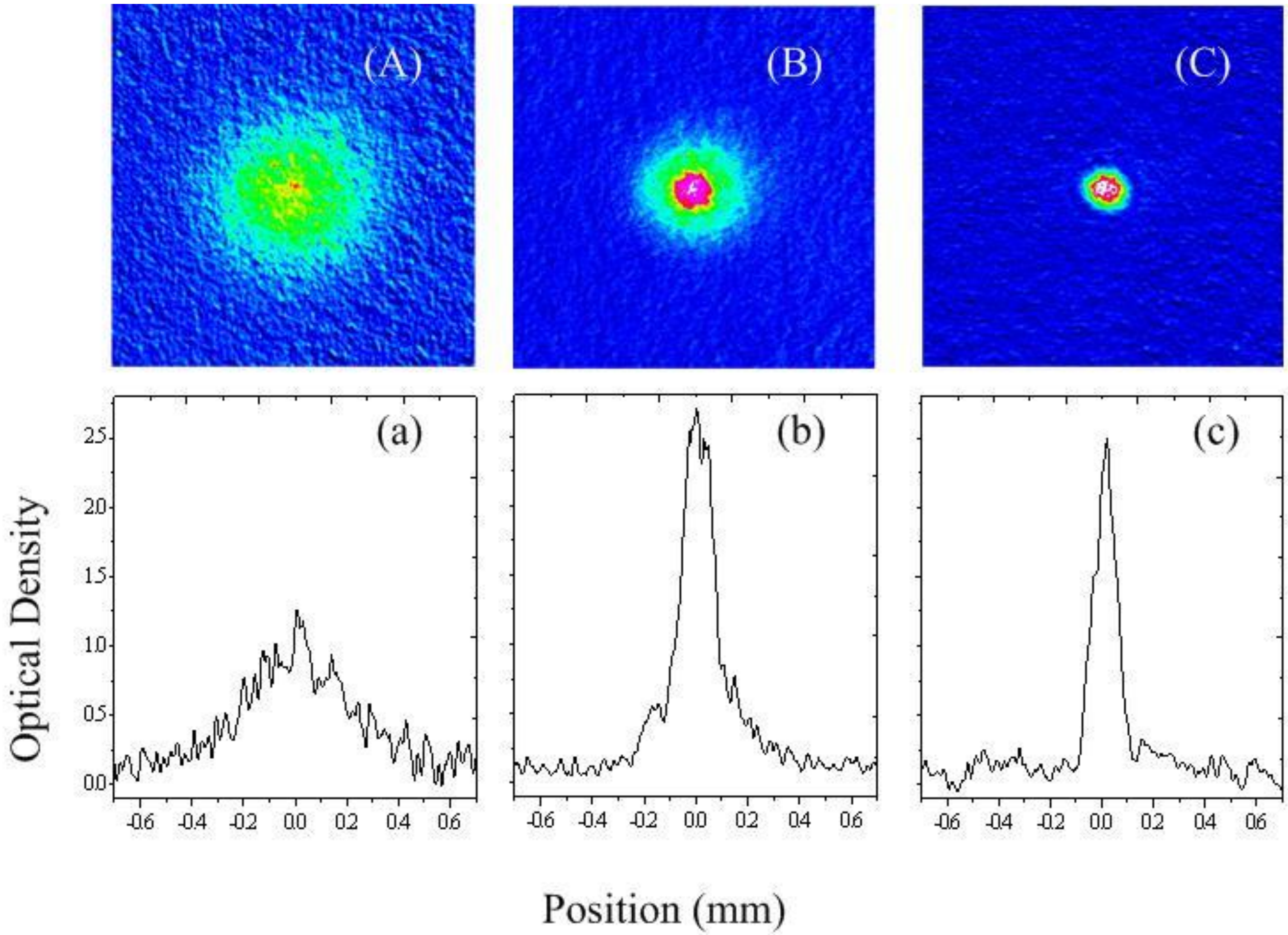





**1064 nm single-frequency laser**

**P1=380mw P2=650mw**

**W1=25um W2=33um**




N=1.5×$10^5$

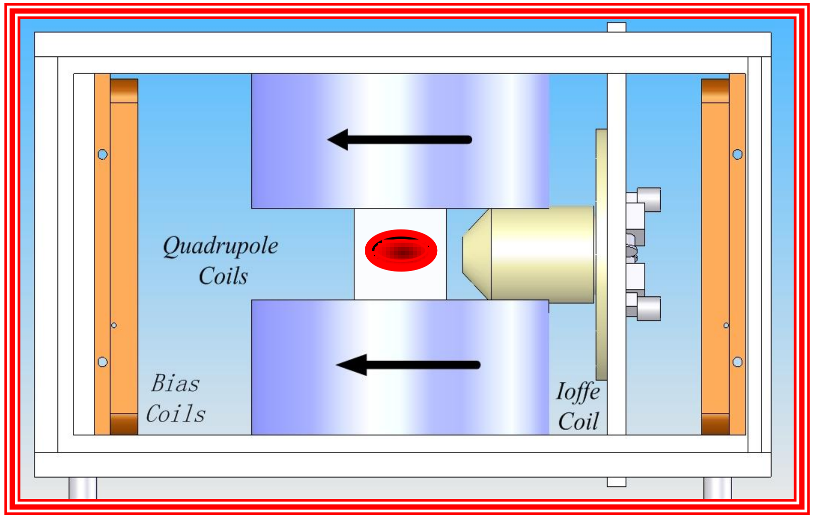
30 ms free expansion time.

# Feshbach resonance

**Beginning: Evaporation in optical trap**

**Number: $^{87}Rb\&^{40}K$----7-8(10)*$10^5$**

**Temperature: 1-2 μk**



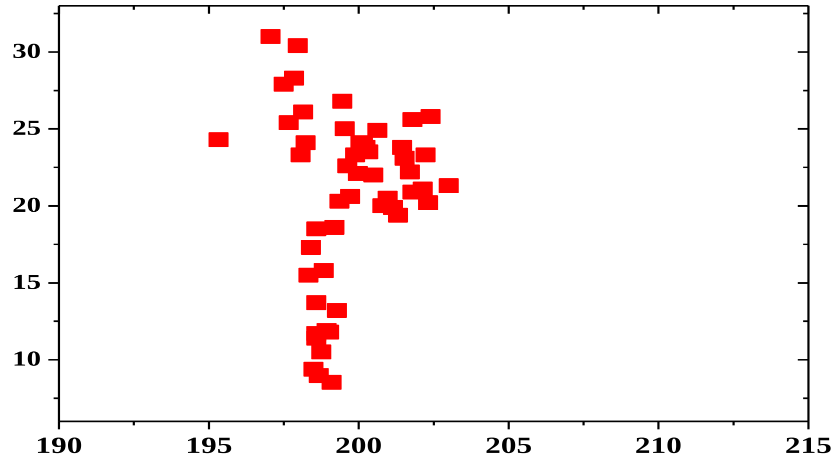

## ❖Feshbach resonance

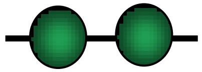
**Key point:**

**Stability of magnetic field**

1. Prepare of spin state
2. Ramp magnetic field
3. Measure the atomic losses and heating
4. Position and width of Feshbach resonance

# Observed Feshbach resonances in 40K



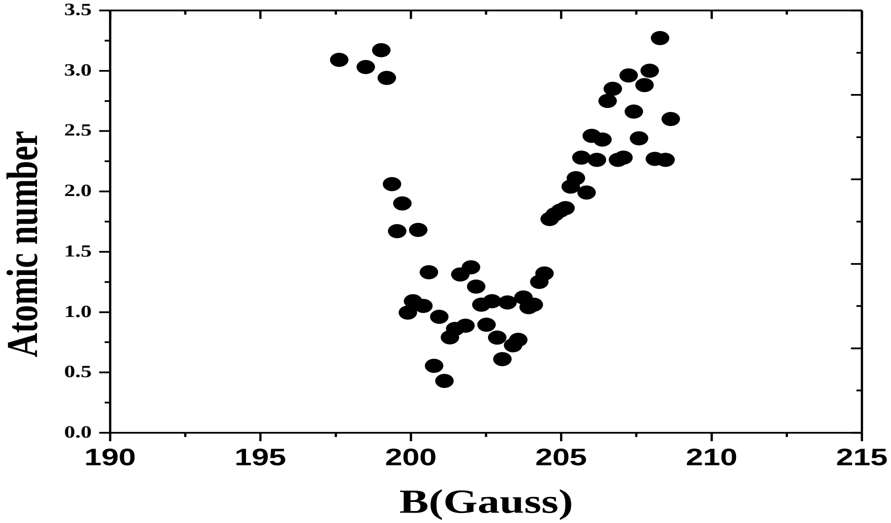



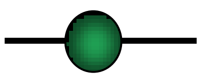
$|9/2,-7/2\rangle$

$|9/2,-9/2\rangle$

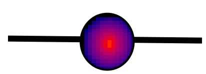
P-wave $B_0$= 198.8 G

$|9/2,-7/2\rangle$



$|9/2,-7/2\rangle$

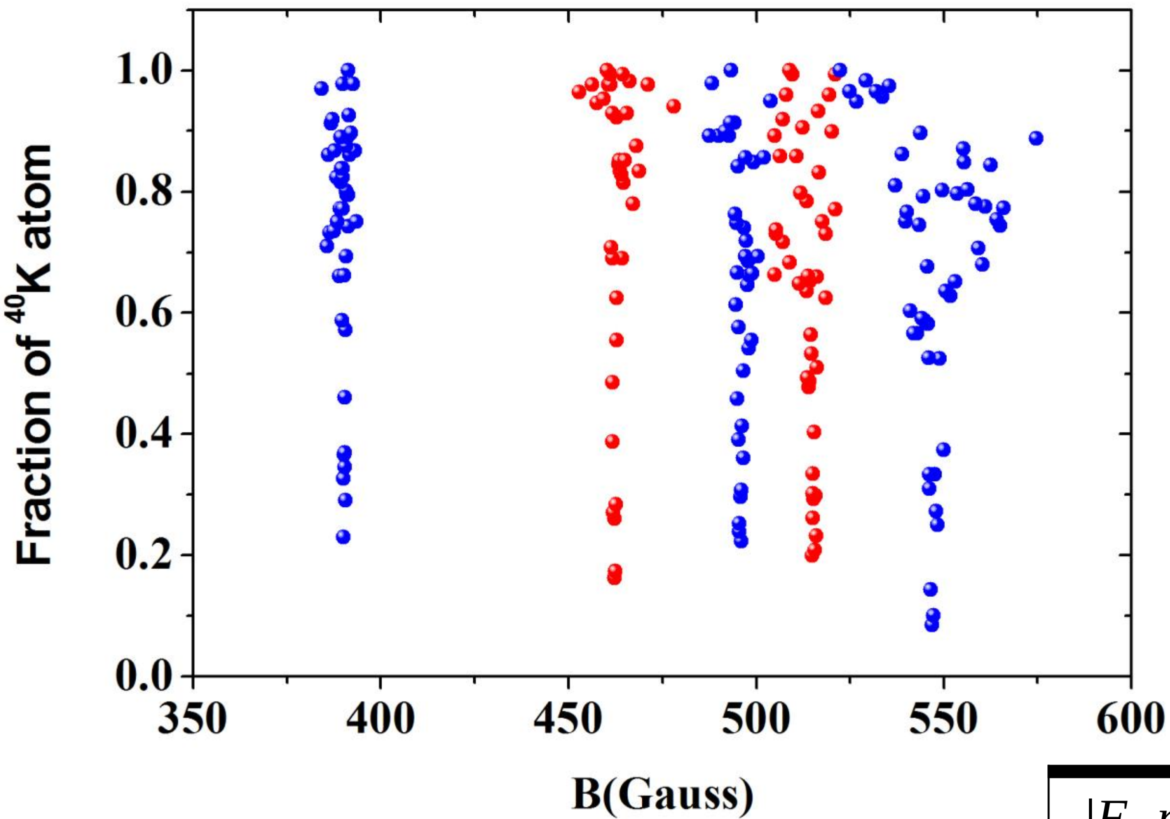


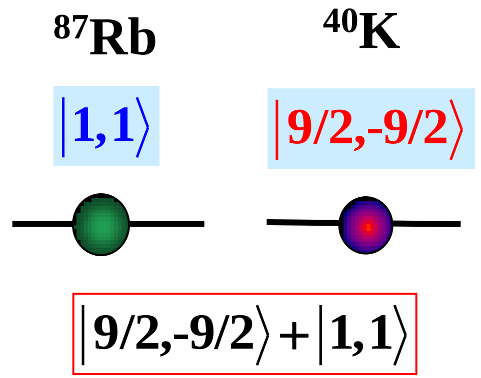
$|9/2,-9/2\rangle$

S-wave $B_0$= 202.1 G

$|9/2,-9/2\rangle + |9/2,-7/2\rangle$

# Observed Feshbach resonances in $^{40}K$+$^{87}Rb$



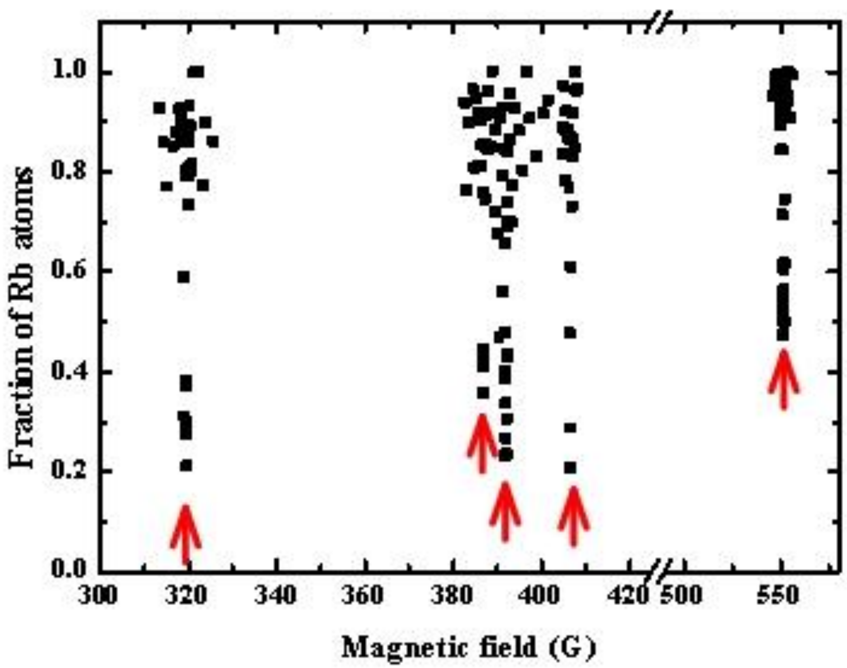



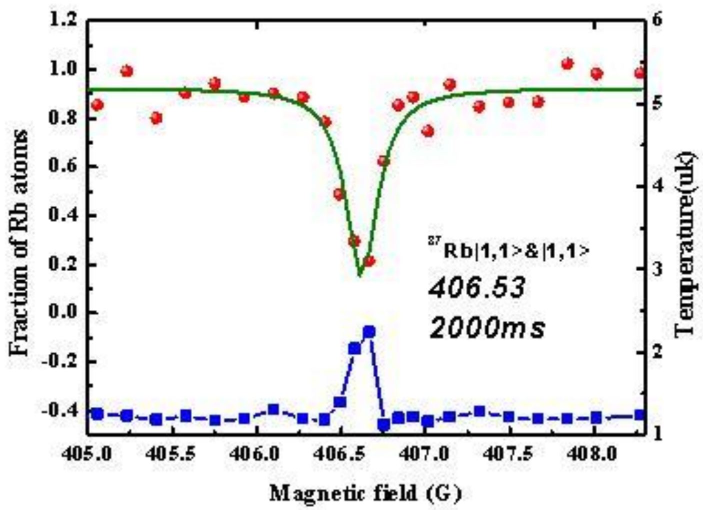

| $\|F_1,m_{F1}\rangle + \|F_2,m_{F2}\rangle$ | $B_{expt}$/G | $L$ |
|---|---|---|
| $\|1,1\rangle + \|9/2,-9/2\rangle$ | **462.45** | 0 |
| | **495.71** | 0 |
| | **515.75** | 1 |
| | **546.89** | 0 |

## ❖Feshbach resonance

# Feshbach resonance $^{87}$Rb $|1,1\rangle \& |1,1\rangle$

| $\|F_1,m_{F1}> + \|F_2,m_{F2}>$ | $B_{expt}$/G | $l$ |
|---|---|---|
| \|1,1> + \|1,1> | 319.3 | 2 |
| | 387.25 | 2 |
| | 406.54 | 0 |
| | 551.47 | 2 |

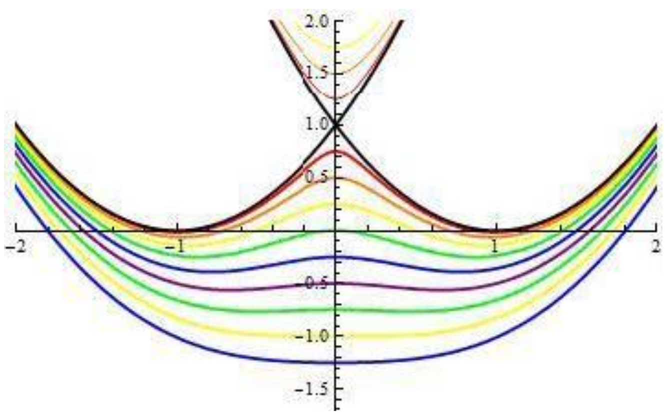


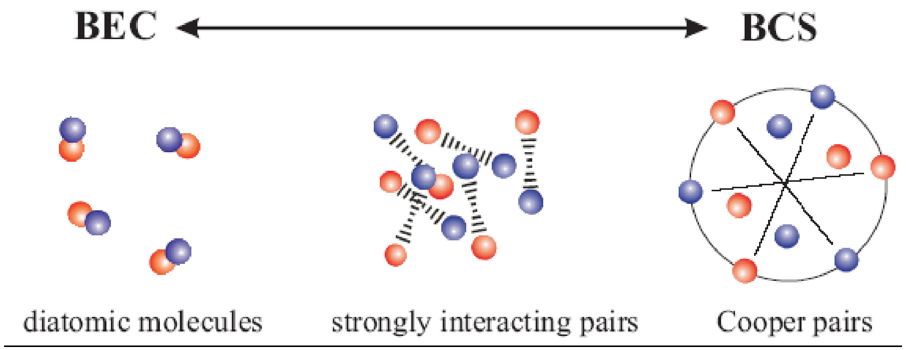



# Future Plan

**BEC-BCS crossover with spin-orbit coupling**

**Method:  RF  and Raman spectrum**




**BEC-BCS crossover**

# Acknowledgement

## Experiment:

Pengjun Wang

Zhengkun Fu

Shijie Chai

Lianghui Huang

Zengming Meng

## Cooperation (Theory) :

**Hui Zhai' group** (Tsinghua University ) :

Zengqiang Yu

Jiao Miao

**Swinburne University of Technology**

Hui Hu,  Xiaji Liu

**Rice University**

Han Pu

# Thank you!


Thank you!