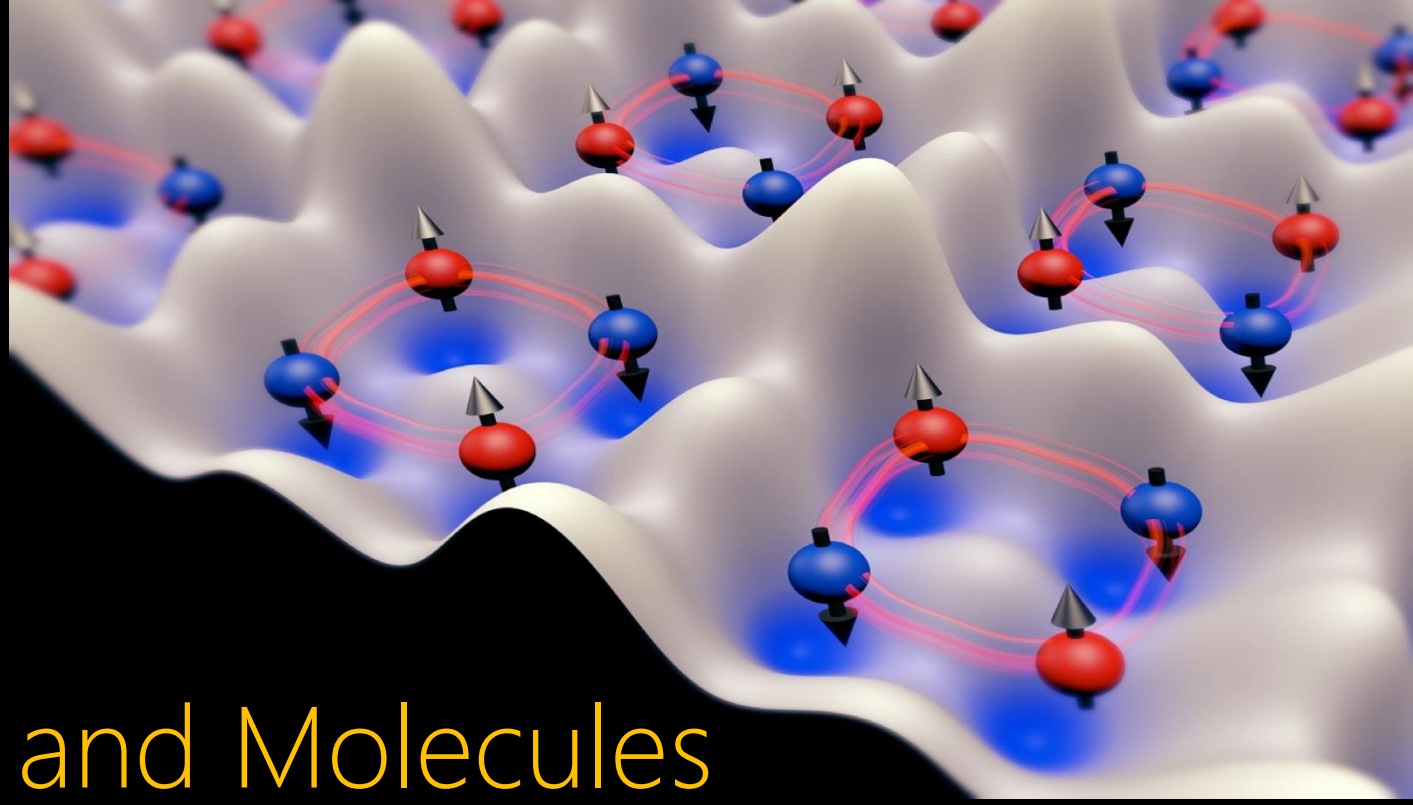
Quantum Simulation and Computation with Ultra-cold Atoms and Molecules



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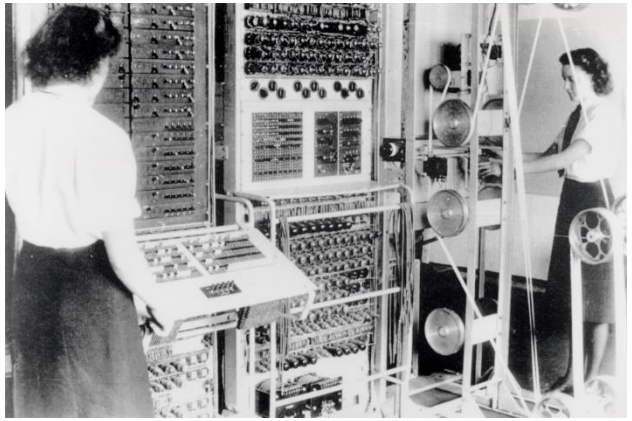
Part I: Overview and fundamental concepts

Thirst for computational capacity

In 1943: "I think there is a world market for maybe five computers"

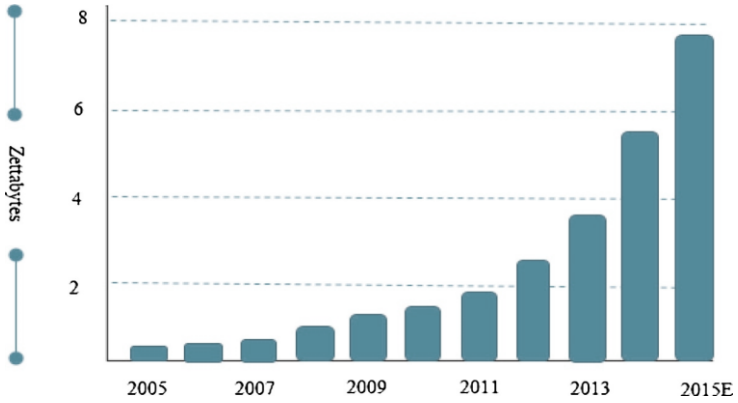
--Thomas Watson, Chairman of IBM



Colossus, weight: 1 ton, power: 8.5kw, 5 kOPS (operations per second)

In 2010's: The computing power in a mobile phone is larger than the total computing power used in Apollo Program!

Apple A12, power: <5W, 5 trillion OPS



The world's data volume roughly grow 40% per year

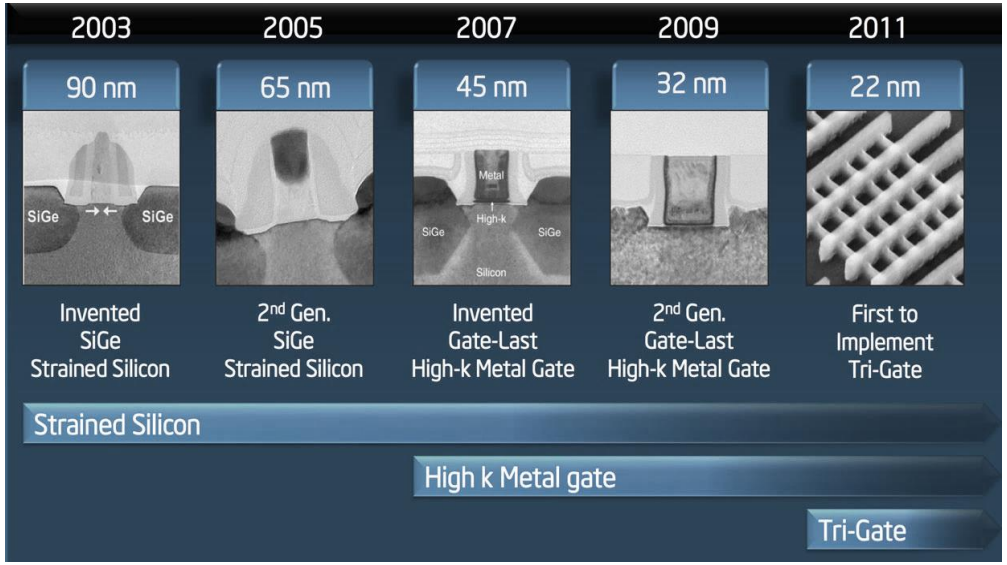
Challenges in the computational capacity

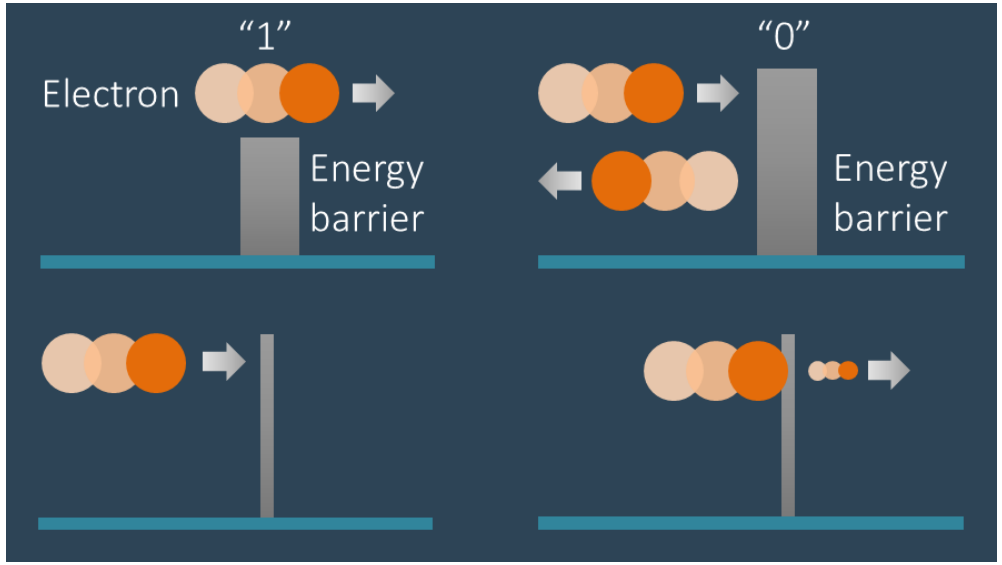
Classical computational bottleneck

The world's total computing power is insufficient to search a target in 2^{80} database within a year

A technological limit

The Moore's law that predicts the transistor density doubles every 18 months has come to an end





2017, 14 nm ➡ 2022, 4 nm ➡

0.2 nm (atomic scale) ➡ ???

Tunneling induced leakage ➡

The "0/1" logic in the transistors will fail

Challenges in the computational capacity

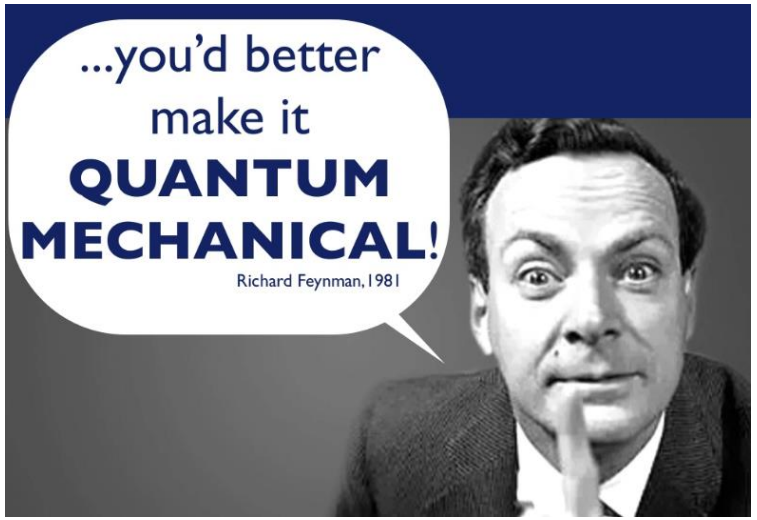
Much more hardly accessible for classical computers to simulate a quantum system

A quantum system of 300 two-level particles:

- Described by a 2^{300} dimensional Hilbert space ➡ Larger than total number of atoms in the known Universe!

Natural solution: quantum simulator

Consisting of superposition quantum states engineered to simulate a quantum system



Concept of Quantum Computer

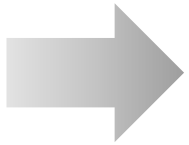
Quantum parallelism

Quantum Parallelism

Bits		Qubits
0 or 1	V. S.	0 + 1
00, 01, 10 or 11		00 + 01 + 10 + 11
000, 001, 010……		000 + 001 + 010 + ……

Evaluating function f(x) for many different x simultaneously

$$U\frac{1}{\sqrt{2^N}}\sum_{i=0}^{2^N-1}|i\rangle|0\rangle=\frac{1}{\sqrt{2^N}}\sum_{i=0}^{2^N-1}|i\rangle|f(i)\rangle$$



Exponentially speedup!

Quantum computation

Shor Algorithm (1994):

E.g. factor a 300-digit number with

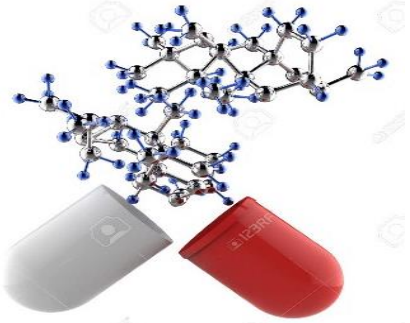
- Classical THz computer: 150,000 years
- Quantum THz computer: 1 second!

- Code-breaking can be done in minutes, not in millennia
- Public key encryption, based on factoring, will be vulnerable!

Code-breaking

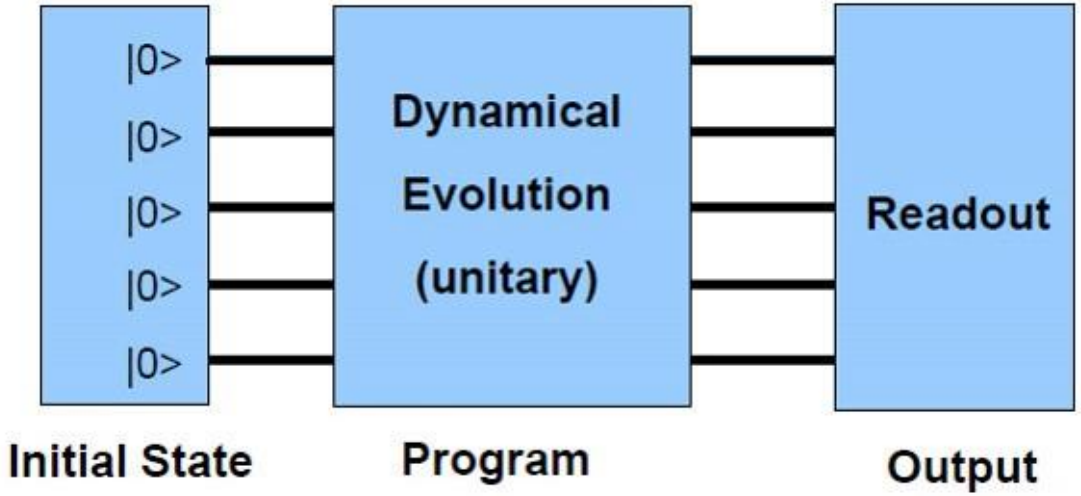
Weather forecast

Financial analysis



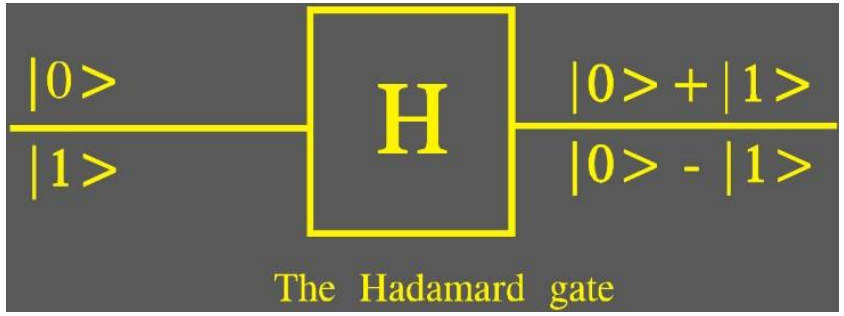
Drug design

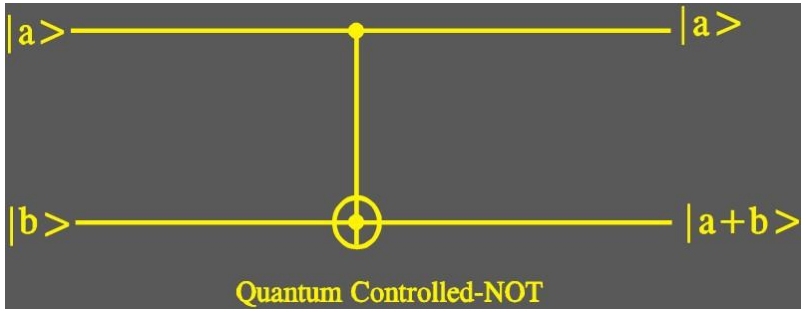
Quantum circuit computation model



Single-qubit SU(2) gates + two-qubit controlled-NOT gates ➡

Universal quantum computation [Lloyd, PRL 75, 346 (1995)]





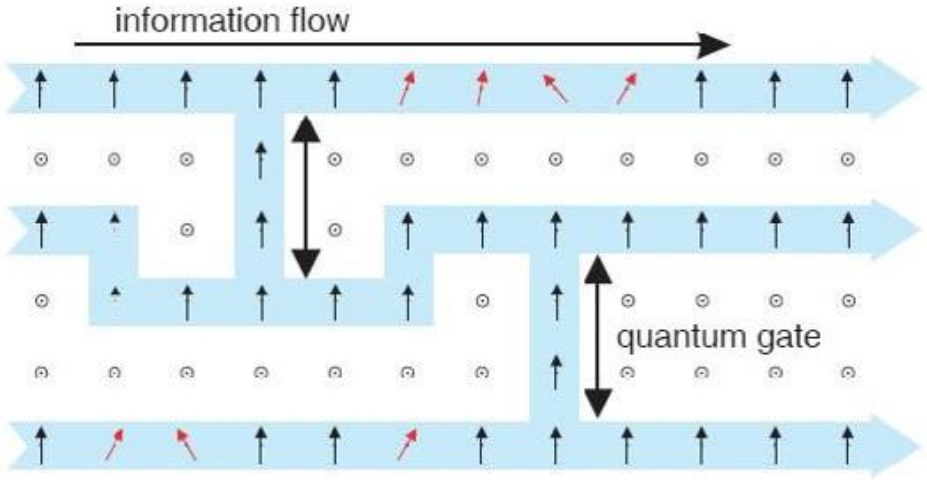
00→00
01→01
10→11
11→10

One-way quantum computation model

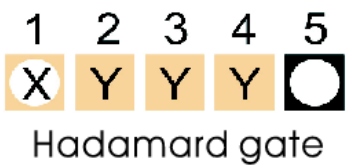
- Universal QC resource: multi-particle entanglement

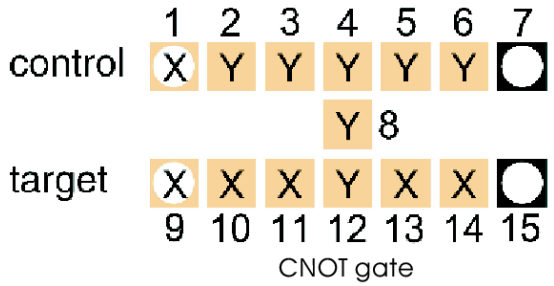
Cluster state $|\Phi\rangle_C$:

$$\sigma_x^{(a)} \bigotimes_{a' \in ngbh(a)} \sigma_z^{(a')} |\Phi\rangle_C = \pm |\Phi\rangle_C$$



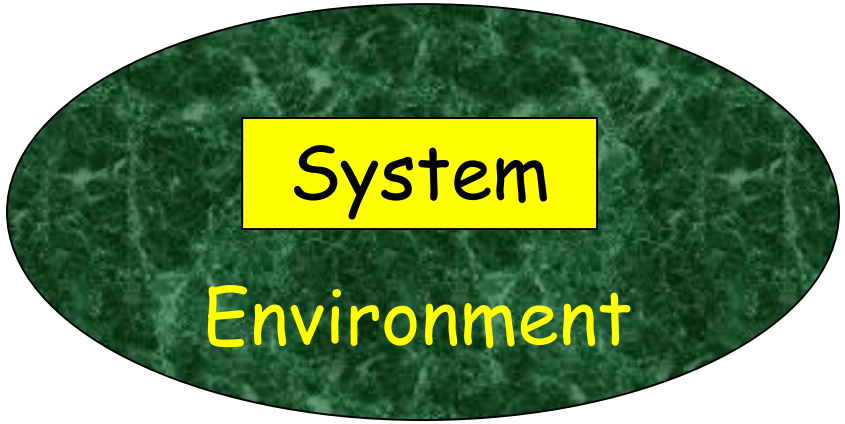
- Quantum gate is implemented by measuring particles in a certain order and in a certain basis





Raussendorf and Briegel, PRL 86, 5188 (2001)

Scalability: fault tolerable qubits



Inevitable noise ➡ qubit error during quantum computation

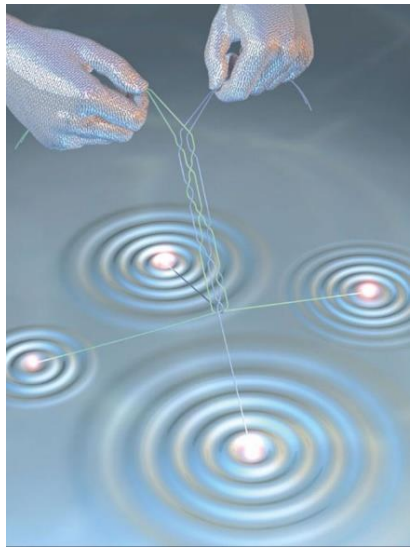
- Error-correction code
  - Shor, PRA 52, R2493 (1995) 9qubits
  - Steane, PRL 77, 793 (1996) 7qubits
  - Laflamme *et al.*, PRL 77, 198 (1996) 5qubits

☒Challenge: traditional error-correction codes require error rate < 2×10^{-5} !

Quantum simulation

☒ Achieving a programmable universal quantum computer (even a prototype) is a long-term process, maybe need 20-30 years or more

☑ Fortunately, scalable quantum simulator is achievable in the near future!



A quantum simulator

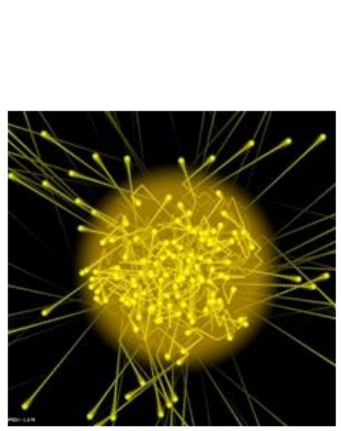
- Manipulating Hamiltonian of a controllable quantum system to mimic the evolution of another complex quantum system
- Do not need high precise quantum logical gates and entanglement of so many qubits

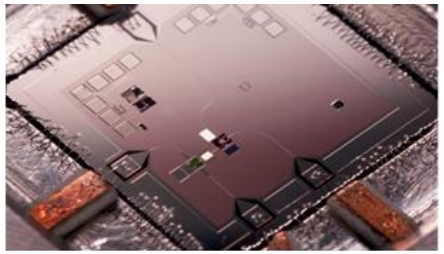
To solve various complex problems in condensed matter physics:

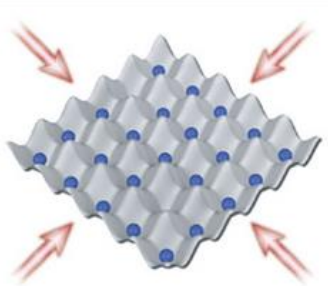
- High-temperature superconducting
- (fractional) Quantum Hall effect

……

Candidates for quantum computation and simulation







Super conductors

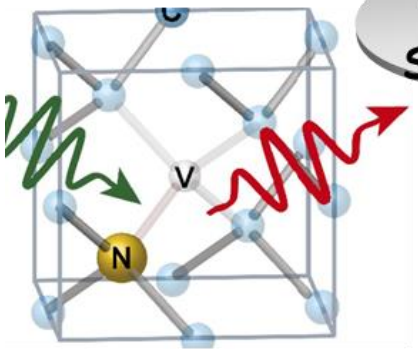
Cold atoms

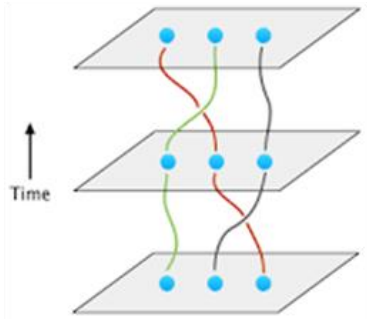
Photons

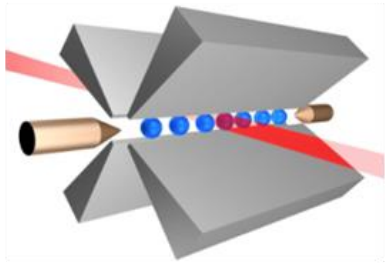
Trapped ions

Solid states

Topological

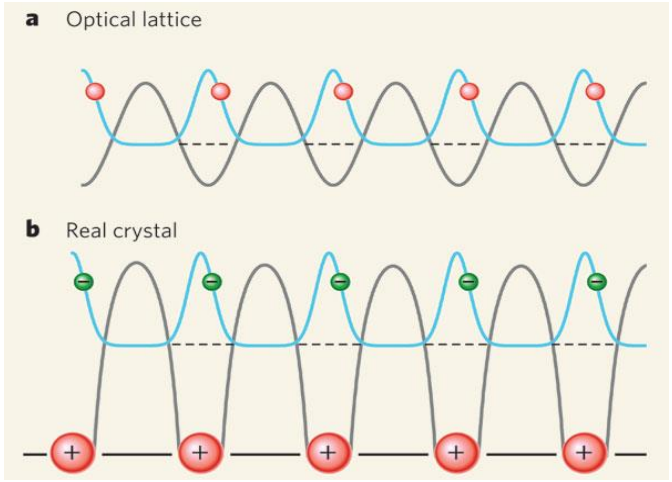


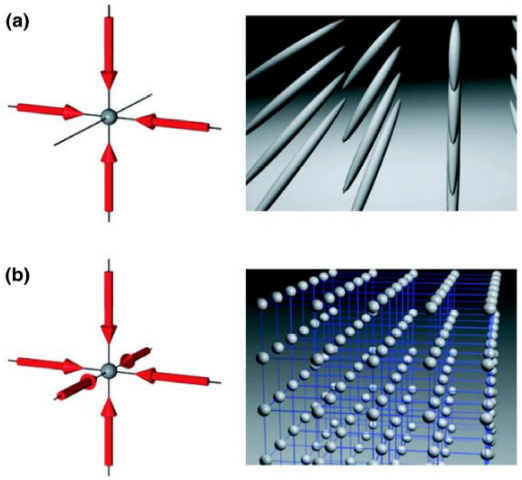


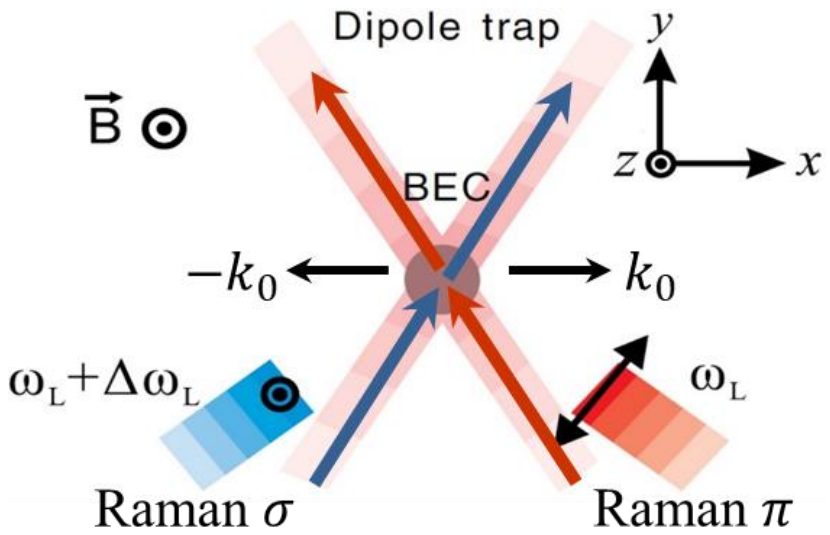


Ultra-cold atoms: a novel system

"Quantum engineering" of Hamiltonians







Optical lattices:

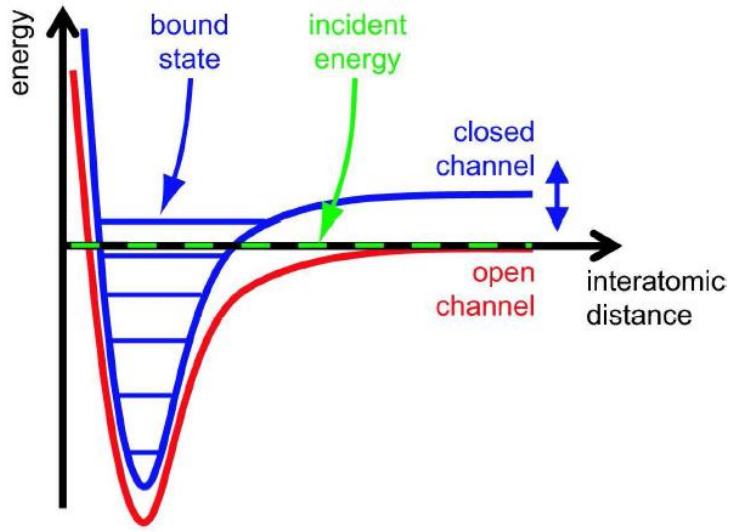
☑ To mimic crystal structures

☑ To entangle many atoms

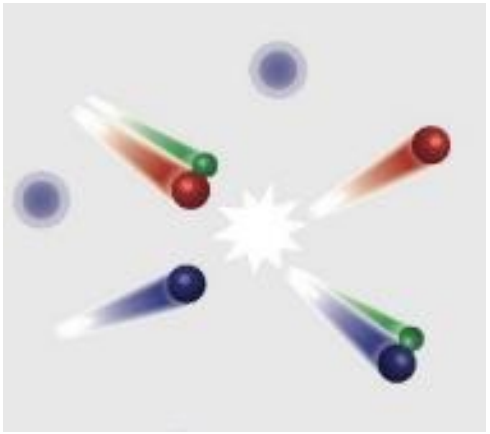
☑ To synthesize artificial gauge potentials by Raman technique

Ultra-cold atoms: a novel system

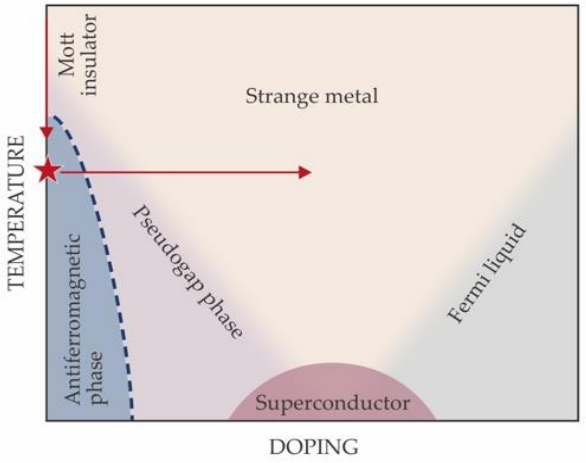
"Quantum engineering" of Hamiltonians



☑ Tunable atom-atom interaction strength by Feshbach resonance



☑ To study ultra-cold chemical dynamics



☑ To simulate electron correlation in lattices

Why do we need ultra-cold atoms?

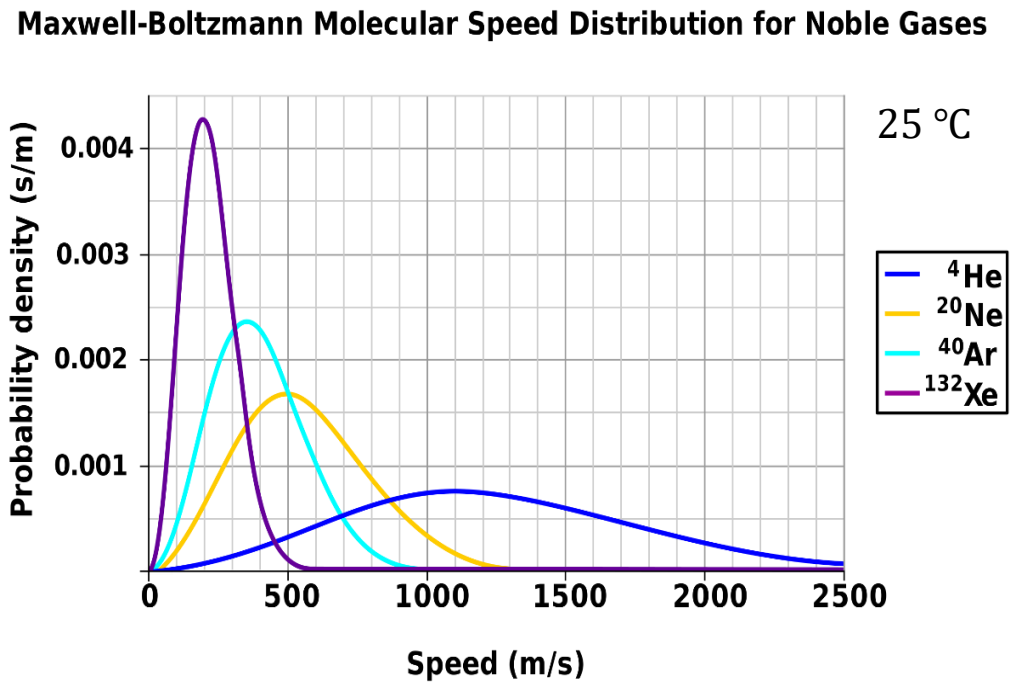
From classical statistics to quantum statistics

- Atomic ensemble at room temperature T

  Maxwell-Boltzmann statistics

$$\overline{n}_i(\varepsilon_i) = \frac{g_i}{e^{(\varepsilon_i - \mu)/k_B T}}$$

g_i: degeneracy
ε_i: energy of the state
μ: chemical potential
k_B: Boltzmann constant
T: temperature



(quasi-) Gaussian distribution

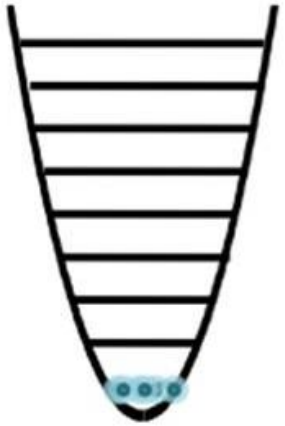
Why do we cool atoms to ultralow temperature

From classical statistics to quantum statistics

- Atomic ensemble at near zero temperature

Bose-Einstein statistics

$$\bar{n}_i(\varepsilon_i) = \frac{g_i}{e^{(\varepsilon_i-\mu)/k_BT} - 1}$$

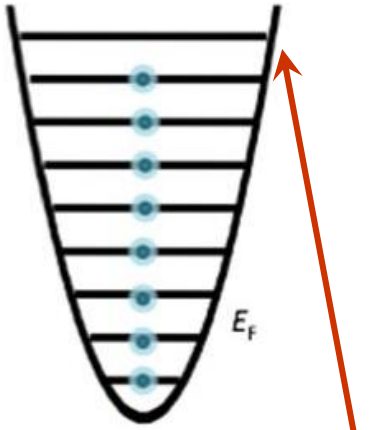


Bose Einstein Condensate (BEC):

all atoms collect to the ground state

Fermi-Dirac statistics

$$\bar{n}_i(\varepsilon_i) = \frac{g_i}{e^{(\varepsilon_i-\mu)/k_BT} + 1}$$



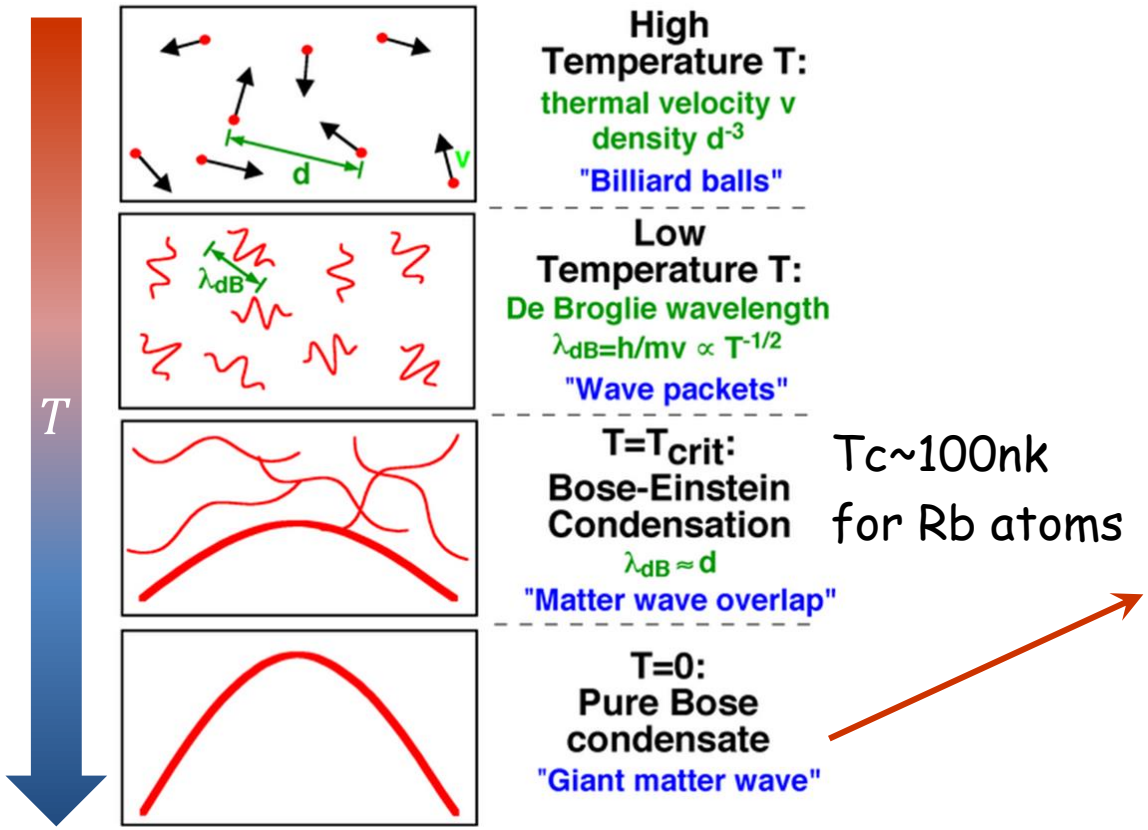
Fermi degeneracy:

- One atom per state due to Pauli exclusion principle
- Atoms fill from the lowest energy level, up to the Fermi energy E_F

Why do we cool atoms to ultralow temperature

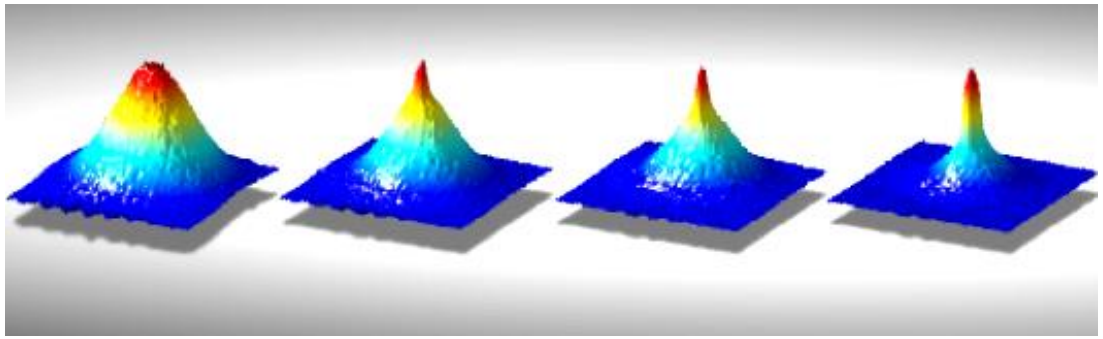
Significant quantum effect

de Broglie wavelength of particles $\lambda = \frac{h}{\sqrt{3mk_BT}}$, k_B is Boltzmann constant



Tc~100nk for Rb atoms

Gaussian profile → Thomas-Fermi profile

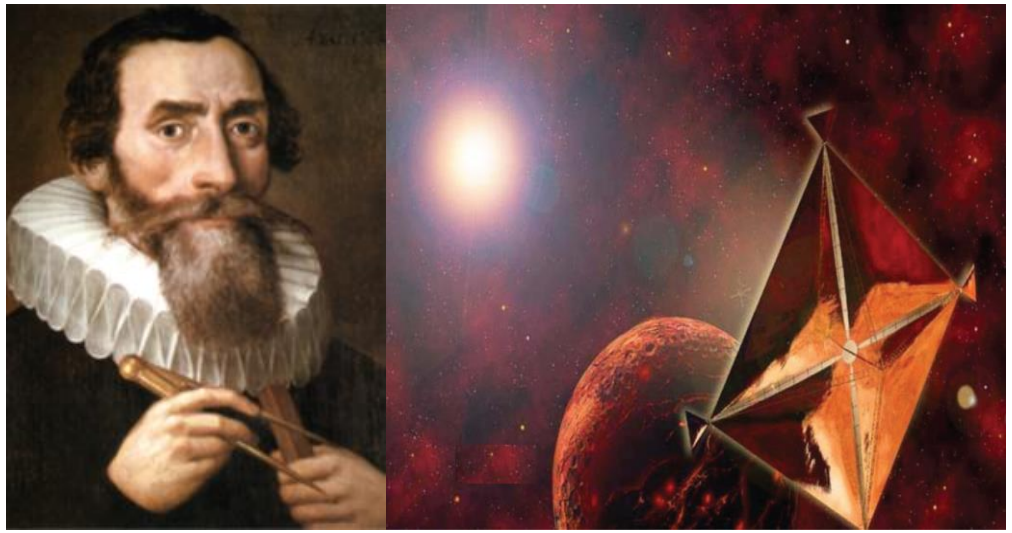


Atoms condensed to a narrow momentum space

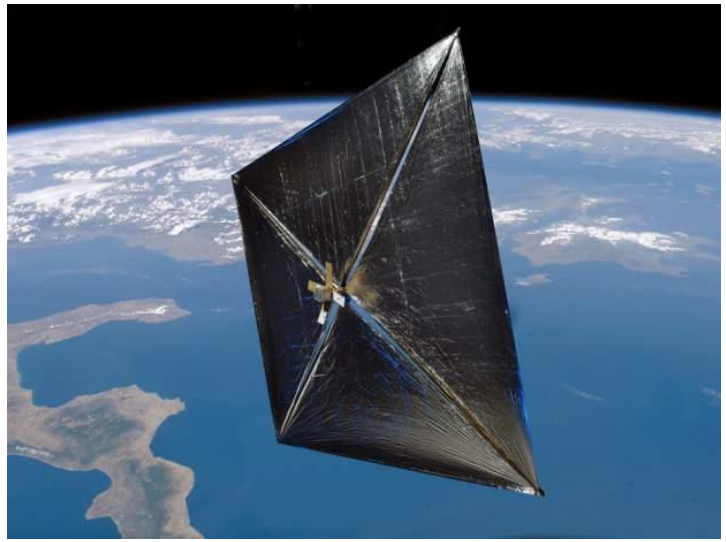
First achievement of BEC, Cornell, Wieman and Ketterle (1995), Nobel Prize in Physics 2001

How to cool atoms?

Optical radiation pressure



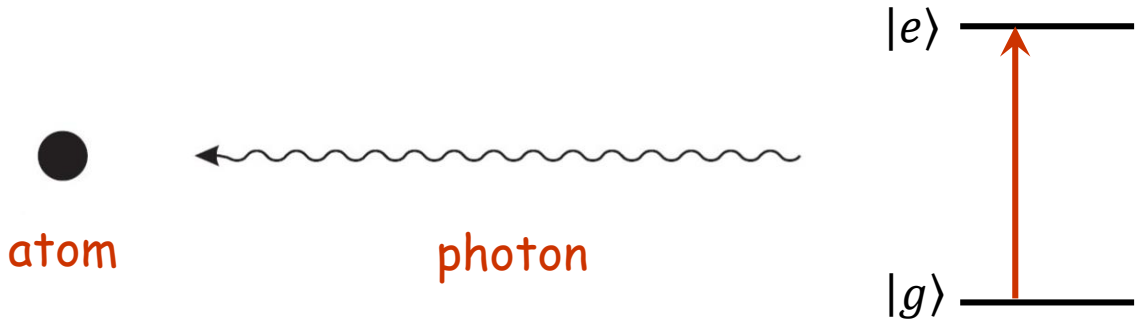
Johannes Kepler (1571-1630)



"Let us create vessels and sails adjusted to the heavenly ether, and there will be plenty of people unafraid of the empty wastes"

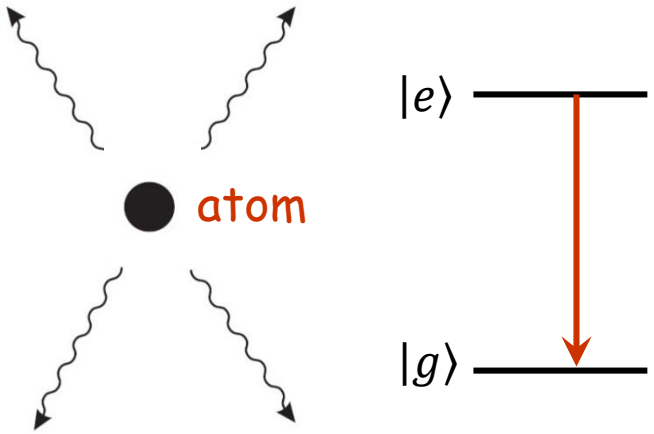
- Momentum of a photon $p = \hbar k$
- Solar Sail Demonstrator ('Sunjammer') by NASA: using the pressure of sunlight itself to provide propellant-free transport

Light pressure for atoms



An atom absorbs a photon

- Obtains momentum $\hbar k$
- To excited state from ground state



The atom decay back to ground state via spontaneous emission

- Directions of emitted photon is random and isotropic
  ➡ Average emitting momentum is 0
- Total effect: the atom obtain momentum $\hbar k$ ➡ the atom have a scattering force $F_{\text{scatt}} = -\sigma I/c$

Acceleration can be 10,000g

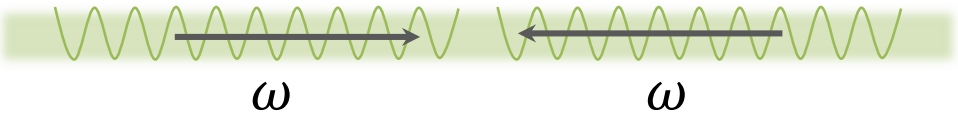
σ: absorption cross section
I: light intensity

Hänsch and Shawlow, Opt. Commun. 13, 68 (1975)

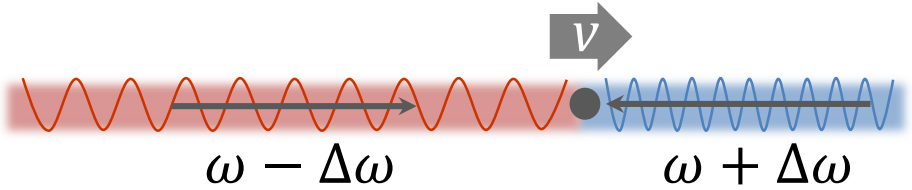
Doppler cooling

Doppler effect

For stationary observer:

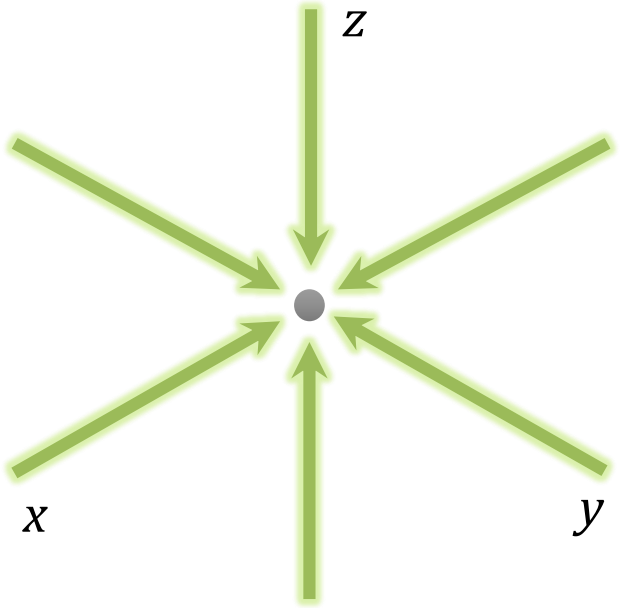


For moving atoms:

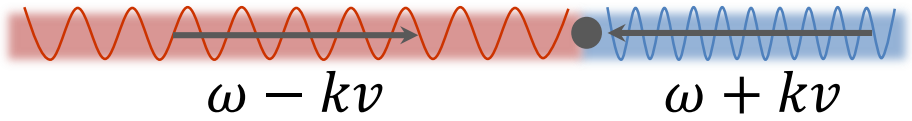


$$\Delta\omega = kv$$

- If we set $\omega + \Delta\omega = \omega_0$ (ω_0 is the transition frequency of the atoms), atoms will only absorb the photons oppositely running to its movement direction ➡ slow down
- Using 3D Doppler cooling to slow down atoms moving in all directions



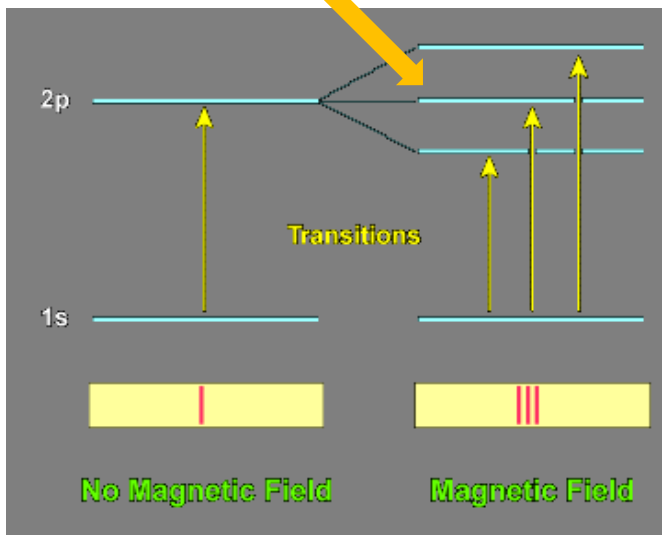
Magneto-optical trap (MOT)

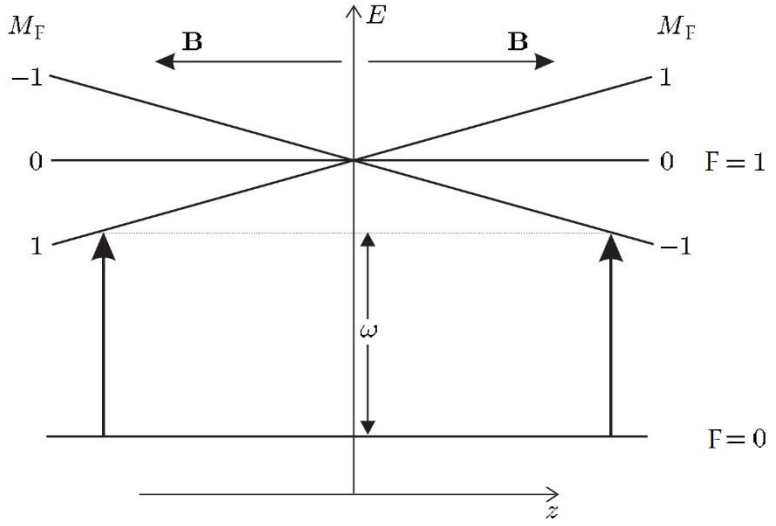


When atoms are slowed down, the oppositely running laser's frequency will not be resonant with atom's transition ➡ atoms will not absorb opposite photons any further. How to continue cooling?

Using Zeeman effect to tune atom's transition frequency

$$\Delta\omega_B = \pm\frac{\mu_B}{\hbar}B$$



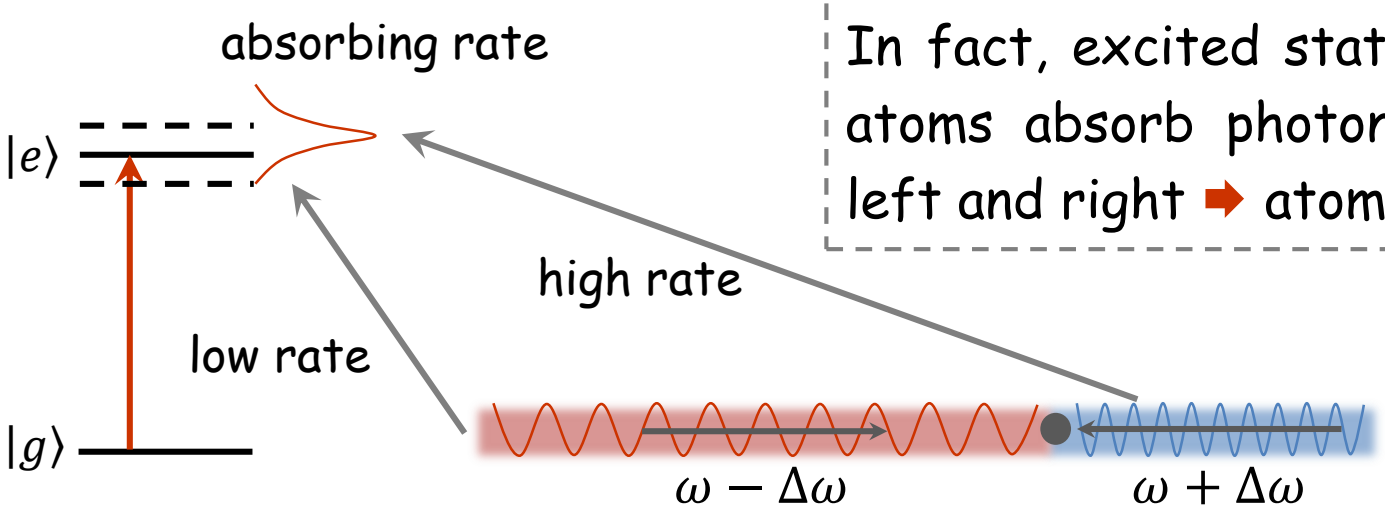


With magnetic field gradient, atom's transition frequency varies with positions:

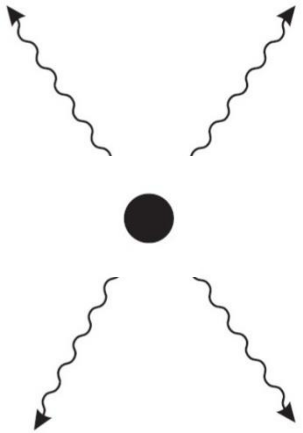
$\omega_0 + \Delta\omega_Z \quad (\Delta\omega_Z = \frac{\mu_B}{\hbar}\frac{\mathrm{d}B}{\mathrm{d}z}Z)$ ➡

The atoms with velocity in a specific range can always find the resonant frequency at certain place!

Limit of Doppler cooling



In fact, excited state has a line width (decay rate Γ), atoms absorb photons from both lasers coming from left and right ➡ atoms feel forces from both directions



- The average total force of atoms:

$$F = F_{\text{scatt}}(\omega - \omega_0 - kv) + F_{\text{scatt}}(\omega - \omega_0 + kv) \approx -2\frac{\partial F}{\partial \omega}kv$$

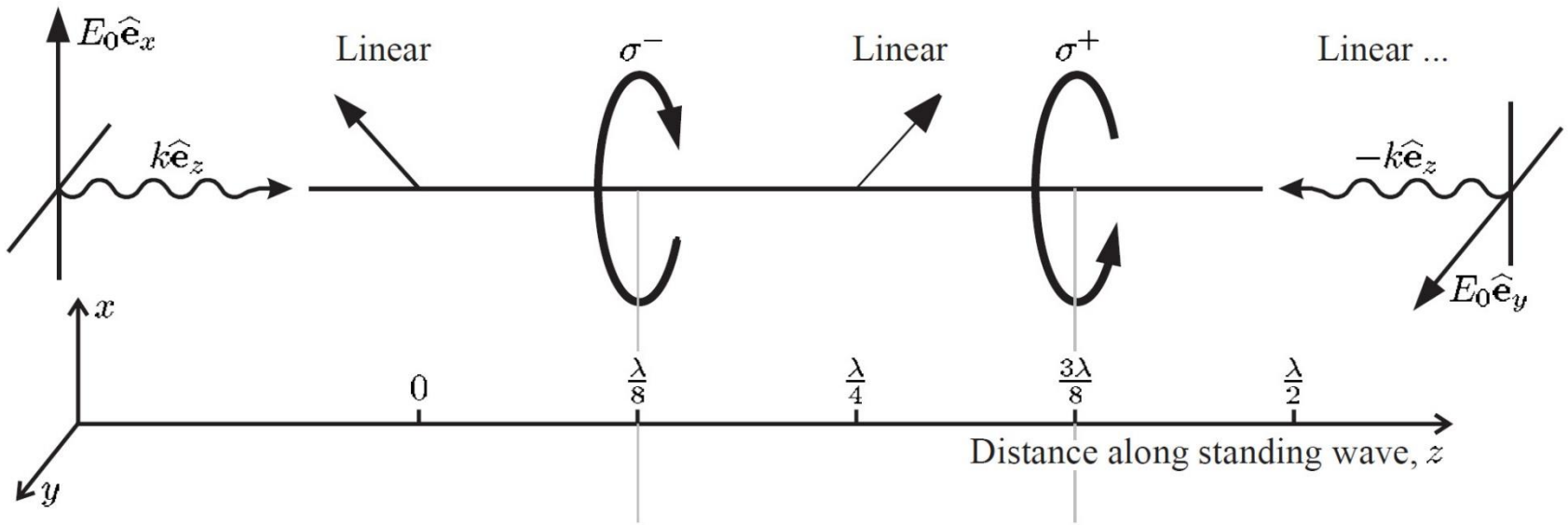
- Statistical fluctuation of spontaneous emission directions ➡ Fluctuation of force ΔF
- When $v \to 0$, $\Delta F \sim F$ ➡ laser heating!

Doppler limit (around 100uk): $T_D = \frac{\hbar\,\Gamma}{2k_B}$, Γ is the spontaneous emission rate

Optical molasses

Sub-Doppler cooling with polarization gradient potential

Two counter propagating orthogonal linearly polarized fields

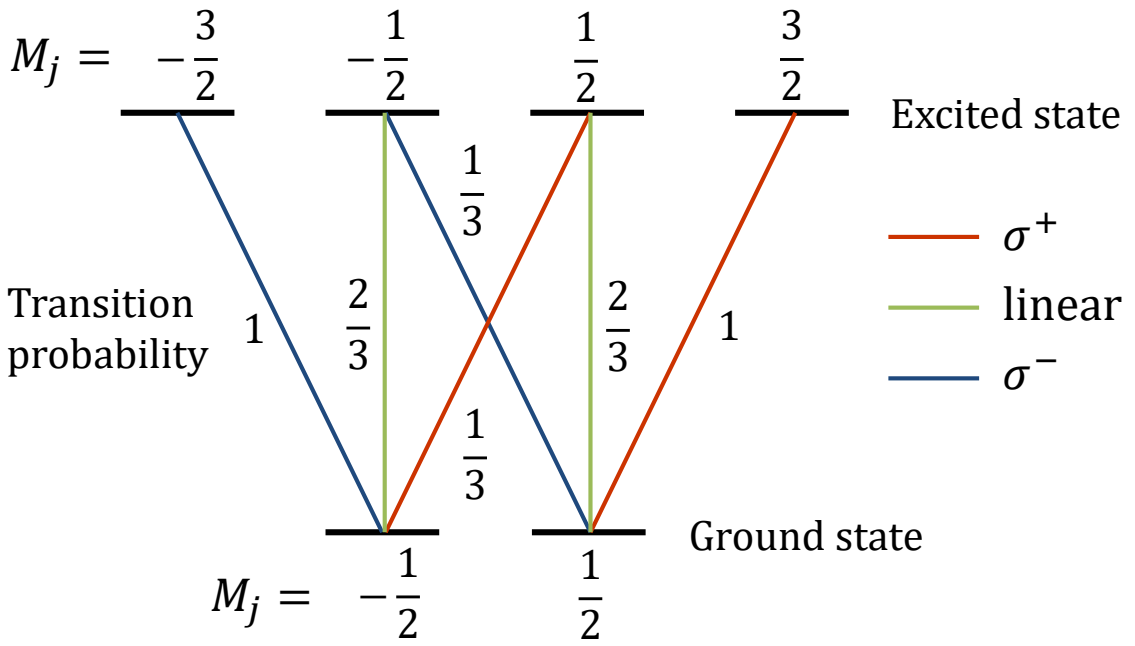


Spatially varying polarization:

$$E(z,t) = E \cdot e^{i(\omega t + kz)}\left(\hat{\mathrm{e}}_x + e^{i(-2kz+\phi)}\hat{\mathrm{e}}_y\right)$$

Optical molasses

Transition diagram with different polarizations:



Polarization-dependent lattice potentials:
Potential induced by atom-light interaction, proportional to transition probability

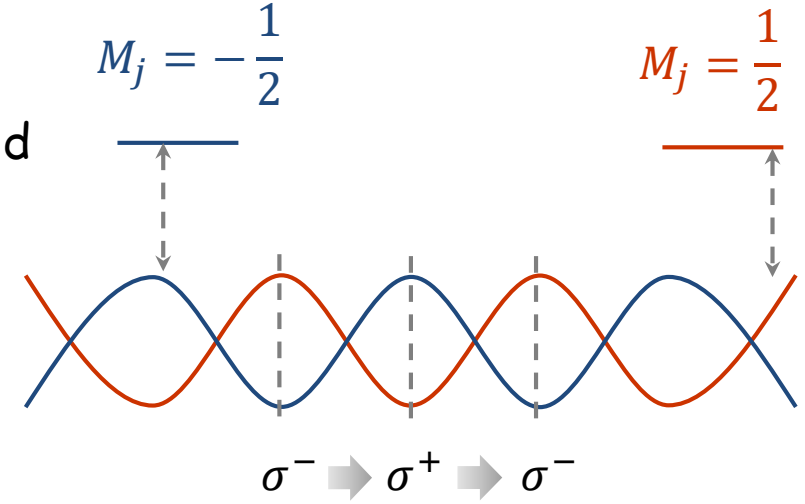
$$U_{\pm} = U_0 \cdot (-2 \pm \sin 2kz)$$

$$U_0 = \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I$$

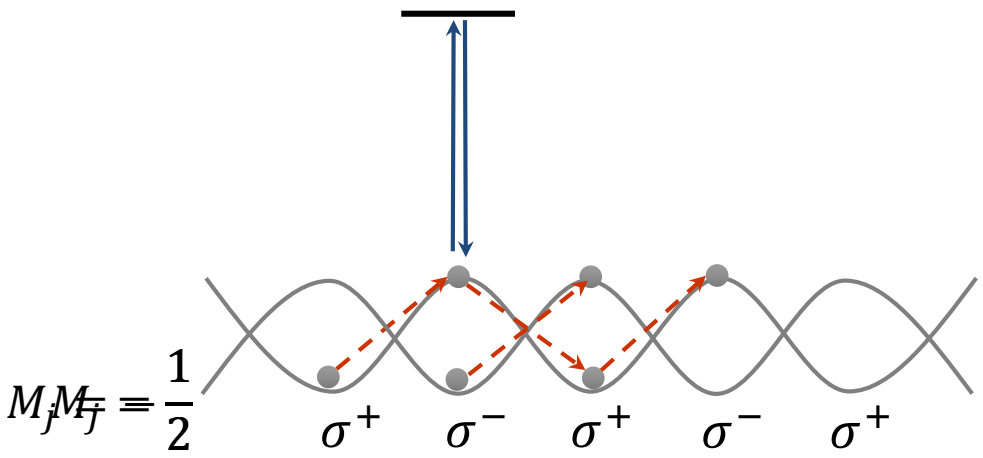
Γ: line width
Δ: detune
I: light intensity

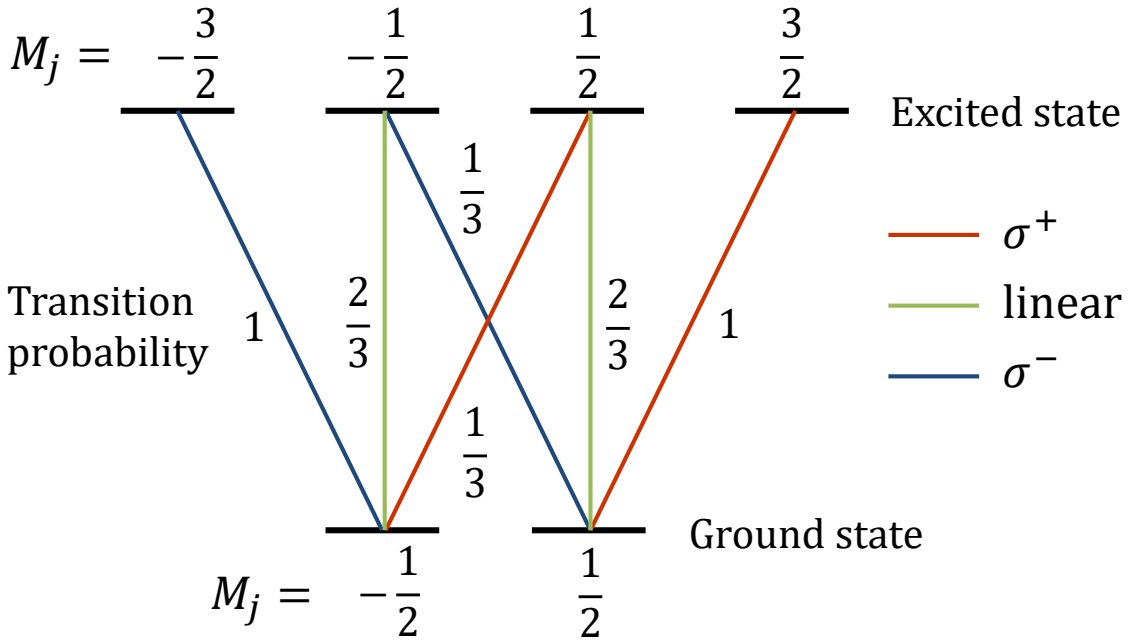
Energy level without light field

Energy level with light field



Sisyphus cooling





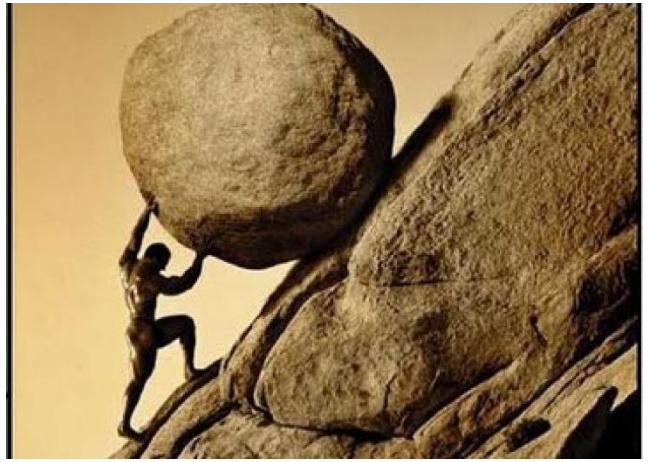
For an moving atom:

Step 1: "climbing" in potential, loss kinetic energy

Step 2: absorbing σ^- photon at the top of potential (smallest detune, high transition probability), excited to upper state and decay ➡

- If decay to $|1/2\rangle$ (p=1/3), nothing would happen, repeat step 1
- If decay to $|-1/2\rangle$ (p=2/3), different potential

Step 3: climb a hill and loss kinetic energy again



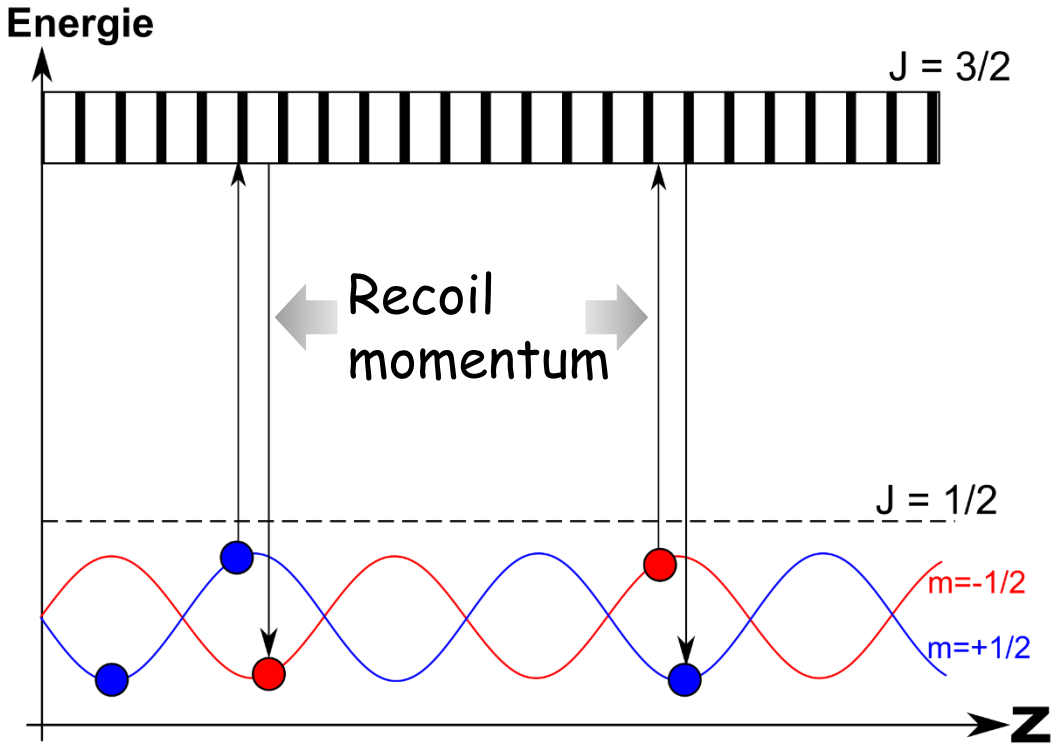
Sisyphus' punishment

Cooling atoms with laser

MOT + Optical molasses:

Chu, Tannoudji and Phillips, method to cool and trap atoms with laser light

Noble Prize in Physics 1997



Limit of Sisyphus cooling:

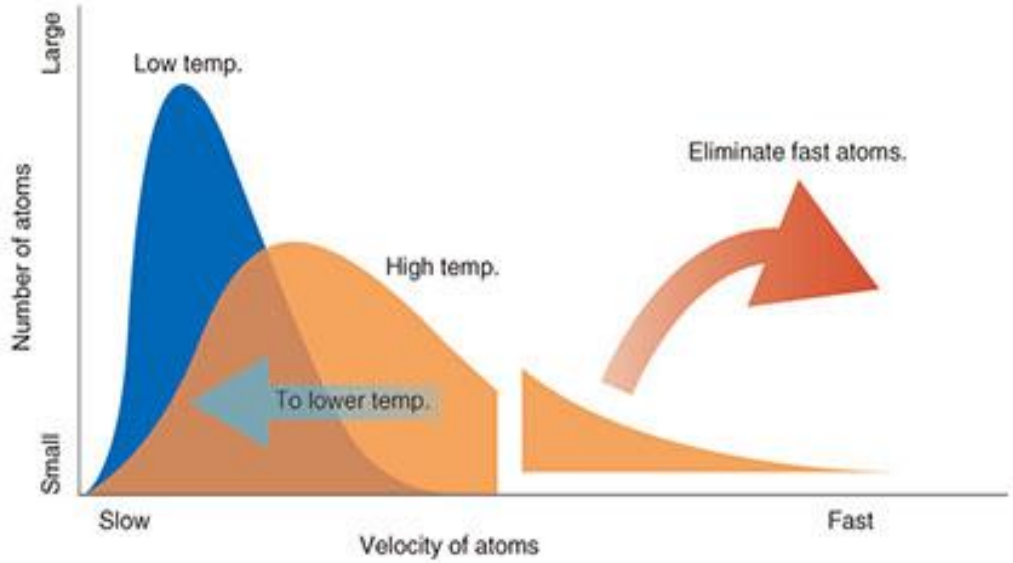
Recoil momentum of photons in transition

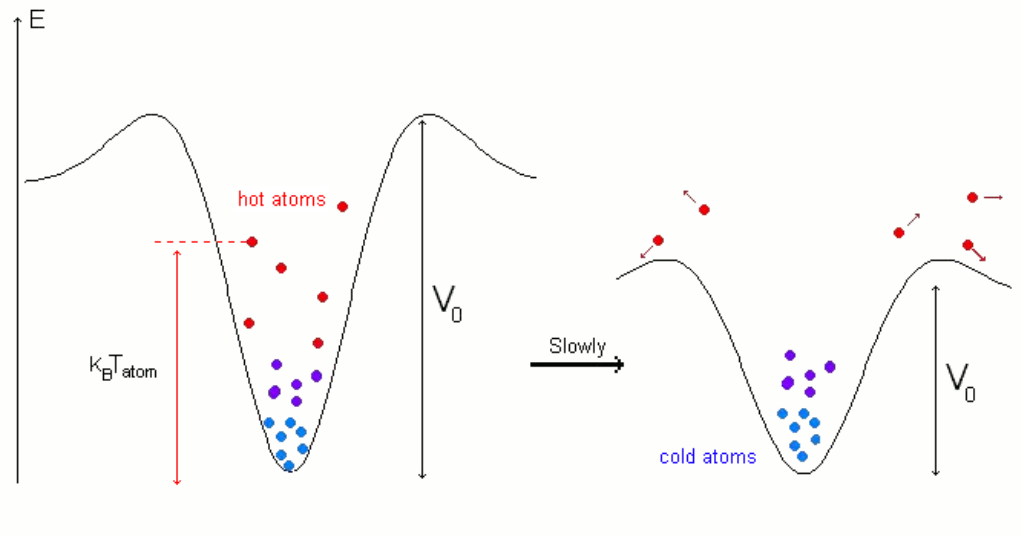
$$T_R = \frac{\hbar^2 k^2}{k_B M}$$ M is the mass of an atom

For ^{87}Rb atom, $T_R \sim 1\mu k$

Further cooling by evaporative cooling

Evaporative cooling in daily life





In view of physicist: thermal equilibrium is re-established through collisions

To cool atoms:
Ramp down optical potential, hotter atoms will escape from trap

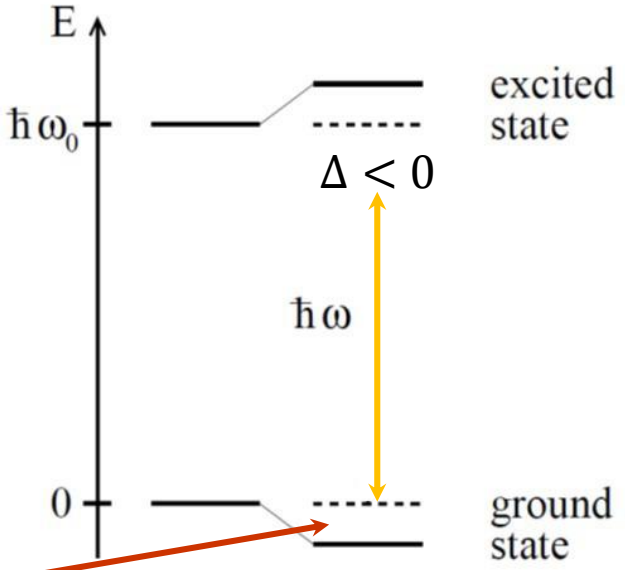
Optical potential induced by light-atom interaction

Optical trap for evaporative cooling

- Light field: $E(r,t) = \hat{e}\tilde{E}(r)\exp(-i\omega t) + \text{c.c.}$
- Induced atomic dipole moment: $p = \alpha E$

  polarizability of atom $\alpha \propto \frac{\Gamma}{\Delta}$, $|\Delta| \gg 0$

  (Γ: line width, Δ: detune)

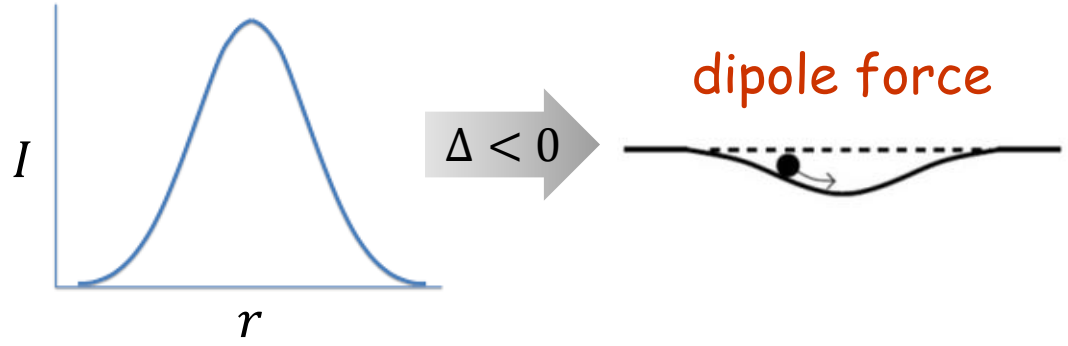


- Interaction between E and p results in energy shift of atomic levels:

$$U(r) = -\frac{1}{2}\langle p \cdot E\rangle = \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I(r)$$

(I: light intensity)

- Gradient of light intensity will provide a dipole force $F = -\nabla U(r) \propto -\frac{\Gamma}{\Delta}\nabla I(r)$

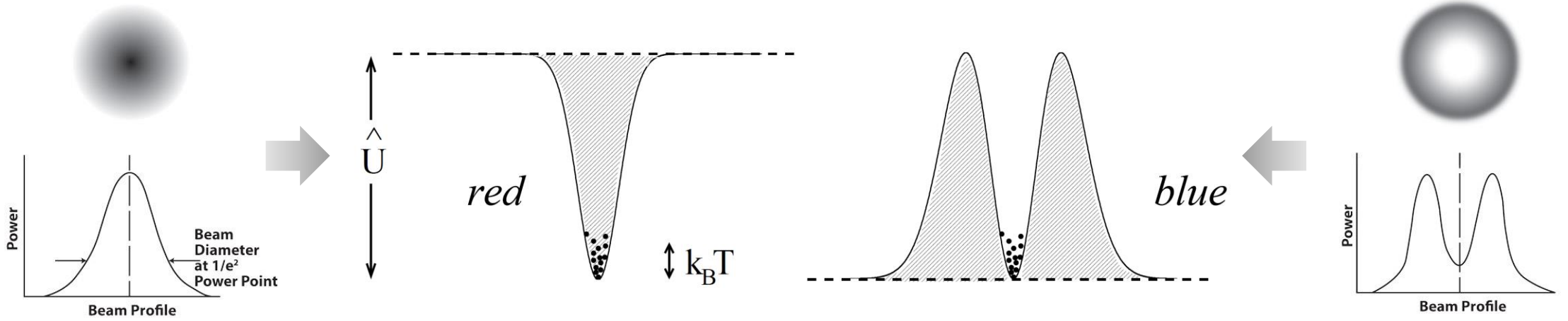


Optical potential induced by light-atom interaction

Red and blue detuned trap

$$U(r) \propto \frac{\Gamma}{\Delta} I(r)$$

- Red detuning ($\Delta < 0$): a trap is formed at the position of maximal intensity
- Blue detuning ($\Delta > 0$): a trap is formed at the position of minimal intensity



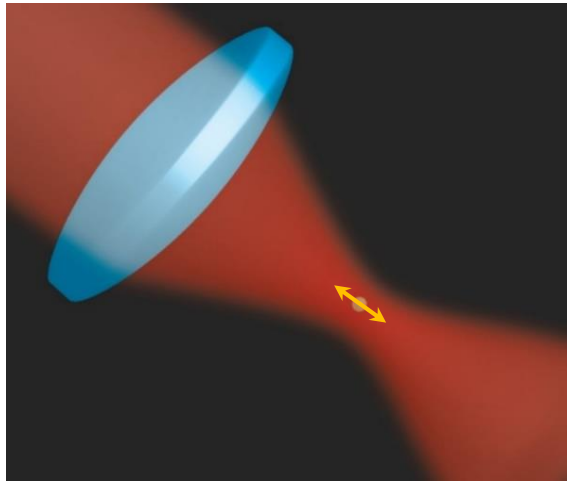
TEM_{00} mode of Gaussian beam

TEM_{01} mode of Gaussian beam

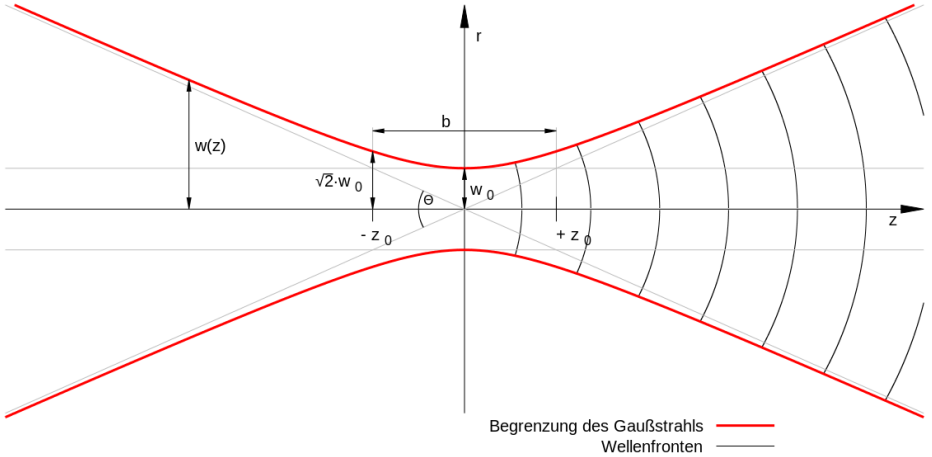
Grimm *et al.*, Adv. At. Mol. Opt. Phys. 42, 95 (2000)

Optical traps

Gaussian beam to form a 3D optical trap



Atoms are trapped near the waist

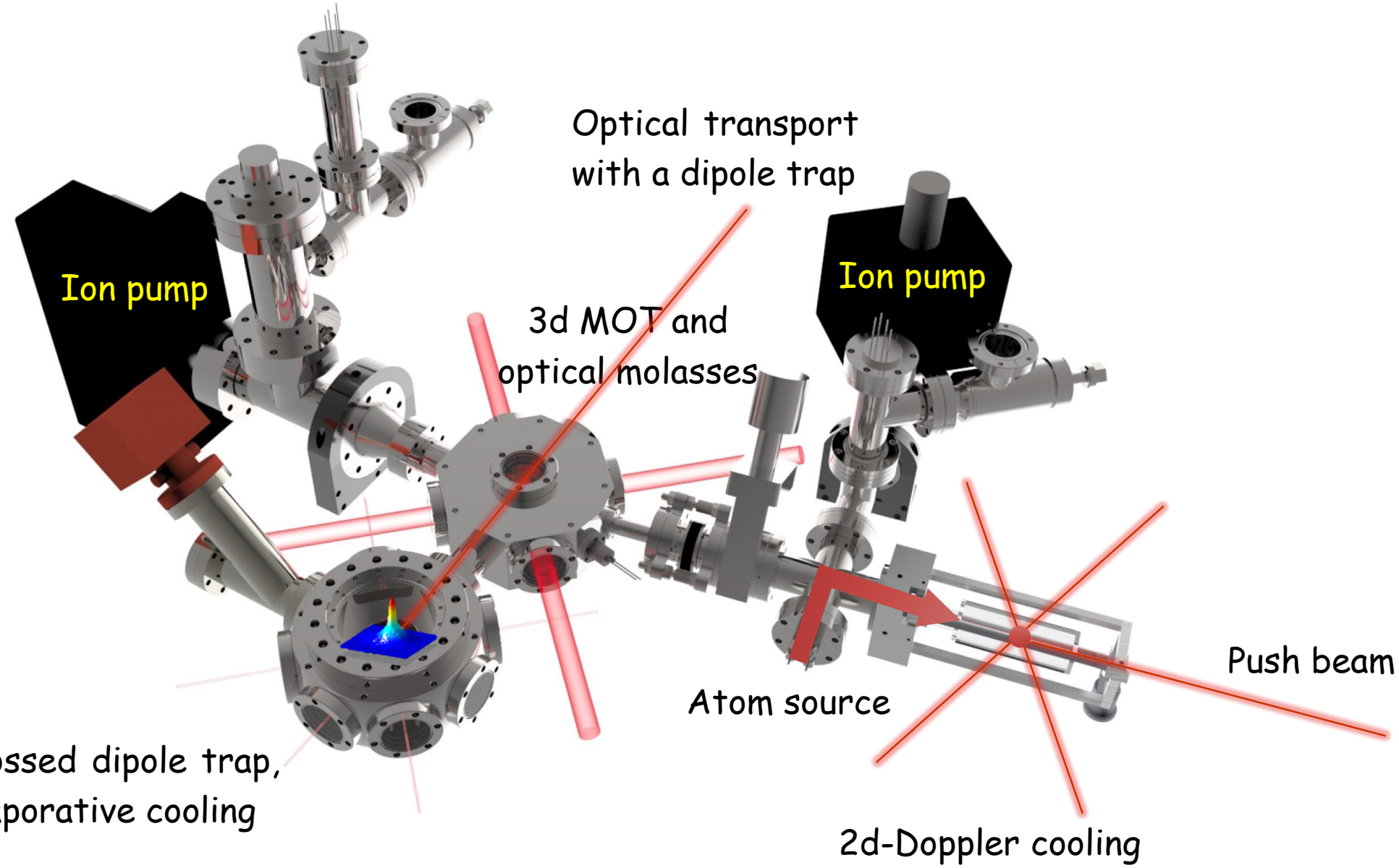


Gradient of intensity in z-direction is small

Cross beams to trap atoms at the waist

Decrease the intensity of light, evaporative cooling to around 100 nk ➡ achieving BEC

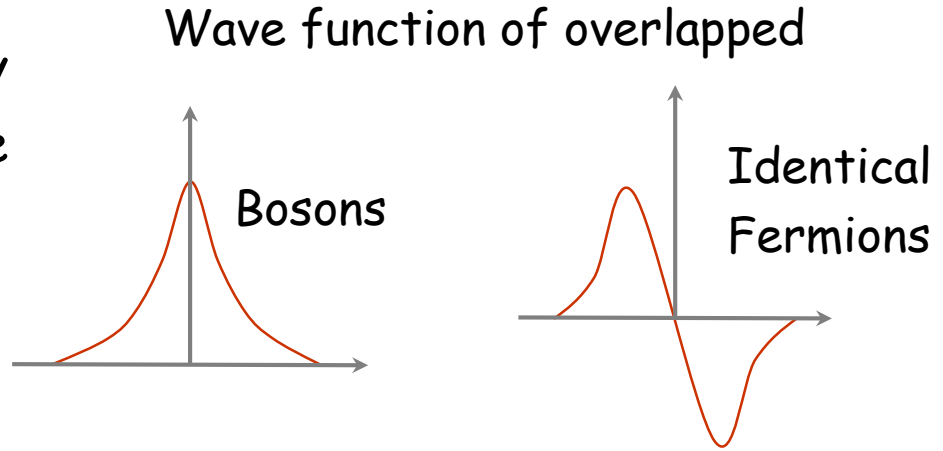
Typical route for cooling atoms



Evaporative cooling of Fermi atoms

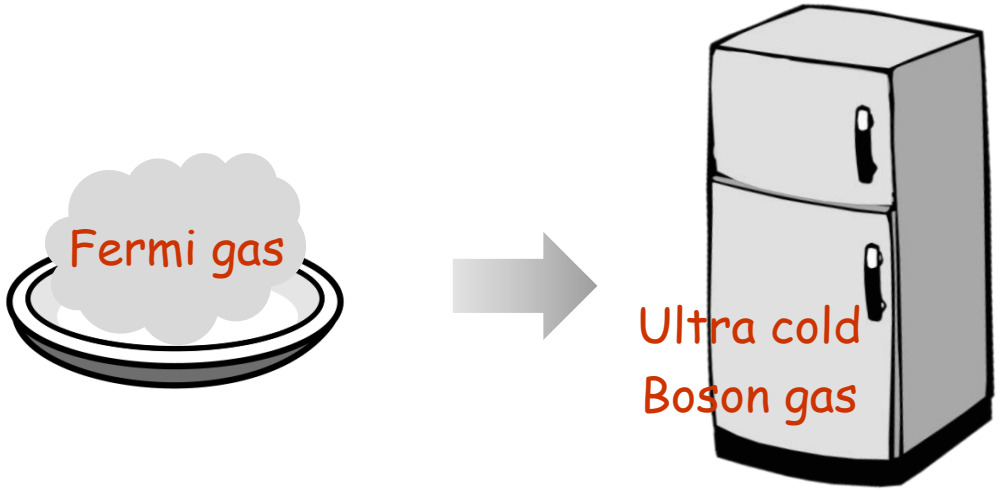
Physical problem: identical Fermions cannot stay close enough to undergo effective collisions due to Pauli blocking

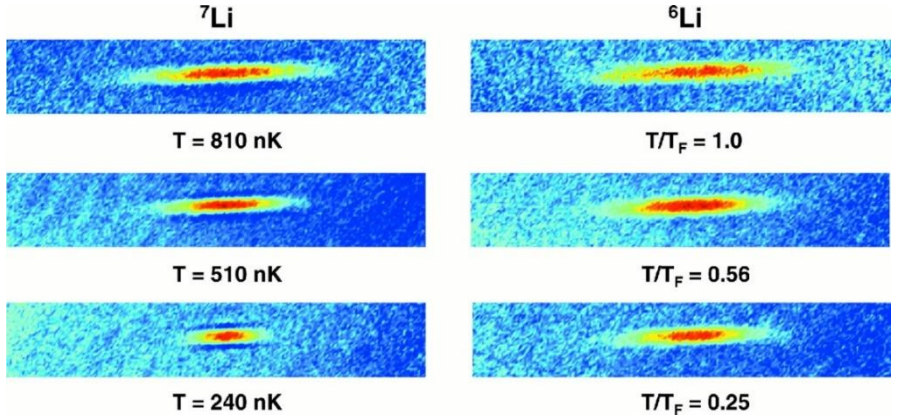
Evaporative cooling cannot happen!



Solutions:

- Sympathetically cooling by another coolant (Boson)



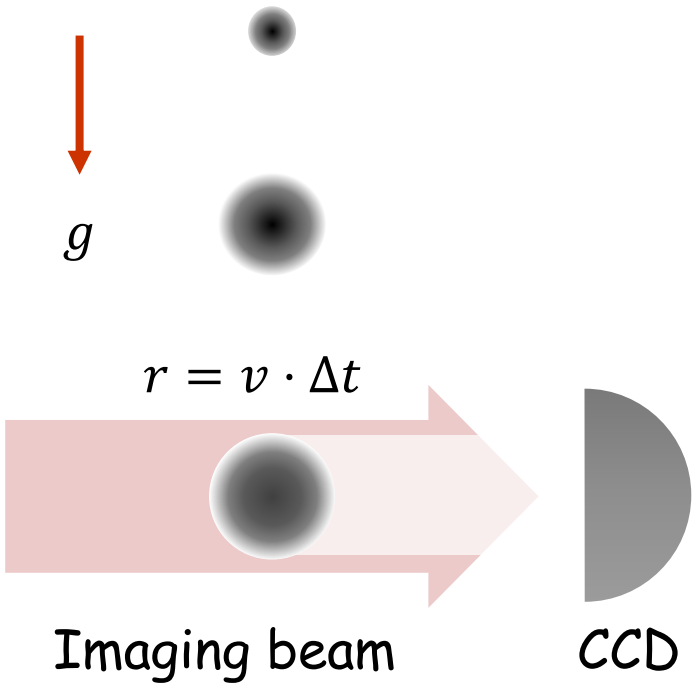


Observation of degenerate Fermi gas by sympathetically cooling

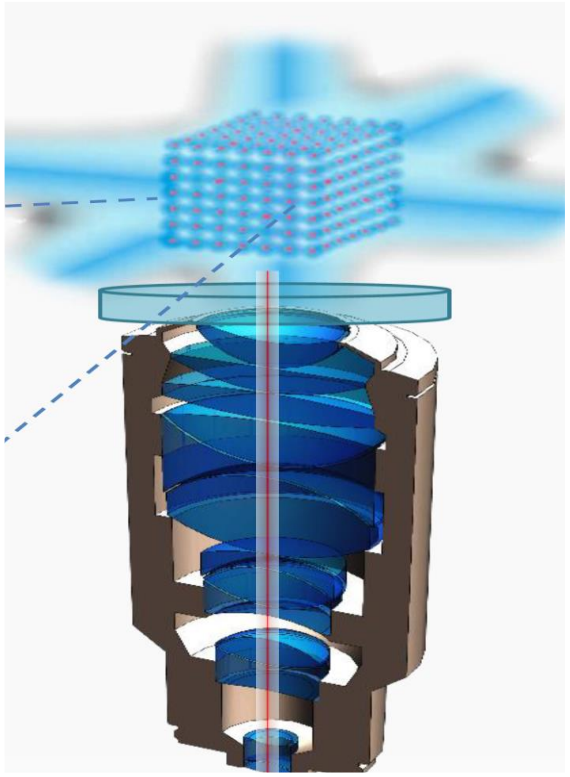
Truscott *et al.*, Science 291, 2570 (2001)]

Typical detection methods

Time of flight (TOF)



In-situ imaging



TOF images reflect the momentum distribution of the atoms ➡ derive information of temperature and coherence

Via in-situ imaging with a high-resolution microscope ➡ Real-space density distribution of the atoms

Part II: Quantum computation and simulation with atomic spin entanglement in optical lattices

Dai *et al.*, Nature Physics 12, 783 (2016)
Dai et al., Nature Physics 13,1915 (2017)

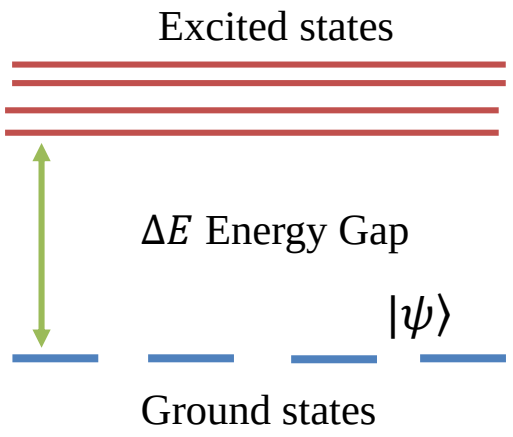
Topological quantum computing

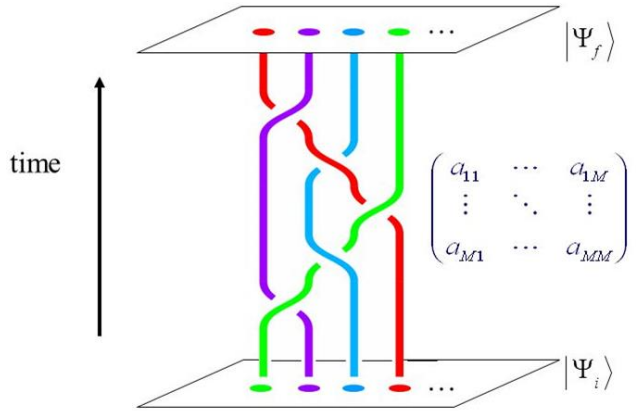
Protect quantum bits/gates at the physical level

- Kitaev, Ann. Phys. 303, 2 (2003); Ann. Phys. 321, 2 (2006)
- Raussendorf *et al.*, Ann. Phys. 321, 2242 (2003)
- Nayak *et al.*, RMP 80, 1083 (2008)

➡ Relax the error threshold rate from 10^{-5} to 10^{-2}

Protect qubits with energy gap





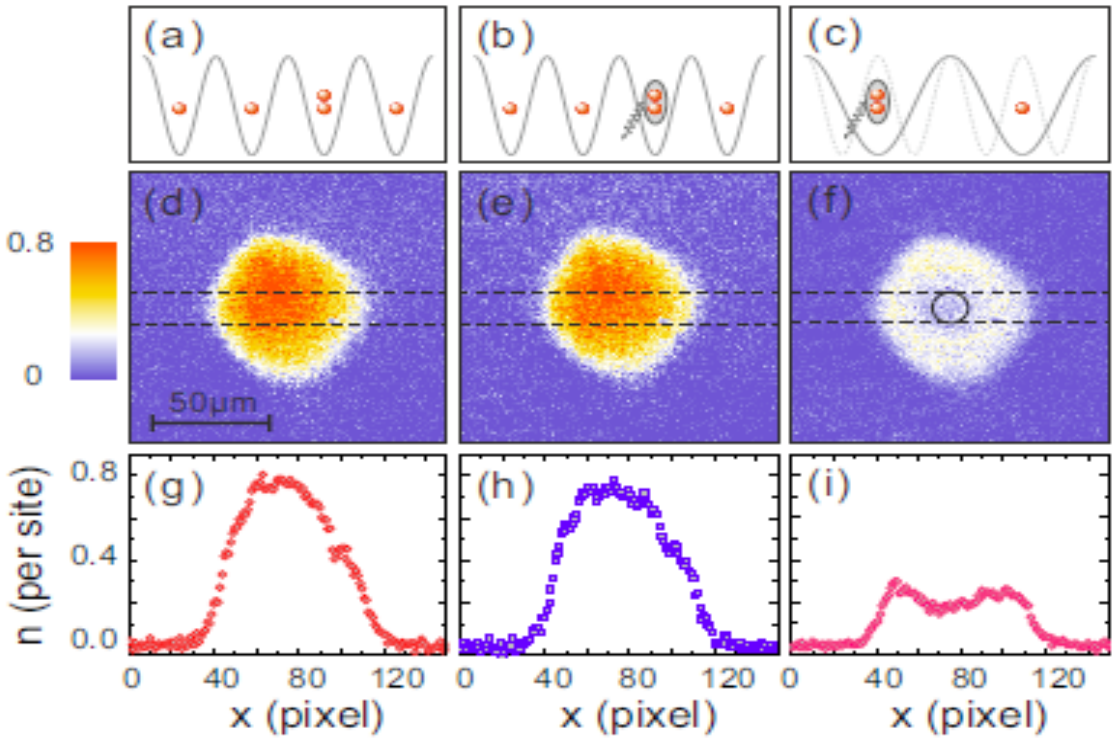
Quantum gates: Braiding Anyons

☒ No naturally occurring system is likely to have a Hamiltonian of the Kitaev model

☑ Purpose-engineered systems of optical lattices or Josephson junction arrays

--Anthony J. Leggett

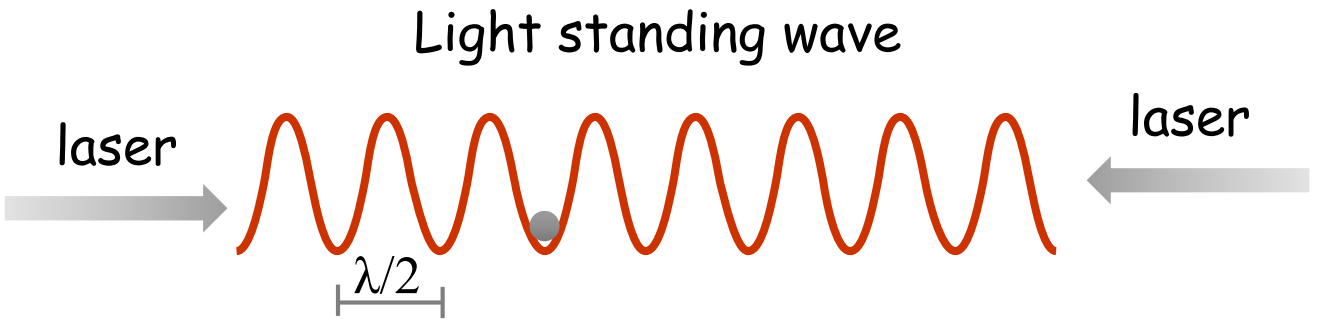
Scalability: atoms in optical lattice



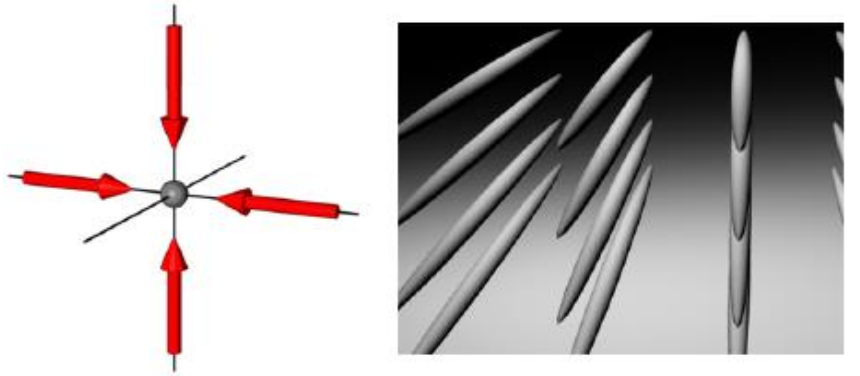
Atom-atom entanglement in optical lattices (^{87}Rb)

- ☑ Generate large number atom-atom entanglement
- ☑ Demonstrate the braiding Anyons required by topological quantum computation

Optical lattices

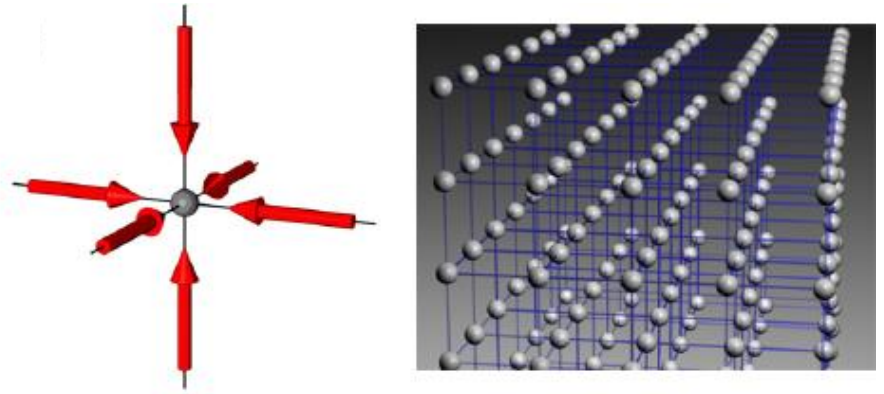


1D optical lattice $V(x) = V_0 \cos^2(kx)$



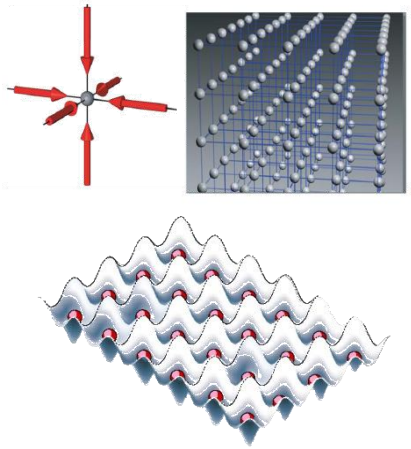
2D optical lattice

- Interference of counter-propagating laser beams
  - ➡ a spatially periodic pattern
- "Lattice": periodic optical dipole potential
  - ➡ atoms are cooled and collected in the locations of potential minima

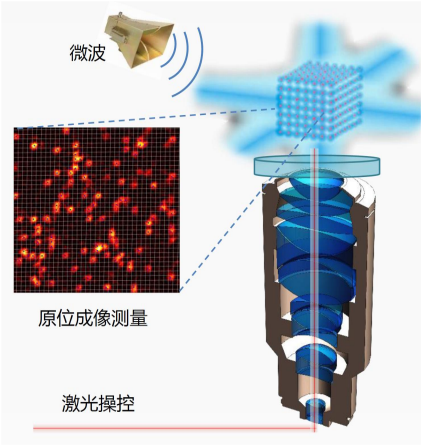


3D optical lattice

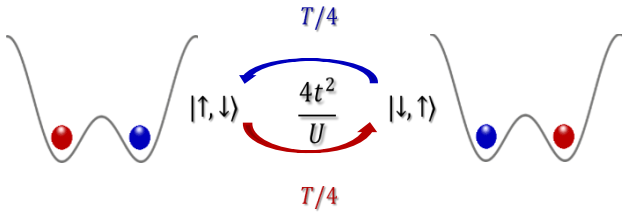
Scalability: atoms in optical lattice



Optical lattice: an array of well coherently controlled cold atoms

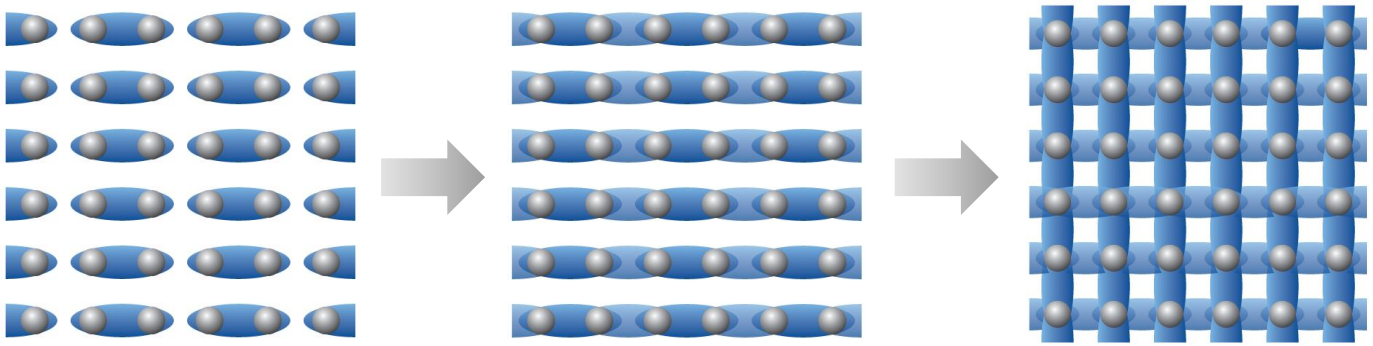


in-situ imaging: only one atom trapped in a lattice



Spin exchange interaction: generate spin-spin entanglement

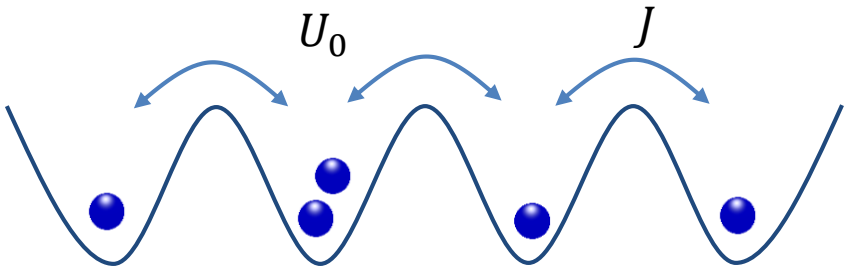
Multi-atom entanglement!



Vaucher *et al.*, NJP 10, 023005 (2008)

Preparing one atom per site

Bose-Hubbard model (BMH)

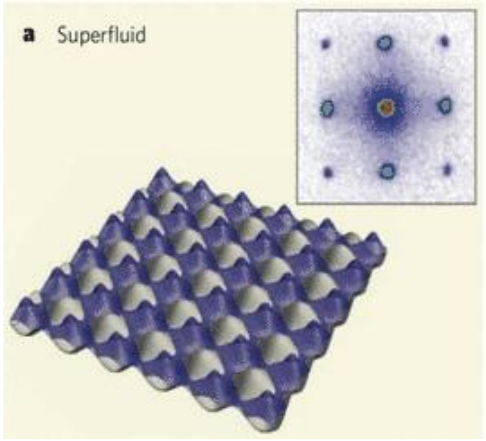


$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U_0}{2} \sum_i \hat{n}_i(\hat{n}_i - 1) - \sum_i \mu_i \hat{n}_i,$$

J: nearest-neighbor tunneling

U_0: onsite interaction

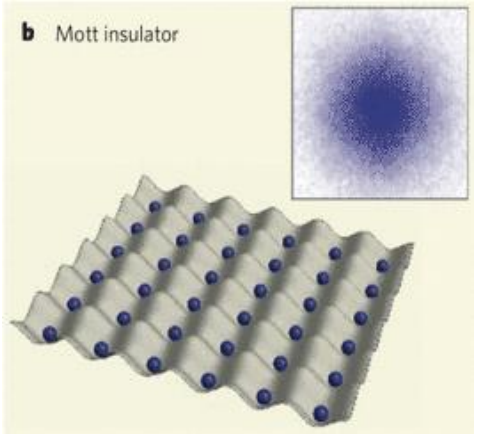
Theory: Jaksch *et al.*, PRL 81, 3108 (1998)



$U_0 \ll J$

superfluid phase

Phase transition

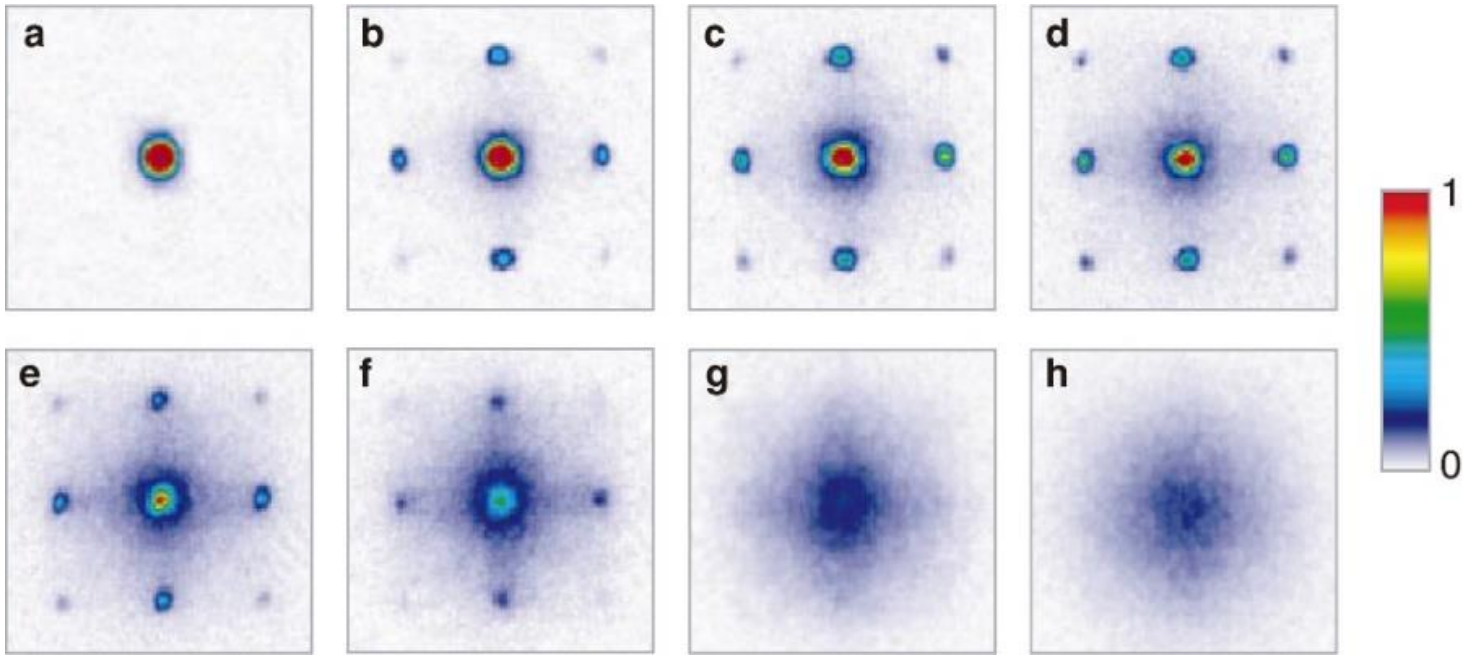


$U_0 \gg J$

Mott insulator phase

Through the phase transition, one atom per site can be prepared

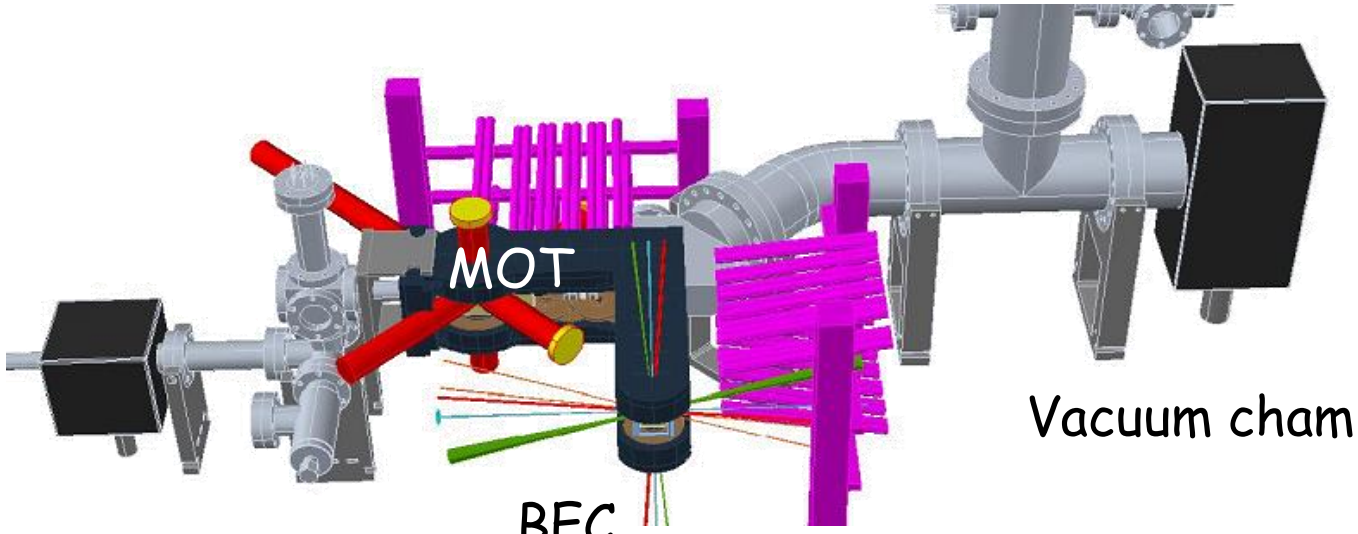
Phase transition from SF to MI

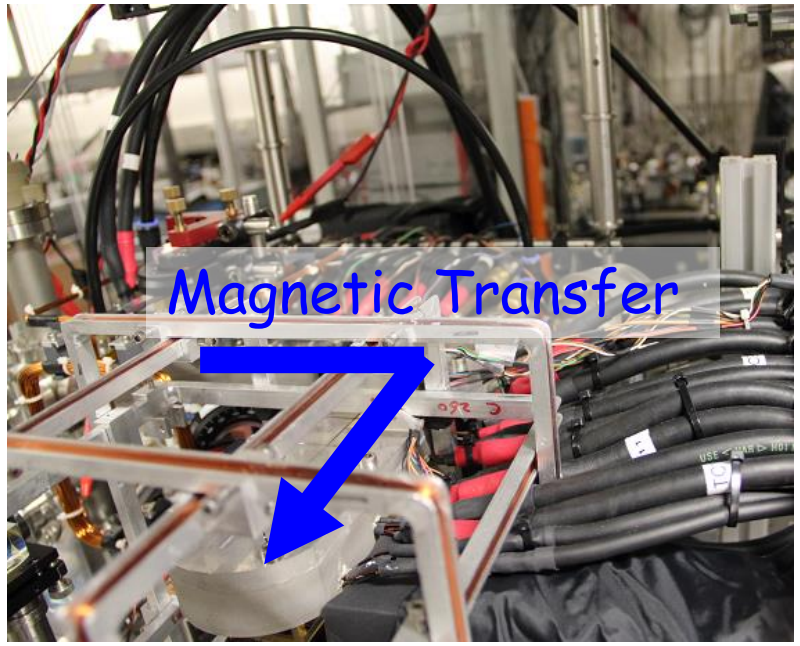


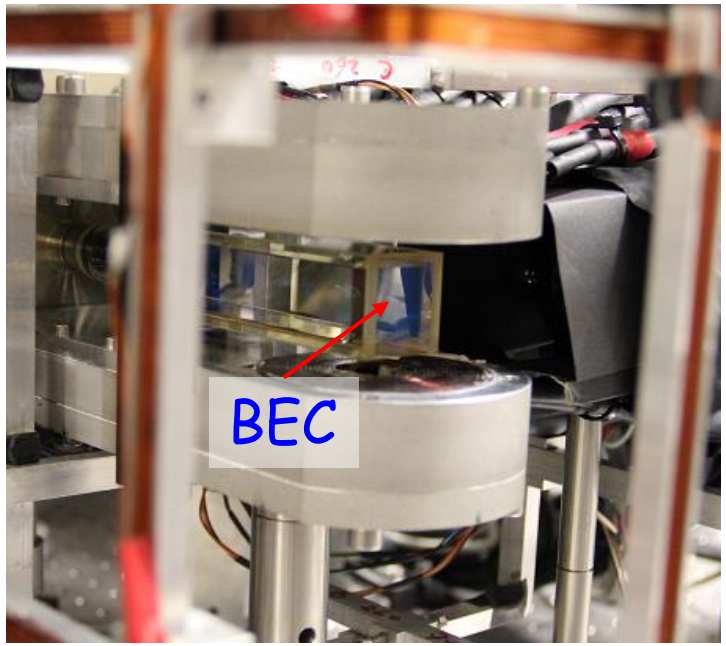
Fist observation of quantum phase transition from a superfluid to a Mott insulator

Greiner *et al.*, Nature 415, 39 (2002)

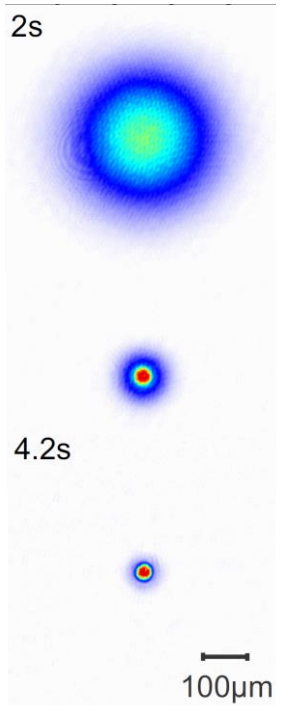
Experimental setup

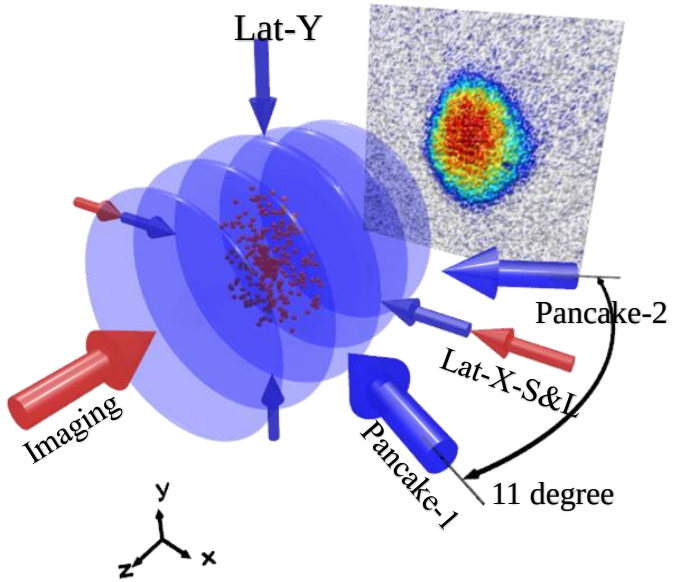


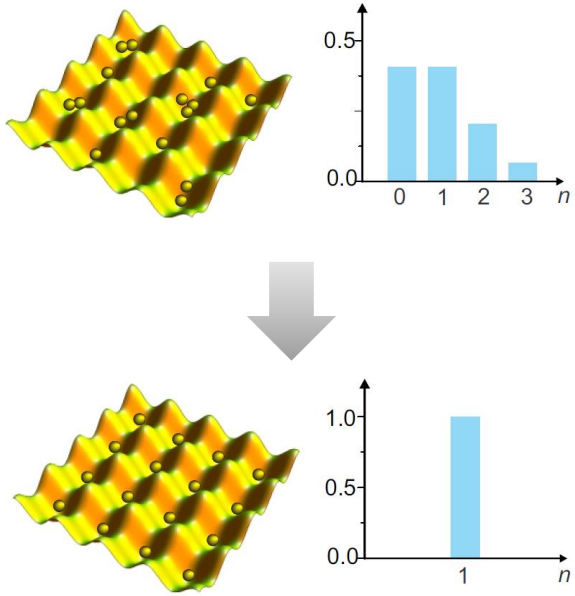




Prepare a 2D quantum gas with in-situ imaging



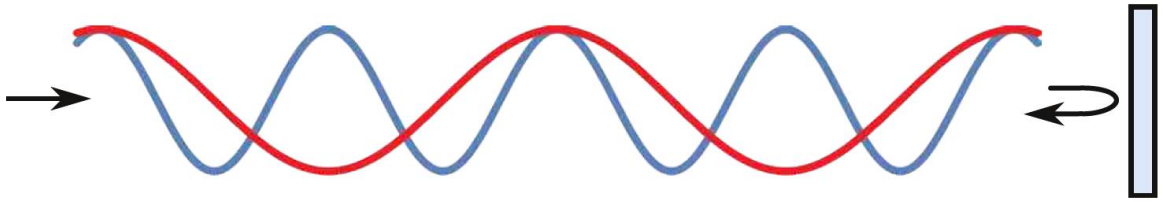




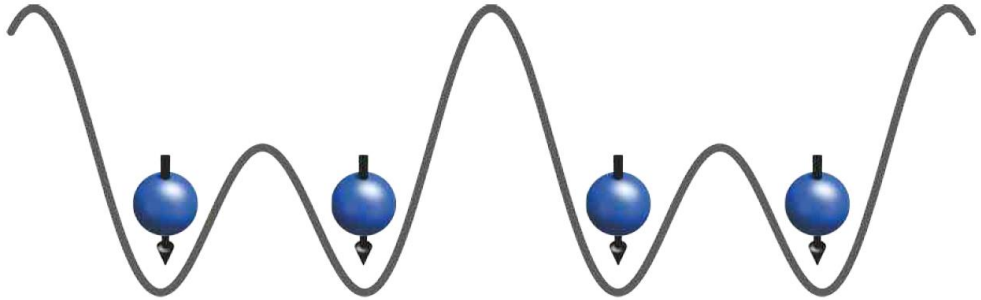
- ^{87}Rb: $|F = 1, m_F = -1\rangle$ BEC 2×10^5 atoms
- Load into a pancake lattice N_{2D}~15000, T_{2D}=23(3) nK
- SF to MI transition by ramping up lattice depth

Objective: NA=0.48, resolution 2 μm

Optical super-lattice



$\lambda_s = 767\text{nm}, \ \lambda_l = 1534\text{nm}$



$|\downarrow\rangle = 5S_{1/2}|F = 1, m_F = -1\rangle$ $|\uparrow\rangle = 5S_{1/2}|F = 2, m_F = -2\rangle$

Isolated double wells: $V(x) = V_s \cos^2(2kx + \phi_x) + V_l \cos^2(kx)$

Theory: Duan *et al.*, PRL 91, 090402 (2003)

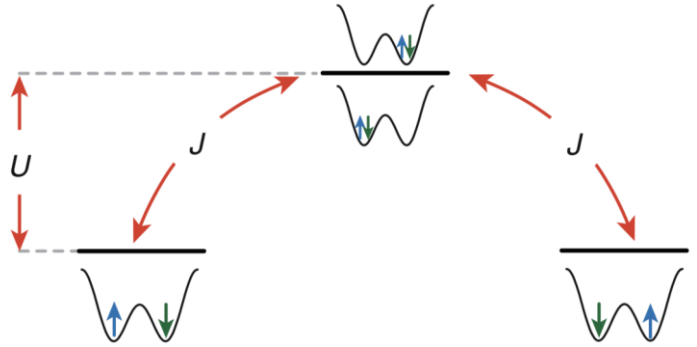
Experiment: Trotzky *et al.*, Science 319, 295 (2008)

Spin super-exchange: generating spin entanglement

BHM (two-site, spin dependent)

$$\hat{H} = \sum_{\sigma=\uparrow,\downarrow} [-J(\hat{a}^{+}_{\sigma L}\hat{a}_{\sigma R} + \hat{a}^{+}_{\sigma R}\hat{a}_{\sigma L})] + U[\hat{n}_{\uparrow L}\hat{n}_{\downarrow L} + \hat{n}_{\uparrow R}\hat{n}_{\downarrow R}]$$

Interaction dominated $(U \gg J)$,
in low-energy state subspace
$\{|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle, |\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle\}$



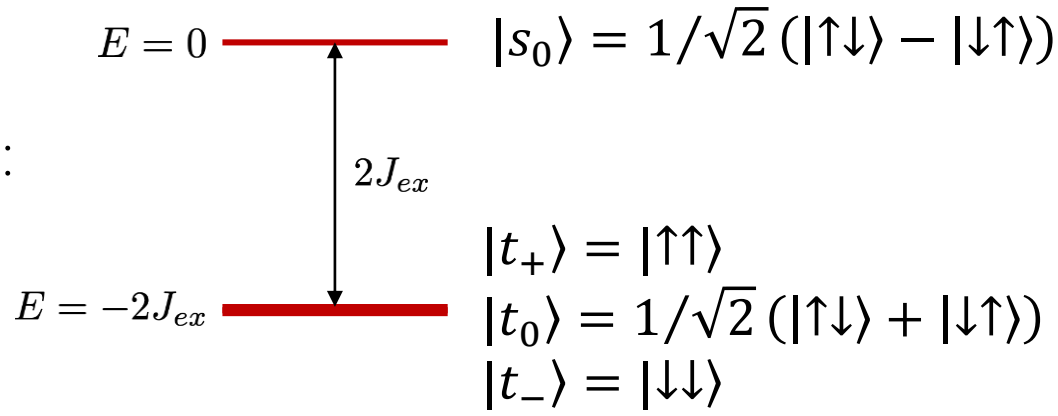
Single atom tunneling is suppressed

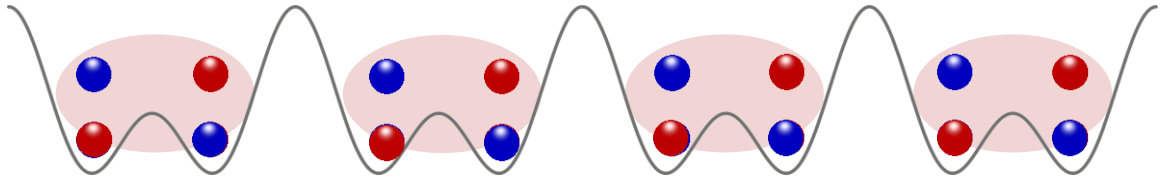
$$\hat{H}_{\text{eff}} = J_{ex}\begin{pmatrix} -1 & -1 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ 0 & 0 & -2 & 0 \\ 0 & 0 & 0 & -2 \end{pmatrix} = -2J_{ex}\hat{S}_L \cdot \hat{S}_R + C$$

$$J_{ex} = 2J^2/U,\ \hat{S}_j = \left(\hat{S}_j^x, \hat{S}_j^y, \hat{S}_j^z\right),\ \hat{S}^k = \frac{1}{2}\sigma_k$$

Spin super-exchange: generating spin entanglement

Energy spectrum:





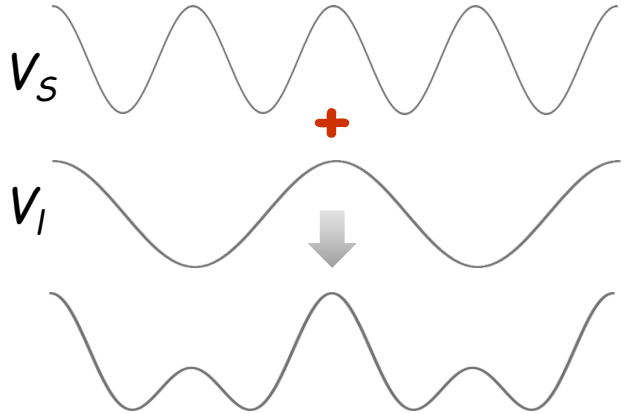
- Initial state: $|\uparrow\downarrow\rangle = \frac{1}{\sqrt{2}}(|t_0\rangle + |s_0\rangle)$, degenerate with $|\downarrow\uparrow\rangle = \frac{1}{\sqrt{2}}(|t_0\rangle - |s_0\rangle)$
- Spins will oscillate between two configurations with a period of $1/J_{ex}$
- Stop the oscillation by increasing the barrier to create spin entanglement

$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + i|\downarrow\uparrow\rangle)$$

Theory: Duan *et al.*, PRL 91, 090402 (2003)

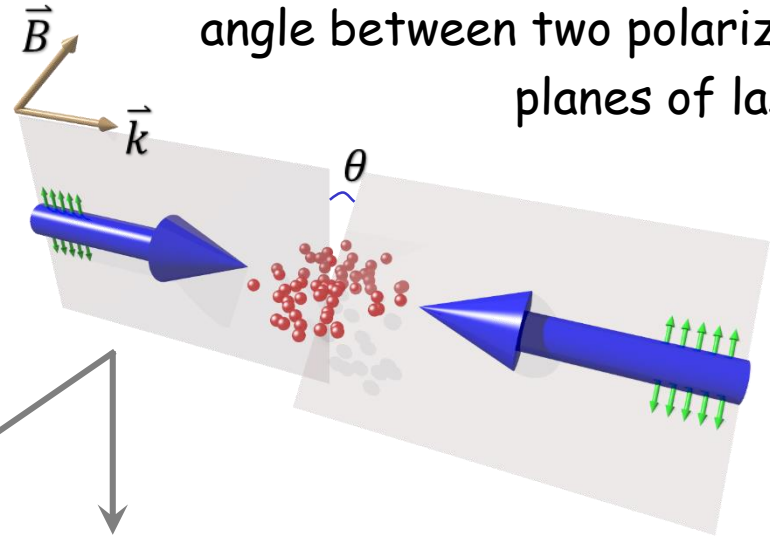
Spin-dependent superlattices

Normal super-lattice



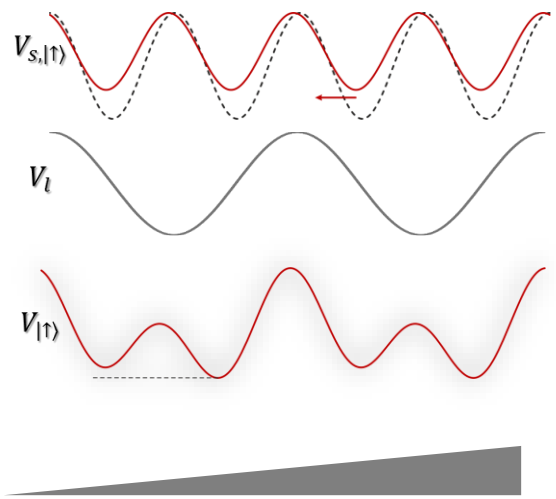
Spin-dependent superlattice

angle between two polarization planes of laser S

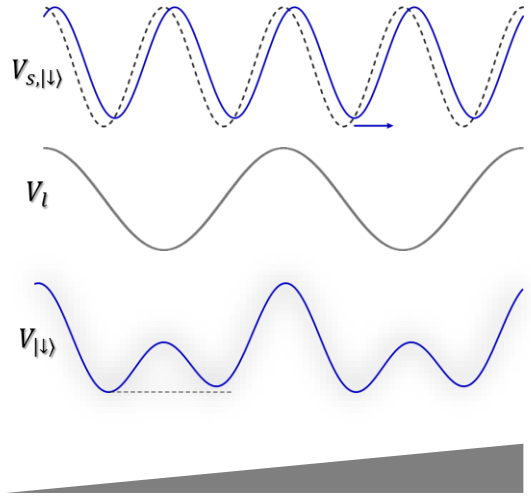


- $|\uparrow\rangle = 5S_{1/2}|F = 2, m_F = -2\rangle, g_F = 1/2$
- $|\downarrow\rangle = 5S_{1/2}|F = 1, m_F = -1\rangle, g_F = -1/2$

Left well is higher



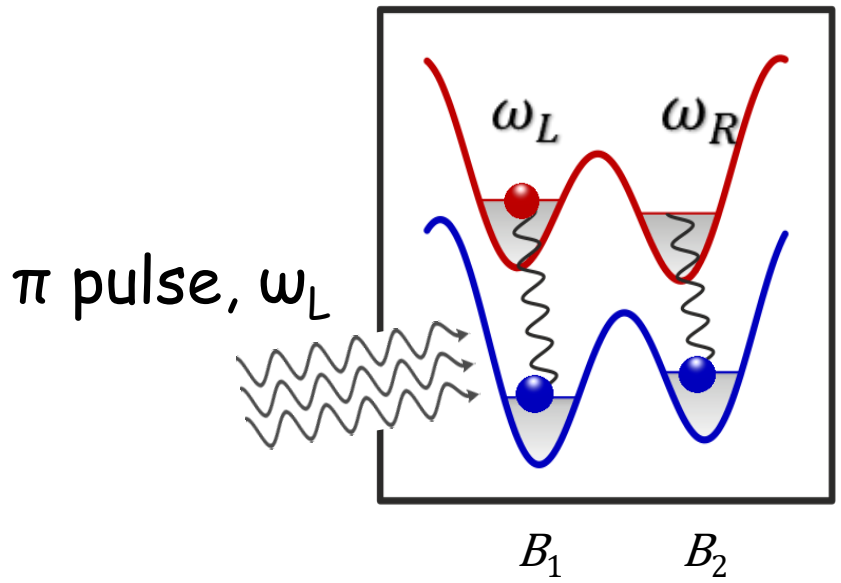
∇B

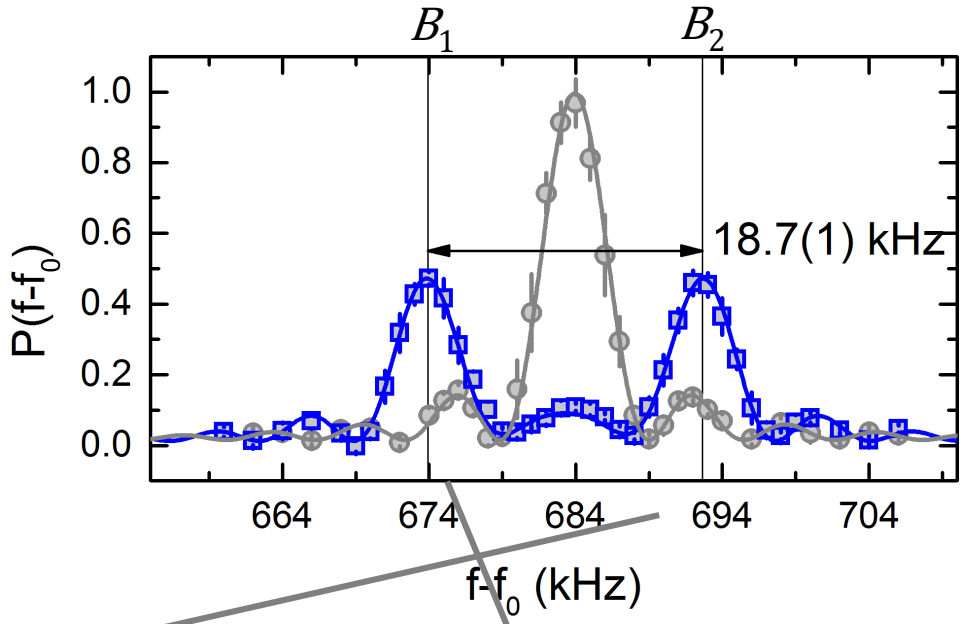


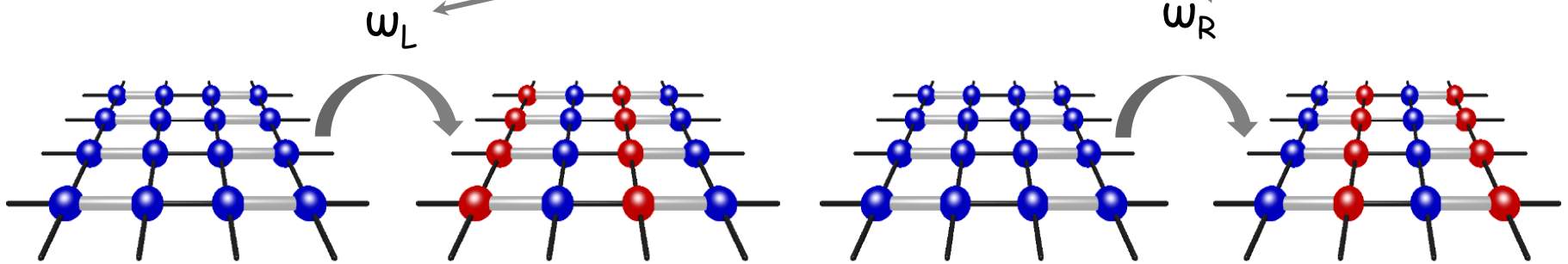
Right well is higher

Spin-dependent superlattices

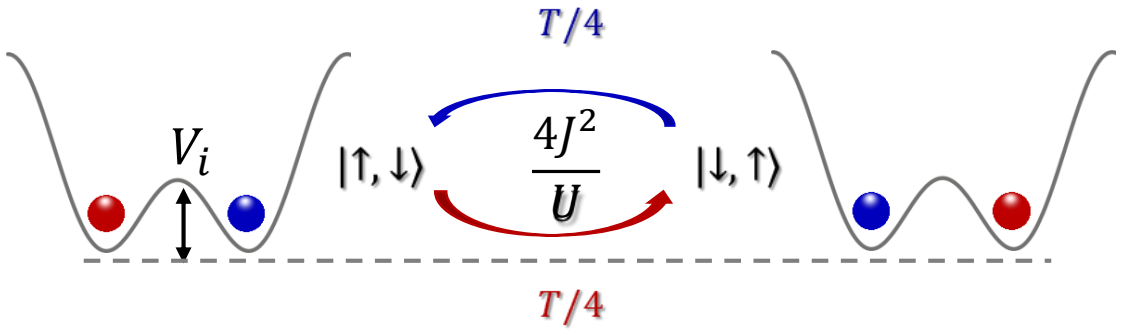
Effective magnetic gradient caused by spin-dependent superlattice







Spin super-exchange: generating spin entanglement



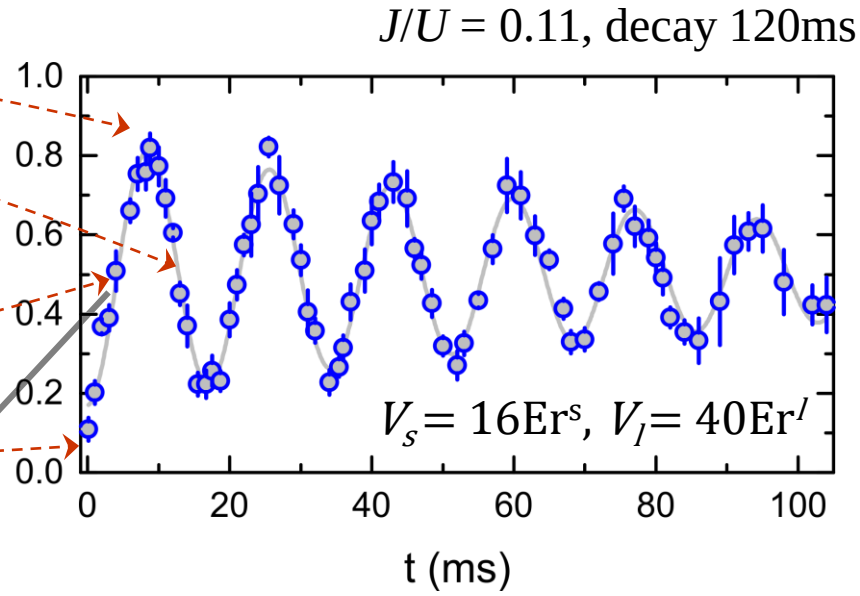
- Switch off effective magnetic gradient, $|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$ degenerate
- Decrease V_i → spin oscillation

$$|\phi\rangle = \frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle + i|\uparrow,\downarrow\rangle)$$

$|\downarrow,\uparrow\rangle$

$\frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle - i|\uparrow,\downarrow\rangle)$

$|\uparrow,\downarrow\rangle$



- Increase V_i → Freeze entangled state

How to detect entanglement?

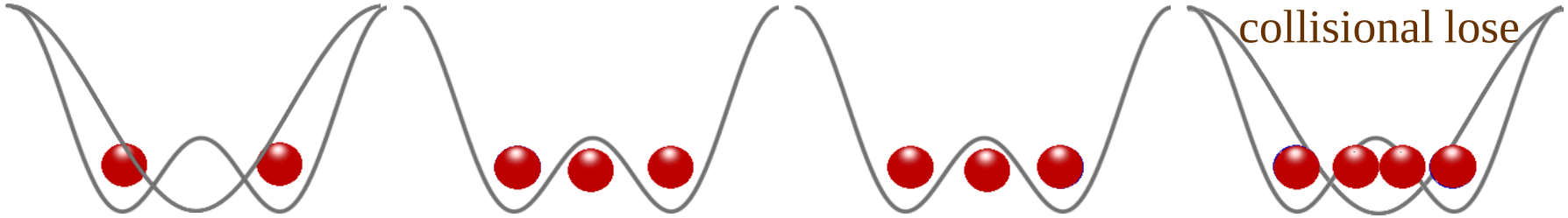
Entanglement detection

Entangled state: $|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle)$

Spin-dependent collisional loss: identify $|\downarrow\downarrow\rangle$ from 4 orthogonal states $|\downarrow\downarrow\rangle$, $|\uparrow\downarrow\rangle$, $|\downarrow\uparrow\rangle$, $|\uparrow\uparrow\rangle$,

- Imaging spin-up atoms
- Merging and killing
- Count N_1
- Count N_2
- π pulse

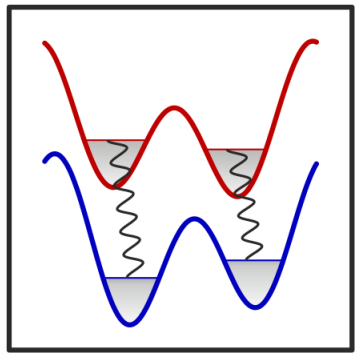
Spin-dependent collisional lose



$$N_{\downarrow\downarrow} = N_{Total} - N_1 - N_2$$

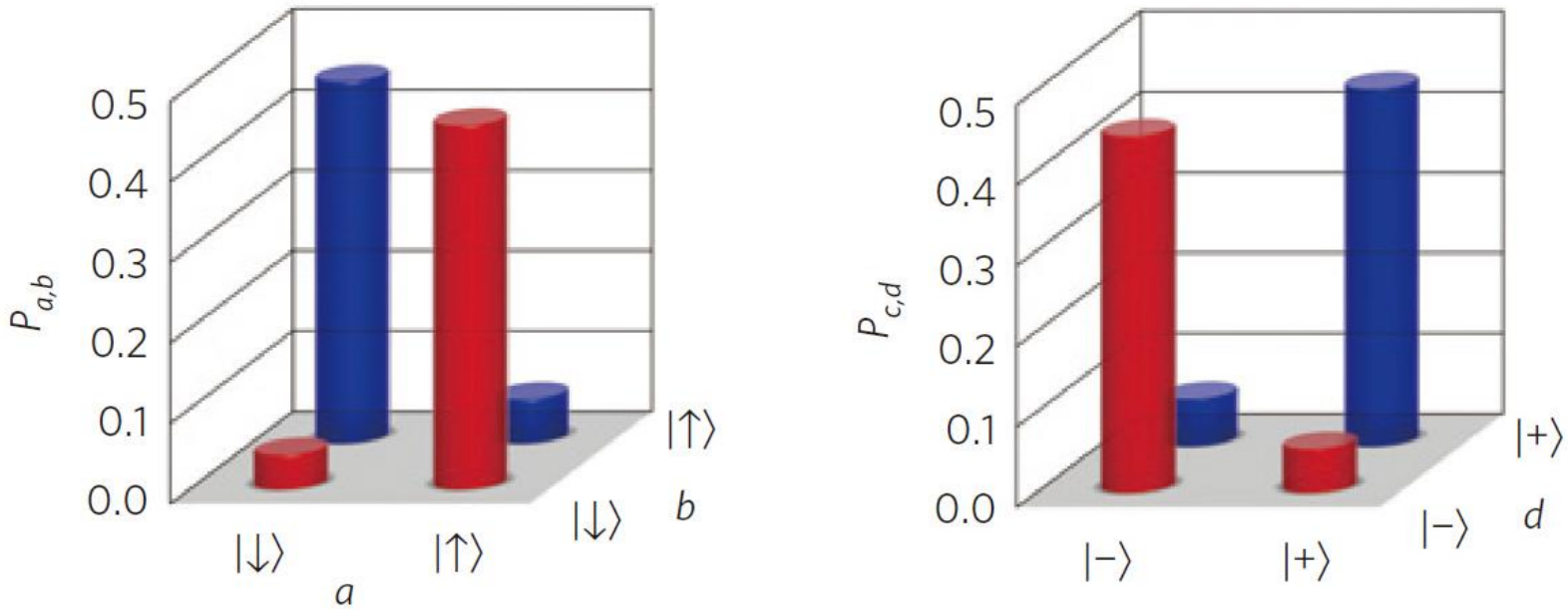
Identify $|\uparrow\downarrow\rangle$, $|\downarrow\uparrow\rangle$, $|\uparrow\uparrow\rangle$:

transfer to $|\downarrow\downarrow\rangle$ by left/right π pulse



Entanglement detection

Probabilities in different basis

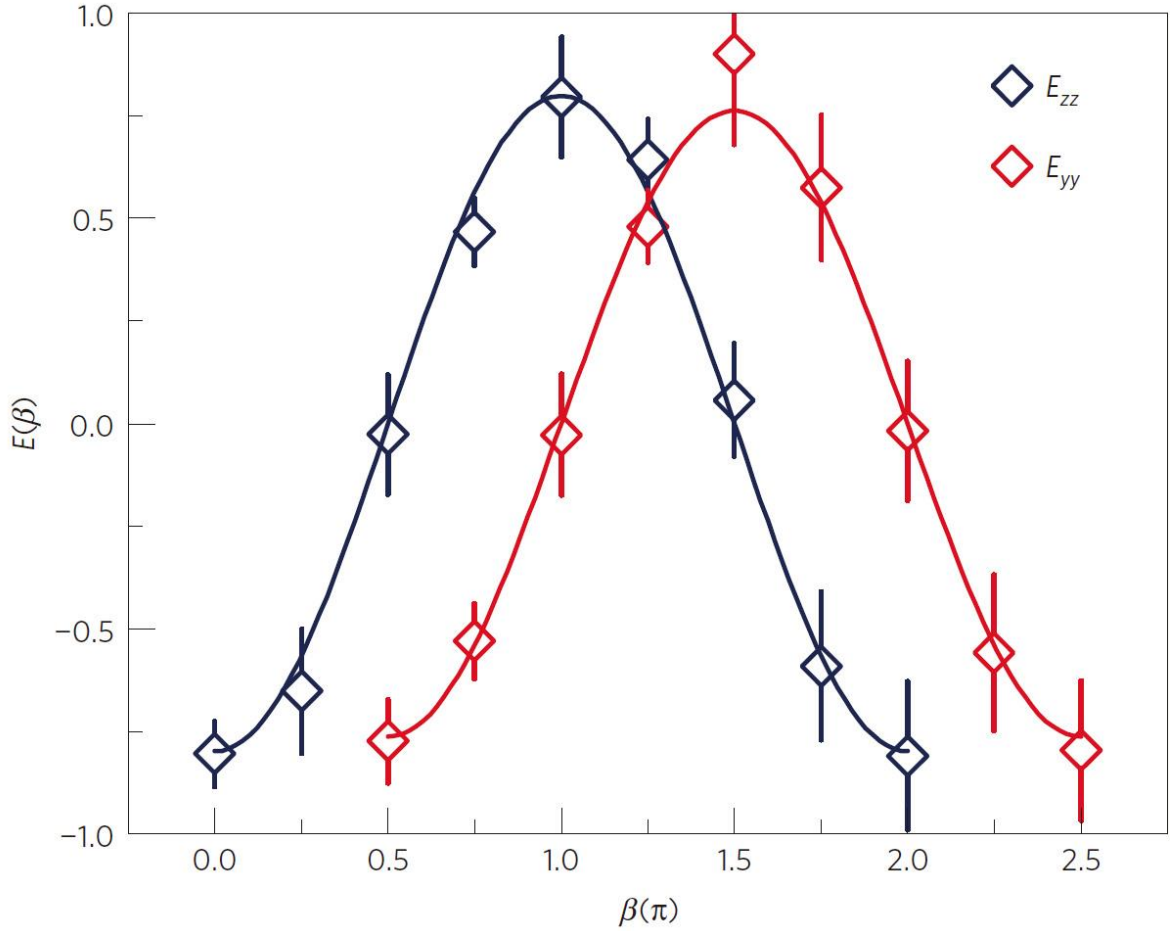


$$F \geq (P_{\uparrow,\downarrow} + P_{\downarrow,\uparrow} - 2\sqrt{P_{\uparrow,\uparrow}\, P_{\downarrow,\downarrow}} + P_{+,+} + P_{-,-} - P_{+,-} - P_{-,+})$$

$$\geq (P_{\uparrow,\downarrow} + P_{\downarrow,\uparrow} - P_{\uparrow,\uparrow} - P_{\downarrow,\downarrow} + P_{+,+} + P_{-,-} - P_{+,-} - P_{-,+})$$

$$= 0.79 \pm 0.06$$

Spin correlation curve and entanglement



Violation of CHSH type Bell's inequality $S = 2.21 \pm 0.08$

Dai *et al.*, Nature Physics 12, 783 (2016)

Kitaev model: Toric code

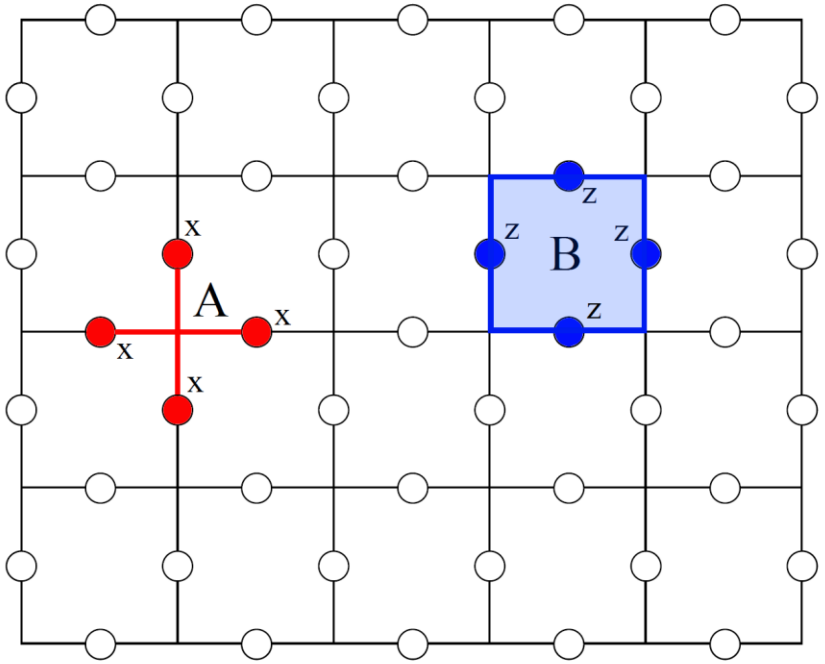
Manipulating the interaction and entanglement of atomic spins in optical lattices ➡ mimic a unit Hamiltonian of the Toric code model and demonstrate fractional Anyonic statistics

Hamiltonian:

$$H_0 = -\sum_s A_s - \sum_p B_p$$

$$A_s = \prod_{j \in \mathrm{star}(s)} \sigma_j^x$$

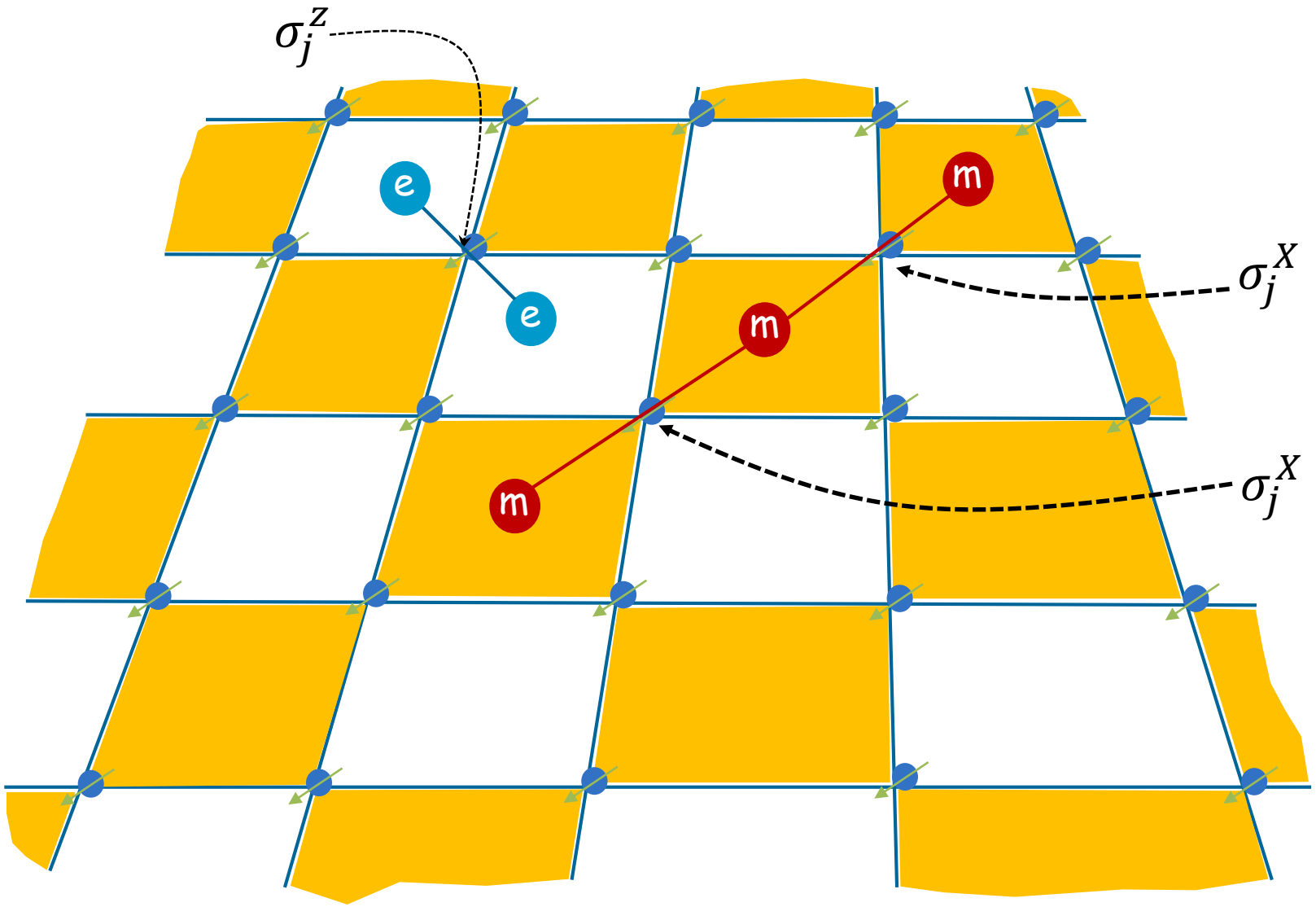
$$B_p = \prod_{j \in \mathrm{boundary}(p)} \sigma_j^z$$



- Four-body interaction
- Abelian Anyons: *e*, *m* excitations

Kitaev, Annals of Physics 303, 2 (2003)

Toric code -- Braiding



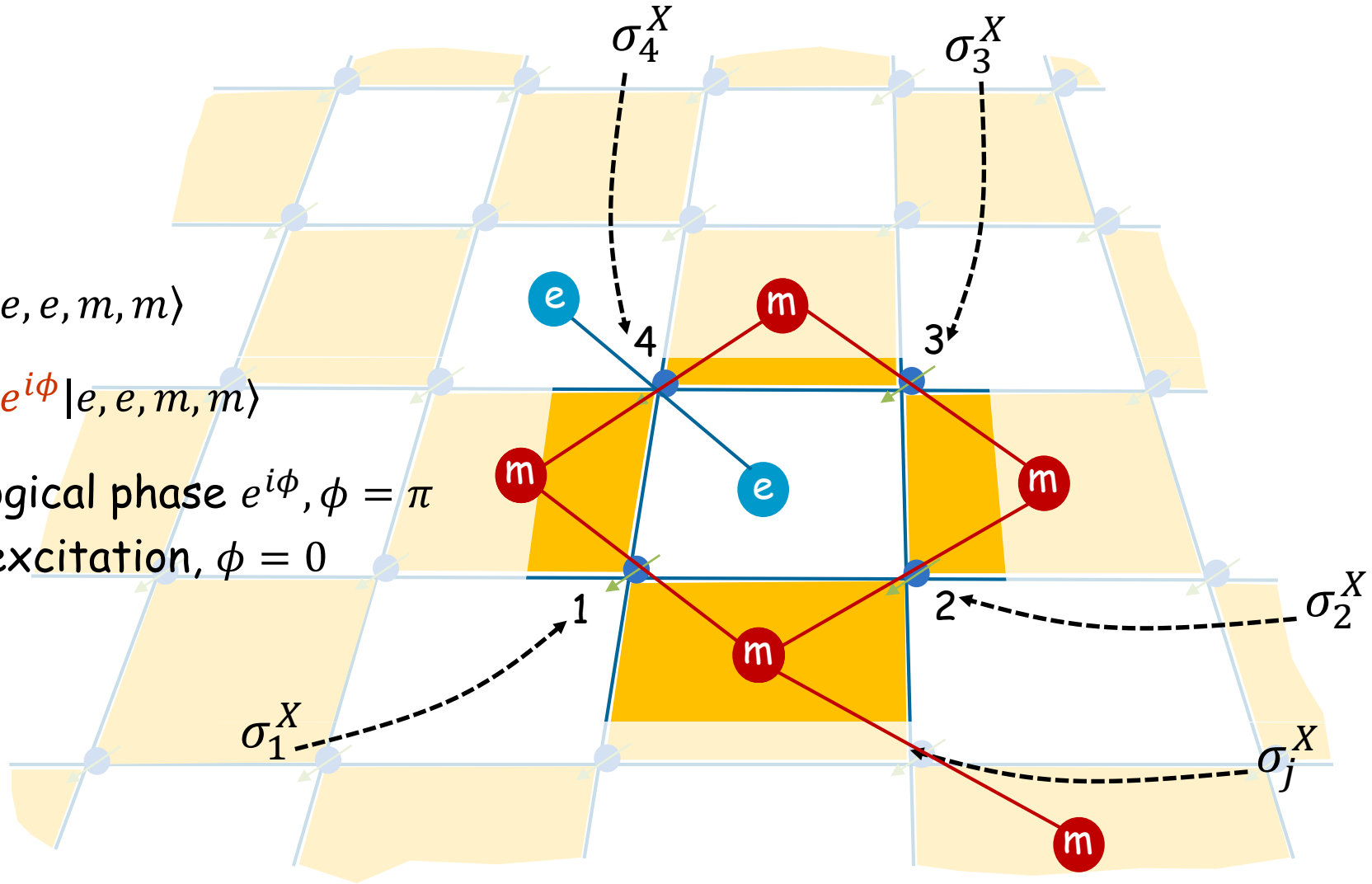
Toric code -- Braiding

$|\varphi\rangle = |e, e, m, m\rangle$

$|\varphi'\rangle = e^{i\phi}|e, e, m, m\rangle$

Topological phase $e^{i\phi}, \phi = \pi$

No e-excitation, $\phi = 0$



Questions

Can we build a many-body quantum system which is described by the Toric-code Hamiltonian?

Requirements:

- Create the four-body interaction
- Demonstrate the topological phase

Previous efforts:

Theory: Han *et al.*, PRL 98,150404 (2007)

Experiments: Lu *et al.*, PRL102, 030502 (2009). photons

Pachos *et al.*, NJP 11, 083010 (2009). photons

Barreiro *et al.*, Nature 470, 486 (2011). ions

Song *et al.*, PRL 121, 030502 (2018). superconductors

No background Hamiltonian ➡ There is no energy gap to protect the qubit!

2D-optical superlattice

BHM

$$\hat{H} = \sum_{\sigma=\uparrow,\downarrow} [-J(\hat{a}^{+}_{\sigma L}\hat{a}_{\sigma R} + \hat{a}^{+}_{\sigma R}\hat{a}_{\sigma L})] + U[\hat{n}_{\uparrow L}\hat{n}_{\downarrow L} + \hat{n}_{\uparrow R}\hat{n}_{\downarrow R}]$$

$J << U$

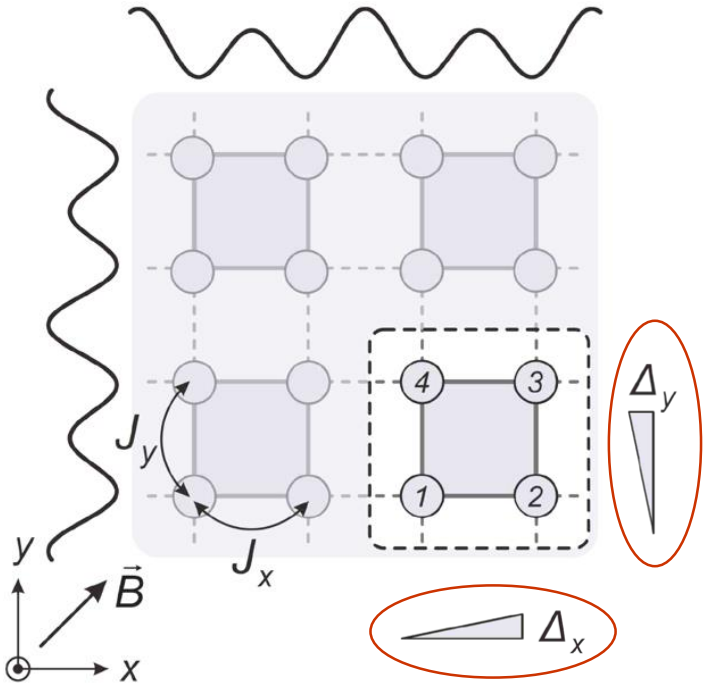
Super-exchange dominated :

$$H_{ex} = -2J_{ex}S_L \cdot S_R$$

In isolated plaquettes one can suppress super-exchange by 2D effective magnetic gradients

Ring-exchange dominated :

$$H_{\square} = -J_{\square}\hat{\sigma}_1^x\hat{\sigma}_2^x\hat{\sigma}_3^x\hat{\sigma}_4^x, J_{\square} = 40\,J^4/U^3$$



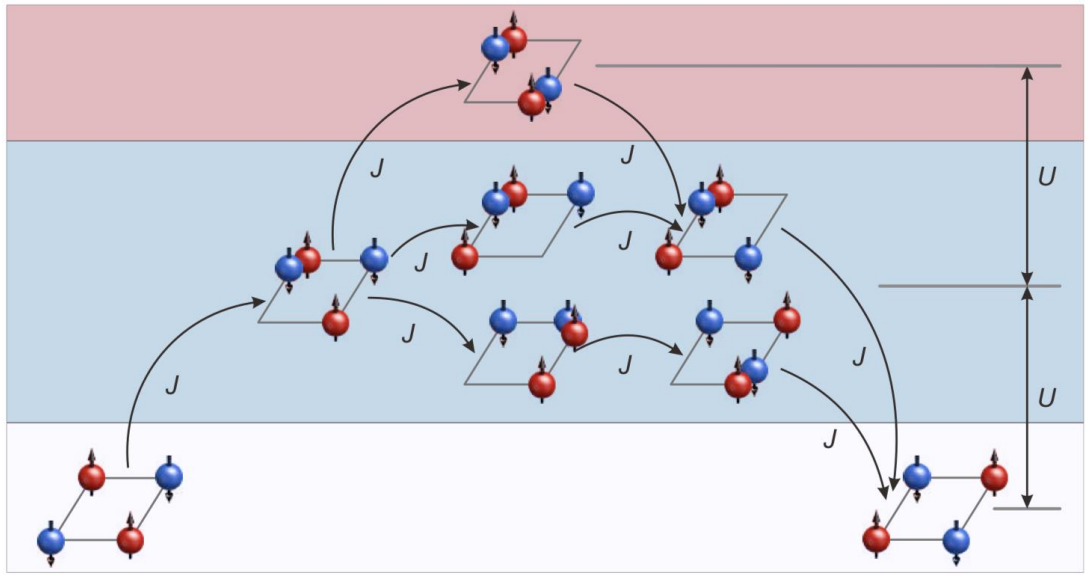
isolated plaquettes

Paredes & Bloch, PRA77, 23603 (2008)

Suppress super-exchange

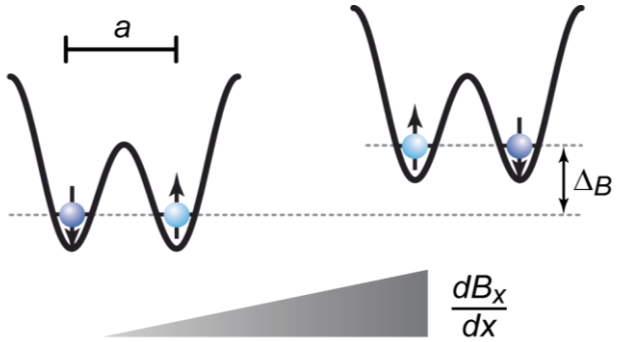
Super-exchange is dominant:

$|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$ are degenerate

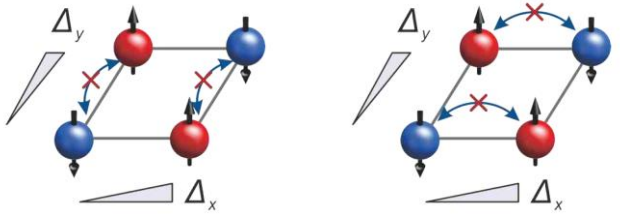


Low-energy state subspace:

$\{|\uparrow\downarrow\uparrow\downarrow\rangle, |\downarrow\uparrow\downarrow\uparrow\rangle, |\uparrow\uparrow\downarrow\downarrow\rangle, |\uparrow\uparrow\downarrow\downarrow\rangle, |\uparrow\downarrow\downarrow\uparrow\rangle , |\downarrow\uparrow\uparrow\downarrow\rangle\}$



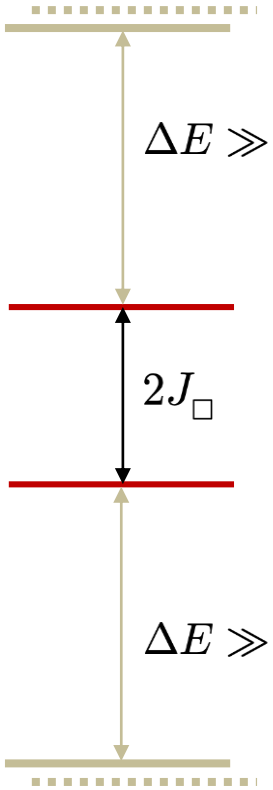
$\Delta_{x(y)} >> 4J^2/U$



Super-exchange is suppressed:

Non-degeneration due to effective magnetic gradients

Minimum Toric code Hamiltonian



Energy spectrum:

$$|A^-\rangle = 1/\sqrt{2}\,(|\uparrow,\downarrow,\uparrow,\downarrow\rangle - |\downarrow,\uparrow,\downarrow,\uparrow\rangle)$$

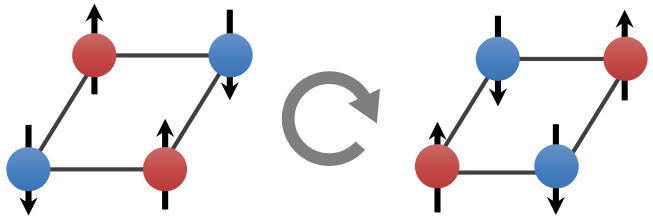
$$|A^+\rangle = 1/\sqrt{2}\,(|\uparrow,\downarrow,\uparrow,\downarrow\rangle + |\downarrow,\uparrow,\downarrow,\uparrow\rangle)$$

$$J_{\square} = 40\,J^4/U^3$$

In reduced subspace $\{|\uparrow\downarrow\uparrow\downarrow\rangle, |\downarrow\uparrow\downarrow\uparrow\rangle\}$

$$H = J_{\square}(|A^-\rangle\langle A^-| - |A^+\rangle\langle A^+|)$$

$$= -J_{\square}\hat{\sigma}_1^x\hat{\sigma}_2^x\hat{\sigma}_3^x\hat{\sigma}_4^x$$

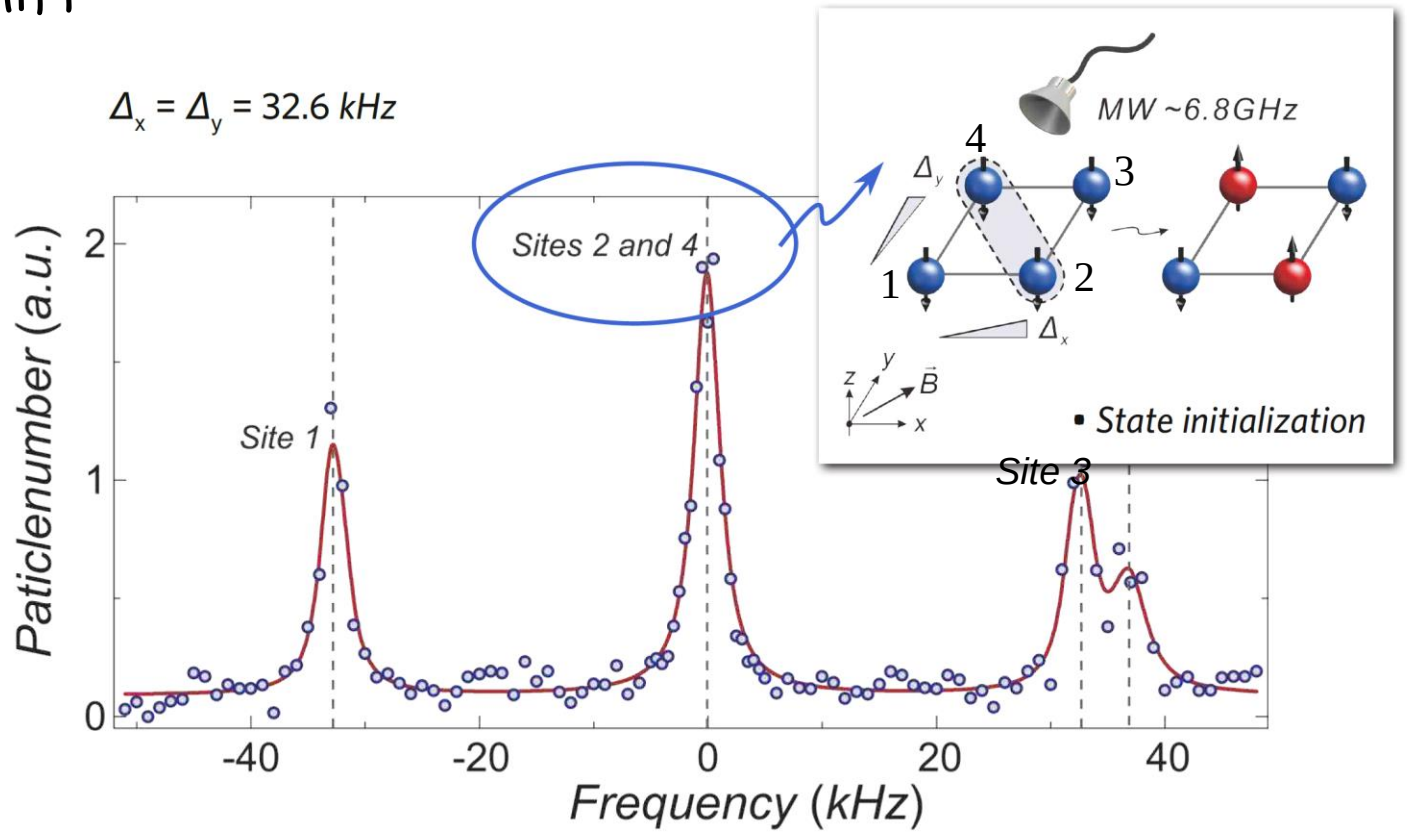


Ring-exchange

Site-resolved addressing: state initialization

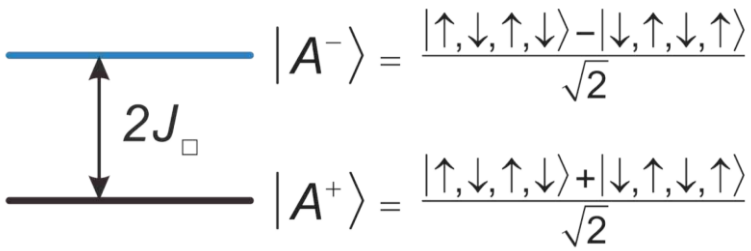
Due to the 2D effective magnetic gradients, the atoms on sites 2 and 4 have the same Zeeman shift

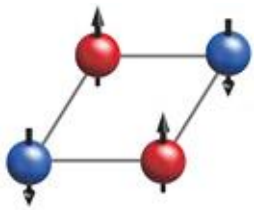
Flip atoms on sites 2 and 4 to prepare an anti-ferromagnetic order



• Settings: $V_{xs} = V_{ys} = 150\ E_r$ $V_{xl} = V_{yl} = 56.3\ E_r$ $\theta_x = \theta_y = \pi/3$

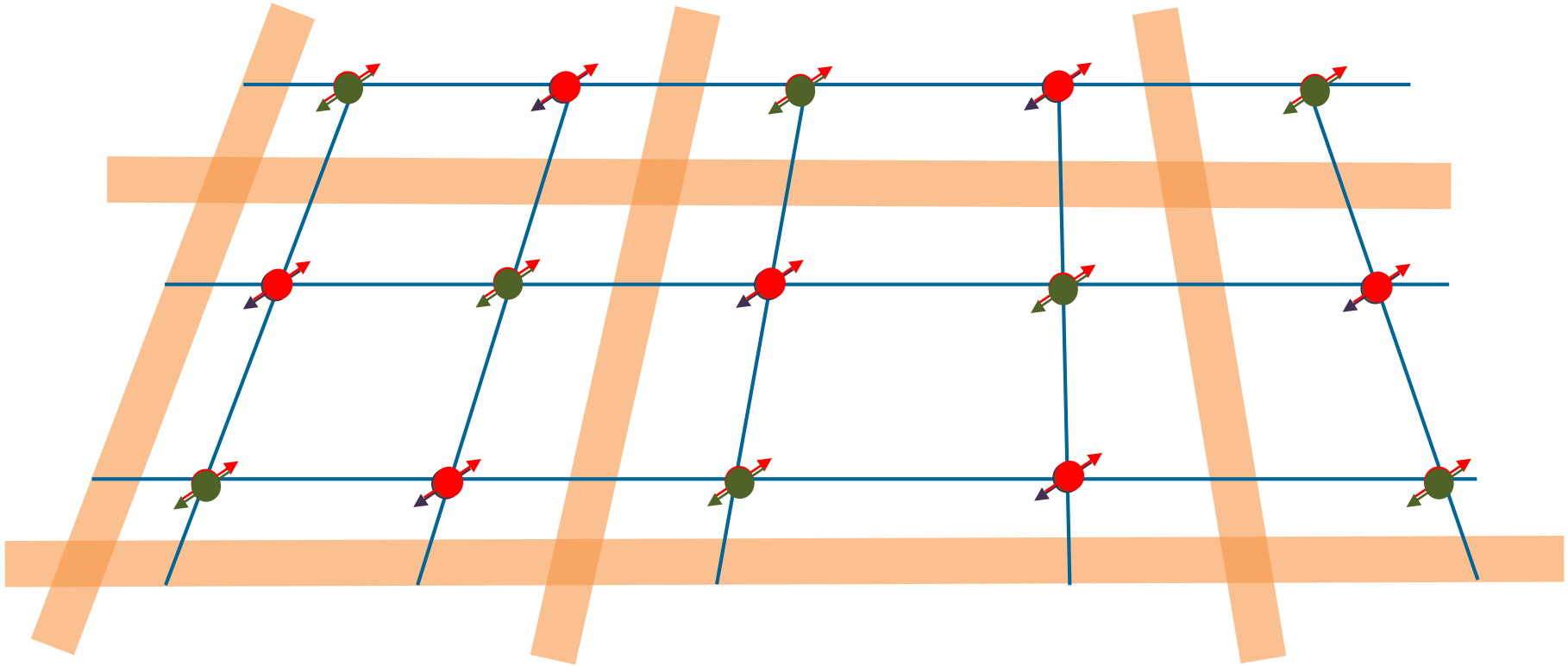
Ring exchange driven oscillation





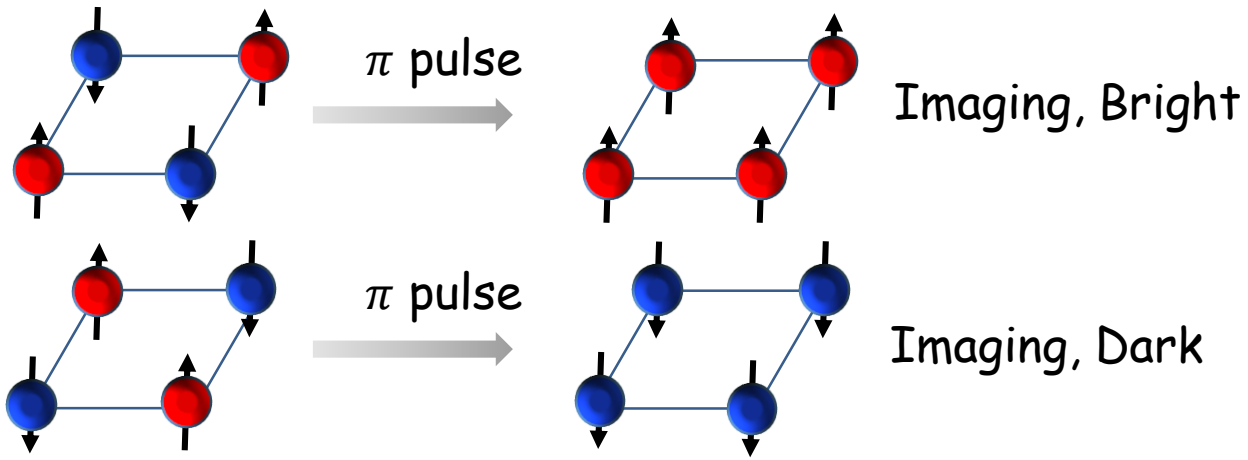
Initial state

$$= \frac{1}{\sqrt{2}}(|A^-\rangle + |A^+\rangle)$$



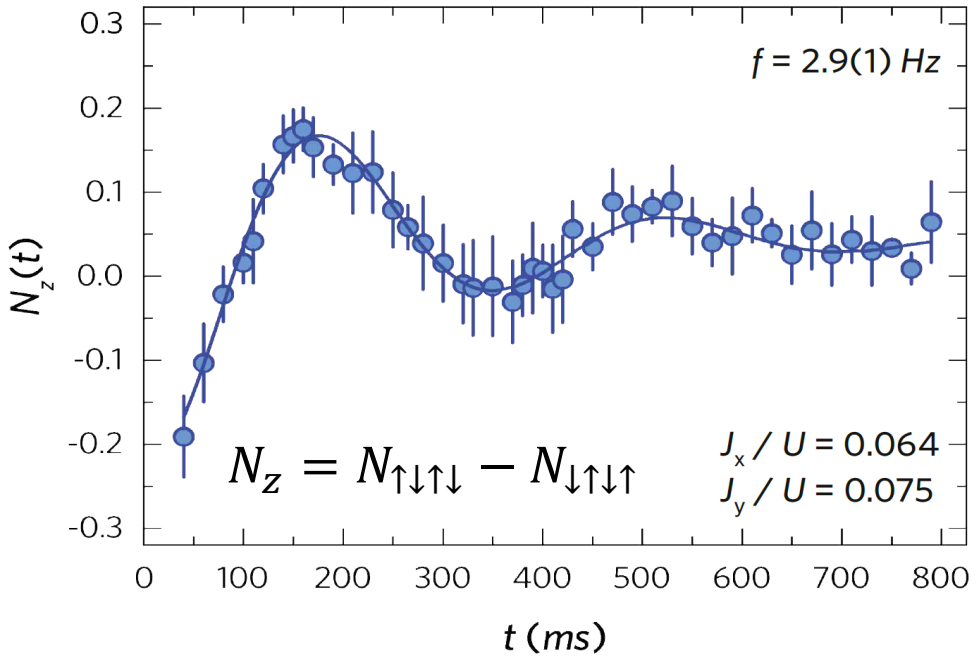
Observation of ring exchange driven oscillation

Count the populations of different states



Imaging, Bright

Imaging, Dark



Settings:

$V_{xl} = V_{yl} = 10\ E_r$

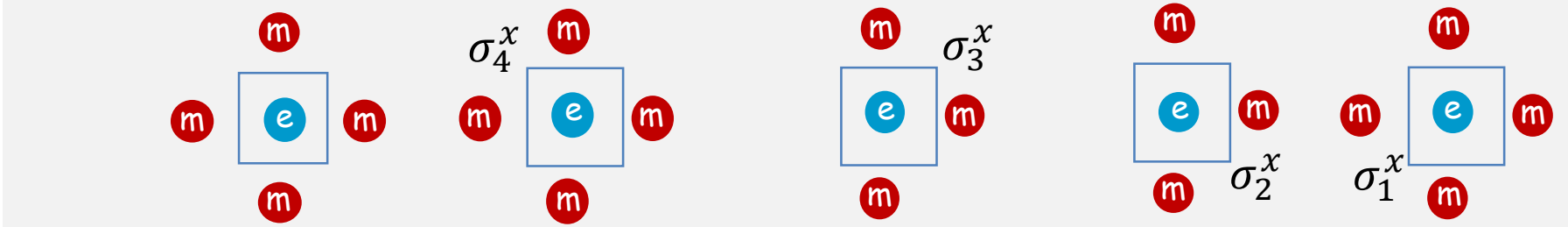
$\Delta_x = 115(1)\ Hz$

$V_{ys} = 18.2(1)\ E_r$

$V_{xs} = 19.2(1)\ E_r$

$\Delta_y = 145(1)\ Hz$

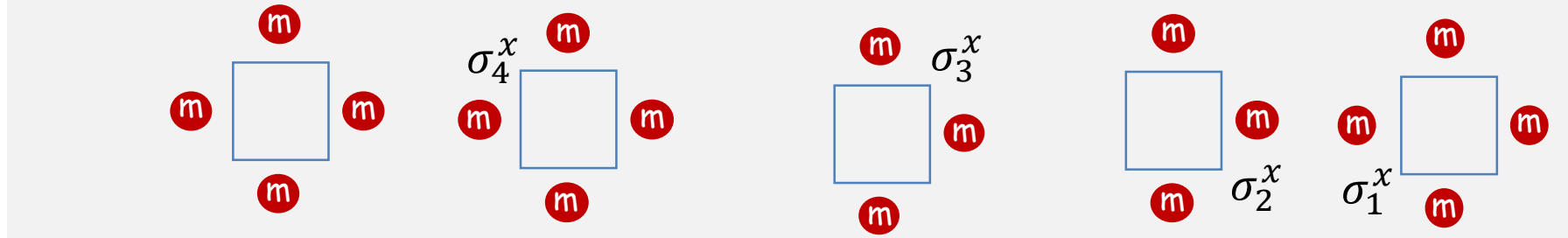
Topological phase of Abelian anyons, $\theta = \pi/2$



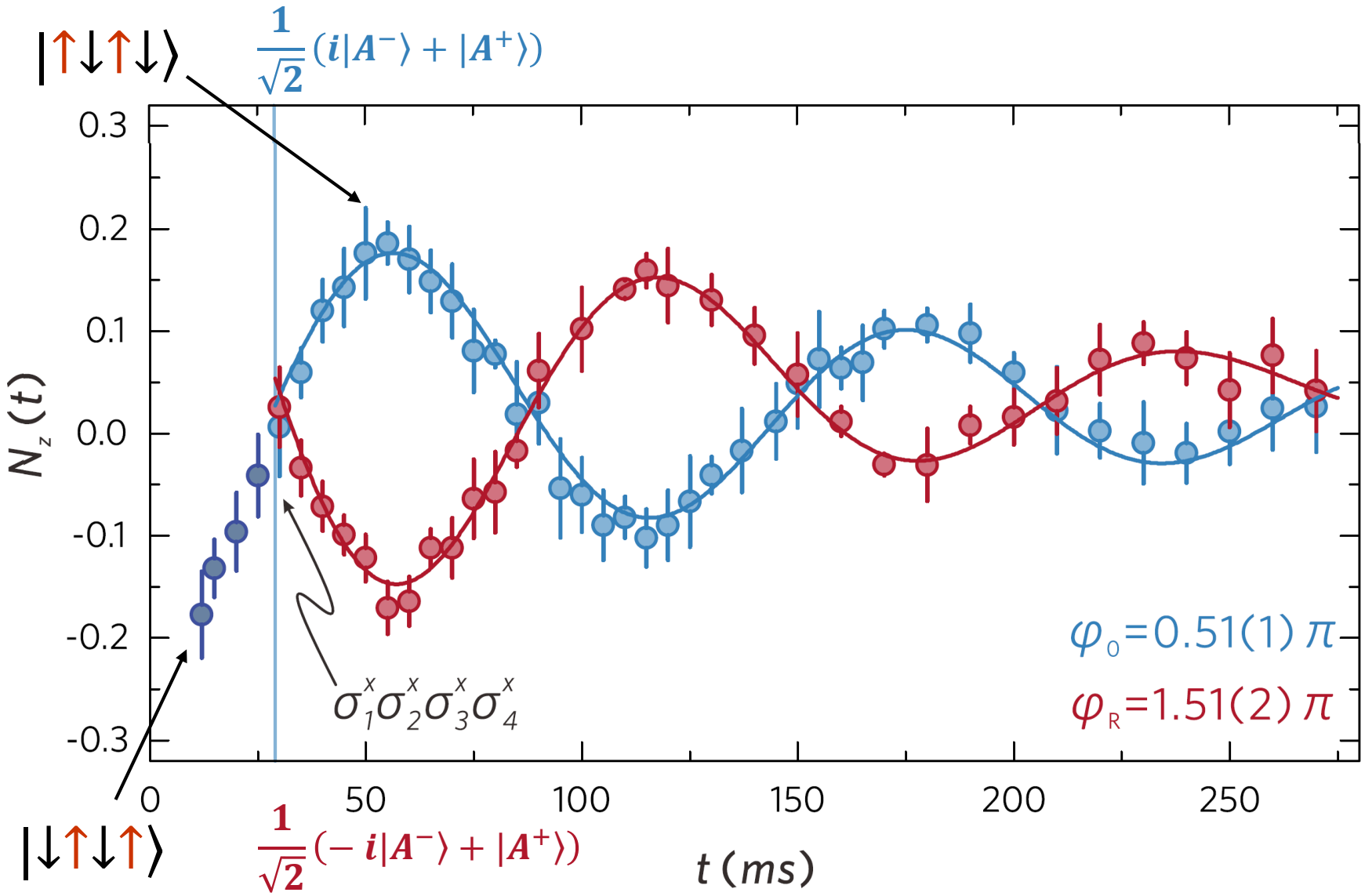
$|A^-\rangle$ $\qquad\qquad$ $-|A^-\rangle$

$$\psi_i = \frac{1}{\sqrt{2}}(i|A^-\rangle + |A^+\rangle) \longrightarrow \psi_f = \frac{1}{\sqrt{2}}(-i|A^-\rangle + |A^+\rangle)$$

$|A^+\rangle$ $\qquad\qquad$ $+|A^+\rangle$



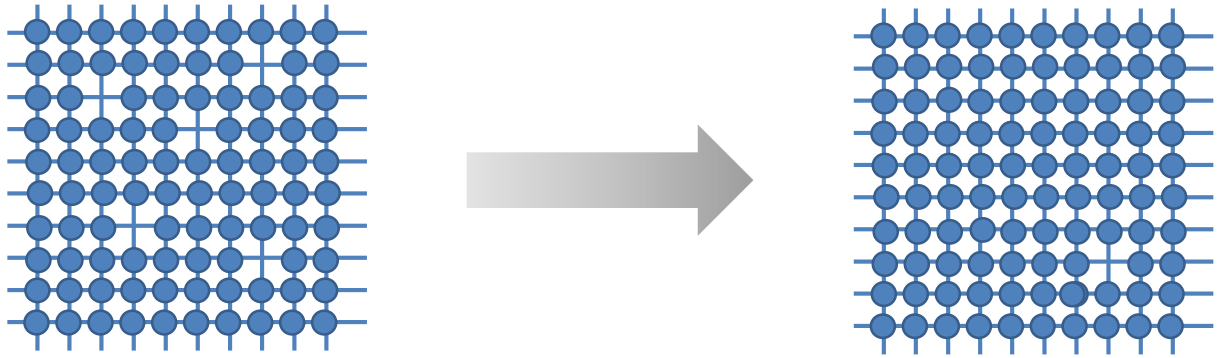
Observation of anyonic fractional statistics



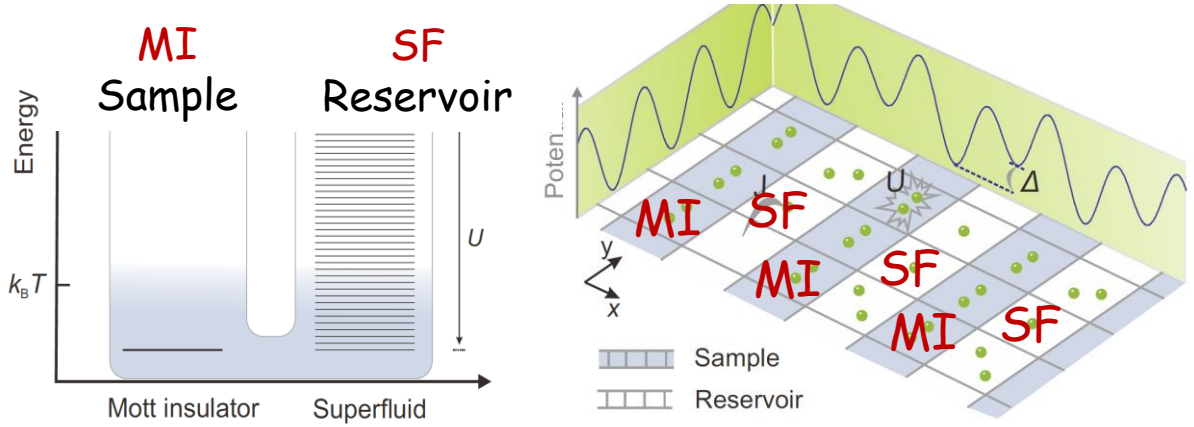
Dai *et al*, Nature Physics 13, 1195 (2017)

Outlook: towards large entangled state

- Generation of multi-atom entanglement: remove defects, connect the atom pairs
  Challenge: cool the atoms in optical lattices?



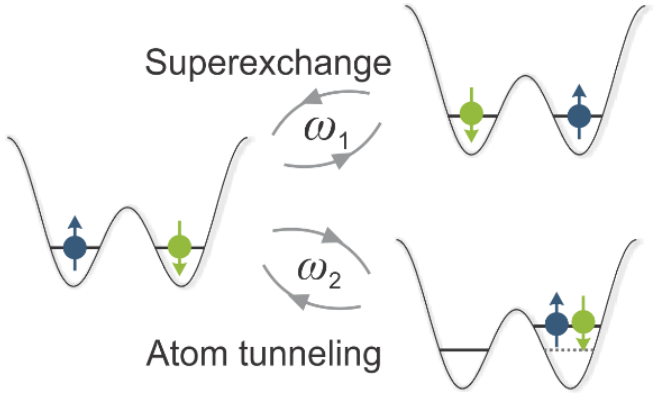
- MI samples, staggered immersed in SF reservoirs [arXiv 1901. 01146]
- Entropy of MI taken away by the SF, 60-fold reduction; 10,000 sites, 0.8% defects

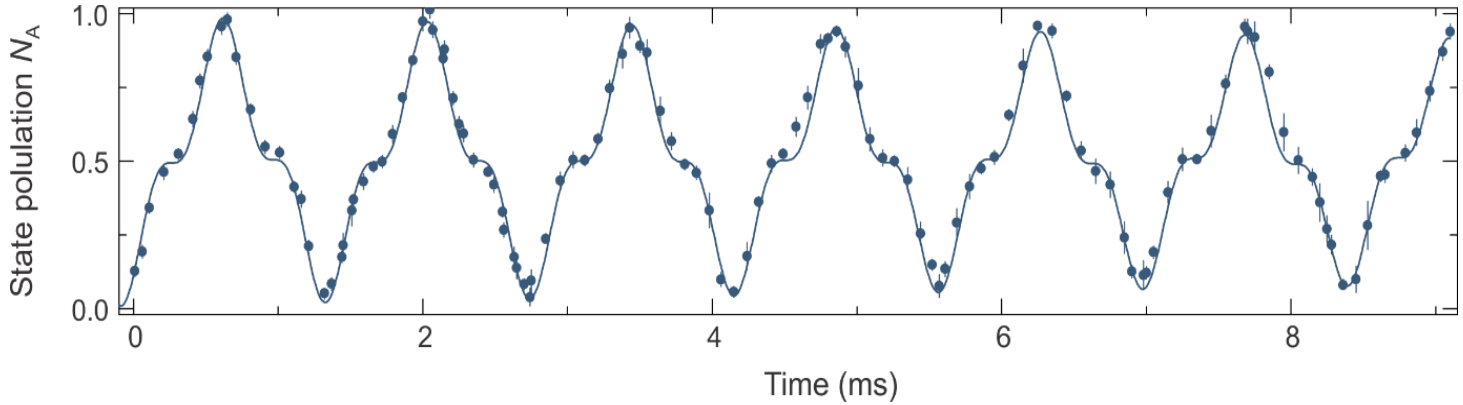


Motivated by the theoretical schemes:
Griessner *et al*, PRL (2006)
Ho and Zhou, PNAS (2009)

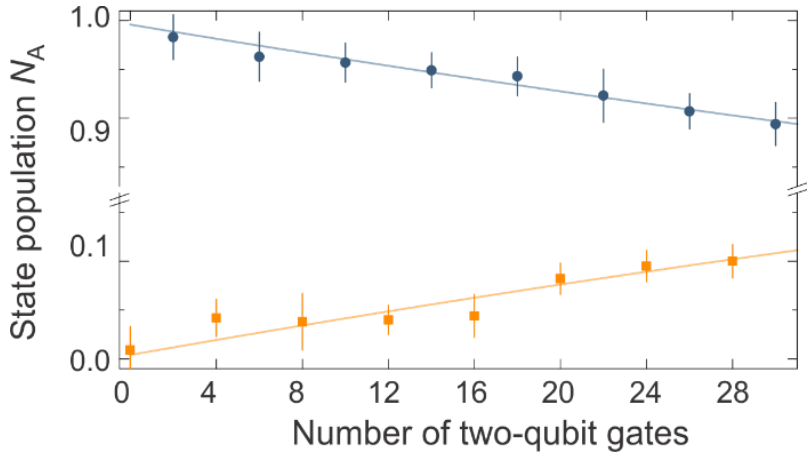
Outlook: towards large entangled state

- Two qubits entangling gates with superexchange after cooling: 99.3%
- Lifetime of entanglement: ~700ms

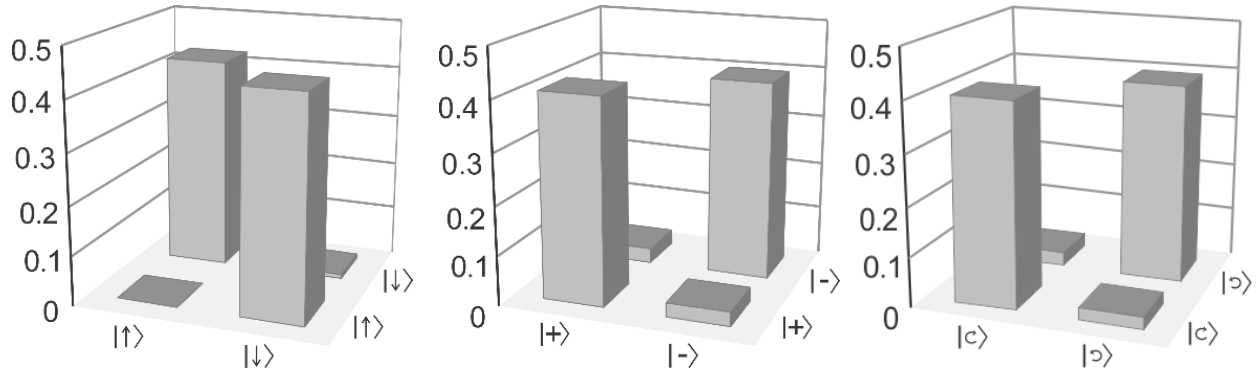




Fast exchange gates



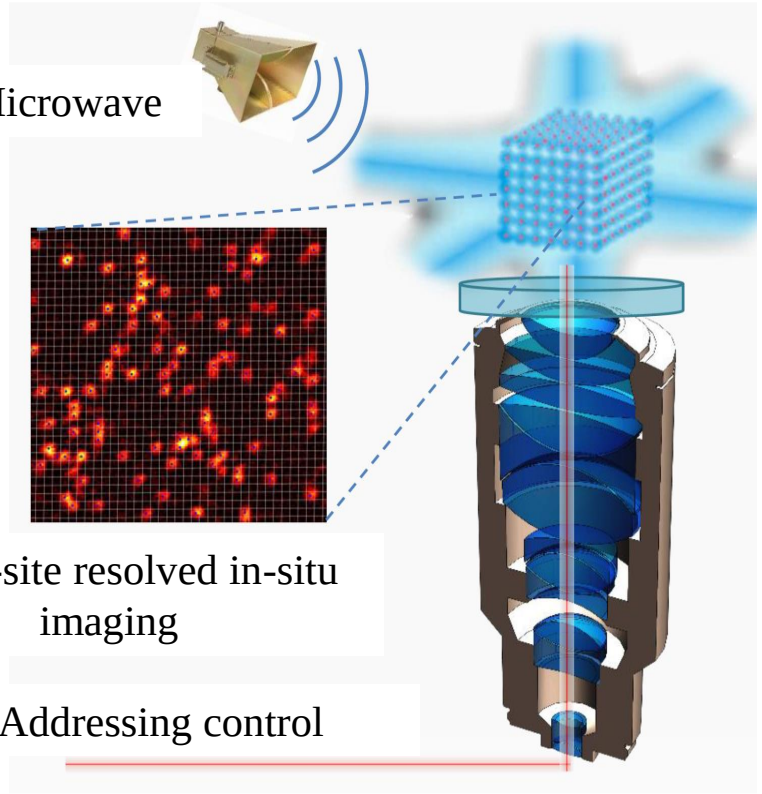
Fast exchange dynamics

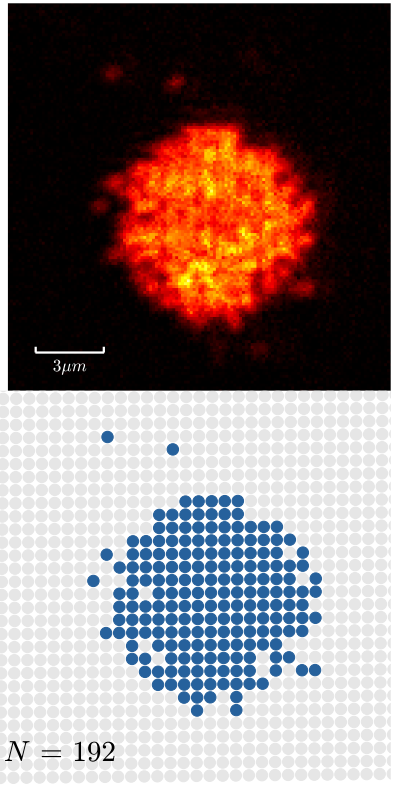


Fidelity = 99.3(1)% (in preparation)

Outlook: towards large entangled state

- High-resolution imaging system



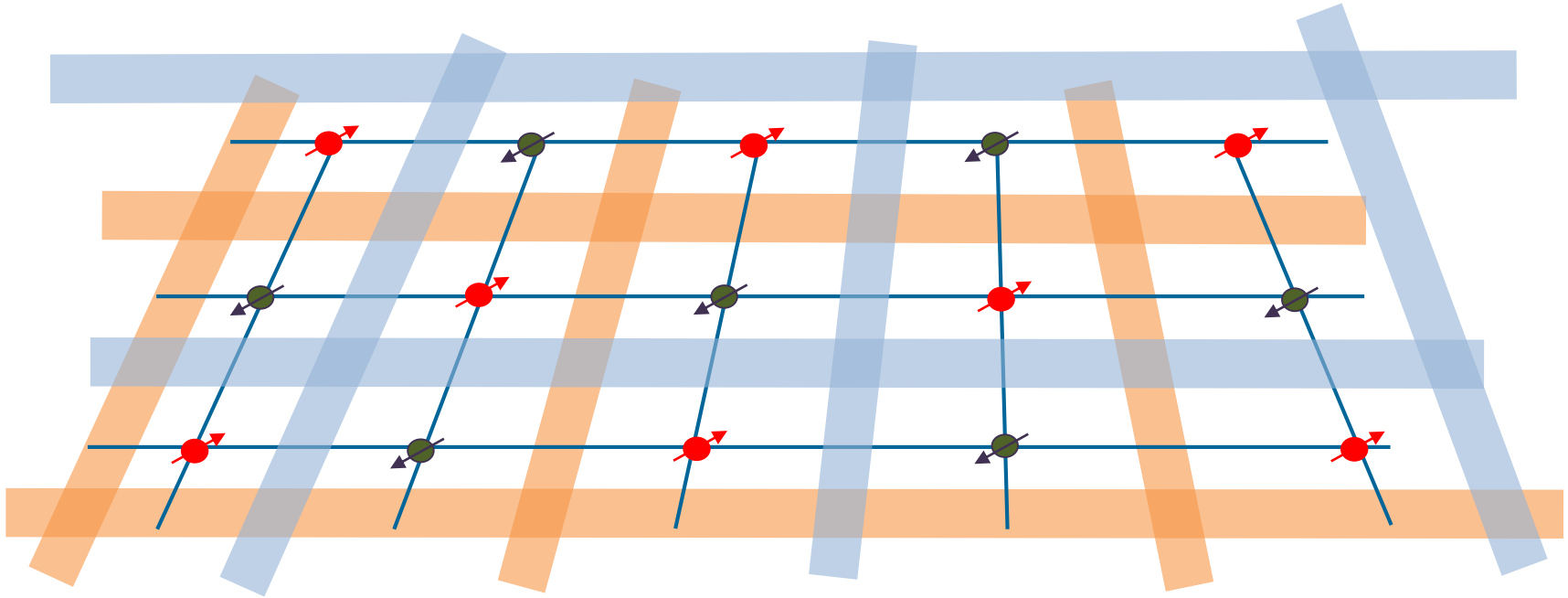


Numerical aperture: NA=0.8; Resolution: 690 nm

- Large entangled state; e.g. 100 (10x10) particles, how to identify?
  Simulating spin dynamics.
- Challenge theoreticians at an unprecedented level

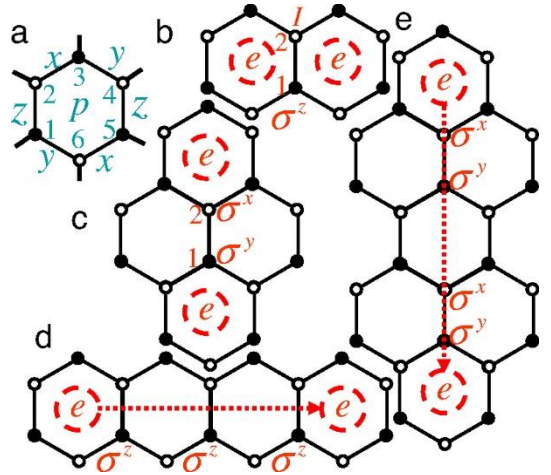
Outlook: simulating topological materials

- Couple the plaquettes: a many-body strongly correlated topological system



Reviews on topological matters with ultracold atoms:

- Goldman, Budish & Zoller, Nat. Phys. (2016)
- Zohar *et al*. Rep. Prog. Phys. (2016)



- Extend to fermionic systems; non-Abelian …
  - Theory: Zhang *et al*, PNAS (2007)

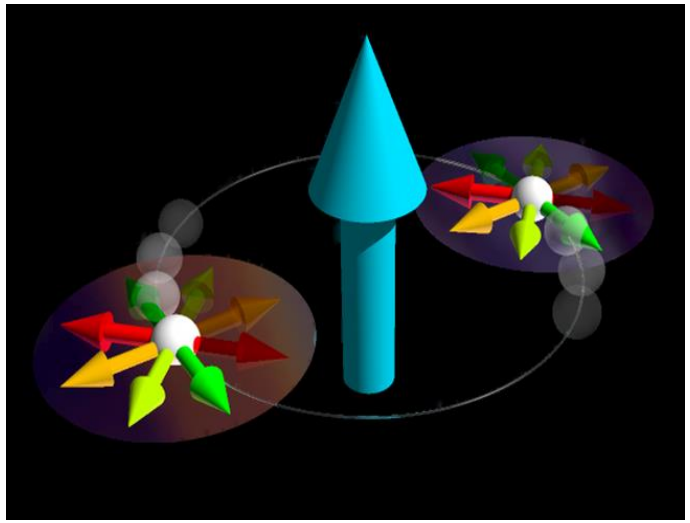
Part III: Quantum simulation of Gauge potential with neutral atoms

Zhang *et al.*, PRL 109, 115301 (2012)
Ji *et al.*, Nature Physics 10, 314 (2014)
Wu et al., Science 354, 83 (2016)
Sun *et al.*, PRL 121, 250403 (2018)

Spin-orbit coupling (SOC)

Electrons moving in an electric field:

- Electron experiences a magnetic field proportional to its velocity and
- Couples to its spin by the magnetic dipole interaction



Gauge potential coupling to electrons' spin

$$H = \frac{1}{2m}\left(\boldsymbol{k} - \frac{q}{c}\boldsymbol{A}(\mathbf{s})\right)^2 + V + q\varphi(\mathbf{s})$$

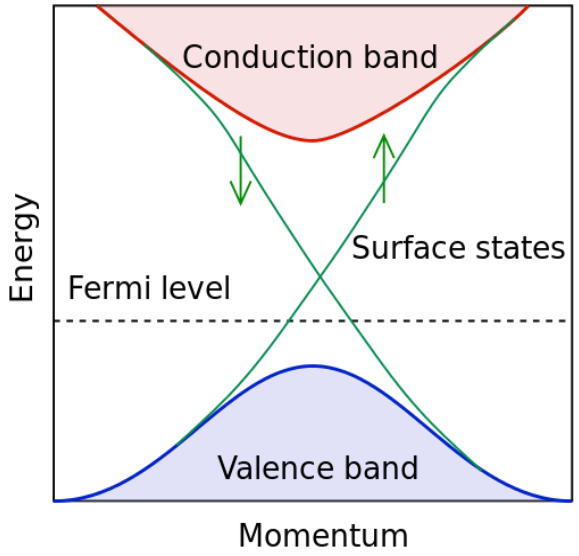
$\boldsymbol{s}$: spin of an electron
$A(\boldsymbol{s})$: vector potential
$\varphi(\boldsymbol{s})$: scalar potential

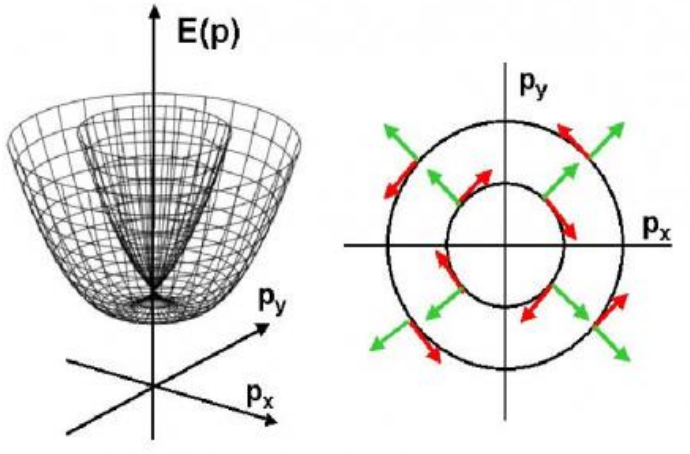
Novel quantum system

SOC leads to numerous interesting quantum phenomena in electron systems

- Quantum Hall effect
- Spin-Hall effect
- Topological insulator
- Majorana Fermions
- Weyl Fermions

...





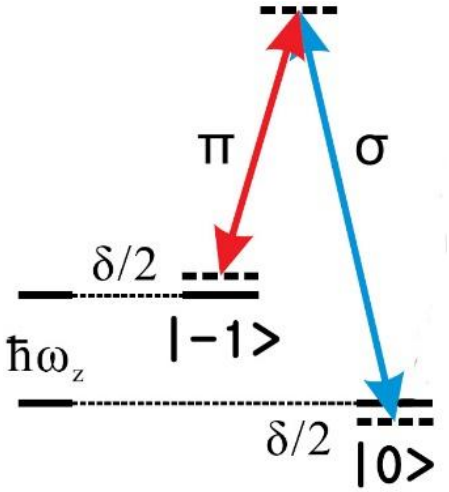
However, uncontrollable in natural materials!

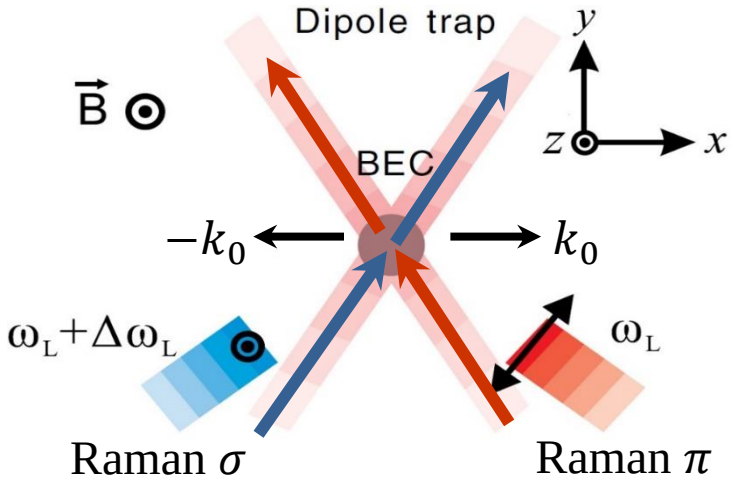
Synthesize Gauge potential with neutral atoms

Mimicking spin-orbit coupling with BEC: coupling inner states with momentum

Theory: Liu *et al.*, PRL 102, 046402 (2009)

Experiment: Spielman's group, Nature 471, 83 (2011)





Raman process:

$|-1\rangle \rightarrow |0\rangle$: obtaining momentum $-k_0$

$|0\rangle \rightarrow |-1\rangle$: obtaining momentum k_0

$$H = \frac{1}{2m}\left(k_x - \frac{1}{2}k_0\sigma_z\right)^2 + \frac{\delta}{2}\sigma_z + \frac{\Omega}{2}\sigma_x$$

V. S.

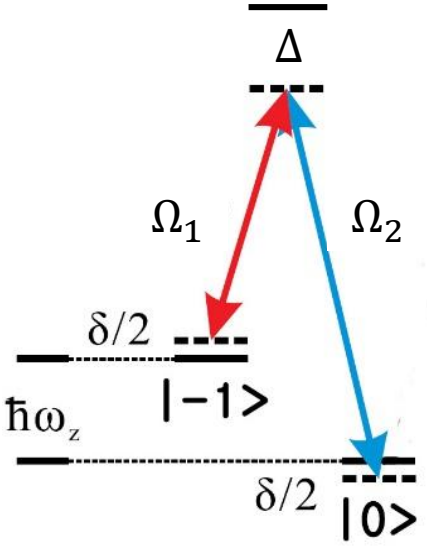
$$H = \frac{1}{2m}\left(\boldsymbol{k} - \frac{q}{c}\boldsymbol{A}(\boldsymbol{s})\right)^2 + V + q\varphi(\boldsymbol{s})$$

Synthesize Gauge potential with neutral atoms

$$H = \frac{1}{2m}\left(k_x - \frac{1}{2}k_0\sigma_z\right)^2 + \frac{\delta}{2}\sigma_z + \frac{\Omega}{2}\sigma_x$$

Coupling strength (Raman Rabi frequency) $\Omega = \frac{\Omega_1\Omega_2}{\Delta}$

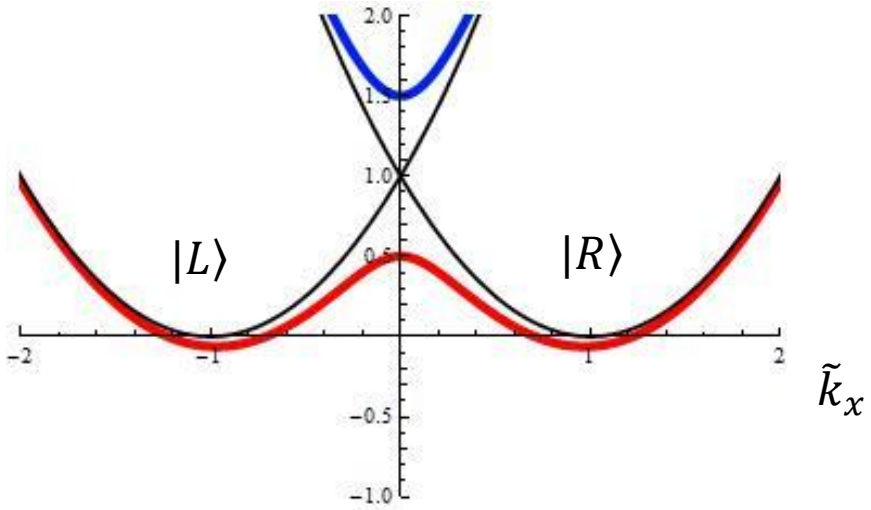
$\Omega_1 = \frac{\varepsilon_1 E_1}{\hbar}$, ε is transition dipole moment



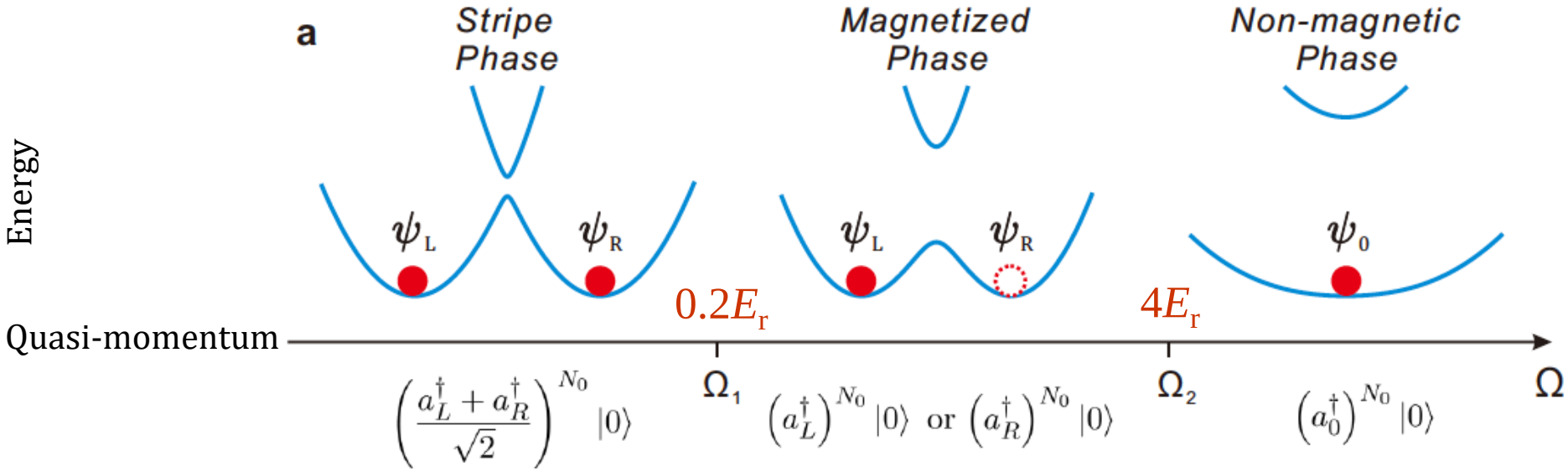
For $\Omega \ll 4E_r$ (recoiling energy $E_r = \frac{\hbar^2 {k_0}^2}{2m}$), the eigenstates of H are:

$|L\rangle = |-1\rangle + \alpha|0\rangle$, $|R\rangle = |0\rangle + \alpha|-1\rangle$

$\alpha \ll 1$ is determined by coupling strength Ω and two-photon detuning δ



Phase diagram at zero temperature



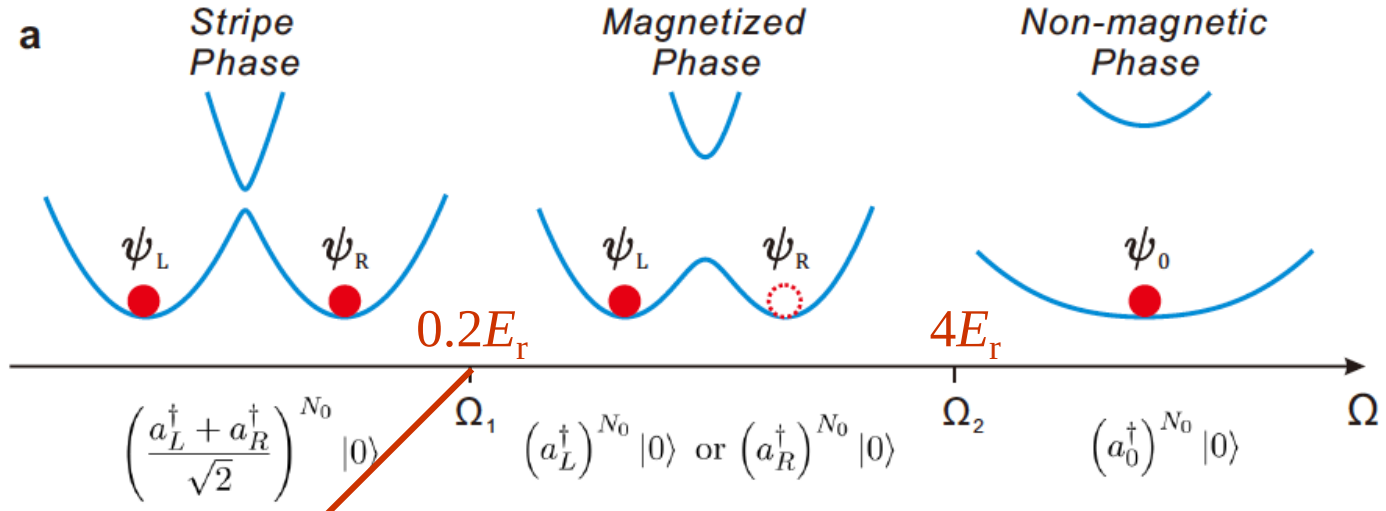
Two energy minima of momentum state

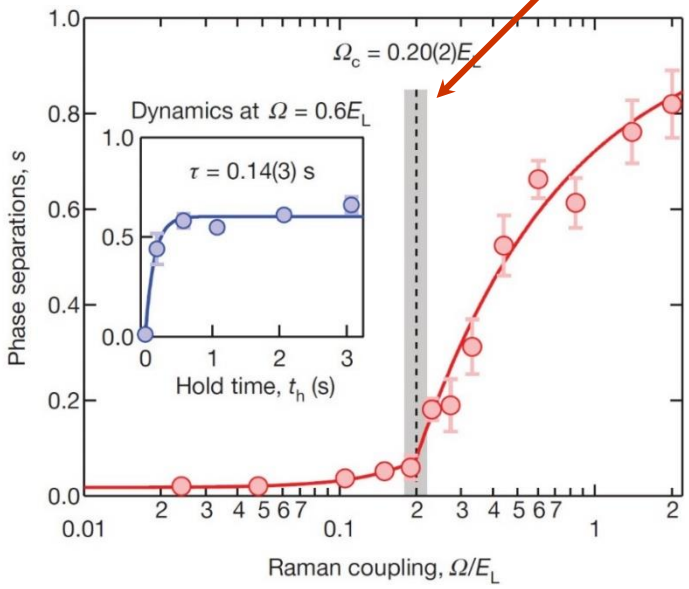
One energy minimum of momentum state

Theoretical phase diagram involving SO-coupling

- Wang *et al.*, PRL 105, 160403 (2010)
- Ho and Zhang, PRL 107, 150403 (2011)

Phase diagram at zero temperature



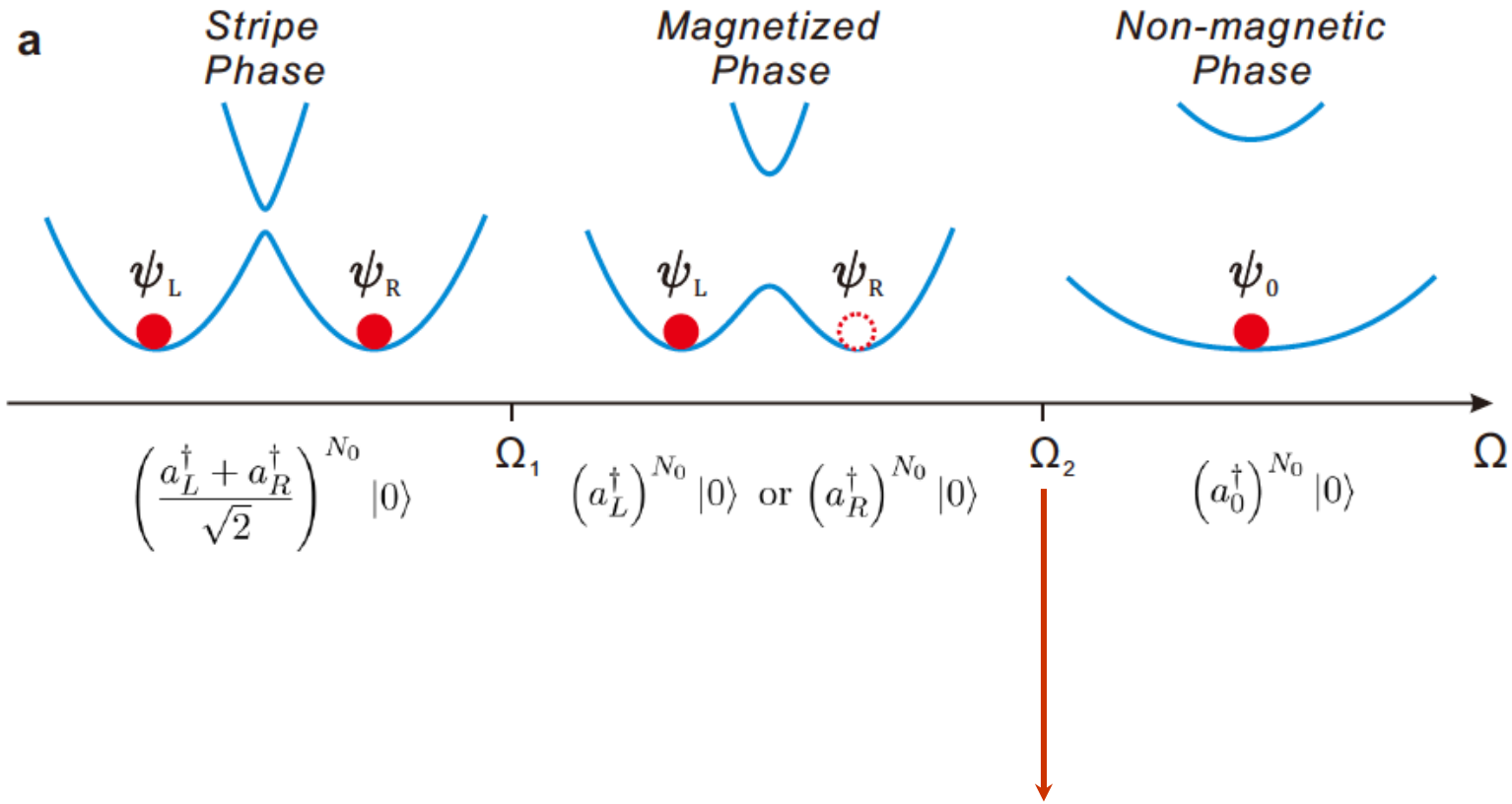


Statistics $S = 1 - \dfrac{\langle n_L n_R \rangle}{\sqrt{\langle n_L^2 \rangle \langle n_R^2 \rangle}}$

- S=0: perfect mixture
- S=1: complete phase separation

Spielman's group, Nature 471, 83 (2011)

Phase diagram at zero temperature

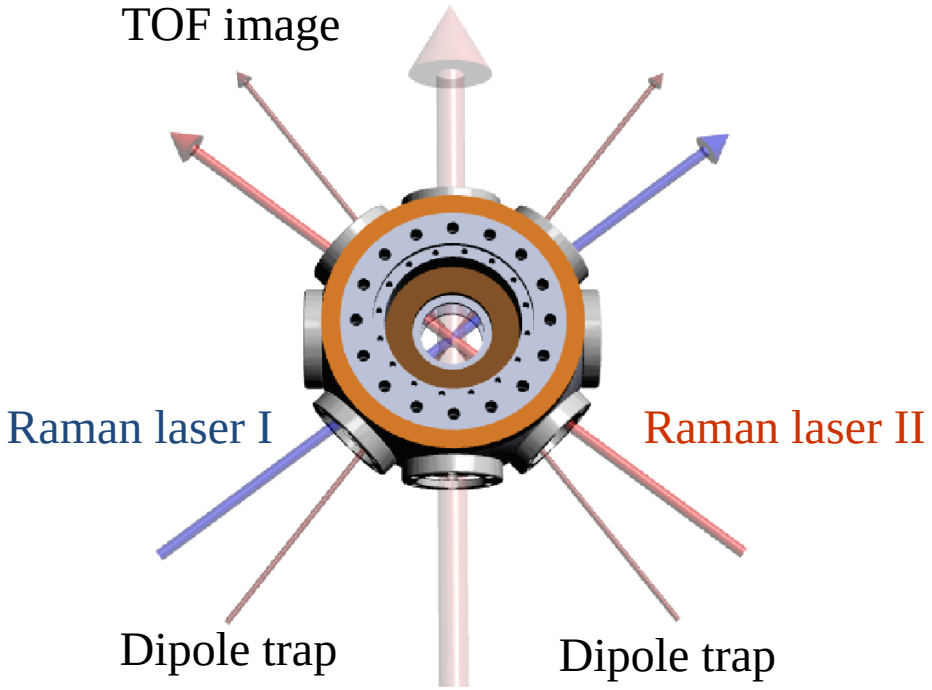


However, to characterize the second order phase transition quantitatively

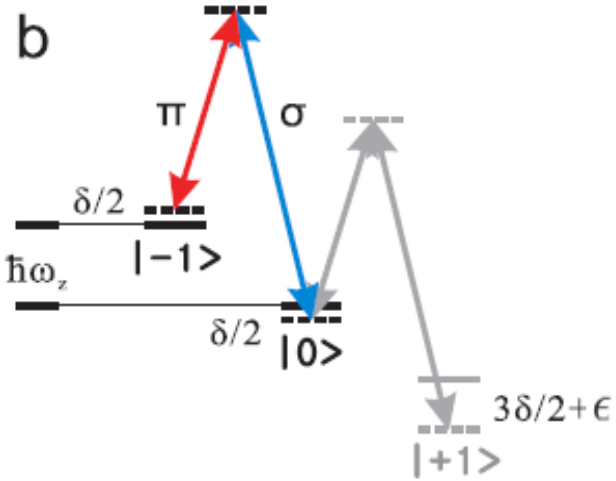
☒ The static way is not valid since the ground state only occupies single momentum minimum in both two phases

☑ Method: measurements based on dynamical process

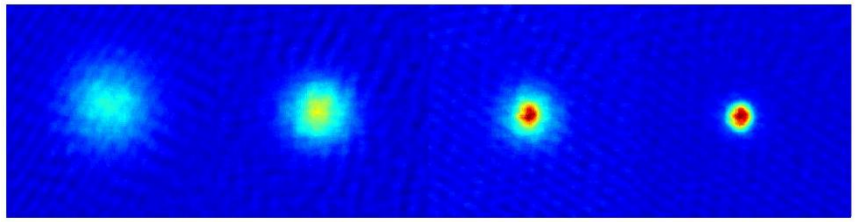
Realization of 1D SO coupling



Raman coupling

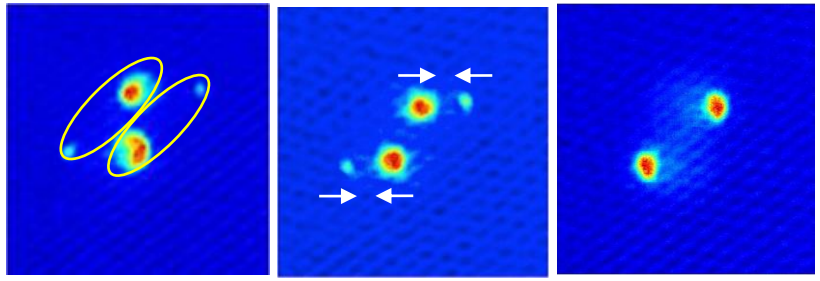


BEC in Optical dipole trap



Pure condensate: ~2×10^5 ^{87}Rb atoms

Trapping frequency: {50,50,80}Hz

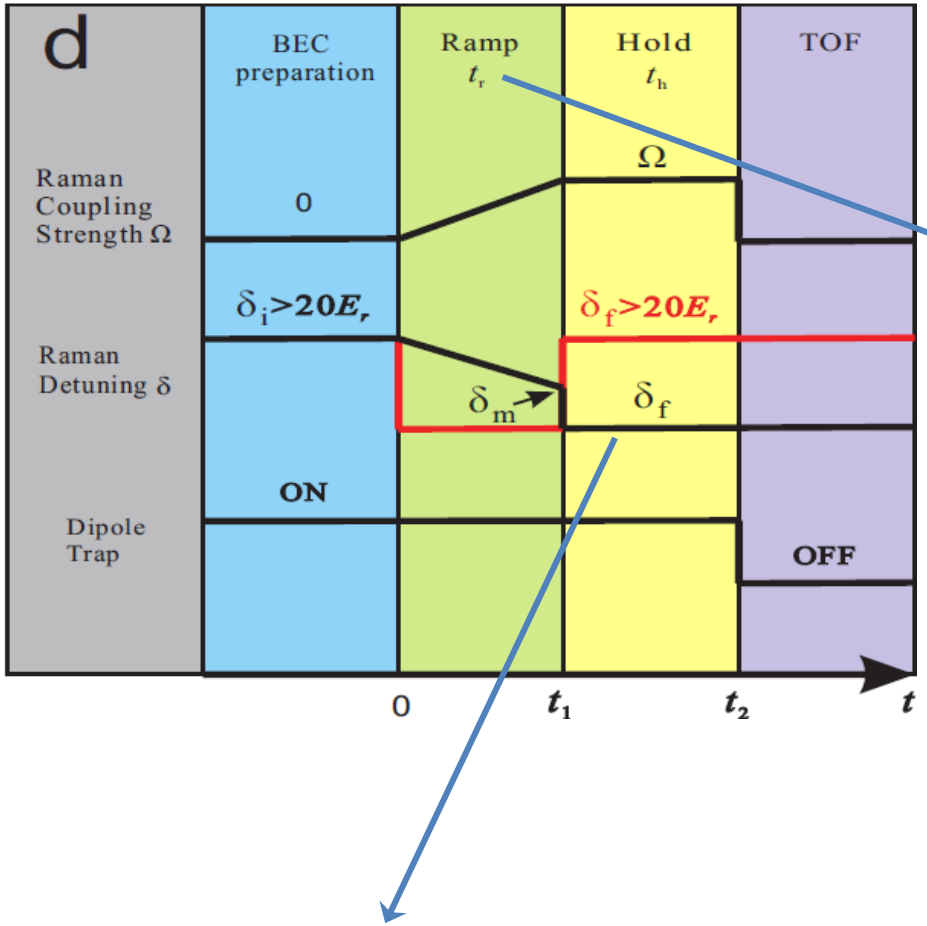


$\Omega<4E_r$ Increase Ω $\Omega>4E_r$

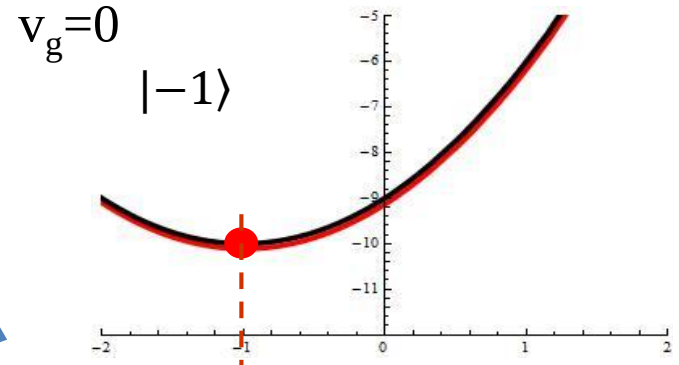
Double well in k-space

Excite the collective dipole oscillation

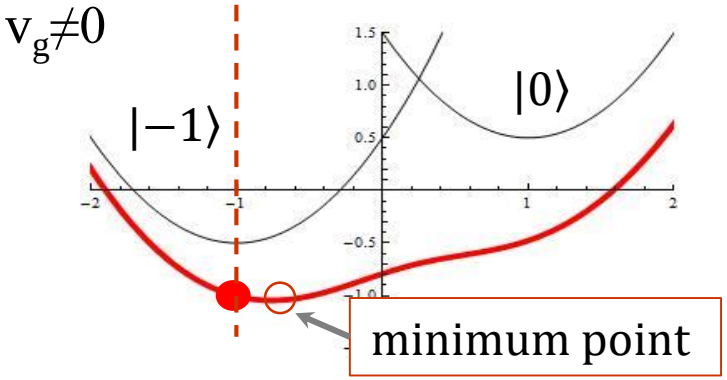
Time sequence of the experiment



Raman detuning is jumped to the final value



- BEC always stay on the minimum point of the dispersion curve

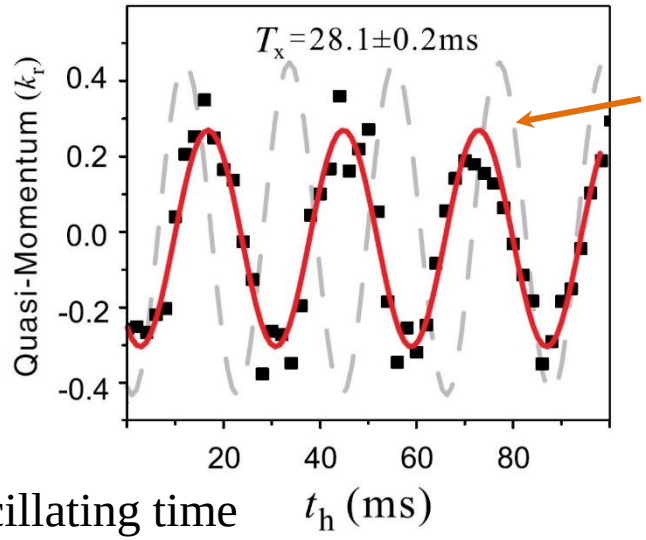


- Local minimum quickly move away from the initial minimum point ➡ BEC get an impulse and start to oscillate

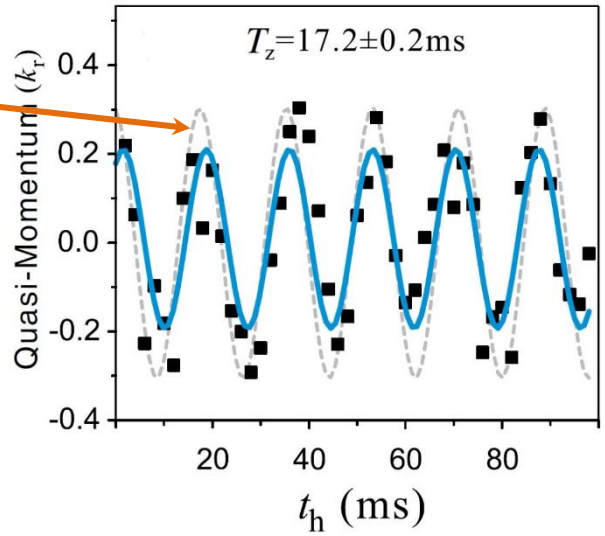
Collective dipole & spin state oscillations

- Dipole oscillation frequency shift away from trap frequency (measured with $\Omega = 3.3Er$)

Along x-axis (with SOC)

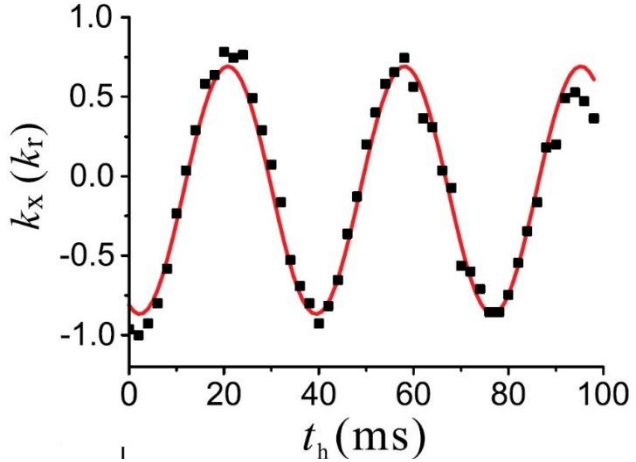


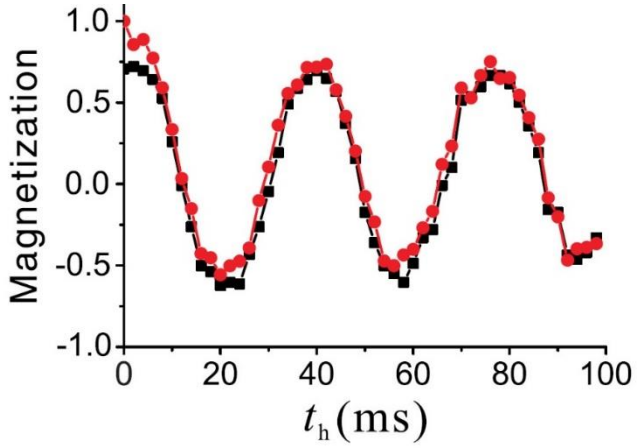
trap frequency



Along z-axis (without SOC)

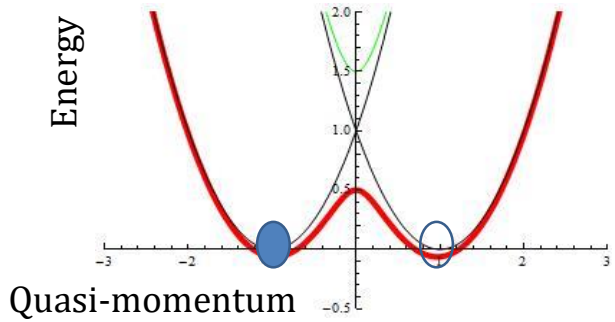
- Spin-state oscillation is highly correlated with momentum oscillation (measured with $\Omega = 4.8Er$)





Phase diagram at zero temperature

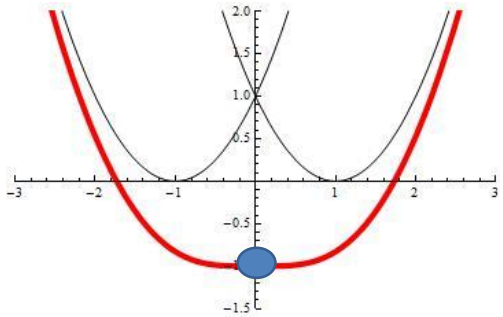
$\Omega < 4E_r$



Magnetized phase: small χ

all atoms are in $|-1\rangle$ or $|0\rangle$

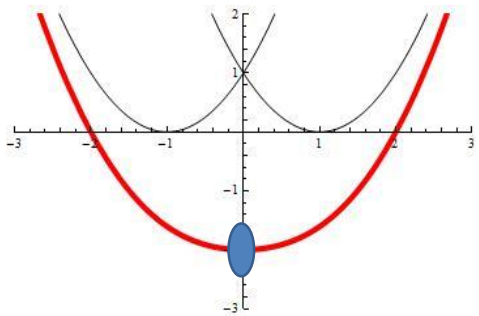
$\Omega = 4E_r$



Phase transition point

large $\chi \dashrightarrow \infty$

$\Omega > 4E_r$



Non-magnetic phase: small χ

Equal population of $|-1\rangle$ and $|0\rangle$

Spin polarizability χ: how easy or hard a system could be spin polarized

Evaluating infinite χ at phase transition point from the experimental data

$$\frac{A_\sigma}{A_k/k_r} = \frac{E_r\chi}{1+E_r\chi}$$

A_σ: amplitude of spin oscillation

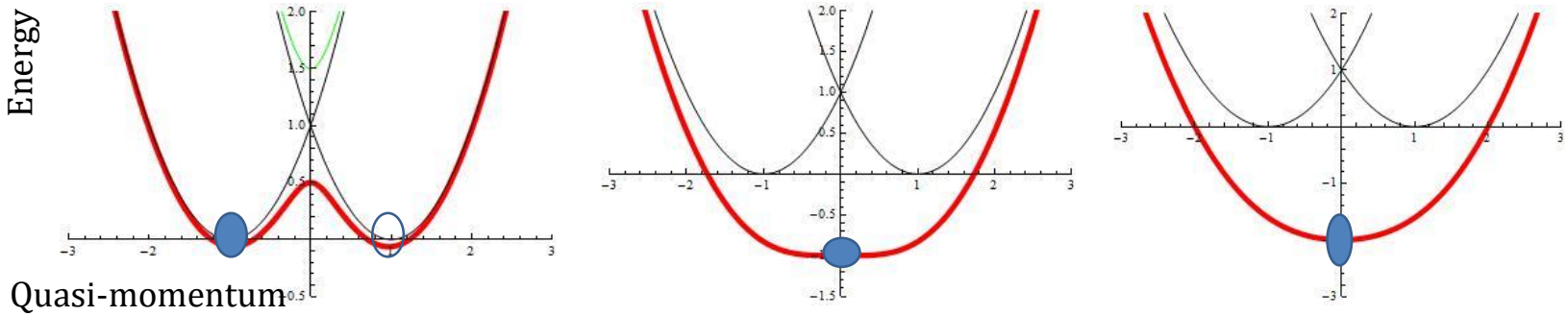
A_k: amplitude of momentum oscillation

When the left value approaching to 1, $\chi \to \infty$

Li *et al.*, EPL 99, 56008 (2012)

Phase diagram at zero temperature

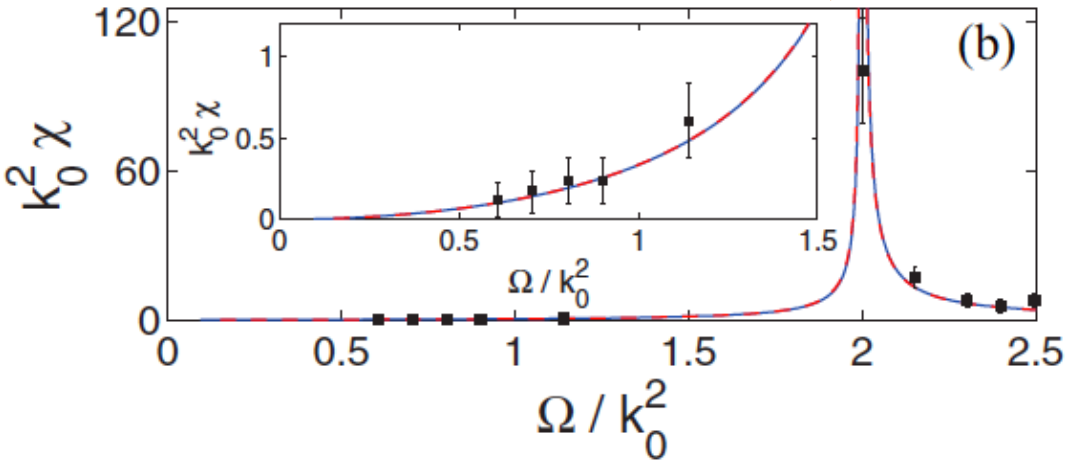
$\Omega < 4E_r$ $\Omega = 4E_r$ $\Omega > 4E_r$



Magnetized phase: small χ
all atoms are in $|-1\rangle$ or $|0\rangle$

Phase transition point
large $\chi \dashrightarrow \infty$

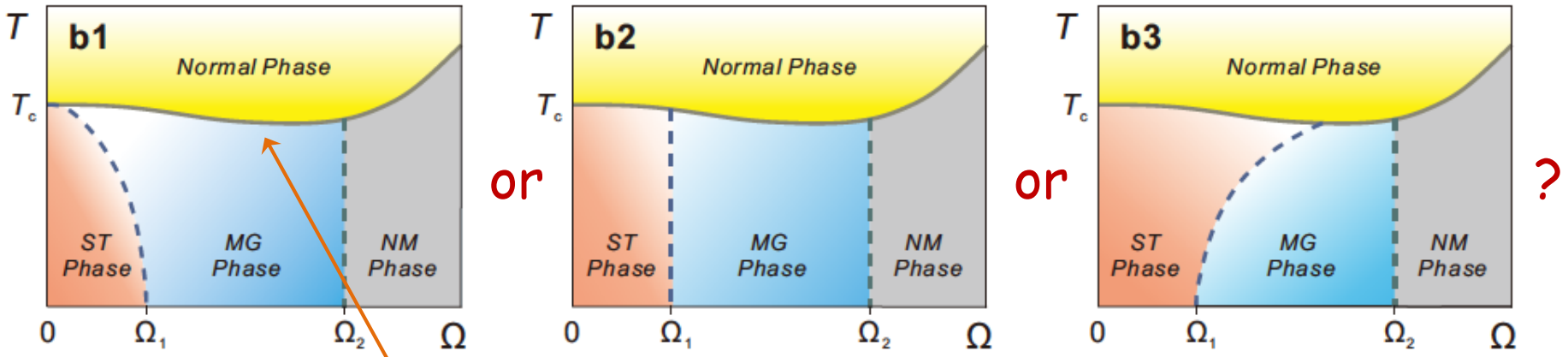
Non-magnetic phase: small χ
Equal population of $|-1\rangle$ and $|0\rangle$



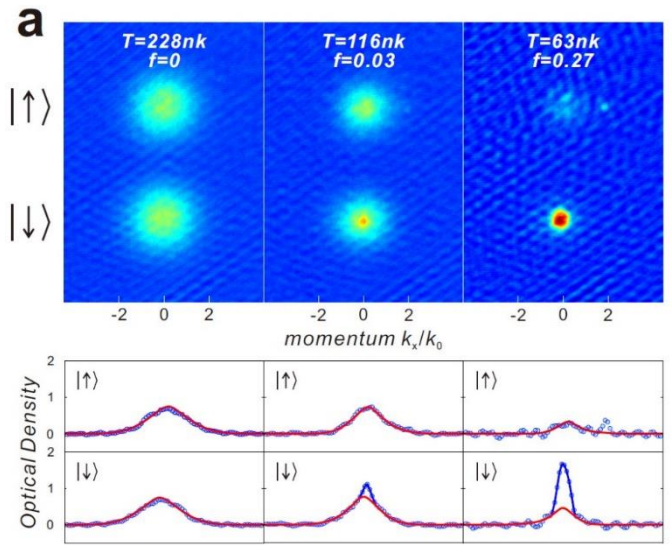
Zhang *et al.*, PRL 109, 115301 (2012)

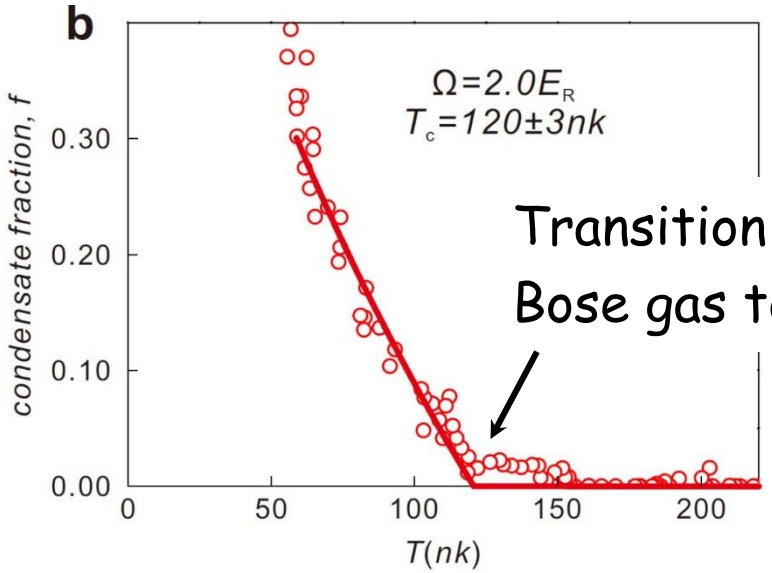
Phase diagram at finite temperature

Yet phase diagram at $T \neq 0$ is unknown



- Identifying the critical temperature



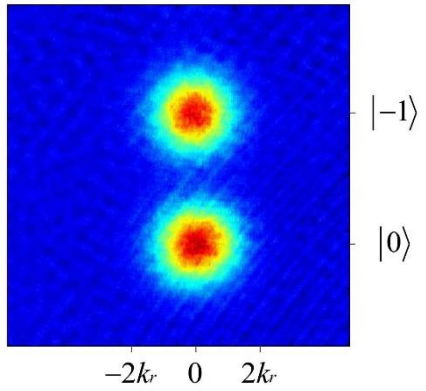
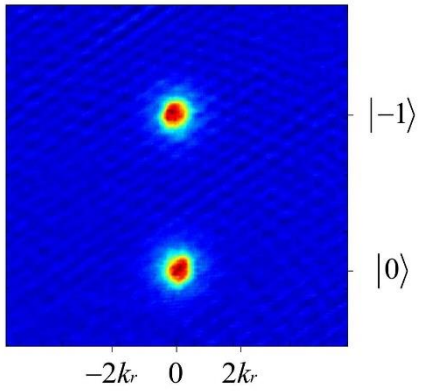
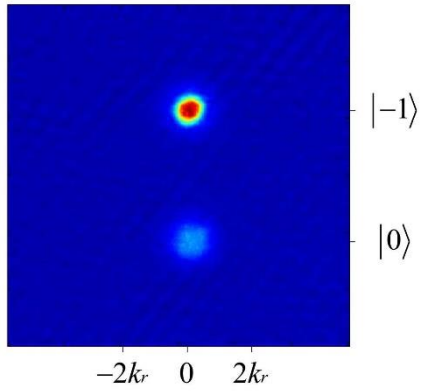
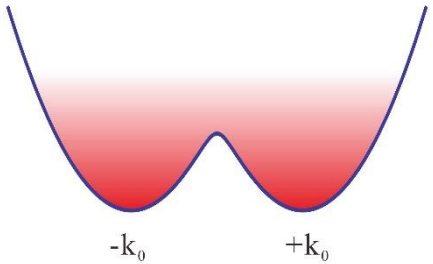
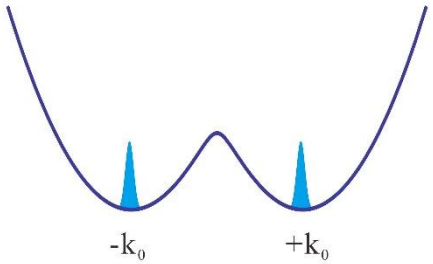
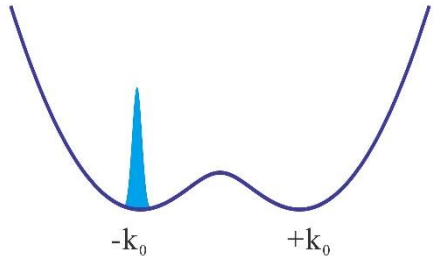


Transition from normal Bose gas to BEC

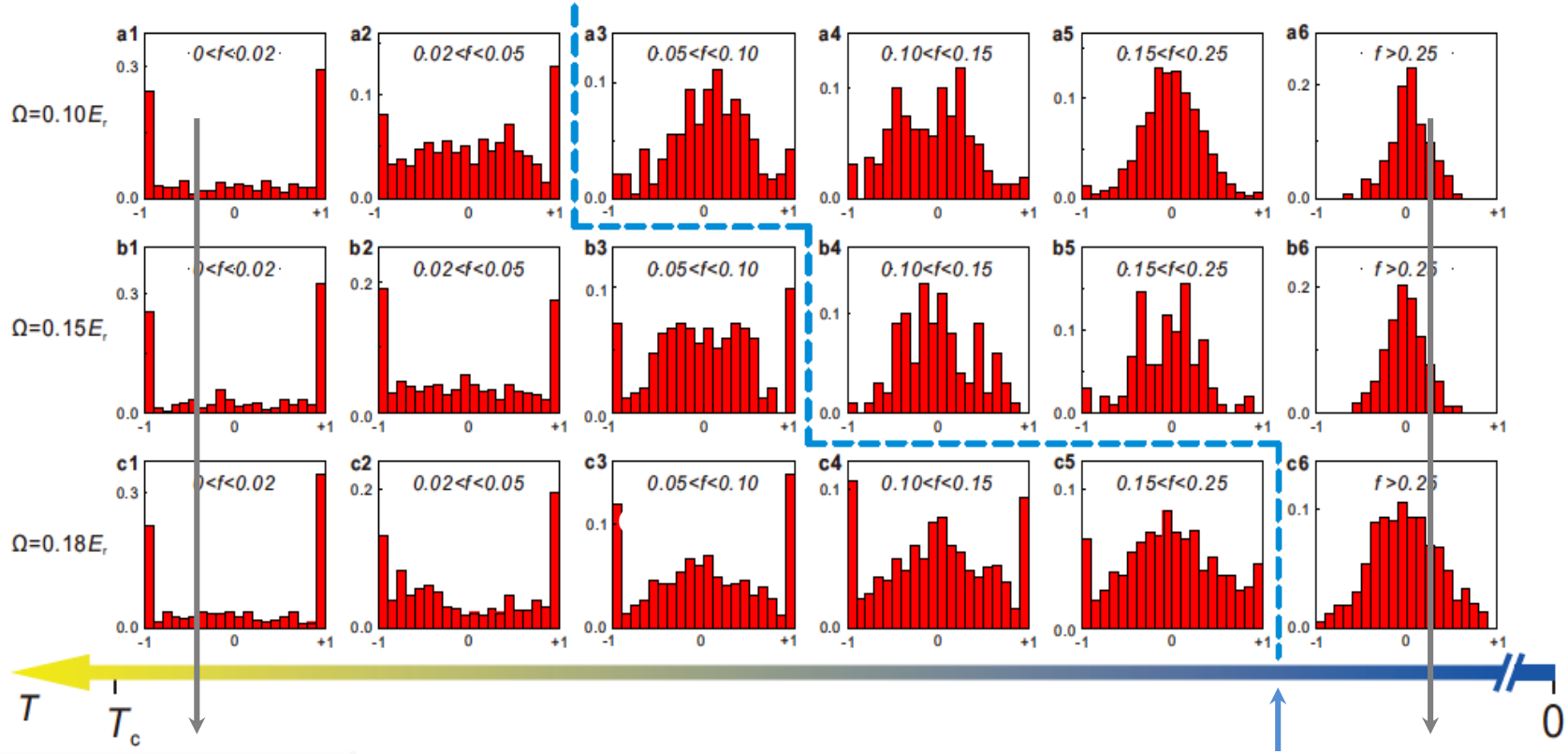
Magnetization and phase transition

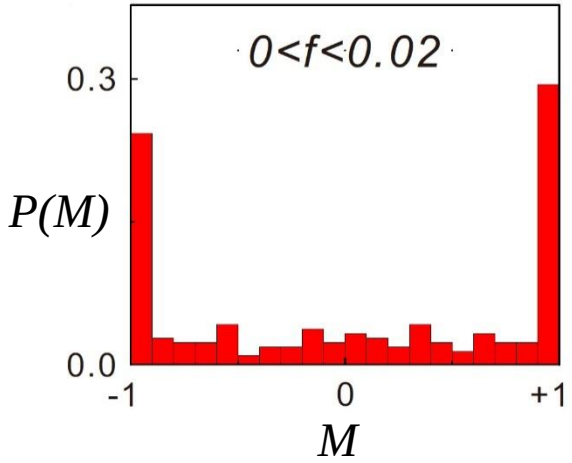
- Discriminating stripe phase and magnetized phase by magnetization *M*:

$$M = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Thermal atoms:	Condensate: ST phase	Condensate: MT phase
		
		
$\langle M \rangle = 0$	$\langle M \rangle = 0$	$\langle M \rangle = \pm\sqrt{16 - \Omega^2}/4$

Magnetization and phase transition





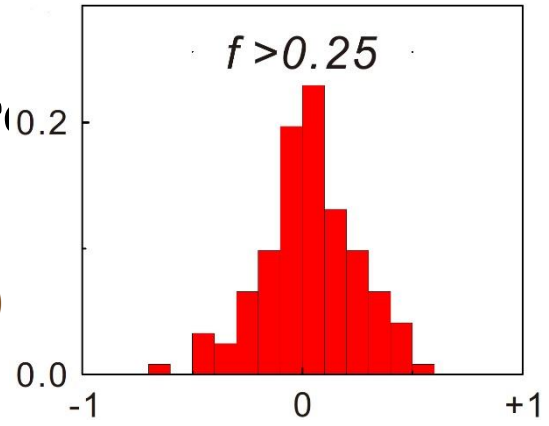
Typical magnetized phase:

Two sharp peaks around $M \approx \pm 1$

Phase tr

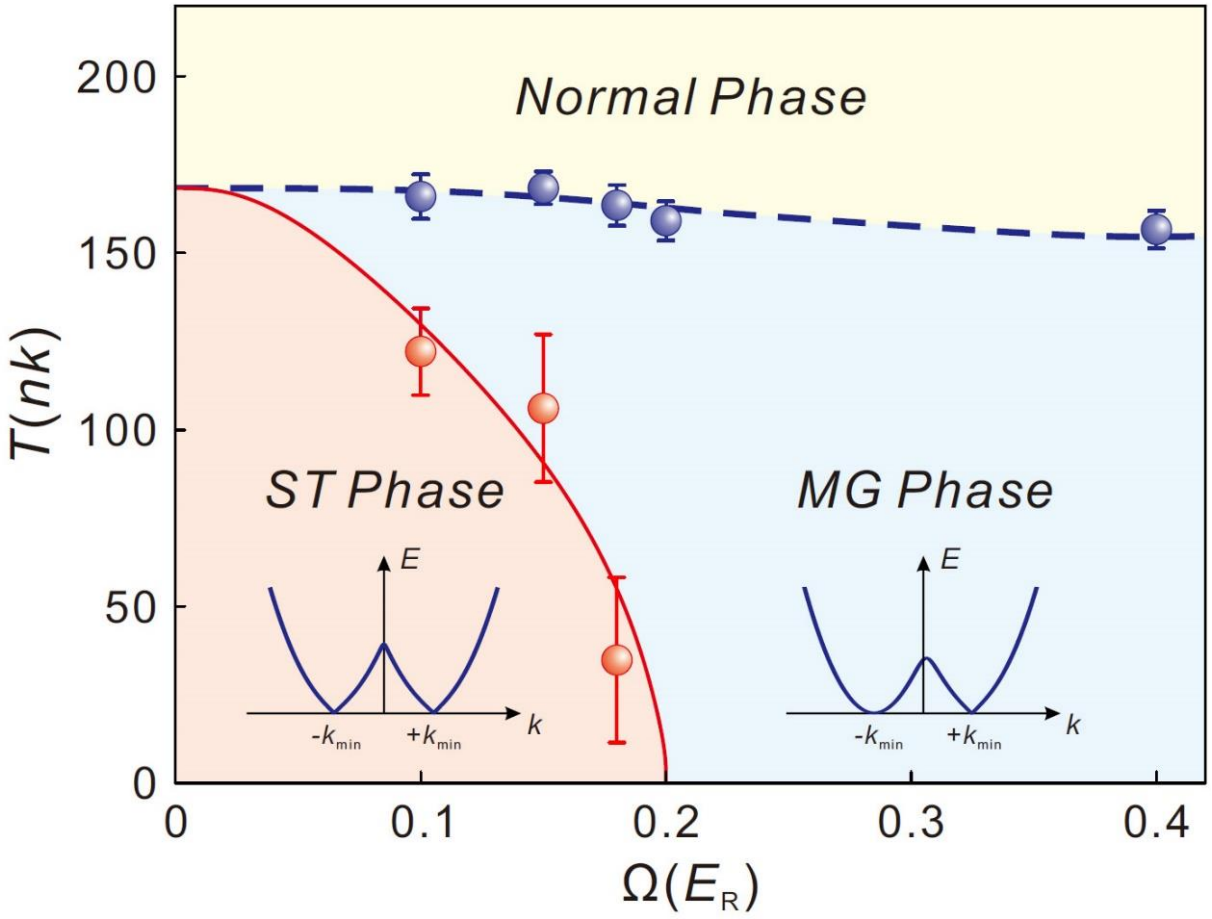
Typical stripe phase:

A board peak centered at $M = 0$



Finite-temperature phase diagram of SOC Bose gas

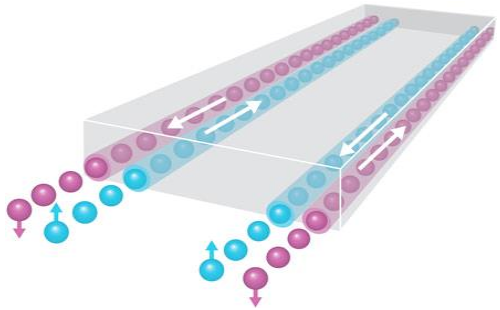
Ji *et al.*, Nature Physics 10, 314 (2014)



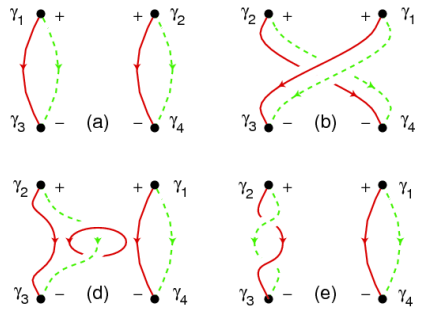
Though theoretical result was not clear yet at that time!

From 1D to 2D spin-orbit coupling

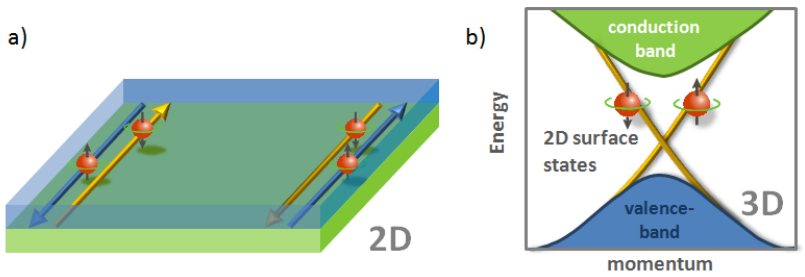
- However, mimicking 1D spin-orbit coupling is like a toy, 1D SOC does not have the real topological properties.
- 2D or higher dimensional SOC play central role in most of topological quantum matters, such as…



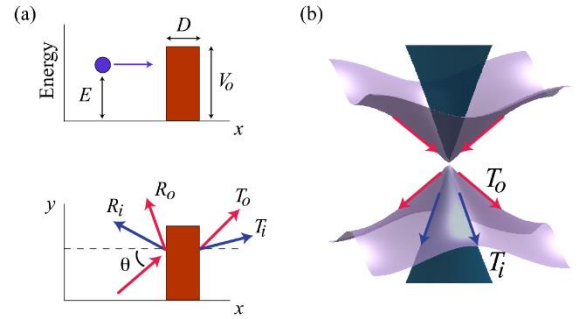
Topological insulators



Majorana Fermions

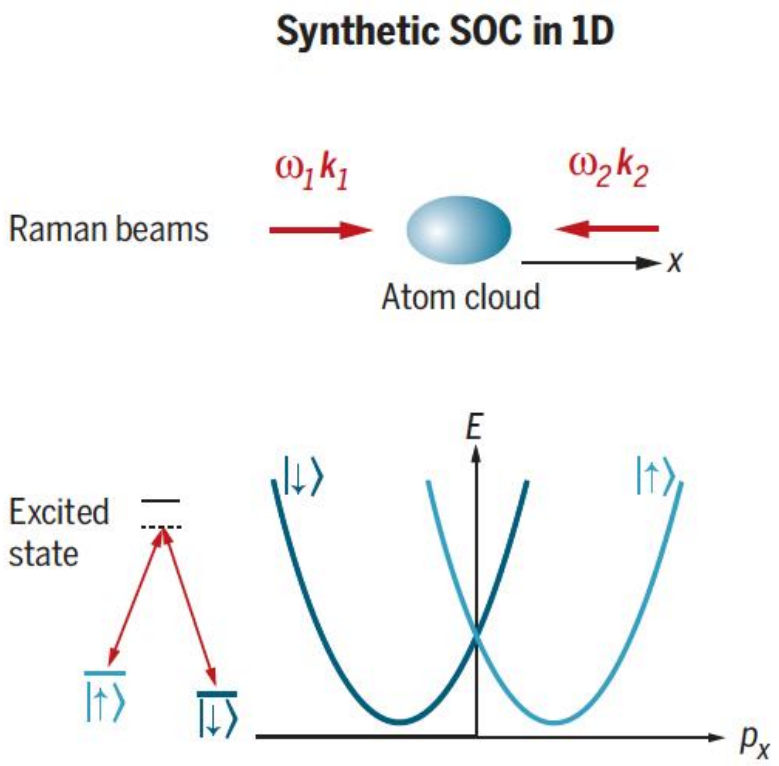


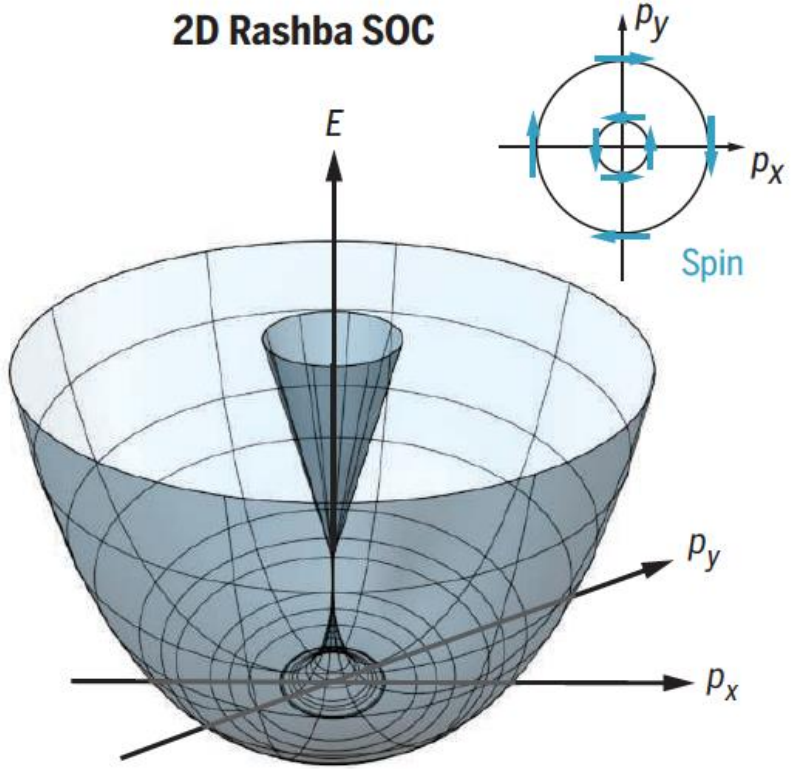
Topological superconductor



Weyl semimetal

From 1D to 2D spin-orbit coupling





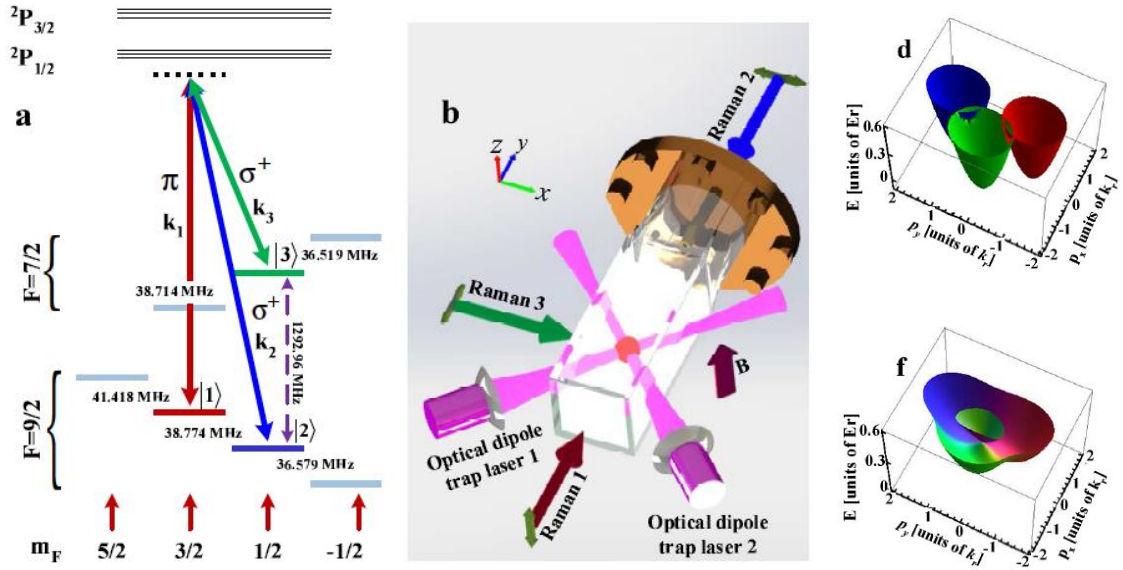
Coupling term: $k_z\sigma_z$ → $k_x\sigma_y + k_y\sigma_z$

Superposition of two 1D SOC

From 1D to 2D spin-orbit coupling

- Some proposals:
  PRL 108, 235301 (2013)
  PRL 111, 125301 (2013)
  PRA 85, 043605 (2012), etc.

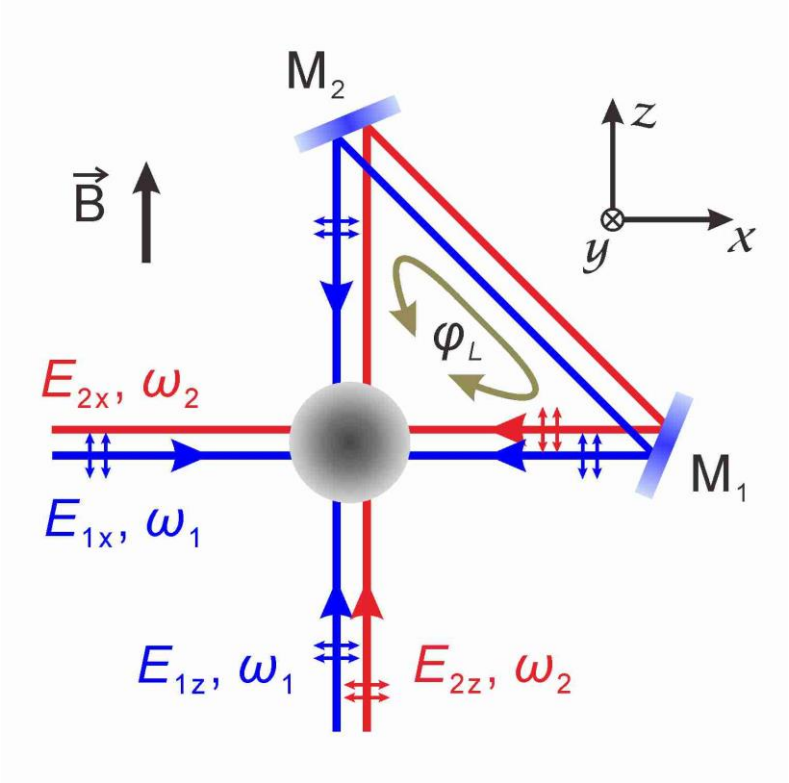
- Experiment:
  2D SOC with Fermion (^{40}K)
  Nature Physics 12, 540 (2016)

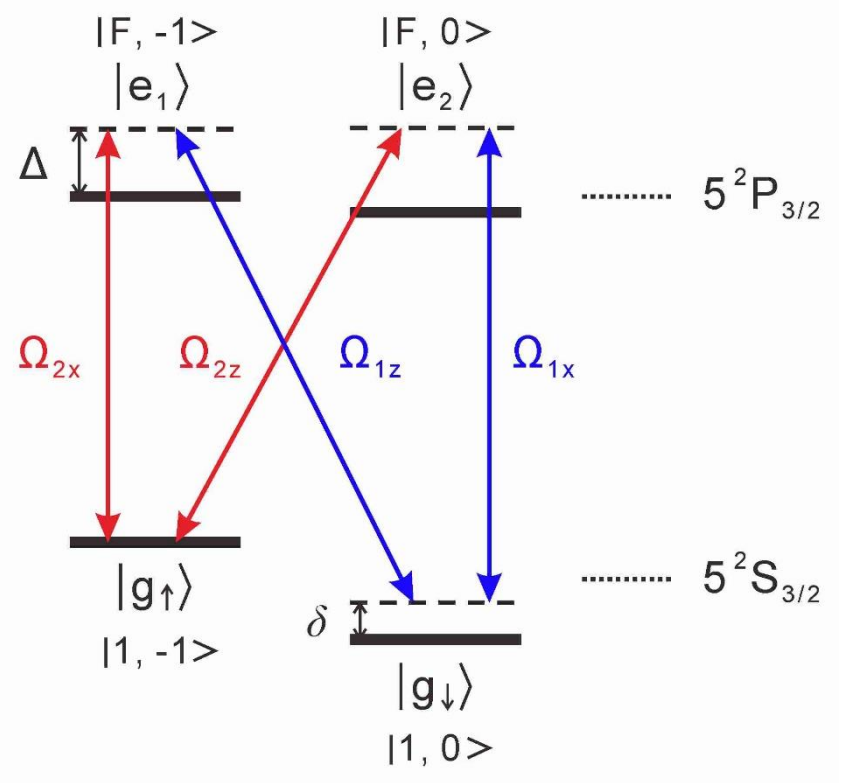


Major challenge:

- Large heating rate
- Phase coherence between atom-laser couplings
- Fast switch on/off the magnetic fields

Optical lattice + running wave scheme





The phase of the lasers go through the loop:

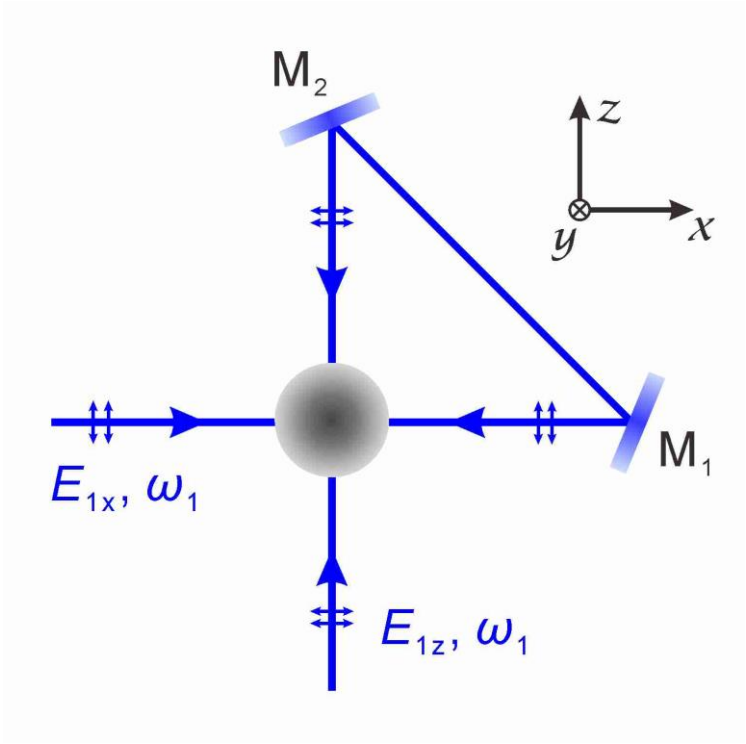
Lattice light ω_1 : $\varphi_L = k_0 L$

Raman light ω_2 : $\varphi_L + \delta\varphi_L = (k_0 + \frac{\delta\omega}{c})L, \delta\omega = \omega_2 - \omega_1$

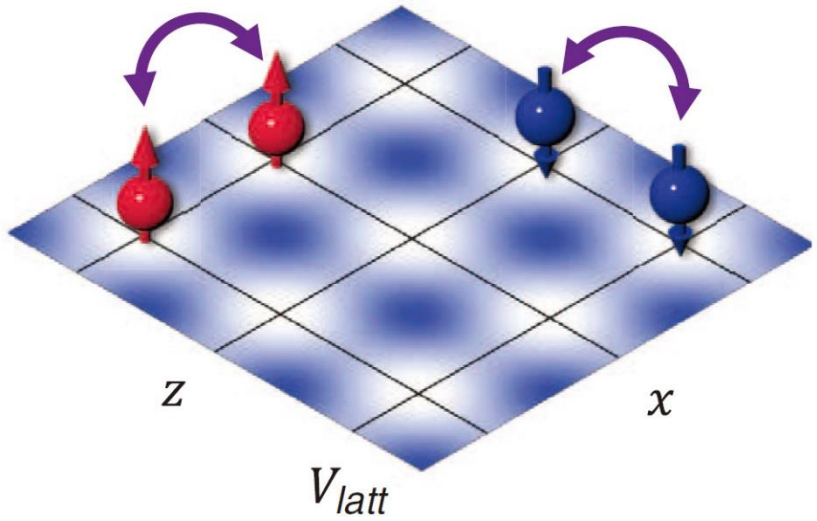
☑ Less lasers and stable energy levels, low heating rate

☑ Robust phase relation

2D Lattice



2D lattice to trap atoms



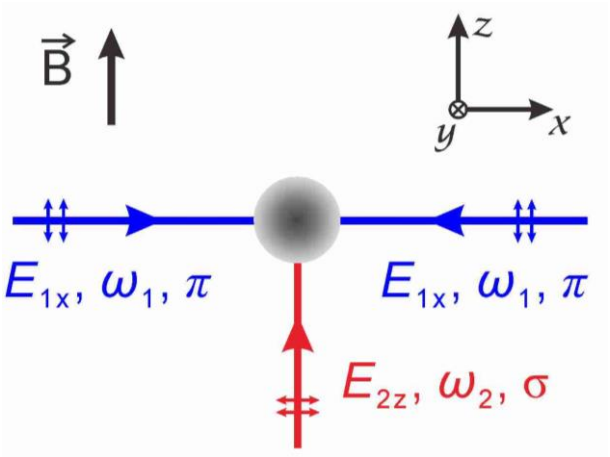
Spin conserved tunneling

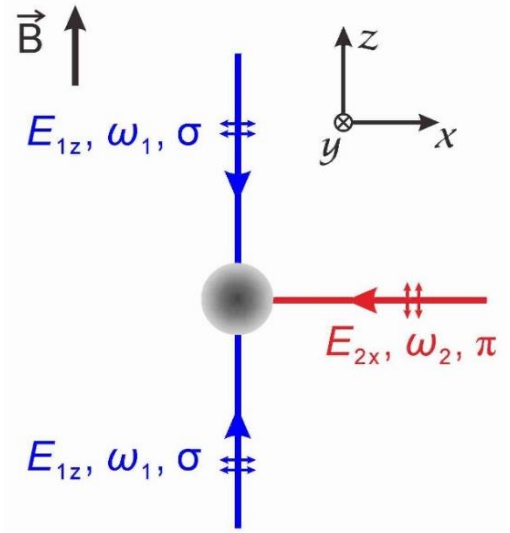
Optical lattice potential:

$$V_{Latt}(x,y) = V_{0x}\cos^2(k_0 x + \frac{\varphi_{1x} - \varphi_{1z} - \varphi_L}{2}) + V_{0z}\cos^2(k_0 z + \frac{\varphi_{1z} - \varphi_{1x} - \varphi_L}{2})$$

Raman coupling lattices

Lattice laser and Raman laser form Raman coupling lattices ➡ spin-flip tunneling





Standing wave

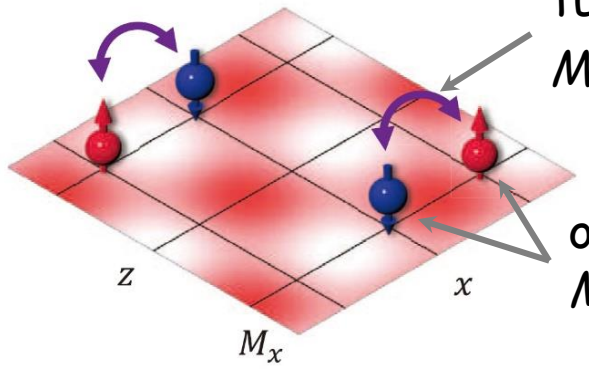
Running wave

Raman coupling strength: $M_x = M_0 \cos k_0 x \, e^{ik_0 z}$

$= M_0 \cos k_0 x \cos k_0 z$

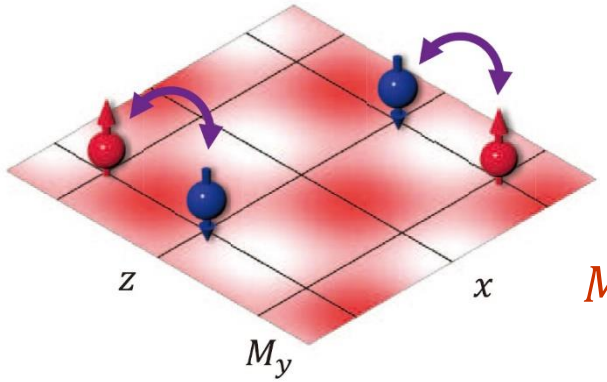
$+ iM_0 \cos k_0 x \sin k_0 z$

In tight binding condition: $M_x = M_0 \cos k_0 x \sin k_0 z$



tunneling:
M = 1

on site:
M = 0



$M_z = M_0 \cos k_0 z \sin k_0 x$

2D spin-orbit coupling

Total coupling potential:

$|g_\uparrow\rangle \rightarrow |g_\downarrow\rangle$: $M_x + M_z e^{-i\delta\varphi_L} = M_x + M_z \cos\delta\varphi_L - iM_z \sin\delta\varphi_L$

$|g_\downarrow\rangle \rightarrow |g_\uparrow\rangle$: $M_x + M_z e^{i\delta\varphi_L} = M_x + M_z \cos\delta\varphi_L + iM_z \sin\delta\varphi_L$

Coupling term in effective Hamiltonian:

$$\begin{bmatrix} \cdots & M_x + M_z \cos\delta\varphi_L - iM_z \sin\delta\varphi_L \\ M_x + M_z \cos\delta\varphi_L + iM_z \sin\delta\varphi_L & \cdots \end{bmatrix}$$

$$= (M_x + M_z \cos\delta\varphi_L)\sigma_x + iM_z \sin\delta\varphi_L\, \sigma_y$$

Effective Hamiltonian: $H = \frac{p^2}{2m} + V_{\text{latt}} + \mathcal{M}_x\sigma_x + \mathcal{M}_y\sigma_y + m_z\sigma_z$

$$\mathcal{M}_x = M_x + M_z \cos\delta\varphi_L$$

$$\mathcal{M}_y = M_z \sin\delta\varphi_L$$

Liu *et al.*, PRL 112, 086401 (2014)

2D spin-orbit coupling

$$H = \frac{p^2}{2m} + V_{\text{latt}} + \mathcal{M}_x\sigma_x + \mathcal{M}_y\sigma_y + m_z\sigma_z$$

$$\mathcal{M}_x = M_x + M_z\cos\delta\varphi_L$$
$$\mathcal{M}_y = M_z\sin\delta\varphi_L$$

If initial state is prepared in the spin up state $|\uparrow\rangle$, when SOC involved:

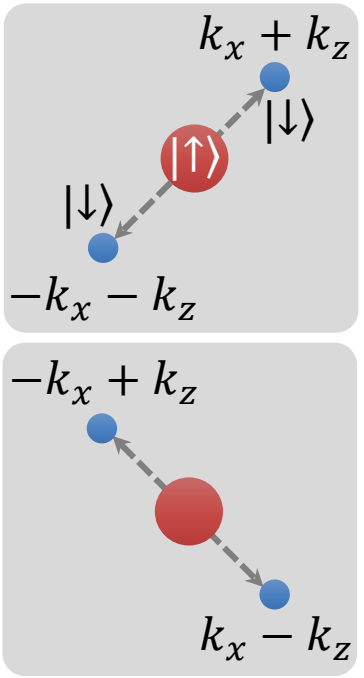
- 1D SOC:

  $\delta\varphi_L = \pi$ ➡ $(M_x - M_z)\sigma_x$

  spin state: $|\uparrow\rangle + \varepsilon(|k_x + k_z\rangle + |-k_x - k_z\rangle)|\downarrow\rangle$

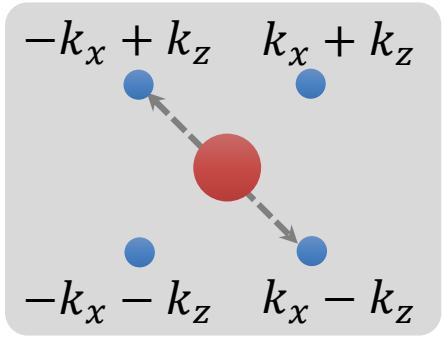
  $\delta\varphi_L = 2\pi$ ➡ $(M_x + M_z)\sigma_x$

  spin state: $|\uparrow\rangle + \varepsilon(|-k_x + k_z\rangle + |k_x - k_z\rangle)|\downarrow\rangle$

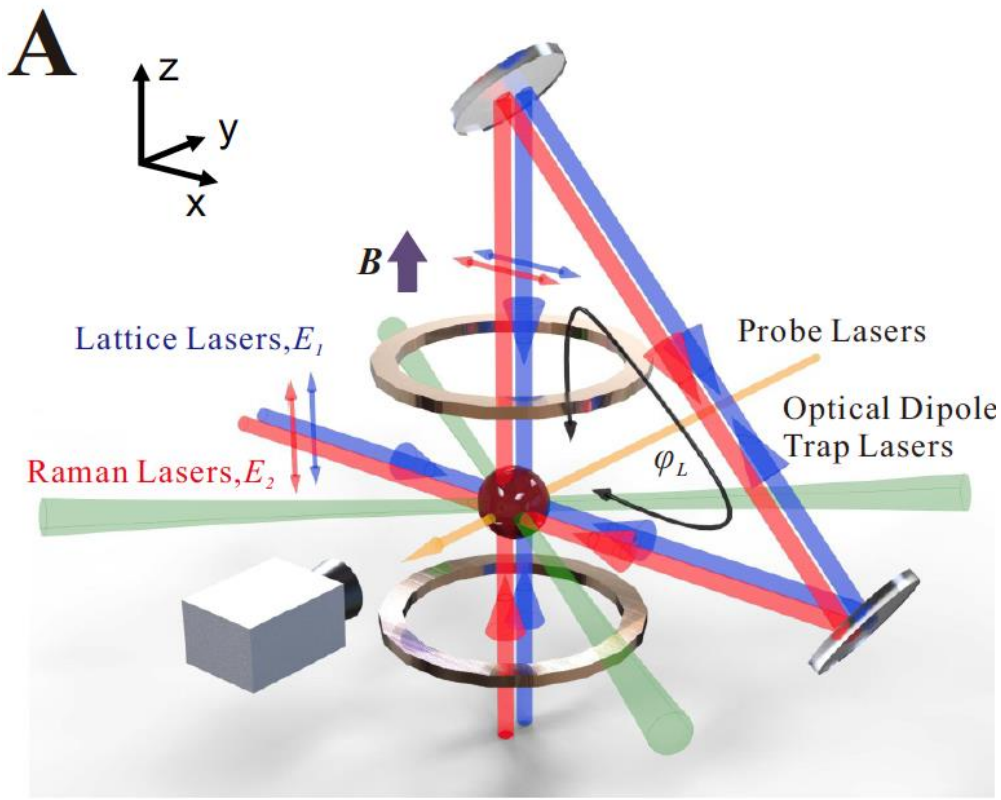


- Optimal 2D SOC:

  $\delta\varphi_L = \frac{\pi}{2}$ ➡ $M_x\sigma_x + M_z\sigma_y$



Experimental setup



- 2D Lattice and Raman Laser Wavelength: 767nm
- Bias field: ~50 Gauss, 2-level system, $\delta\omega = 2\pi \times 35$MH

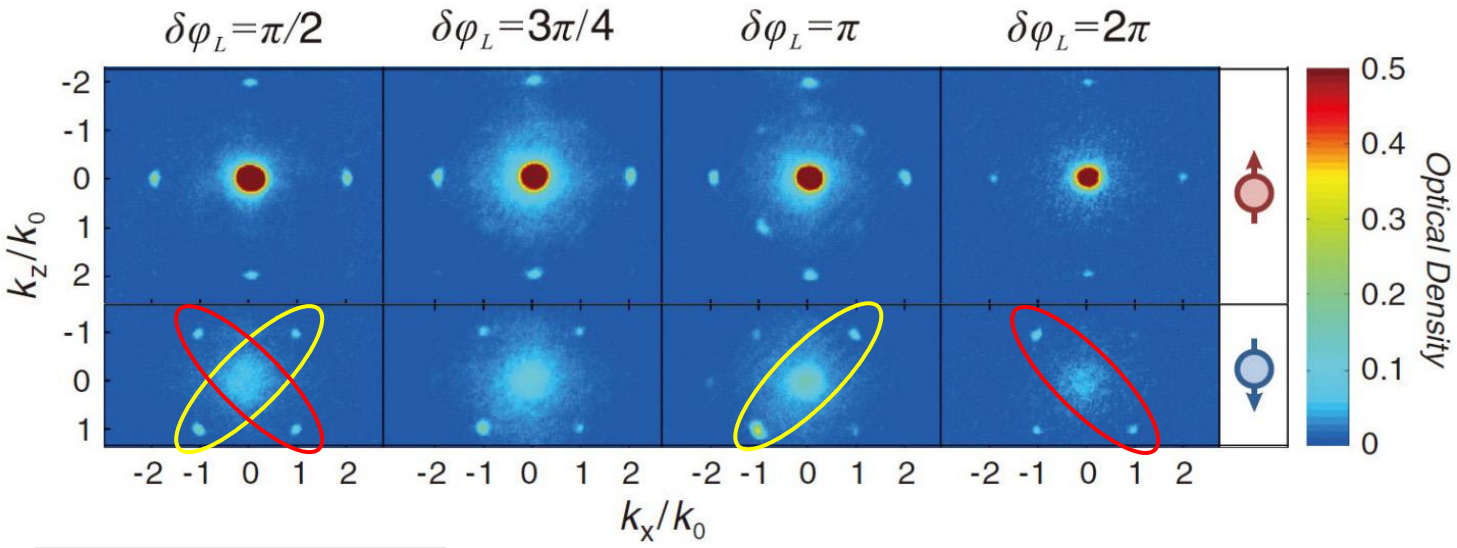
  Wu *et al.*, Science 354, 83 (2016)

Adjust length of the loop

$$H = \frac{p^2}{2m} + V_{\text{latt}}(x, z) + m_z\sigma_z + (M_x - M_y \cos\delta\varphi_L)\sigma_x + M_y \sin\delta\varphi_L\sigma_y$$

1D-2D spin-orbit coupling crossover

- BEC of ^{87}Rb
- Adiabatically ramp up the lattice and Raman coupling
- Lattice depth: $V_0 = 4.16E_r$, Raman coupling: $M_0 = 1.32E_r$
- Probe: TOF + Stern Gelach
- Lifetime ~ 300ms



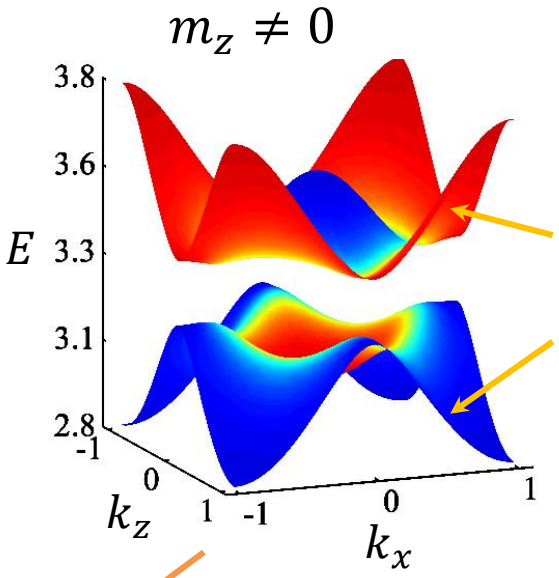
Optimal 2D SOC	1D SOC	1D SOC
$M_x\sigma_x + M_z\sigma_y$	$(M_x - M_z)\sigma_x$	$(M_x + M_z)\sigma_x$

- Initially, all atoms are spin-up
- Peripheral clouds are caused by spin conserved tunneling
- Involve Raman coupling and detect number of spin-down atoms
- Adjust phase to observe 1D-2D SOC crossover

Topological feature

$$H = \frac{p^2}{2m} + V_{\text{latt}} + \mathcal{M}_x\sigma_x + \mathcal{M}_y\sigma_y + m_z\sigma_z$$

Calculated band structure:



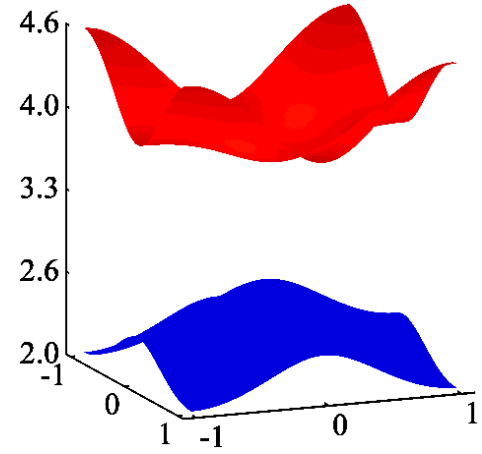
First excited band

Spin up

Spin down

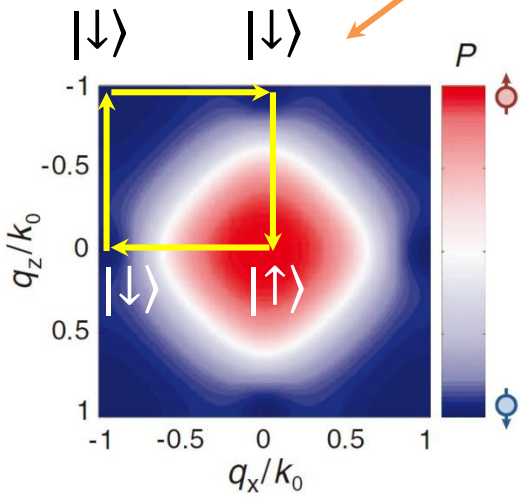
Lowest band

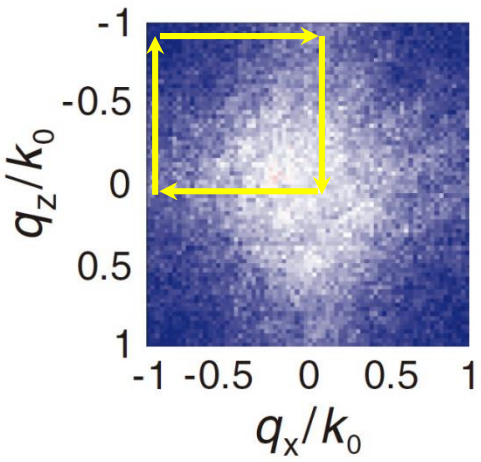
Increasing m_z



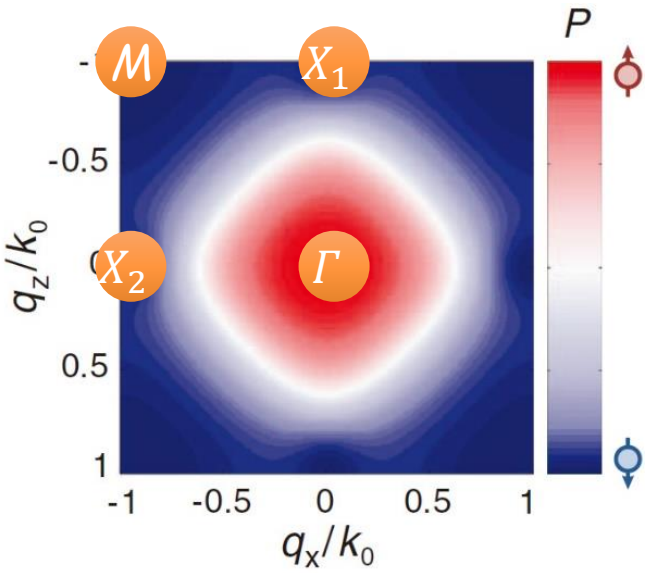
Topological feature: spin flips around along a closed circle

Trivial: spin does not flips around





Topological feature



Detect spin populations at 4 symmetric momenta M, X_1, X_2 and Γ, multiply signs

$$\Theta = \prod_{j=1}^{4} \mathrm{sgn}\left[P(\Lambda_j)\right] = \begin{matrix} +1 & \text{Trivial} \\ -1 & \text{Topological} \end{matrix}$$

Chern number

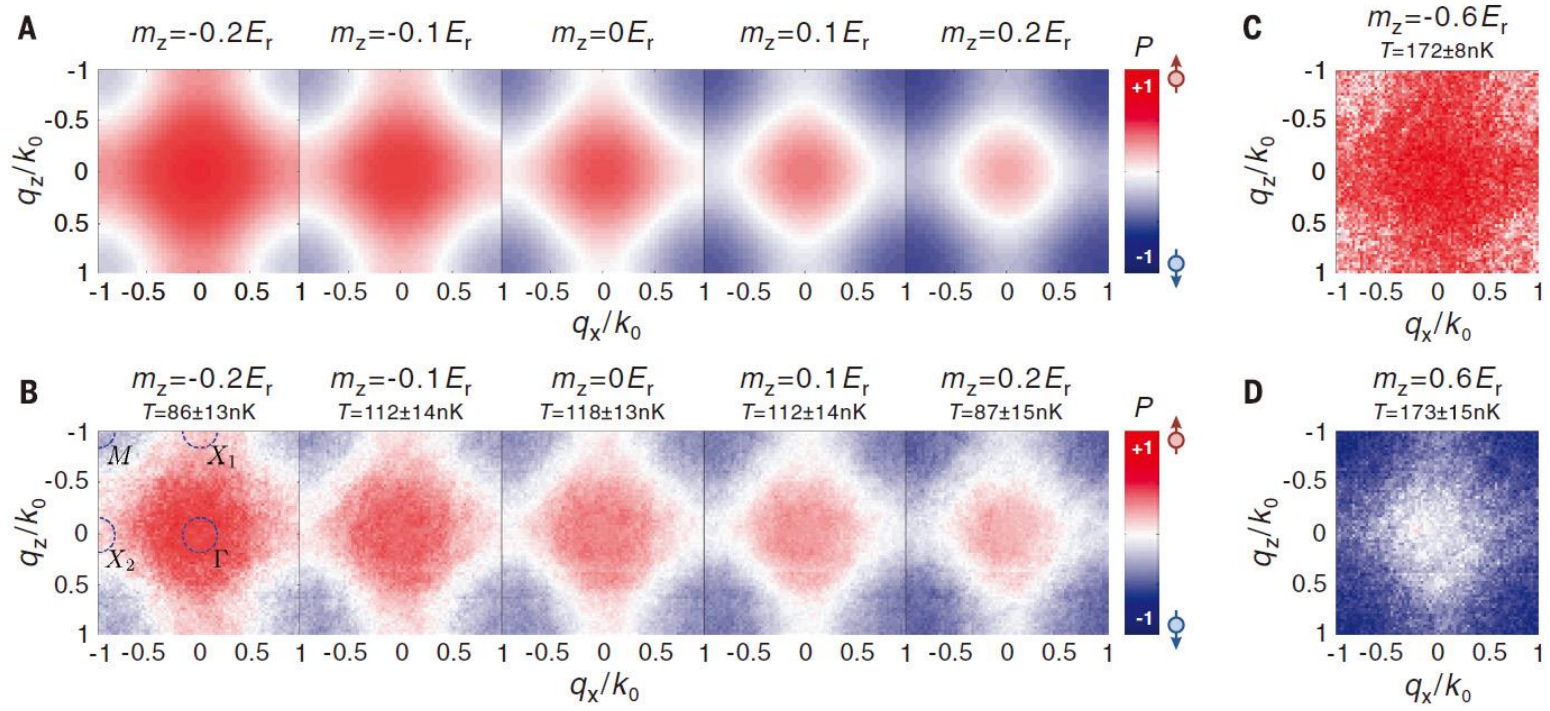
$$\mathrm{Ch}_1 = -\frac{\Theta}{4}\sum_{j=1}^{4} \mathrm{sgn}\left[P(\Lambda_j)\right]$$

Liu *et al.*, PRL 111, 120402 (2013)

Observation of topological feature

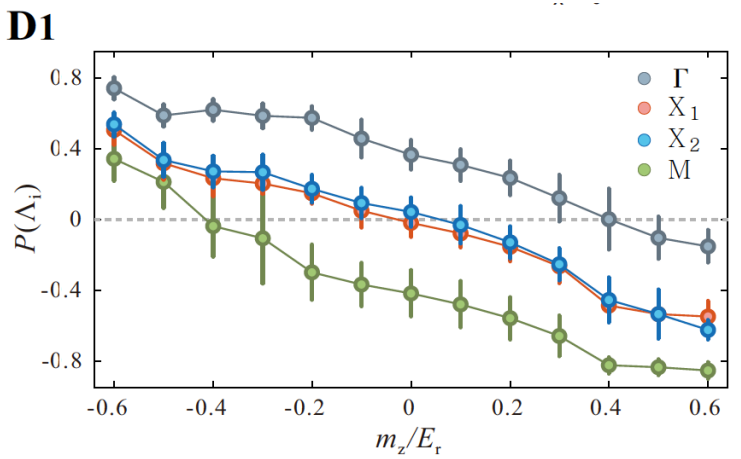
Numerical calculations

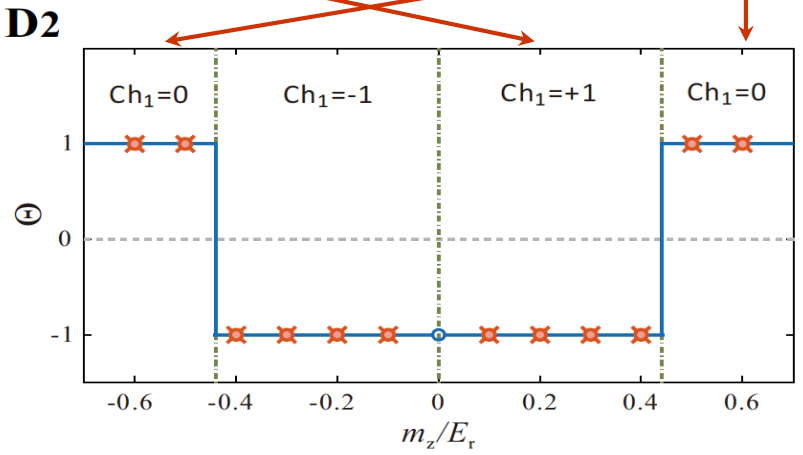
Experimental measurements



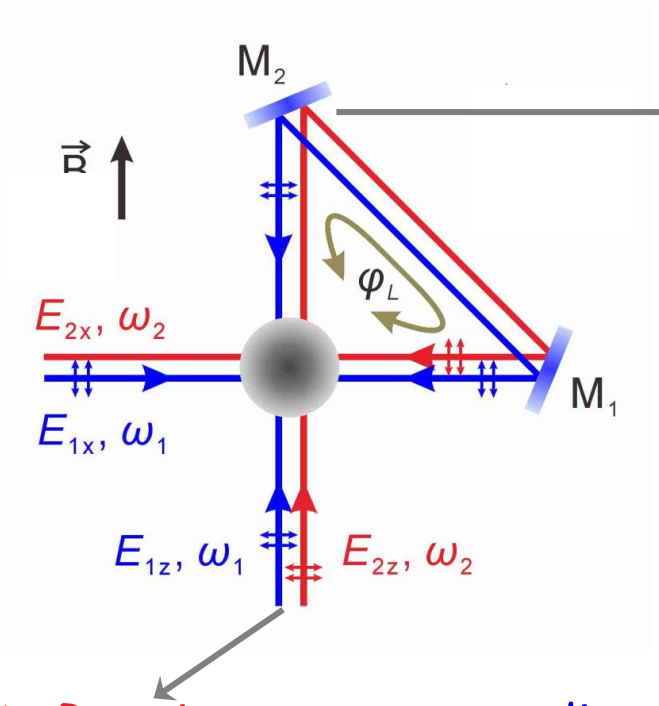
topological

trivial

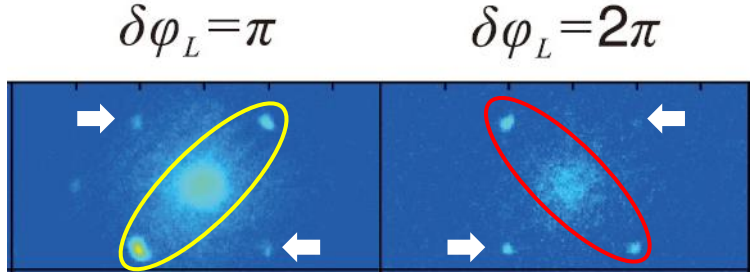




Some drawbacks

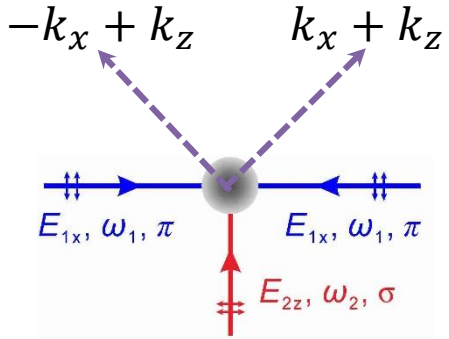


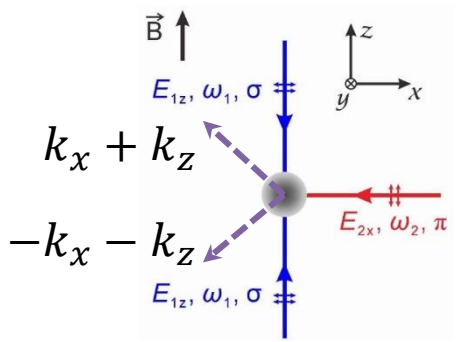
- Unstable optical setup: imperfect interference cause low SNR



Noise

- Running wave + standing wave: asymmetric Raman coupling





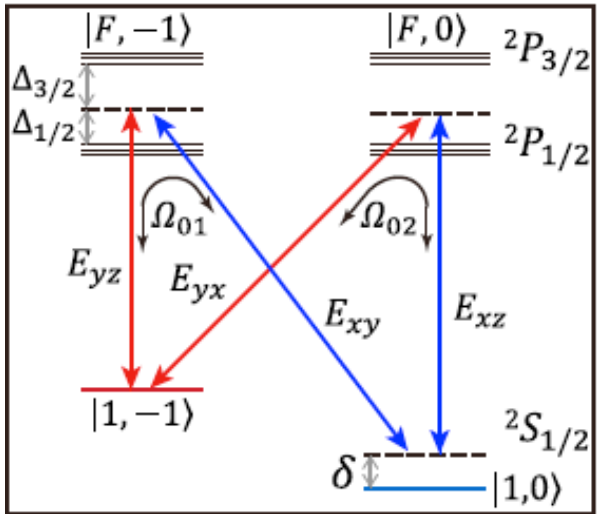
- Lead to asymmetric band structure, cause the missing of topological feature in large Raman coupling strength
- Tight-binding approximation is required

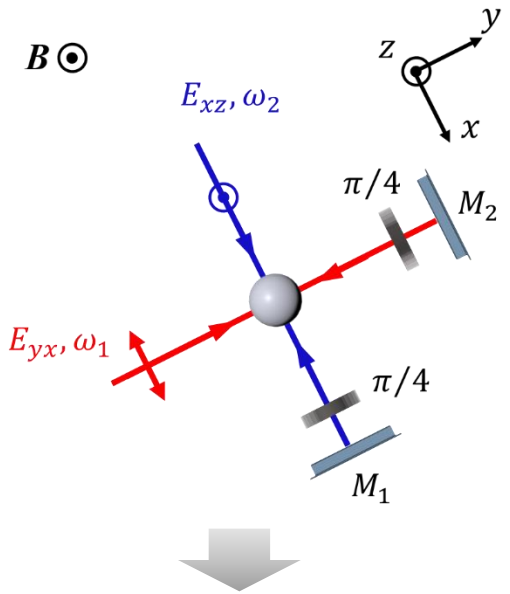
Symmetric 2D Raman lattices

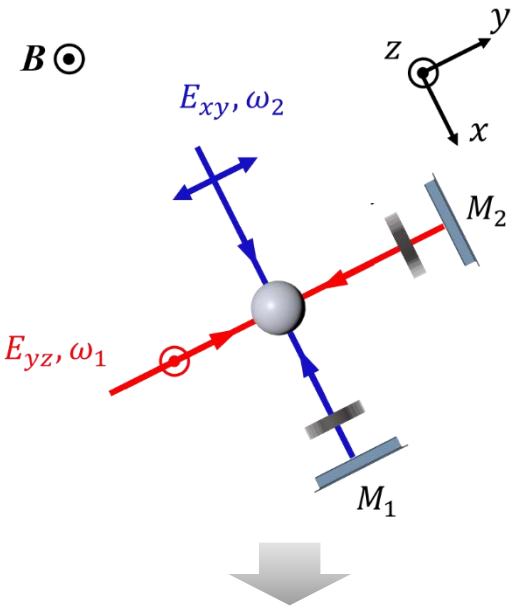
Two running waves alone x and y directions play as lattice laser and Raman laser

E_{xz}, E_{xy}: y, z components of polarization of x-running wave

E_{yx}, E_{yz}: x, z components of polarization of y-running wave





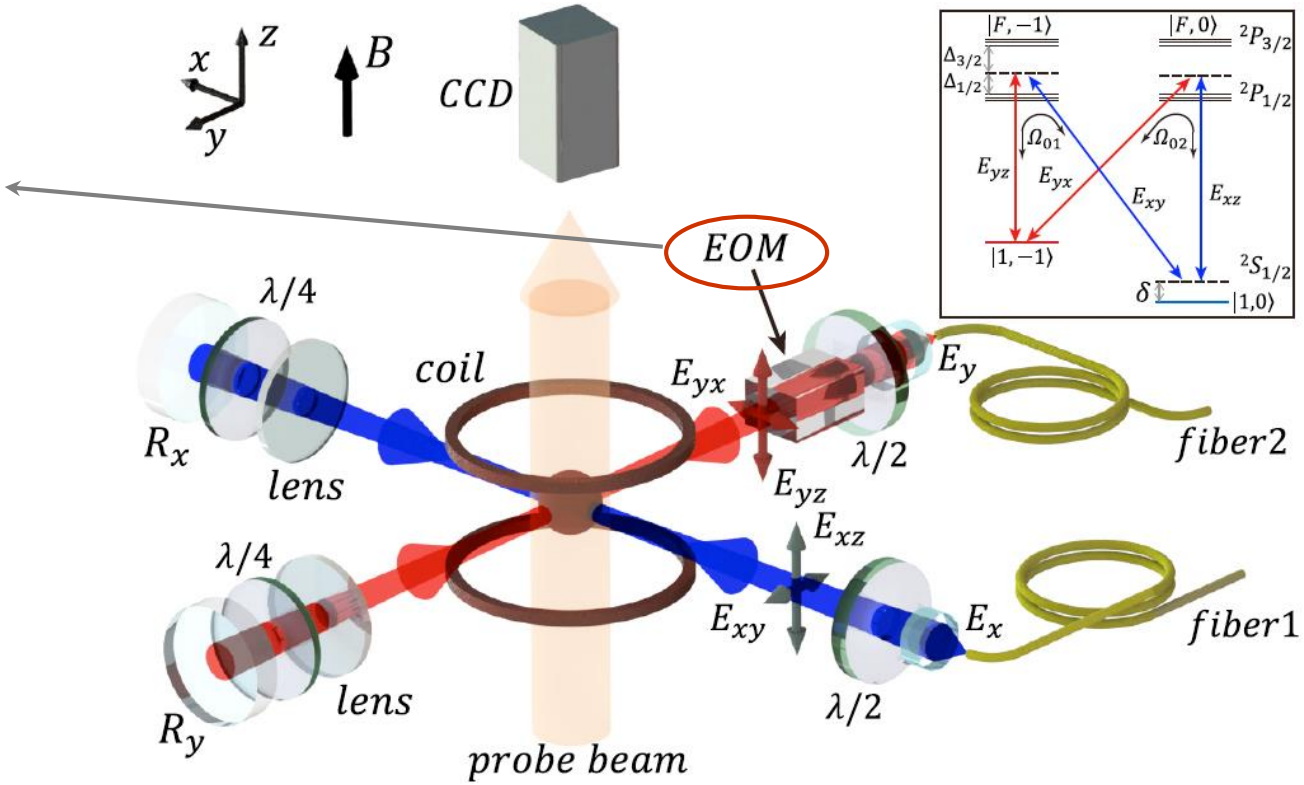


- Two 1D Raman coupling strength: $M_x = M_0 \cos k_0 x \sin k_0 y$ $M_y = M_0 \cos k_0 y \sin k_0 x$
- Relative phase can be adjusted by the phase between polarization components

Symmetric 2D Raman lattices

Experimental setup

Adjusting phase between E_{yx}, E_{yz}



- ☑ Symmetric lattice and Raman lasers
- ☑ Adjustable phase between polarizations, avoiding path instability

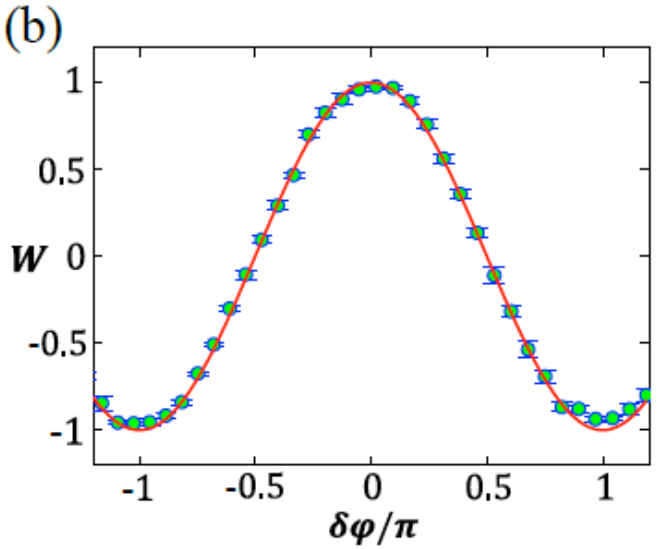
→ Two symmetric Raman coupling with different polarizations

Symmetric 2D Raman lattices

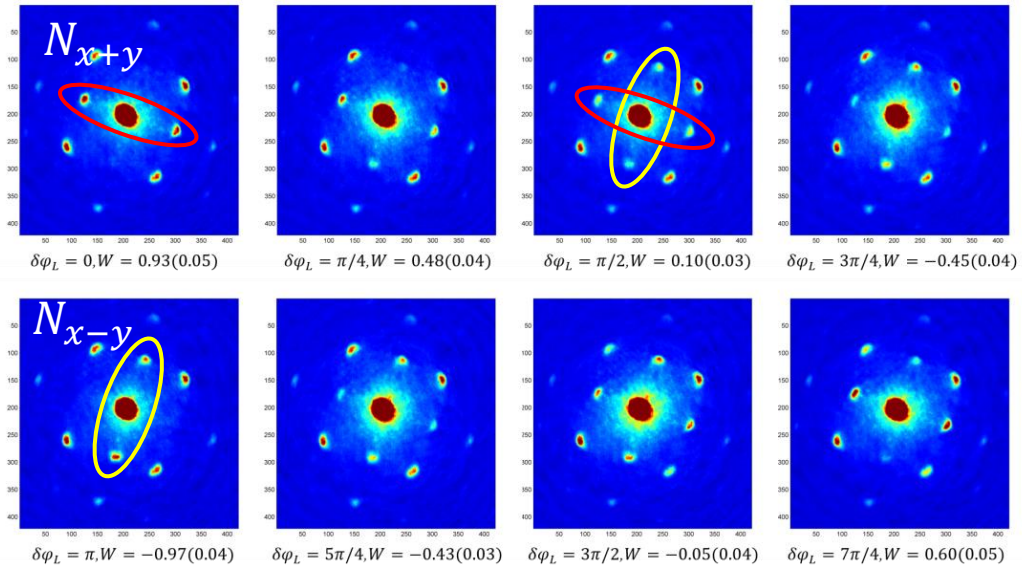
High SNR

Interference of Raman couplings

$$W(\delta\varphi) = \frac{N_{\hat{x}+\hat{y}} - N_{\hat{x}-\hat{y}}}{N_{\hat{x}+\hat{y}} + N_{\hat{x}-\hat{y}}}$$



Stable phase



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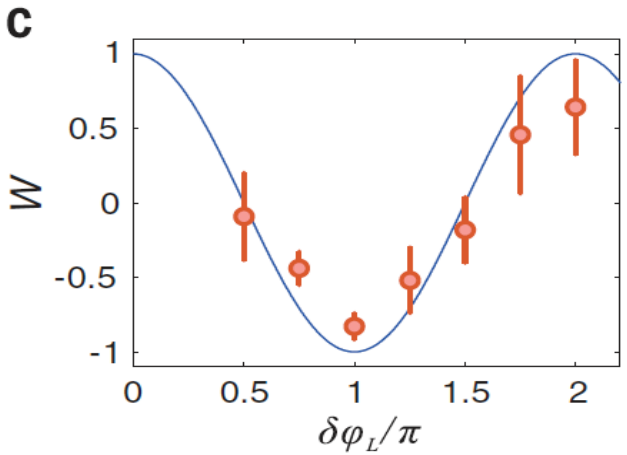
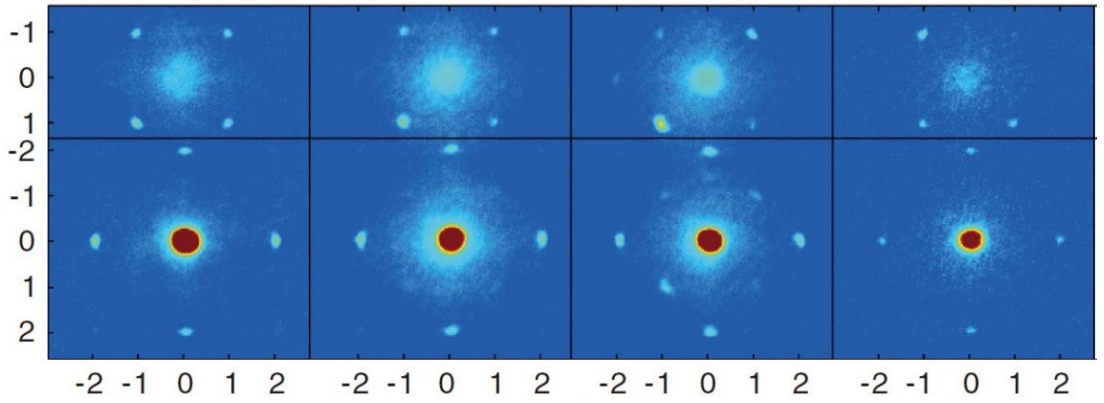
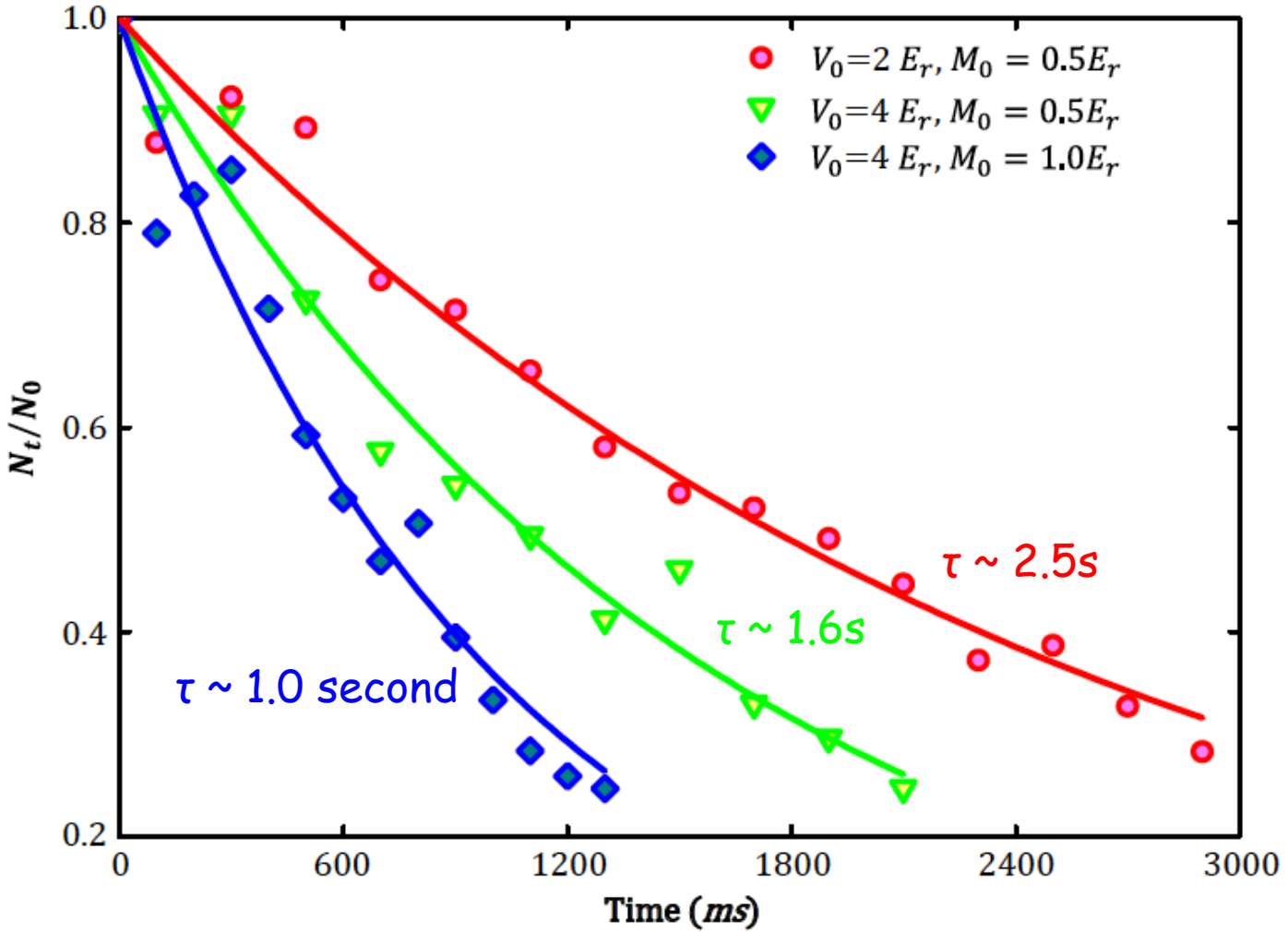


Unstable phase



Symmetric 2D Raman lattices

Long lifetime

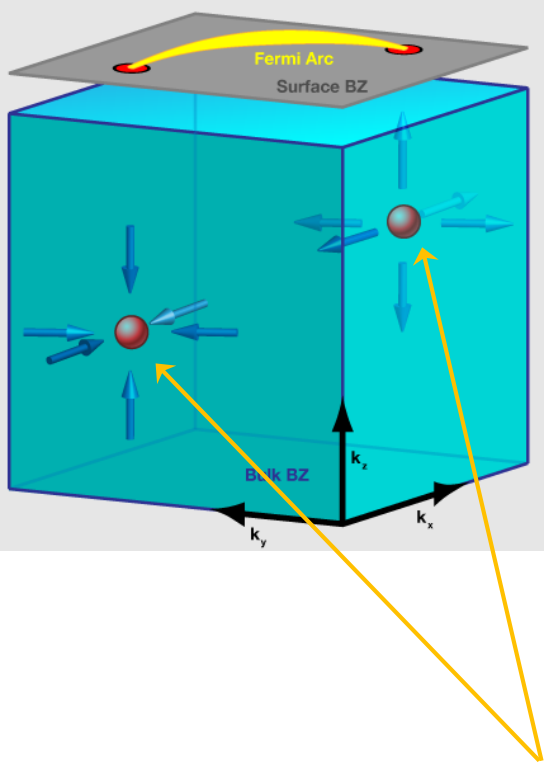


Lifetime in 2016 paper:
~ 300ms

Sun *et al.*, PRL 121, 250403 (2018)

Outlook

Observing Weyl points with 3D SOC (experiment in progress)



Weyl semimetal: a new kind topological phase of matter

☑ Low energy consumption electronic transmissions

☑ Topological quantum computing

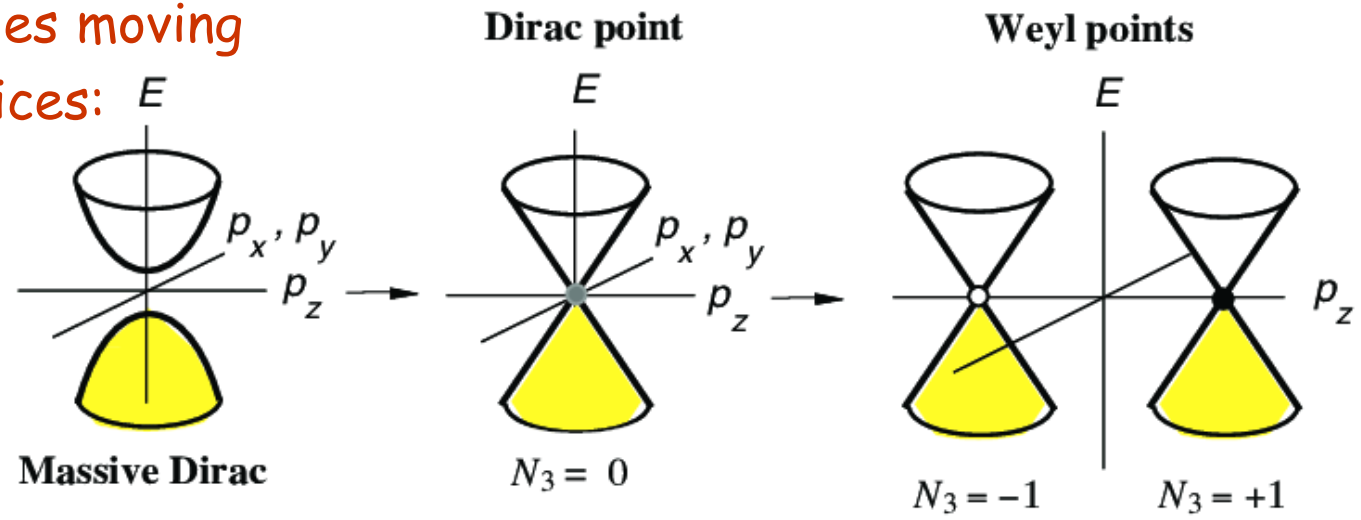
……

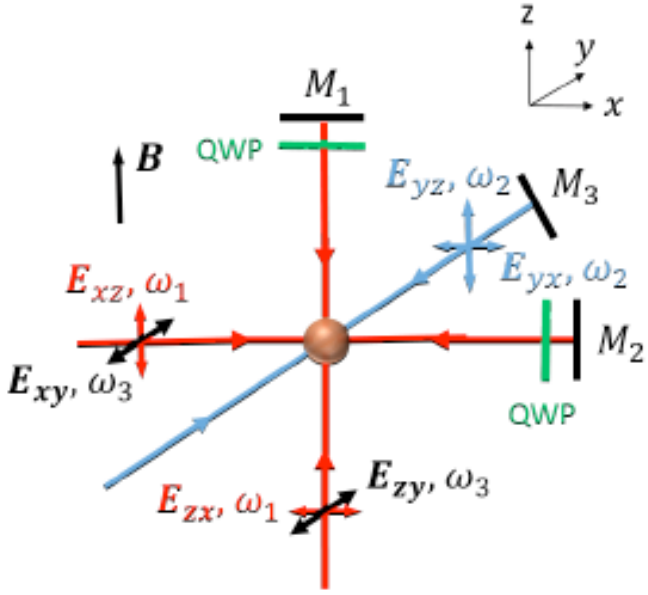
Feature: Dirac point is separated into two Weyl points

Outlook

Observing Weyl points with 3D SOC (experiment in progress)

Particles moving in lattices:





Massive particle Massless particle With 3D SOC

- With 3d-SOC, the Dirac point can be separated to two Weyl points with opposite chiral number
- The dispersion of Weyl points are linear in all 3 dimensions
- The regions containing only two Weyl points have not yet been observed in condensed matter materials

Part IV: Quantum simulation with ultra cold molecules

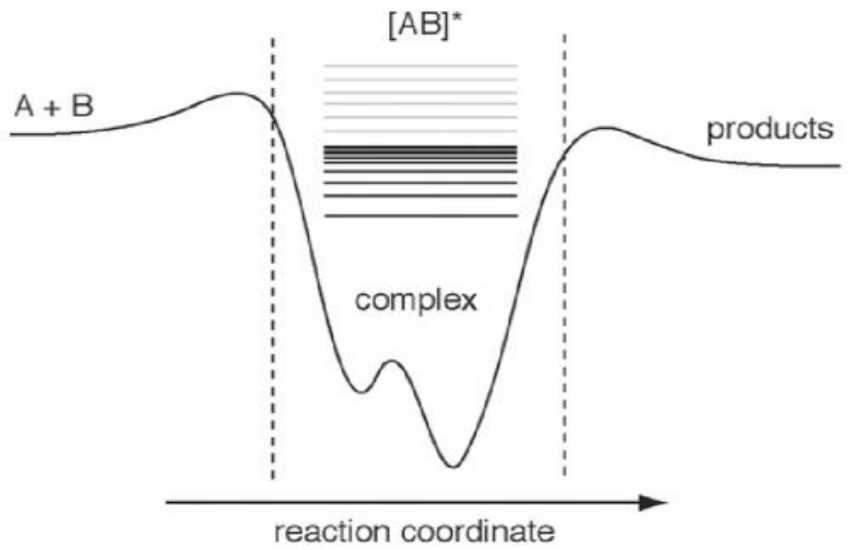
Bose-Fermi Mixture

Rui *et al.*, Nature Physics 13, 699 (2017)
Yang *et al.*, Science 363, 261 (2019)

Ultra-cold chemistry

Conventional reactions/collisions

- Hard-sphere classical collision
- Average of many partial waves
- Average of many rovibrational states



☒ Very hard to study quantum effects!

V. S.

Ultracold reactions/collisions

- de Broglie wave quantum collision
- Single partial wave, pure *s*- or *p*- wave
- Reactants in a single quantum state

Quantum mechanics dominated

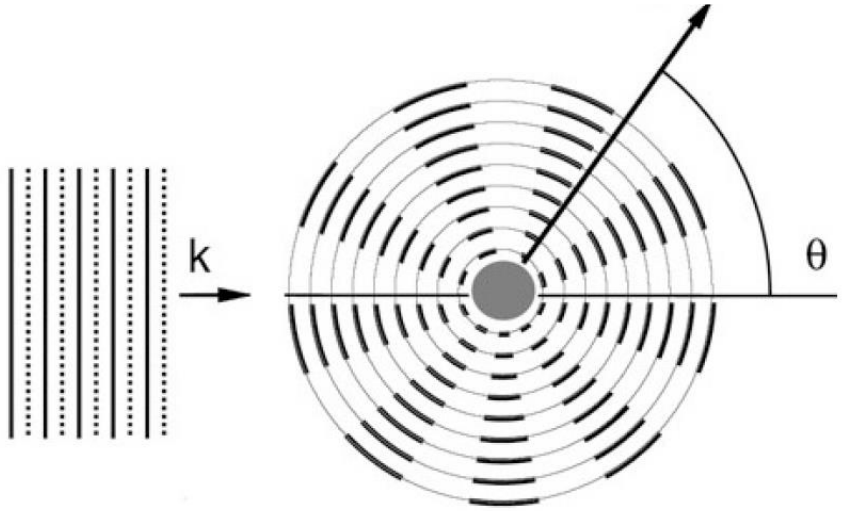
☑ resonances and tunneling

☑ quantum interference

☑ quantum statistics

Understand how quantum mechanics affects chemical reactions!

Scattering of atoms



Schrödinger equation

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(r)\right]\Psi(r) = E\Psi(r)$$

Partial wave expansion, if V is isotropic

$\Psi(r) = r^{-1}\sum_L \Psi_l(r)P_l(\cos\Theta)$

P_l is Legendre function

Asymptotic solution

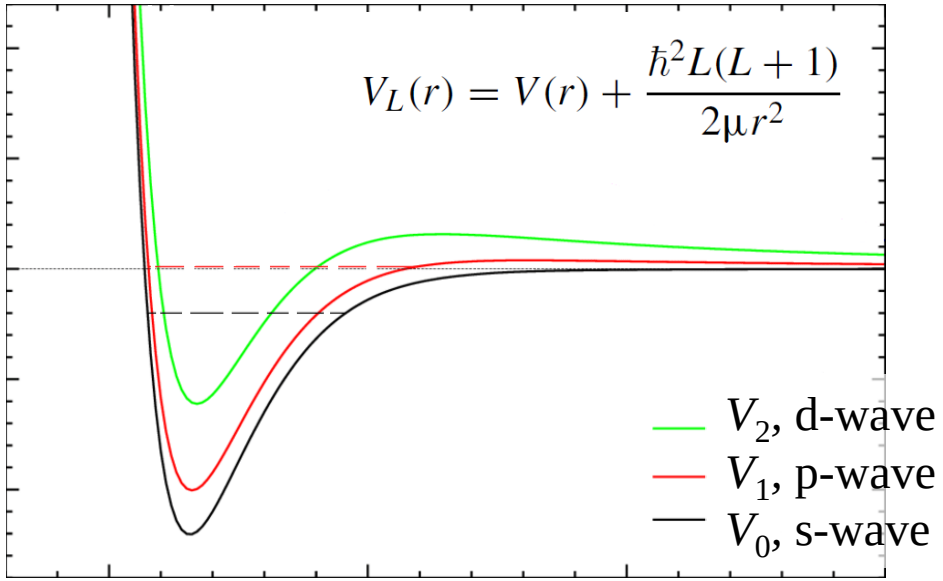
$$\Psi(r) \sim \Psi_0(r) + f(\Theta)\frac{e^{ikr}}{r}, r \to \infty$$

$f(\Theta)$ is scattering probability amplitude to be solved

Orbital angular momentum $l = 0, 1, 2\ldots$

➡ s, p, d… partial wave

Scattering of atoms



For each partial wave

$$\left[-\frac{\hbar^2}{2\mu}\frac{\mathrm{d}^2}{\mathrm{d}r^2} + V_l(r)\right]\Psi_l(r) = E\Psi_l(r)$$

Asymptotic solution

$$\Psi_l(r) \sim \sin(kr - \pi l/2 + \delta_l), r \to \infty$$

$$f(\Theta) = \frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)\left(e^{2i\delta_l} - 1\right)P_l(\cos\Theta)$$

In low energy scattering, only s wave is important: phase shift $\delta_0 \ll 1$ is proportional to k

S-wave scattering length $a = -\delta_0/k$

The interaction can be replaced by a simplified Fermi contact pseudopotential

$$V_{\mathrm{pseudo}}(r) = \frac{2\pi\hbar^2}{\mu}a\delta(r)\frac{\partial}{\partial r}r$$

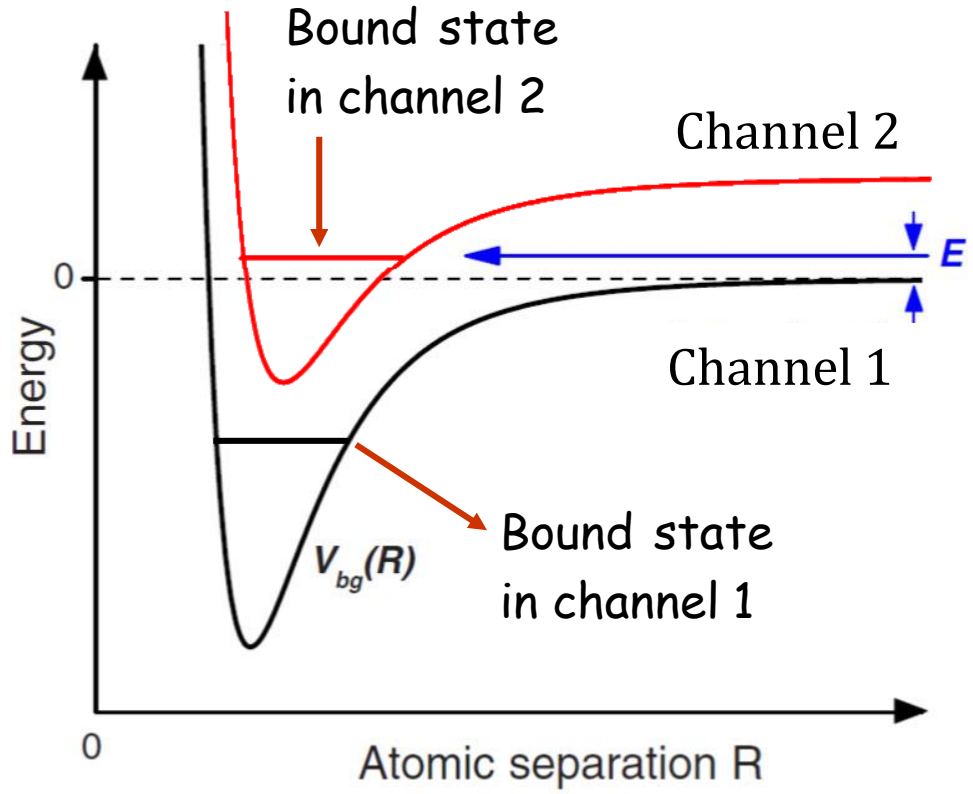
$a > 0$: repulsive

$a < 0$: attractive

Controls the interaction by adjusting scattering length

Atomic Feshbach resonances

Scattering involving different internal states



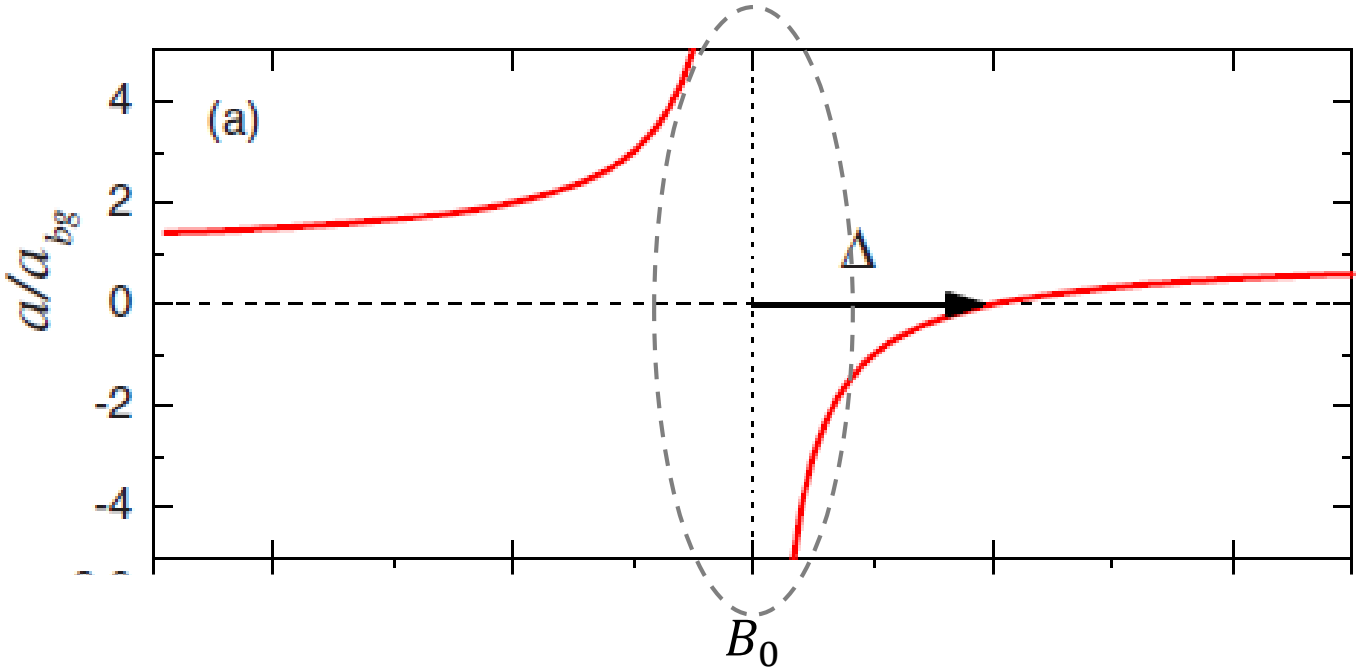
Feshbach resonances:

- Channel 1: Potential for two atoms in an internal state $|\Psi_1\rangle$ (set the internal energy of $|\Psi_1\rangle$ to be 0)
- Atoms cannot form bound state in this channel since the energy of bound state is always less than kinetic energy E
- Channel 2: Potential for two atoms in internal state $|\Psi_2\rangle$ with higher internal energy
- In channel 2, there exist a bound state with energy close to the collisional energy in channel 1
- If there is coupling between $|\Psi_1\rangle$ and $|\Psi_2\rangle$, two atoms scattering in channel 1 can temporary form a bound state in channel 2

Atomic Feshbach resonances

The energy of bound state in channel 2 can be tuned by magnetic field to coincide with collisional energy in channel 1

Scattering length will be greatly enhanced $a(B) = a_{\mathrm{bg}}\left(1 - \frac{\Delta}{B - B_0}\right)$



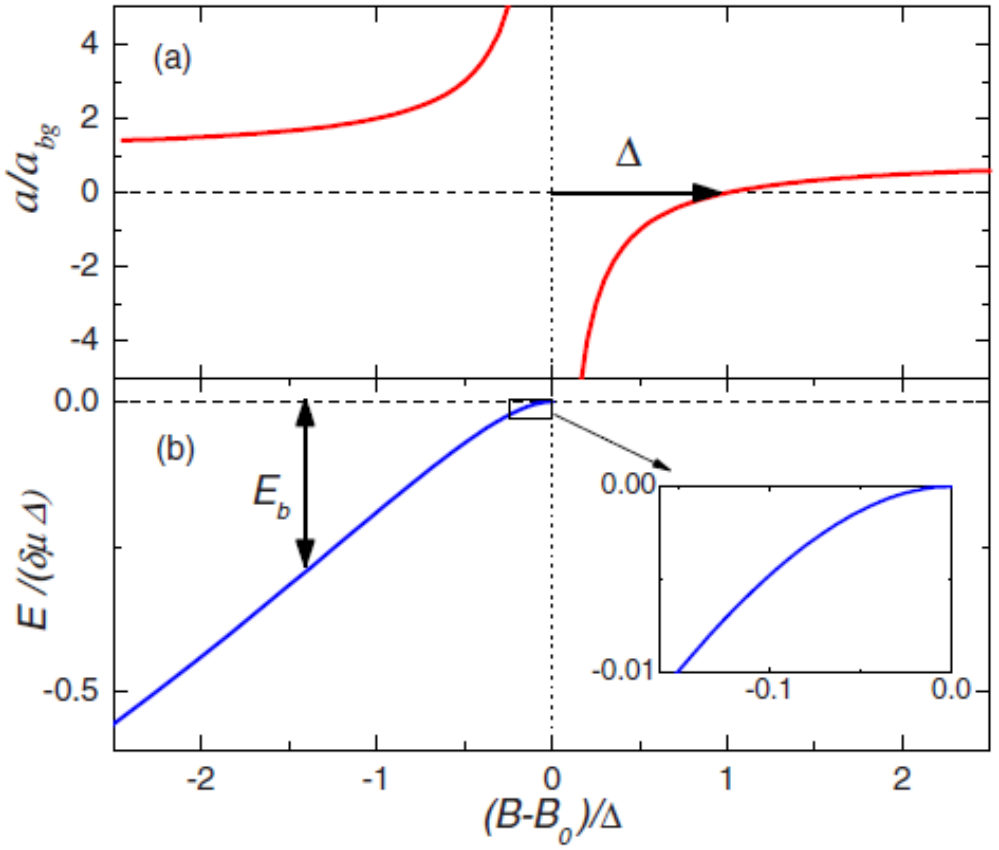
a_{bg}: background scattering length

Δ: width of resonance

B_0: position of the resonance

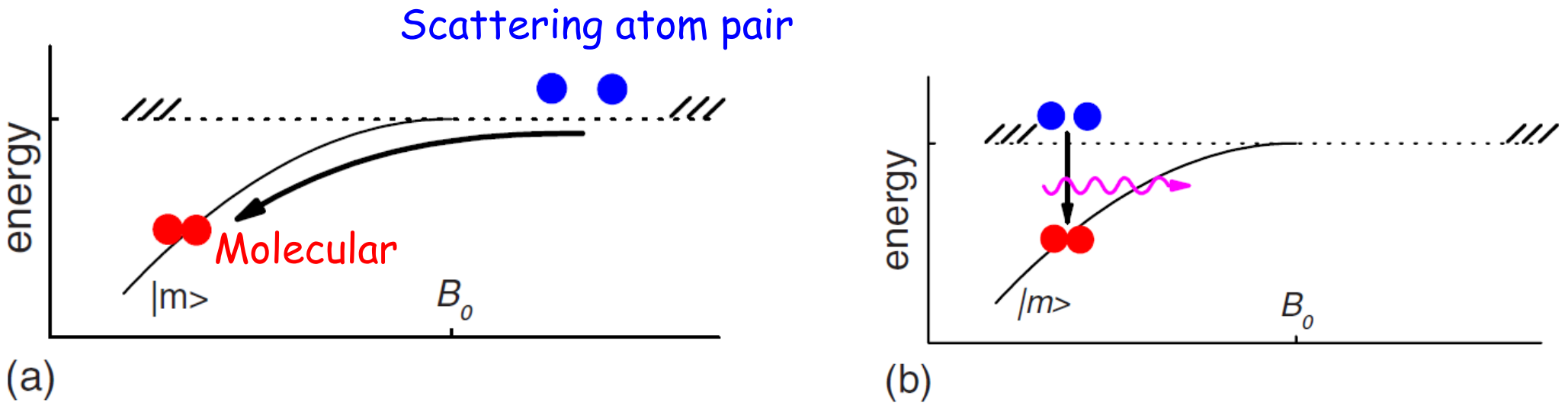
Ultra-cold Feshbach molecular

For large positive values of scattering length a, Feshbach molecular state exists, with binding energy $E_b = \hbar^2/(2\mu a^2)$, μ is the reduced mass



Chin, *et al.*, RMP 82, 1225 (2010)

Forming Feshbach molecule



Magnetic field is ramped across the resonance ➡ adiabatically convert interacting atom pairs into one molecule

Or radio frequency field drives the transition from scattering state to molecular state

Study ultra-cold chemistry with Feshbach molecules

Ultracold chemistry weakly bound molecules

Exothermic reactions with weakly bound molecules

Stwalley, Contemp. Phys. 19, 65 (1978); Can. J. chem. 82, 709 (2004)

☑ Novel reaction: Single reaction channel dominant

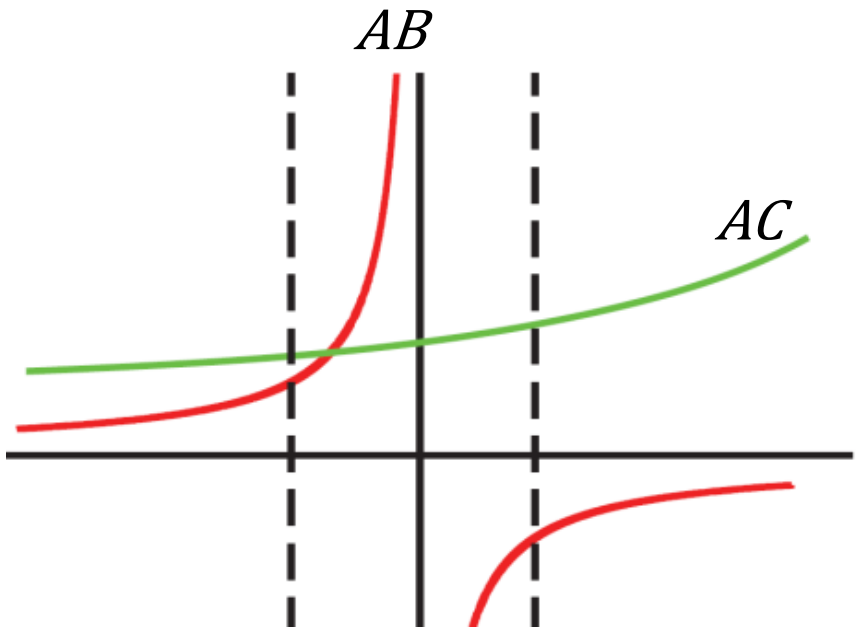
☒ Weakly bound molecules do not exist at high temperatures

☑ Ultracold chemistry with Feshbach molecules!

Reqiurement: weakly bound reactant and product molecules coexist ➡ Overlapping Feshbach resonances

D'Incao *et al.*, PRL 103, 083202 (2009)

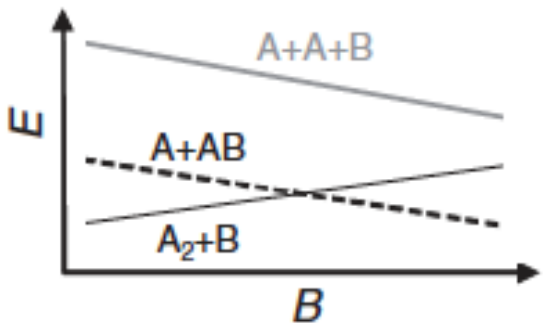
- Released energy small and tunable
- Reaction products can be trapped and observed
- State-to-state reaction dynamics

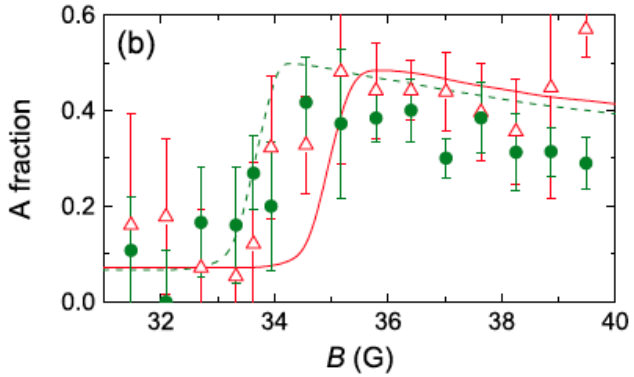


$$AB + C \rightarrow AC + B$$

Ultra-cold exothermic reaction with Feshbach molecules

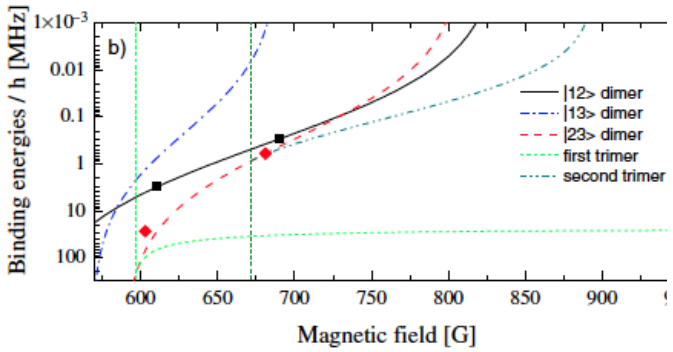
$A_2 + B \rightarrow AB + A$ (A, B are different internal states of Cs atom)

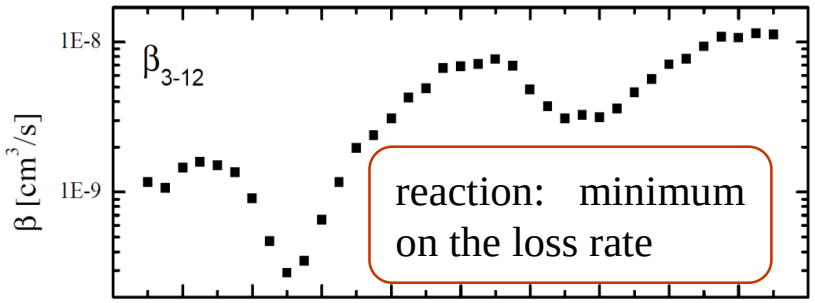




Lompe *et al.*, PRL105, 103201 (2010)

$|1,2\rangle + |3\rangle \rightarrow |2,3\rangle + |1\rangle$ (Li atom)





Knoop *et al.*, PRL 104, 053201 (2010)

☒ Only overall loss rate of molecule reactant is measured

State-to-state reaction dynamics remains challenging!

Na-K ultra-cold Bose-Fermi mixture

Our goal:

- Detect the atom and molecule products
- Demonstrate the selectivity of the reaction
- Study the state-to-state reaction dynamics

Overlapping Feshbach resonance of $^{23}Na^{40}K$ dimers (^{40}K: Fermion, ^{23}Na: Boson)

	B_0	ΔB
$^{23}Na\|1,1\rangle$+ $^{40}K\|9/2,-5/2\rangle$	96.5	0.5
	106.9	1.8
	138	**30**
$^{23}Na\|1,1\rangle$+ $^{40}K\|9/2,-3/2\rangle$	116.9	0.5
	129.5	**4.6**
	175	20

Mimicking reactions with internal states of atoms:

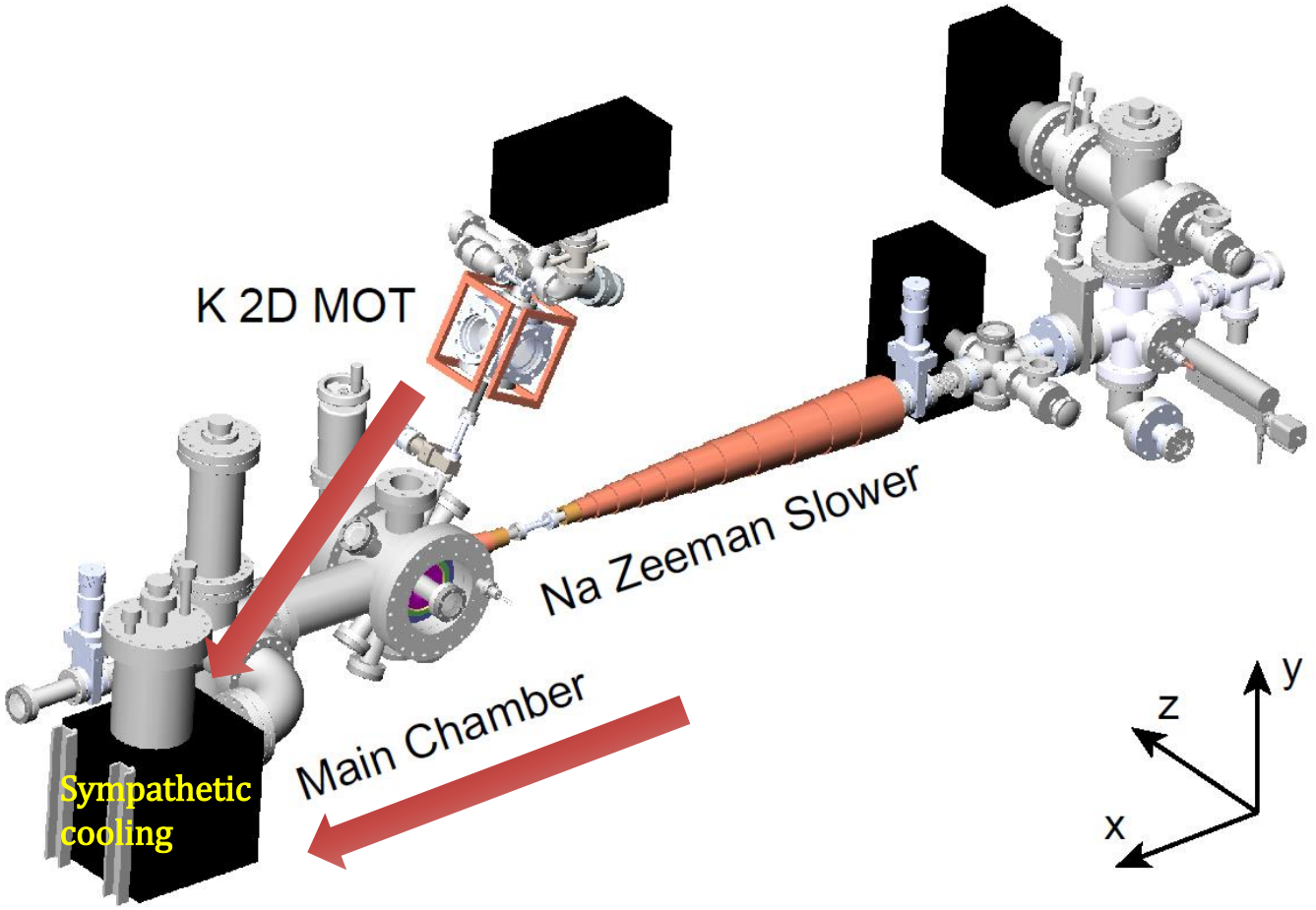
$$^{23}Na|1,1\rangle \rightarrow A$$
$$^{40}K|9/2,-5/2\rangle \rightarrow B$$
$$^{40}K|9/2,-3/2\rangle \rightarrow C$$

Reaction: $AB + C \rightarrow AC + B$

Park *et al.*, PRA 85, 051602 (2012)

Na-K ultracold Bose-Fermi mixture

Experimental setup



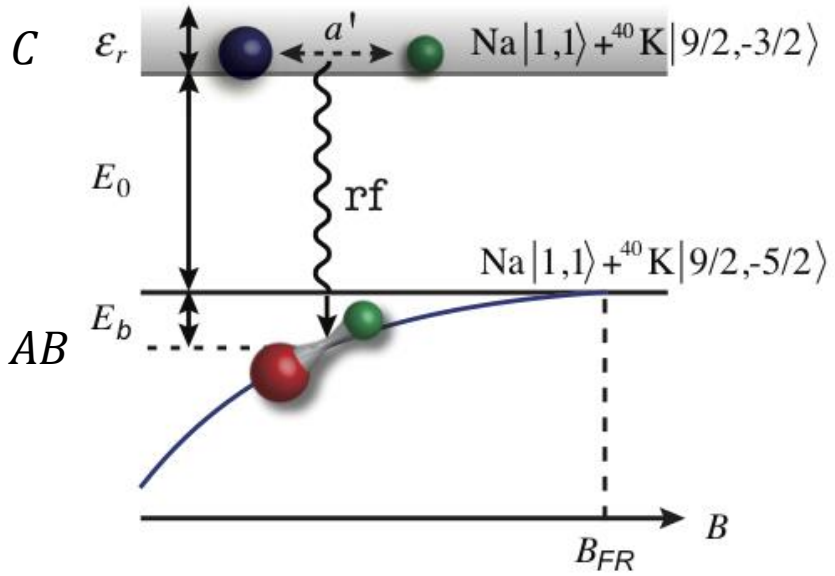
Initial state: ~3×10^5 ^{23}Na, ~1.6×10^5 ^{40}K @ 500-600 nK

Form Feshbach molecules

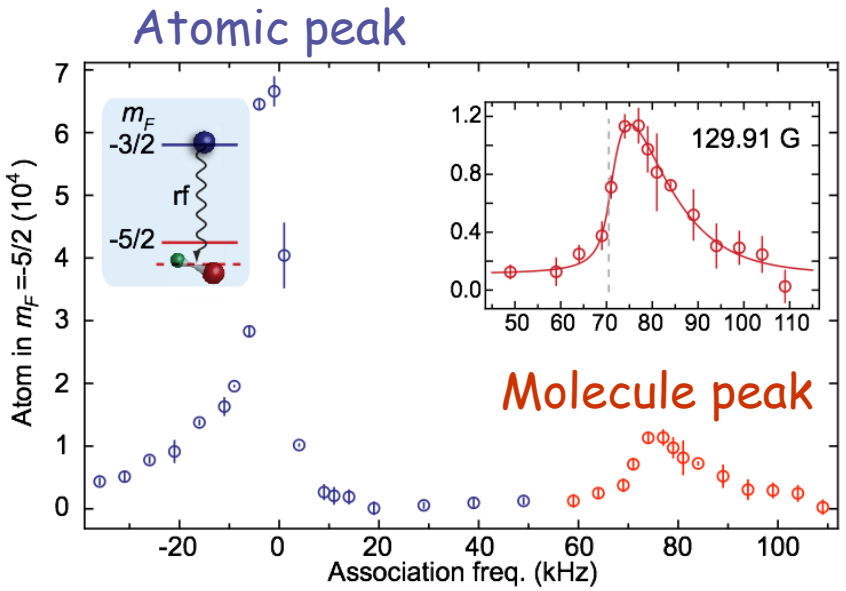
Preparing AB from A and C: $AB + C \rightarrow AC + B$ → Reaction product to be identified

If preparing AB from A and B: ☒ Low conversion efficiency ➡ residual B

Radio frequency association @ B~130 G, RF Rabi frequency ~ 20 kHz



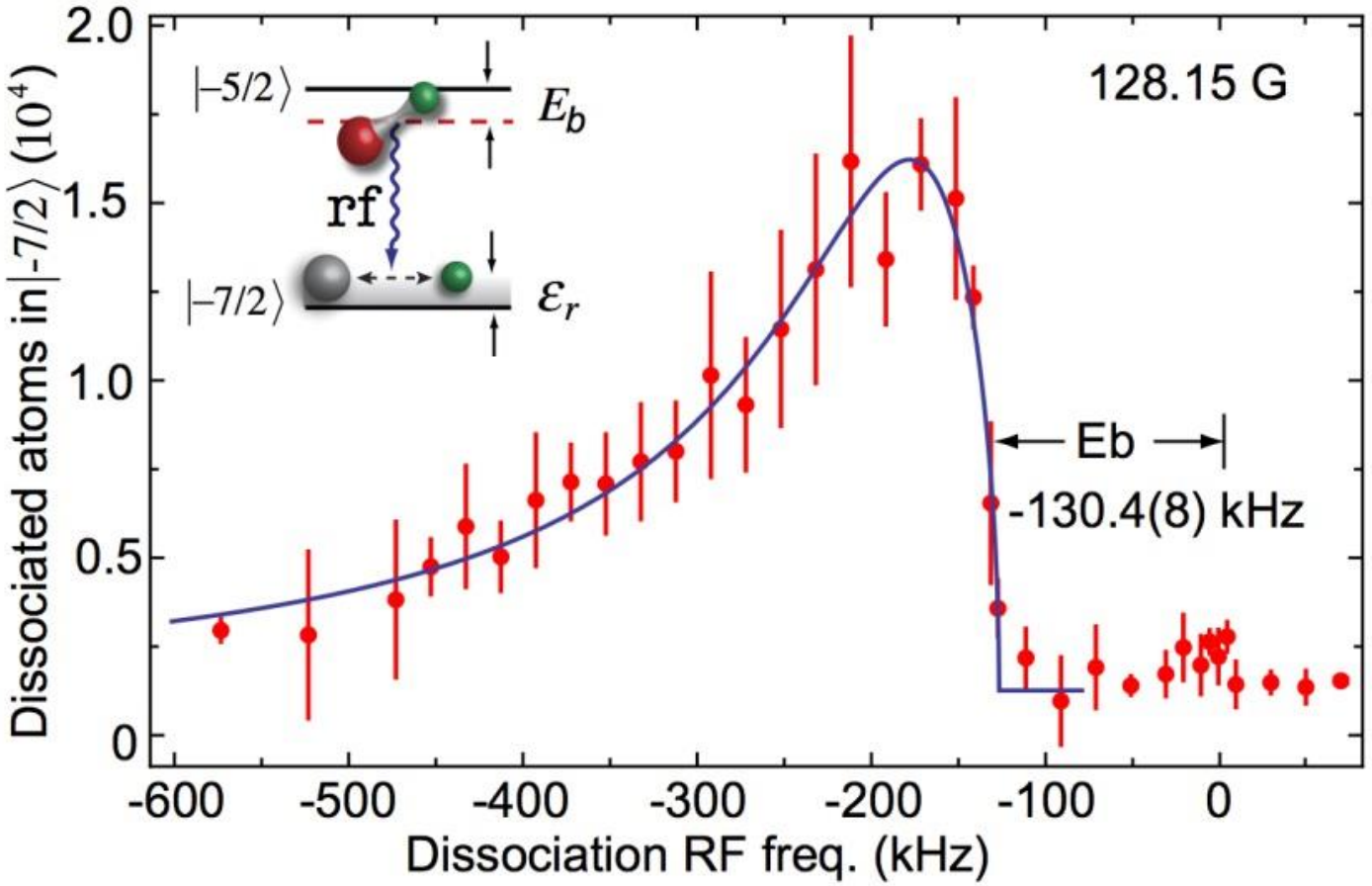
Chin *et al.*, PRA 71,012713 (2005)
Klempt *et al.*, PRA 78,061602 (2008)



Wu *et al.*, PRL 109, 085301 (2012)
Ulmanis *et al.*, NJP 17, 055009 (2015)

Characterizing Feshbach resonances

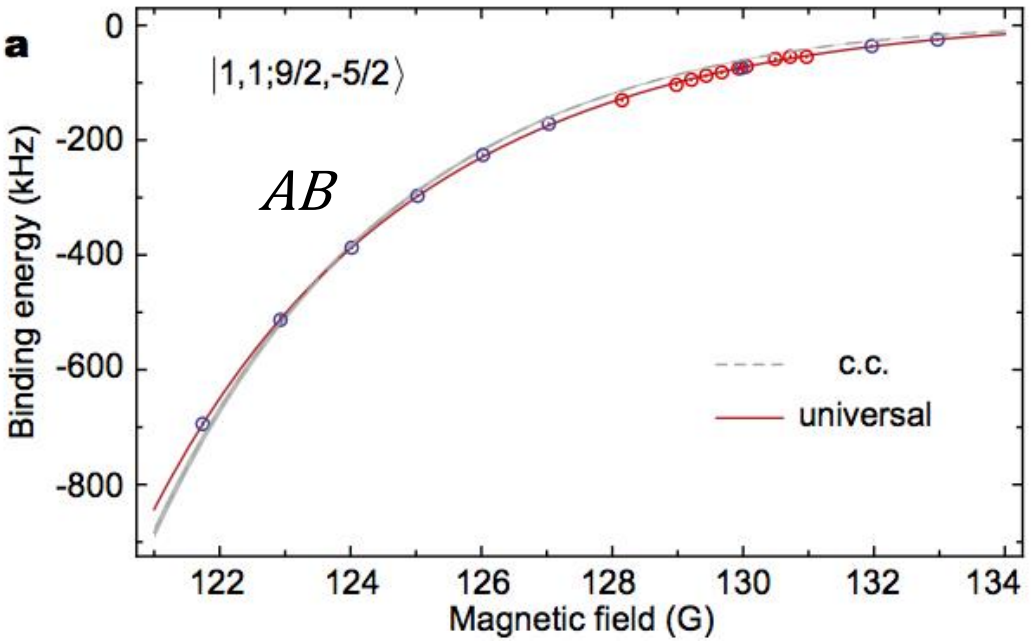
Measuring binding energy of the Feshbach molecules:
Dissociation to internal state ^{40}K|9/2,-7/2>



Characterizing Feshbach resonances

Binding energies of two Feshbach molecules

internal energy of $A+B$

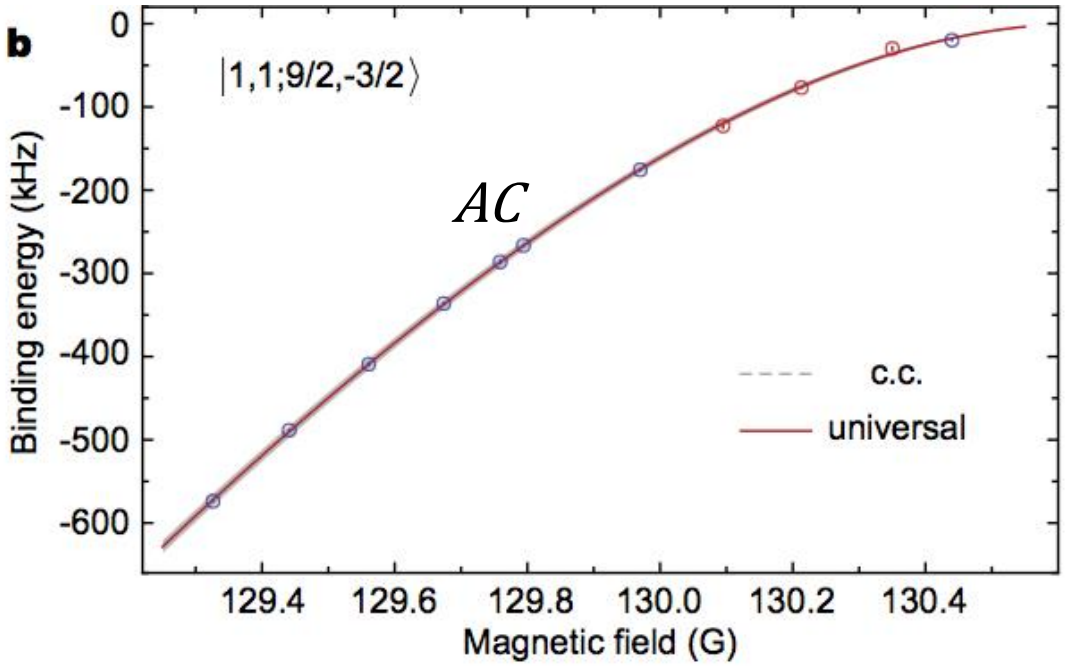


a_{bg} = - 455(18)a_0

B_0 = 138.71(20) G

DB = - 34.60(34) G

internal energy of $A+C$



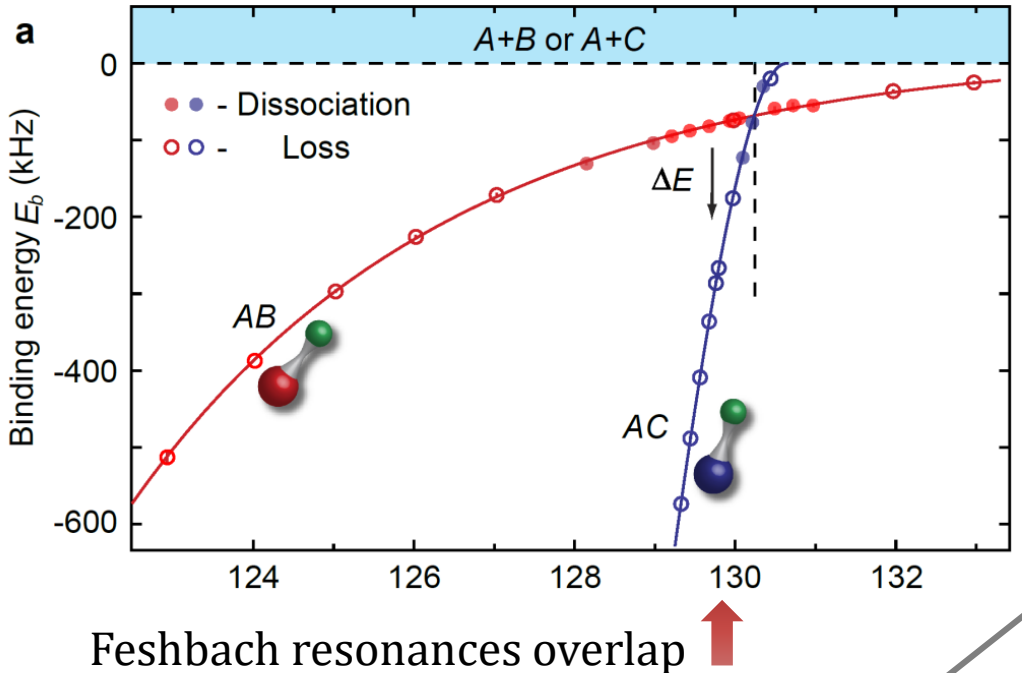
a_{bg} = 126(9)a_0

B_0 = 130.637(14) G

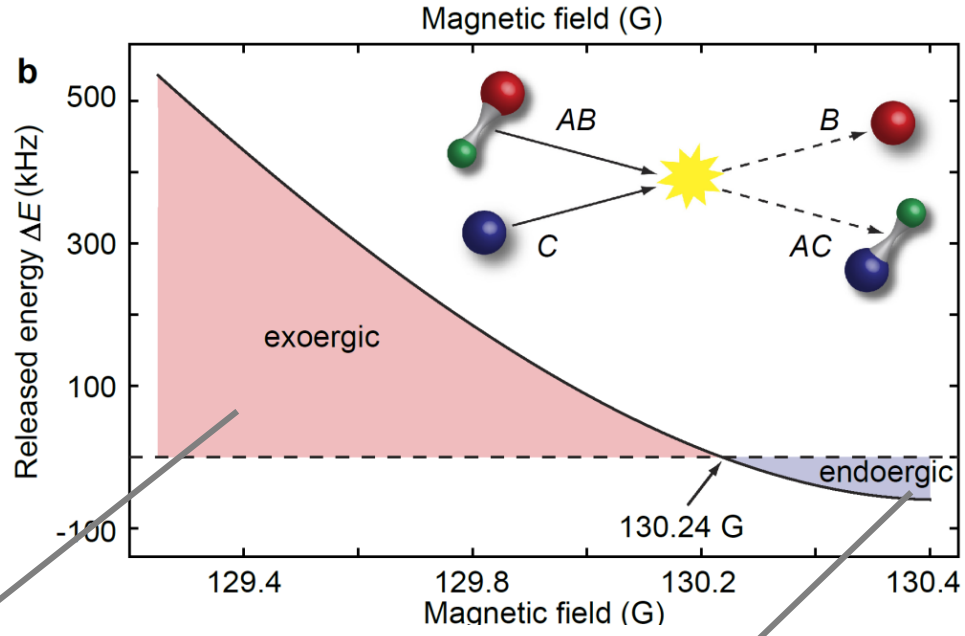
DB = 4.0(4) G

Overlapping Feshbach resonances

Binding energy and released energy in a reaction



Feshbach resonances overlap

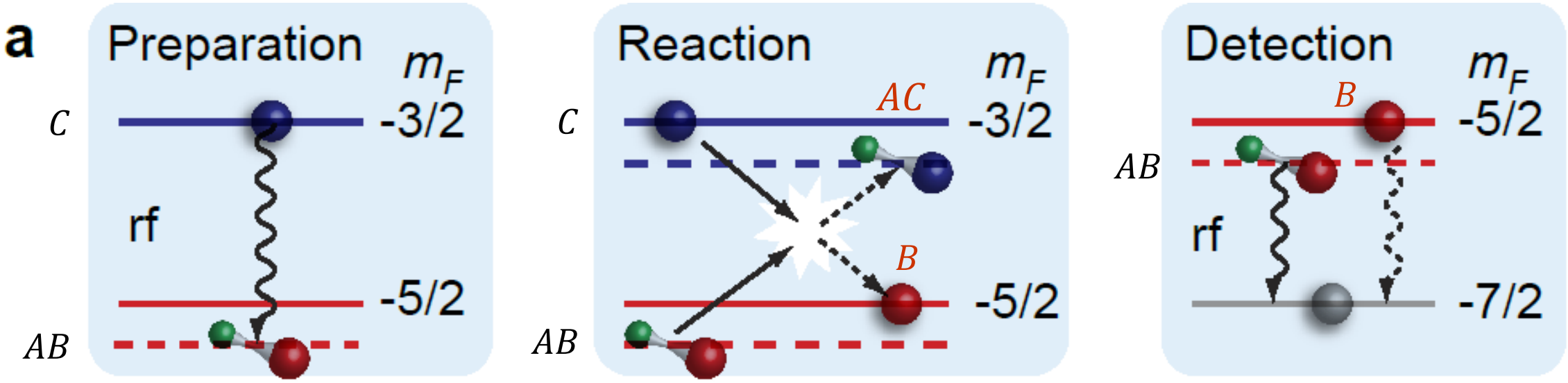


☑ Exothermic reaction magnetic field window 129.4-130.24 G

☒ Endothermic regime, for magnetic field larger than 130.24 G, reaction can be switched off

Observation of atom product B

Prepare the reactants and observe the products



rf association of AB from A and C

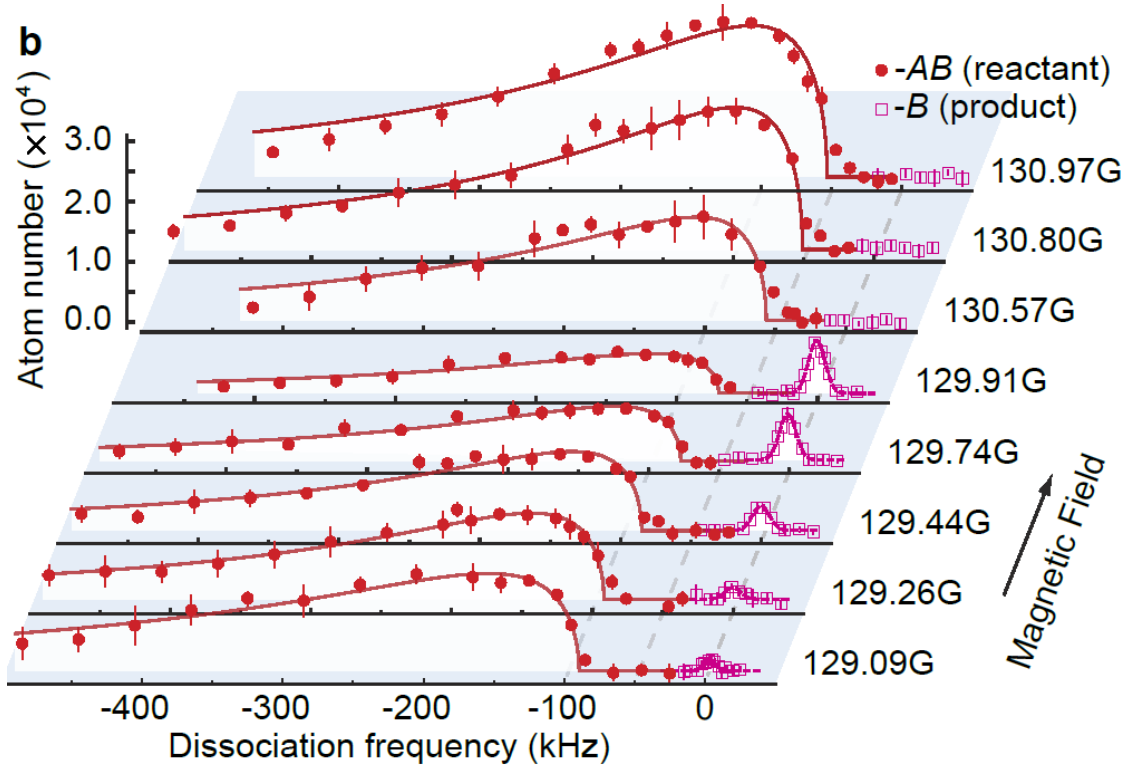
After a short hold time

$AB + C \rightarrow AC + B$

AB and B detection with dissociation to |9/2,-7/2>

Observation of atom product B

Prepare the reactants and observe the products

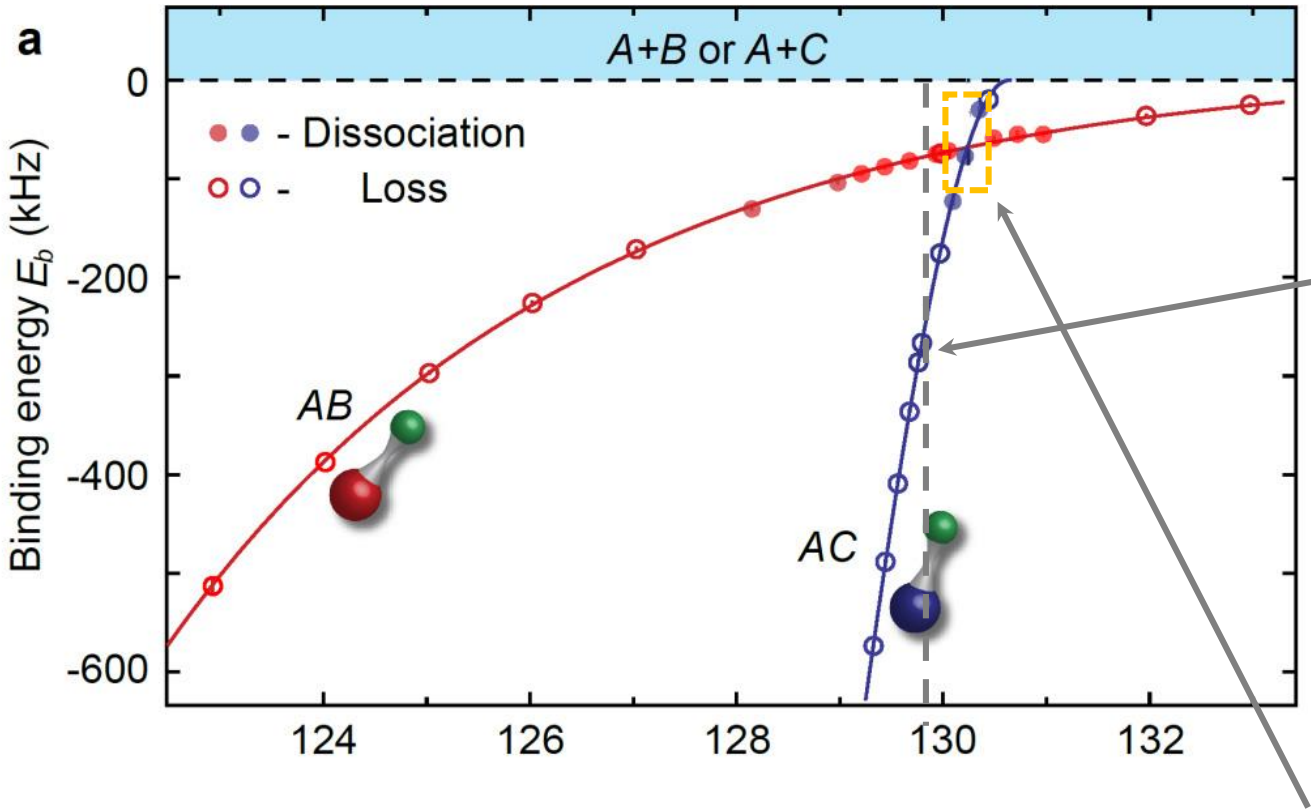


- ☑ B and AB signals are clearly separated in rf spectrum
- ☑ B atom appears in the desired magnetic window

Strong evidence but not smoking gun

- ☒ Breaking AB molecule due to unknown mechanism can also produce B atom
- ☑ Observe AC molecule product!

Observation of molecule product



Detecting AC molecule is difficult. Above experiment is performed at the region of B<129.9G ➡ large binding energy of AC, cannot be dissociated

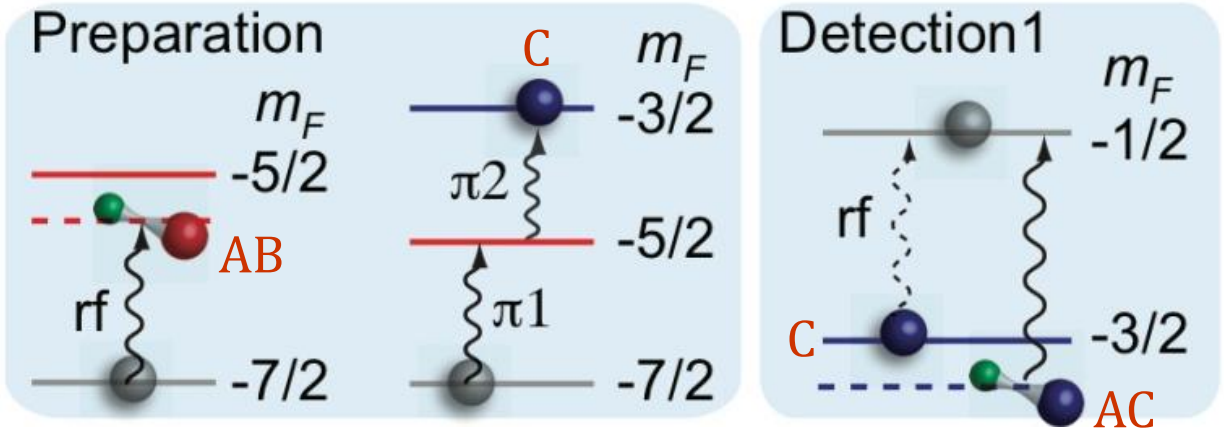
- But in small AC binding energy region, since its narrow magnetic field window, creation of AB molecule from A+C is suppressed: coexist two resonances, the creation efficiency of AB is $F_{\mathrm{bf}} \propto (1 - a_{\mathrm{AC}}/a_{\mathrm{AB}})^2, a_{\mathrm{AC(B)}}$ are scattering length

Chin *et al.*, PRA 71,012713 (2005)

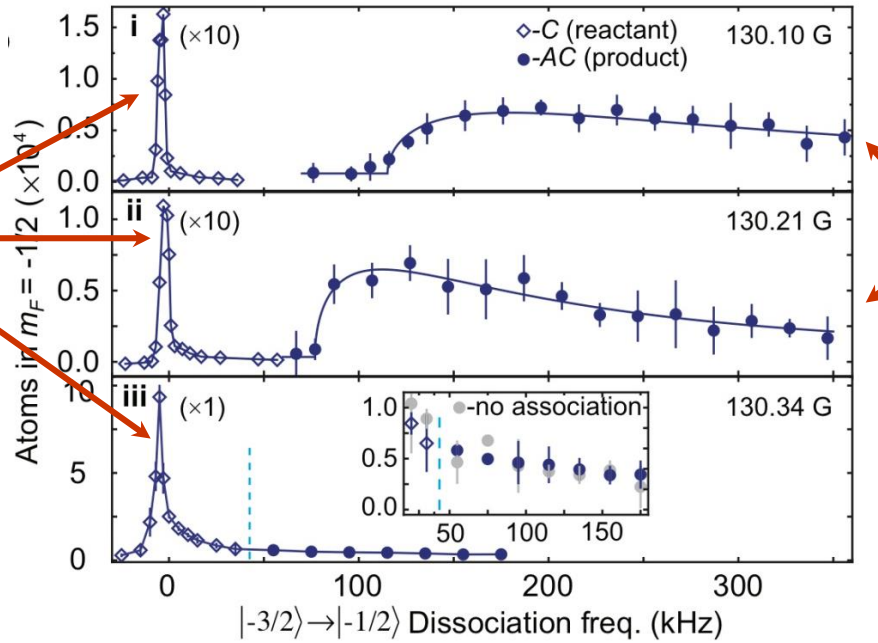
Observation of molecule product

Solution:

- Association AB from $A + |9/2, -7/2\rangle$
- Two π pulses to prepare C
- Dissociation AC into $A + |9/2, -1/2\rangle$
- $|9/2, -1/2\rangle$ initially unoccupied



Atomic peak of C



Molecule peak of AC

Observation of the molecule product: smoking gun!

State-to-state reaction dynamics

Reaction dynamics

$$\dot{N}_{AB} = -\gamma_{AB} N_{AB},$$
$$\dot{N}_{B} = \beta_r \bar{n}_C N_{AB},$$

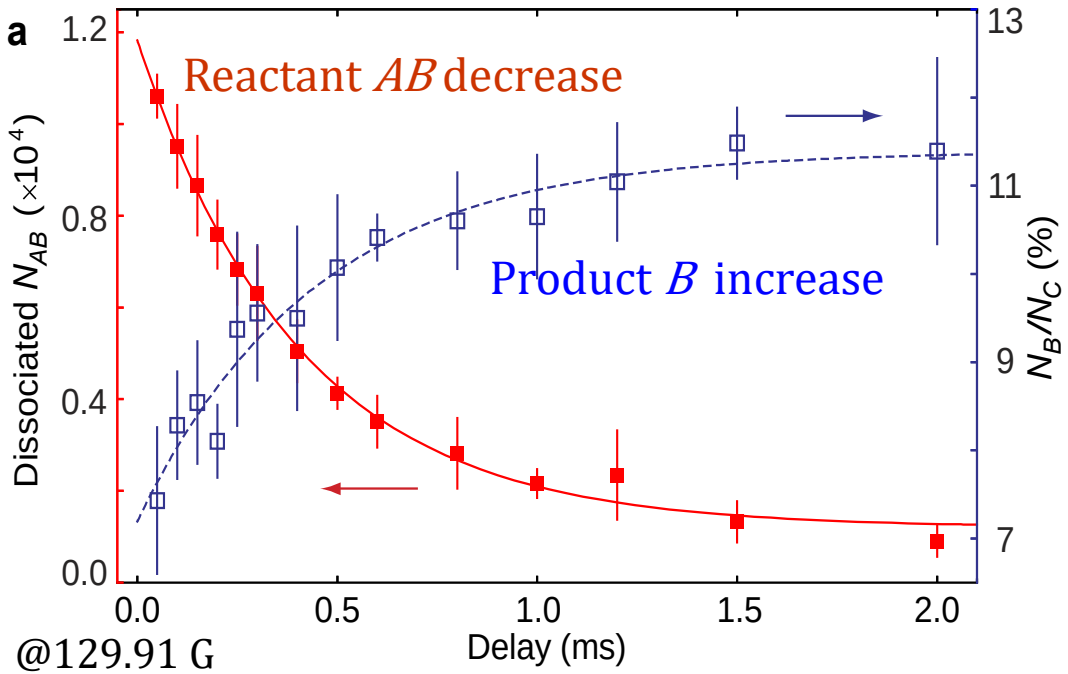
Solution

$$N_{AB}(t) = N_{AB}(0) e^{-\gamma_{AB} t},$$
$$N_B(t) = \frac{\beta_r \bar{n}_C N_{AB}(0)}{\gamma_{AB}} (1 - e^{-\gamma_{AB} t}) + N_B(0)$$

Reaction rate coefficient

$$\beta_r = \frac{\Delta N_B \gamma_{AB}}{\alpha N_C N_{AB}(0)}$$

with $\Delta N_B = N_B(\infty) - N_B(0)$ and $a = \left(\frac{m_K \bar{\omega}_K^2}{4\pi k_B T_K} \right)^{3/2}$



$N_{(.)}$: number of atom or molecule

$\bar{n}_C$: average density of C atom

γ_{AB}: decay rate of AB molecule

$\bar{\omega}_K$: average trap frequencies of K atom

☑ Obtain the reaction rate coefficient in the exothermic regime

Rui *et al.*, Nature Physics 13, 699 (2017)

Physical chemistry

Manipulation of ultra-cold molecules

New frontier of physical chemistry!

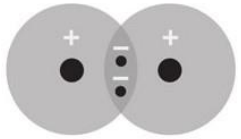
- Physical chemistry: study the molecule collisions at the quantum level
- Major problems:
  - Potential energy surface (PES): solve the multi-electron Schrödinger equation for fixed nuclei configuration
  - Collision or reaction dynamics: simulate the dynamics of the nuclei under the PES

However, solving multi-electron Schrödinger equation to obtain PES is extremely difficult!

a few nuclei + many electrons + coulombic interaction

$$H = \sum_{\alpha} \frac{p_\alpha^2}{2m_n} + \sum_{i} \frac{p_i^2}{2m_e} + \sum_{\alpha,\beta} \frac{Z_\alpha Z_\beta}{|R_\alpha - R_\beta|} + \sum_{i,j} \frac{e^2}{|r_i - r_j|} - \sum_{\alpha,i} \frac{Z_\alpha e}{|R_\alpha - r_i|}$$

H atom
- Exactly solvable



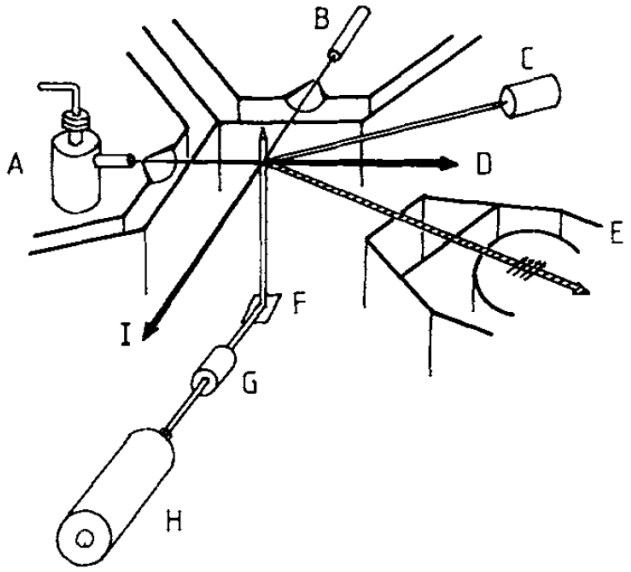
H_2 molecule
- Born–Oppenheimer potential
- Two-nuclei problem

.....

$H+H_2$ collision
- Potential energy surface
- Three-nuclei dynamics

Molecule collisions

Conventional way: obtaining information of PES by experiments



Molecule beam scattering: state-to-state collision dynamics

D. Herschbach and Y. T. Lee, Nobel Prize in Chemistry (1986)

- Prepare the collision particles in a vibrational and rotational state
- Detecting the collision products resolving the vibrational and rotational state, angular distribution

☒ Quantum phenomenon is difficult to observe in molecule collisions (conventional collisions @ a few hundred Kelvin)

- Average of many partial waves
- Average of many internal states
- Short de Broglie wave length

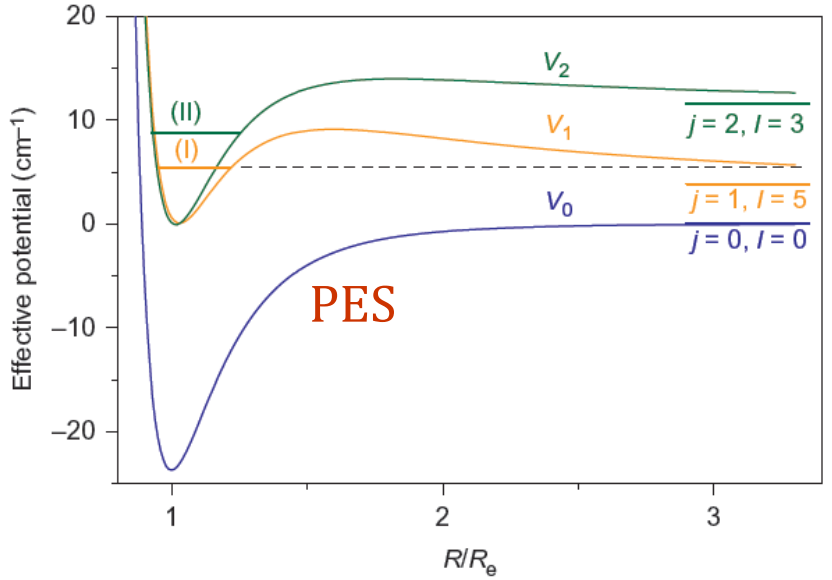
Cold collisions

Cold collisions @ a few Kelvin or sub Kelvin

- ☑ Suppression of high partial waves
- ☑ Initial states easily prepared
- ☑ Long de Broglie wave length

Scattering resonance is remarkable quantum phenomenon

- Collision energy coincides with a bound state (Feshbach or shape resonances)
- Extremely sensitive to the details of PES ➡ Direct probe of PES!



Yuan Tseh Lee, Molecular Beam studies of elementary chemical process (Nobel Lecture), Angew. Chem. 26, 939 (1987)

Cold collisions

Collisional resonances with cold molecule beams

Atom-molecule reaction

- $F/Cl+H_2/HD/D_2$ reaction

Skodje *et al.*, PRL 85, 1206 (2000)
Qiu, *et al.*, Science 311, 1440 (2006)
Dong *et al.*, Science 327, 1501 (2010)
Wang *et al.*, Science 342, 1499 (2013)
Yang *et al.*, Science 347, 60 (2015)

- $He+H_2$ ionization

Henson, *et al.*, Science 338, 234 (2012)
Lavert-Ofir, *et al.*, Nat. Chem. 6, 332 (2014)
Klein *et al.*, Nat. Phys. 13, 35 (2017)

Atom-molecule inelastic collision

- He+NO/CO

Vogels *et al.*, Science 350, 787 (2015)
Bergeat *et al.*, Nat. Chem. 7, 349 (2015)

Molecule-molecule inelastic collision

- O_2+H_2

Chefdeville *et al.*, Science 341, 1094 (2013)

- $HD+D_2$

Perreault *et al.*, Science 358, 356 (2017)

- $NO+H_2$

Vogels *et al.*, Nat. Chem. 10, 435 (2018)

These questions can be effectively solved with numerical calculations

Ultra-cold collision

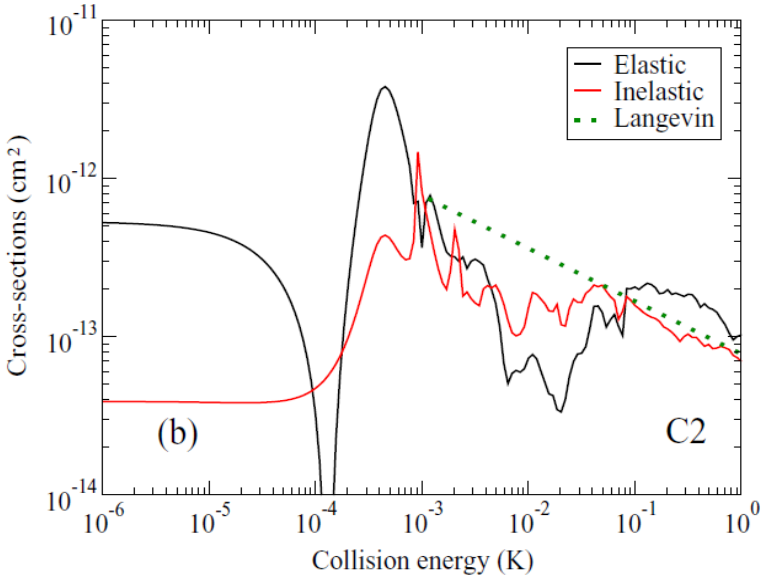
Collision at nearly absolutely zero temperatures

☑ Single partial wave
☑ Single quantum state
☑ Long de Broglie wavelength
☑ Highly quantum mechanical

Scattering resonance is a rule rather than an exception @ ~ 0 K

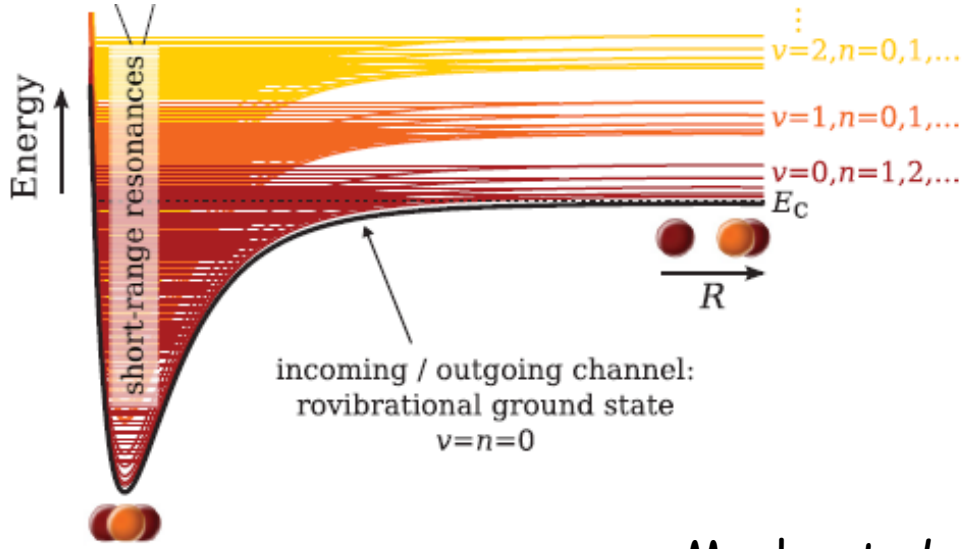
Collisions involving light particles (Rb+OH, N+NH, Mg+NH, O_2+O_2 ...)

- Computation possible
- Many predictions
- Lack of experimental demonstrations



Ultra-cold collision

Collisions involving alkali-metal (heavy molecules) diatomic molecules



Mayle *et al.*, PRA 85 062712 (2012)

Computation extremely difficult

- Heavy molecules
- Deep potential energy surface
- Many closed channels
- Highly resonant
- Many nuclear spin and electron spin degrees of freedom

Ultra-cold collision

Collisions involving alkali-metal (heavy molecules) diatomic molecules

Created alkali-metal diatomic molecules

- RbK, JILA (2008)
- RbCs, Innsbruck, Durham
- NaRb, HongKong
- LiNa, MIT
- NaK, MIT, MPQ

Possible atom-molecule collisions

$Na + LiNa$	$Rb + NaRb$
$K + LiK$	$Cs + NaCs$
$Rb + LiRb$	$Rb + KRb$
$Cs + LiCs$	$Cs + KCs$
$K + NaK$	$Cs + RbCs$

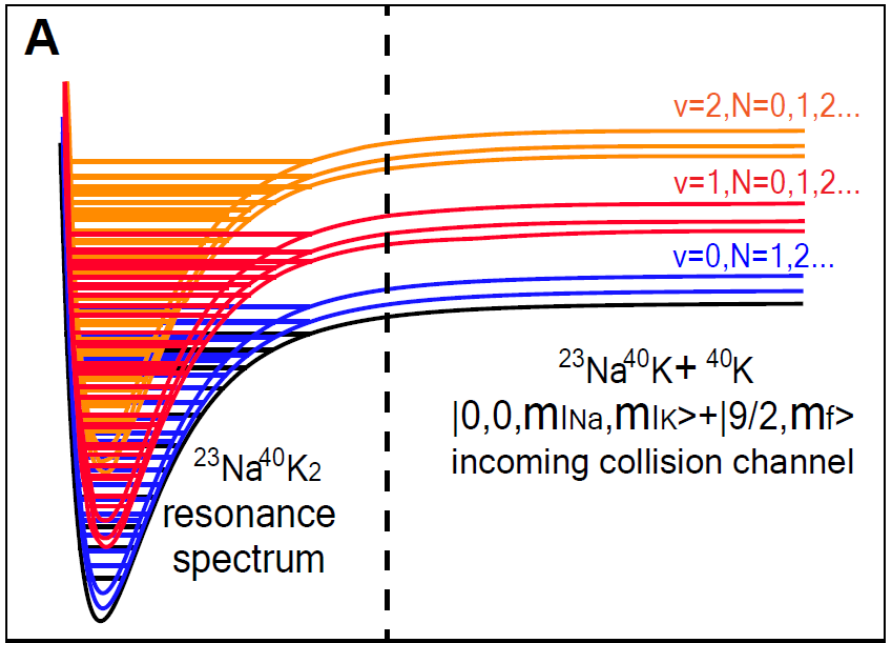
We are interested in the collision between NaK molecules and K atoms

Ultra-cold molecule

$^{23}Na^{40}K+^{40}K$ ultra-cold collision

- Deep PES ~ 1900 cm^{-1}
- Statistical model estimates ~ 1 resonance per G

	D_e (cm^{-1})	C_6 (a.u.)	ρ_{rv} (mK^{-1})	E_{vdW} (mK)	ρ_{rv} (units of E_{vdW}^{-1})
K + NaK	1851	6297	1.22	0.150	0.18



"For s-wave resonances… measurements of two-body loss versus field for molecules in their first excited state would supply a reasonable observable"

Mayle, *et al.*, PRA 85 062712 (2012)

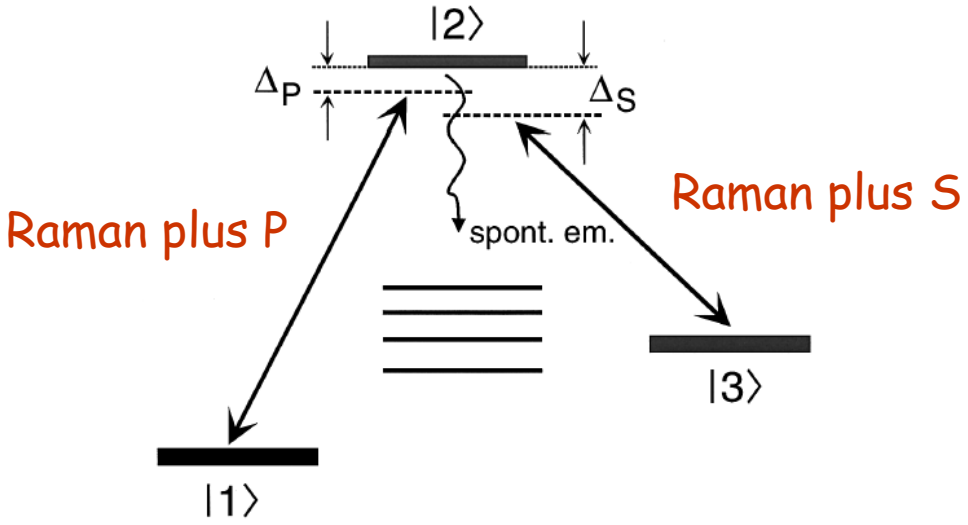
Scattering resonance → Scattering section → Enhanced losses

Signal: detect resonantly enhanced losses by varying the magnetic field

Transfer Feshbach molecule to rovibrational state

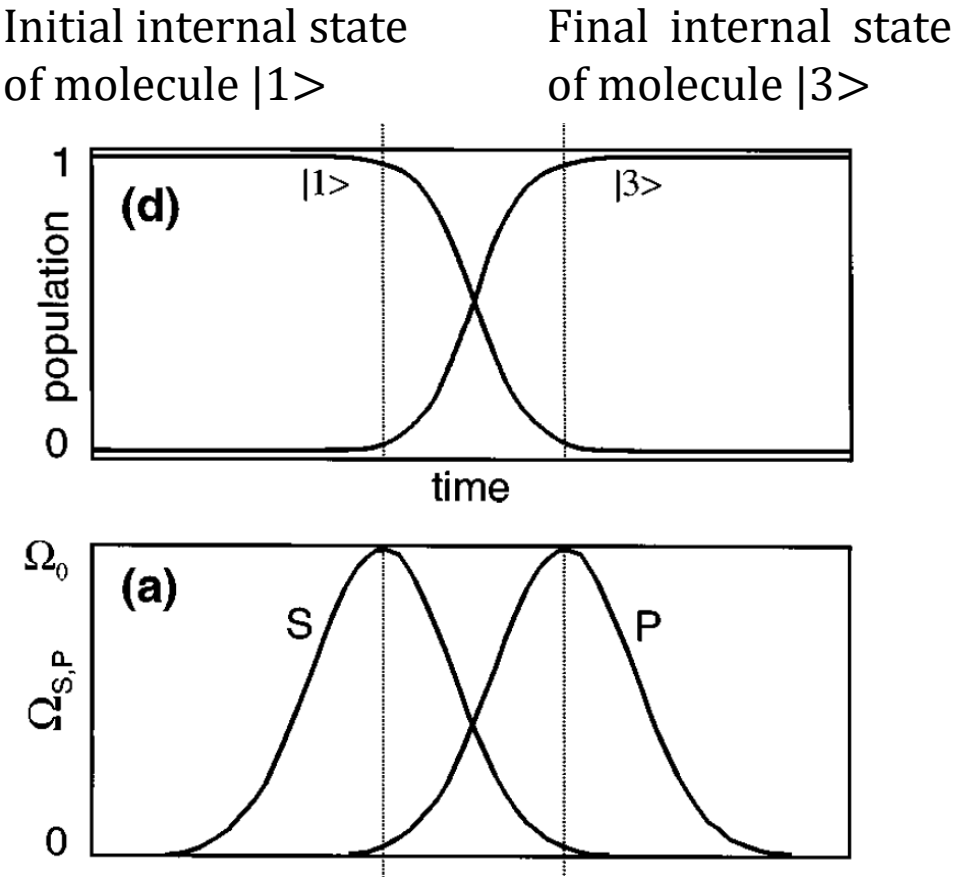
Feshbach molecules are weakly bound molecules, but not conventional molecules in rovibrational state ➡

Transformed to rovibrational state with Stimulated Raman adiabatic passage (STIRAP)



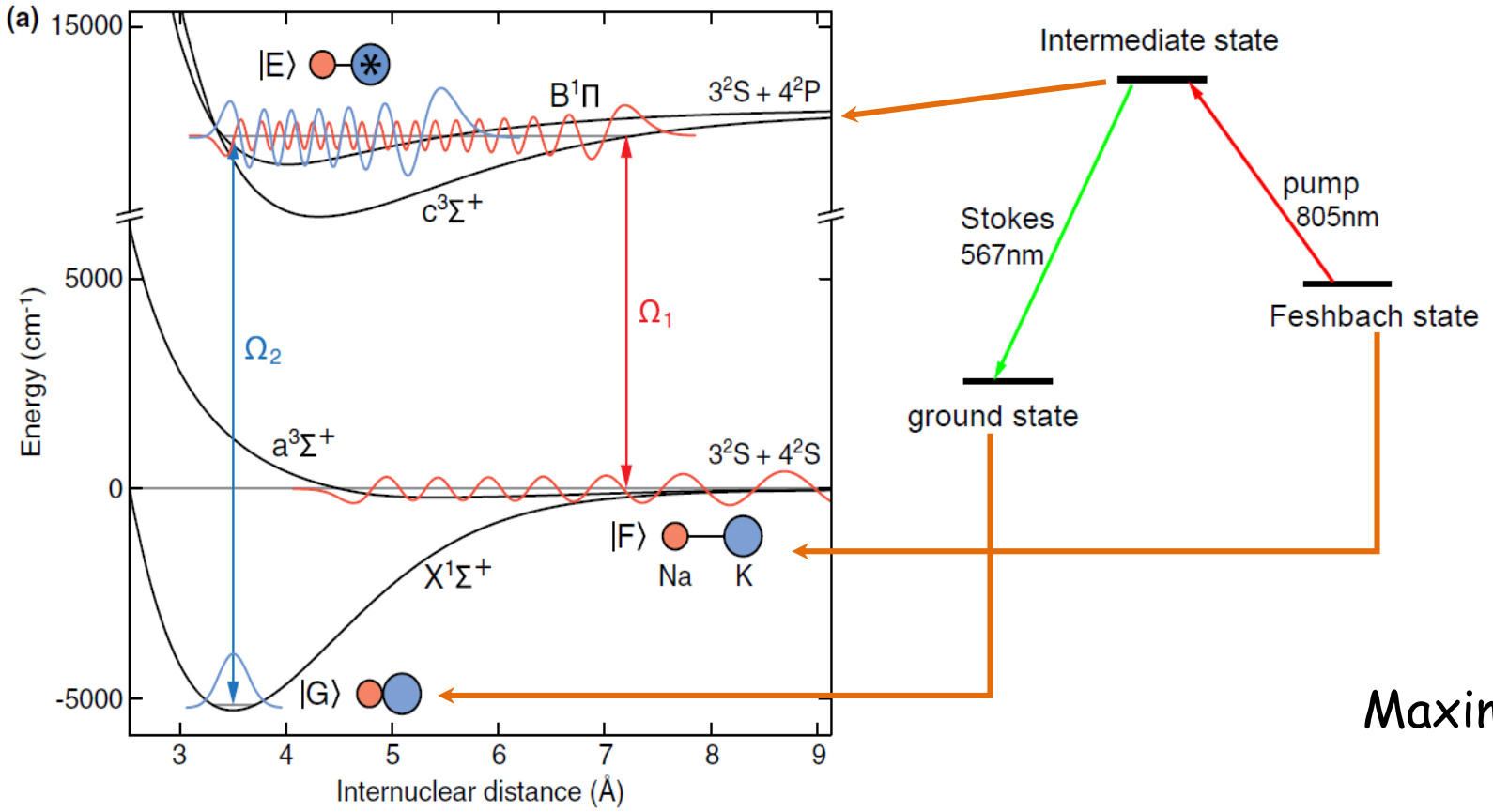
Dark state $|a^0\rangle = \cos\Theta|1\rangle - \sin\Theta\,|3\rangle$

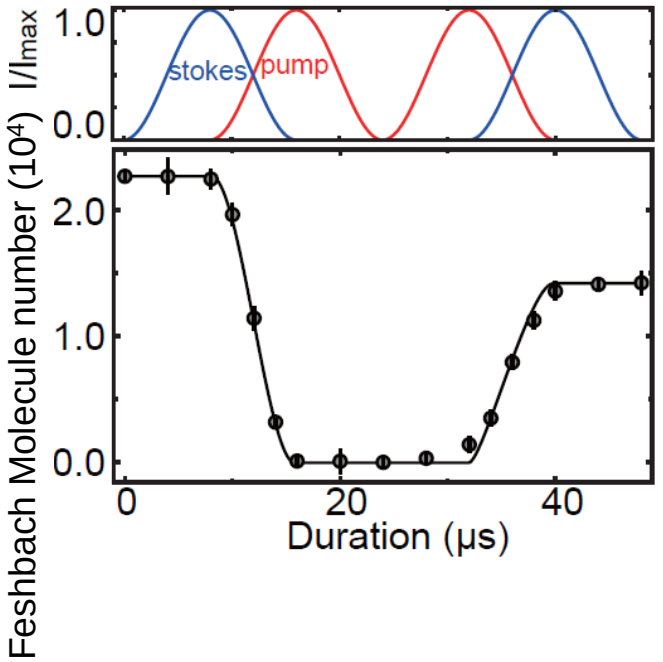
$$\tan\Theta = \frac{\Omega_P(t)}{\Omega_S(t)}$$



Stimulated Raman adiabatic passage

Transfer Nak Feshbach state to rovibrational state



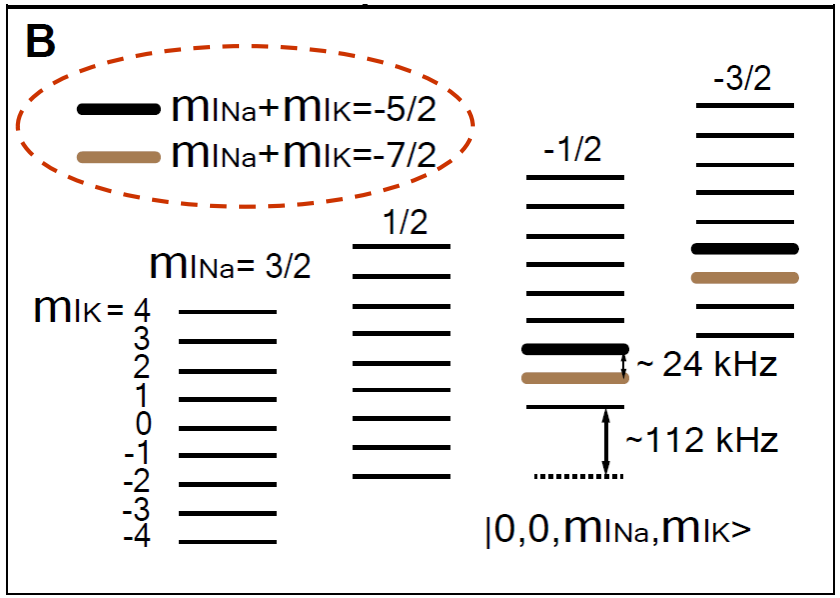


Maximum one-way efficiency ~78%

Park *et al.*, PRL 114, 250302 (2015)

Hyperfine levels

Energy levels of ground state NaK



4 hyperfine levels of the rovibrational ground sate are selected

hyperfine ground state
$\|0,0,-1/2,-2\rangle$
$\|0,0,-1/2,-3\rangle$
$\|0,0,-3/2,-1\rangle$
$\|0,0,-3/2,-2\rangle$

Rotation

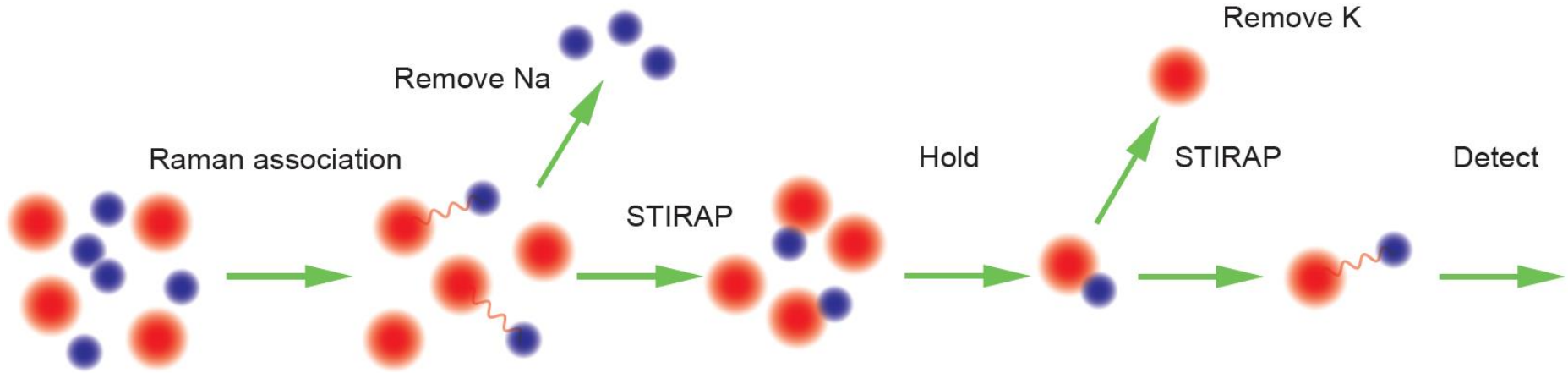
Vibration

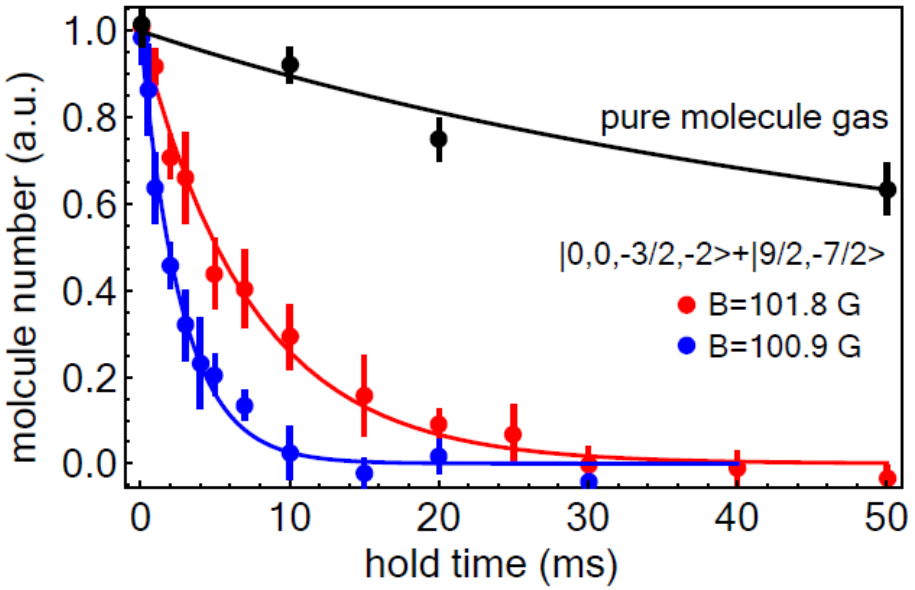
Nuclear spin of Na

Nuclear spin of K

Observation of enhanced loss

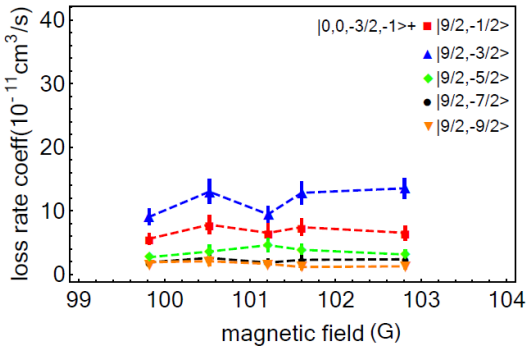
At fixed magnetic field ~100G, close to atomic Feshbach resonance

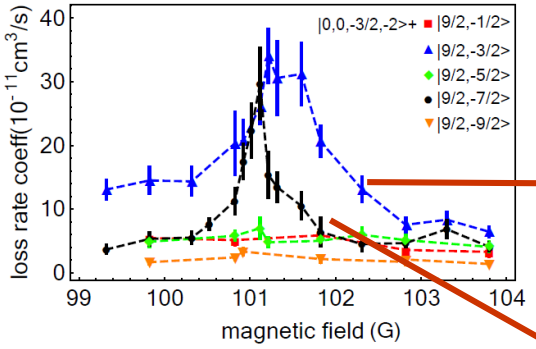


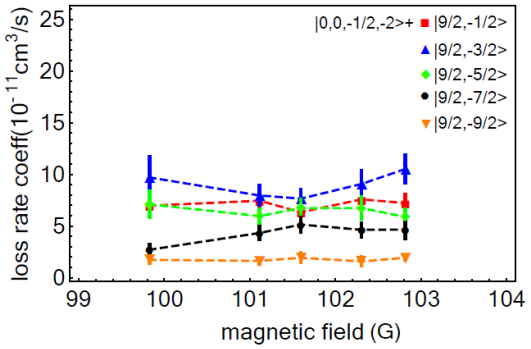


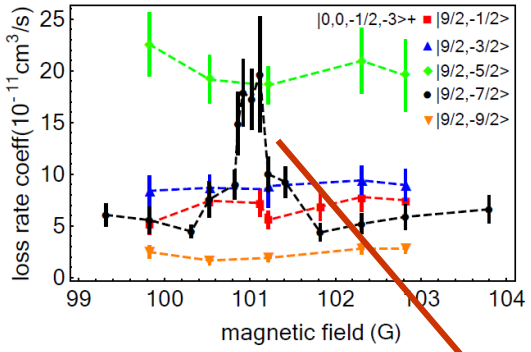
- 20 spin states combinations: ^{40}K in |9/2,-9/2>…|9/2,-1/2> and 4 hyperfine levels of NaK molecule
- Measure molecule loss
- Extract loss rate coefficient

Observation of enhanced loss

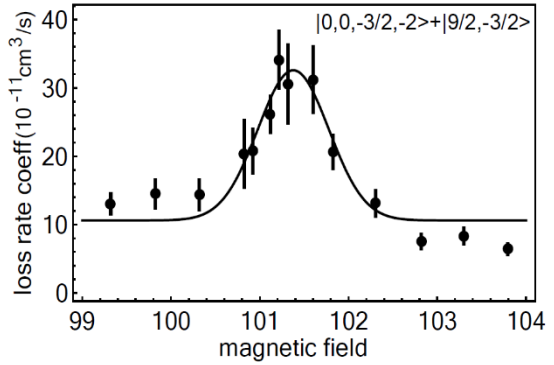




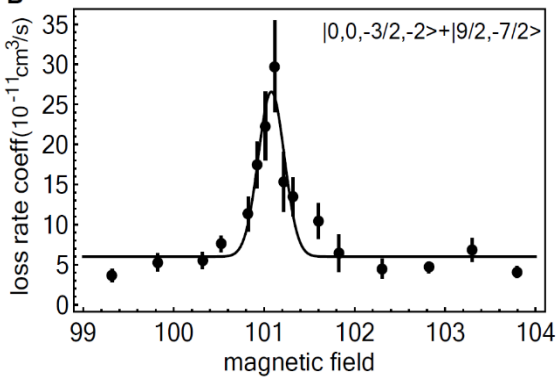




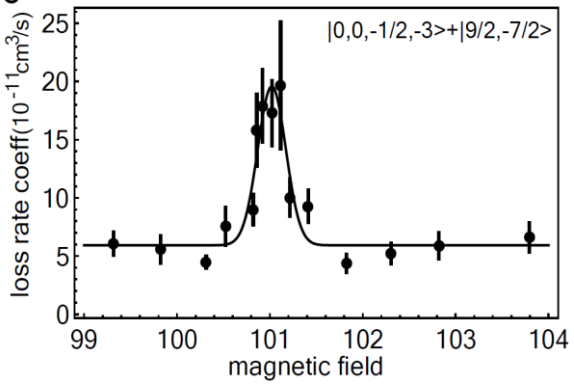
A



B



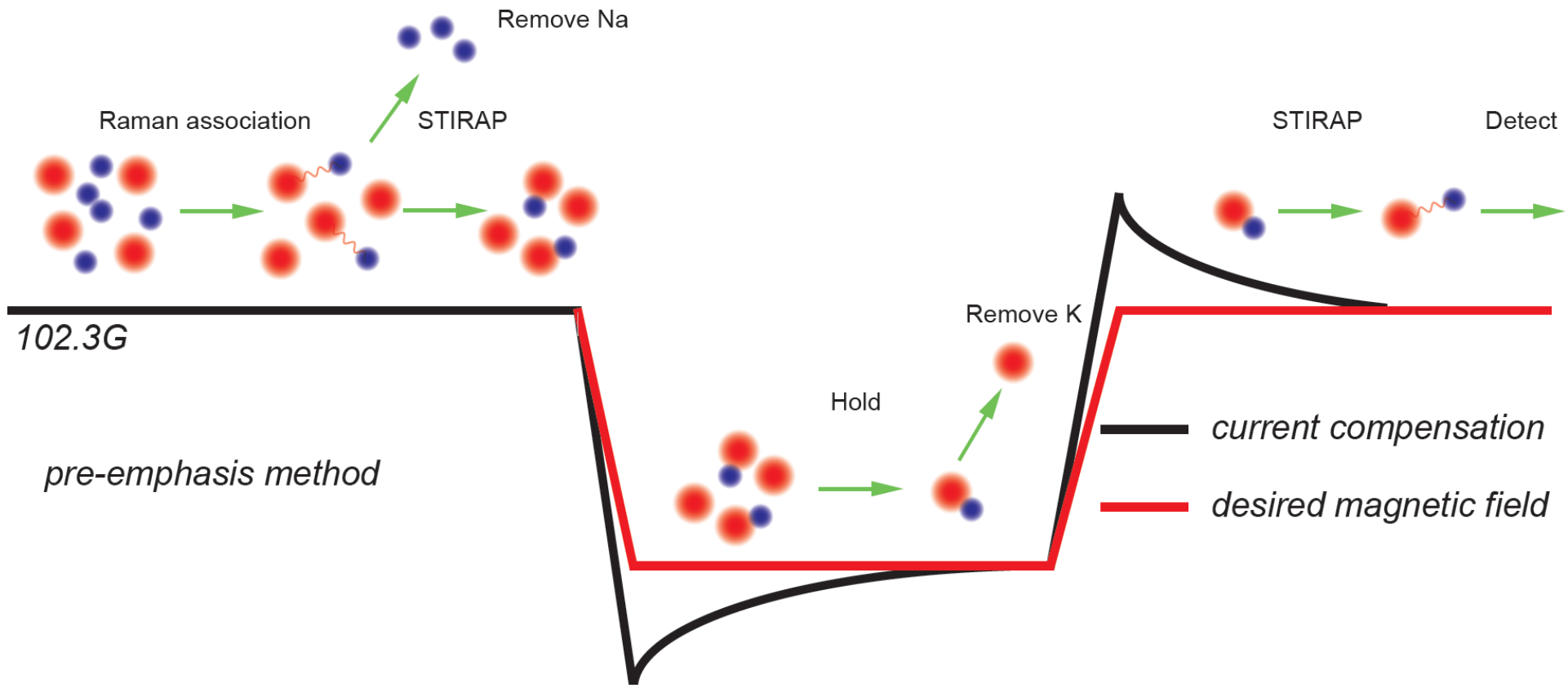
C



incoming collision channel	B_0 (G)	ΔB (G)
$\|0,0,-3/2,-2\rangle + \|9/2,-3/2\rangle$	101.4	0.6
$\|0,0,-3/2,-2\rangle + \|9/2,-7/2\rangle$	101.1	0.2
$\|0,0,-1/2,-3\rangle + \|9/2,-7/2\rangle$	101.0	0.2

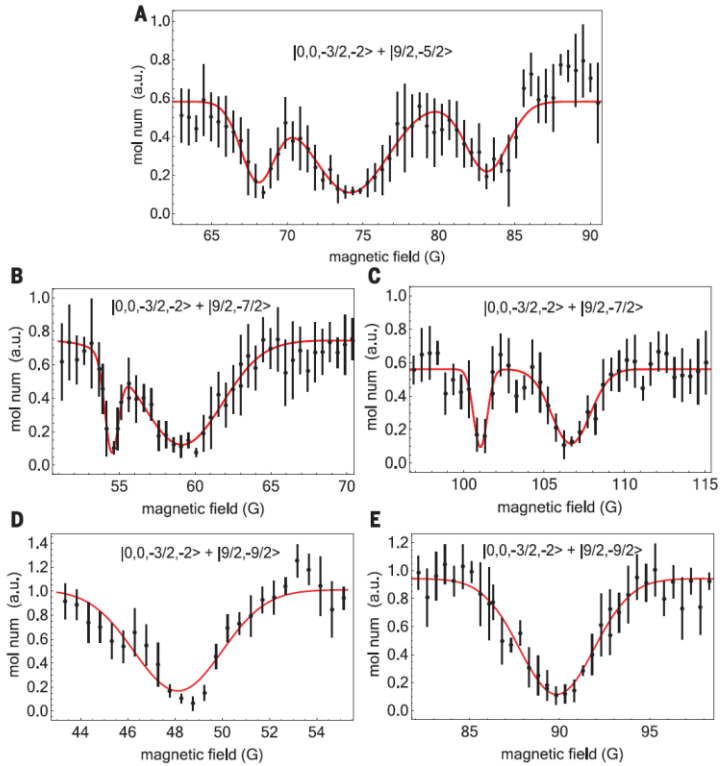
3 loss features are observed

Sweep the magnetic field



- Residual magnetic field induced by eddy current
- Compensate the residual magnetic field by programing the current of the magnetic coil

Loss features



method	collision channel	B_0 (G)	ΔB (G)
I	$\|0,0,-3/2,-2\rangle$ $\|9/2,-3/2\rangle$	101.4	0.6
	$\|0,0,-3/2,-2\rangle$ $\|9/2,-7/2\rangle$	**101.1***	0.2
	$\|0,0,-1/2,-3\rangle$ $\|9/2,-7/2\rangle$	101.0	0.2
II	$\|0,0,-3/2,-2\rangle$ $\|9/2,-5/2\rangle$	68.0	1.6
		74.2	3.5
		83.2	2.0
	$\|0,0,-3/2,-2\rangle$ $\|9/2,-7/2\rangle$	54.5	0.6
		59.1	3.7
		101.0*	0.6
		106.7	1.7
	$\|0,0,-3/2,-2\rangle$ $\|9/2,-9/2\rangle$	48.1	2.6
		89.8	2.9

- 8 new loss features are observed in the range 43-120 G, in total 11 atom-molecule Feshbach resonances in $^{23}Na^{40}K+^{40}K$ ultra-cold collisions
- Probe the K-Na-K PES (49 electrons +3 nuclei) with exceptional resolution

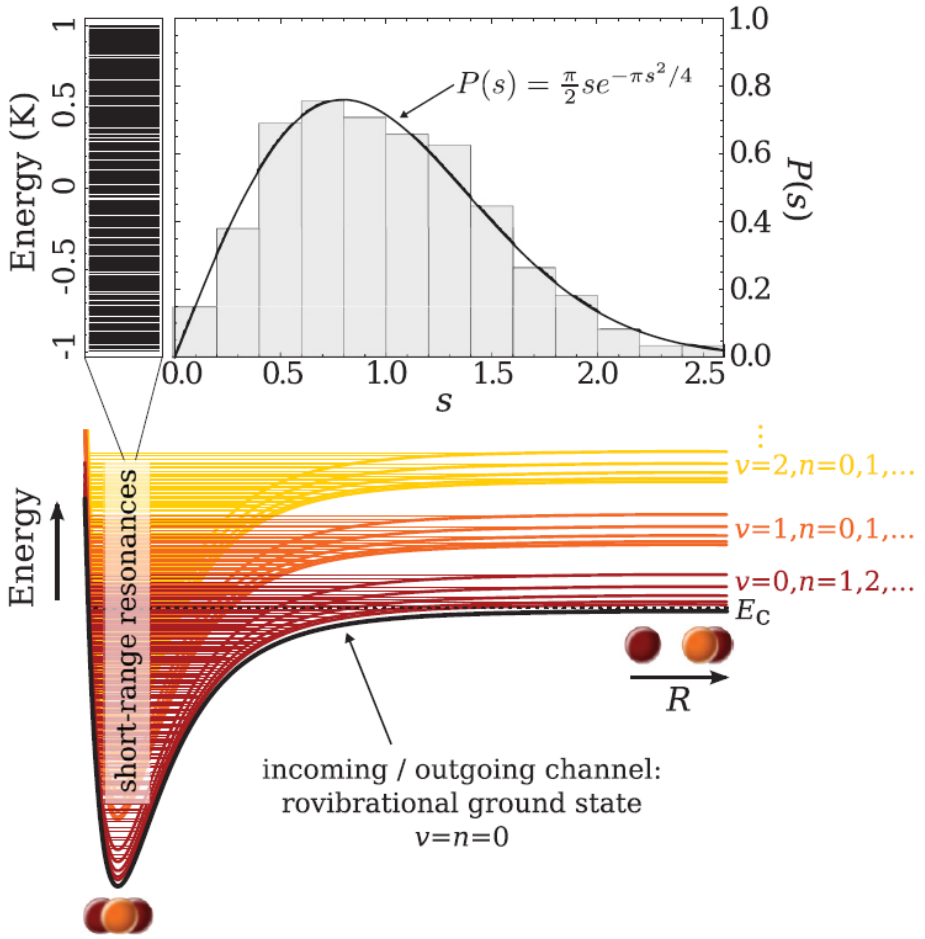
Yang *et al.*, Science 363, 261 (2019)

Outlook

Many open questions in ultracold Chemistry:

- Density of resonant states
- The role of nuclear spins in the collisions
- Detect the collision product
- Association of triatomic molecule

……



Part V: Towards Fermi-Hubbard model

Fermi-Fermi/Bose Mixture

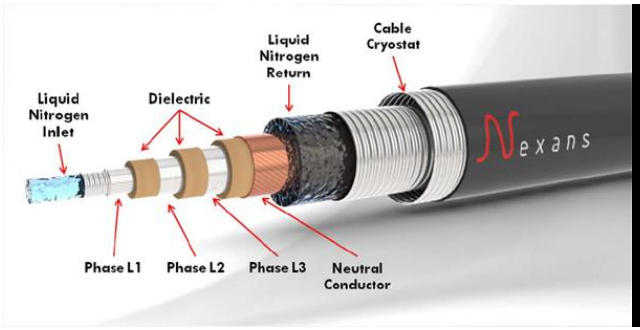
Yao *et al.*, PRL 117 145301 (2016)
Yao *et al.*, Nature Physics 15, 570–576 (2019)

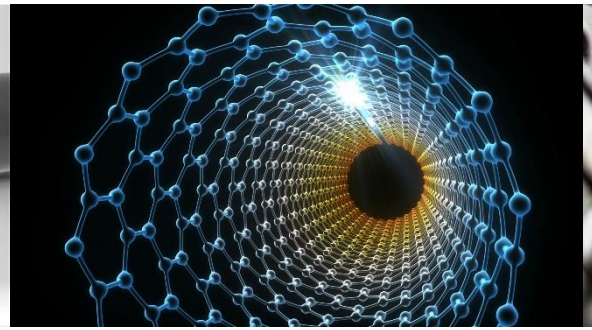
Fermi-Hubbard model

Advanced quantum materials: driving force of the modern technology

- High T_c superconductor
- Carbon nanotube
- Giant magnetoresistance

……





Key problem：understanding the electron correlation in lattices

The most important model: Fermi-Hubbard model (P. W. Anderson)

$$\hat{H} = -\sum_{\langle \mathrm{n,m} \rangle} \left(\hat{c}^{\dagger}_{n,\sigma} \hat{c}_{n,\sigma} + \mathrm{h.c.} \right) + U \sum_{\mathrm{n}} \hat{n}_{\mathrm{n},\uparrow} \hat{n}_{\mathrm{n},\downarrow}$$

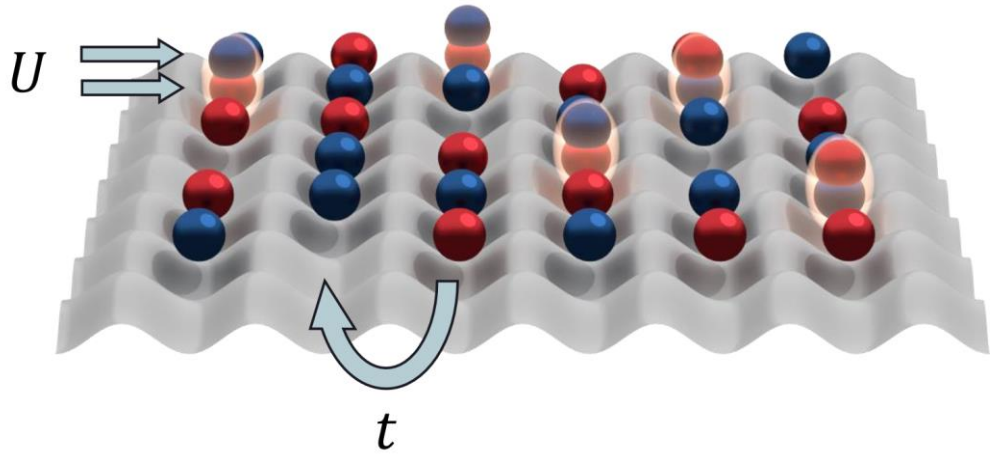
Tunneling between lattice sites

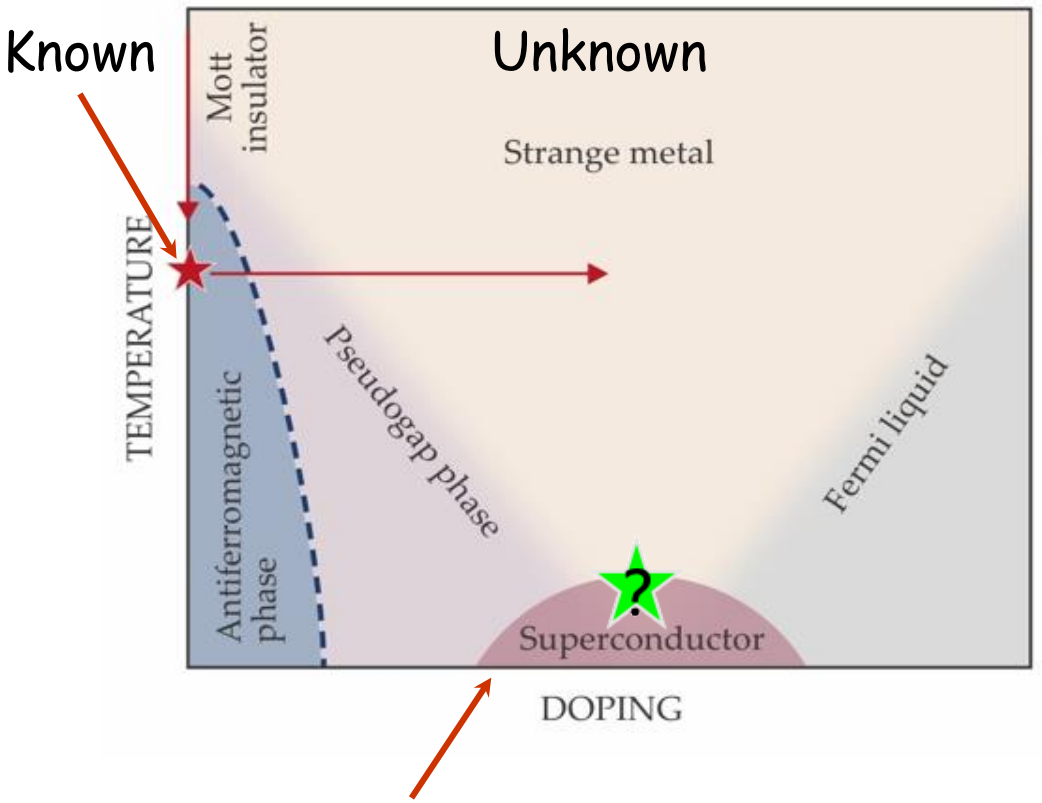
On-site interactions

Quantum simulation of Fermi-Hubbard model

Main challenges:

- Particle doping
- Cooling (extremely-low-entropy)





- High temperature superconductor may exist in this region (d-wave superconductivity)
- Many other interesting quantum phenomenon:
  Quantum magnetism, pseudo-gap physics, doping and pairing……

With two-species mixture of Li and K atoms
Fermi-Fermi (Bose) mixture

To explore particle doping system

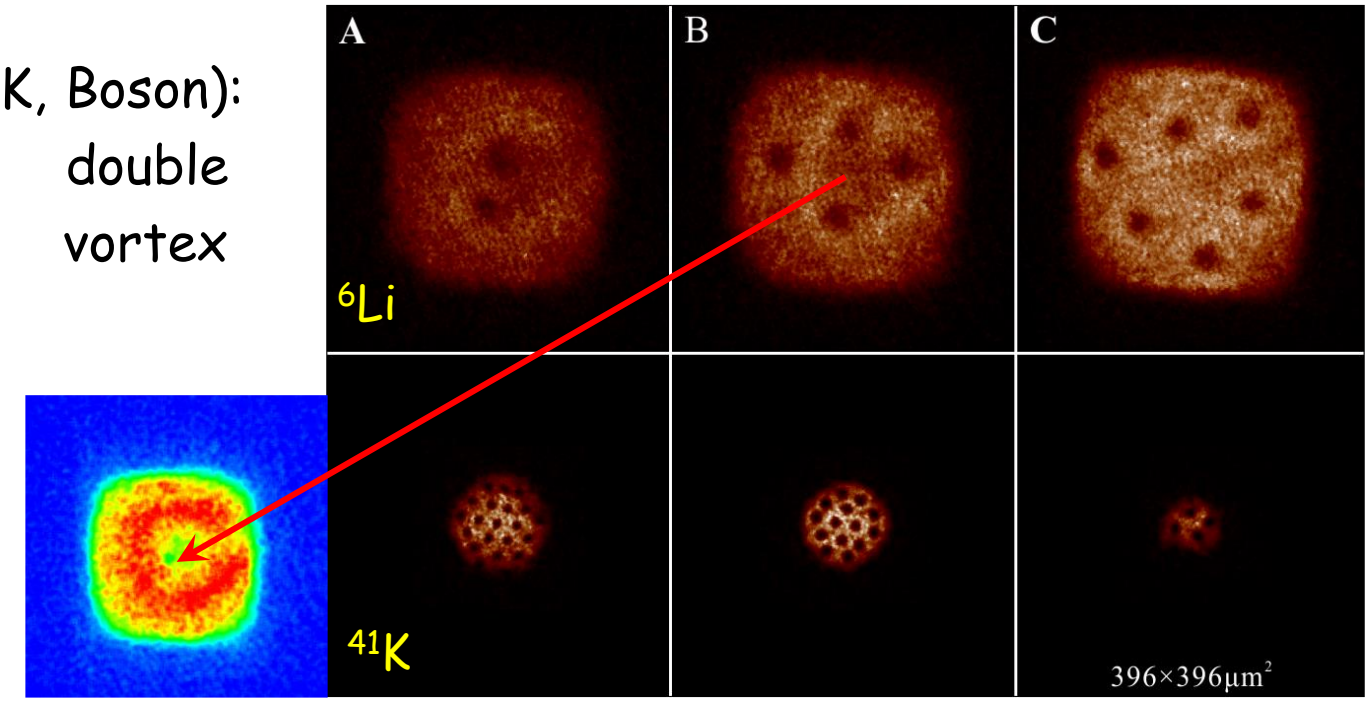
Bose and Fermi double superfluid with strong coupling heteronuclear particles

In real materials:

- ☑ ^{4}He (Boson) superfluidity was achieved in 1938
- ☑ ^{3}He (Fermion) superfluidity was achieved in 1972
- ☒ Uncontrollable strong interactions between the two isotopes makes mixture unstable
  - ➡ Double superfluidity of ^{4}He and ^{3}He has not been observed

With ultra-cold atoms (^{6}Li, Fermion, ^{41}K, Boson):

- ☑ Conclusive evidence of the double superfluidity: co-existence of vortex lattices in two isotopes
- ☑ Density deformation caused by strong coupling between two species



Yao *et al.*, PRL 117 145301 (2016)

To explore d-wave superfluidity

Difficulties for d-wave Feshbach resonances:

☒ Narrow resonances width (~mG) ➡ hard to manipulate

☒ Short lifetime (~ms) ➡ far less than the many-body equilibrium time

☒ High temperature (~100μk) ➡ quite short De Broglie wavelength, dominated by classical physics

Degenerate Bose gases near a d-wave shape resonance:

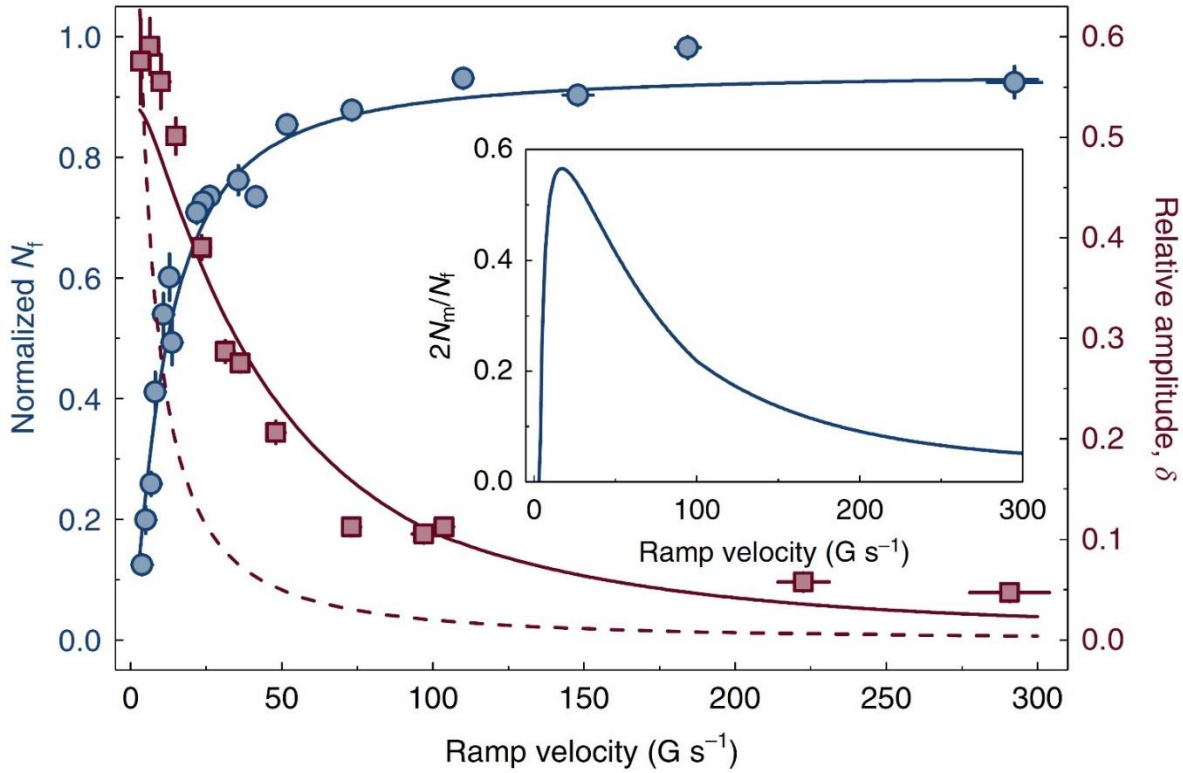
☑ Showing existence of d-wave molecules

☑ Wide resonance (~G)

☑ Long lifetime (~100 ms)

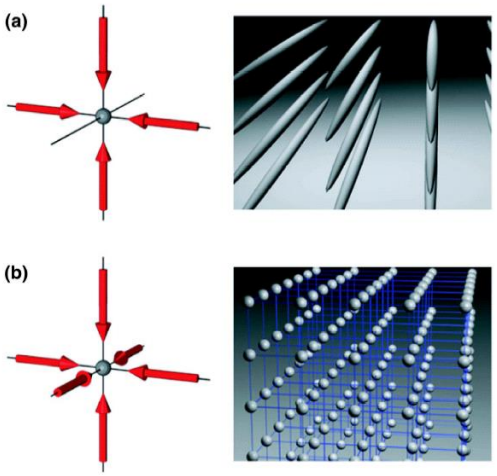
☑ Low temperature (below T_c)

Ideal system for quantum simulation of d-wave interaction

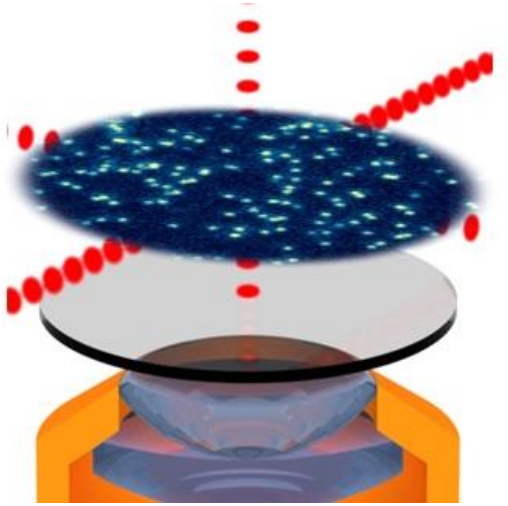


Yao *et al.*, Nature Physics 15, 570–576 (2019)

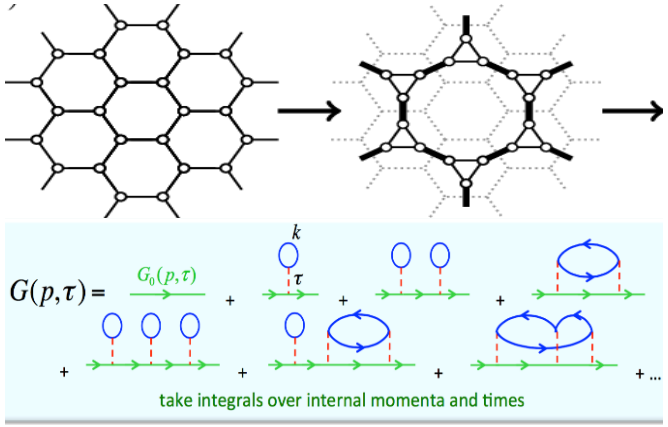
Outlook



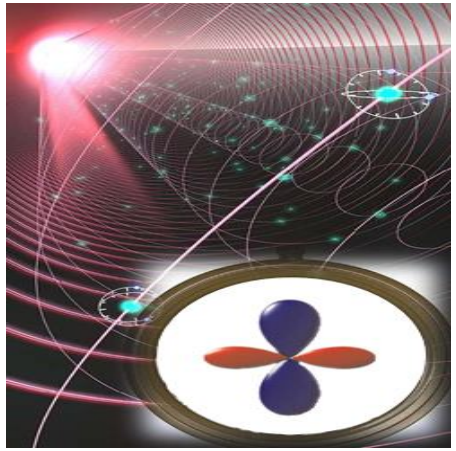
Loading mixtures in optical lattices, to find novel cooling method for lower entropy system



Developing single-site addressing techniques for the two species



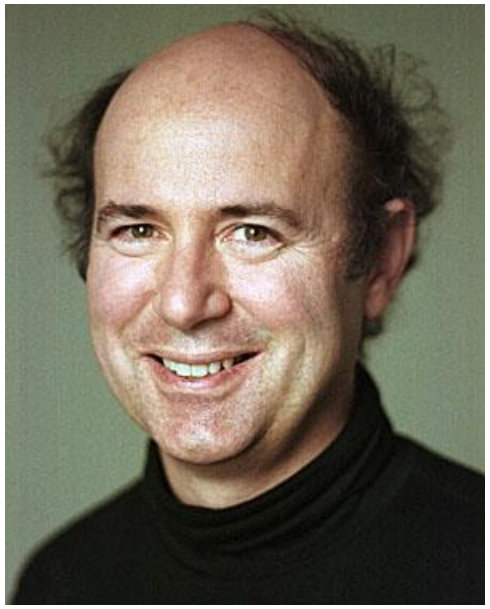
Developing high-efficient numerical methods to benchmark experiments



Open question: How to detect d-wave superfluid?

Summary

▶ **Quantum computation** will both call on and enable algorithms for increasingly sophisticated quantum gadgetry. Within 100 years it will become the central method of chemistry and materials science.



Physics in 100 years, Frank Wilczek, Physics Today 69, 32 (2016)

Thank you for your attention!