Quantum simulations of gauge potentials using ultracold neutral atoms

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Outline

- Laser cooling and Trapping of neutral atoms
- Probe of cold atoms
- Ultracold quantum gases: properties
- Quantum simulation using ultracold quantum gases
  * synthetic vector gauge potentials

Cooling methods

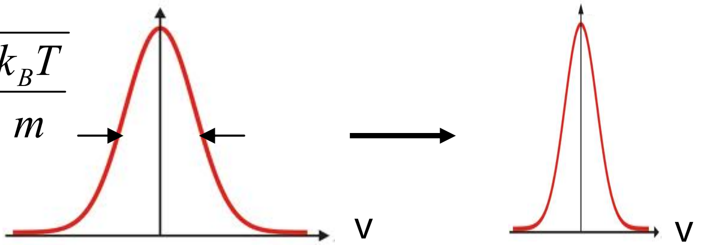
1. Cryogenics
   - Liquid Nitrogen: 77K
   - Liquid Helium: 4.2K
   - He^3-He^4 dilution refrigerator: 0.01K

2. Laser cooling
   - Doppler cooling: 10^{-4} K
   - Polarization gradient cooling: 10^{-6} K= 1μK

3. Evaporative cooling: no lower limit (< 10^{-7} K)

∗ Cooling atoms: reduce velocity spread

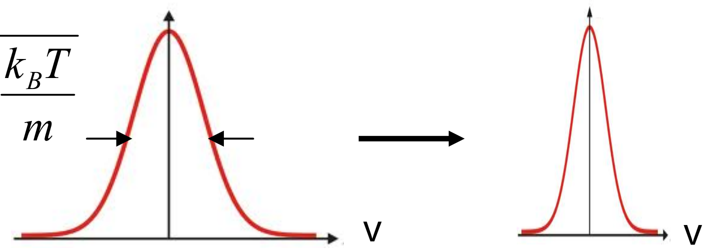
$$v_{width} \approx 2\sqrt{\frac{k_B T}{m}}$$



External and internal states of the atoms

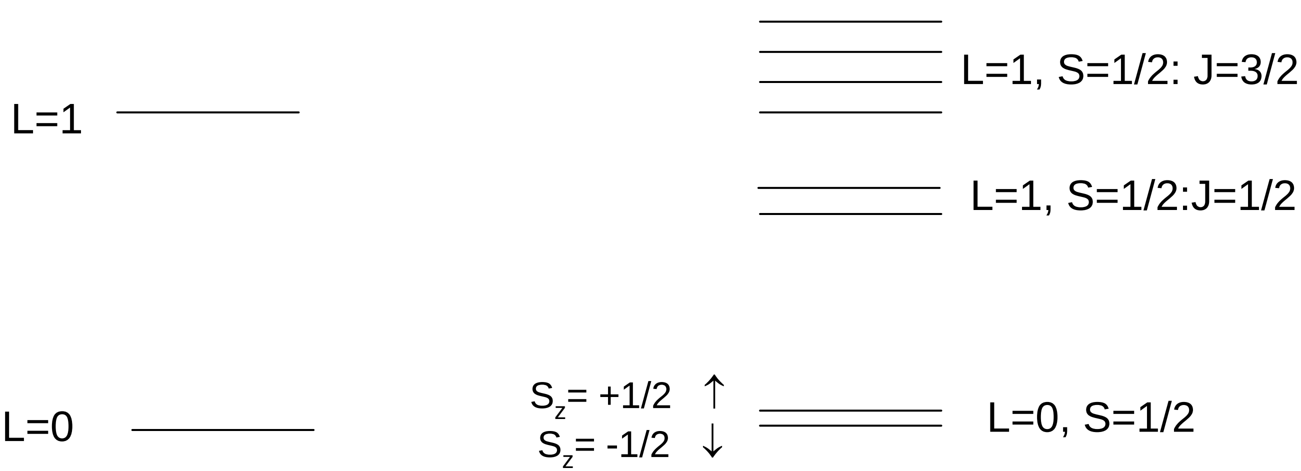
Cooling of atoms: reduce velocity spread:
external center of mass motion

$$v_{width} \approx 2\sqrt{\frac{k_B T}{m}}$$

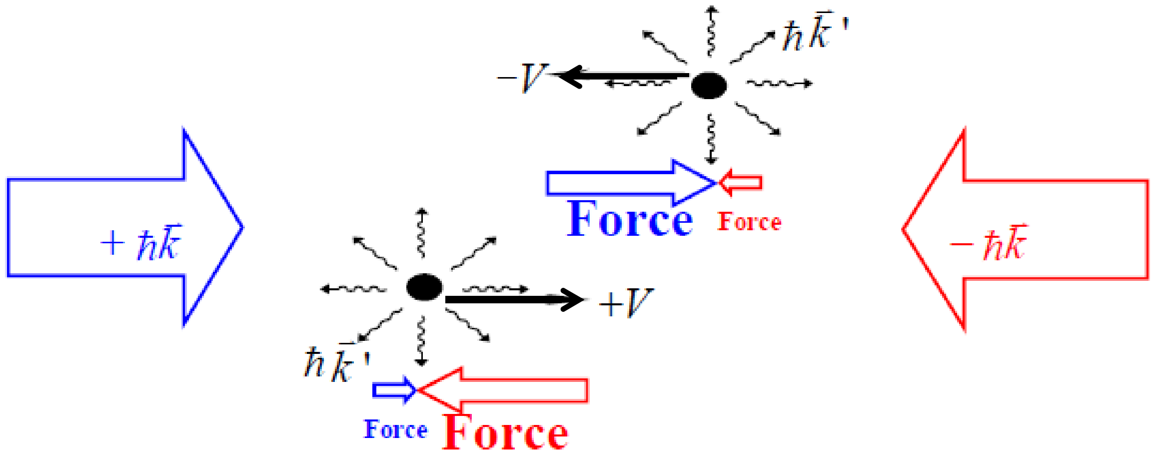


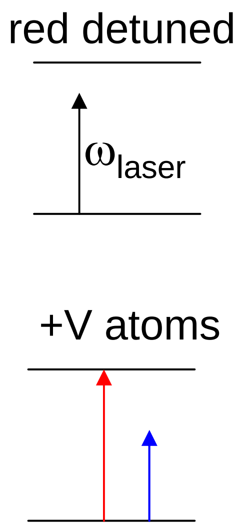
Internal degree of freedom: spin states

no spin | with electronic spin



Doppler cooling





- Two counter-propagating laser beams, red-detuned ($\omega_{laser} < \omega_0$)

- Radiation pressure and Doppler shift: atoms moving to the right observe frequency of the right beam closer to $\omega_0 \rightarrow$ absorb more photons from the right beam, net force to the left

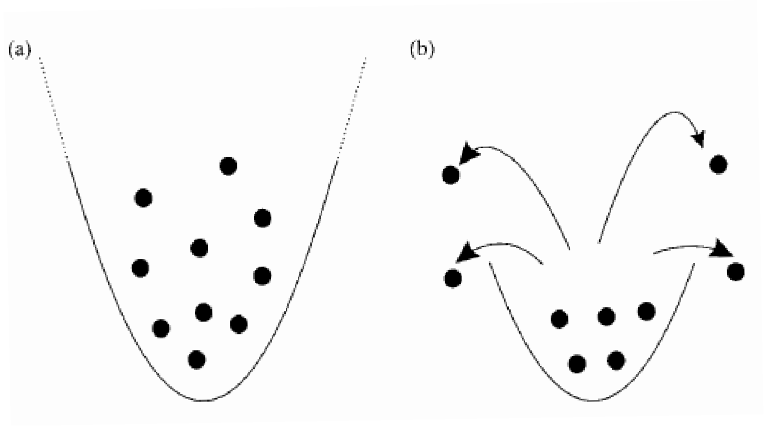
- Friction force for atoms against their motion: $F = -\alpha v$

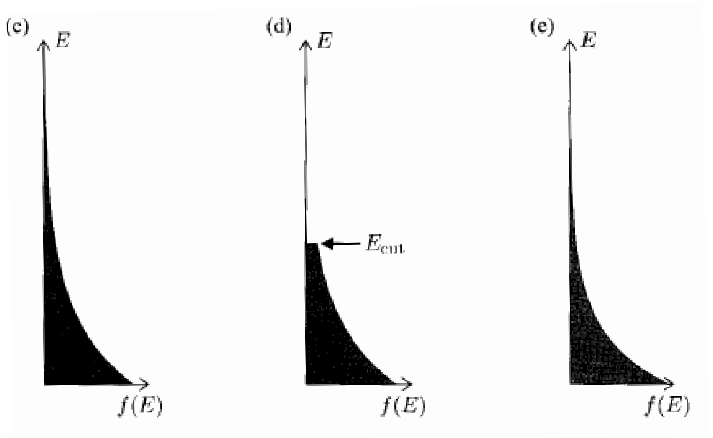
∗**1997 Nobel Prize in Physics**

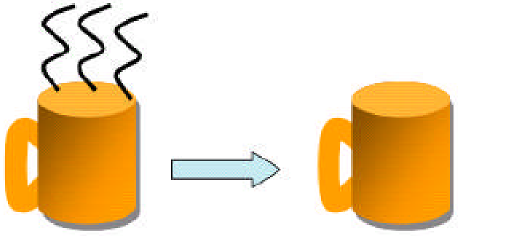
∗Slide adapted from Ite Yu, NTHU, Taiwan

Evaporative cooling

remove hot atoms → remaining atoms rethermalize and are cooled down







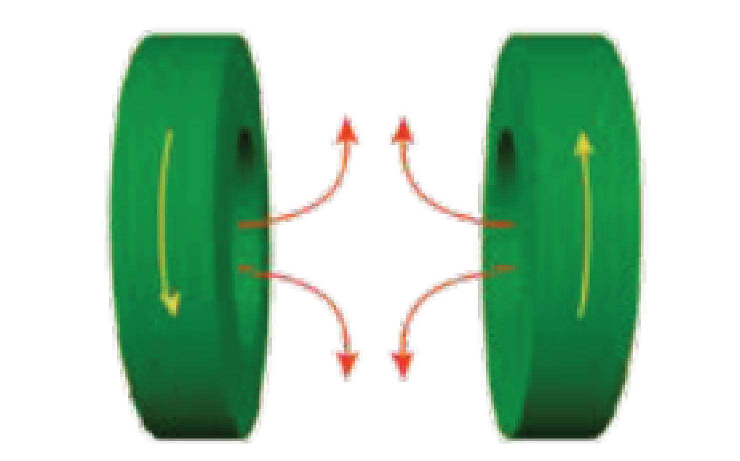
Magnetic trapping potentials: Zeeman shift

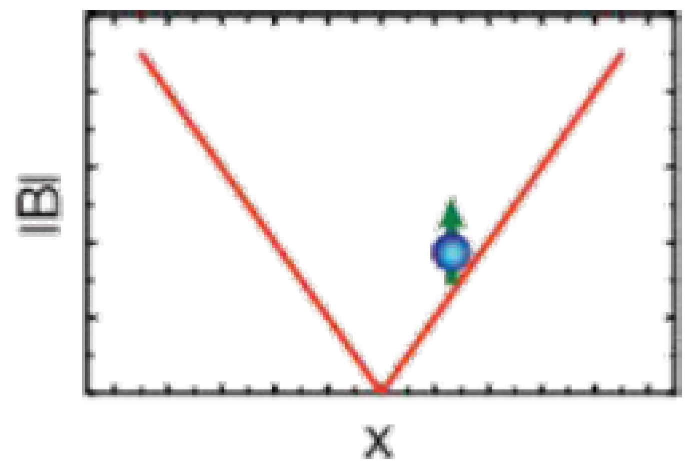
An atom in an external magnetic field

Energy $E = -\vec{\mu} \cdot \vec{B}$

Force $\vec{F} = -\vec{\mu} \cdot \nabla \vec{B}$

B(r)





Optical trapping potentials : AC stark shift

Trapped atoms in light fields

Dipole moment $\vec{d} = \alpha \vec{E}$

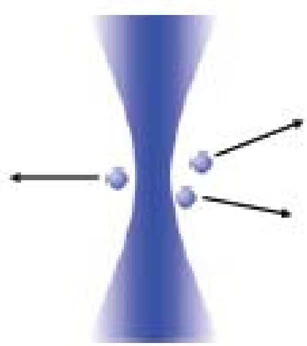
Energy $U_{dip} = -\vec{d} \cdot \vec{E}$

$\propto \alpha(\omega)\, I(r)$

Red detuning $\Delta<0$

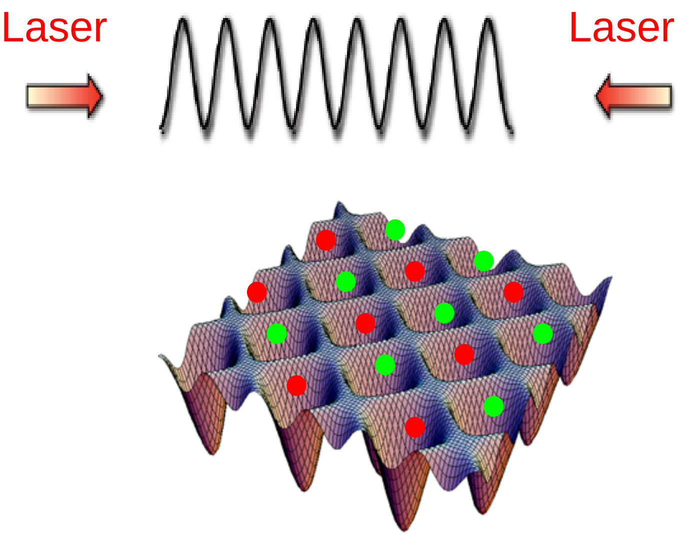
Atoms are trapped
in intensity maximum

Blue detuning $\Delta>0$



Atoms are repelled
from intensity maximum

Optical lattice



Ultracold quantum gases

ultracold atoms: degenerate, non-classical gases

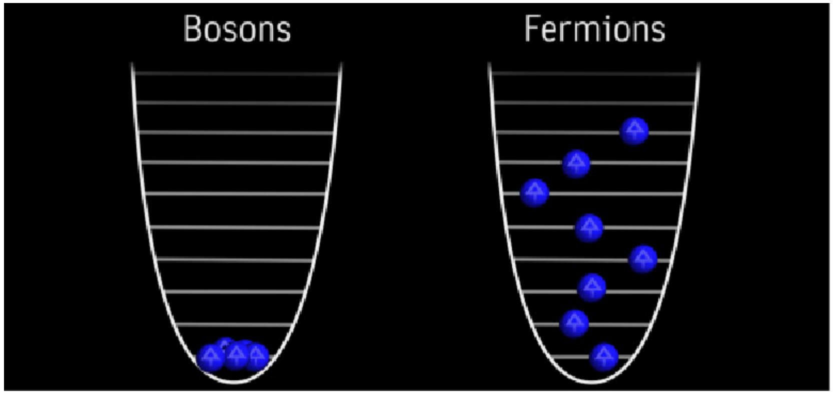
$$\frac{N}{V}\lambda_{dB}^3 \geq 1$$

$\frac{N}{V}$: density

λ_{dB}: de Broglie thermal wave length

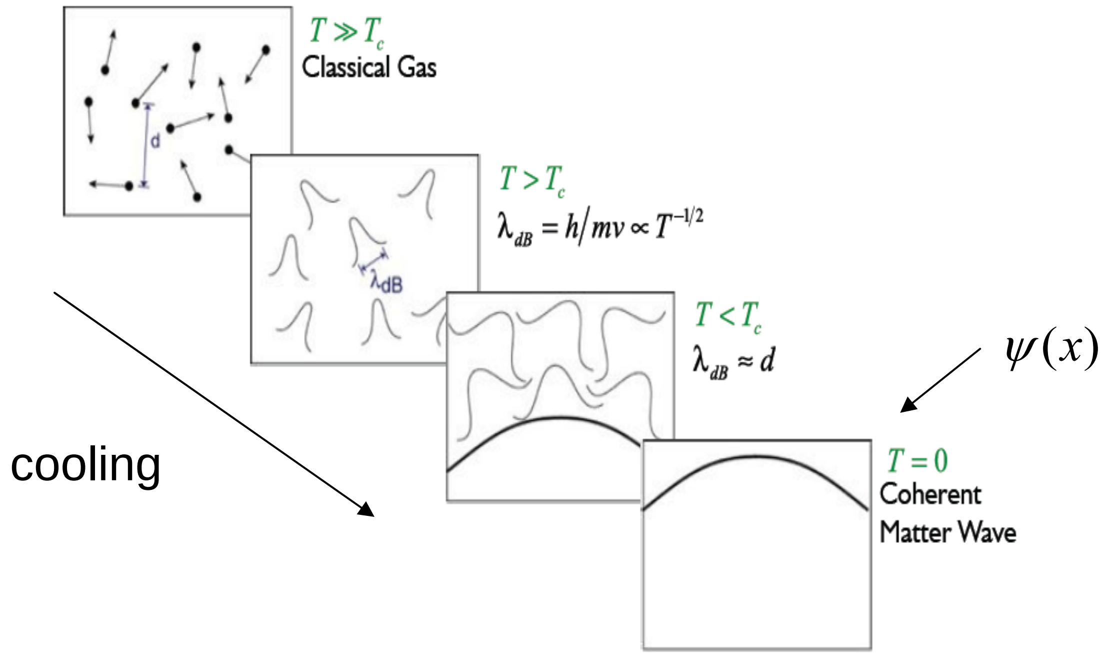
Quantum statistics:
Bose-Einstein: bosons, e.g. photons, ^{4}He
Fermi-Dirac: e.g. electrons, protons, ^{3}He

Ex. Bose-Einstein condensate (BEC) , Degenerate Fermi gas (DFG)



General references:
1. Many body physics with ultracold atoms, Rev. Mod. Phys. **80**, 885 (2008).
2. Making, probing, and understanding Bose-Einstein condensates, arxiv cond-mat 9904034

Bose-Einstein condensate (BEC)



- macroscopic occupation of a single-particle state $\varphi_0(x)$ described by the order parameter $\psi(x) = \sqrt{N}\varphi_0(x)$: macroscopic wavefunction (exist for weakly interacting bosons)

$$i\hbar \frac{\partial \psi(r,t)}{\partial t} = \frac{\hbar^2}{2m}\nabla^2\psi(r,t) + V(r)\psi(r,t) + \underline{g|\psi(r,t)|}^2\psi(r,t)$$

interaction energy

Time dependent Gross-Pitaevskii Equation (TDGPE)

∗**2001 Nobel Prize in Physics**

Introduction: ultracold quantum gases

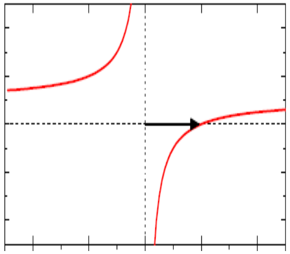
ultracold atoms: degenerate, non-classical gases

(1) cold and dilute: contact interaction $V(r-r') = \frac{4\pi\hbar^2 a}{m}\delta(r-r')$

a : s-wave scattering length

(2) tunable interaction: Feshbach resonance

a vs. magnetic field B



(3) nearly disorder free

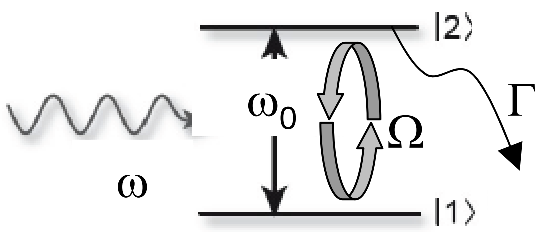
precisely controlled magnetic and optical potentials

Zeeman shift (magnetic) — AC stark shift (optical potentials)

$\rightarrow$ ideal for quantum simulation:

model systems for condensed-matter physics

Probing atoms: absorption imaging



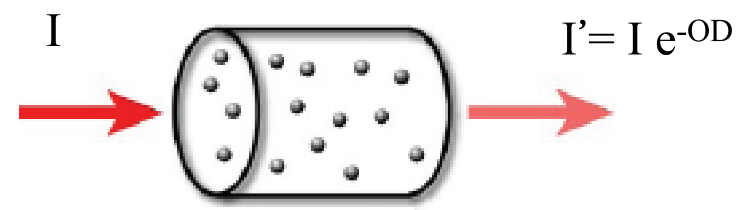


image:
$OD(x,y)=N_{2D}(x,y)\ \sigma$

Absorption:

$$\text{Optical density OD} = \frac{I' - I}{I} \quad \text{for OD} << 1$$

$$\text{OD} = \frac{\text{total scattered photon}}{\text{incoming probe photon}} = \frac{N\Gamma_{sc}}{IA/\hbar\omega}$$

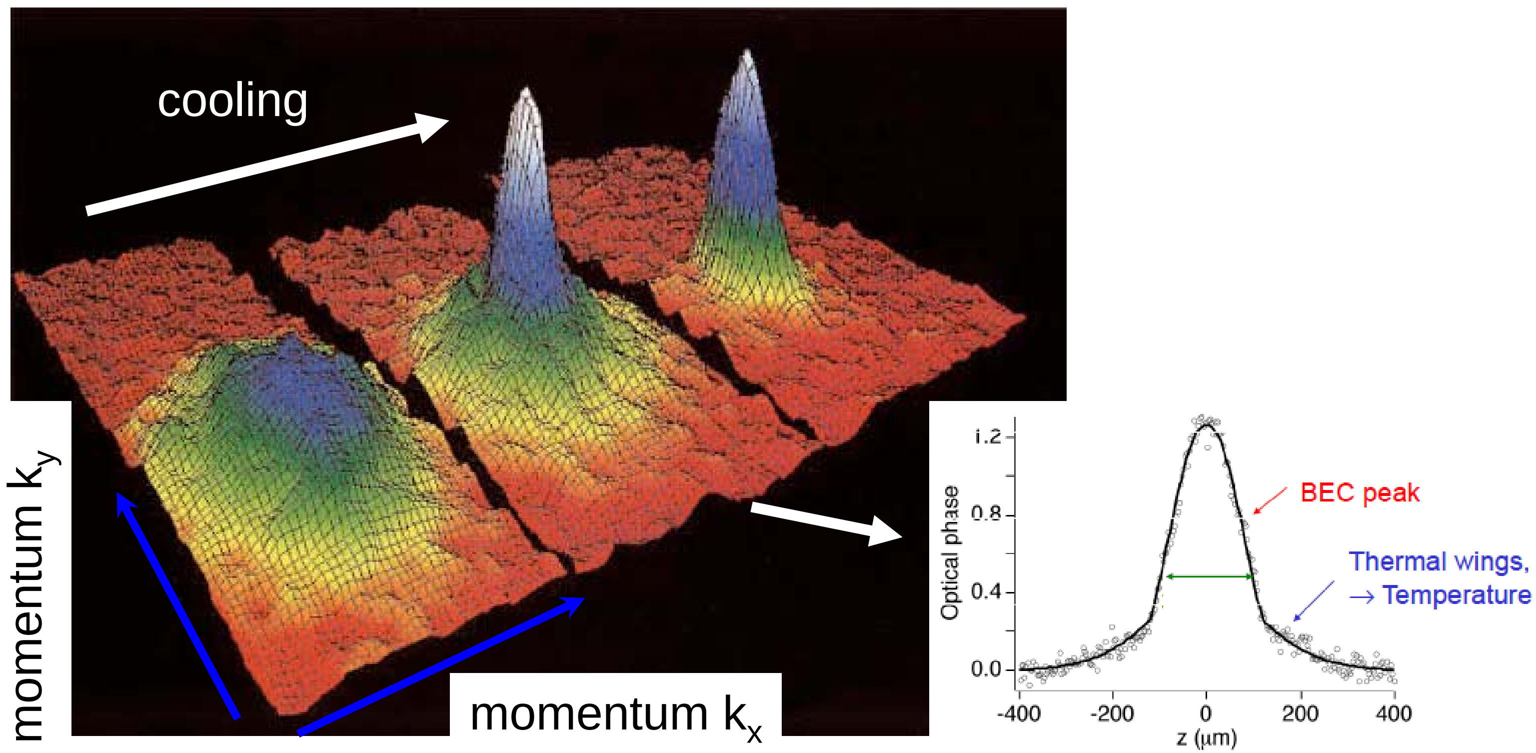
$$= \frac{N\sigma}{A}$$

Γ_{sc}: scattered photon# per atom
σ : scattering cross section per atom

Probe the atoms: time-of-flight (TOF) imaging

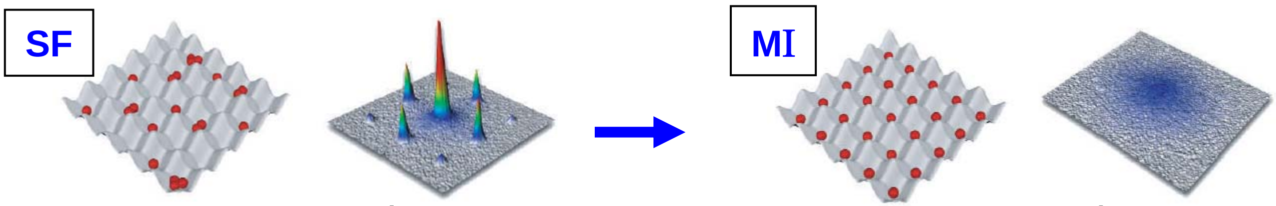
- Switch off trap, free expansion → imaging
- measure momentum k distribution : k mapped to x
  (1) ballistic expansion: no interaction during TOF
  (2) after long expansion $t \gg 1/\omega$

thermal→ thermal+BEC→ ~ pure BEC



Ultracold atoms have realized iconic condensed matter systems

- superfluid → Mott-insulator transition: BEC in optical lattices

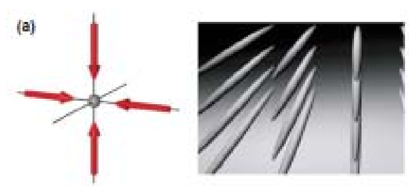


x-space k-space x-space k-space

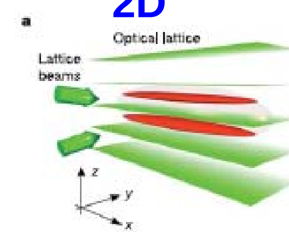
Ref: Greiner et al., 2003

- low dimensional systems: 1D, 2D physics

1D

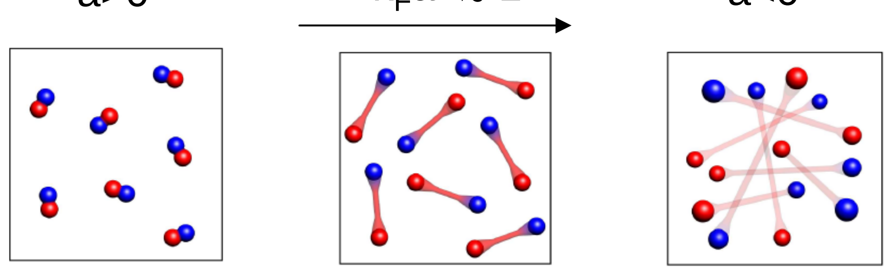


2D



- BEC-BCS (Bardeen-Cooper-Schrieffer) crossover:
  two-component Fermi gas, interaction tuned from repulsive →attractive

a>0 $k_F a \gtrsim 1$ a<0



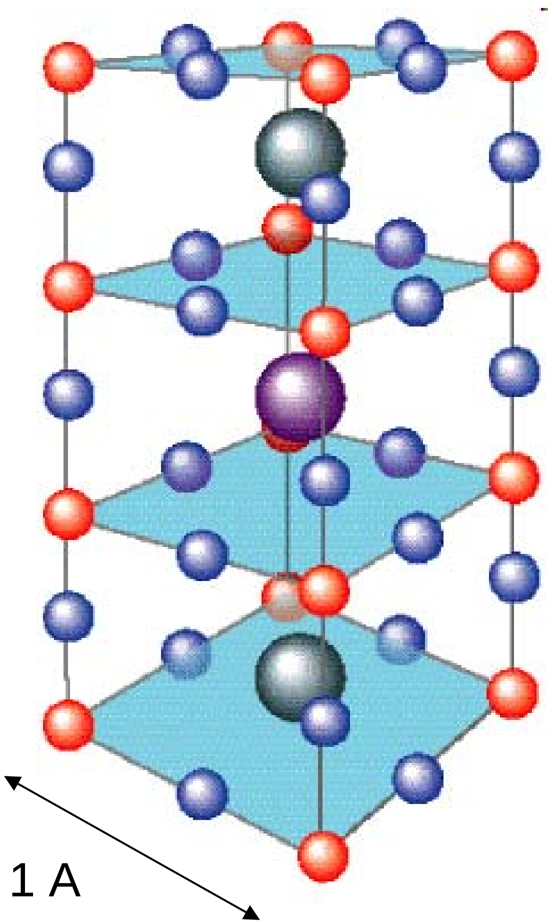
BEC of molecules Crossover superfluid BCS state

Ref: JILA, MIT, 2004

Simulating Quantum Magnetism

t ~ ps

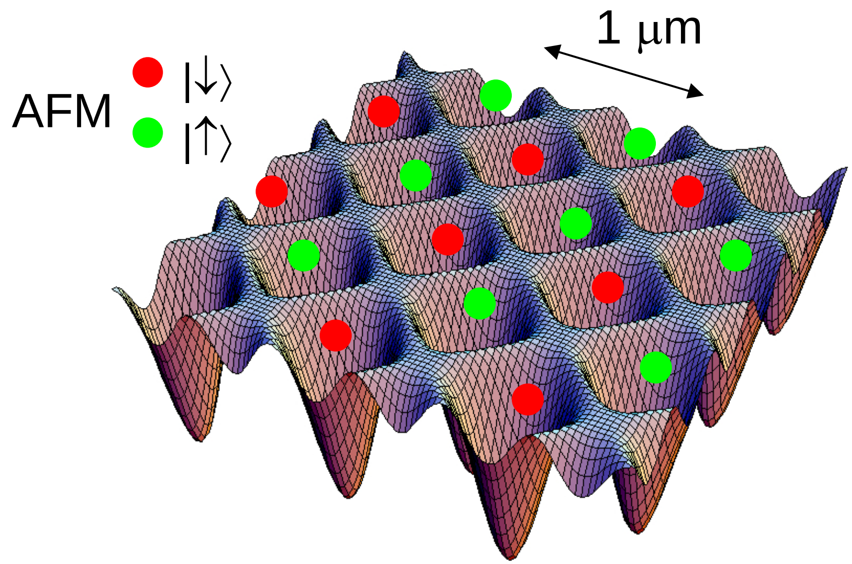
T=100 K



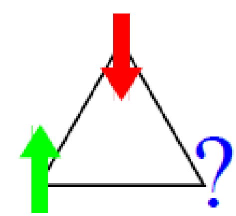
Condensed matter system

t ~ ms

T=100 nK



Frustrated magnetism

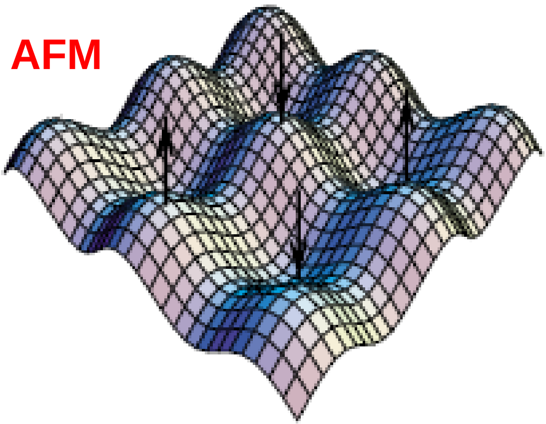


Ultracold atoms in optical lattices

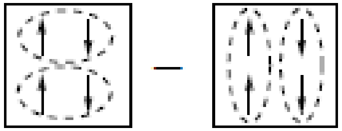
Fermions in a lattice:
Towards understanding high-T_c superconductors

Cold atom systems can provide insights into origin of high T_c SC

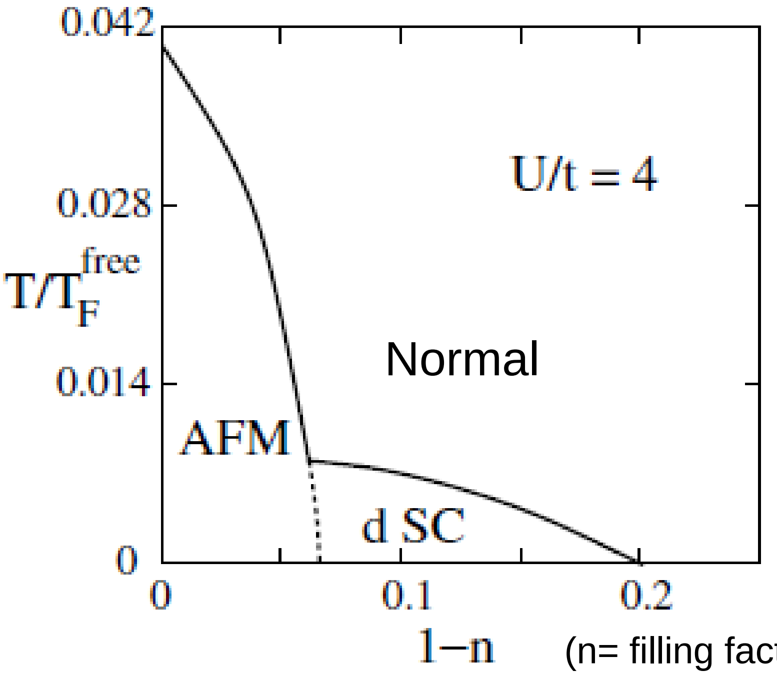
AFM



d-wave SC



Repulsive fermions in an optical lattice



(n= filling factor)

Ref: Hofstetter et al., PRL, 2002.

New type of simulation: synthetic gauge potentials

to “charge” neutral atoms by creating a “ synthetic vector gauge potential A* ”

Charged particles in external electric and magnetic fields

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

$$B = \nabla \times A$$

$$E = -\nabla\phi - \frac{\partial A}{\partial t}$$

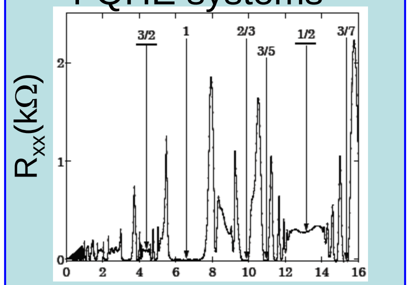
ϕ : scalar potential
A: vector potential
p: canonical momentum
H: Hamiltonian operator

B: magnetic field
E: electric field

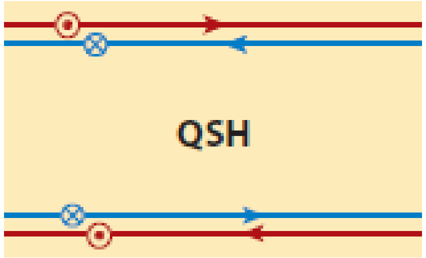
New type of simulation: synthetic gauge potentials

to “charge” neutral atoms by creating a “ synthetic vector gauge potential A^* ”

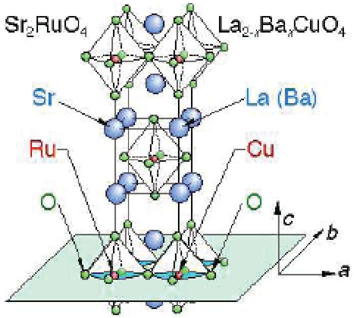
FQHE systems



Topological insulators, 2D
(Quantum spin Hall effects)



p-wave superconductor



- new approach to generate large B* to study quantum-Hall physics

2D system and $\nu = N_{2D}/N_v \leq 1$
N_{2D}= atom#, N_v= # of flux quanta

- bosonic ν =1 state: w/ binary contact interaction, nonabelian, for topological quantum computation

Ref: N. R. Cooper, 2008

- Spin-dependent $\vec{A}^*(\vec{\sigma})$: spin-orbit coupling
  TR preserved topological insulators, topological superconductors:
  nonabelian gauge potentials → $[A_i^*, A_j^*] \neq 0$

Importance of SO coupling

- Realizing topological insulators w/o breaking time reversal symmetry

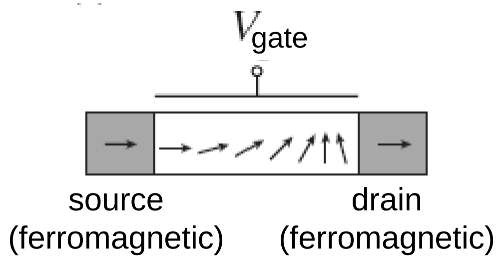
- w/ interaction→ topological superconductors
  leading to anyons, Majorana fermions,
  non-Abelian statistics, topological quantum computing

  Ref: Qi and Zhang, Physics Today (2009), Fu and Kane, PRL (2008)
  Sau et al., PRL (2010), Nayak et al., Rev. Mod. Phys. (2008)

- Spin-dependent A*: $A_i^*(\vec{\sigma})$ non-abelian gauge potentials $\left[A_i^*, A_j^*\right] \neq 0$

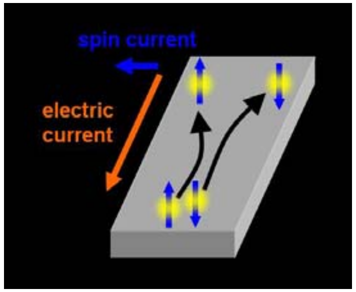
- Promising for spintronics

Datta-Das spin field-effect transistor



Datta and Das (1990) ; Vaishnav et al. (2008)

Spin Hall effects



Kato. et al. (2004);
Beeler et al. in Spielman group (2012)

Introduction of synthetic gauge potentials

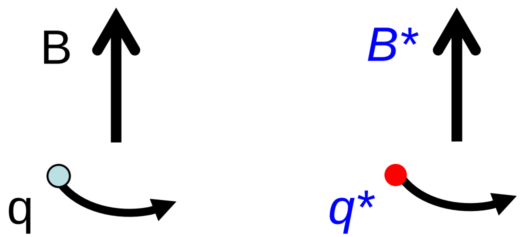
- Optically induced vector gauge potential A^* for neutral atoms:

$$H = \frac{(p - q^* A^*)^2}{2m^*} + V(x)$$

$\rightarrow$ synthetic electric and magnetic fields

$$E^* = -\frac{\partial A^*}{\partial t}, B^* = \nabla \times A^*$$

- Create synthetic field B^* for neutral atoms:
  effective Lorentz force $F = qv \times B$
  to simulate charged-particles in real magnetic fields



charge q $\quad$ ^{87}Rb

- Light-induced potential to generate B^* in lab frame, no rotation of trap:
  (1) steady B^*, not metastable
  (2) easy to add optical lattices

B* in rotating frame:
Coriolis force$\leftrightarrow$Lorentz force

rotation: technical limit on B^*

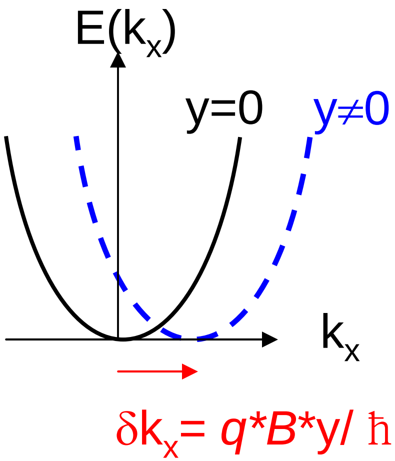
Principles

- charged particle *q* in a real field $\vec{B} = B\hat{z}$, Landau gauge A_x=By

$$H_B = \frac{\hbar^2}{2m}\left[(k_x - \frac{qA_x}{\hbar})^2 + k_y{}^2\right]$$

$$\delta k_x \equiv \frac{qA_x}{\hbar} = \frac{qBy}{\hbar}$$

$$\vec{B} = \nabla \times \vec{A}$$



- to simulate w/ laser-atom interaction

- laser photons : create δk_x= momentum shift along *x*

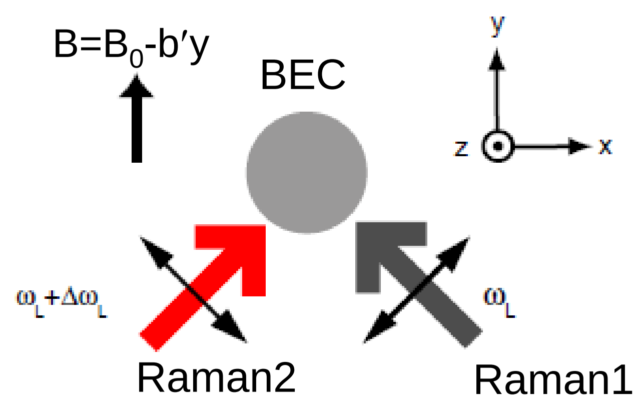
$\rightarrow$ make $\delta k_x(\Delta)$ Δ=laser-atom detuning

$\rightarrow$ make $\Delta=\Delta' y$: $\delta k_x(y)$

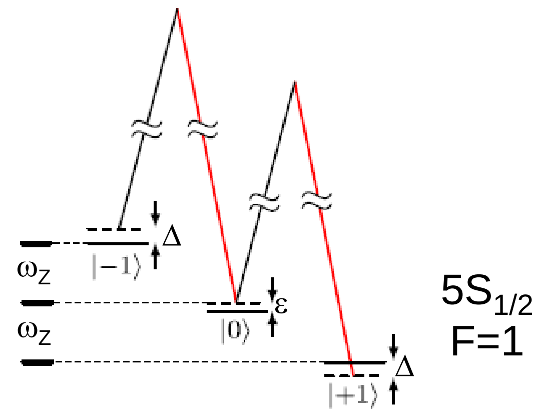
$\rightarrow$ synthetic field $\frac{q^* B^*}{\hbar} = \frac{\partial(\delta k_x)}{\partial y}$ along *z*

Synthetic vector potentials (I):
synthetic magnetic field B^*

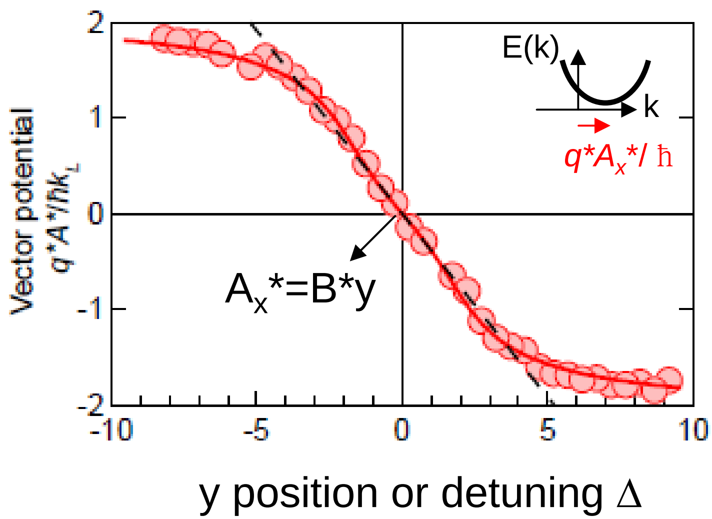
a. Raman-dressed BEC



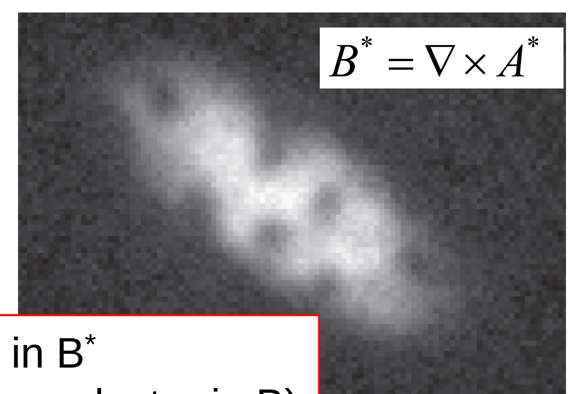
b. Level diagram



c. Vector potential A_x^* vs. position y



d. Synthetic magnetic field B^*, $A_x^*=B^*y$

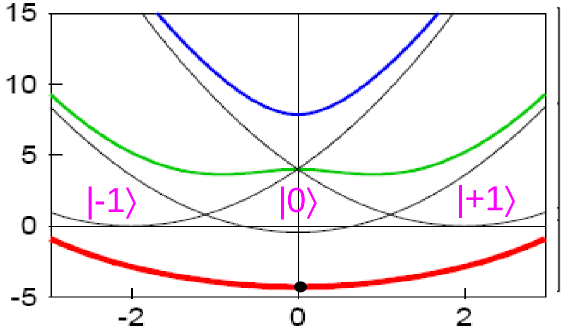


superfluid in B^*
(like superconductor in B)

Reference: Y.-J. Lin et al., Nature **462**, 628 (2009),
Y.-J. Lin et al., PRL **102**, 130401 (2009).

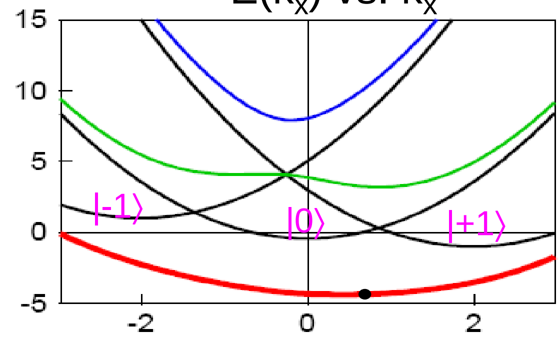
Adiabatic loading into the dressed state: uniform A*

(d) $E(k_x)$ vs. k_x



measure δk_x from spin $|0,k_x = \delta k_x\rangle$

(e) $E(k_x)$ vs. k_x



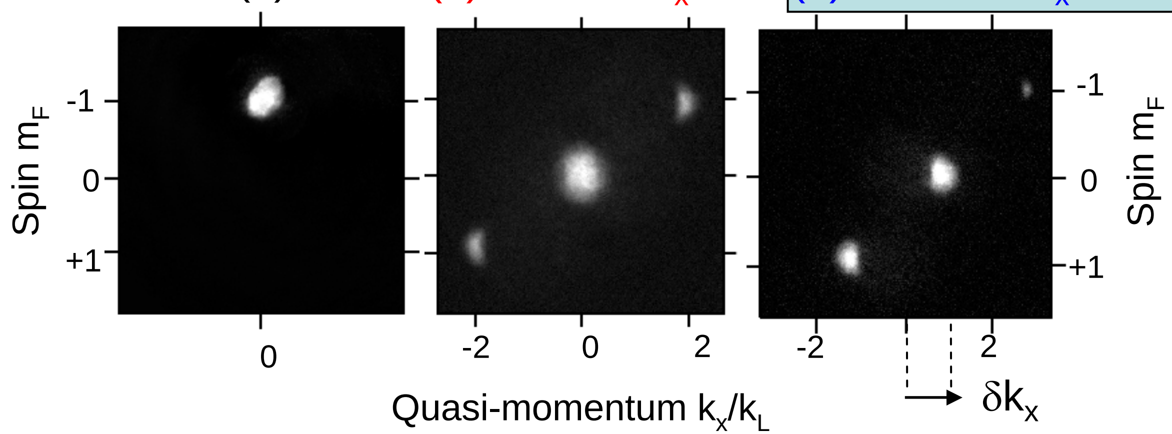
$\delta k_x(\Delta)$
$=q^*A^*(\Delta)/\hbar$

$P_{can} = \hbar \bullet \delta k_x = q^* A^* \neq 0$

$\langle \dot{x} \rangle_{m_F} = 0$ **!**

Time-of-Flight images of $|-1,k_x+2\rangle$, $|0,k_x\rangle$, $|+1,k_x-2\rangle$

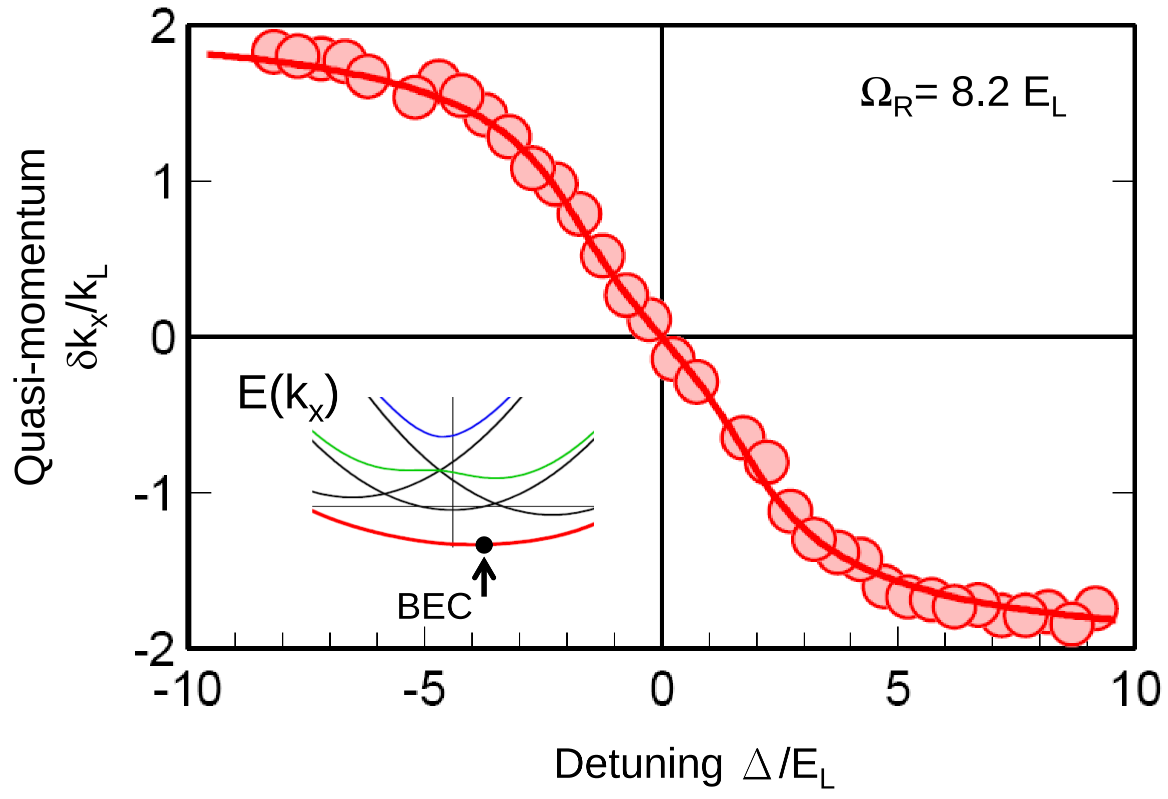
(a) → (b)(c) → (d) $\Delta = 0$, $\delta k_x = 0$ → (e) $\Delta \neq 0$, $\delta k_x \neq 0$



Uniform vector potential A* vs. detuning Δ

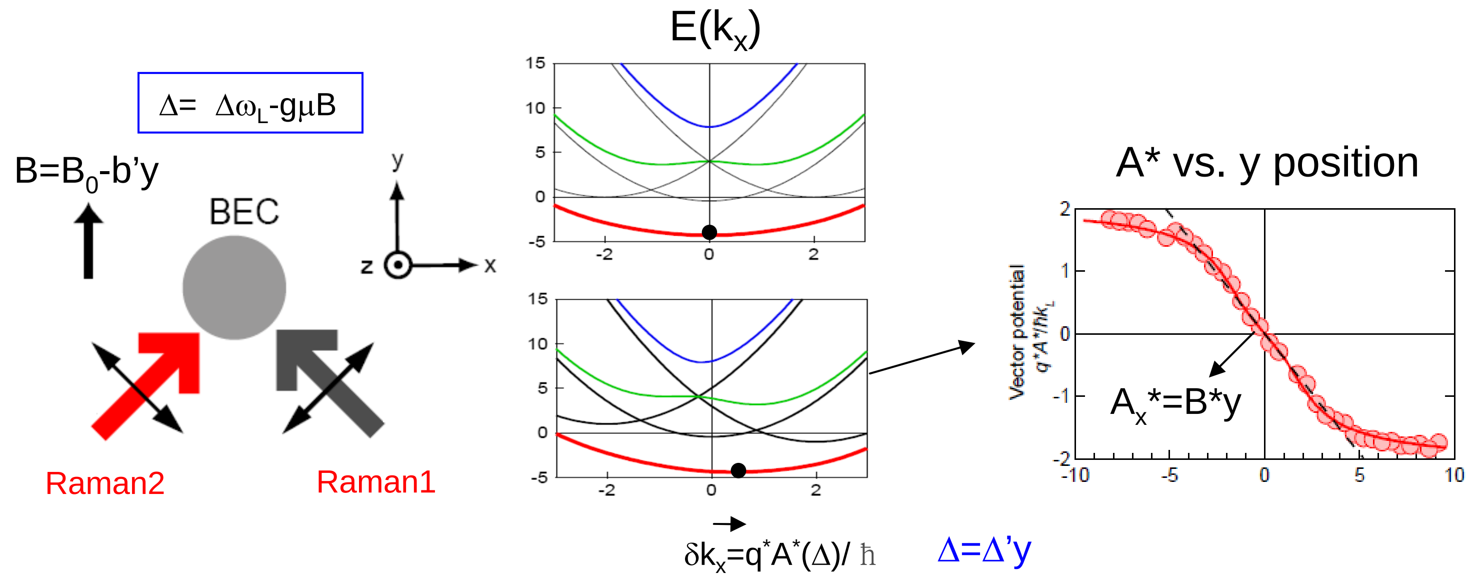
effective vector potential $q^*A^*/\hbar$ = measured quasi-momentum k_x

vector potential $q^*A^*/\hbar$ vs. detuning Δ

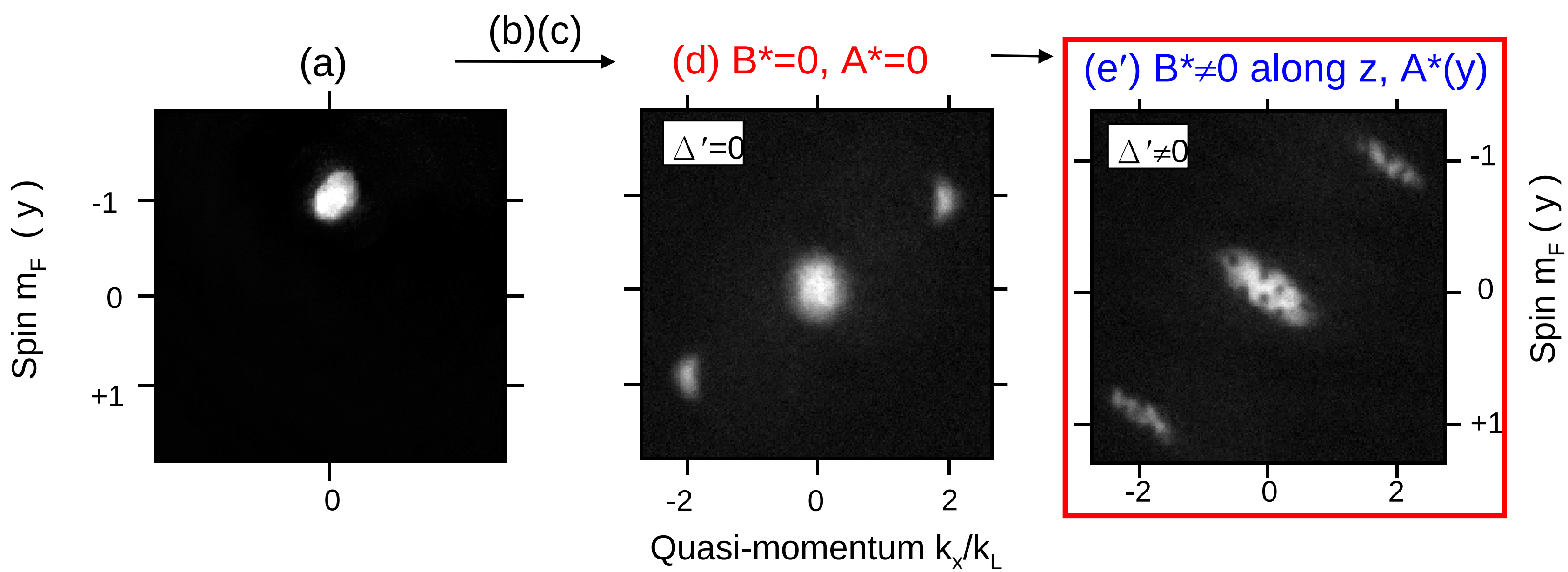


Ref: Y.-J. Lin et al., PRL **102**, 130401 (2009).

Synthetic field B*= ∇×A*

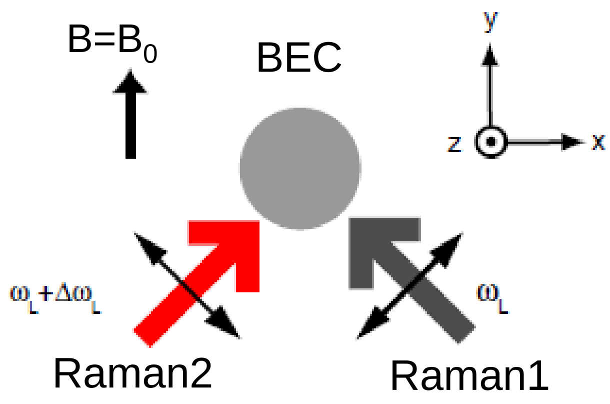


Time-of-Flight images of |-1,k_x+2 〉, |0,k_x 〉, |+1,k_x-2 〉

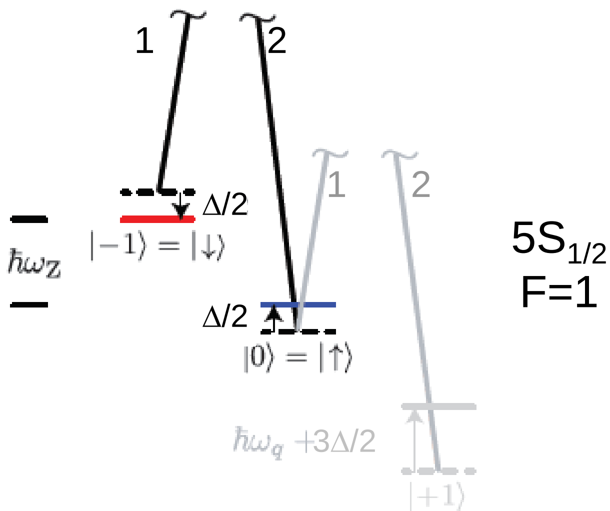


Synthetic vector potentials (II):
spin-orbit coupling

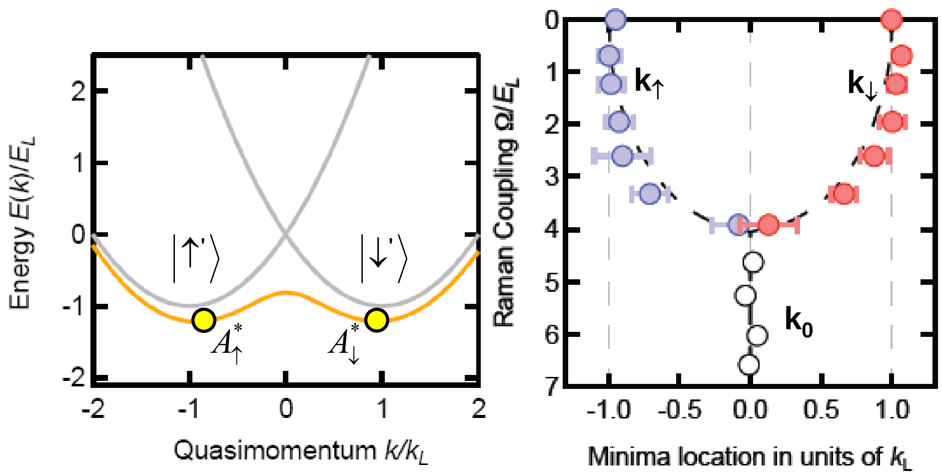
a. Raman-dressed BEC



b. Level diagram

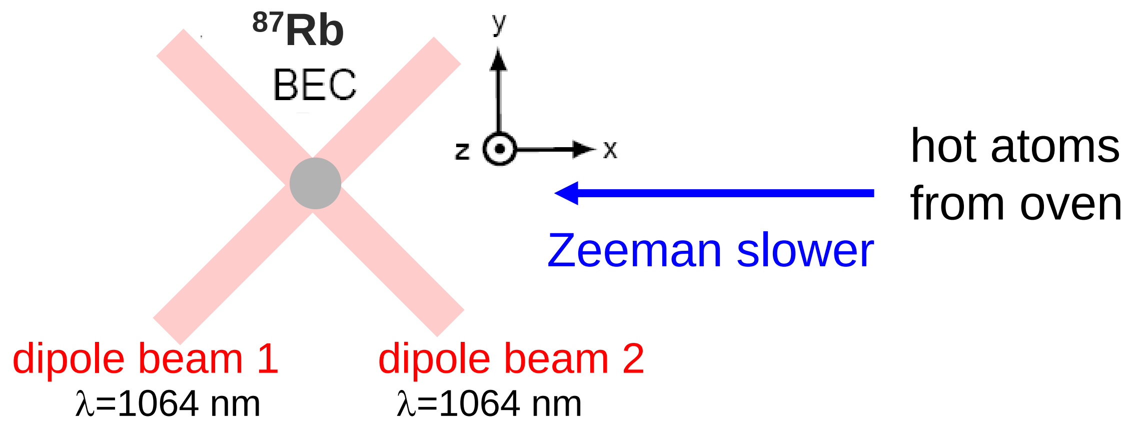


c. Spin dependent A*: spin-orbit coupling



Reference: Y.-J. Lin, K.J.-Garcia and Ian Spielman, Nature **471**, 83 (2011).

Setup: BEC production



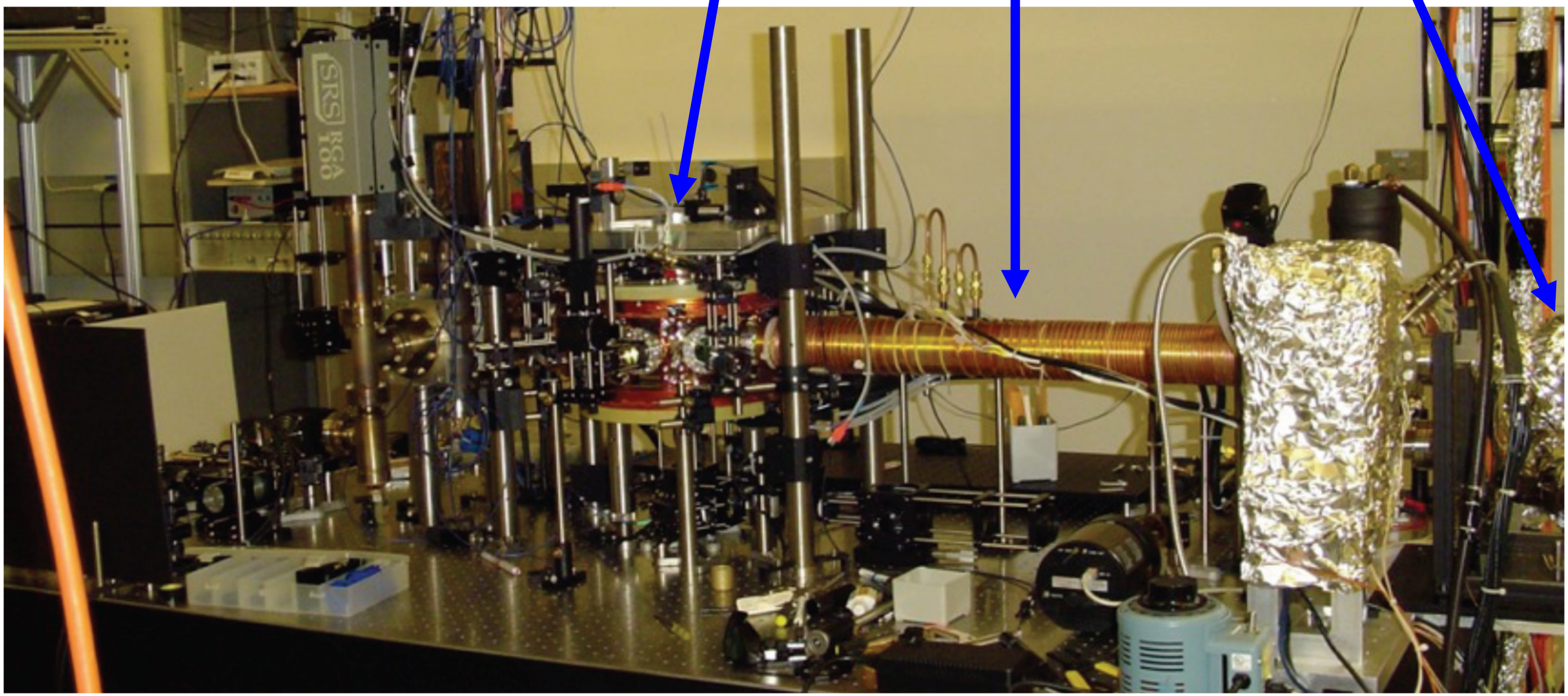
- load Magneto-Optical trap (MOT) from Zeeman slower: ~ 10^9 atoms in 3 s
- rf-evaporative cooling in a quadrupole magnetic trap for 3 s, $|F=1, m_F = -1\rangle$
- single beam optical dipole trap + weak magnetic trap:
  evaporate in hybrid potential for ~ 7 s $\rightarrow$ 2 x10^6 atoms in BEC
- load the BEC into the crossed dipole trap: 5 x10^5 atoms
- total cycle time~ 15 s

Actual experimental Setup in NIST

Main chamber:
cold atoms here

Zeeman slower

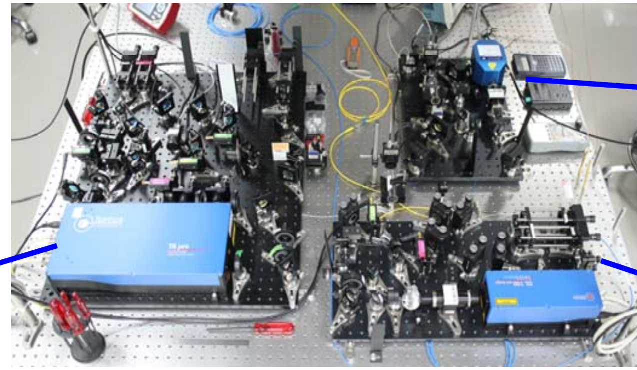
hot atomic oven



Current experiment in IAMS: towards BEC

Diode lasers for laser cooling

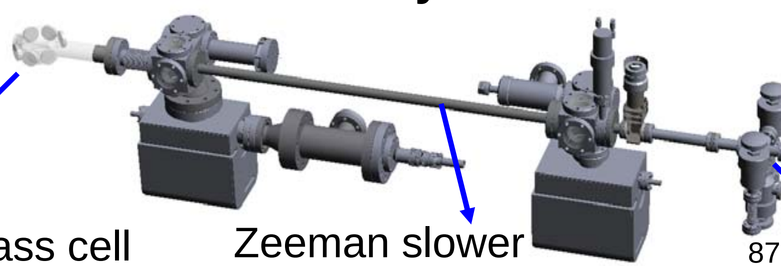
MOT laser
(cooling)



Reference laser
(locked to atomic cell)

Repumper laser
(repumping)

Vacuum system



BEC/MOT glass cell

Zeeman slower

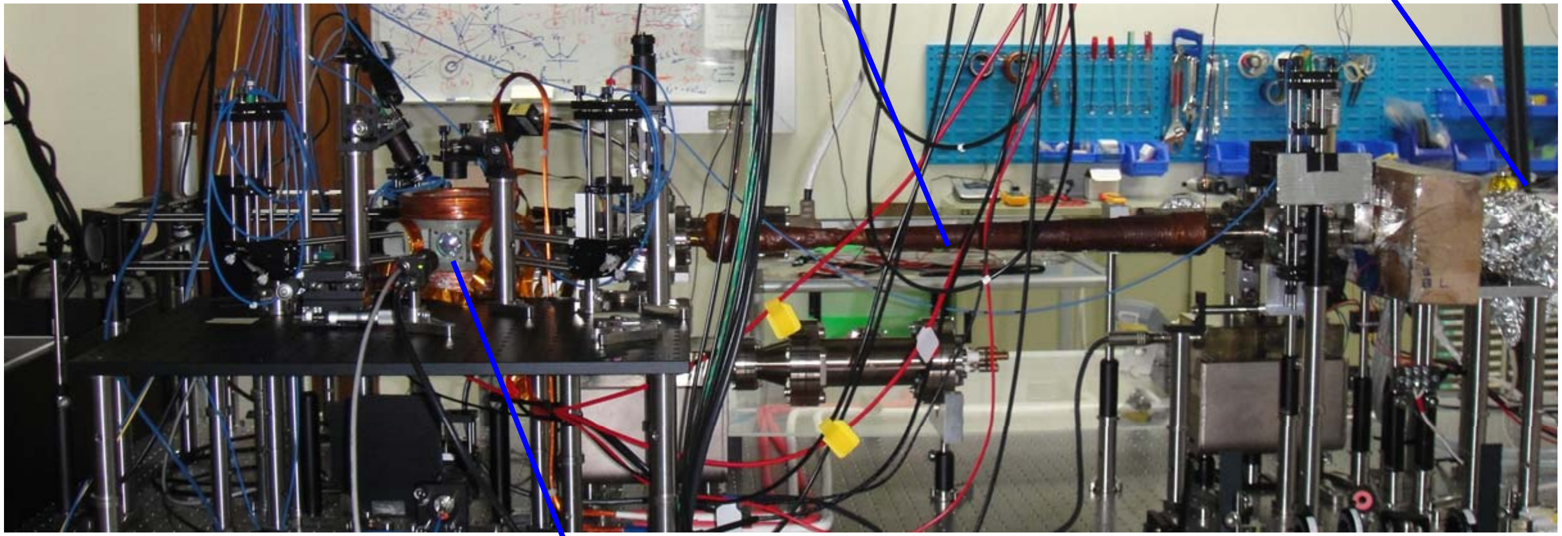
^{87}Rb /^{40}K Atomic oven

Current status of experiment in IAMS:

cold atoms in magnetic traps

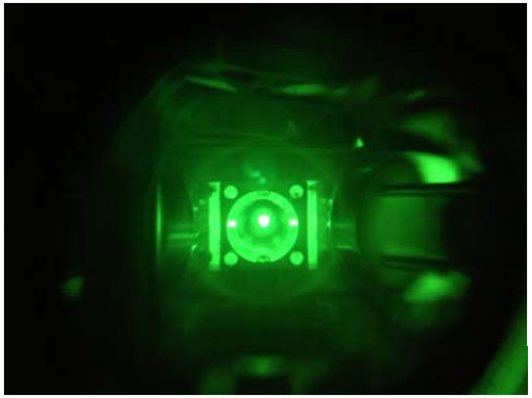
Zeeman slower

^{87}Rb Atomic oven



laser cooled and trapped atoms

MOT



Magneto-Optical Trap (MOT)

→ sub-Doppler cooling

→ captured in magnetic traps

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Summary

- Ultracold quantum gases:
  precisely known Hamiltonian, w/ tunable parameters
  quantum simulation as model systems of condensed-matter physics

- Cold atoms:
  ∗ superfluid→Mott-insulator transition
  ∗ BEC-BCS crossover
  ∗ synthetic vector gauge potentials
  ∗ quantum magnetism