Toward generating synthetic gauge potentials for a Bose-Einstein condensate in a toroidal trap

IAMS

Yu-Ju Lin

Institute of Atomic and Molecular Sciences, Academia Sinica, Taiwan

APCWQIS 2014, December 15, 2014, NCKU

Outline

• introduction of synthetic vector gauge potentials for ultracold neutral atoms: synthetic magnetic field and spin-orbit coupling

• experiment direction:
(i) generate synthetic magnetic flux Φ_B in a toroidal trap
(ii) detection atomic circulations induced by Φ_B

• We have achieved a ^{87}Rb Bose-Einstein condensate (BEC) with up to 3×10^5 atoms in a crossed optical dipole trap

• current experimental work and plan

Introduction: ultracold quantum gases

ultracold atoms: degenerate, non-classical gases

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

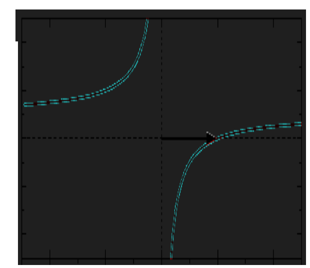
$\frac{N}{V}$: density λ_{dB}: de Broglie wave length

(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

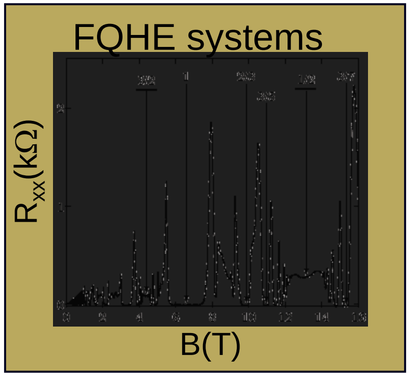
↙ Zeeman shift ↘ AC stark shift

→ ideal for quantum simulation:

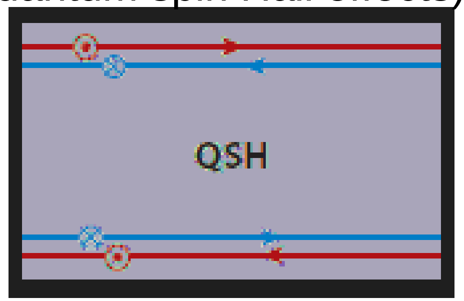
model systems for condensed-matter physics

Quantum simulations of synthetic gauge potentials

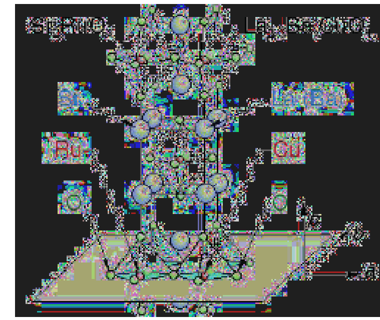
to "charge" neutral atoms by creating a " synthetic vector gauge potential A^* "



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 → $\left[A_i^*, A_j^*\right] \neq 0$

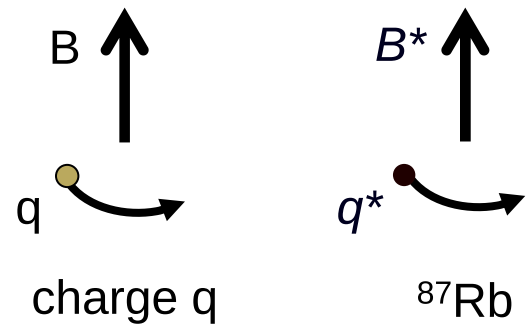
Introduction of synthetic gauge potentials

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

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

$\rightarrow$ synthetic electric and magnetic fields $\quad E^* = -\frac{\partial A^*}{\partial t}, B^* = \nabla \times A^*$

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



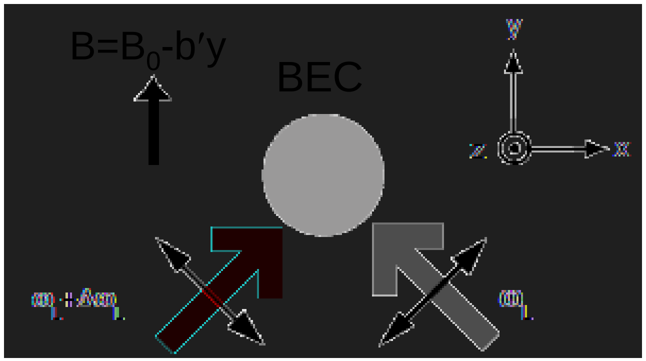
- Light-induced potential to generate *B^** in lab frame, <u>no rotation of trap</u>:
  (1) steady *B^**, not metastable
  (2) easy to add optical lattices

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

rotation: technical limit on *B**

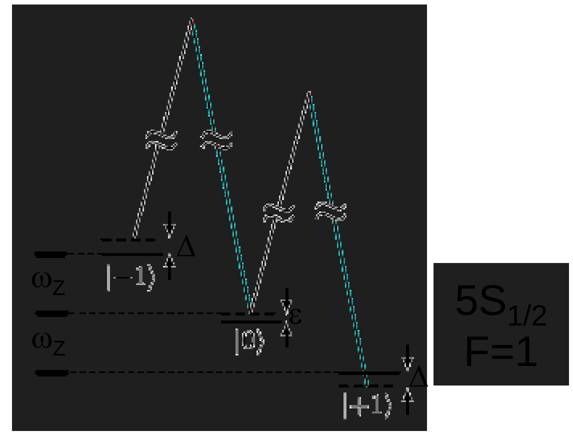
Synthetic vector potentials (I): synthetic magnetic field B^*

a. Raman-dressed BEC

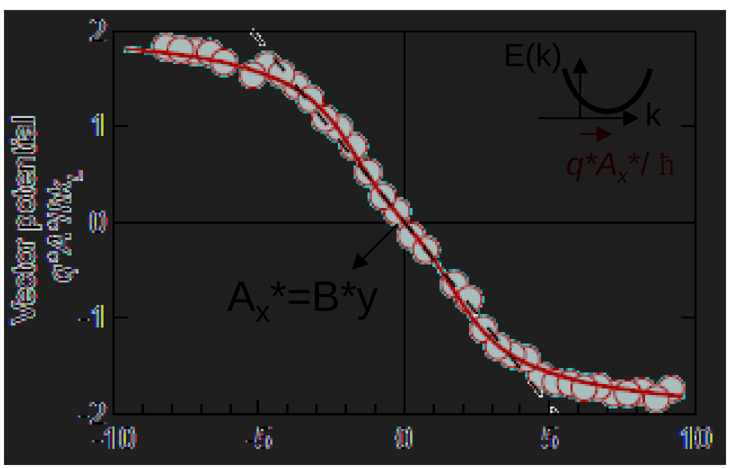


Raman2 Raman1

b. Level diagram

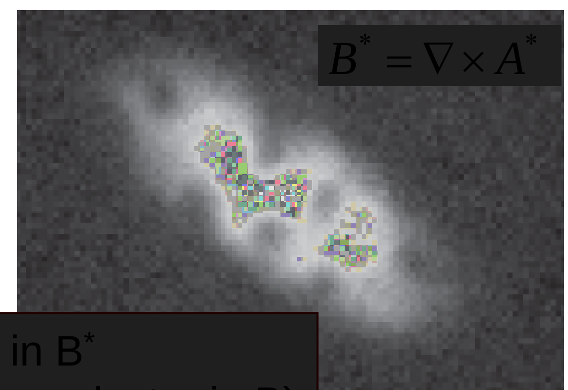


c. Vector potential A_x^* vs. position y



y position or detuning Δ

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

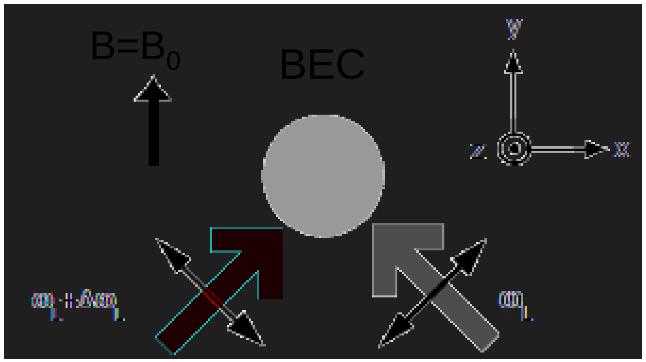


superfluid in B^*
(like superconductor in B)

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

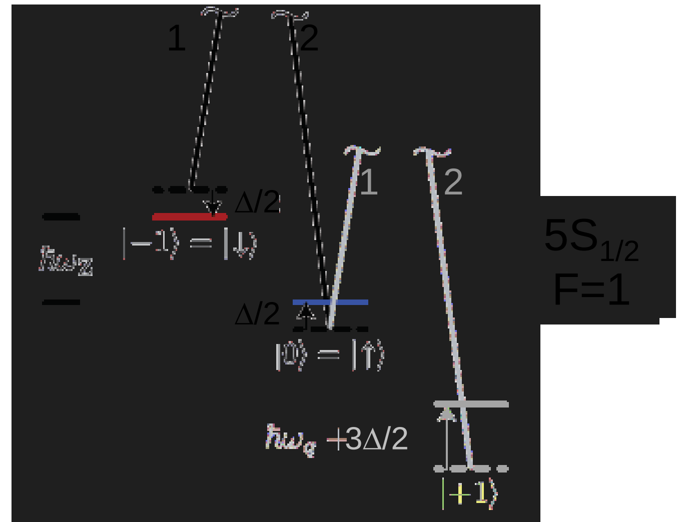
Synthetic vector potentials (II): spin-orbit coupling

a. Raman-dressed BEC

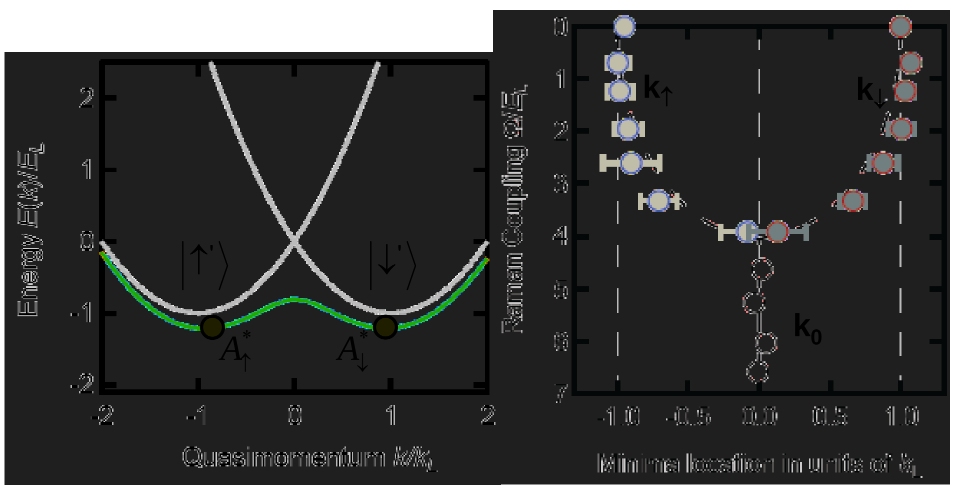


Raman2 Raman1

b. Level diagram



c. Spin dependent A^*: spin-orbit coupling



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

Outline

• introduction of synthetic vector gauge potentials for ultracold neutral atoms: synthetic magnetic field and spin-orbit coupling

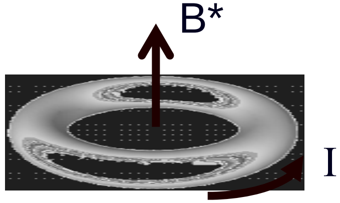
• experiment direction:
(i) generate synthetic magnetic flux Φ_B in a toroidal trap
(ii) detection atomic circulations induced by Φ_B

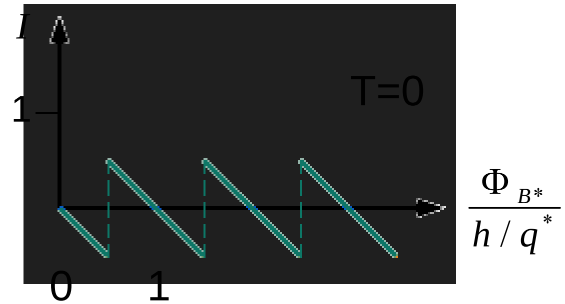
• We have achieved a ^{87}Rb Bose-Einstein condensate (BEC) with up to $3\text{x}10^5$ atoms in a crossed optical dipole trap

• current experimental work and plan

Atomic currents vs. magnetic flux

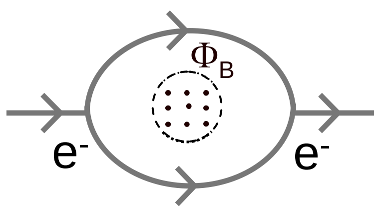
Equilibrium atomic currents I vs. B*: expect Aharonov-Bohm oscillation





Aharonov-Bohm effect:

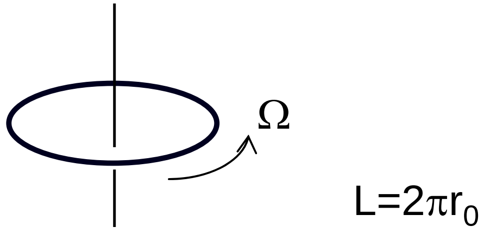
e^- in a 2-arm interferometer enclosing a magnetic flux Φ_B



probability $\propto 1 + Cos\left(2\pi \frac{\Phi_B}{h/e}\right)$

Atomic currents: analog between rotation and B*

B* = rotation and go to the rotating frame



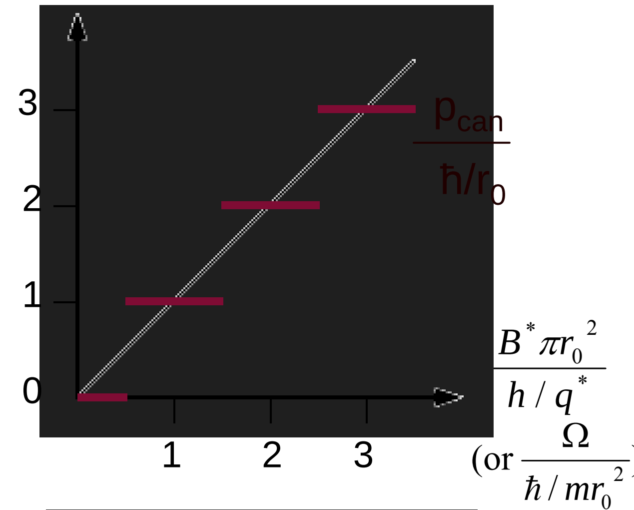
1D ring, radius r_0, rotating velocity Ω

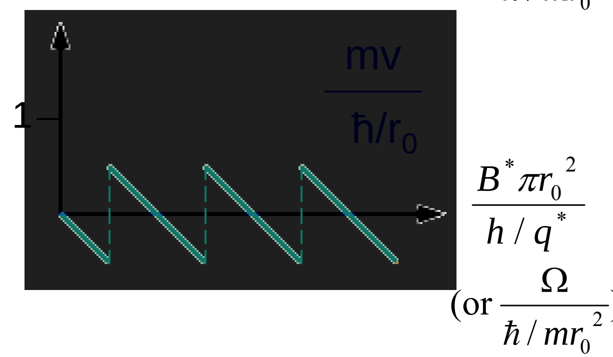
rotation	B^*
velocity in the rotating frame ↔	velocity of q* in B*

$$m\vec{v} = \vec{p}_{can} - m\Omega r_0 \hat{\phi} \leftrightarrow \vec{p}_{can} - \frac{q^* B^*}{2} r_0 \hat{\phi}$$

v = equilibrium current
= nonclassical rotational inertia
→ a measure of SF

P_{can} and mv vs. B* (or rotation)





Traditional methods to create B* : rotation

rotating neutral atoms

$F_{Coriolis} = 2m\Omega v_{rot}$

$\Omega \leftrightarrow qB/2m$

charge *q* in *B*

$F_{Lorentz} = qvB$

$$H_{rot} = \frac{\hbar^2}{2m}\left[(k_x - \frac{m\Omega y}{\hbar})^2 + (k_y + \frac{m\Omega x}{\hbar})^2\right] + V'(r)$$

$$V'(r) = \frac{1}{2}m(\omega^2 - \Omega^2)r^2$$

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

$$V(r) = \frac{1}{2}m\omega^2 r^2$$

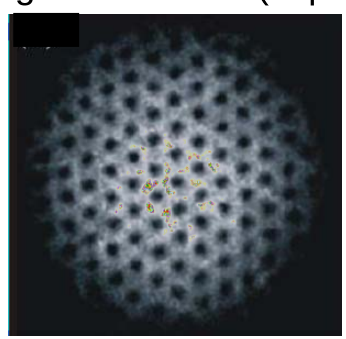
w/ mean field interaction

N_v vortices, $L/N = N_v/2$ (large N_v)

N_v vortices or flux quanta

(one vortex $\leftrightarrow$ $\Phi_0 = h/q$)

rotating neutral BEC (experiment)



$\Omega/\omega = 0.975$, R~ 30μm

Coddington et al., JILA, 2004

Generating magnetic flux

transfer angular momentum, modify dispersion E(ℓ)

- Raman beams w/ OAM (orbital angular momentum), transfer $\Delta\ell$ to atoms
- shift of dispersion minimum: $\ell_{\min}$ (controlled by detuning)

$$1\text{D}: H = \frac{\hbar^2}{2mr_0^2}\left(\frac{\partial}{i\partial\phi} - \ell_{\min}\right)^2$$

$$\vec{p}_{can} - q^* A^* \hat{\phi}$$

$$\underline{r_0 q^* A^* = \hbar \ell_{\min}}$$

$$\text{flux } \Phi_B = \oint A^* dl = h\ell_{\min}$$

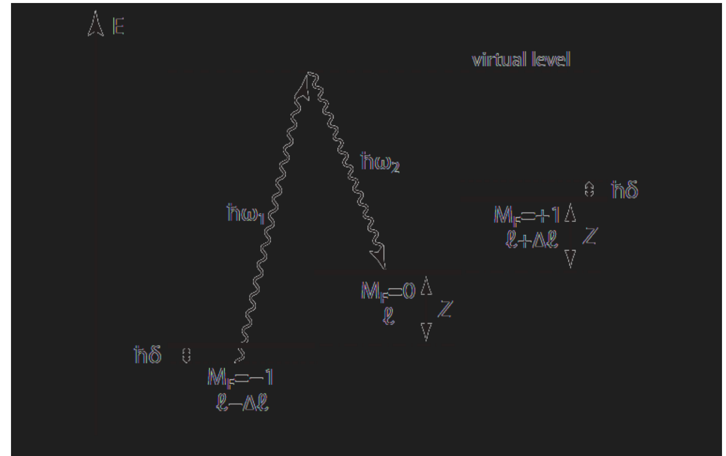
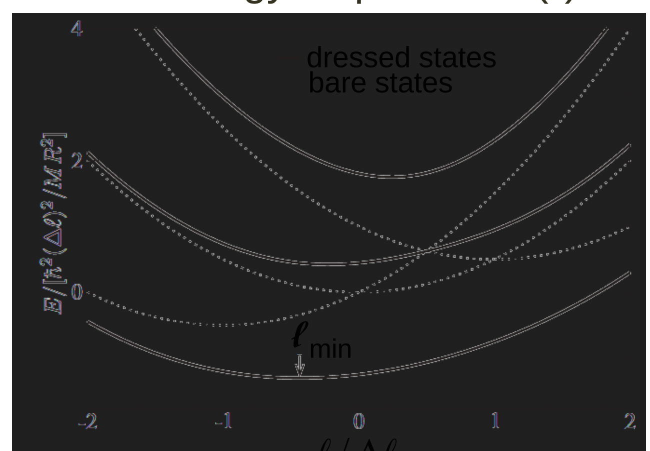


FIG. 2. Sketch of a two-photon Raman transition between hyperfine levels, adapted from Spielman *et al.* [21,22].

Energy dispersion E(ℓ)



Ref: Lin et al., PRL (2009)
S.T.John, Z. Hadzibabic and N. R. Cooper, PRA (2011) (adapted figure source)

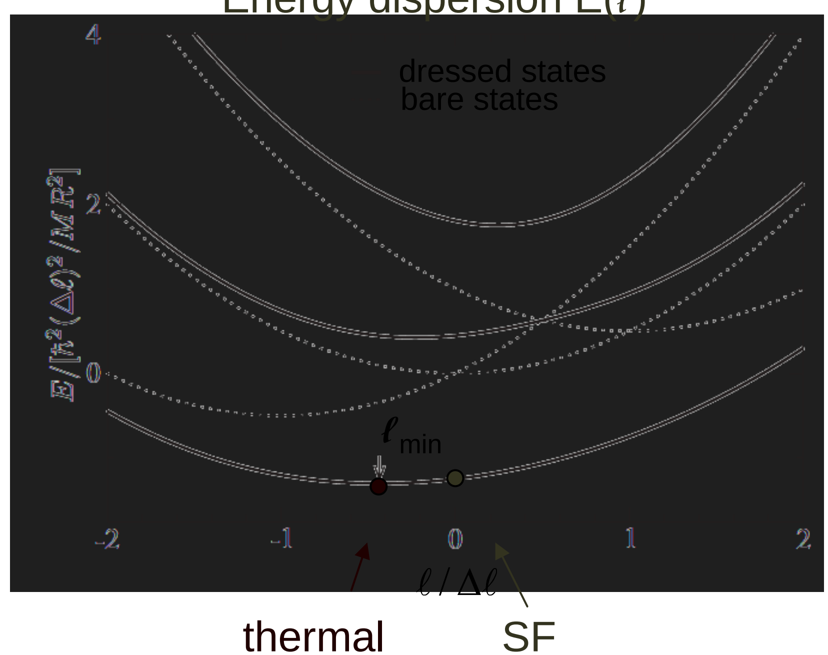
Detecting dressed atoms' angular momentum

dressed state: $|-1, \ell - \Delta\ell\rangle$, $|\,0, \ell\rangle$, $|+1, \ell + \Delta\ell\rangle$
spin $m_F = 0, \pm 1$

- dressed state $\langle \ell \rangle$ = population weighted average with m_F
  = group velocity $\propto dE/d\ell$

- thermal atoms' ensemble average: $\ell = \ell_{min}$, v=0
  SF: $\ell = 0$, $v \neq 0$

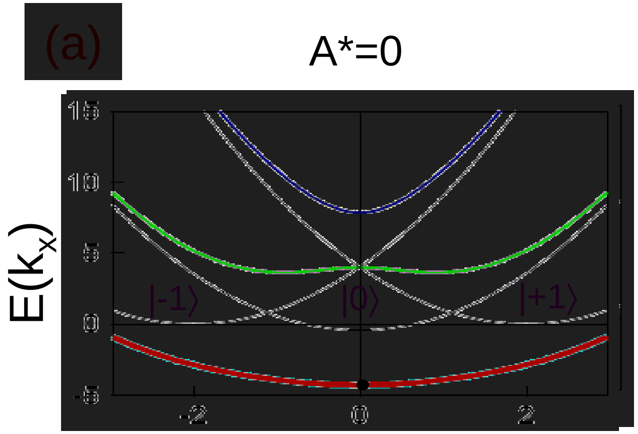
Energy dispersion E(ℓ)



dressed state with uniform A*

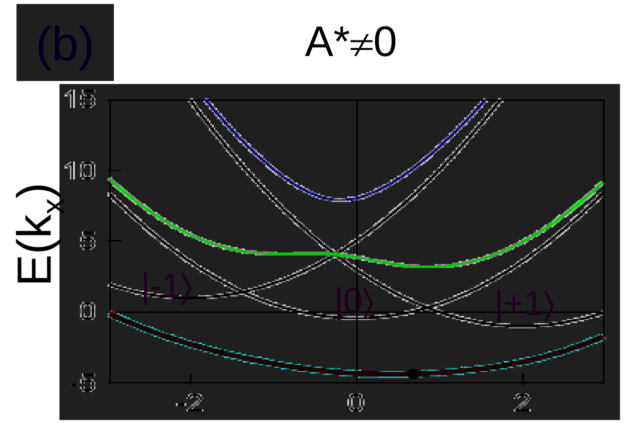
Energy dispersion $E(k_x)$

$A^*=0$



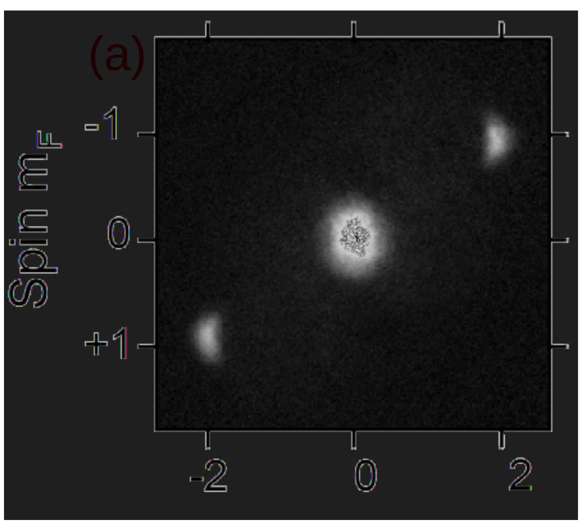
Quasi-momentum k_x/k_L

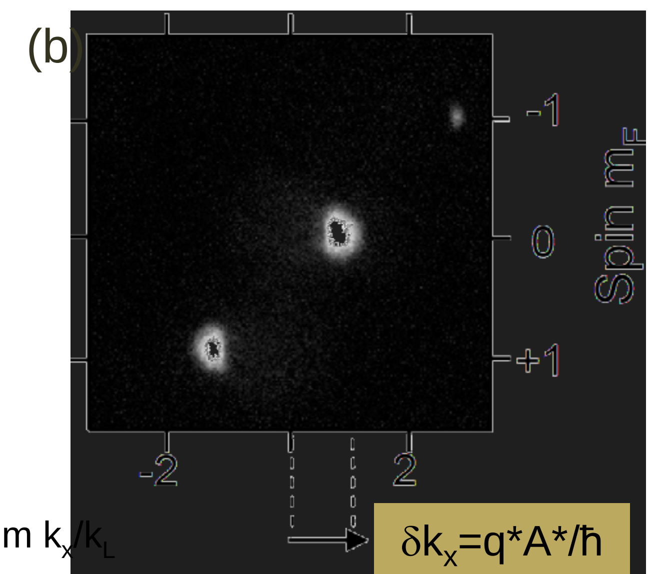
$A^*\neq 0$



$\delta k_x = q^*A^*/\hbar$

Spin-resolved Time-of-Flight (TOF) images





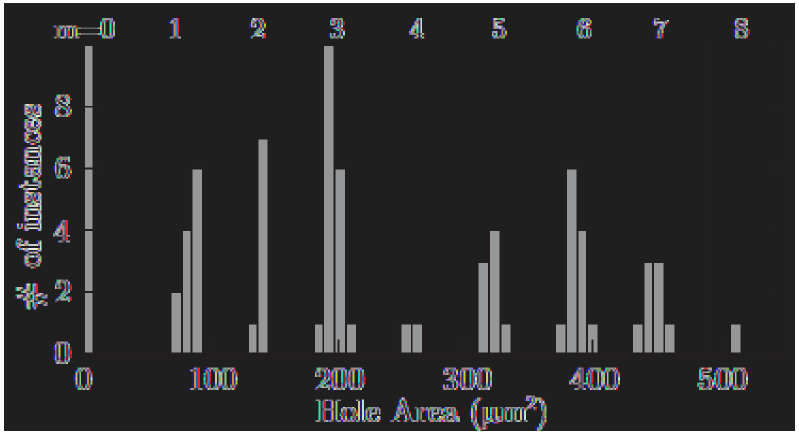
Quasi-momentum k_x/k_L

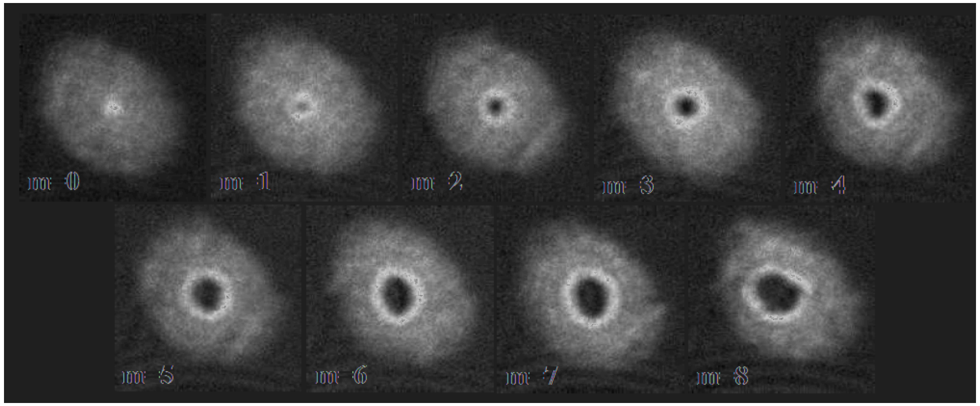
Detection of angular momentum ℓ

angular momentum: from hole size in TOF images

circulation of stirred BEC determined by the hole sizes in 10ms TOF ($\ell \to$m)

ramp down$\to$ release $\to$TOF





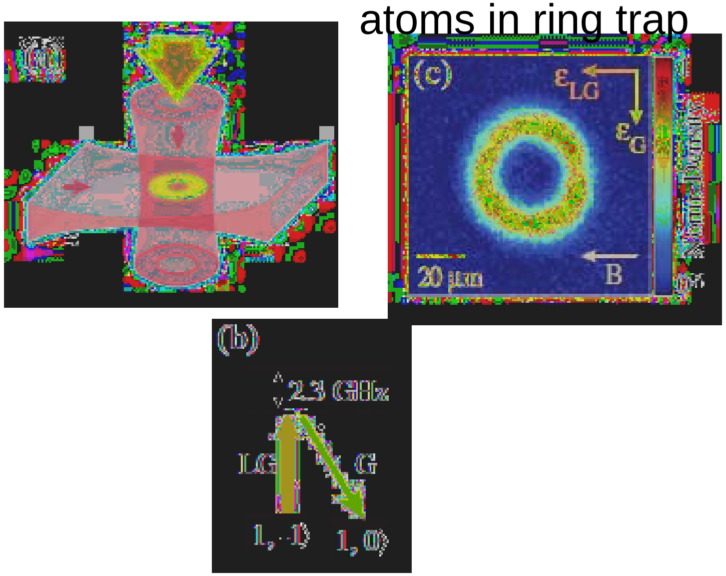
Ref: Murray et al, arxiv cond-mat.quat-gas 1309.2257v1
experiment: NIST Na ring BEC

Setup: ring trap geometry

Typical setup:
light sheet + ring beam

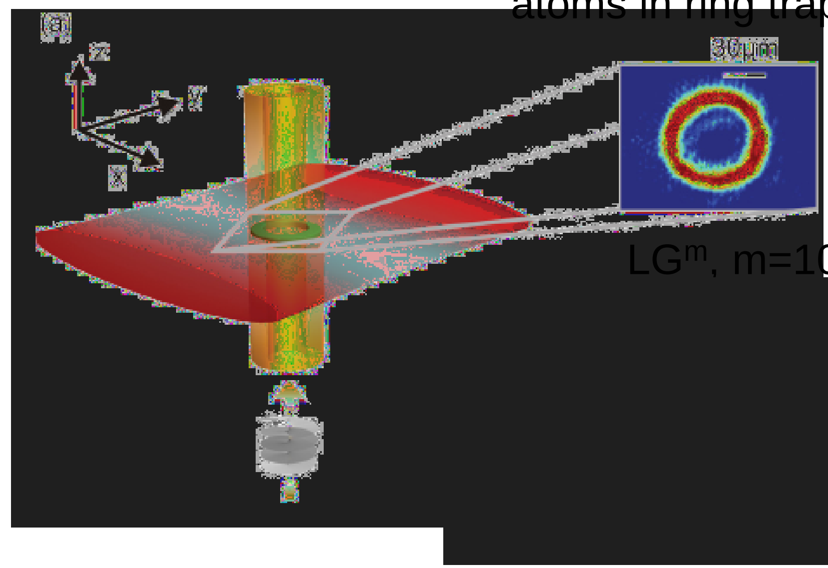
NIST Na ring BEC

atoms in ring trap



Cambridge group Rb ring BEC

atoms in ring trap



LG^m, m=10

Ref: Ramanthan et al., PRL (2011)

Ref: Z. Hadzibabic group, PRA (2012)
PRL(2013)

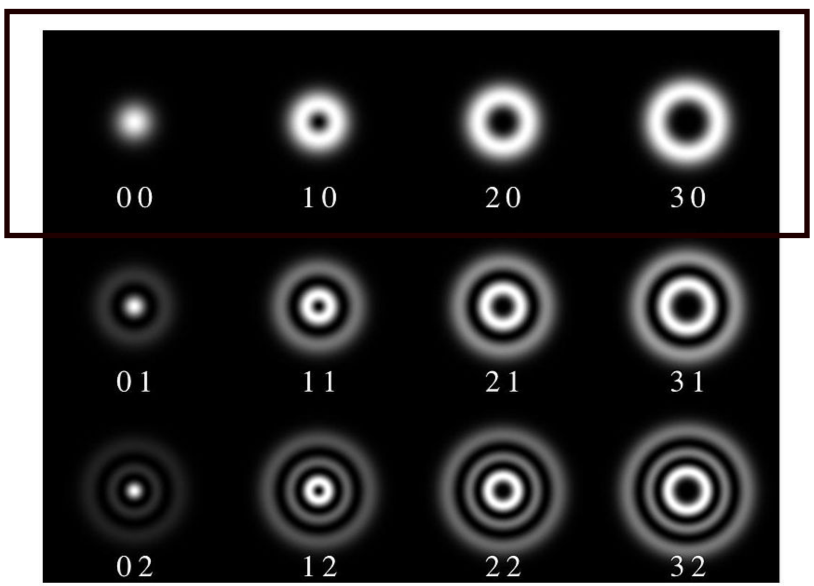
Laguerre-Gaussian beam LG^m

Laguerre-Gaussian beams LG_n^m

m= phase winding

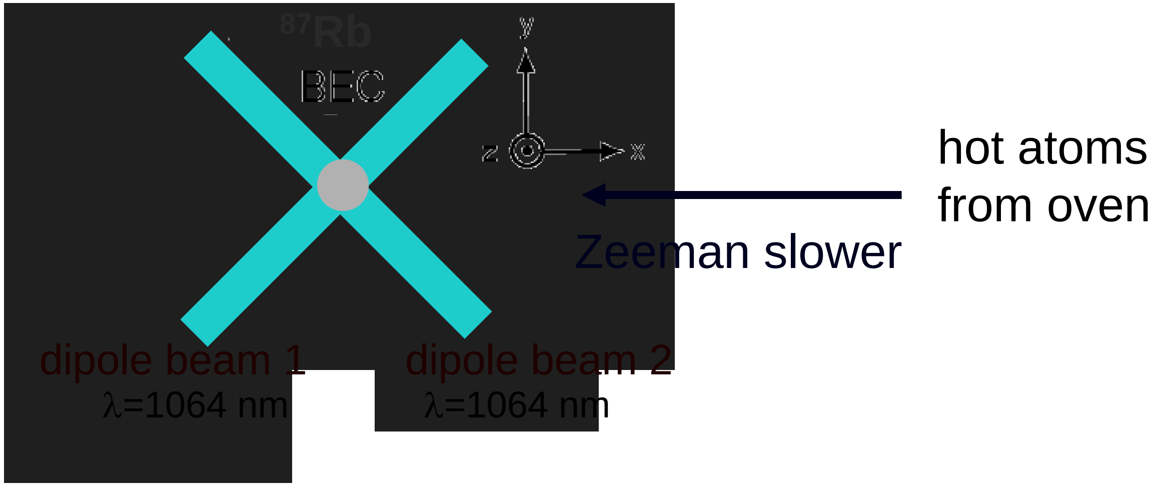
n= radial index

$$LG_0^m = LG^m \propto r^m e^{-r^2/w^2} e^{im\phi}$$



$$LG_0^m = LG^m$$

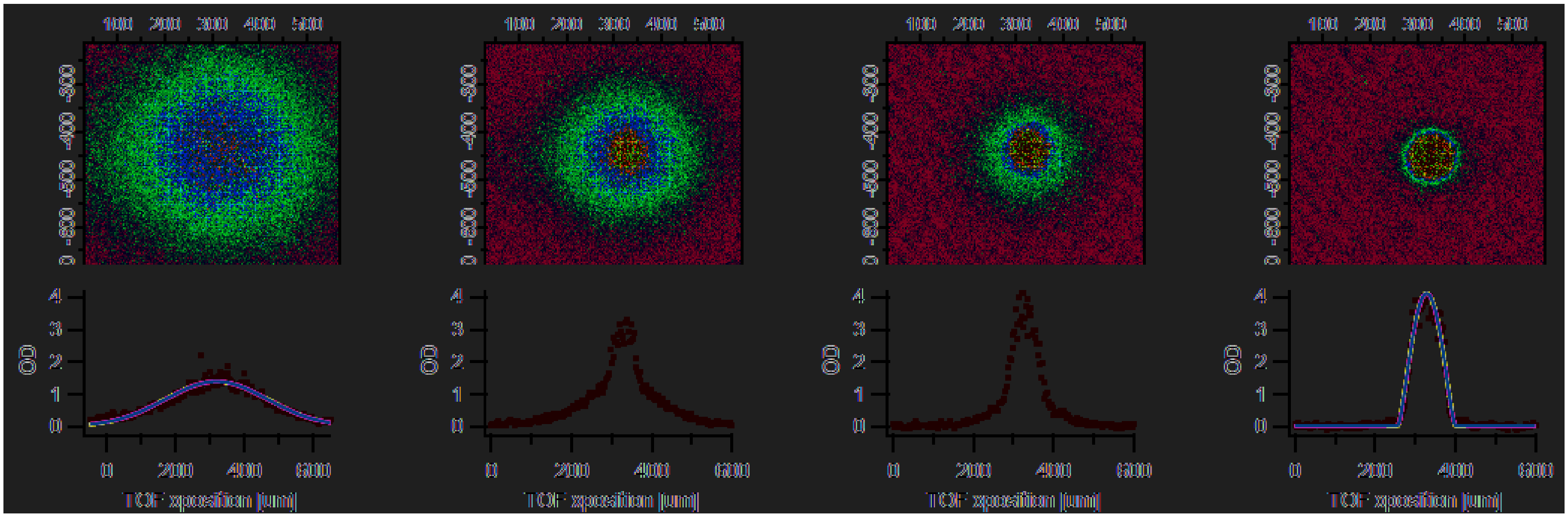
Experiment: BEC production



- load Magneto-Optical trap (MOT) from Zeeman slower: ~ 8×10^8 atoms in 3 s
- polarization gradient cooling >~ 10 ms to ~8 μK
- rf-evaporative cooling in a quadrupole magnetic trap for 3.5 s, $|F=1, m_F = -1\rangle$
- crossed optical dipole trap + weak magnetic trap:
  evaporate in hybrid potential for ~ 7s
  → ramp off magnetic gradient in 2.5s
  → BEC in crossed dipole trap: 3×10^5 atoms
- total cycle time~ 20 s

Thermal atoms to BEC

20ms Time of Flight



thermal

bimodal

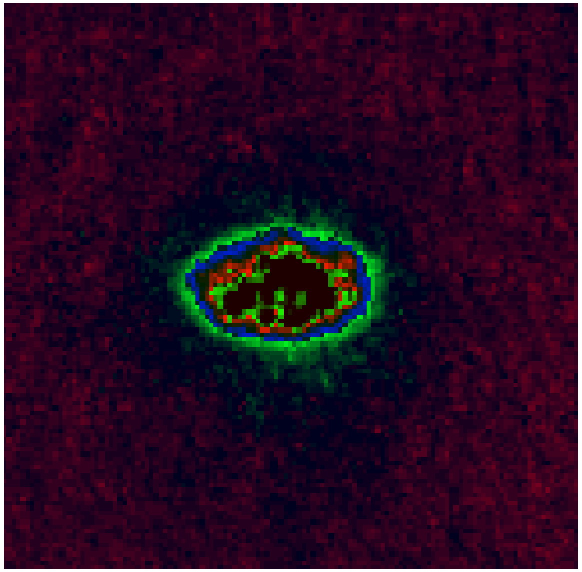
bimodal

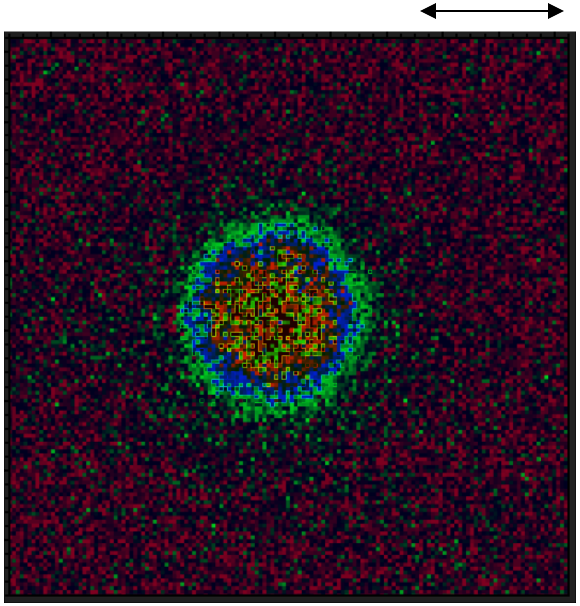
BEC
atom number
N~ 10^5

cooling

Optimized BEC

BEC number ~ $3x10^5$

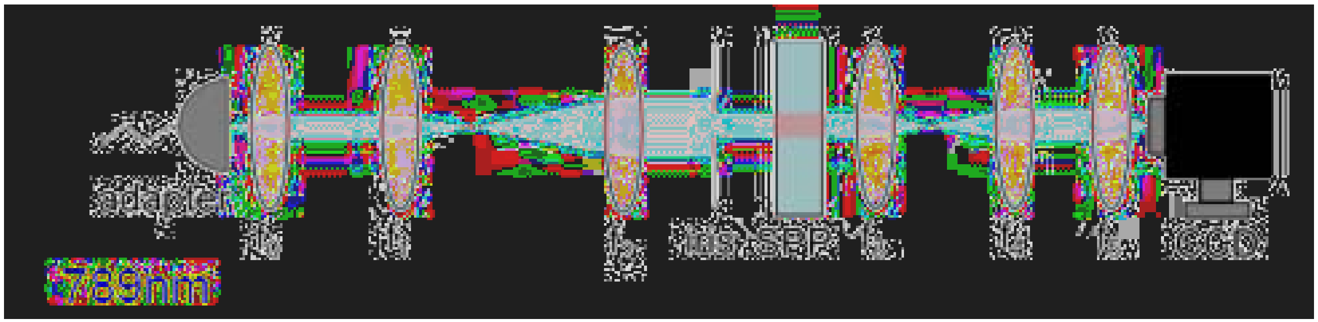




Experiment: generating magnetic flux

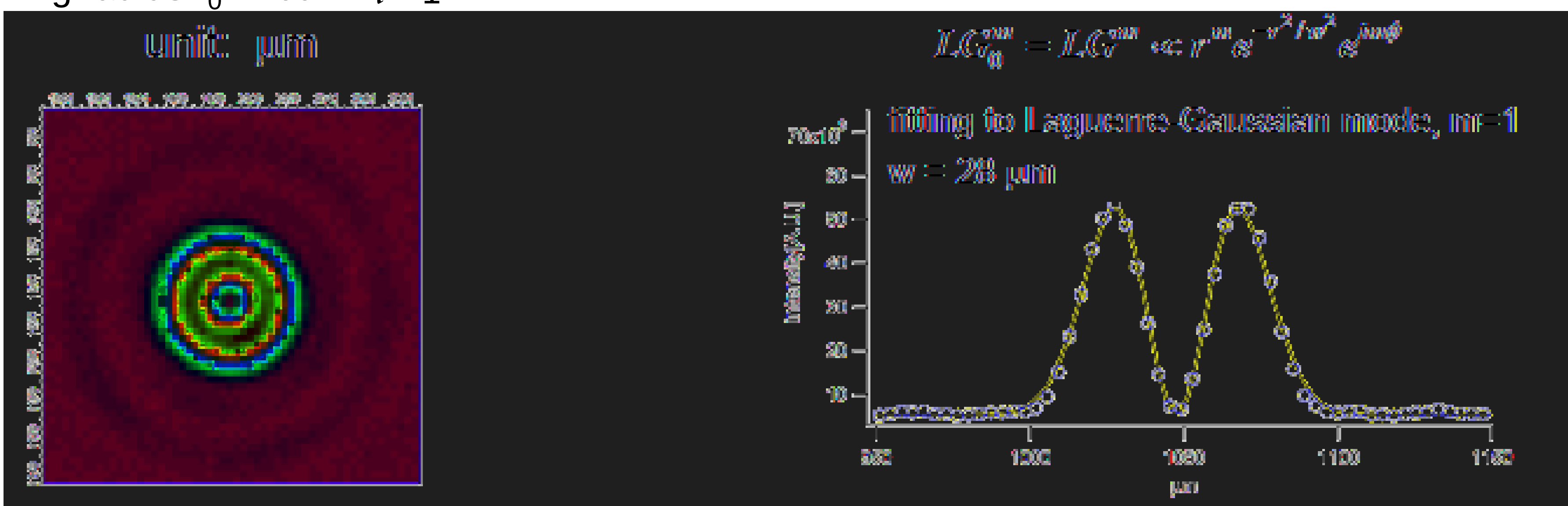
Raman beam with OAM= $\ell\hbar$

spiral phase plate (SPP): generate phase winding $e^{i\ell\phi}$



CCD image

ring radius r_0~ 20um $\ell = 1$



Ongoing work

• loading atoms into the ring trap: crossed light sheet beam+ ring beam

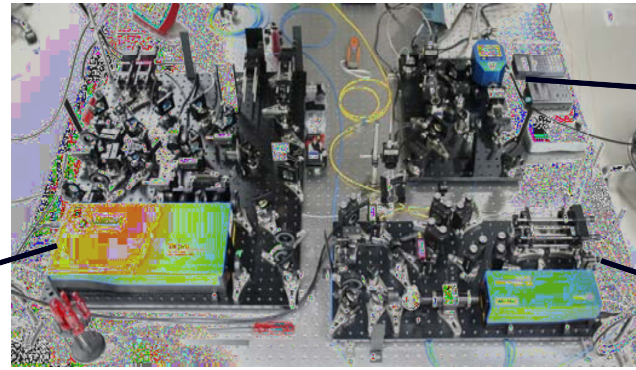
• making smooth ring-shaped trapping potentials, and combining multiple beams

• stability of the experiment

• finite temperature effects, detection of thermal atoms

Experimental setup

Diode lasers for laser cooling

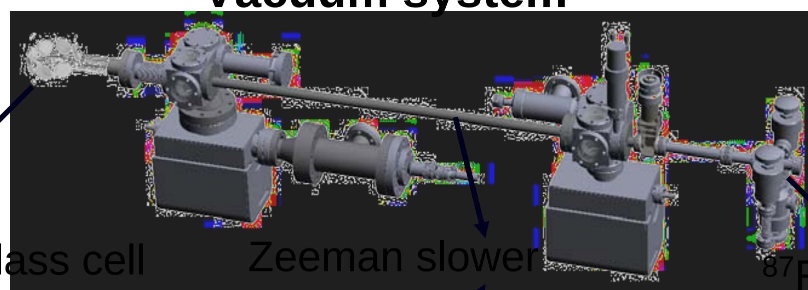


Reference laser
(locked to atomic cell)

MOT laser
(cooling)

Repumper laser
(repumping)

Vacuum system

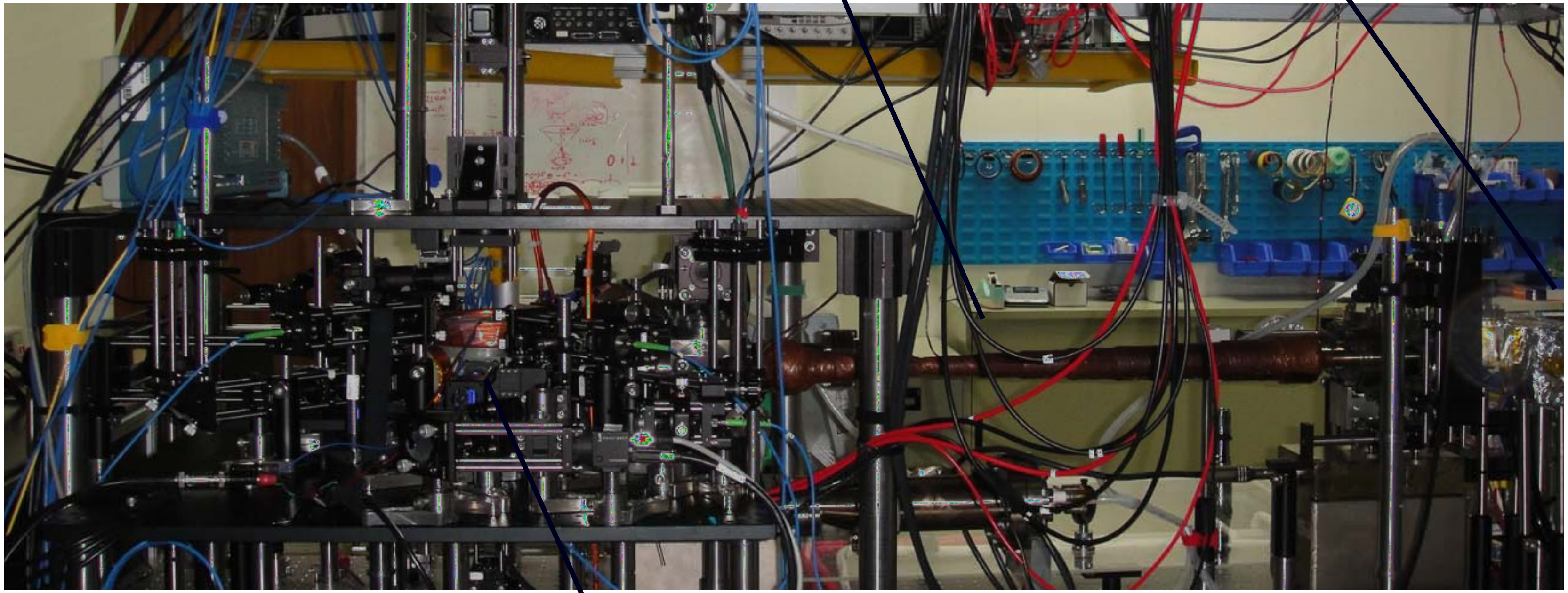


BEC/MOT glass cell

Zeeman slower

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

Experimental setup



Acknowledgements

NIST

Karina Jimenez-Garcia

Robert Compton

James Trey Porto

William Phillips

Ian Spielman

IAMS

Cheng-An Chen

Pan-Pan Huang

Jung-Bin Wang

Chin-Yeh Yu

Gergely Imreh

IAMS

中央研究院 ACADEMIA SINICA

科技部 Ministry of Science and Technology

Summary

• synthetic vector gauge potentials for ultracold neutral atoms

• have achieved ^{87}Rb BEC with up to $3x10^5$ atoms in a crossed dipole trap

• next: produce BEC in a ring trap

• toward generating atomic circulation from a magnetic flux Φ_B and A^* by Raman beams with OAM