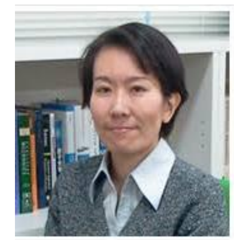
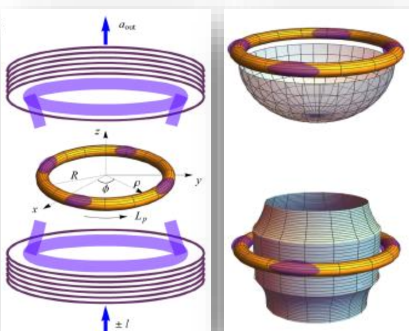
# Solving Problems in Atomic Superfluid Rotation using Cavity Optomechanics*

| Postdocs | | Graduate students | | Faculty | |
|---|---|---|---|---|---|
|  |  |  |  |  |  |
| P. Kumar | N. Daloi | N. Pradhan | S. Kalita | R. Kanamoto | P. Mishra |




**Mishkat Bhattacharya**

School of Physics and Astronomy
&
Future Photon Initiative
Rochester Institute of Technology



N. Pradhan et al., Physical Review A **109**, 023524 (2024)
N. Pradhan et al., Physical Review Research **6**, 013104 (2024)
S. Kalita et al. Physical Review A **107**, 013525 (2023)
*P. Kumar, et al. Physical Review Letters **127**, 113601 (2021)


CAREER

2024

# AMO Theory group @ RIT

Rochester Institute of Technology: 20,000students+1100 faculty

School of Physics and Astronomy: ~ 40 fulltime faculty,

PhD Program in Astrophysics

MS in physics started in 2018

PhD in Physics started in 2024!!

Future Photon Initiative

$T \gg$

THEORY (RIT)

MB

Prof. RIT

Brandon. R.

MITRE, Princeton

Wenchao Ge

Asst. Prof. U Rhode Is

Pardeep K.

Postdoc Max Planck Erlangen

K. Xiao

Postdoc RIT

S. Sharma

Postdoc KAIST South Korea

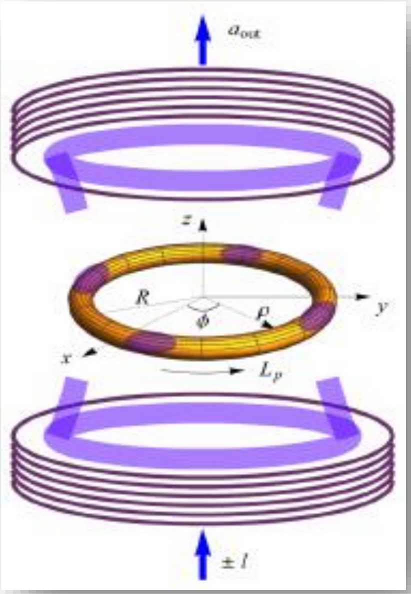
A. Kani

Postdoc OIST Japan

2 Postdoc positions open: mb6154@gmail.com

# Outline

- Atomic Superfluid Rotation
- Cavity Optomechanics
- Rotation Sensing
- Conclusion

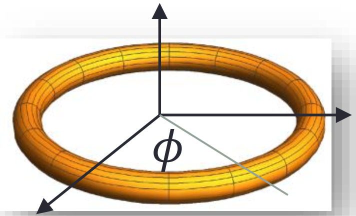


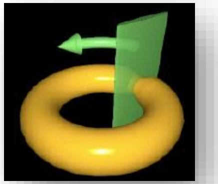
*L. Amico et al., Roadmap on Atomtronics,
*AVS Quantum Sci.* **3**, 039201 (2021)

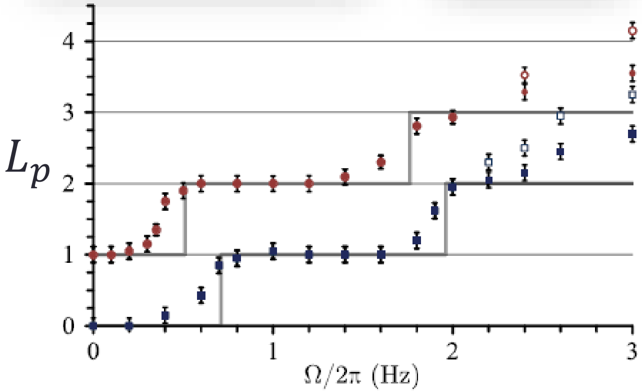
*M. Aspelmeyer et al. Cavity Optomechanics
*Reviews of Modern Physics* **82**, 1155 (2014)

# Quantized Persistent Currents in a Ring BEC

## Persistent currents





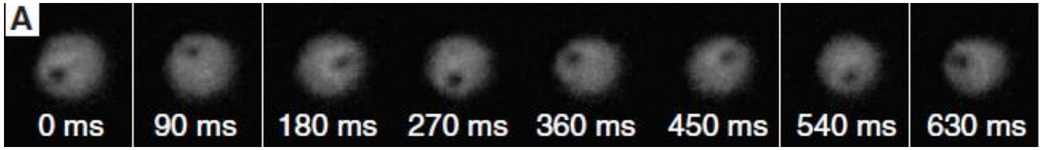

Wright et al., PRL **110**, 025302 (2013)

$$\psi = \sqrt{\frac{n}{2\pi}}\, e^{iL_p\phi}, L_p = 0, \pm 1, \pm 2, \ldots$$

## Why the ring BEC is important

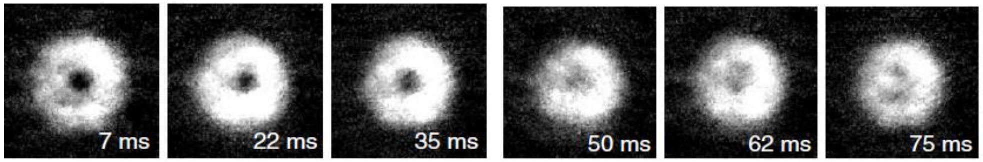
PRL **99**, 260402 (2007)

1. The ring trap pins the vortex down.




$L_p = 1$ in a harmonically trapped BEC [Science **329**, 1182 (2010)]

2. It topologically stabilizes high circulation.




$L_p = 2$ in a harmonically trapped BEC [PRL **93**, 160406 (2004)]

3. Metastable currents persist for minutes !
   - Beattie et al., PRL **110**, 025301 (2013)

Supersonic: $L_p \simeq 350$: Guo et al., PRL **124**, 025301 (2020)

Hypersonic: $L_p \simeq 40{,}000$: Pandey et al., Nature **570**, 205 (2019)

# Ring BECs: A Paradigm of Quantum Rotation

Superfluid hydrodynamics

- Z. Mehdi et al., SciPost Phys. **11**, 080 (2021)
- J. Polo et al., PRL **123**, 195301 (2019)
- K. C. Wright et al., PRL **110**, 025302 (2013)

Matter wave interferometry

- S. Pandey et al., PRL **126**, 170402 (2021)
- C. Ryu et al., Nat. Comm. **11**, 3338 (2020)

Atomtronic circuits

- J. Polo et al., PRL **121**, 0904040 (2018)
- S. Eckel et. al, Nature **506**, 200 (2014)

Topological defect formation

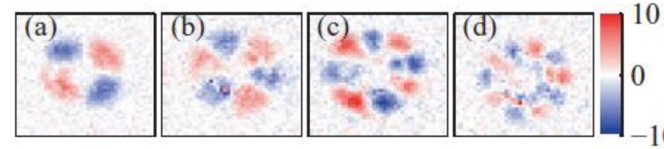
- Aidelsburger et. al, PRL **119**, 190403 (2017)

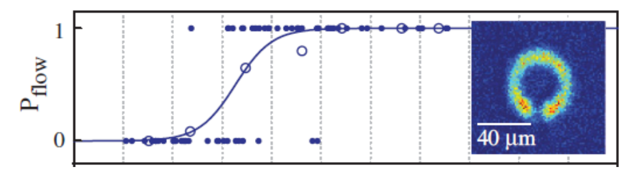
Cosmological simulations

- S. Eckel et. al, PRX **8**, 021021 (2018)

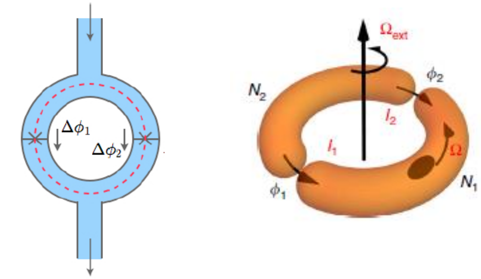
Fermionic supercurrents (BCS-BEC crossover)

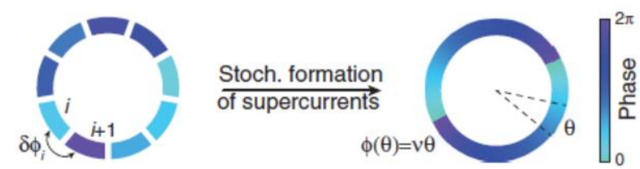
- Y. Cai et al. PRL **128**, 150401 (2022)
- G. Del Pace et al., Phys. Rev. X **12**, 041037 (2022)
- G. Pecci et al., PRR **3**, L032064 (2021)
- J. W. Park et al, PRL **121**, 225301 (2018)

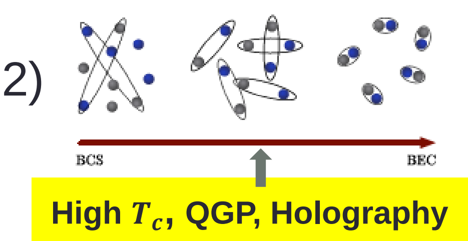



S Q U I D



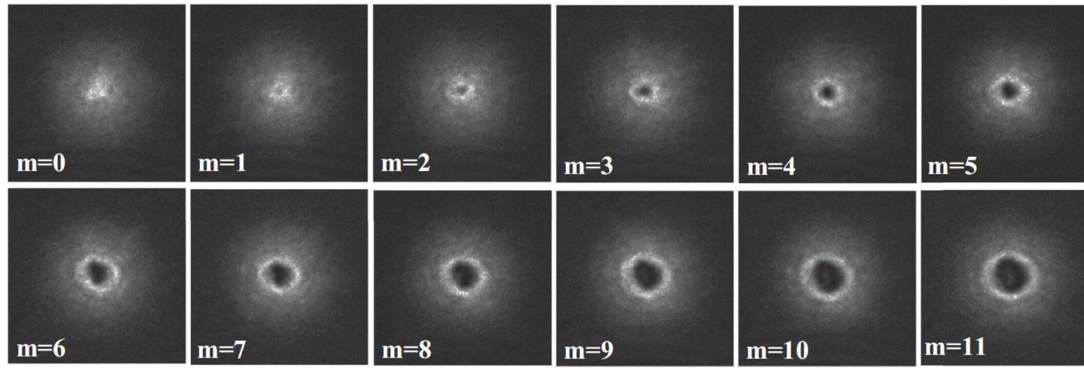



# Measuring the Ring BEC Rotation

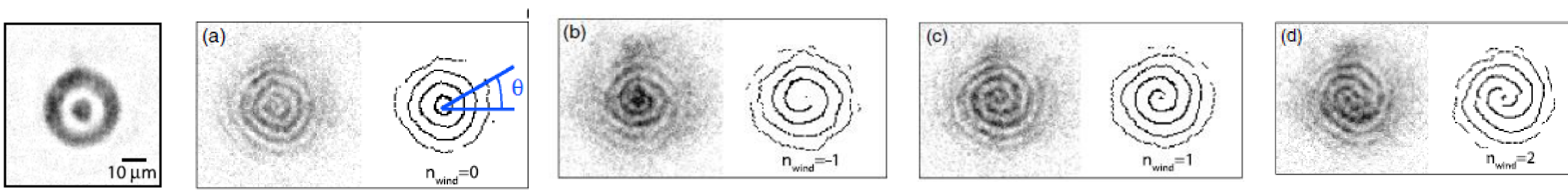
## Measure the radius after time of flight expansion

N. Murray et al.,
Phys. Rev. A **88**, 053615 (2013)
K. C. Wright et. al,
PRL **110**, 025302 (2013)



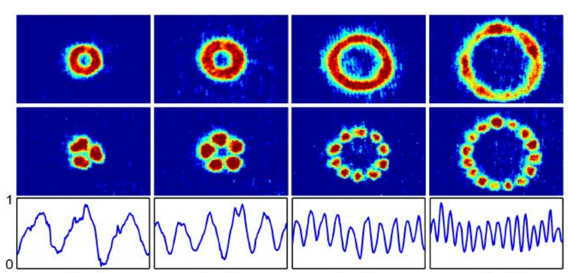

## Interfere with central non-rotating BEC

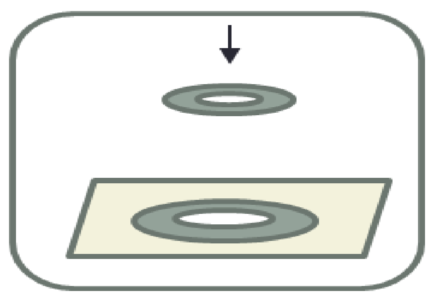
Corman et. al, PRL **113**, 135302 (2014)




## More complicated schemes

Moulder et. al, PRA **86**, 013629 (2012)



Absorption imaging

← Destructive!!

# Measuring the Ring BEC rotation

**Required**: A measurement technique that works

1. Non-destructively
   +
2. *In situ*
   +
3. In real time

→

**Aims:**

- Observing system dynamics in real time + *in situ* - the ideal aim of experiments
- Following historical precedent
- Coherent and reversible control
  - undoing phase slips
- Storing and retrieve information
  - quantum memory
- Detecting fermionic superfluidity directly without projecting to the BEC regime…

## Superconductors

- Nat. Comm. **8**, 85 (2017)
- Nature Physics **5**, 651 (2009)
- Nature **397**, 308 (1999)

## Superfluid He

- Nat. Comm. **12**, 2645 (2021)
- Science **366**, 1480 (2019)
- Nature **441**, 588 (2006)

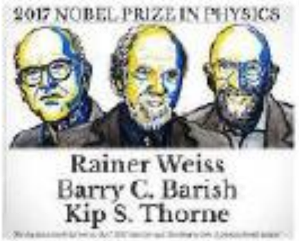
## Simply connected BECs

- *In situ* detection of vortices in BEC, PRA **91**, 023631 (2015)
- Real-time dynamics of single vortex lines in BECs, Science **329**, 1182 (2010)
- Vortex precession in BECs, PRL **85**, 2857 (2000)
- Rotational superradiance… arXiv:2404.1013v1 (2024)

Minimally destructive, Doppler measurement of a Quantized flow in a ring-shaped BEC,
A. Kumar et al., NJP **18**, 025001 (2016)

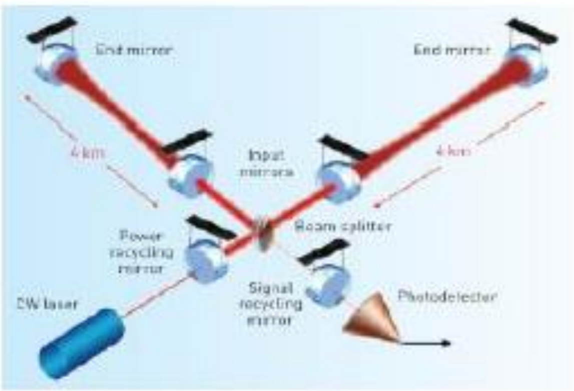
# Cavity Optomechanics

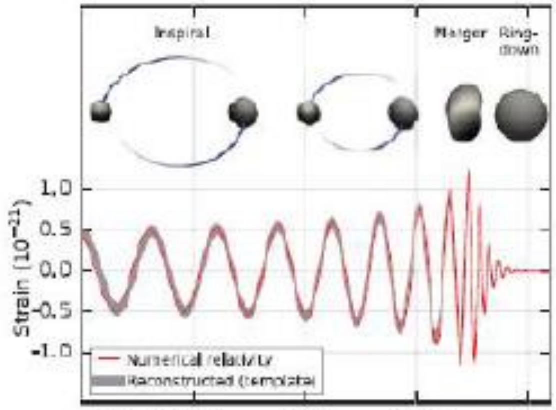
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016




## Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)




→ LIGO is a cavity optomechanical device !!

Displacement = Strain x Length of int. arm
$\approx 10^{-18} m$

Also...

**Accelerometry**
A. G. Krause, M. Winger, T. D. Blasius, Q. Lin and O. Painter,
*Nat. Photon.* **6** 768 (2012)

**Magnetometry**
S. Forstner et. al,
*PRL* **108** 120801 (2012)

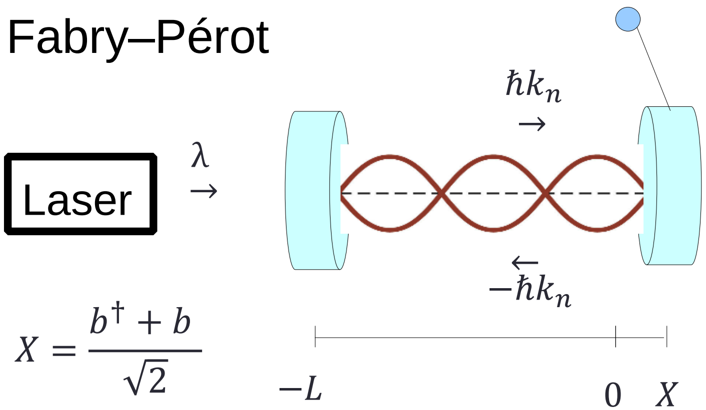
**Thermometry**
J. Millen et. al,
*Nat. Nano.* **9** 425(2012)

5

*M. Aspelmeyer et. al
*Reviews of Modern Physics* **82**, 1155 (2014)
*S. Bose, K. Jacobs and P. Knight, PRA **56**, 4175 (1997)

# The Radiation Pressure interaction

Fabry–Pérot




$$X = \frac{b^\dagger + b}{\sqrt{2}}$$

C. K. Law, PRA **51**, 2537(1995)

$$H = \hbar\omega_c a^\dagger a + \hbar\omega_m b^\dagger b + \hbar G a^\dagger a X + H_E$$

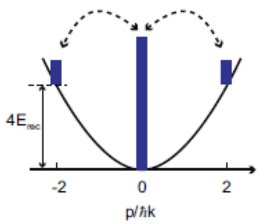
↗ optical mode ↑ mechanical oscillator ↑ radiation pressure interaction ↖ environment

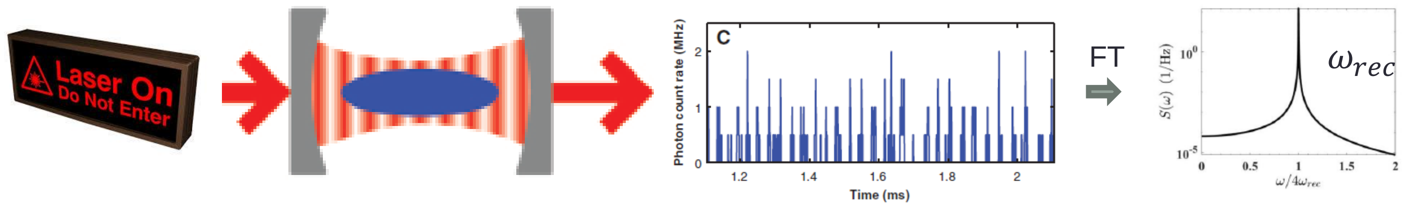
## TOOLBOX FOR MEASURING AND MANIPULATING MECHANICAL MOTION

1. Sub-quantum limit detection of mechanical motion..Nature Physics **15**, 745 (2019)
2. Detection of quantum back-action……………………………. Science **339**,801(2013)
3. Back-action-evading measurement of motion……….Nat. Comm. **10**, 2086 (2019)
4. Squeezing of mechanical quadrature of motion………….Science **349**, 952 (2015)
5. Preparation of quantum mechanical ground state…..MB…PRL **99**, 073601 (2007)
6. Storing and retrieving optical information from mechanical elements…………………………..………PRL **107**, 133601 (2011)
7. Phonon lasing………………………..………PRL **113**, 030802 (2014)
8. Entangling multiple mechanical oscillators…….Nature **556**, 478 (2018)

….

# Nondestructive Measurement of Linear BEC motion




$$\omega_{rec} = \frac{\hbar k^2}{2m}$$

Cavity Optomechanics with a Bose-Einstein Condensate, F. Brennecke et al., Science **322**, 235 (2007)

Real-time observation of fluctuations at the driven-dissipative Dicke phase transition, PNAS **110**, 11763 (2013)

Dynamical Instability of a Bose-Einstein Condensate in an Optical Ring Resonator, D. Schmidt et al., Phys. Rev. Lett. **112**, 115302 (2014)

Observing chiral superfluid order by matter-wave interference, T. Kock et al., Phys. Rev. Lett. **114**, 115301 (2019)

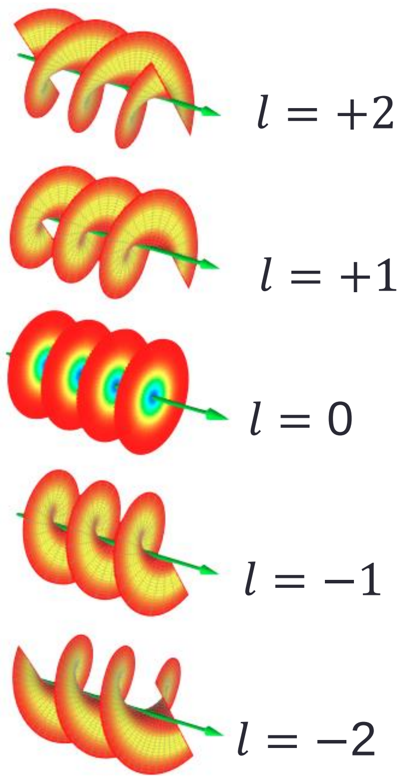
Entangled light from Bose-Einstein Condensates, H. T. Ng and S. Bose, New Journal of Physics **11**, 043009 (2009)

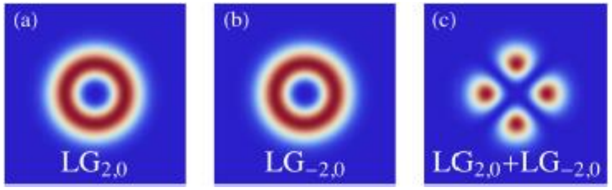
Cavity QED with Quantum Gases
Mivehvar et al., Advances in Physics **70**, 1 (2021)

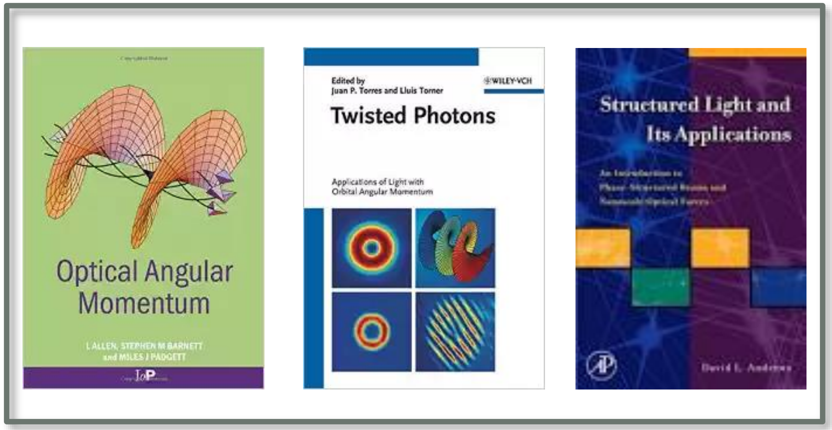
## Typical parameters

| | | |
|---|---|---|
| Atom number | $N$ | $10^5$ |
| Trap frequency | $\omega$ | 200 Hz |
| Atomic linewidth | $\gamma_0$ | $2\pi \times 3\ MHz$ |
| Detuning | $\Delta$ | $10^4\gamma_0$ |
| Beam waist | $\omega_0$ | $25\mu m$ |
| TF radius | $R$ | $5\mu m$ |
| Cavity linewidth | $\kappa$ | $2\pi \times 1.5\ MHz$ |
| Coupling | $g_0$ | $2\pi \times 10\ MHz$ |
| Cavity photon no. | $\bar{n}$ | 1 |
| Photon count rate | $S$ | $1\ MHz$ |
| Recoil frequency | $\omega_{rec}$ | $2\pi \times 4kHz$ |

# Beams with Orbital Angular Momentum



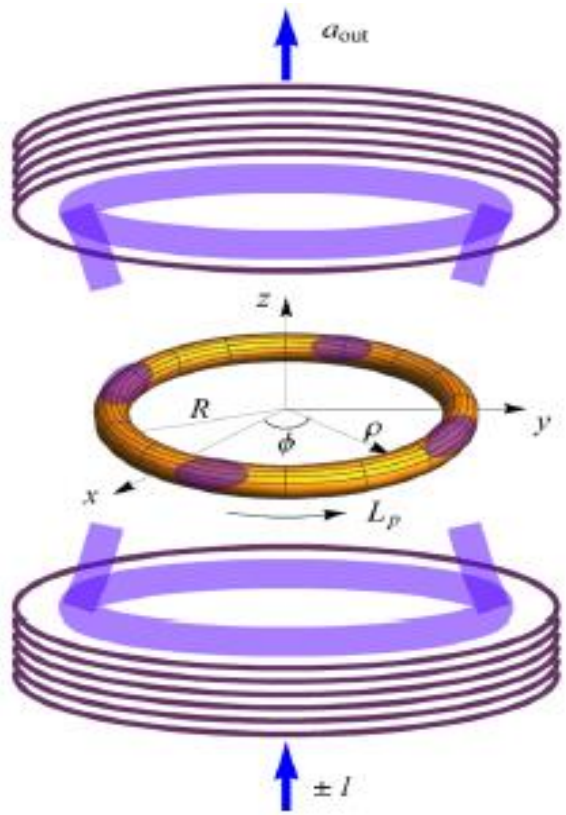




Mirhosseini et al., NJP **17**, 033033 (2015)
Leach et al., Science **329**, 662 (2010)

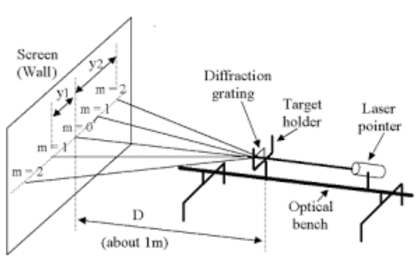
M. Padgett, Optics Express **25**, 11265 (2017)
MB and P. Meystre, PRL **99,** 153603 (2007)
H. Shi and MB, J. Phys. B **49**, 153001 (2016)

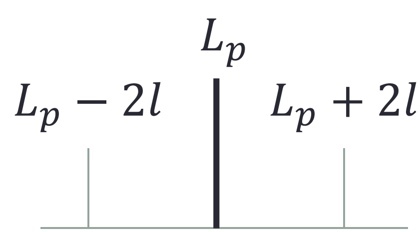
# Ring BEC in a cavity: Detecting $L_p$



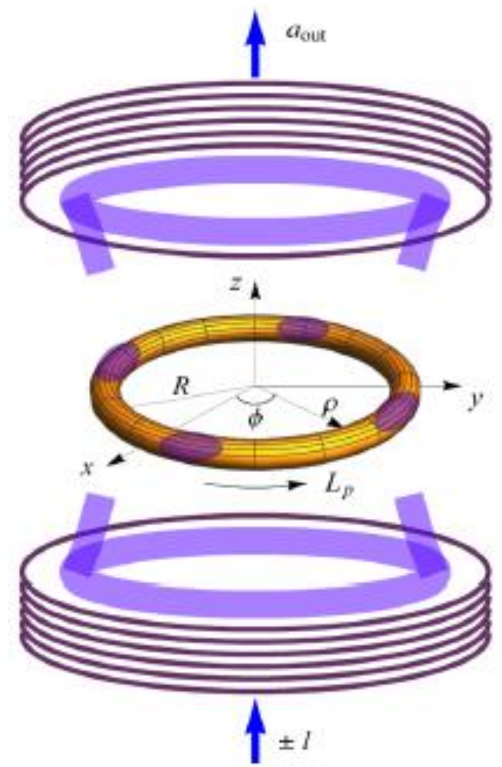

## Measurement Scheme

1. We start with a trapped ring BEC in a cavity.
2. The BEC has winding number $L_p$.
3. We drive the cavity with beams carrying OAM $\pm l\hbar$ far detuned from any atomic transition
4. The BEC matter wave Bragg diffracts from the angular lattice: $L_p \rightarrow L_p \pm 2l$
5. These matter waves beat to modulate the BEC density.
6. These modulations are picked up by the light transmitted by the cavity.
7. Cavity transmission yields $L_p$.



# Ring BEC in a cavity: Detecting $L_p$




**Hamiltonian:**

$$H = \int_0^{2\pi} \Psi^\dagger(\phi)\left[-\frac{\hbar^2}{2I}\frac{d^2}{d\phi^2} + \hbar U_o \cos^2(l\phi) a^\dagger a\right]\Psi(\phi)d\phi + \frac{g}{2}\int_0^{2\pi} \Psi^\dagger(\phi)\Psi^\dagger(\phi)\Psi(\phi)\Psi(\phi)d\phi - \hbar\Delta_o a^\dagger a - i\hbar\eta(a - a^\dagger),$$

$$I = mR^2;\ U_0 = \frac{g_a^2}{\Delta_a};\ g_a = E_0\langle e|d|g\rangle;\ \eta = \sqrt{P_{in}\gamma_o/\hbar\omega_o},$$
$$g = 2\hbar\omega_\rho a_{Na}/R$$

**Ansatz:**

$$\Psi(\phi) = \frac{e^{iL_p\phi}}{\sqrt{2\pi}}c_p + \frac{e^{i(L_p+2l)\phi}}{\sqrt{2\pi}}c_+ + \frac{e^{i(L_p-2l)\phi}}{\sqrt{2\pi}}c_-,$$

Persistent current — Sidemodes

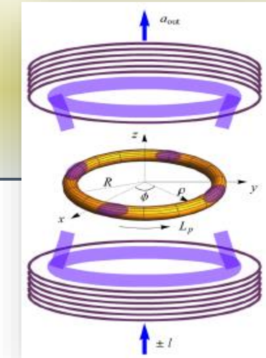
**Normalization:** $c_p^\dagger c_p + c_+^\dagger c_+ + c_-^\dagger c_- = N$

**Recognize:** $c_p \sim \sqrt{N}$ is a macroscopically occupied mode.

$$H = \hbar\omega_c c^\dagger c + \hbar\omega_d d^\dagger d + \hbar\left[G(X_c + X_d) - \tilde{\Delta}\right]a^\dagger a - i\hbar\eta\left(a - a^\dagger\right) + \hbar g\tilde{F}$$

$$\omega_{c,d} = \frac{\hbar(L_p \pm 2l)^2}{2I} \quad \left(c = \frac{c_p^\dagger c_+}{\sqrt{N}}, d = \frac{c_p^\dagger c_-}{\sqrt{N}}, G = \frac{U_0\sqrt{N}}{2\sqrt{2}}, \tilde{\Delta} = \Delta_0 - \frac{U_0 N}{2}\right)$$

# Detecting $L_p$: Equations of Motion



## Collisionless Hamiltonian ($g = 0$)

$$H = \hbar\omega_c c^\dagger c + \hbar\omega_d d^\dagger d + \hbar\left[G(X_c + X_d) - \tilde{\Delta}\right]a^\dagger a - i\hbar\eta(a - a^\dagger)$$

## (Quantum Langevin) Equations of motion

$$\ddot{X}_c + \gamma_m \dot{X}_c + \omega_c^2 X_c = -\omega_c G a^\dagger a + \omega_c \epsilon_c$$
$$\ddot{X}_d + \gamma_m \dot{X}_d + \omega_d^2 X_d = -\omega_d G a^\dagger a + \omega_d \epsilon_d$$
$$\dot{a} = i\left[\tilde{\Delta} - G(X_c + X_d)\right]a - \frac{\gamma_o}{2} a + \sqrt{\gamma_o}\, a_{in}$$

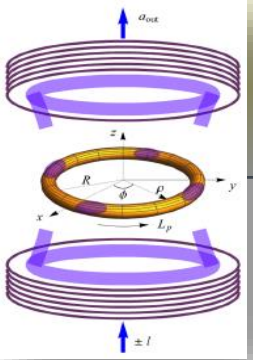
## Heuristic argument (neglecting noise and damping)

For weak optical driving, $X_{c,d}$ will be modulated at $\omega_{c,d}$.
And therefore $a$ will also.

→ So the cavity output will show two peaks at $\omega_{c,d}$.

W. Chen, D. S. Goldbaum, MB and P. Meystre,
PRA **81**, 053833 (2010)

# Detecting $L_p$: Experimental Parameters

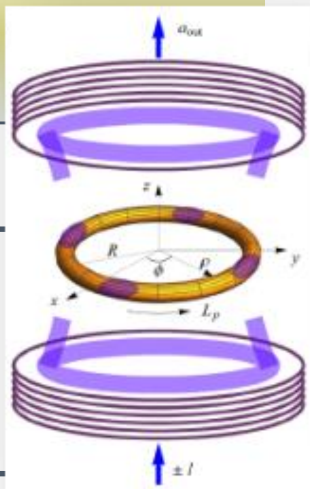


1. Mass of Sodium atom — $m = 23$ amu
2. Number of atoms — $N \sim 1.2 \times 10^4$
3. BEC radius — $R = 12\ \mu\text{m}$
4. Trap frequencies — $\omega_{\rho,z} = 2\pi \times 4 \times 10^{1-2}$ Hz
5. Temperature — $T = 10 - 20$ nK
6. Chemical potential — $\frac{\mu}{\hbar} = 200 - 500$ Hz
7. Winding number of BEC — $L_p = 1 - 5$
8. OAM of light — $l = 1 - 15$
9. Atom velocity — $v_a \sim 0.3 mm/s$
10. Sound velocity — $v_c \sim 1.5 mm/s$
11. Healing length — $\xi = 4 \mu m$
12. Atomic detuning — $\Delta_a = 2\pi \times 4.7$ GHz
13. Mechanical damping — $\gamma_m \sim 2\pi \times 1$ Hz
14. Cavity linewidth — $\gamma_0 = 2\pi \times 1.3$ MHz
15. Cavity detuning — $\Delta' = 0 - 500$ Hz
16. Cavity finesse — $\sim 10^4$
17. Optomechanical coupling — $G = 2\pi \times 260$ kHz
18. Input power — $P_{in} \sim 10$ fW
19. Angular lattice recoil — $\leq 1$KHz

P. Kumar et al., PRL **127**, 113601 (2021)

S. Kalita et al., PRA **107**, 013525 (2023)

# Detecting $L_p$: Noise Spectrum




Linear response $\mathcal{M} \to \mathcal{M}_s + \delta\mathcal{M}$ for $\mathcal{M} = X_c, X_d, a$

Phase quadrature

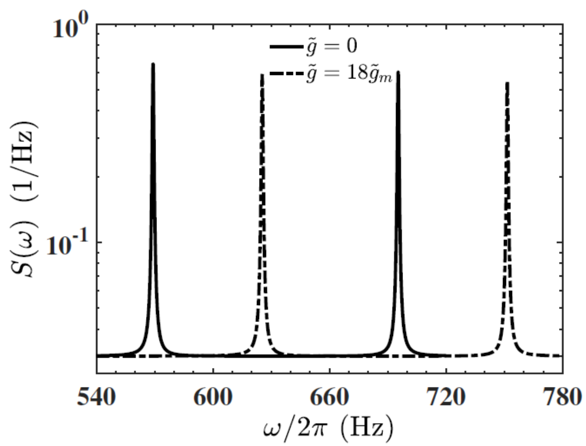
$$P = \frac{i(a_{out} - a_{out}^{\dagger})}{\sqrt{2}}$$

Input-output relation

$$a_{out} = -a_{in} + \sqrt{\gamma_o}\,a$$

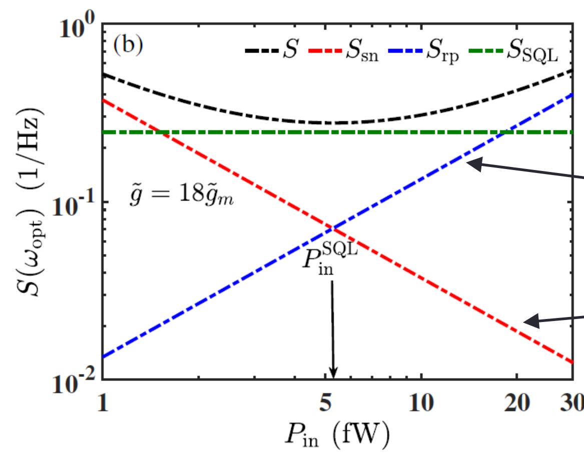
Output Noise Spectrum

$$S(\omega) = \int_{-\infty}^{+\infty} dt e^{i\omega t} \langle \delta P(t) \delta P(t) \rangle$$




$$\omega_c - \omega_d \cong \frac{4lL_p\hbar}{I}$$

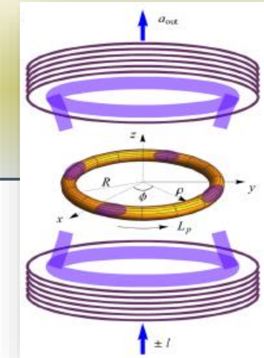
$$S(\omega) = S_{sn}(\omega) + S_{rp}(\omega) + S_{th}(\omega)$$




Backaction noise

Shot noise

# Detecting $L_p$: Sensitivity

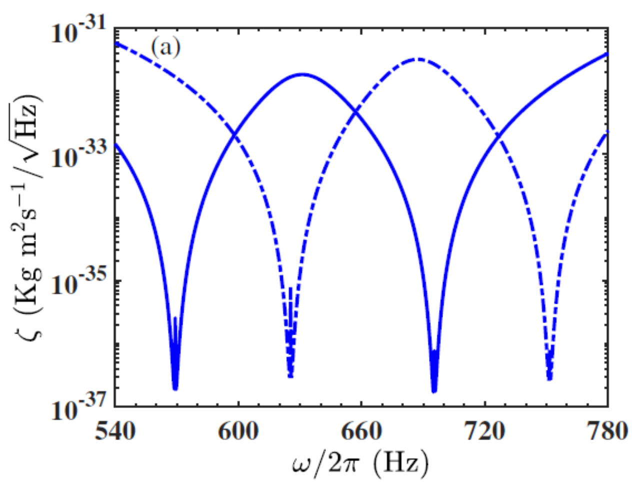


$$\zeta = \frac{S(\omega)}{\partial S(\omega)/\partial \Lambda}\sqrt{t_{meas}}$$

$$\Lambda = \hbar L_p$$

$$t_{meas} = \frac{\gamma_0}{8(a_s G)^2} \sim 60 \text{ ms} \ll 1 \text{ min}$$

→ ~ Real time



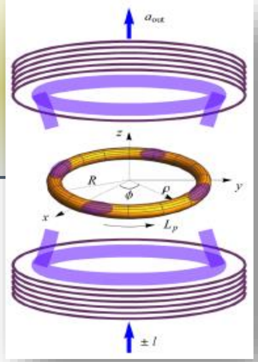

Number of atoms in the sidemodes ~ 10

→ Minimally destructive

$10^{-3}\text{Hz}/\sqrt{\text{Hz}}$ → Thousand times more sensitive than existing methods.

Kumar et al., New Journal of Physics **18**, 025001 (2016)
Ragole and Taylor, PRL **117**, 203002 (2016)
S. Safaei et al, PRA **100**, 013621 (2019)

# Matter wave (bipartite) entanglement




## Logarithmic negativity

$$\mathcal{E}_N = \max[0, -\ln(2\sigma_-)]$$

$$\sigma_- = 2^{-1/2}\left[\Sigma - \sqrt{\Sigma^2 - 4\det(V_{sub})}\right]^{1/2}$$

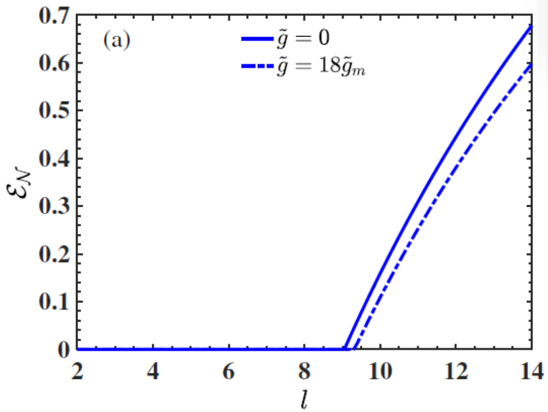
$$\Sigma = \det A + \det B - 2\det C$$

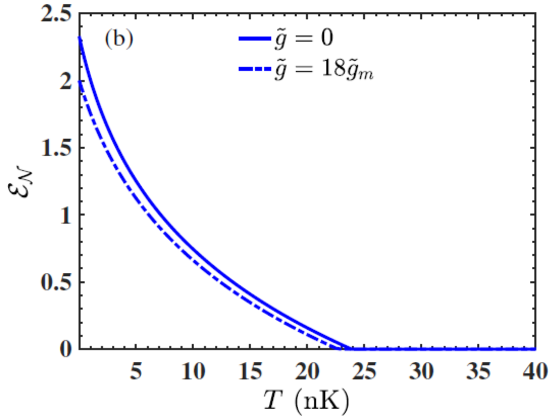
$$V_{\rm sub} = \begin{pmatrix} A & C \\ C^T & B \end{pmatrix}$$

$$V_{X_c X_c} = \langle \delta X_c \delta X_c \rangle$$

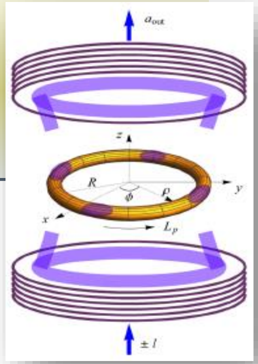
$$FV + VF^T = -D$$

$$F = \begin{pmatrix} 0 & \Omega_c & 0 & 0 & 0 & 0 \\ -\Omega_c & -\gamma_m & -\frac{A}{\Omega_c} & 0 & -\frac{\tilde{\omega}_c G_r}{\Omega_c} & -\frac{\tilde{\omega}_c G_i}{\Omega_c} \\ 0 & 0 & 0 & \Omega_d & 0 & 0 \\ \frac{A}{\Omega_d} & 0 & -\Omega_d & -\gamma_m & -\frac{\tilde{\omega}_d G_r}{\Omega_d} & -\frac{\tilde{\omega}_d G_i}{\Omega_d} \\ G_i & 0 & G_i & 0 & -\frac{\gamma_o}{2} & -\Delta' \\ -G_r & 0 & -G_r & 0 & \Delta' & -\frac{\gamma_o}{2} \end{pmatrix} \quad D = \text{diag}\left(0, \gamma_m(2n_c+1), 0, \gamma_m(2n_d+1), \frac{\gamma_o}{2}, \frac{\gamma_o}{2}\right)$$



# Stochastic Gross-Pitaevskii treatment



$$(i-\Gamma)\frac{d\psi}{d\tau} = \left[-\frac{d^2}{d\phi^2} + \frac{U_0}{\omega_\beta}|\alpha|^2\cos^2(l\phi) - \mu + 2\pi\frac{\gamma}{N}|\psi|^2\right]\psi + \xi(\phi,\tau)$$

$$i\frac{d\alpha}{d\tau} = \left\{-\left[\Delta_c - U_0\langle\cos^2(l\phi)\rangle_\tau + i\frac{\gamma_0}{2}\right]\alpha + i\eta\right\}\omega_\beta^{-1} + i\sqrt{\gamma_0}\,\omega_\beta^{-1}a_{in}$$

---

Scales: $\hbar\omega_\beta = \frac{\hbar^2}{2mR^2}$, $\tau = \omega_\beta t$, $\gamma = \frac{gN}{2\pi\hbar\omega_\beta}$

Noise correlations:

$$\langle\xi(\phi,\tau)\xi^*(\phi,\tau)\rangle = 2\Gamma T\delta(\phi-\phi')\delta(\tau-\tau')$$

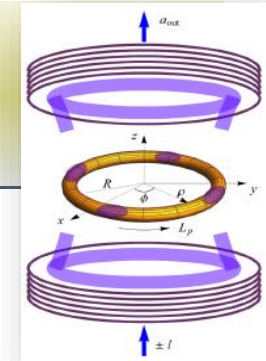
$$\langle a_{in}(\tau)a_{in}^*(\tau')\rangle = \omega_\beta\delta(\tau-\tau')$$

Reminders:

1. $\omega_{c,d} \ll \gamma_0$ (bad cavity limit)
2. $(\mu, k_B T) < \hbar(\omega_r, \omega_z)$ (1D BEC)
3. $U_0|\alpha|^2 < \mu$ (permeable barrier)

⟹ *PRA **74**, 023617 (2006)

# Gross-Pitaveskii treatment: Persistent Current



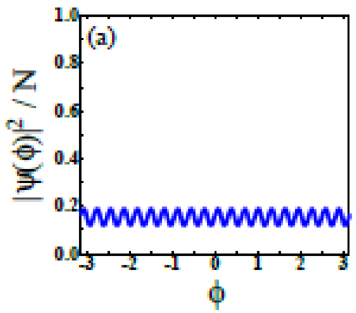
$$\psi(\phi) = \sqrt{\frac{N}{2\pi}} e^{iL_p\phi}$$

Atomic interactions are weakly repulsive

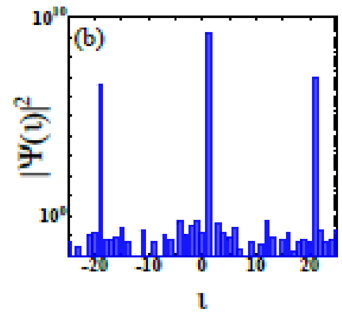
$^{23}Na$

Ryu et al.,
PRL **99**, 260401 (2007)

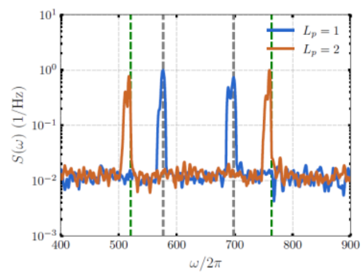
Condensate density



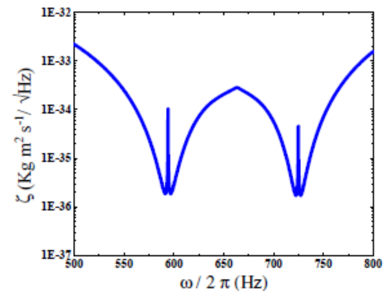

OAM content




Cavity transmission

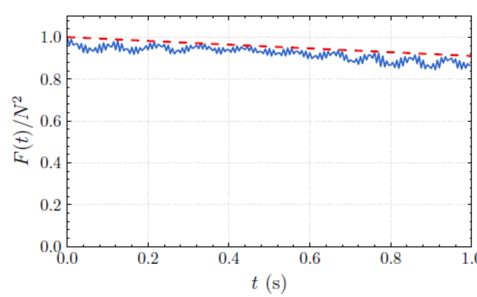



Measurement sensitivity



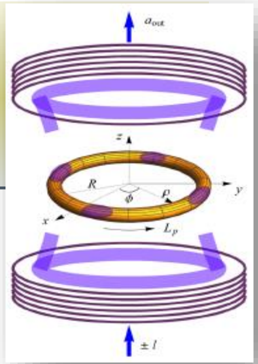

Condensate density autocorrelation

$$F(t) = \int_0^{2\pi} [\psi^*(\phi,t)\psi(\phi,0)]^2 \, d\phi$$




*N. Pradhan et al.,
Physical Review Research **6**,
013104 (2024)

# Gross-Pitaveskii treatment: Superposition



$$\psi(\phi) = \sqrt{\frac{N}{4\pi}}\left(e^{iL_{p1}\phi} + e^{iL_{p2}\phi}\right)$$

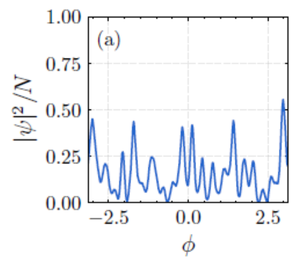
Aghamalyan et al
2015 New J. Phys. 17 045023

Atomic interactions are weakly repulsive

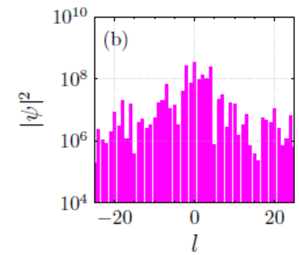
$^{23}$Na

Ryu et al.,
PRL **99**, 260401 (2007)

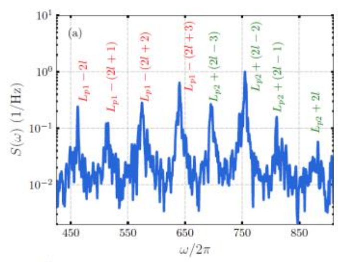
Condensate density



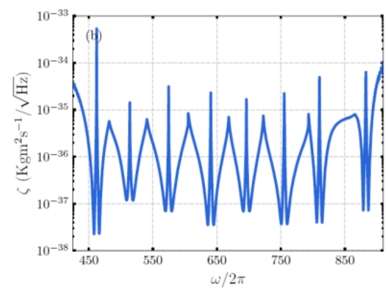

OAM content




Cavity transmission

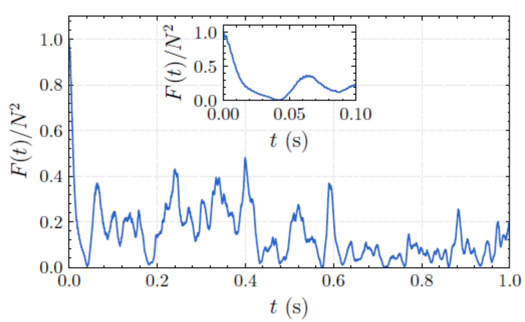



Measurement sensitivity



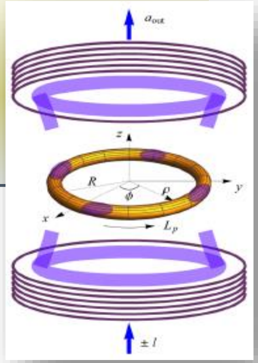

Condensate density autocorrelation

$$F(t) = \int_0^{2\pi} |\psi^*(\phi,0)\psi(\phi,t)|^2 \, d\phi$$




*N. Pradhan et al.,
Physical Review Research **6**,
013104 (2024)

# Gross-Pitaveskii treatment: Bright Soliton



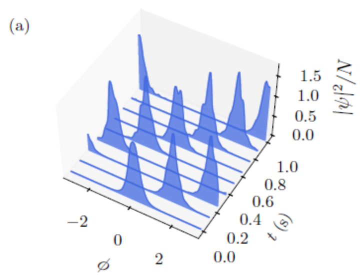

$L_p = 1$

$$\psi(\phi) = \sqrt{\frac{N}{\sqrt{\pi}}} e^{-\phi^2/2} e^{iL_p\phi}$$

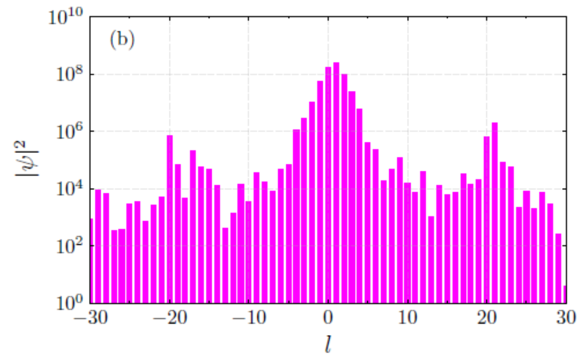
Atomic interactions are attractive

$^7$Li

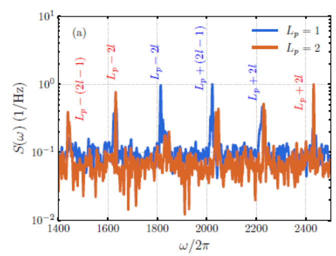
Condensate density



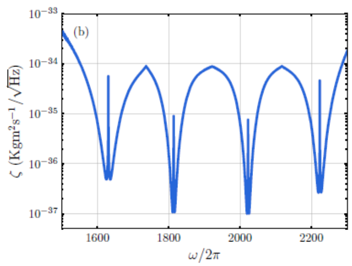

OAM content



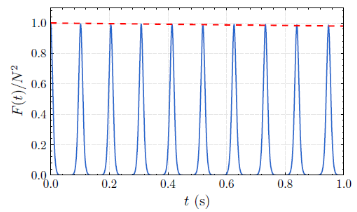

Cavity transmission




Measurement sensitivity




Condensate density autocorrelation



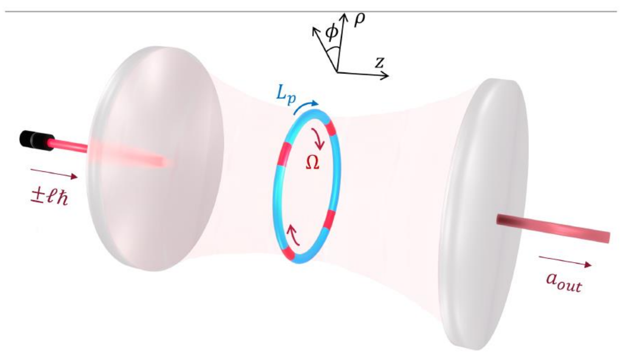

*N. Pradhan et al., Physical Review Research **6**, 013104 (2024)

* Helm et al., PRL **114**, 134101 (2015)

* Cai et al., PRL **128**, 150401 (2022)

* Pace et al., PRX **12**, 041037 (2022)

# Detecting Chirality: Lattice Rotation




*N. Pradhan et al., Physical Review A **109**, 023524 (2024)

## Lattice rotation

$$\cos^2(l\phi) \rightarrow \cos^2(l\phi + \Omega t)$$

$$\Omega < \frac{v_s}{2\pi R}$$

$$v_s = \sqrt{\mu/m}$$

## Sidemode frequencies

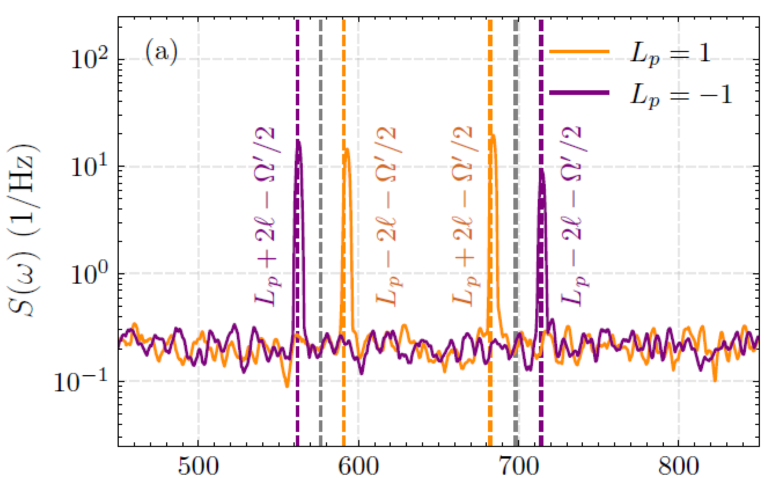
$$\omega_{c,d}(\Omega) = \omega_\beta \left( L_p \pm 2\ell - \frac{\Omega'}{2} \right)^2$$

Non-interacting

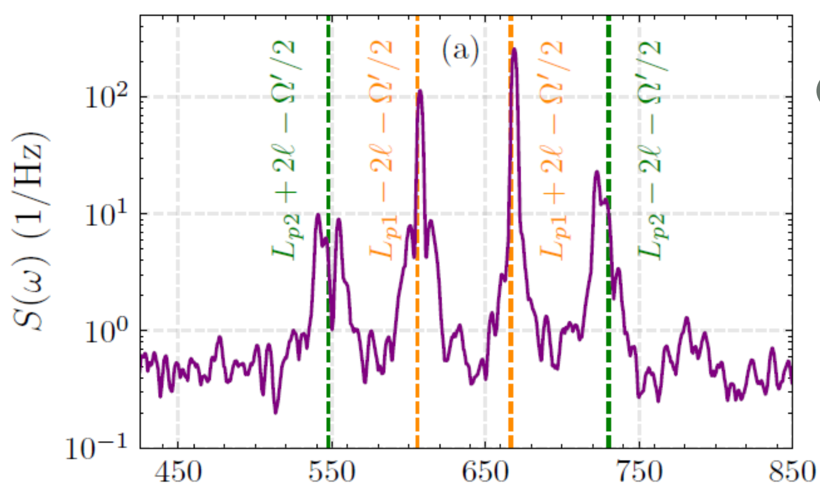
$$\omega'_{c,d} = \left[\omega_{c,d} \left(\omega_{c,d} + 4\tilde{g}N\right)\right]^{1/2}$$

Interacting

## Rotational eigenstate

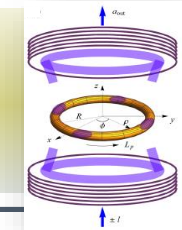



## Counter-rotating superposition

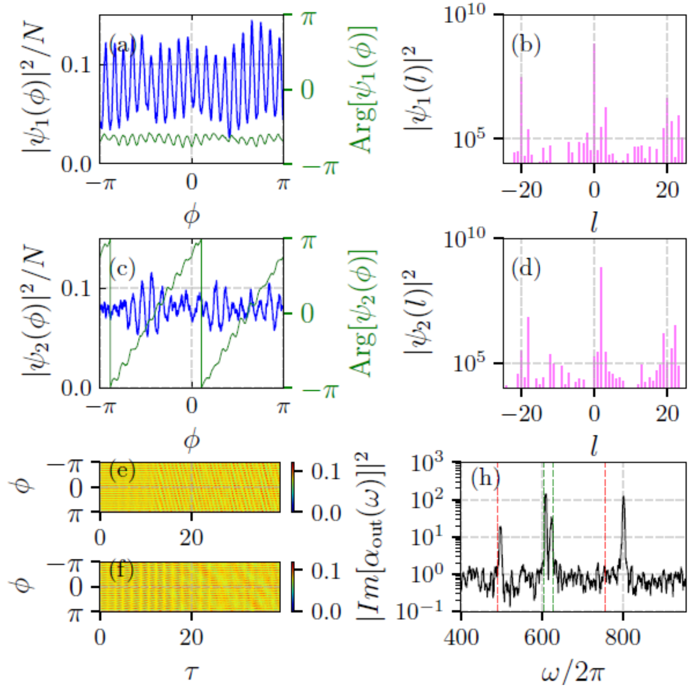



$$\Omega' = 0.5$$

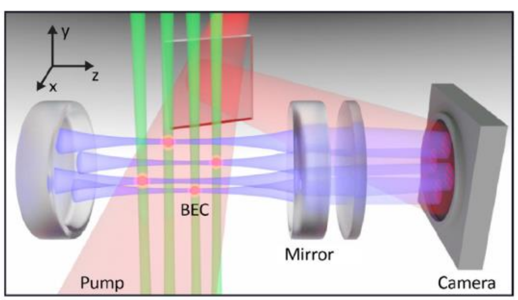
# Future Work: Creating a Stir



- Andreev-Bashkin effect (superfluid drag)
- Detecting supercurrents in the BCS-BEC crossover
- Atomic memory for photons carrying OAM
- Entangling, squeezing, synchronizing rotating matter waves
- Regenerative (laser) action
- Sub - SQL measurements (arXiv:2402.19123)




*Coherent and reversible interface between optics and atomic superfluid rotation.




Marsh et al.,
PRX **11**, 021048(2021)

THANKS !!!

CAREER