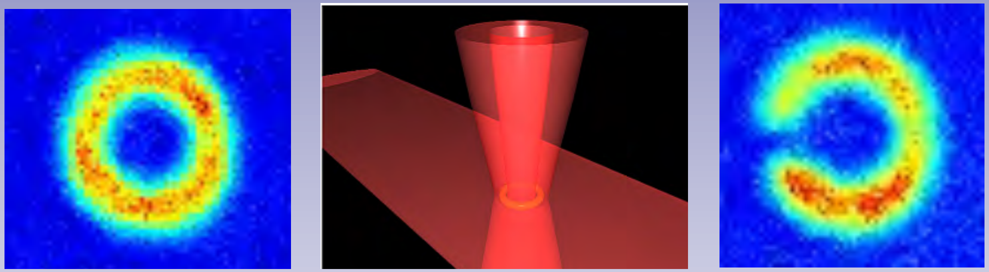
Superfluid Atom Circuits



Gretchen Campbell

Joint Quantum Institute, NIST, University of Maryland

Mid-Atlantic Senior Physicists Group
June 21, 2017

A History of Low-Temperature Physics


Onnes

1911 Superconductivity

1912 Persistent current in superconductors

Atomic physics biased

A ^History of Low-Temperature Physics

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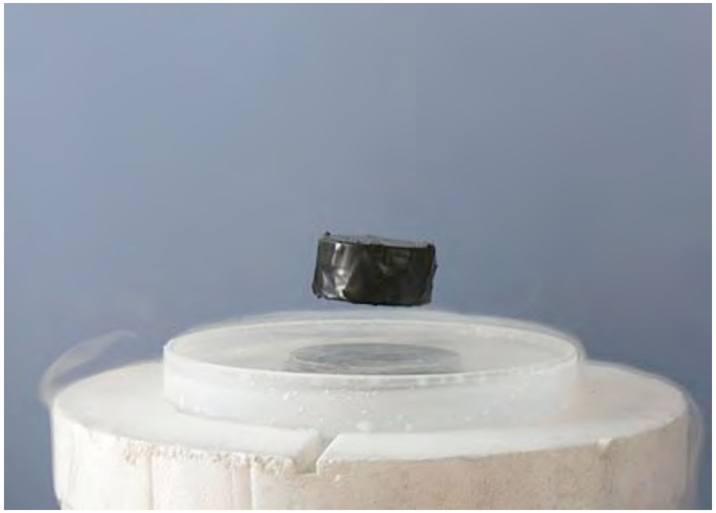

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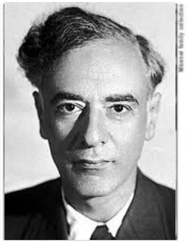
1938 Superfluid liquid ^{4}He

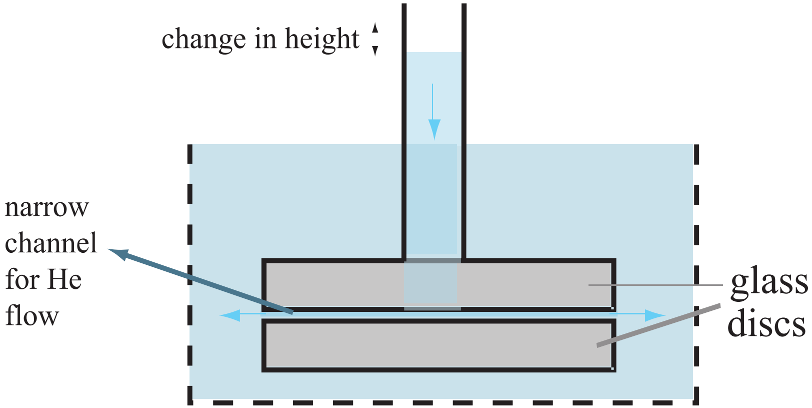
1938 Superfluidity related to Bose condensation

Kapitsa

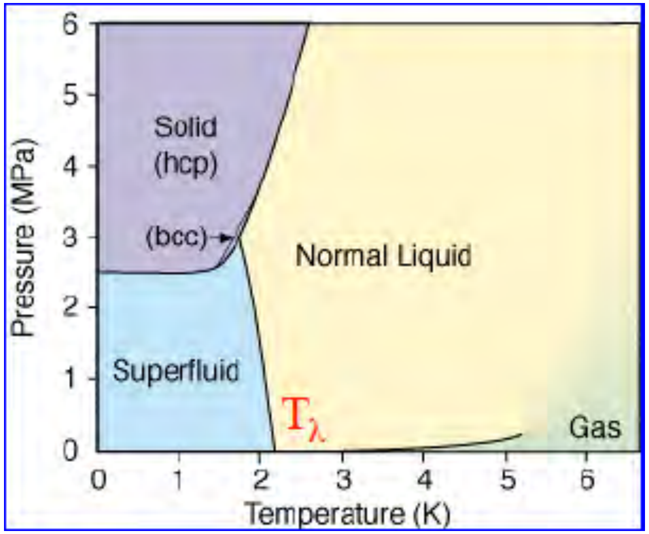
Allen



Landau



Kapitza P, *Nature* **141,** 3558 (1938)



^{4}He Phase Diagram

Atomic physics biased

A ^History of Low-Temperature Physics


Onnes


Kapitsa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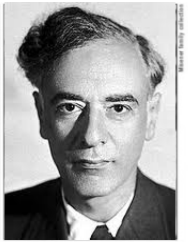
Landau


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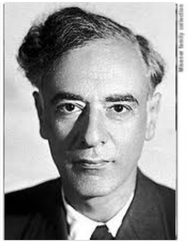
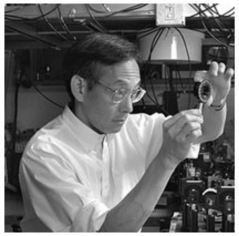
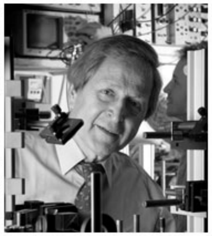

Landau


Onsager


Feynman


Josephson


Chu


Cohen-Tannoudji


Phillips

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1941 Landau critical velocity

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1949 Quantized vortices (Onsager, Feynman)

1962 Josephson effect in coupled superconductors

1988 Laser cooling and trapping of neutral atoms

1995 Bose-Einstein condensate of ultra-cold atoms

What is a Quantum Fluid?

Large number of interacting particles occupying the *same* quantum state

“macroscopic wave function”

$$\psi = |\psi| e^{i\phi}$$

Density

$$\rho = |\psi|^2$$

Velocity

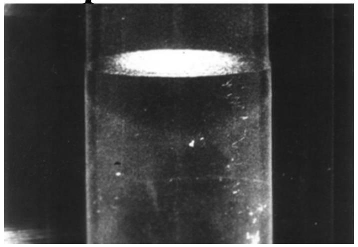
$$v_s = \frac{\hbar}{m} \nabla \phi$$

Chemical potential

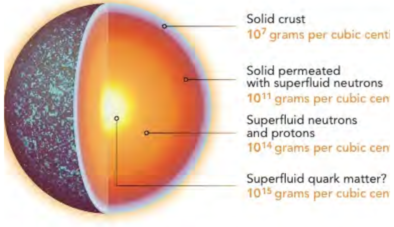
$$\mu = {}^{-\partial\phi}\!/_{\partial t}$$

Superconductors

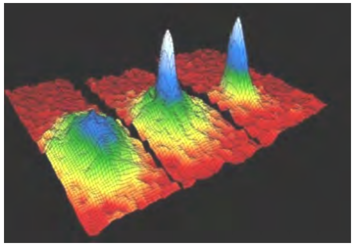
Liquid Helium



Neutron Stars



Atomic Gases



Superfluid Phenomena

Landau Two Fluid model

- Two interpenetrating fluids:
    Normal fluid: π_n, v_n
    Superfluid ρ_s, v_s

Superfluid has zero viscosity up to a critical velocity

Landau Criterion:

An excitation can be created only if the flow velocity exceeds the *speed of sound*

$$v_c = \min\left\{\frac{\varepsilon}{p}\right\}$$

$$v_c = c$$

v_c = critical velocity
c = speed of sound

Superfluid Phenomena

bucket of superfluid

Zero viscosity up to a critical velocity

Quantized Circulation / Persistent Currents

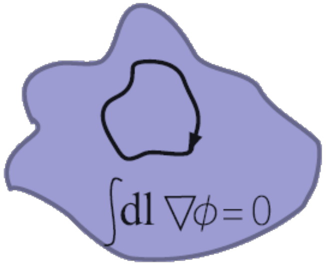
$$\psi = |\psi| e^{i\varphi}$$

$$v = \frac{\hbar}{m}\nabla\varphi$$

$$\oint_C \nabla\varphi \cdot dl = 2\pi n$$

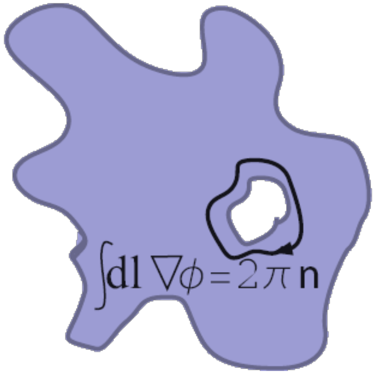
integer "winding number"

Simply-connected geometry



$$\nabla \times \vec{v}(r) = 0$$

Multiply-connected geometry



Superfluid Phenomena

bucket of superfluid

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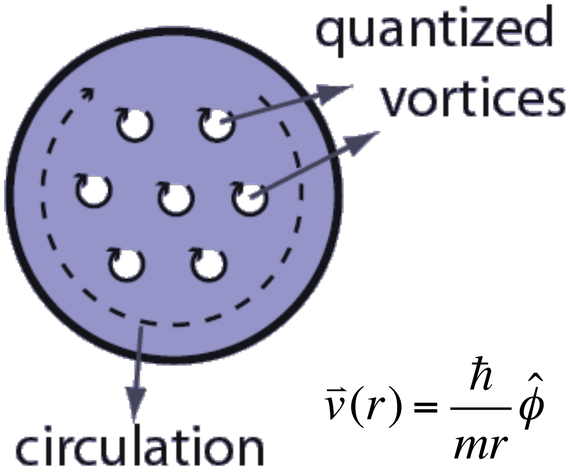
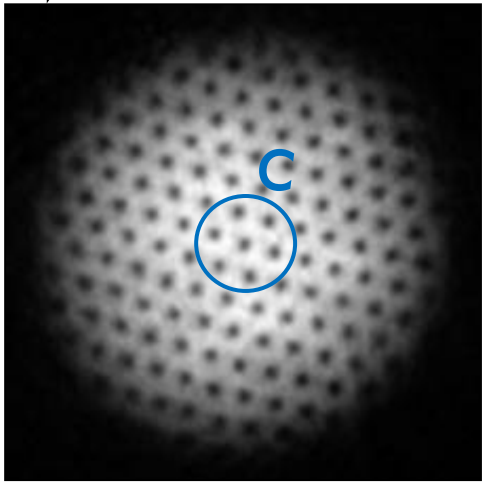
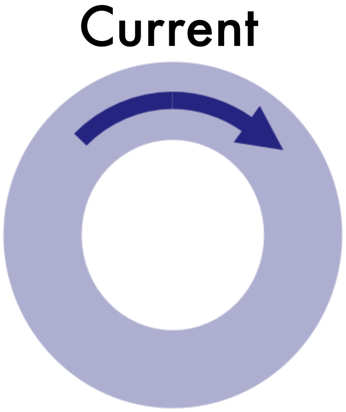


$$\vec{v}(r) = \frac{\hbar}{mr} \hat{\phi}$$

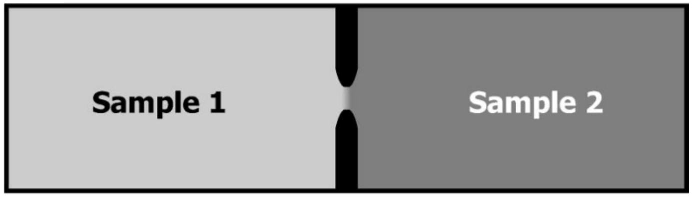


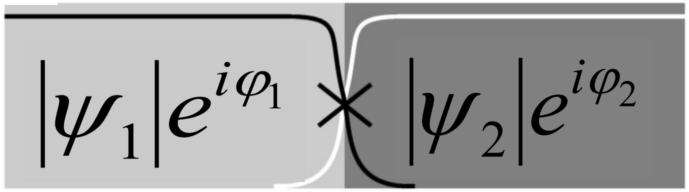
Vortex Lattice in Atomic BEC

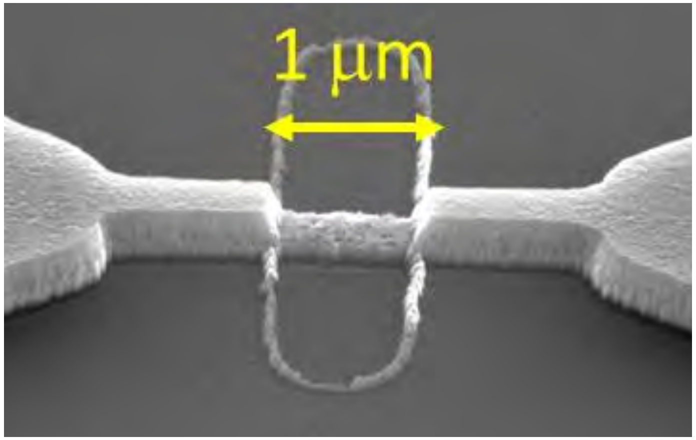


Vortices *trapped* in center of ring!

Josephson Effect







Phase change across weak link

$$\gamma = \varphi_2 - \varphi_1$$

Supercurrent through weak link

$$I = I_c \sin(\gamma)$$

Atomic Bose-Einstein Condensates

1995- First Atomic BEC
Temperatures: T_c ~100nK
Condensate size: 10^5-10^6
Density: $10^{14}/cm^3$

Weakly Interacting:

Chemical potential

$$\mu \propto \rho a_s$$

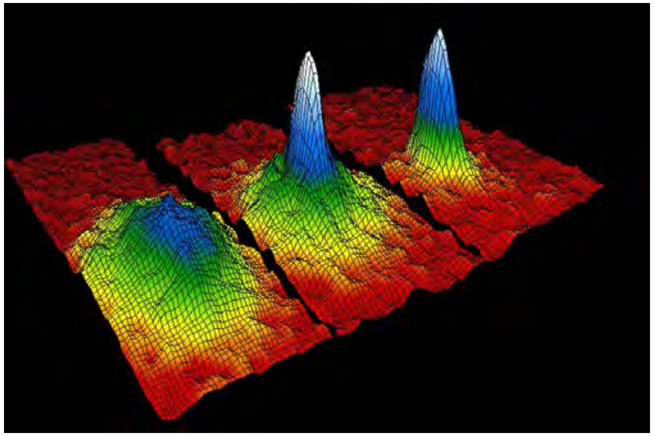
Sound speed

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

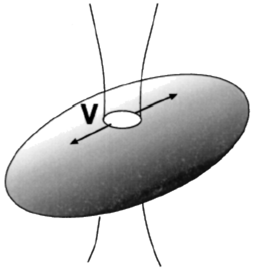
$$\psi = |\psi| e^{i\phi}$$

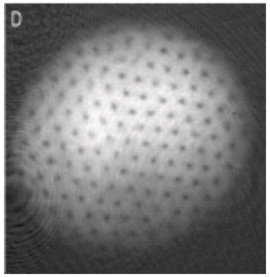
$$v = \frac{\hbar}{m} \nabla \phi$$

μ = chemical potential
ρ = condensate density
a_s = s-wave scattering length, i.e strength of interactions



http://www.colorado.edu/physics/2000/bec/



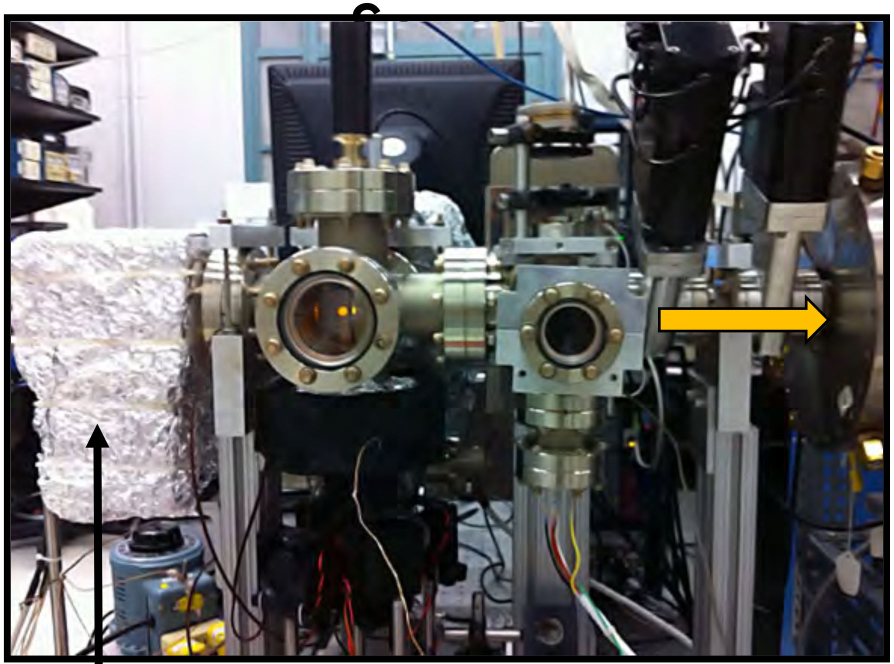


C. Raman *et al*. PRL 83, 2502 (1999).

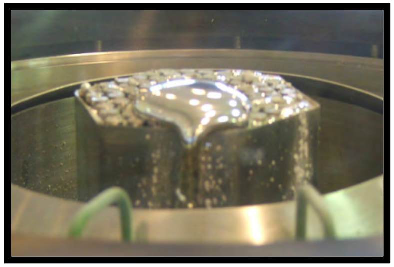
J. Abo-Shaeer et al, *Science* **292,** 476 (2001)

Atomic Bose-Einstein Condensates

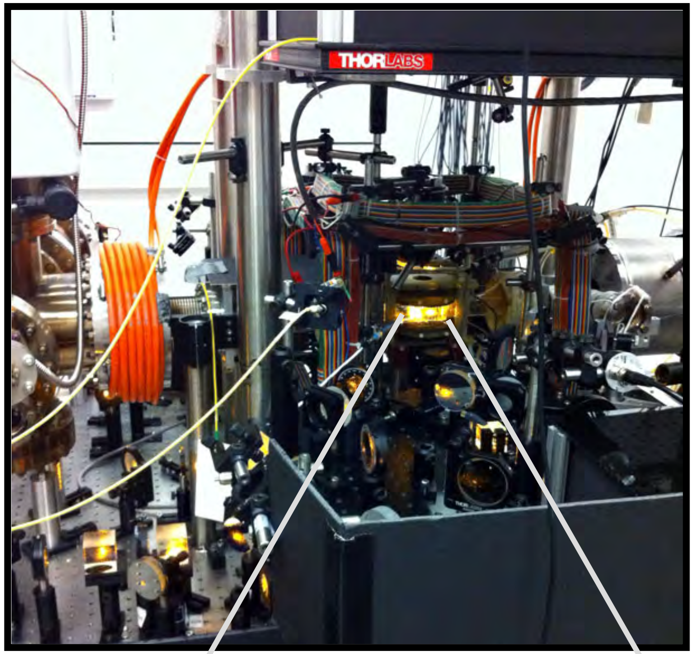
Sodium Atomic Beam



Liquid Sodium Metal (500 K)



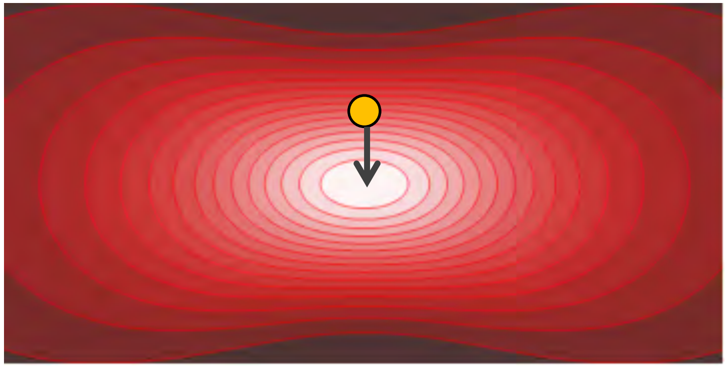
Ultra-High Vacuum Cell
(P = 10^{-14} atm.)



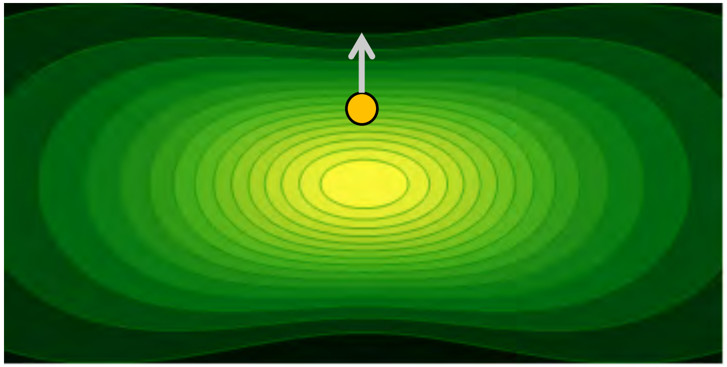
Laser-Cooled Sodium Atoms (≈100 μK)
Transferred to Optical or Magnetic traps for cooling to T_c

Optical Dipole Force

$$F = \frac{1}{2}\alpha(\omega_L)\nabla E^2$$



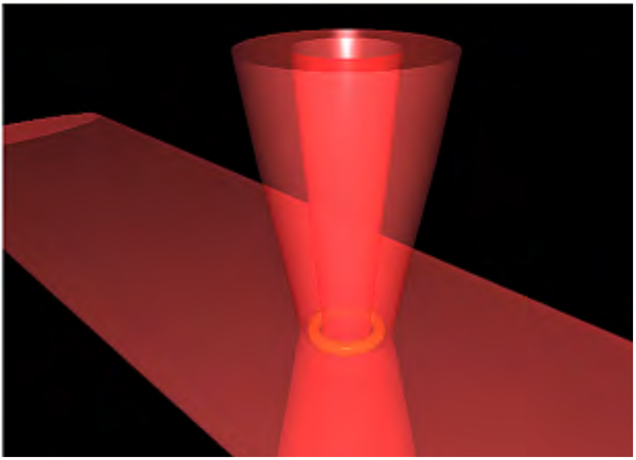
Below Resonance: α > 0
Attracted to high intensity

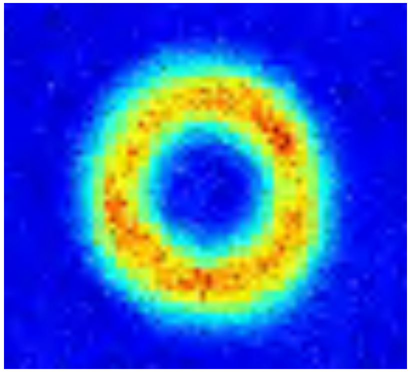


Above Resonance: α < 0
Repelled from high intensity

All hyperfine states can be trapped

BEC and topology?





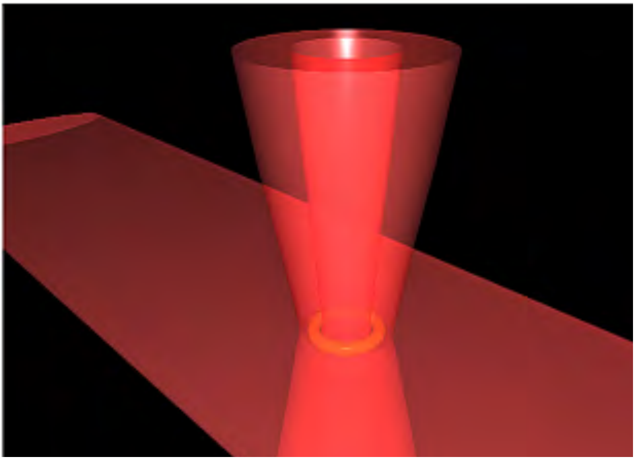
BEC in toroidal trap

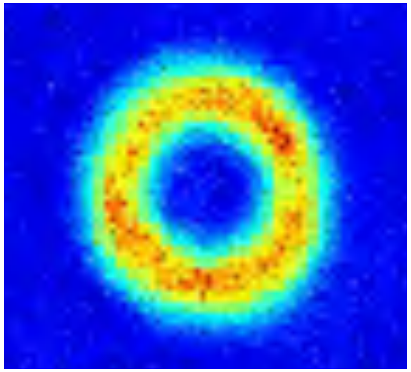
Interesting effects in toroidal traps:

Reduced dimensionality or topological constraints can give rise to different collective phenomena such as:

- Superfluidity
- Superflow

BEC and topology?





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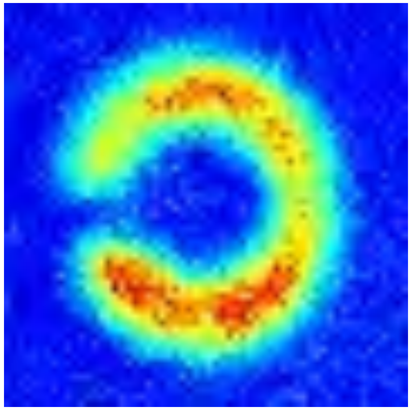

BEC in toroidal trap with barrier

Interesting effects in toroidal traps:

Reduced dimensionality or topological constraints can give rise to different collective phenomena such as:

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- Atomtronic circuits
- SQUID analog (Josephson junction)
- Interferometry/Sensors

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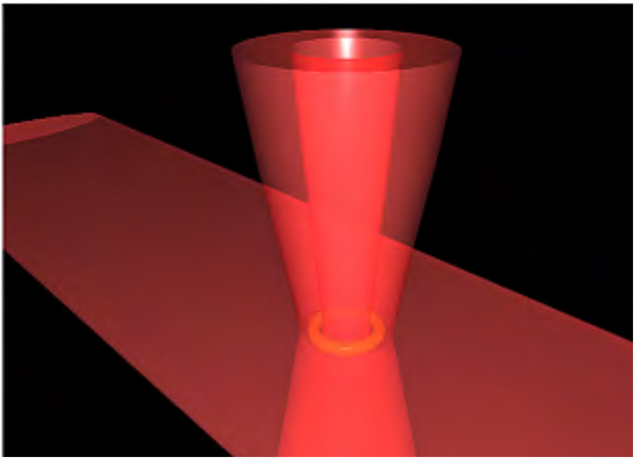

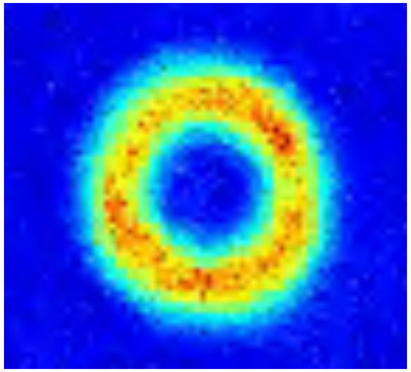

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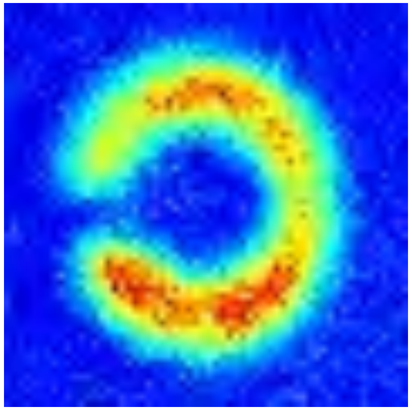

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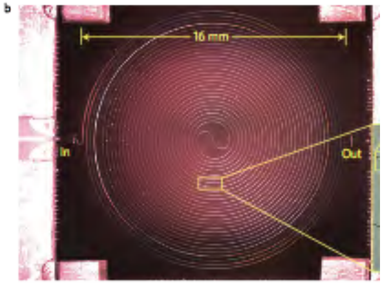
Superfluid(-conducting) circuits

superconducting circuits

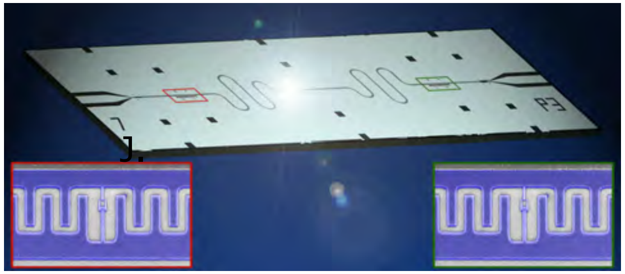
SQUID Magnetometer

Amplifiers



Eom et al. Nature Phys (2012)

Qubits



Majer et al. Nature (2007)

superfluid circuits

^{4}He gyroscope

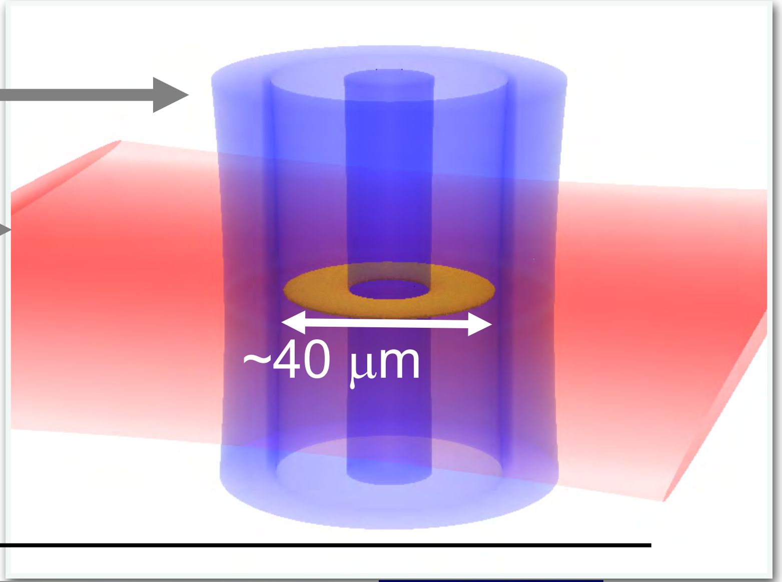
Detection of the Earth's rotation using superfluid phase coherence

Simmonds et al. Nature (2001)

build atomic superfluid circuits

Related work: Los Alamos
ETHZ, ...

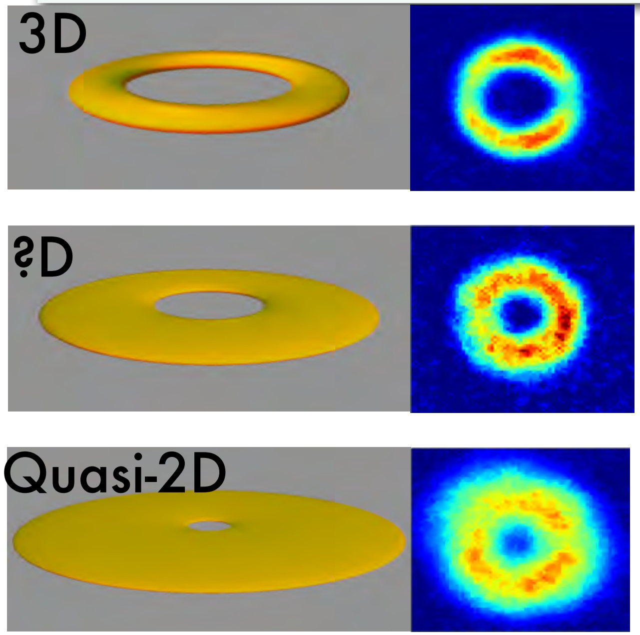
JQI all-optical toroidal trap for BEC



Ring beam

'Sheet' beam

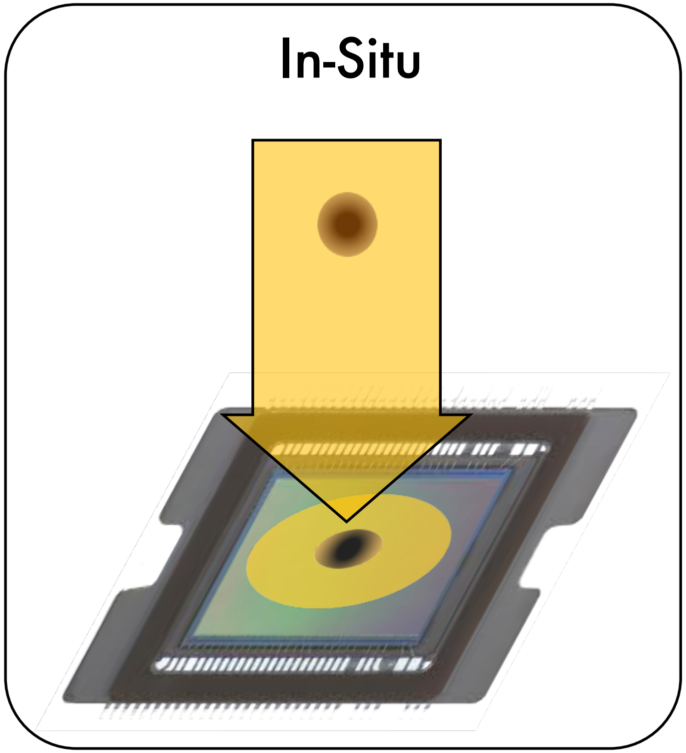
Uniform to:
< 0.5% of typical depth
< 10% of typical μ
μ = chemical potential



Other Ring expts:
Los Alamos (Boshier)
Cambridge (Hadzibabic)
Berkeley (Stamper-Kurn)

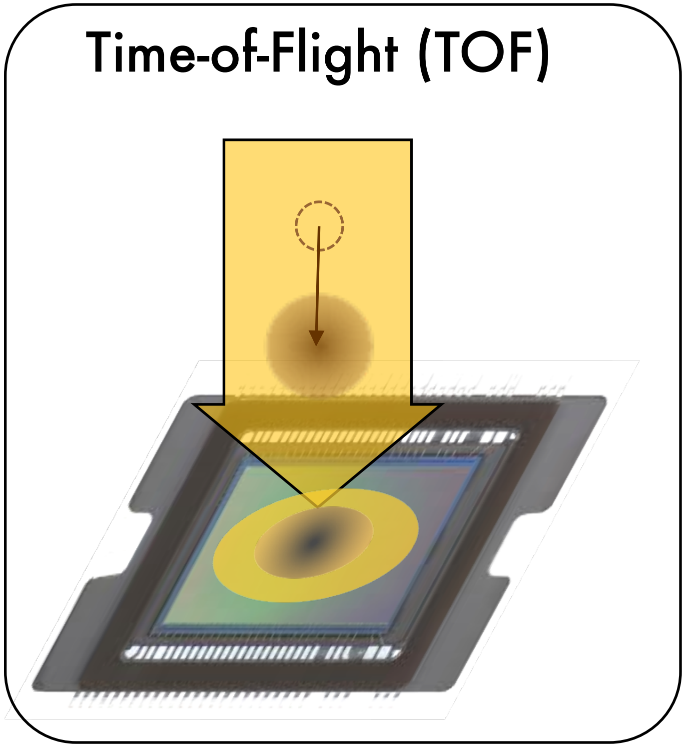
U. Arizona (Anderson)
Oxford (Foot)
Strathclyde (Riis)

Absorption Imaging



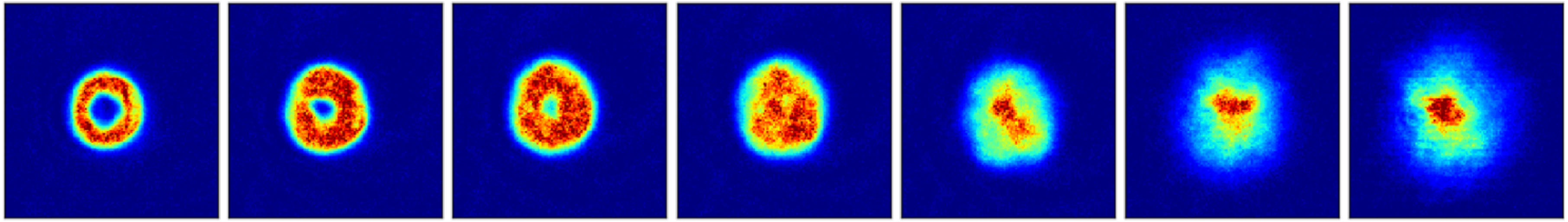
In-Situ

Spatial Information



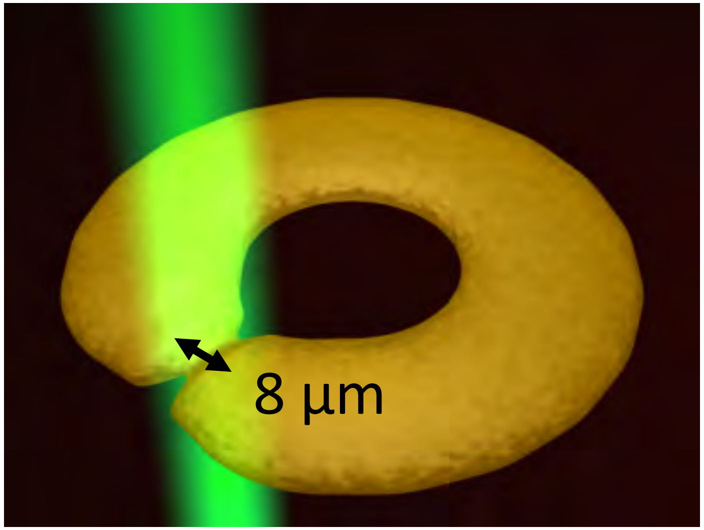
Time-of-Flight (TOF)

Momentum Information

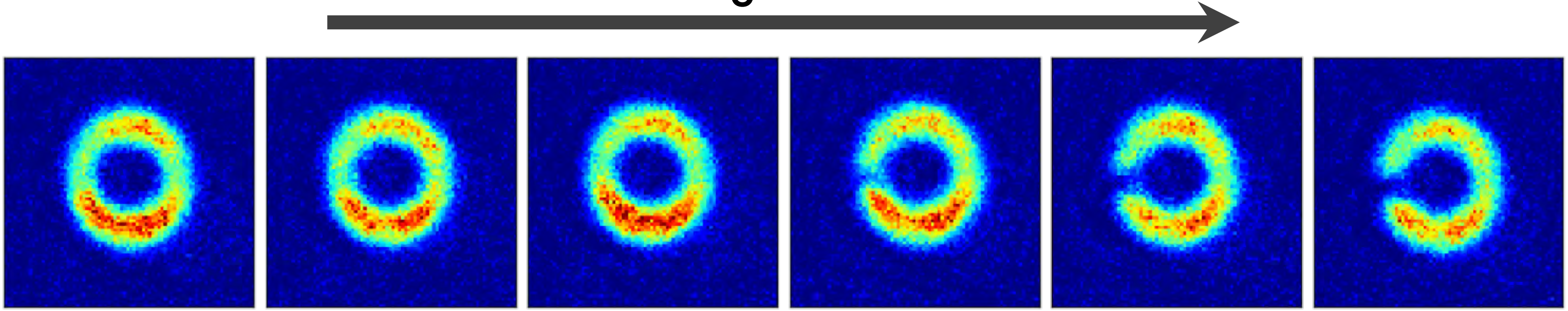


0 ms 2 ms 4 ms 6 ms 8 ms 10 ms 12 ms

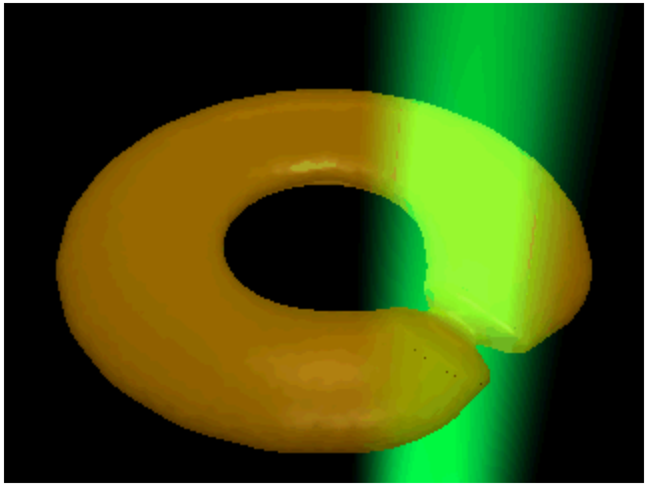
Creating Persistent Currents

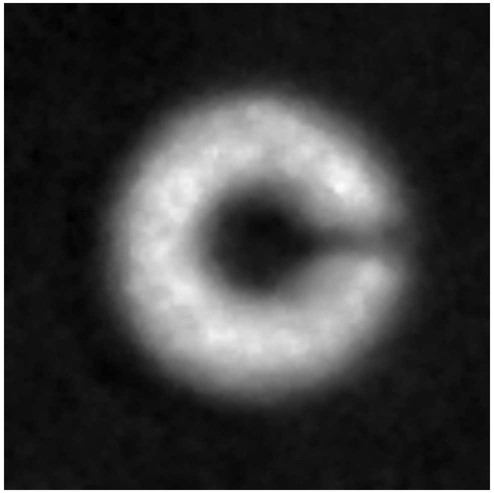


“Blue-detuned” laser creates a region of lower density


Increasing Laser Power

Creating Persistent Currents





CirculationQuanta:

$v_0 =$ 0.15 mm/s

$\Omega_0 =$ 1.2 Hz

Bulk Sound Speed:

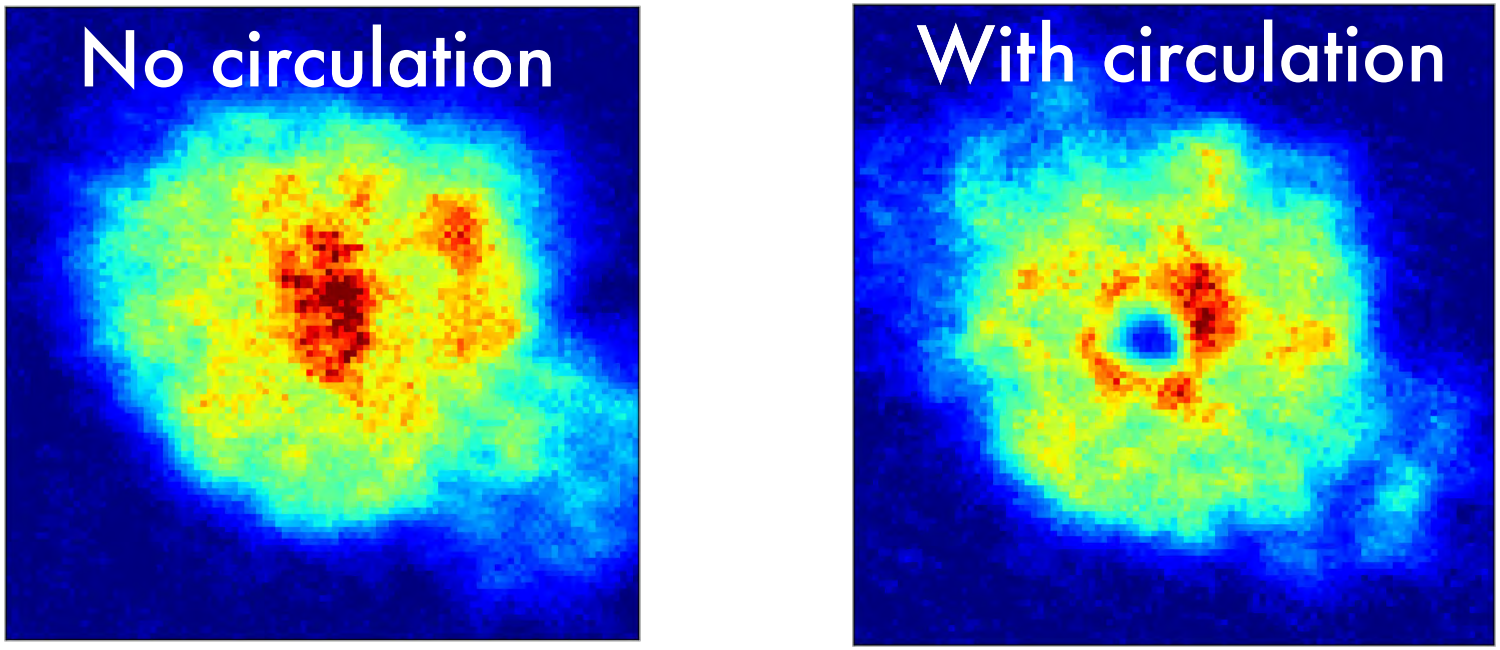
$c =$ 3-5 mm/s

$\Omega_s =$ 20-35 Hz

$\tau_s =$ 50 ms

Readout of the persistent current: Time of Flight

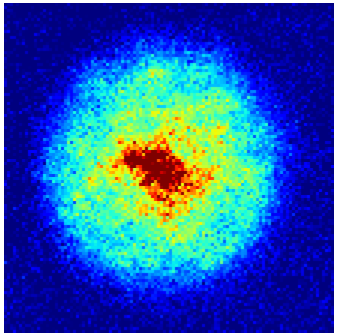
(Images taken after 10 ms expansion)



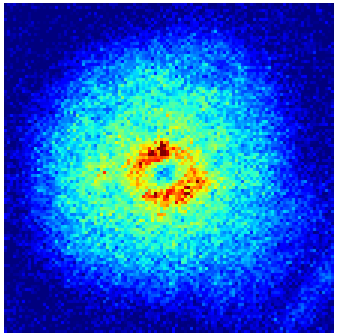
*Circulation is robust for > **1 min***

Limited by: Vacuum (~60 sec. BEC lifetime)
Trap nonuniformity (<5 nK)

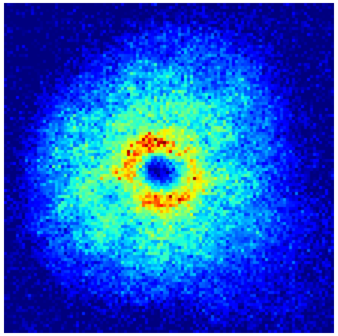
Quantized Current



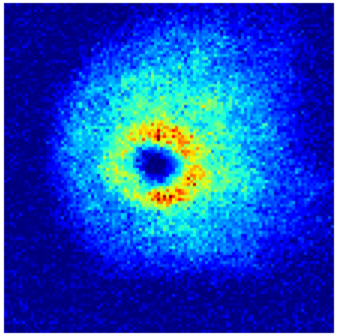
n=0



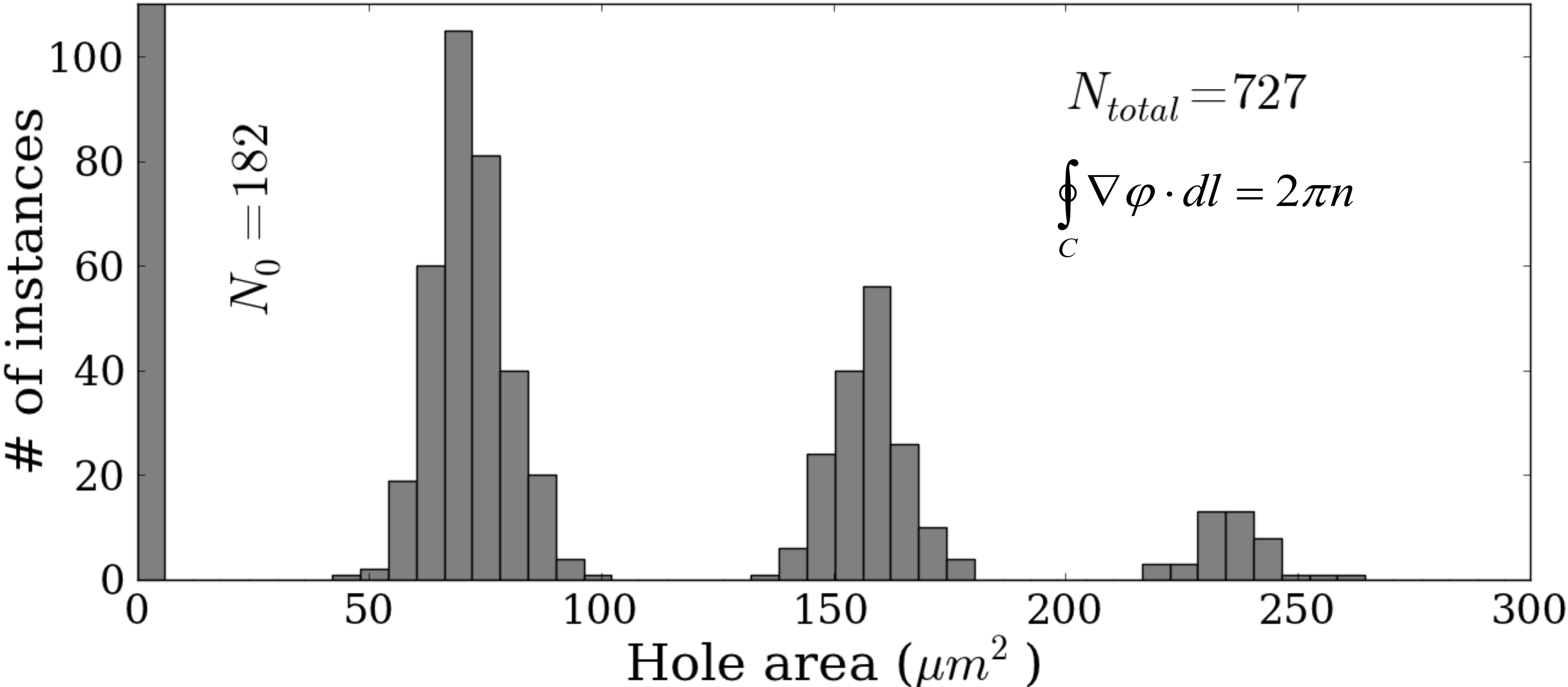
n=1



n=2

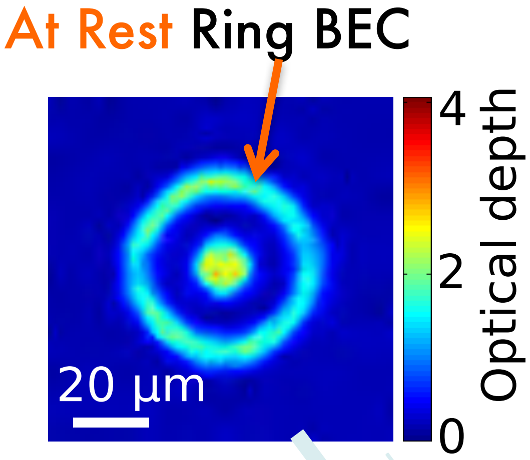


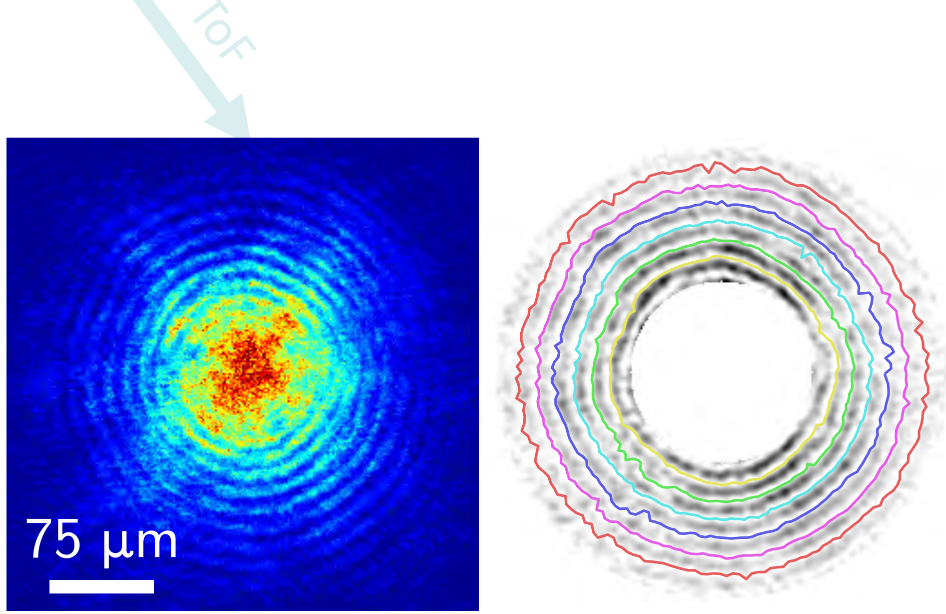
n=3



$$\oint_C \nabla \varphi \cdot dl = 2\pi n$$

Readout of the persistent current: Interferometry

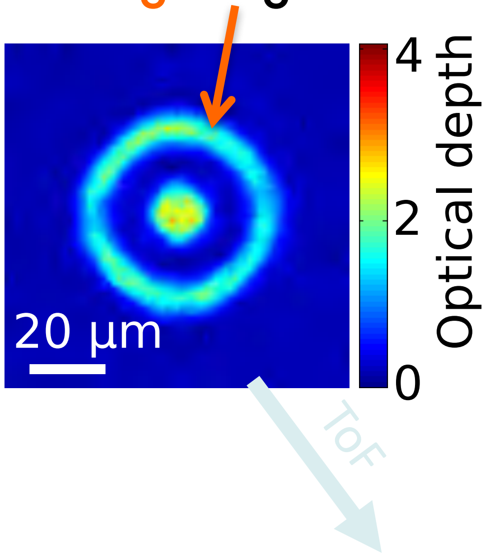




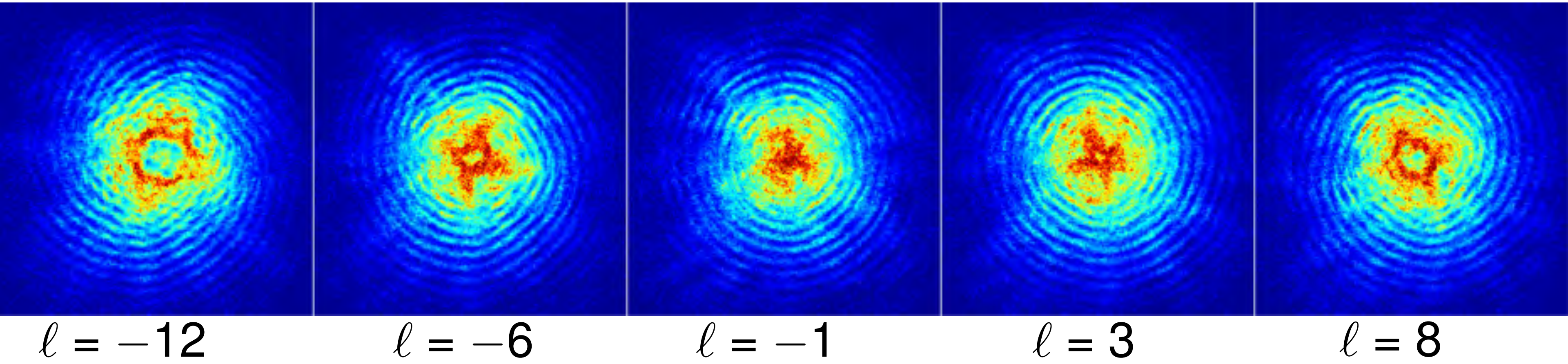
Concentric circles indicate no persistent current

Eckel, S., *et.al.*, *Phys. Rev. X*, **4**, 031052, (2014).

Readout of the persistent current: Interferometry



1. Number of spirals arms tell you the winding number
2. Chirality tells you the direction that the current was flowing

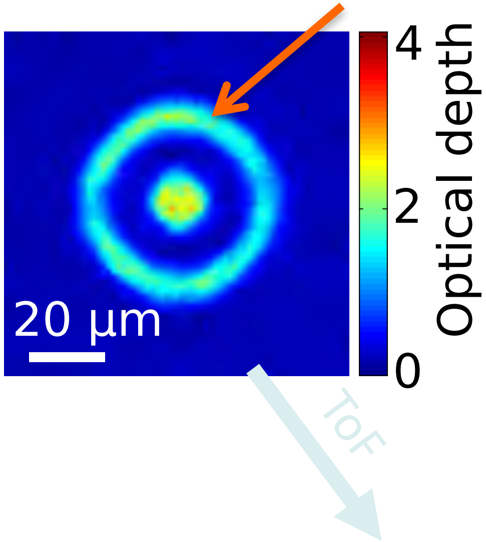

$\ell = -12$ $\ell = -6$ $\ell = -1$ $\ell = 3$ $\ell = 8$

With a persistent current, you get spirals

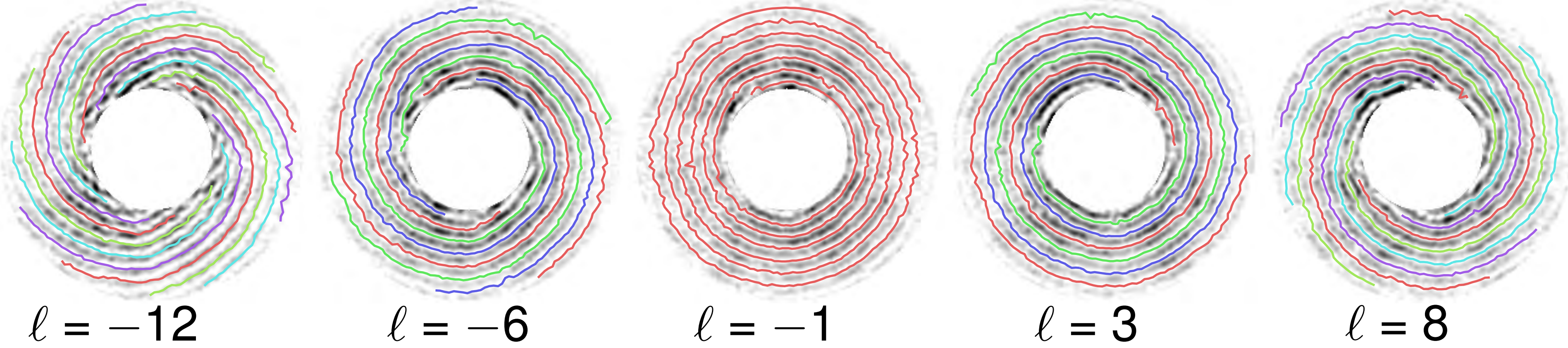
Eckel, S., *et.al.*, *Phys. Rev. X*, **4**, 031052, (2014).

Readout of the persistent current: Interferometry

Rotating Ring BEC



1. Number of spirals arms tell you the winding number
2. Chirality tells you the direction that the current was flowing



With a persistent current, you get spirals

Eckel, S., *et.al.*, *Phys. Rev. X*, **4**, 031052, (2014).

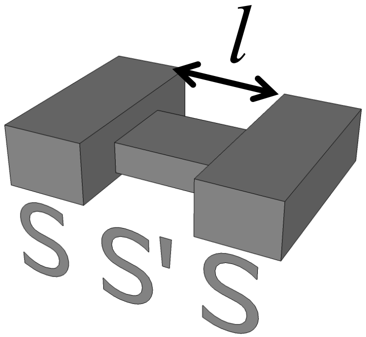
Superfluid Circuits

- How can we make an atom SQUID?

Tunnel Junction vs Weak Links

$$\gamma = \varphi_2 - \varphi_1$$

$$I = I_c \sin(\gamma)$$

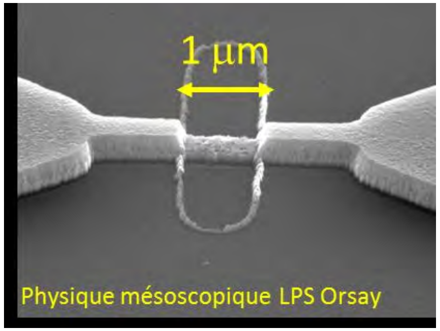


Current-Phase Relation

$$\gamma(I) = \sin^{-1}\left(\frac{I}{I_c}\right) + \boxed{\frac{LI_c}{h}\frac{I}{I_c}}$$

Kinetic/Hydrodynamic Inductance

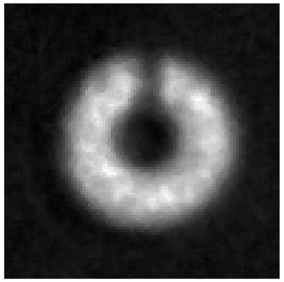
$$L \equiv \frac{ml}{\rho'_{1D}}$$

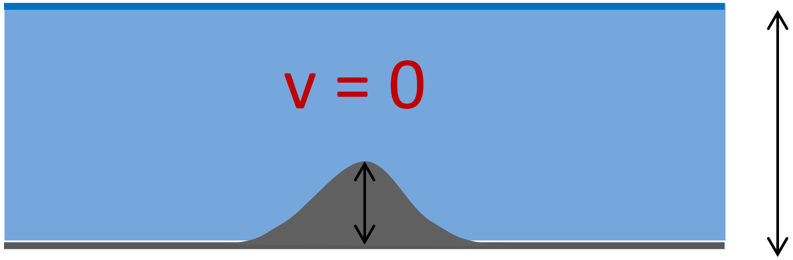


Physique mésoscopique LPS Orsay

- γ is the phase difference across the junction

Rotating the Weak Link

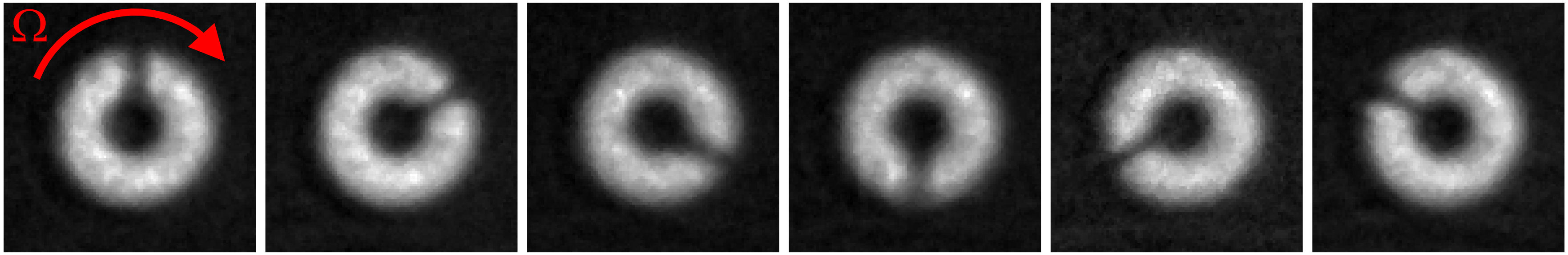


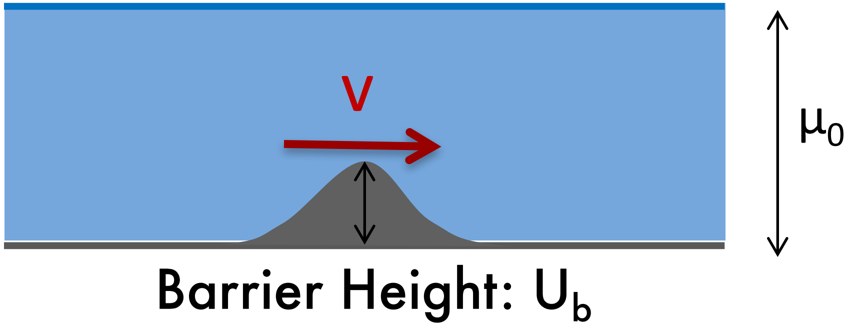


chemical
potential

Barrier Height: U_b

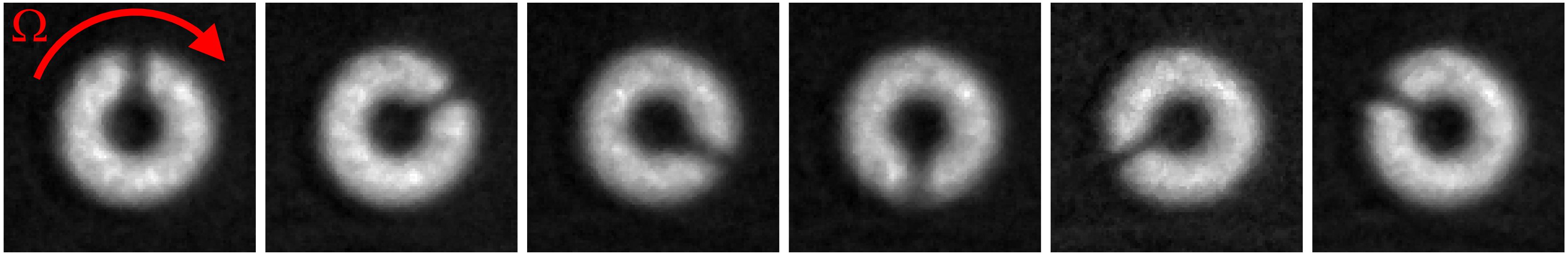
Rotating the Weak Link



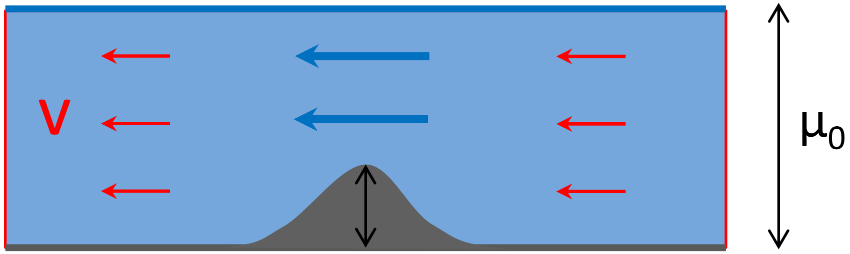


chemical
potential

Rotating the Weak Link

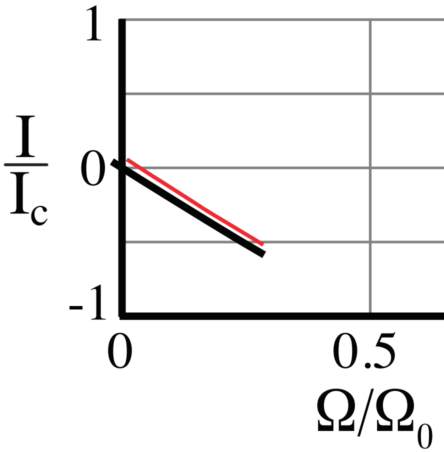


Switch to the rotating frame!

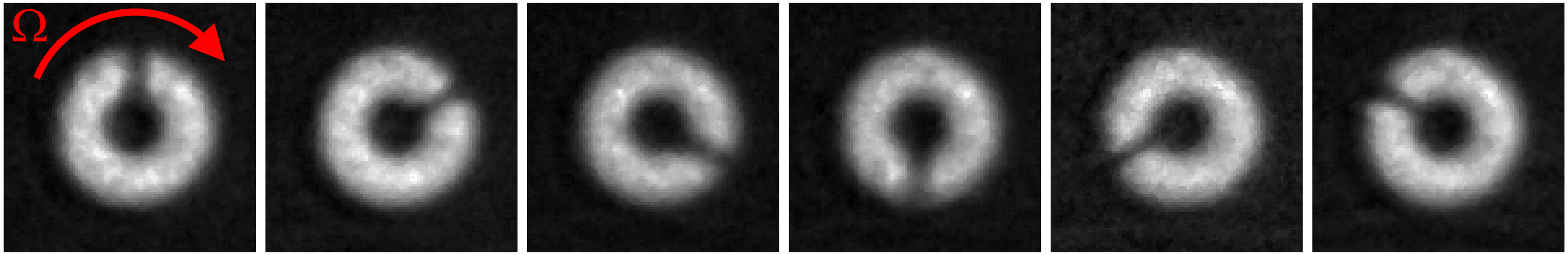


chemical potential

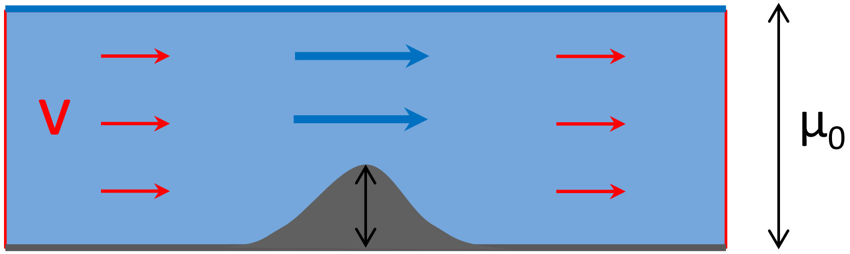
Barrier Height: U_b



Rotating the Weak Link

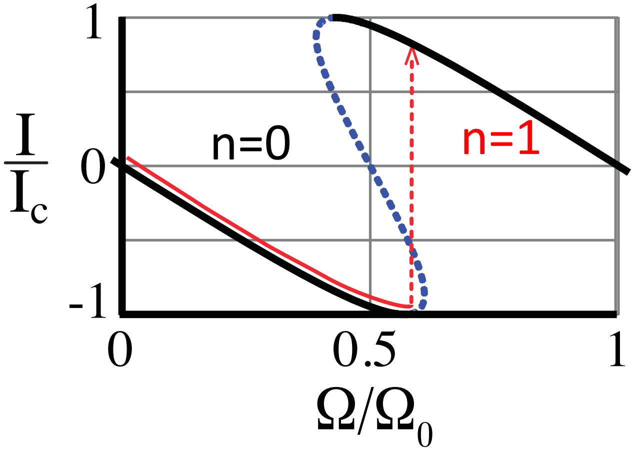


At I_c a phase slip occurs!

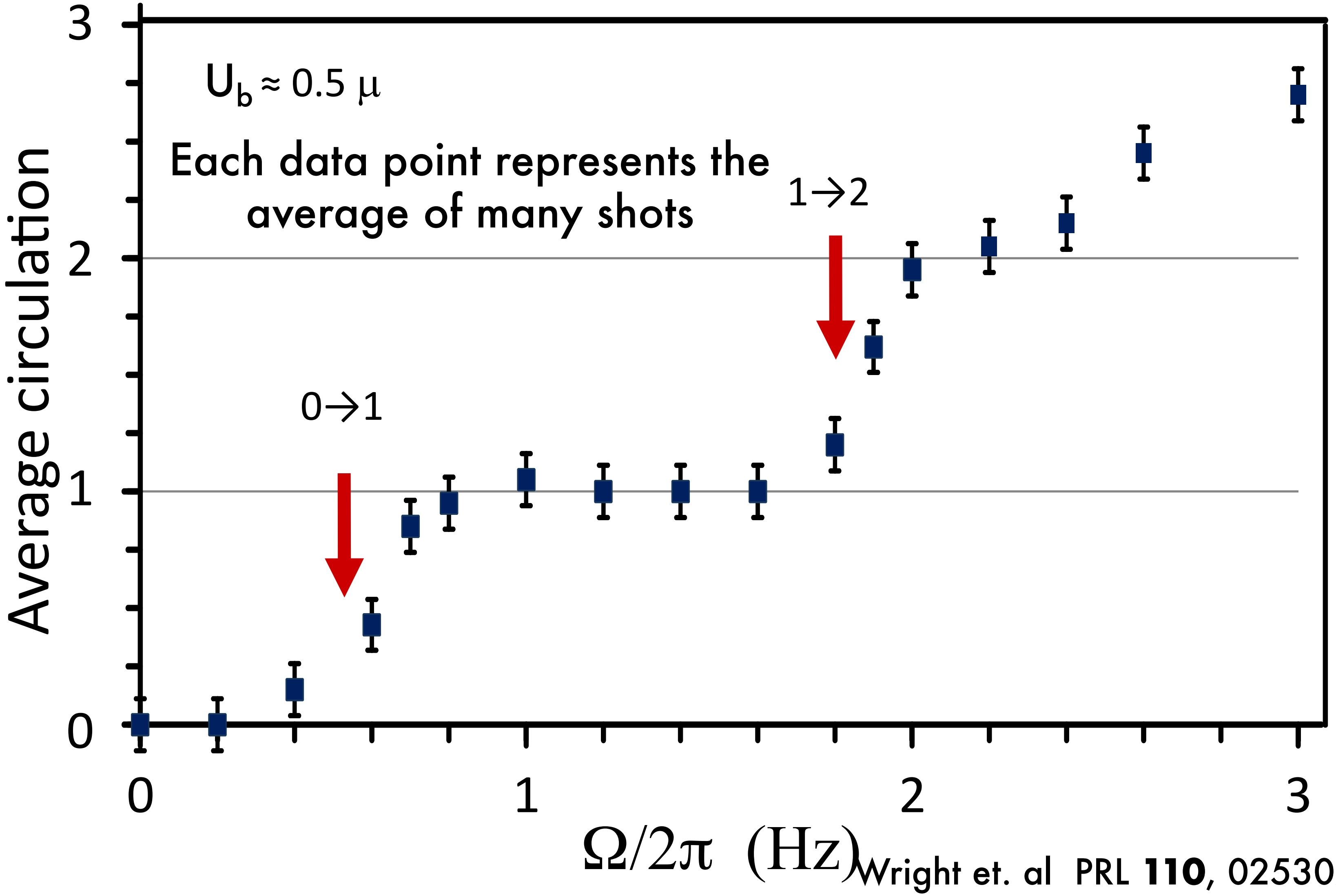


chemical potential

Barrier Height: U_b



Discrete Phase Slips Between Current States



$U_b \approx 0.5\ \mu$

Each data point represents the average of many shots

0→1

1→2

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

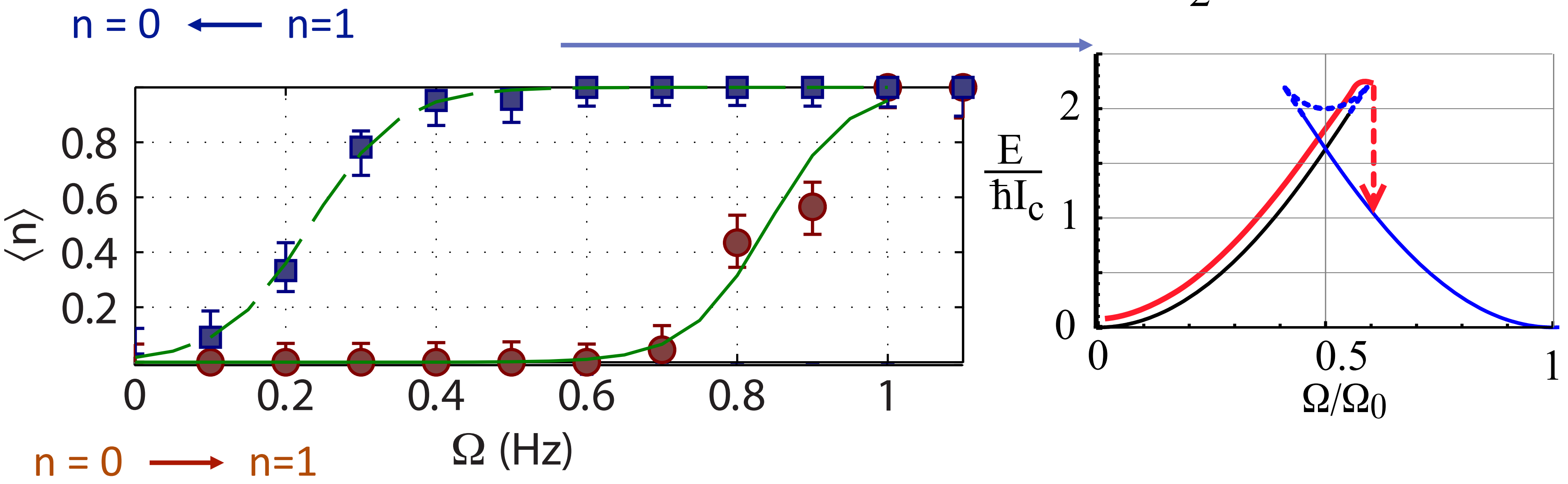
Hysteresis between quantized flow states

$$\gamma(I) = \sin^{-1}\left(\frac{I}{I_c}\right) + \frac{LI_c}{h}\frac{I}{I_c}$$

Kinetic/Hydrodynamic Inductance

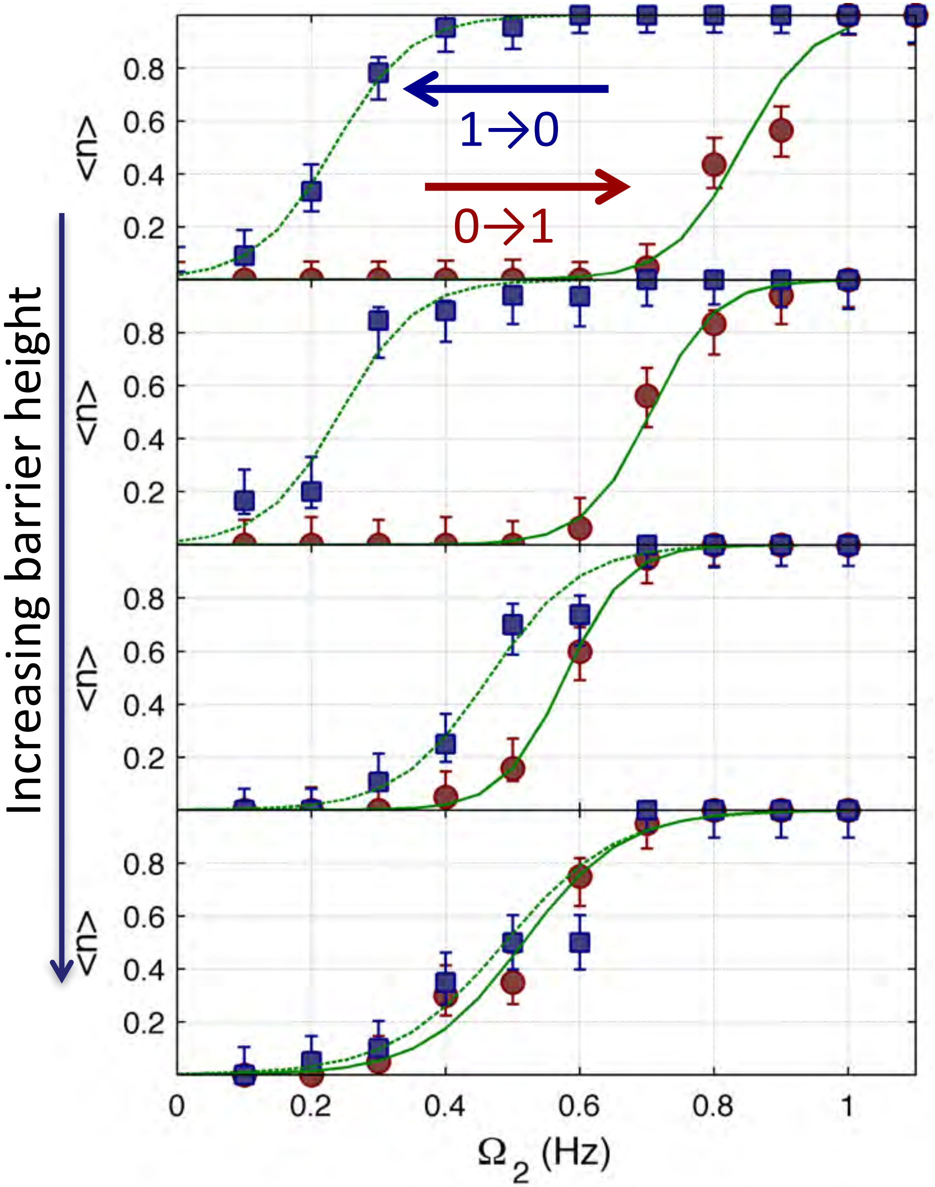
$$L \equiv \frac{ml}{\rho'_{1D}}$$

$$E = \frac{1}{2}LI^2 - \hbar I_c \cos(\gamma)$$



Eckel et. Al Nature **506**, 200 (2013)

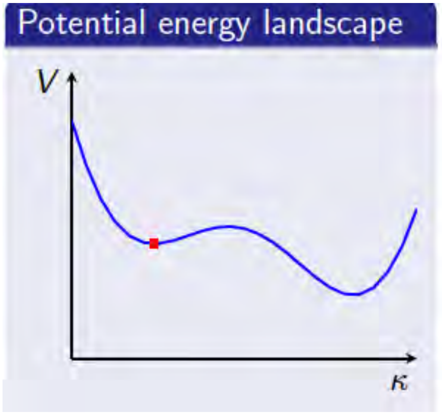
Hysteresis in atomtronic circuits



Eckel et. Al Nature **506**, 200 (2013)

Hysteresis plays in important role in Electronic circuits

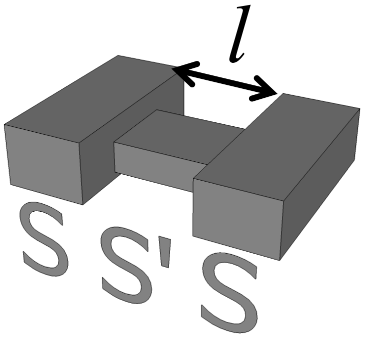
- Memory
- Digital Noise filters
- SQUID magnetometers



We expect hysteresis could be similarly important for atomtronic circuits

Measuring the current-phase relationship

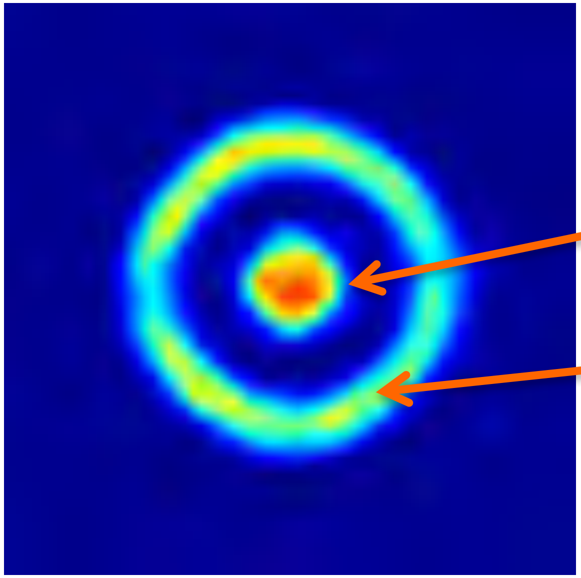
Weak Links



$$\gamma(I)=\sin^{-1}\left(\frac{I}{I_c}\right)+\frac{LI_c}{h}\frac{I}{I_c}$$

The Current-phase relationship determines the behavior of the atom circuit

Using new “Target” trap we can interferometrically measure the phase around the ring

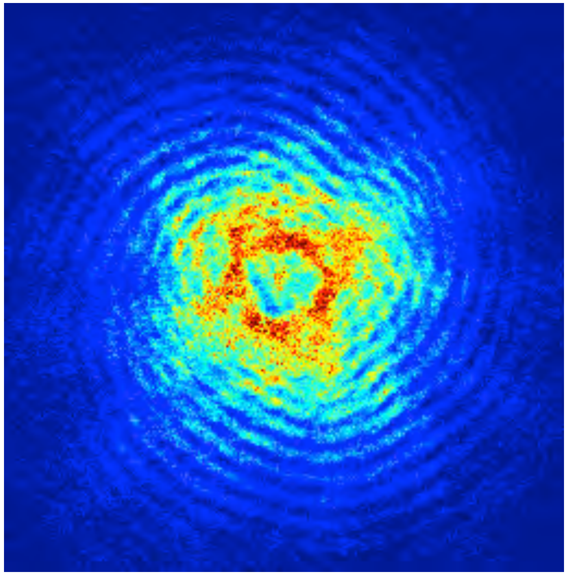


In-situ

Disk BEC at rest (phase reference)

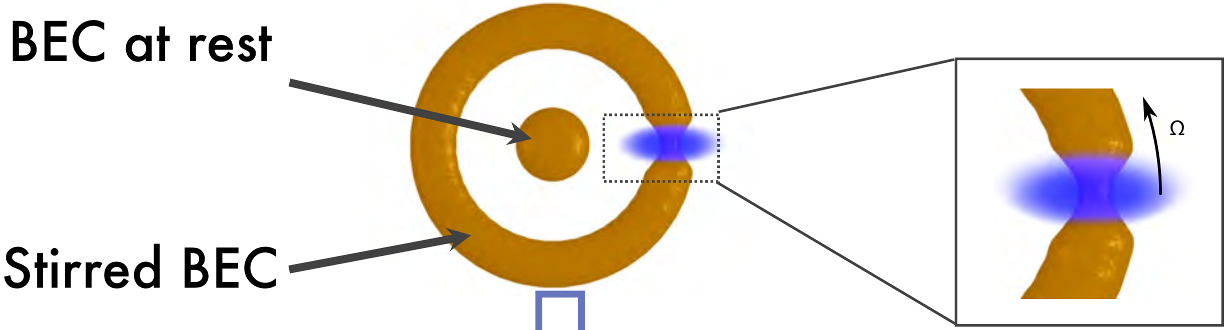
Rotating Ring BEC

A similar trap has been used by the Dalibard group in Paris: PRL 113, 135302 (2014)

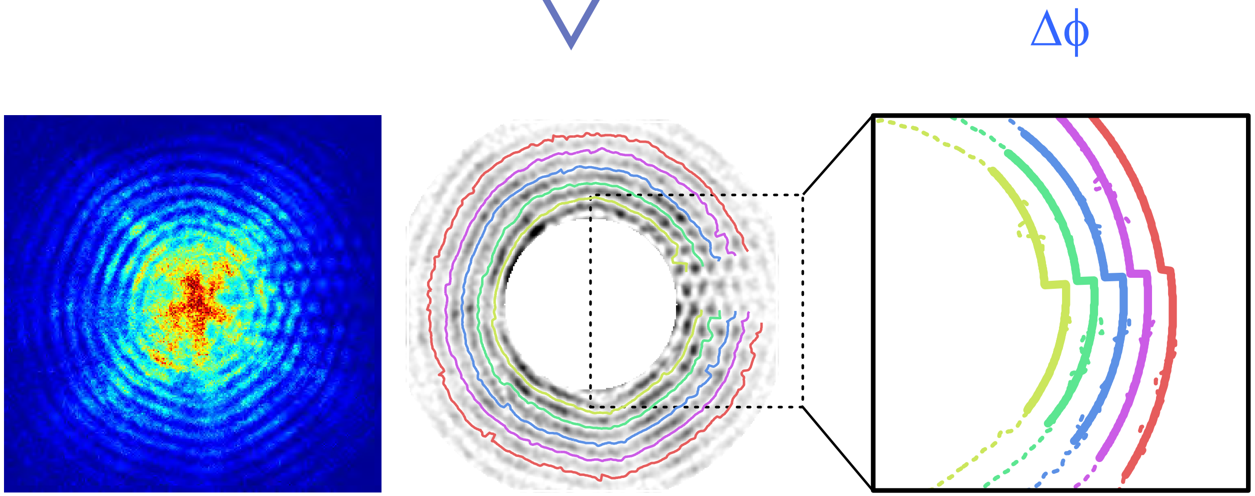


Time-of-flight

Measuring the current-phase relationship

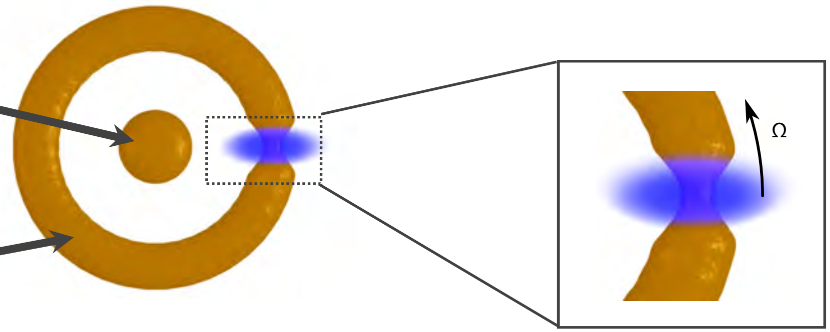


- Interference between phase reference (disk) and flowing superfluid (ring) by free expansion of released clouds



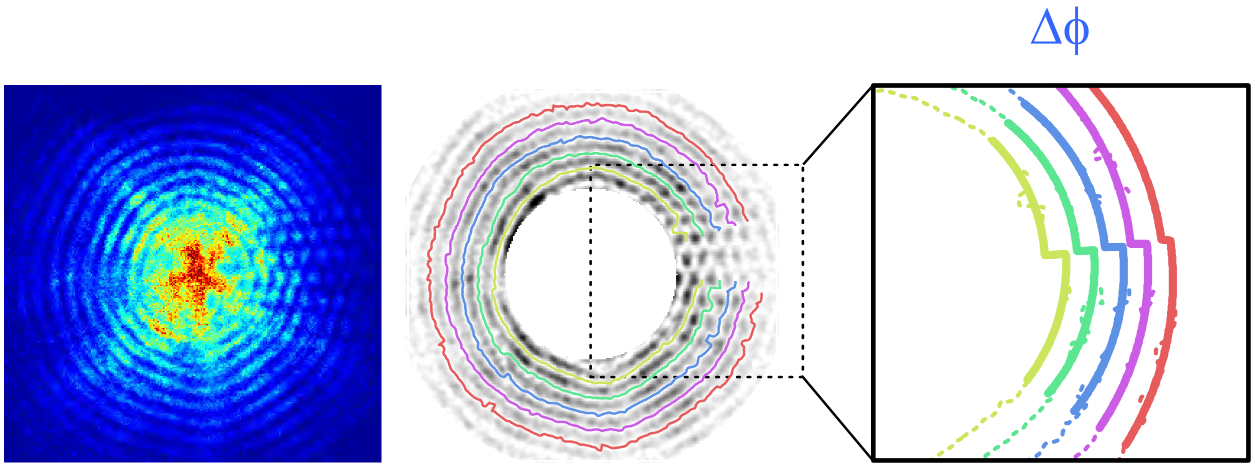
Eckel et. al, PRX **4**, 031052 (2014)

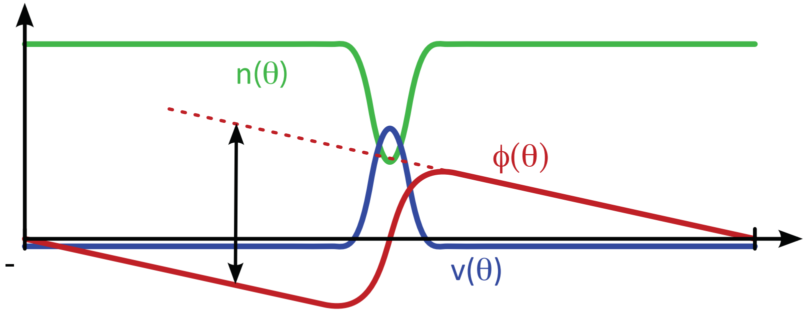
Measuring the current-phase relationship



BEC at rest

Stirred BEC





Phase around the ring

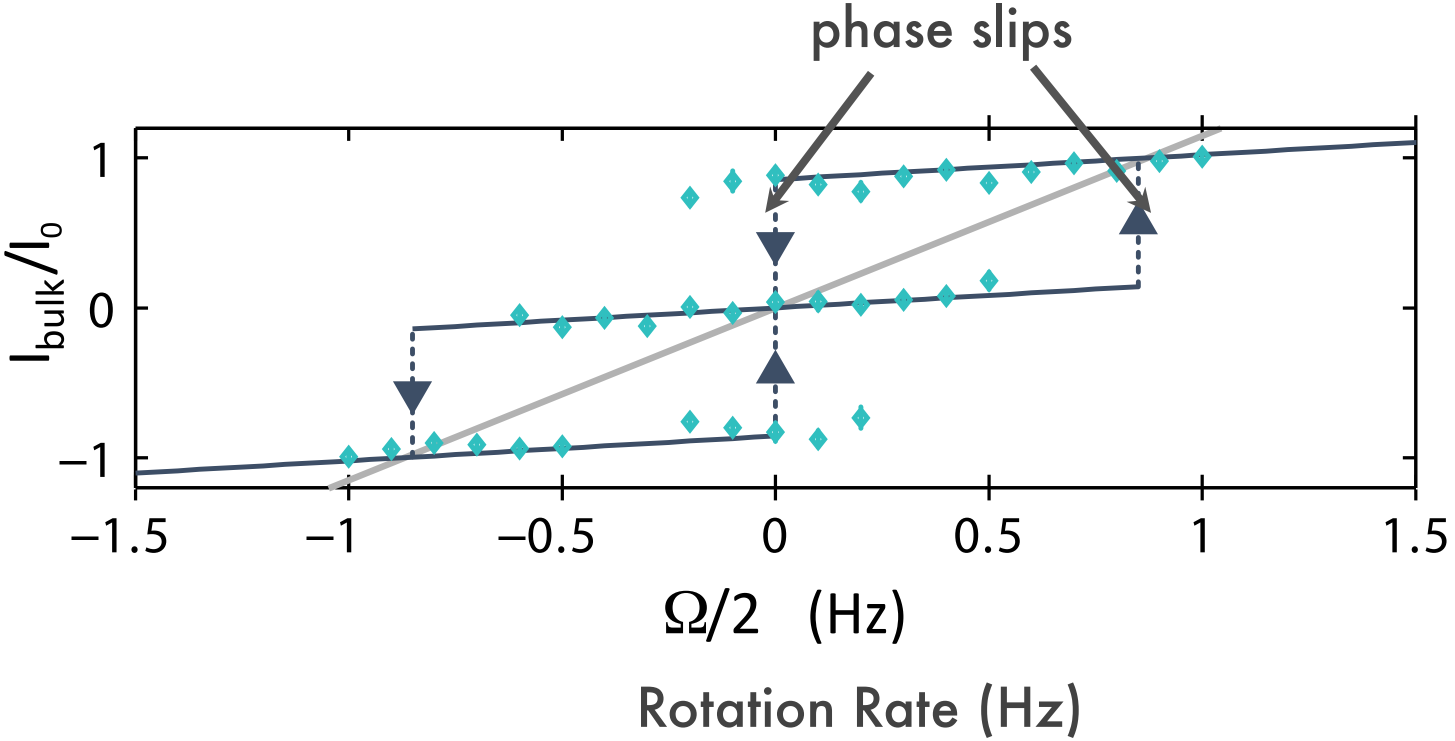
$$\alpha = -\Delta\phi$$

Current around ring

$$I_{\mathrm{Bulk}} = n_{1D}\frac{m}{\hbar}\frac{\alpha}{2\pi R}$$

Eckel et. al, PRX **4**, 031052 (2014)

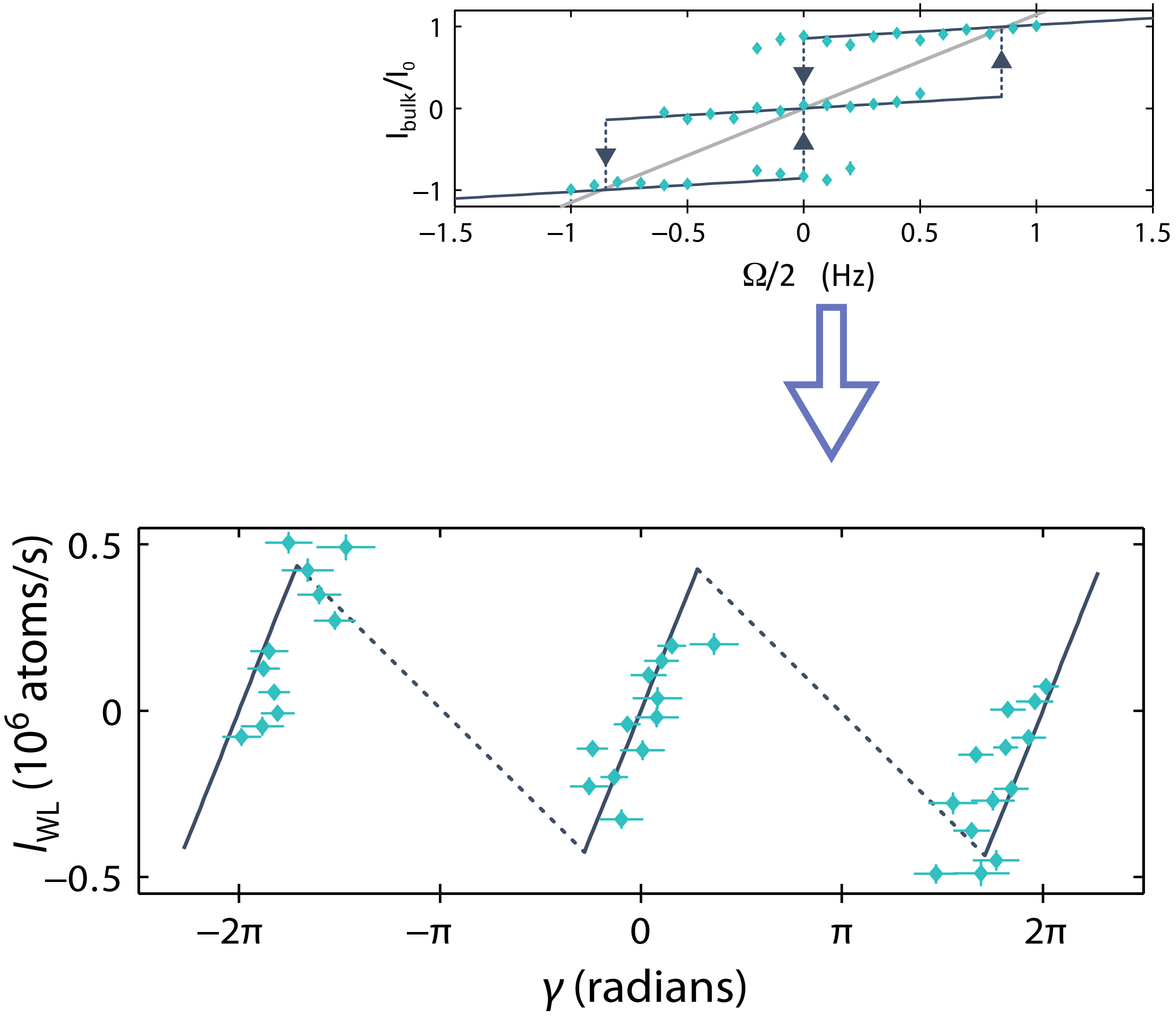
Measuring the current-phase relationship



Current around the ring before phase slips ⟷ Current not quantized as weak link is present

Eckel et. al, PRX **4**, 031052 (2014)

Measuring the current-phase relationship



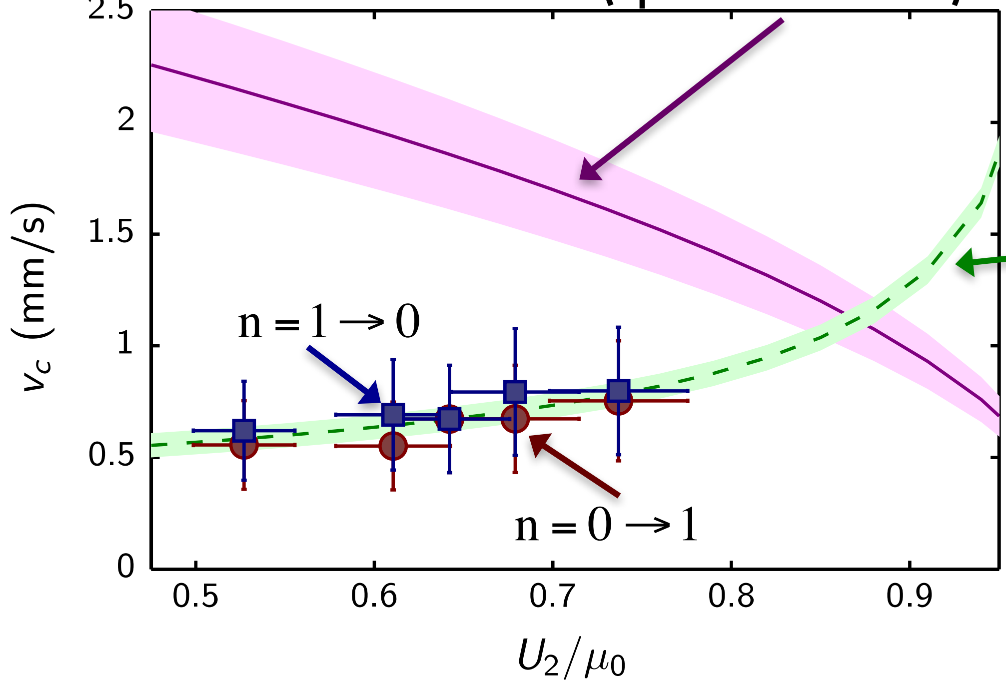
$$\gamma(I) = \sin^{-1}\left(\frac{I}{I_c}\right) + \frac{LI_c}{h}\frac{I}{I_c}$$

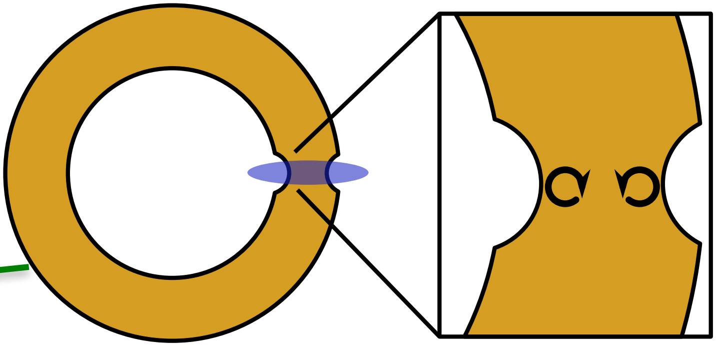
Eckel et. al, PRX **4**, 031052 (2014)

Critical velocity

At what velocity do phase slips occur?

Gross-Pitaevskii Equation
Models Zero temp behavior
(speed of sound)





Toy model which takes into account the effect of:

Magnus Force: $\propto \vec{\omega} \times \vec{v}$
Buoyancy Force: $\propto -\nabla n$

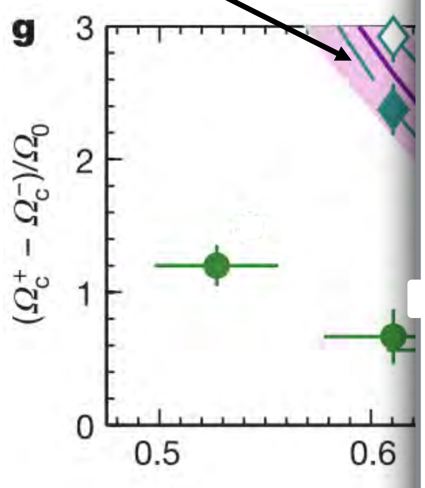
Fetter, Phys. Rev. 153, 285 (1967).

Eckel et. Al Nature **506**, 200 (2013)

What's missing from GPE?

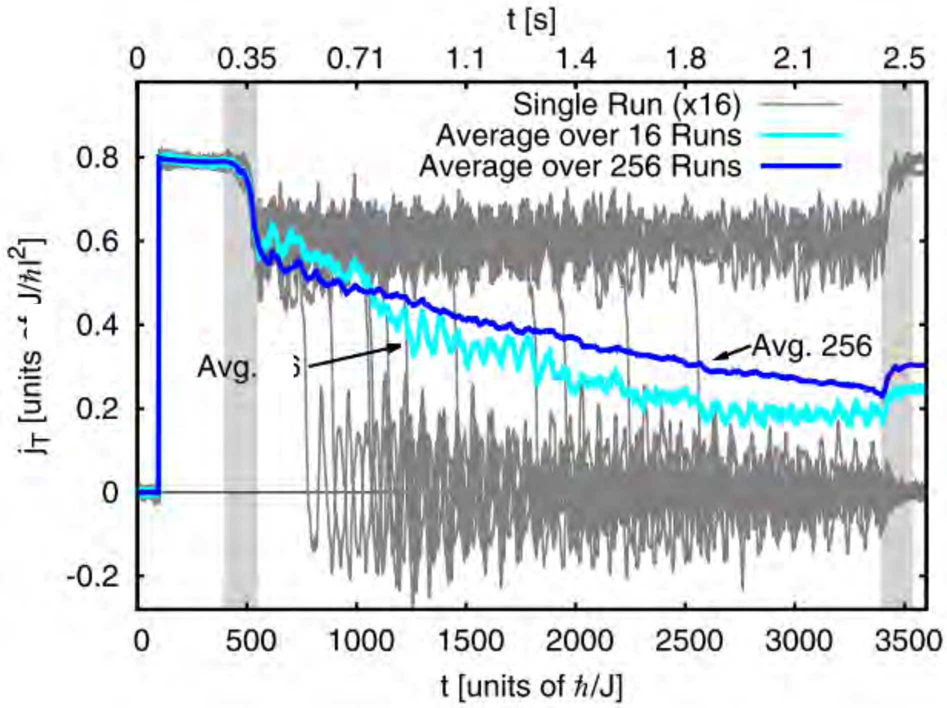
Dissipation?

GPE w/ dissipation



Eckel, S., *et.al.*, *Natu*

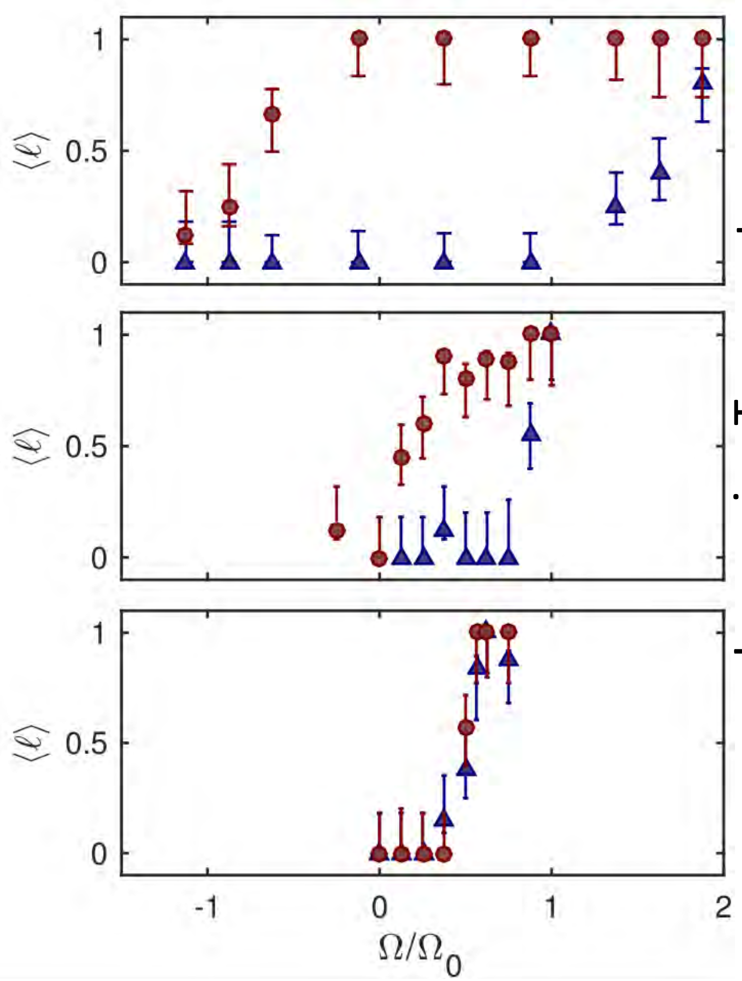
Thermal/quantum fluctuations?



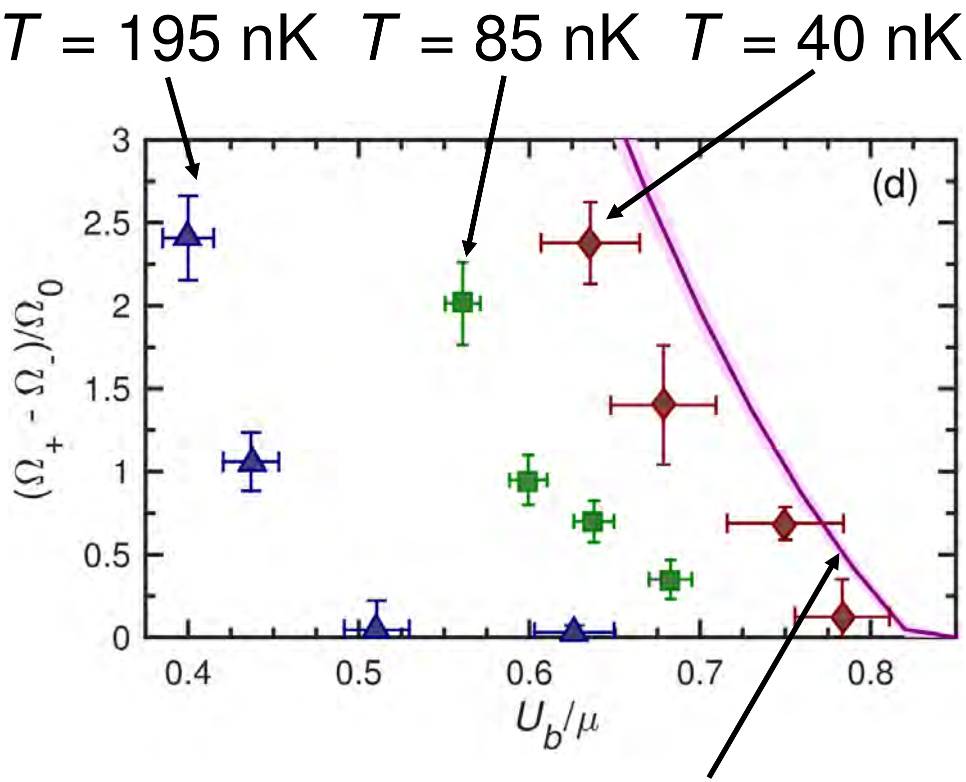
Mathey, A., *et.al.*, *PRA*, **90**, 023604, (2014).

Hysteresis depends on temperature

$$\frac{U}{\mu_0} = 0.62(4)$$



Increasing Temperature



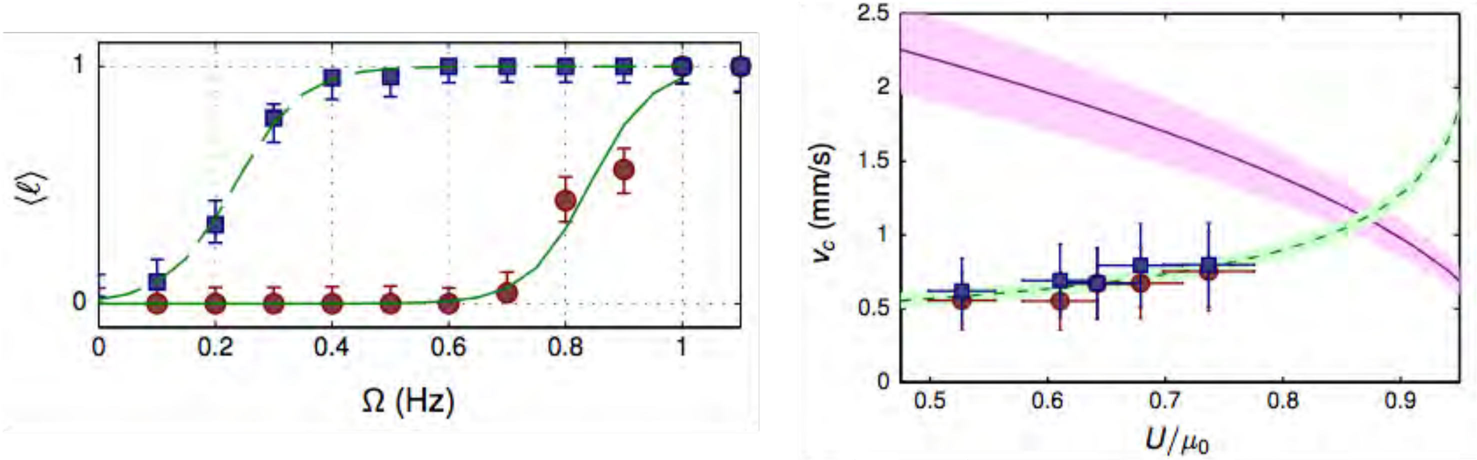
T = 195 nK T = 85 nK T = 40 nK

Speed of sound
(GPE)

Kumar, A., *et.al., in preparation.*

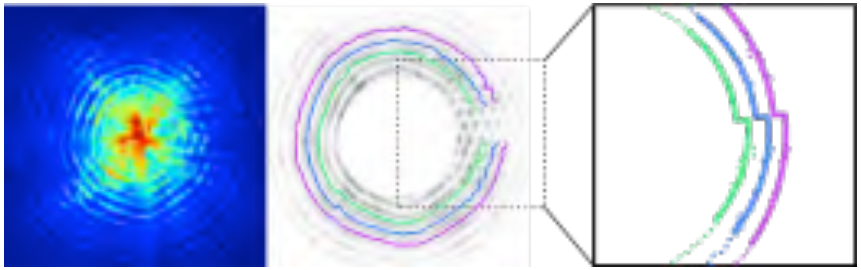
Conclusions

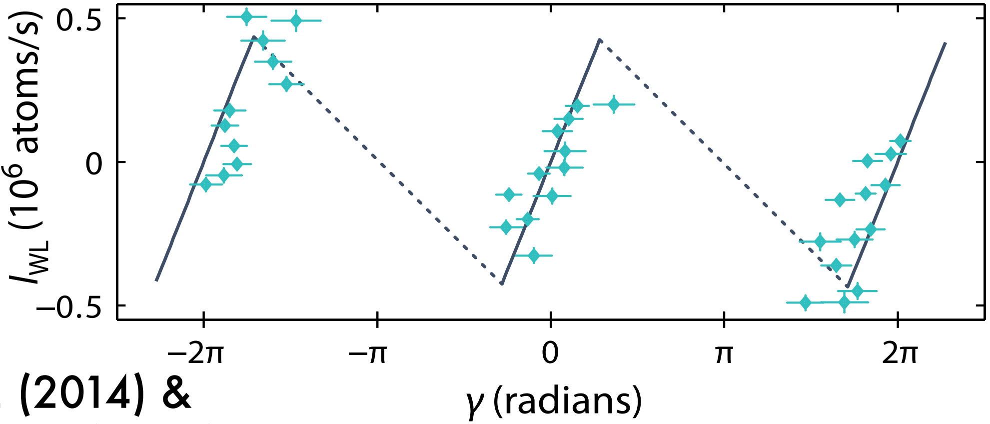
1. We have observed superfluid hysteresis in a cold-atom circuit:



Eckel, S., et.al., *Nature*, 506, 200, (2014).

2. Measured the current-phase relationship of our weak link:



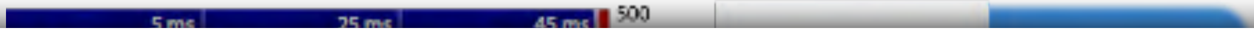


Eckel, S. *et. al.*, *Phys. Rev. X* **4**, 031052 (2014) &
Mathew, R. *et. al.*, *Phys. Rev. A* **92**, 033602 (2015)

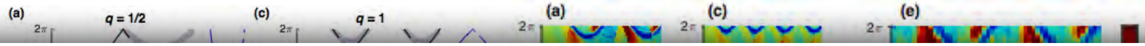
Other experiments:

1. Observed resistive flow and the I-V characteristic

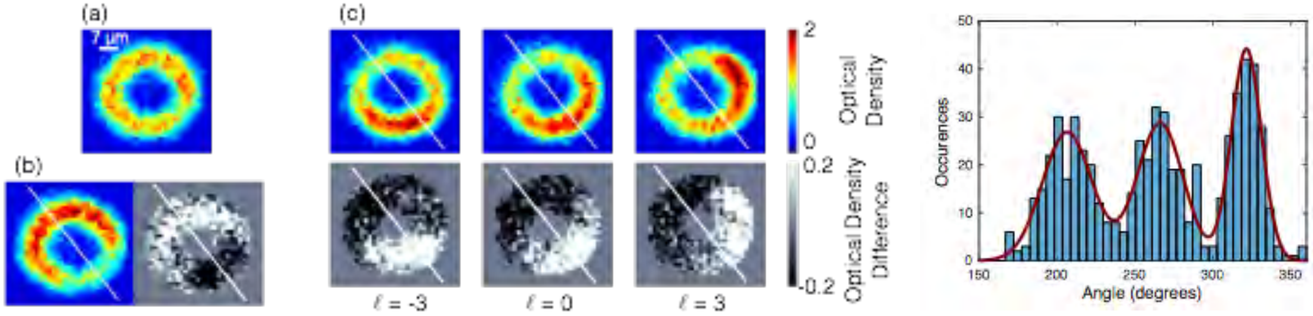
2. Measured the conductance through a channel:



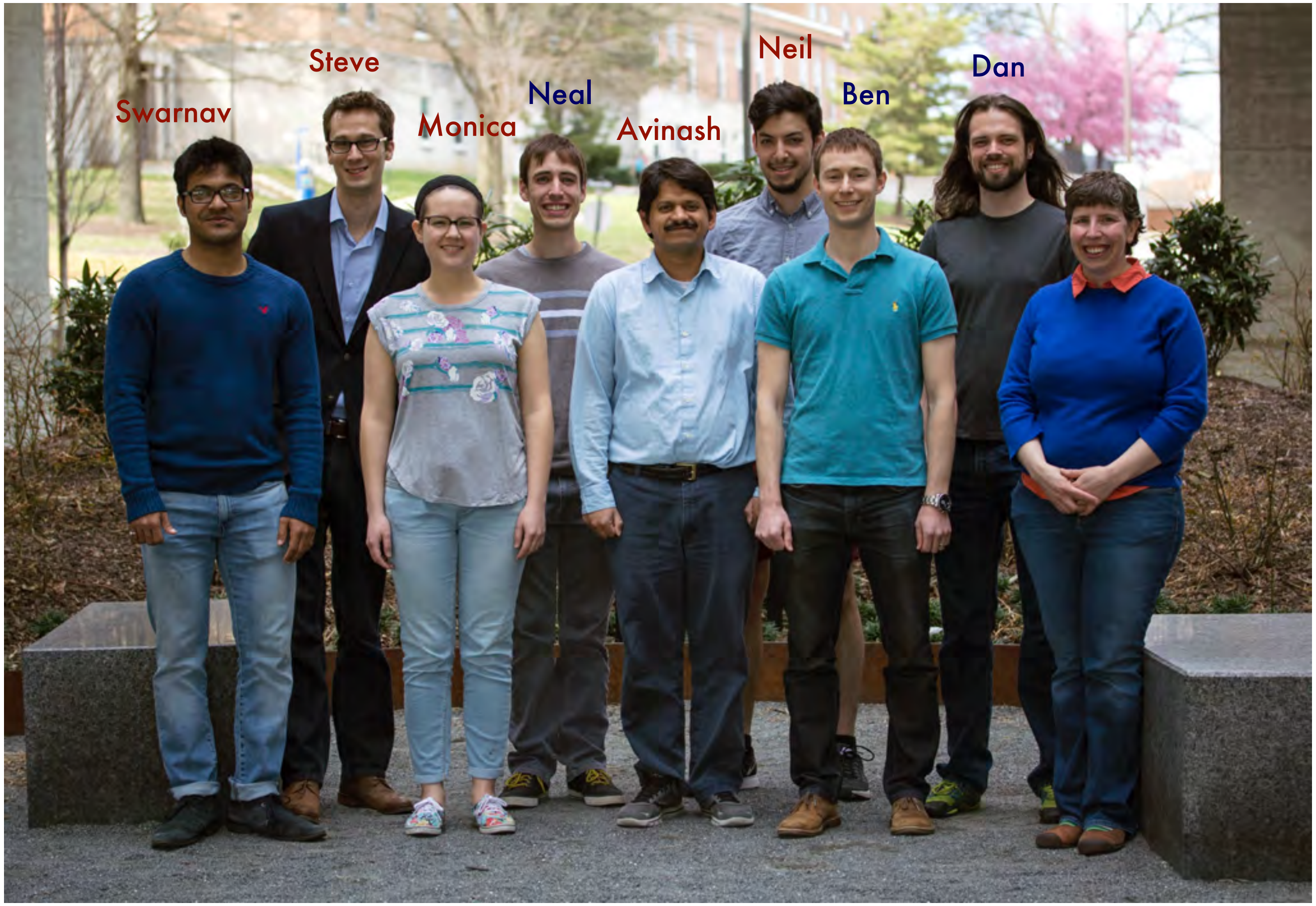
3. Observed resonant sound (phonon) wave packets:



4. Used the Doppler effect with phonons to measure flow:



1. Jendrzejewski, F., Eckel, S., *et. al.*, *Phys. Rev. Lett.*, **113**, 045305 (2014)
2. Lee, J.G., Eckel. S, *et. al.*, arXiv:1506.08413
3. Wang, Yi-Hsieh, *et. al.*, *New J. Phys.* **17** 125012 (2015)
4. Kumar, A., *et. al.*, New J. Phys **18** 025001 (2016)



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