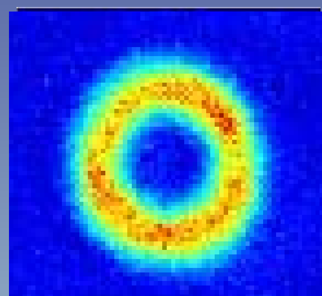
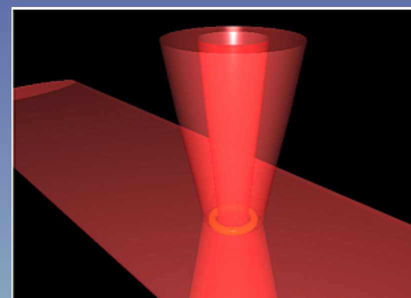
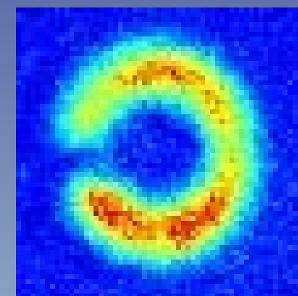
Atom Circuits
Pt I: Persistent Currents in a Toroidal BEC







Gretchen Campbell

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KITP
September 21, 2010

BEC and topology?

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

Interesting effects in toroidal traps

- Soliton propagation and collisions
- Superfluidity
- Superflow (persistent current)
  - hallmark of superfluidity and superconductivity
- Superpostions of macroscopic flow
  - SQUID analog (weak-link, Josephson junction)

- Interferometry/Sensors

Superfluidityvs Superconductivity

•Hallmark of both is persistent flow(current).

•Vorticity and vortex lattices are closely related to persistent current, but flow in a multiply-connected region (e.g., a torus) is a qualitatively different situation.

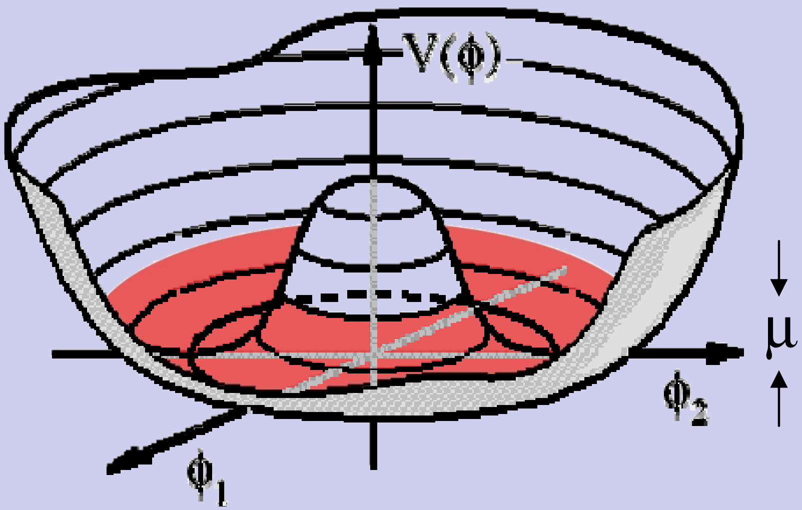
•We intend to study non-trivial circuits of superfluid in toroidal geometries to better understand:

analogies to superconductors
the nature of superfluidity
dynamic control of circuit parameters
vortex tunneling and other vortex behavior
…

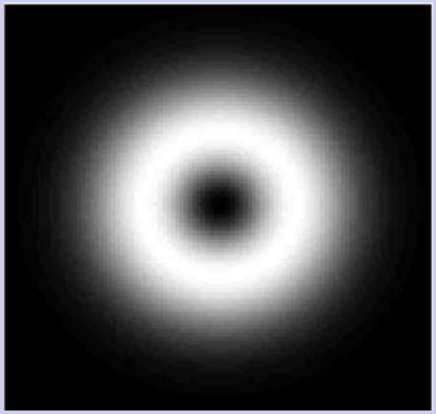
Toroidal or Ring-shaped Traps

Example:

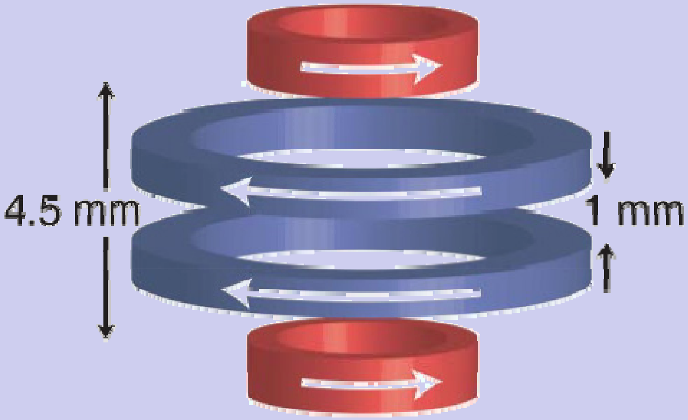
Mexican hat potential



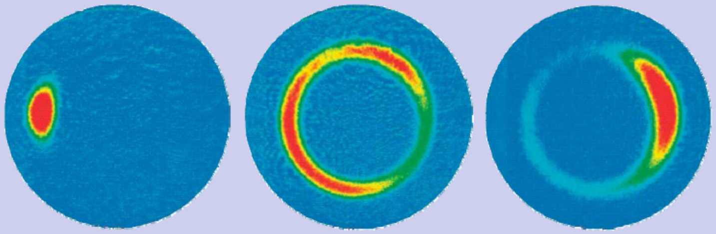
with Laguerre-Gaussian
or Bessel beams



Wright, Arlt, Dholakia, PRA 63, 013608 (2001)



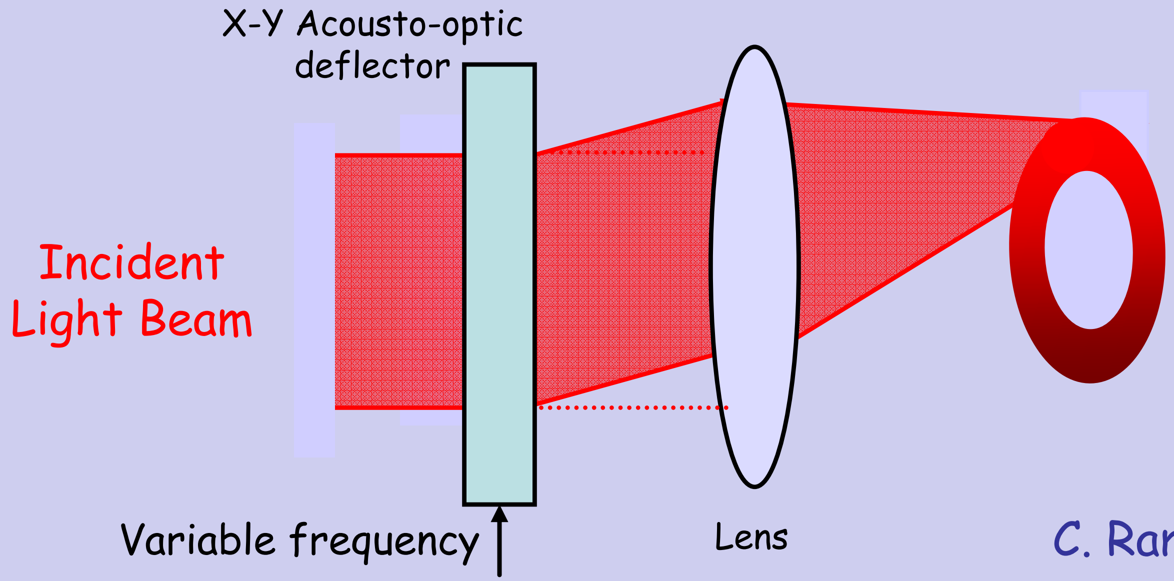
TORT

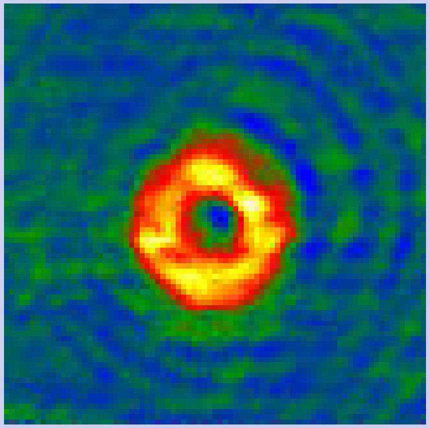


UC Berkeley - S. Gupta *et al.*, PRL 95, 143201 (2005)
U. Strathclyde- A. S. Arnold *et al.*, PRA 73, 041606(R) (2006)

More toroidal traps

Time averaged potential by rapidly scanning a laser beam

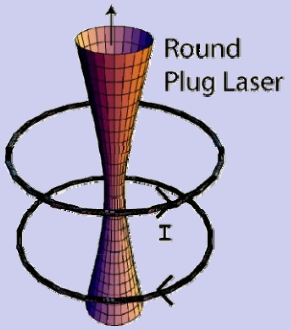


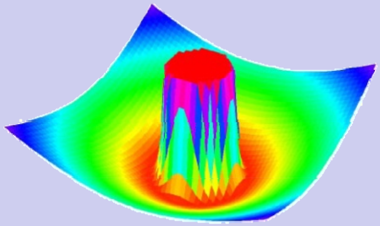


C. Raman and S. R. Muniz - GeorgiaTech

Another approach - plug magnetic trap with blue-detuned laser beam

Quadrupole magnetic trap (linear potential) and focused Gaussian laser beam



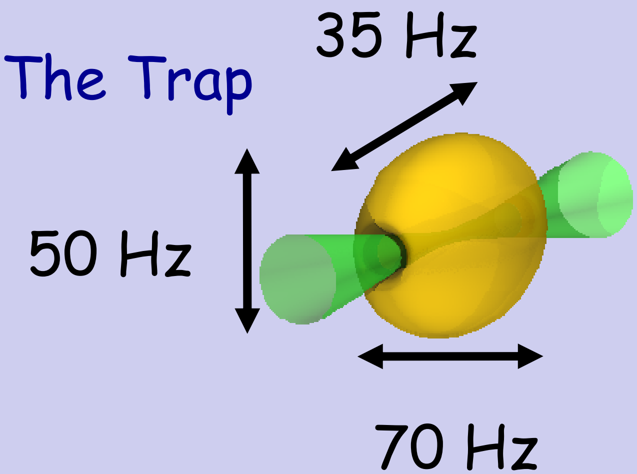


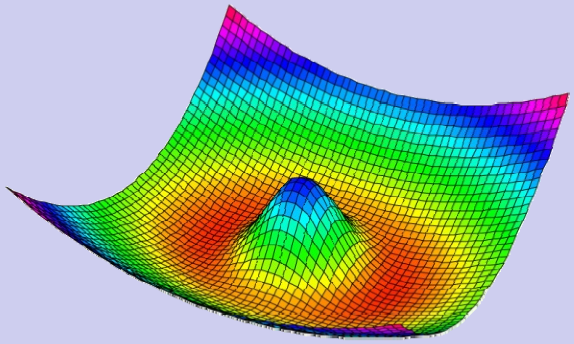
K.B. Davis *et al.*, PRL 75, 3969 (1995)

D.S. Naik and C. Raman, PRA 71, 033617 (2005)

BEC in a toroidal shaped trap

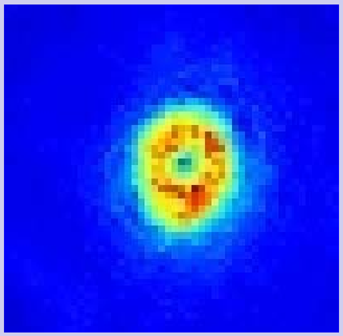
The Trap





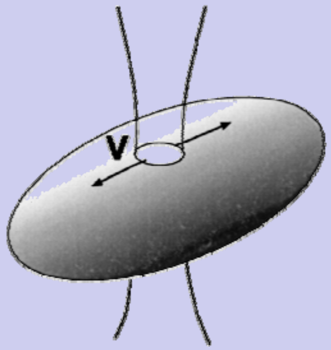
potential variation ~$\mu/3$

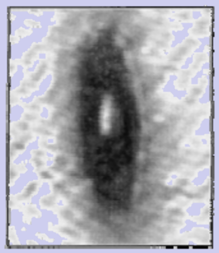
oblong torus
no rotational
symmetry



In situ

Earlier realization used to measure onset of dissipationless flow





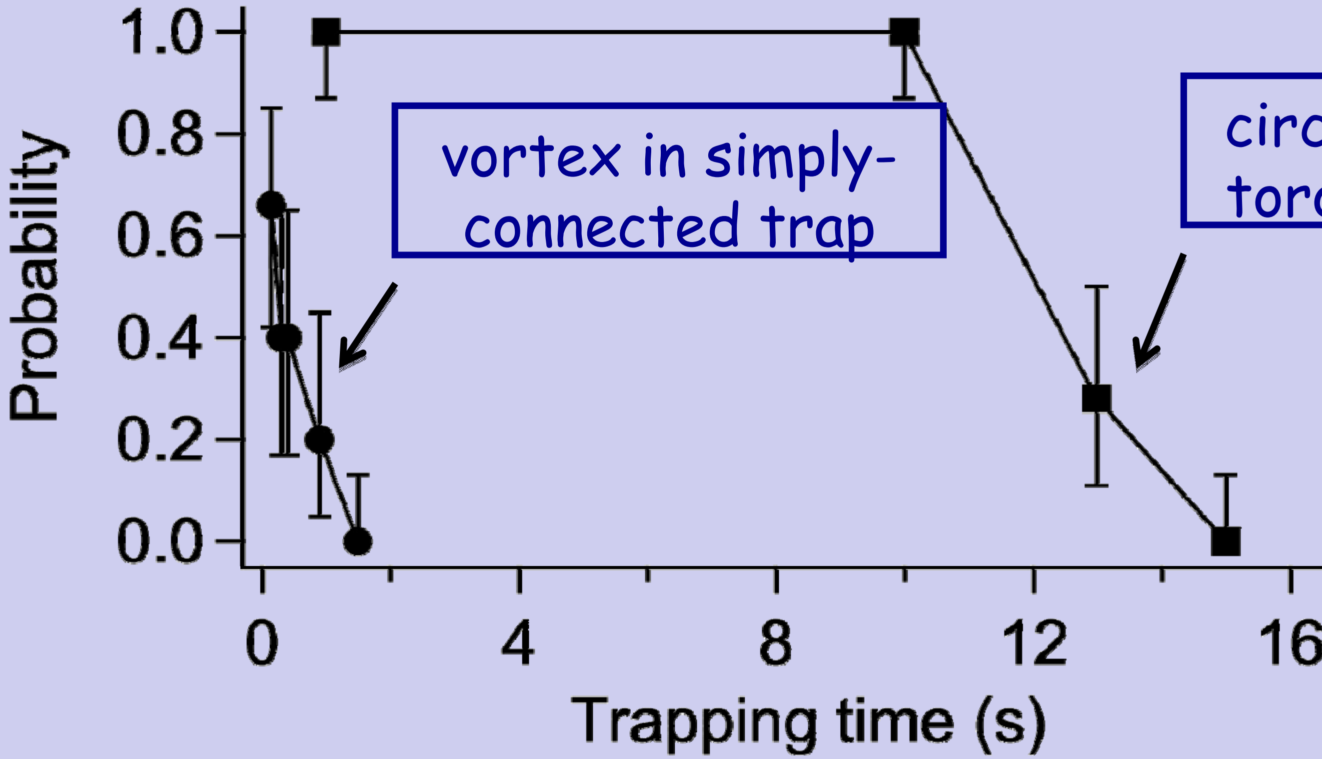
C. Raman *et al.* PRL 83, 2502 (1999).

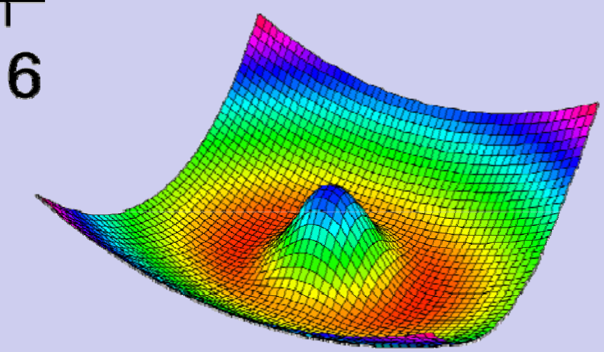
R. Onofrio *et al.* PRL 85, 2228 (2000).

We generate flow by transferring the orbital angular momentum of light to the atoms

Vortex stability

Apply LG-G Bragg pulse to generate rotation (100% efficient)





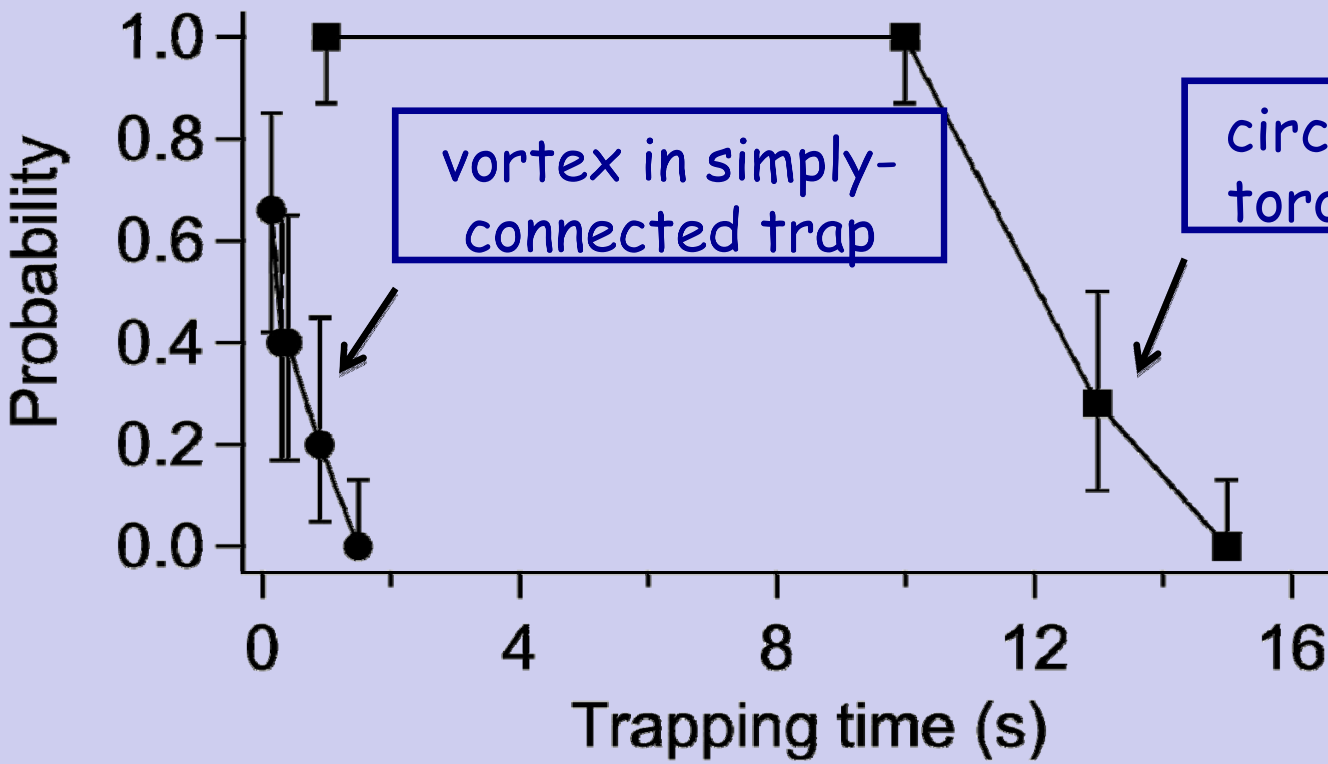
optically pierced magnetic trap

- Direct evidence of superflow lasting 10 seconds
- Flow lifetime limited by technical reasons

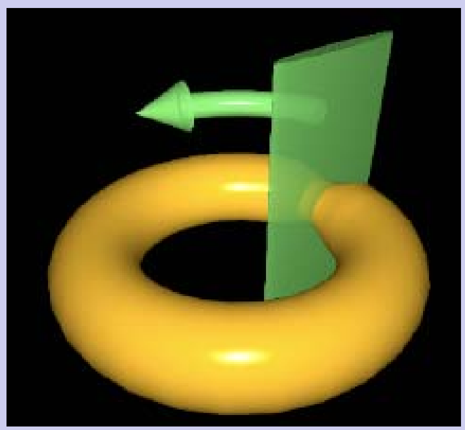
C. Ryu., et al. Phys. Rev. Lett. 99, 260401 (2007)

Vortex stability

Apply LG-G Bragg pulse to generate rotation (100% efficient)



For better stability: all-optical trap design.



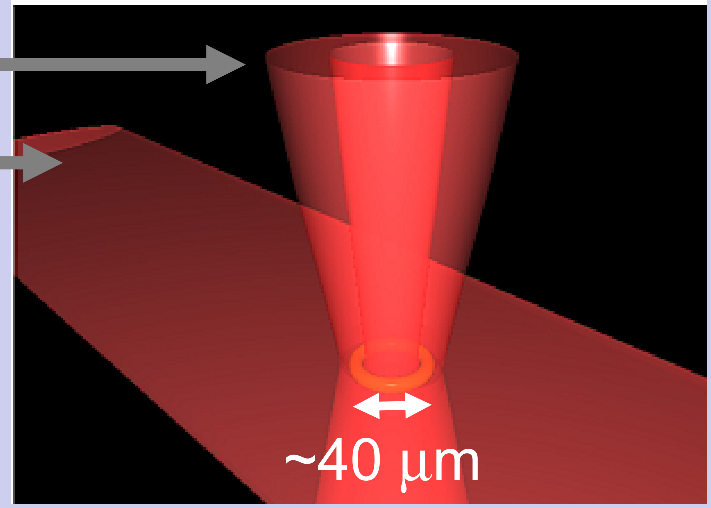
In a toroid, we can introduce circuit elements, like Josephson junctions.

C. Ryu., et al. Phys. Rev. Lett. 99, 260401 (2007)

New NIST all-optical toroidal trap for BEC

LG_{01} ‘Ring’ beam

‘Sheet’ beam



Uniform to:
- < 0.5% of typical depth
- < 10% of typical μ

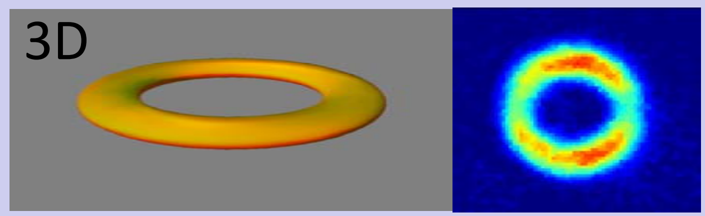
ω_Z: 500-2000 Hz

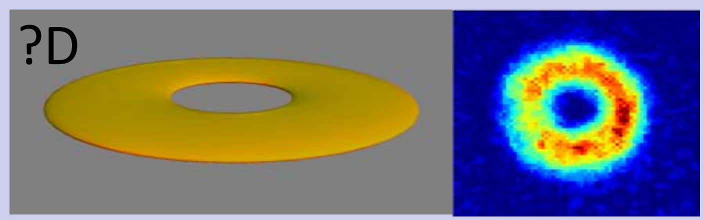
ω_R: 20-160 Hz

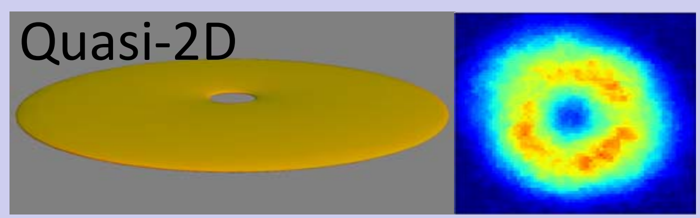
N ~ 1.5×10^5 atoms

μ ~ 50 nK (1 kHz)

T < 40nK



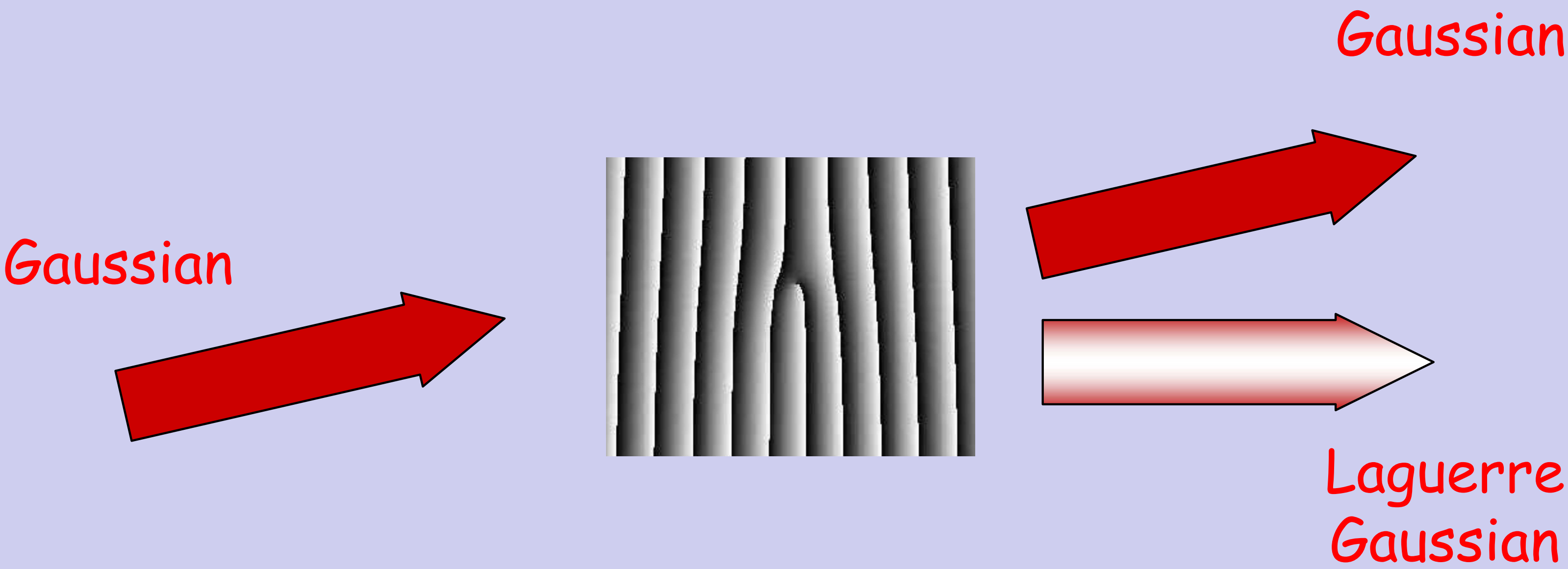


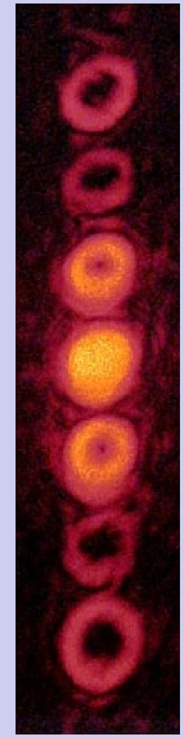


Generation of Laguerre-Gaussian beams

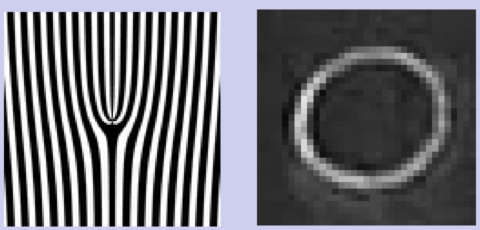
Diffraction gratings with phase singularities

Computer generated holograms, SLM

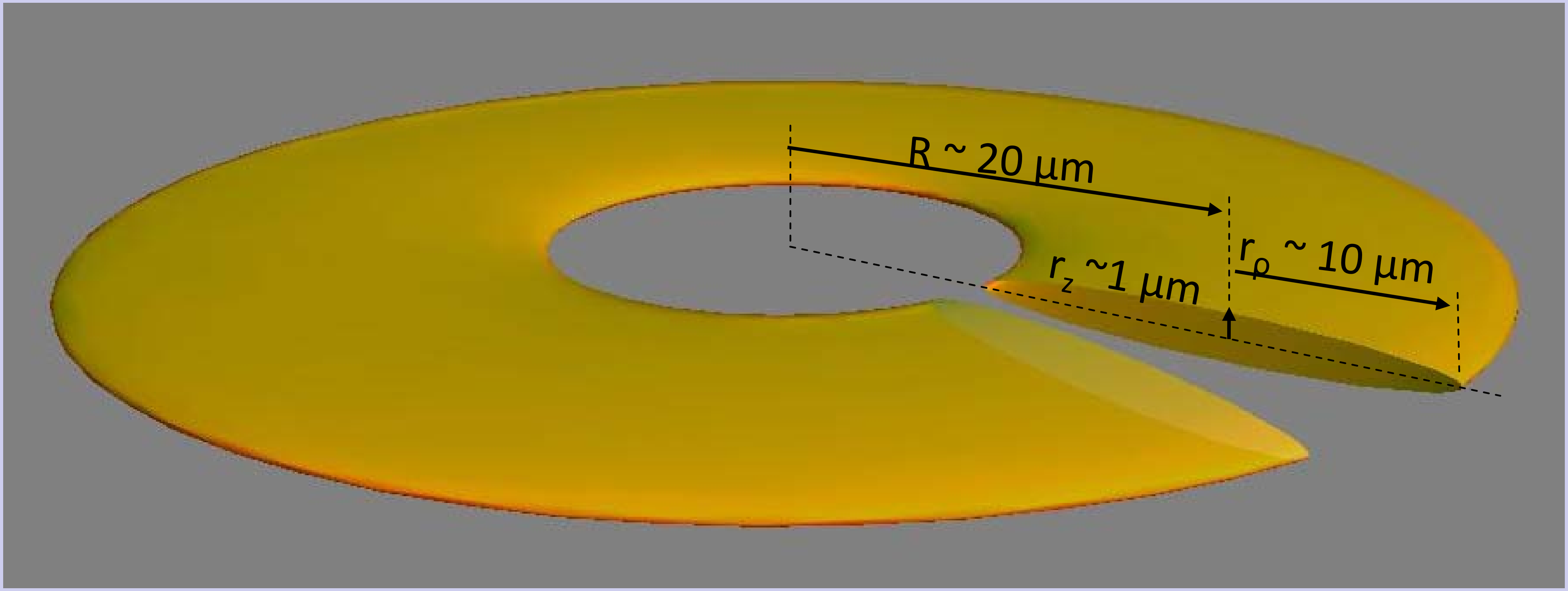




$l = 4$



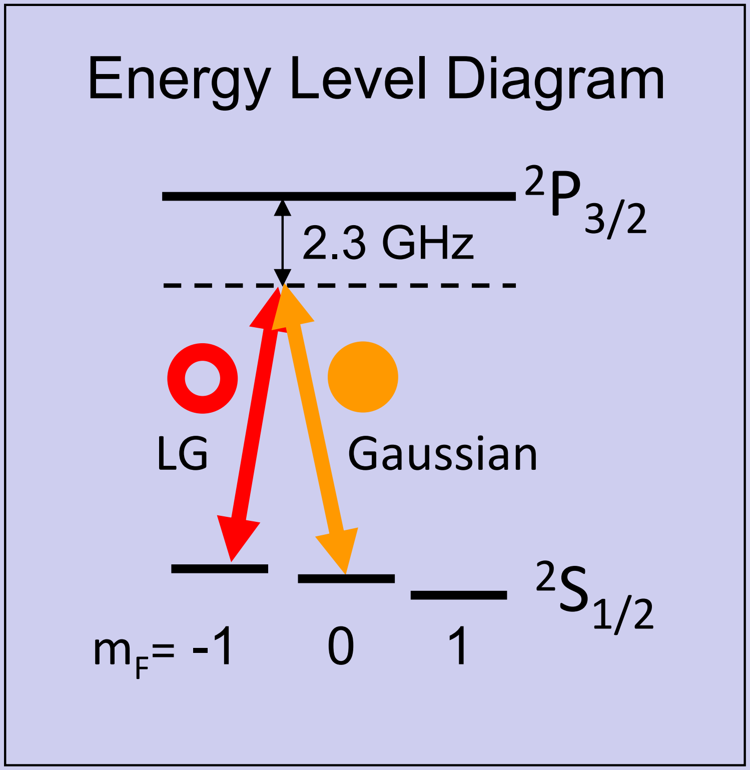
Typical Trap (BEC) Geometry

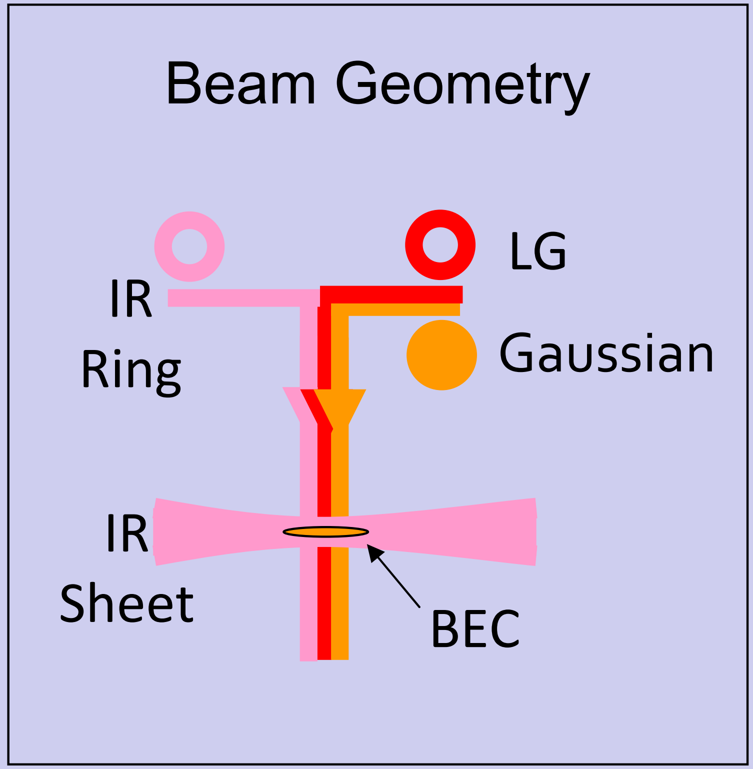


Vertical trap frequency ~ 500 Hz
'Radial' trap frequency ~ 100 Hz
T < 40nK

N~ 1.5 x 10^5 atoms
ρ ~ 5 x 10^{13} atoms/cm^3
μ ~ 1 kHz

Inducing Circulation with OAM Beams





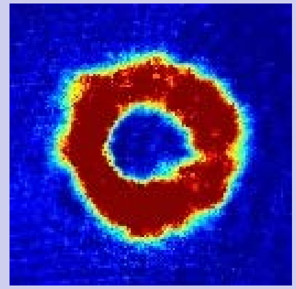
- Raman transfer (angular momentum only!)
- > 90% to final (circulating) state
- Negligible radial excitation of BEC
- Higher circulation states & circulating spin mixtures

K. C. Wright, et al. Phys. Rev. A 77, 041601(R) (2008)

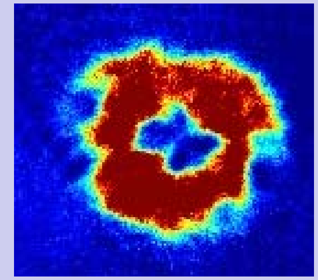
First attempts at persistent current

Sequence:

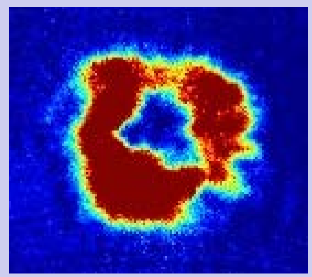
- •Start with BEC
- •Transfer rotation
- •hold 1-20 ms
- •4 ms time-of-flight.
- •Image



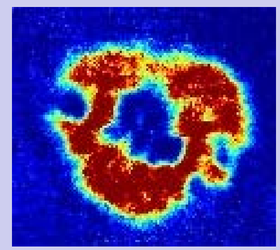
1 ms



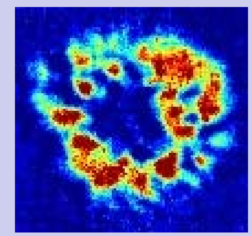
3 ms



5 ms



10 ms

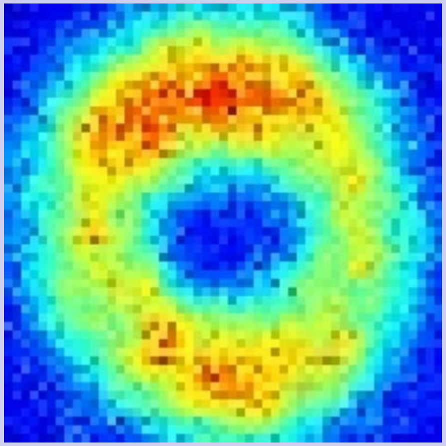


20 ms

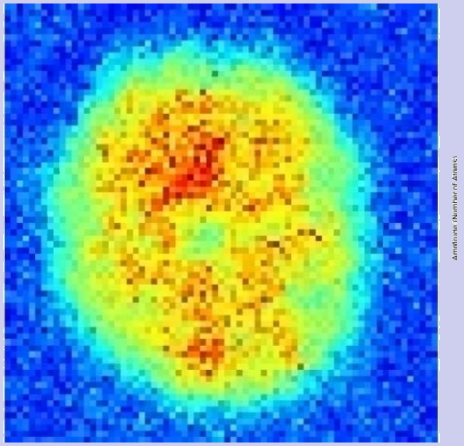
- •High-spatial-frequency creates non-uniformities in the potential
- •In time-of flight: variations in mean-field energy produce spatial phase fluctuations.

All optical trap: take two

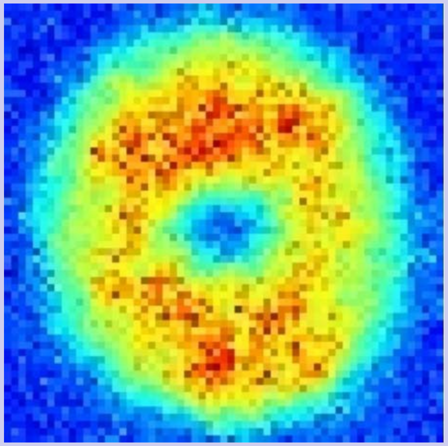
In-Situ



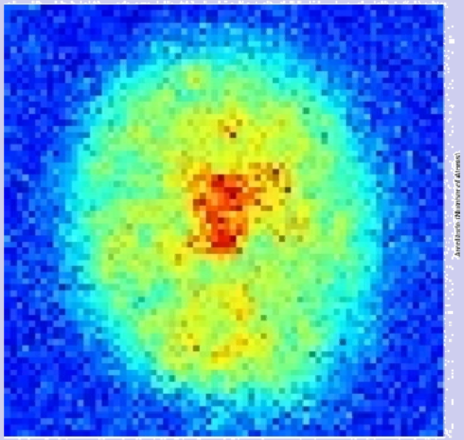
4ms tof



2ms tof

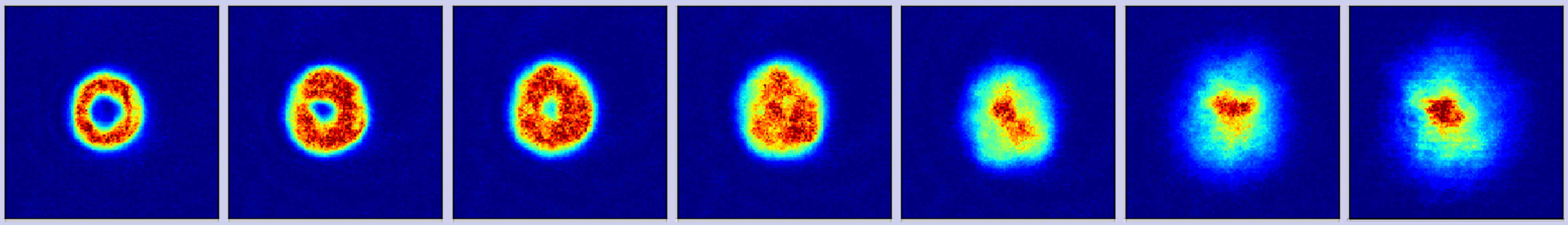


6ms tof



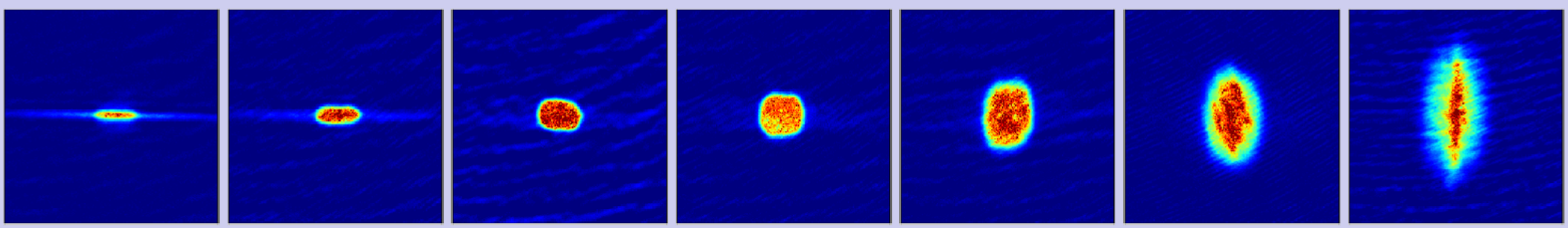
TOF Expansion of the Ring

Top View



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

Side View

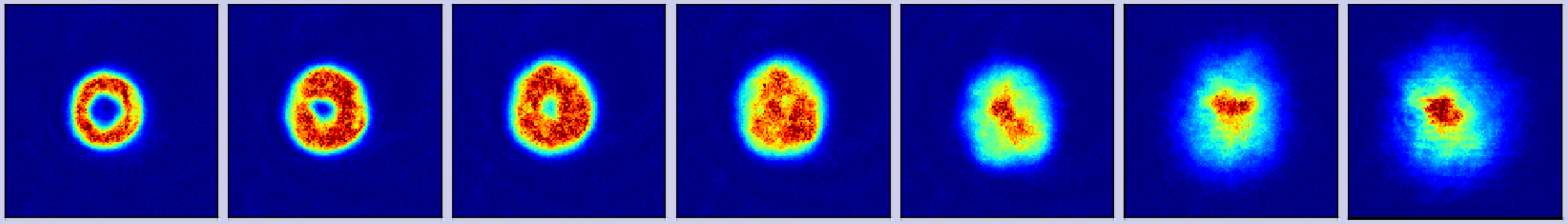


0 ms 2 ms 4 ms 6 ms 8 ms 10 ms 12 ms

Detecting Circulation in TOF

Ring Beam Power

0 ms | 2 ms | 3 ms | 4 ms | 6 ms | 10 ms | 12 ms



Hold at 77mW (100%)

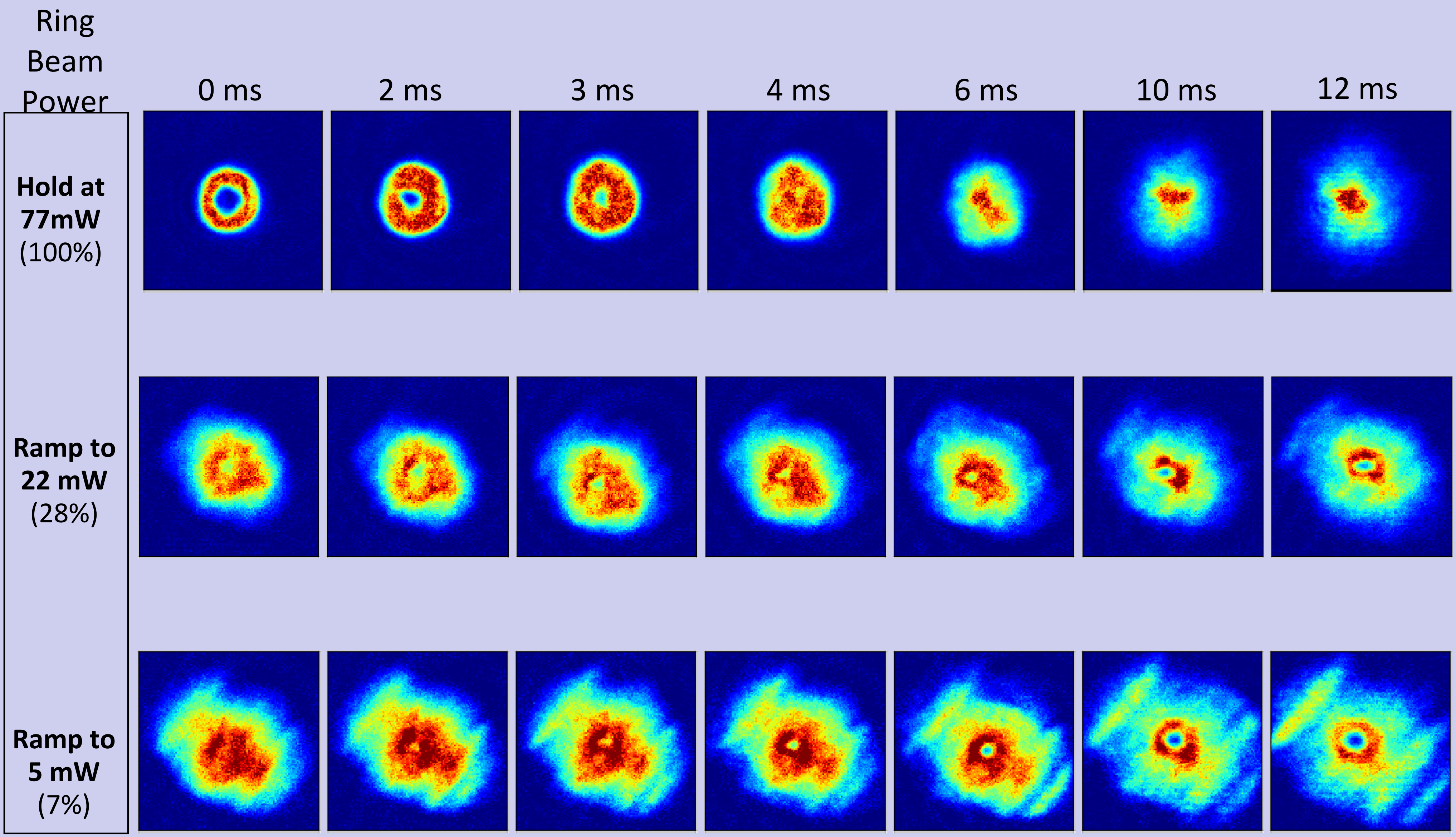
Detecting Circulation:

Radial Relaxation and TOF Expansion

Finite-element 2D GPE simulation
with scaled interaction strength

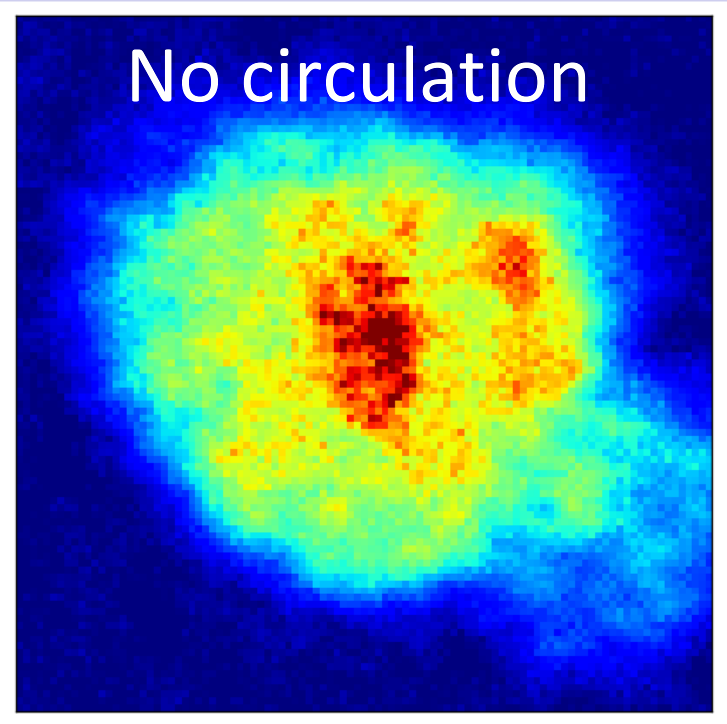
Detecting Circulation in TOF

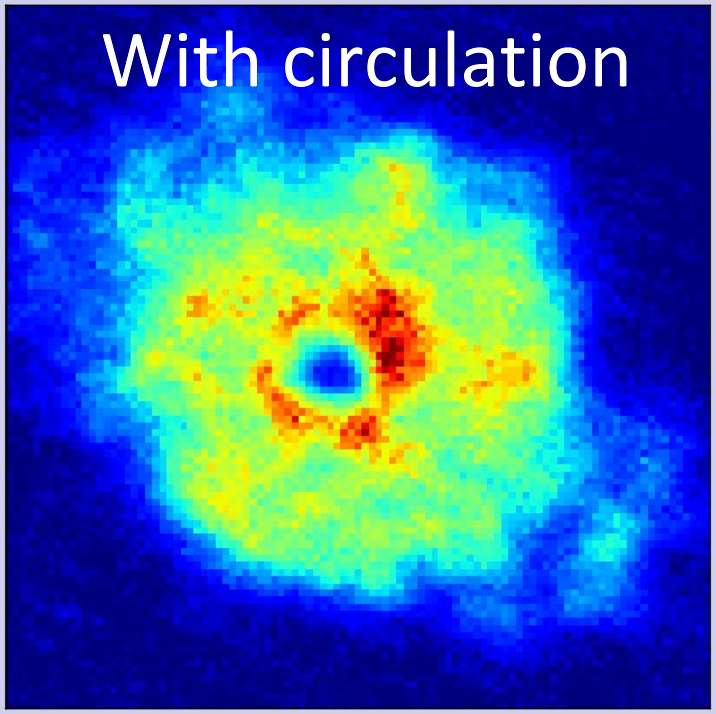
Ramp down the radial confinement over 50 ms before release



Detecting Circulation in TOF

(Images taken after 10 ms expansion)

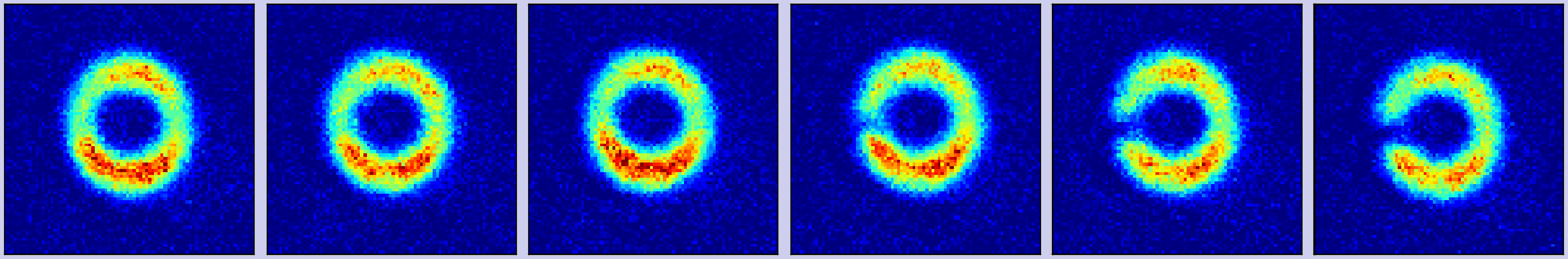


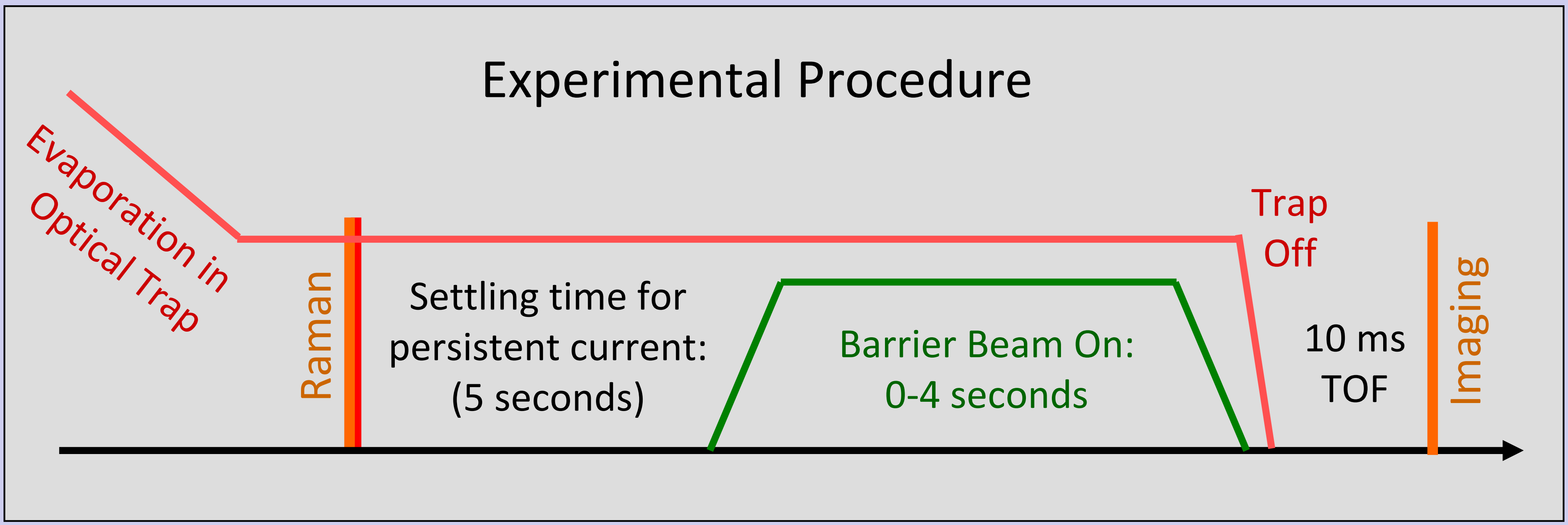


*Circulation is robust for up to **40 seconds***

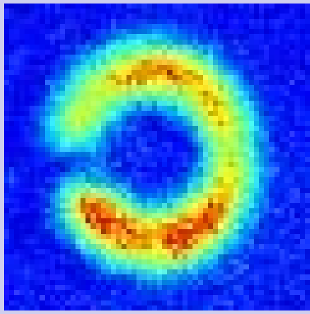
Limited by: Vacuum (~30 sec. BEC lifetime)
Trap nonuniformity (<5 nK)

Breaking the Flow With a Barrier

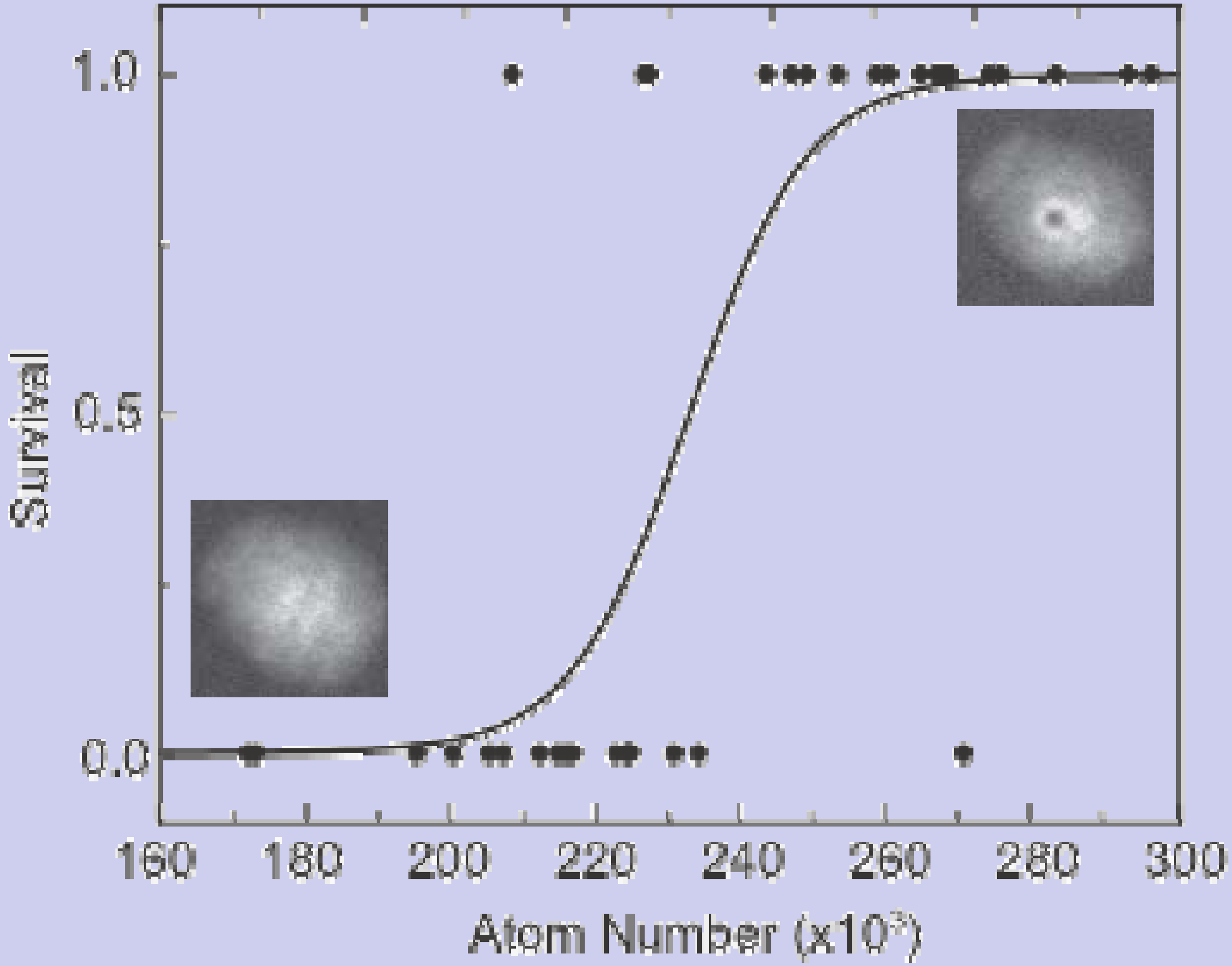




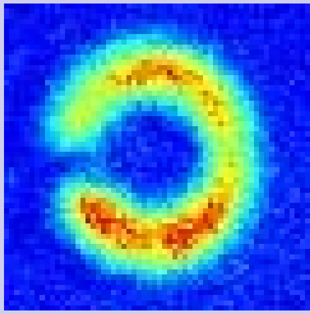
Critical Velocity for superfluid flow

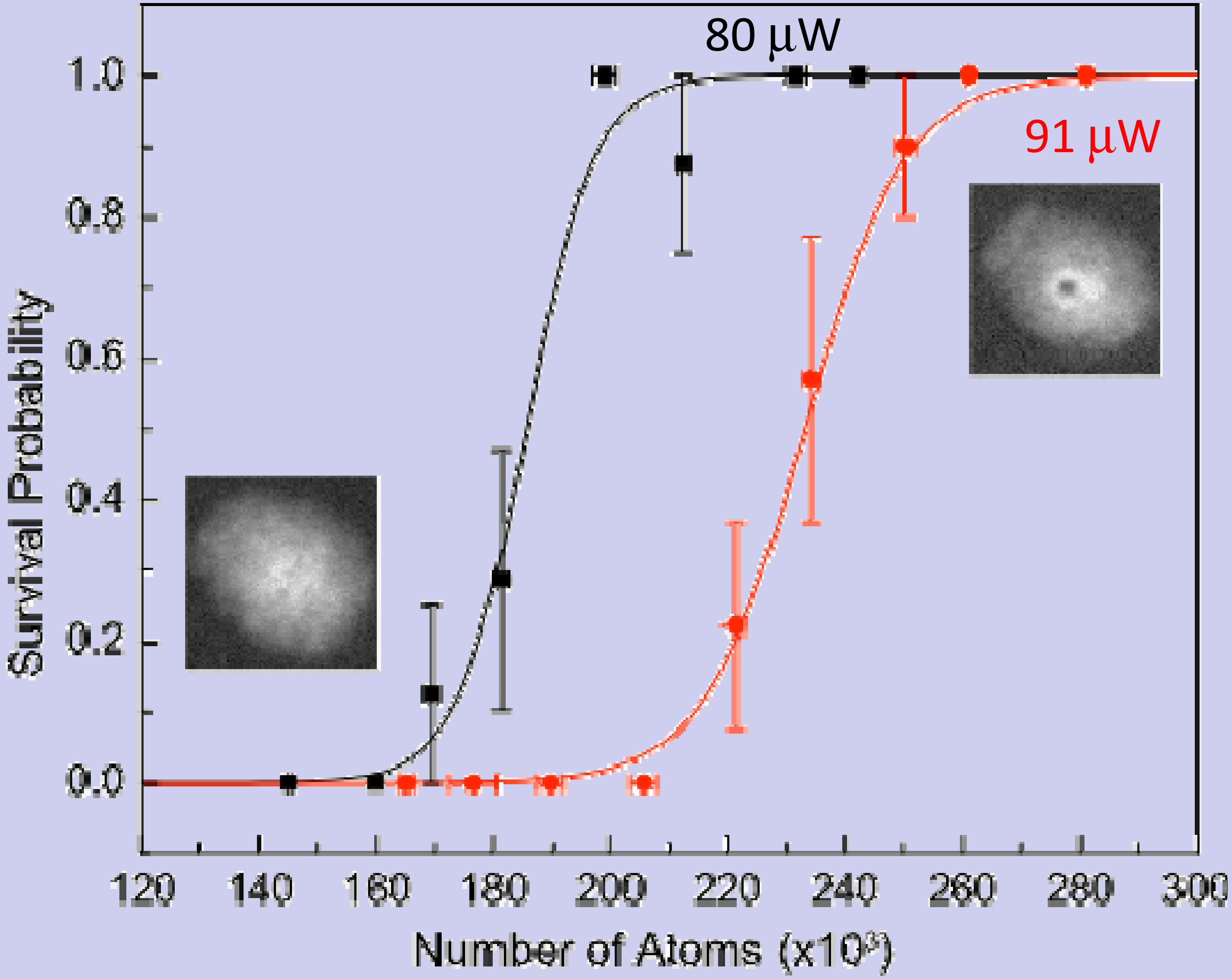


Constant barrier, vary atom number:



Critical Velocity for superfluid flow





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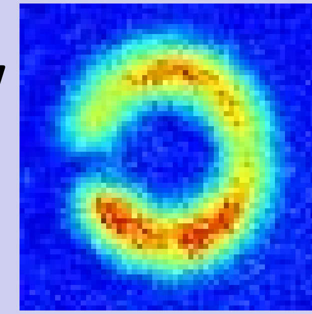
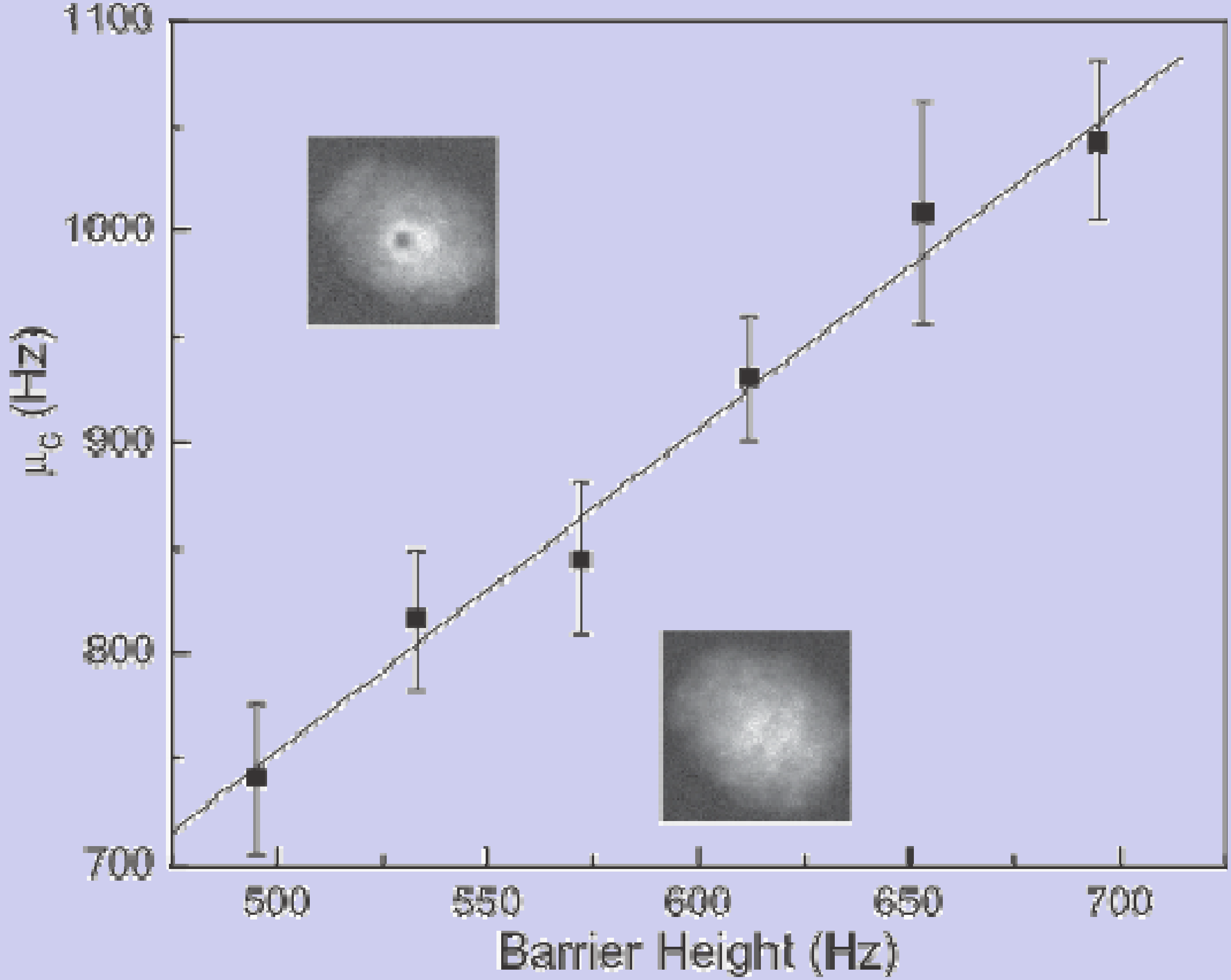
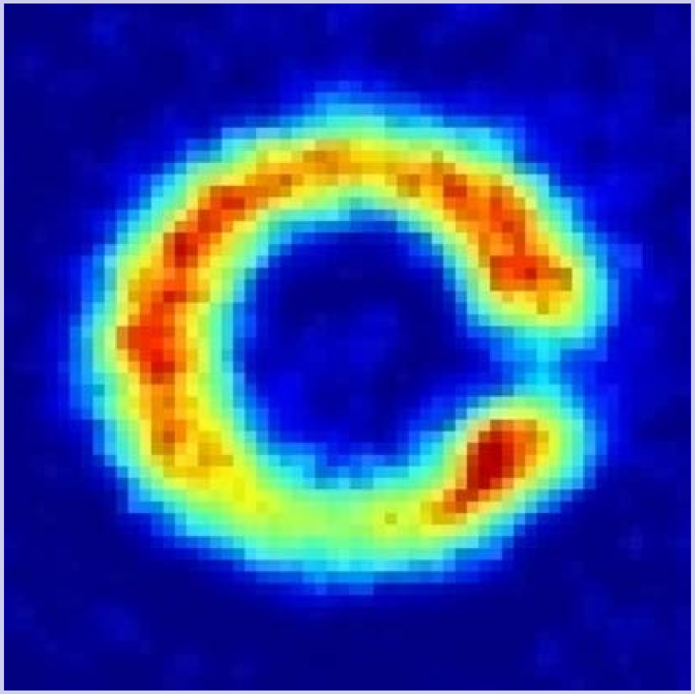




Calculating the critical velocity

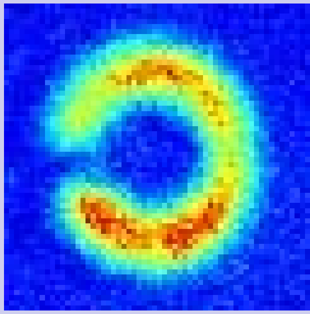


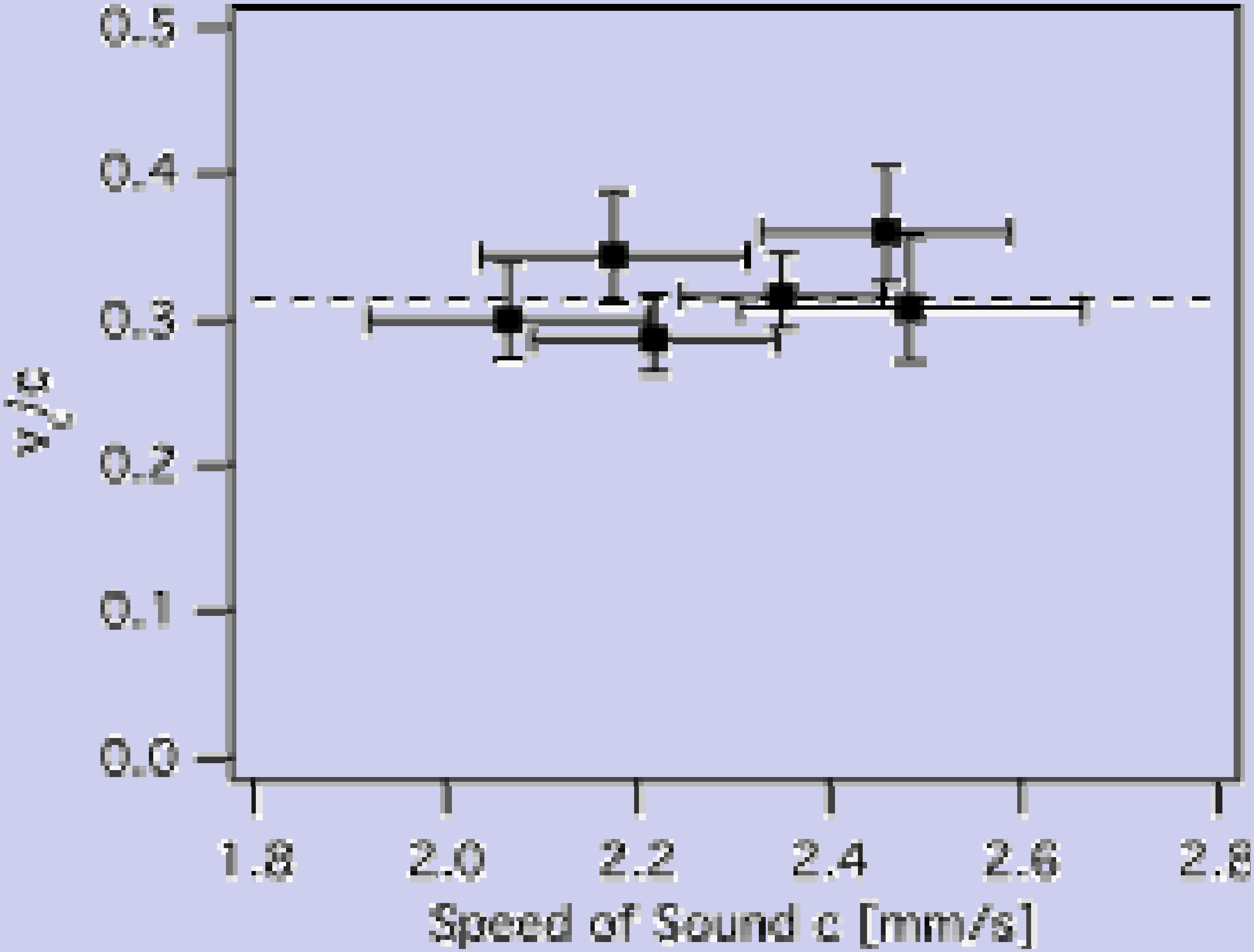
Diameter of Ring: ~ 40 μm
Annular width of ring: ~5 μm
Width of barrier: ~ 5 μm
Healing Length: ~ 1 μm

Constraints:
2π phase winding-sets velocity
But….
Velocity in barrier region higher than bulk velocity

Bumpy potential, varies phase gradient.

Critical Velocity for superfluid flow

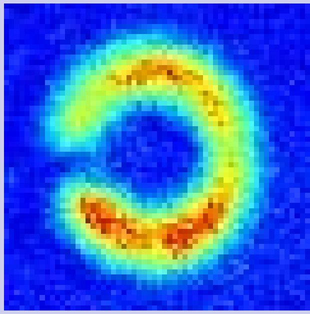


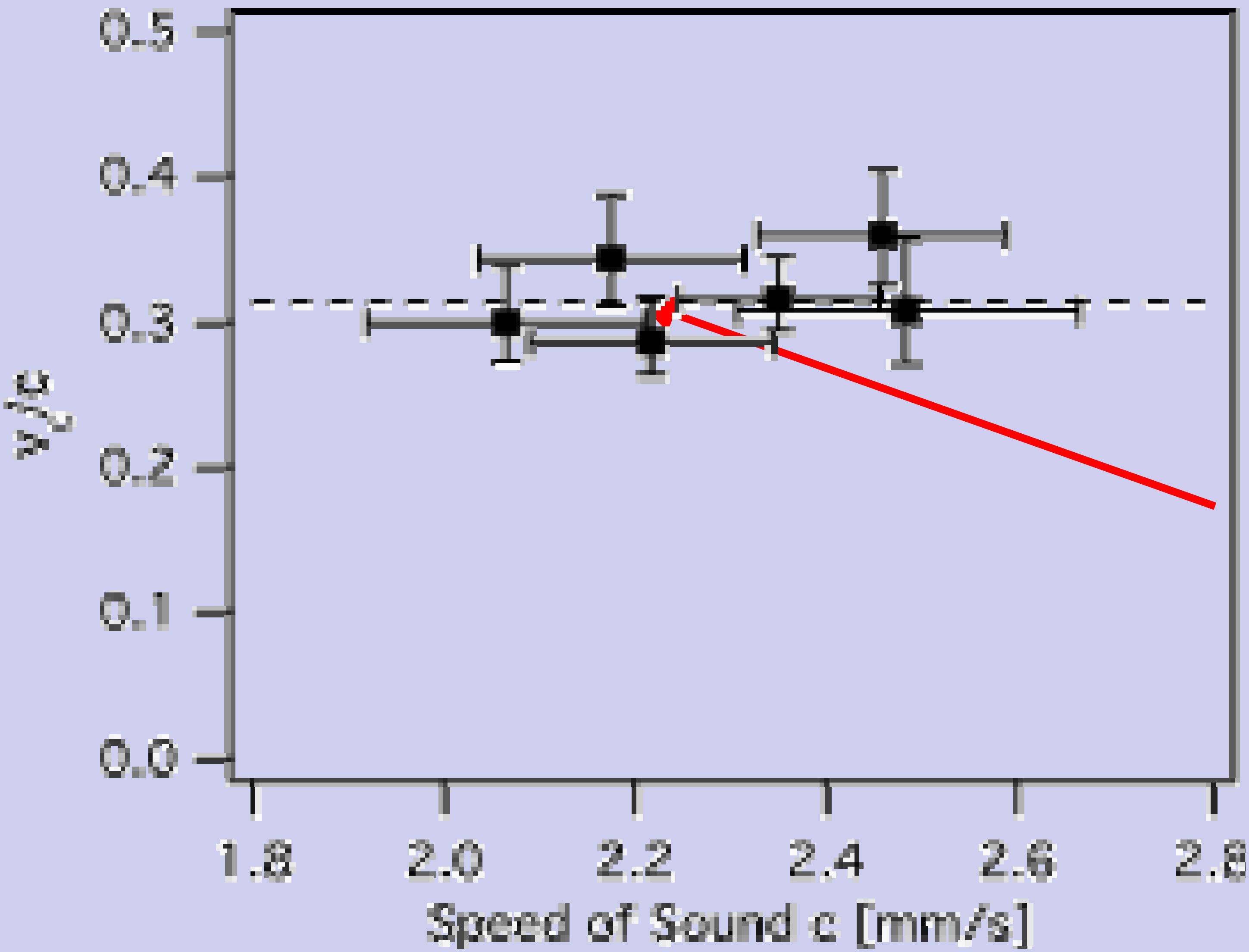


We find the critical velocity v_{cr}= 0.33(5)c

c = speed of sound

Feynman Critical Velocity





d= width of channel

~ 5 μm

ξ = size vortex core

~ 1.3 μm

Superconductors and Superfluids in Mean Field Theory

Ginzburg-Landau for superconductors:

$$F - F_{no} = \int \left[\alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{1}{2m^*}\left|\left(\frac{\hbar}{i}\nabla - \frac{e^*}{c}A\right)\psi\right|^2 + \frac{B^2}{8\pi} \right] dr$$

Gross-Pitaevskii for interacting Bosons:

$$E = \int \left[V(r)|\psi|^2 + \frac{g}{2}|\psi|^4 + \frac{\hbar^2}{2m}|\nabla\psi|^2 \right] dr$$

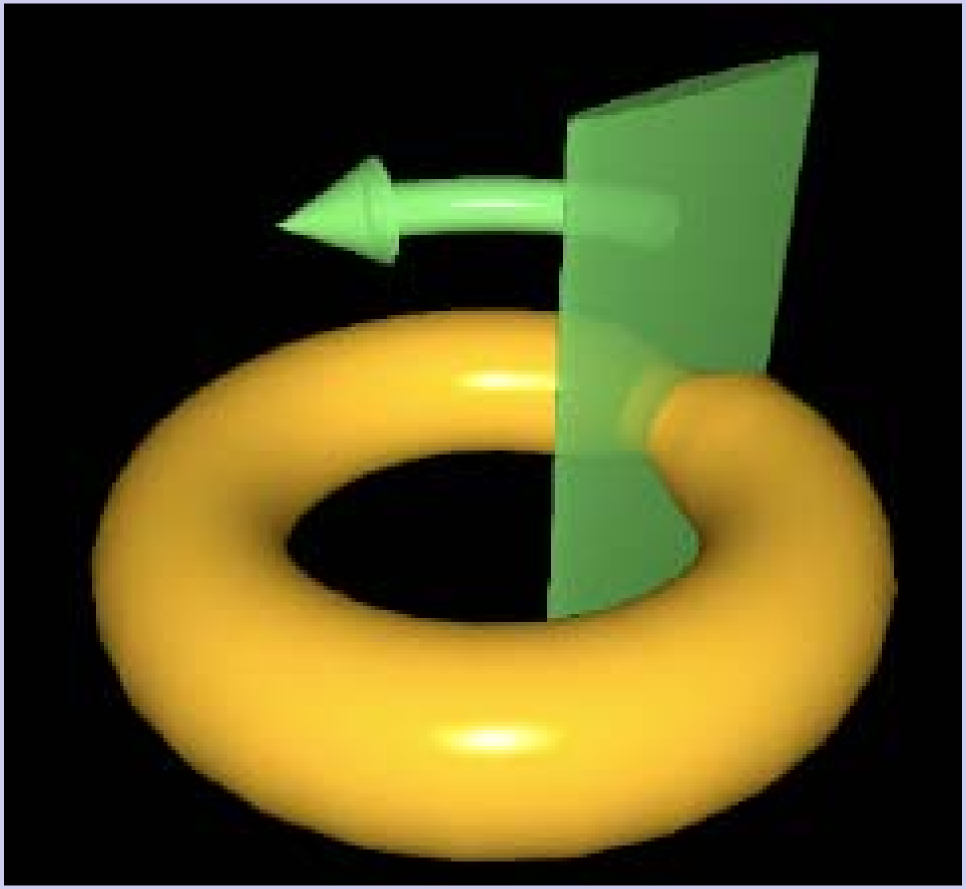
•Formally equivalent except for charge/magnetic field.

•In the frame rotating frame of a barrier moving around a torroidalsuperfluid an effective magnetic field ( ) appears.

•V(**r**) and g experimentally controllable; $\alpha_o$and β determined by material [where $\alpha=\alpha_o(T_c-T)/T_c$]

Superfluid jumps

- Superconducting Josephson junction analog
- Changing the rotation velocity is like changing the applied field to a SQUID.
- What happens if you stir slower than one quantum?
- How fast can you stir?



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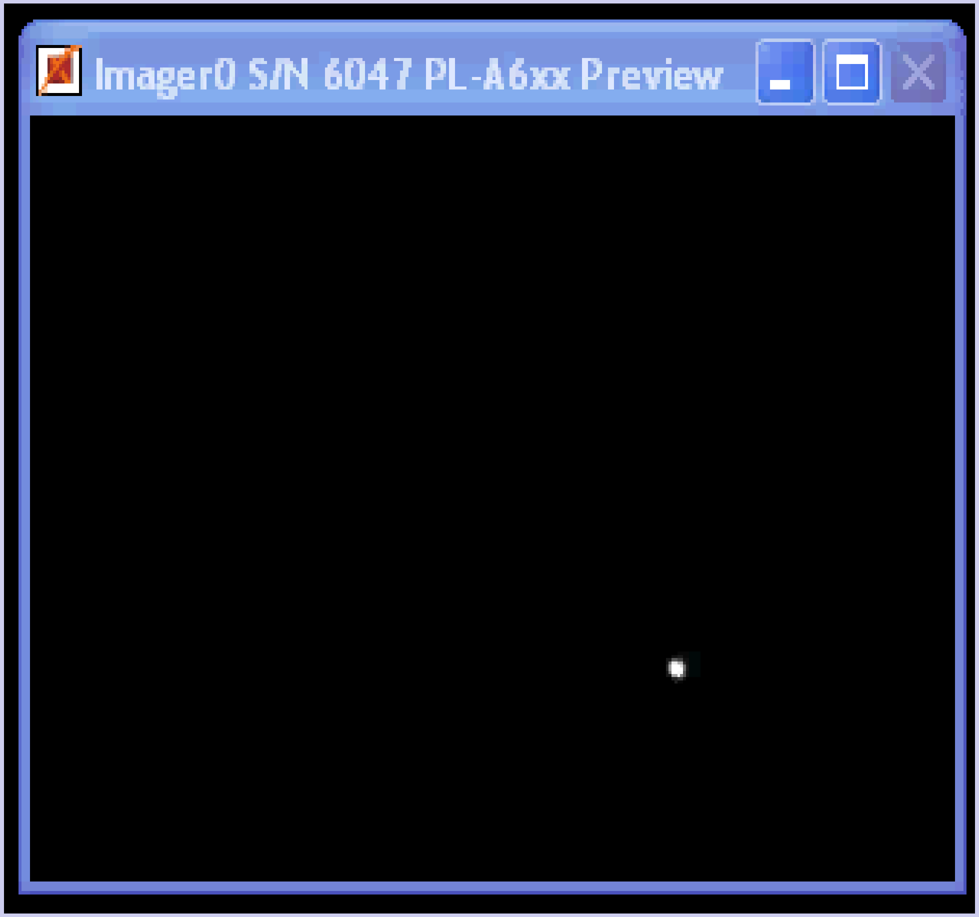
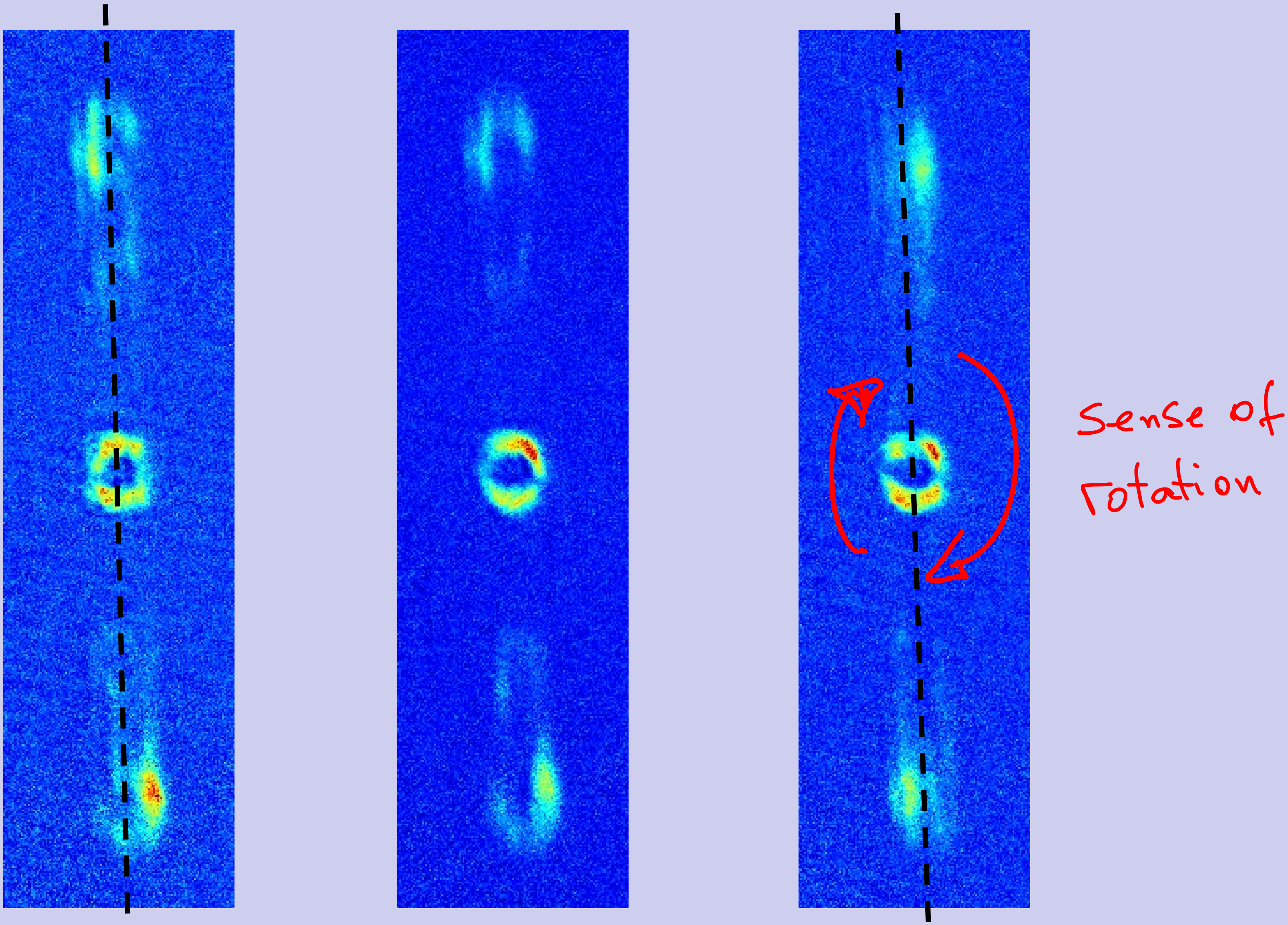


High-resolution Velocity-Spatial Mapping



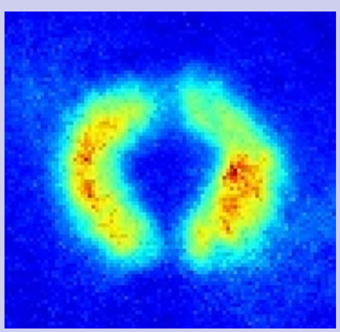
100.8 KHz 100.5 KHz 99.9 KHz

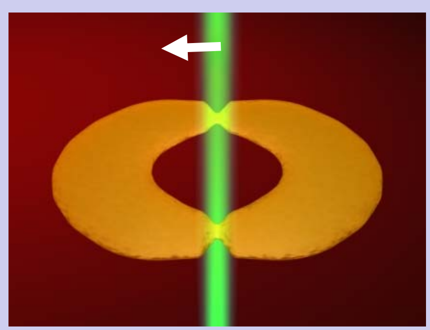
Muniz et al, PRA 73 041605(R) (2006)

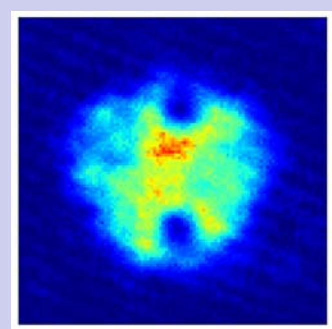
Present &Future Activities

- Systematic measurements of the critical velocity v.s.
  - Trap geometry, barrier geometry, temperature, density…
- Direct observation of decay dynamics
- Flow with a moving barrier

  Combine with artificial fields?
- Josephson-like effects in a BEC circuit
  - Movable double-barrier: analogous to biased DC SQUID
- Higher circulation states (observed!)







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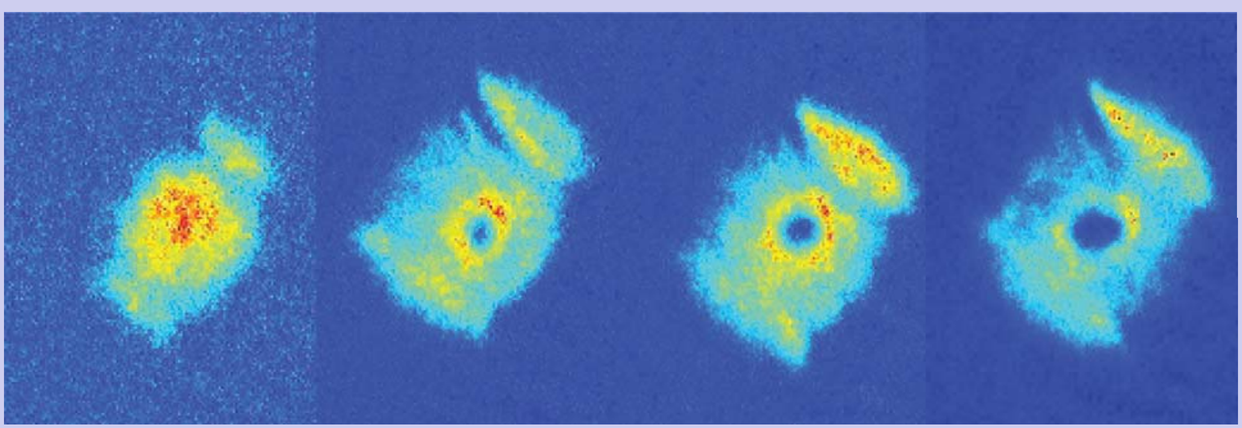
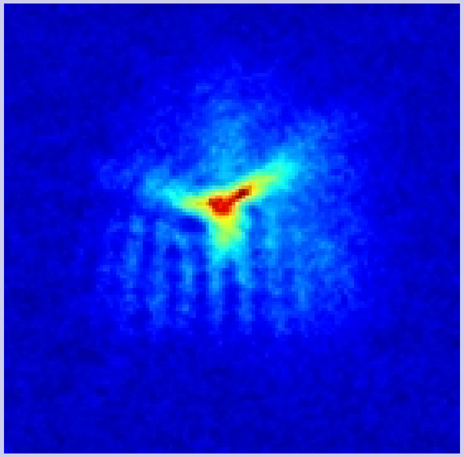
zero one two three

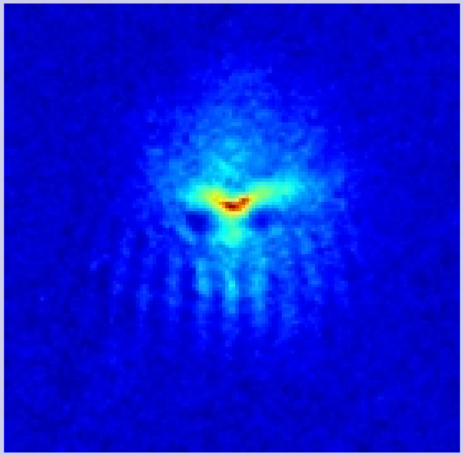


Solitons?

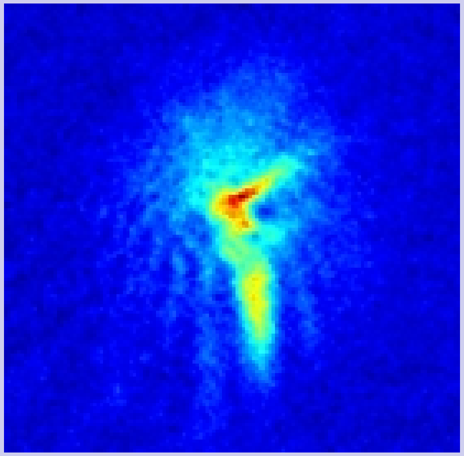
Hold atoms in trap after removing barrier, then release for 10 ms TOF



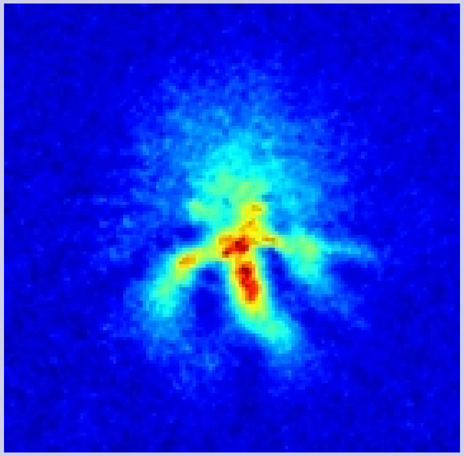
10 us



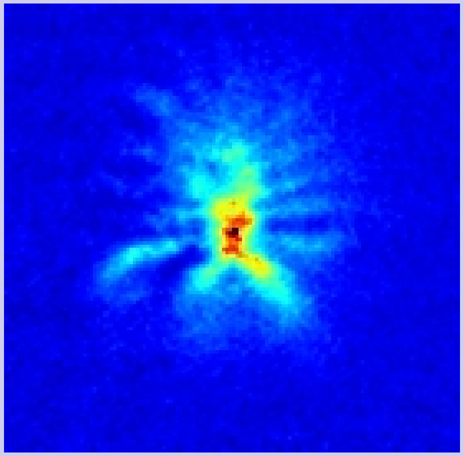
2 ms



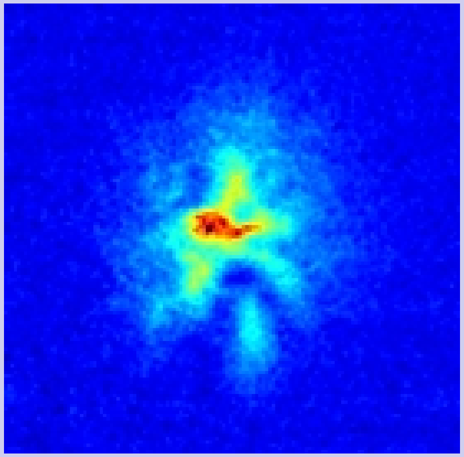
4 ms



10 ms

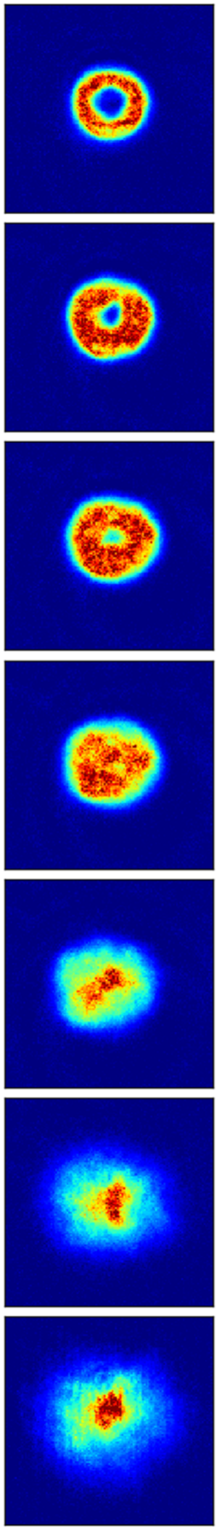


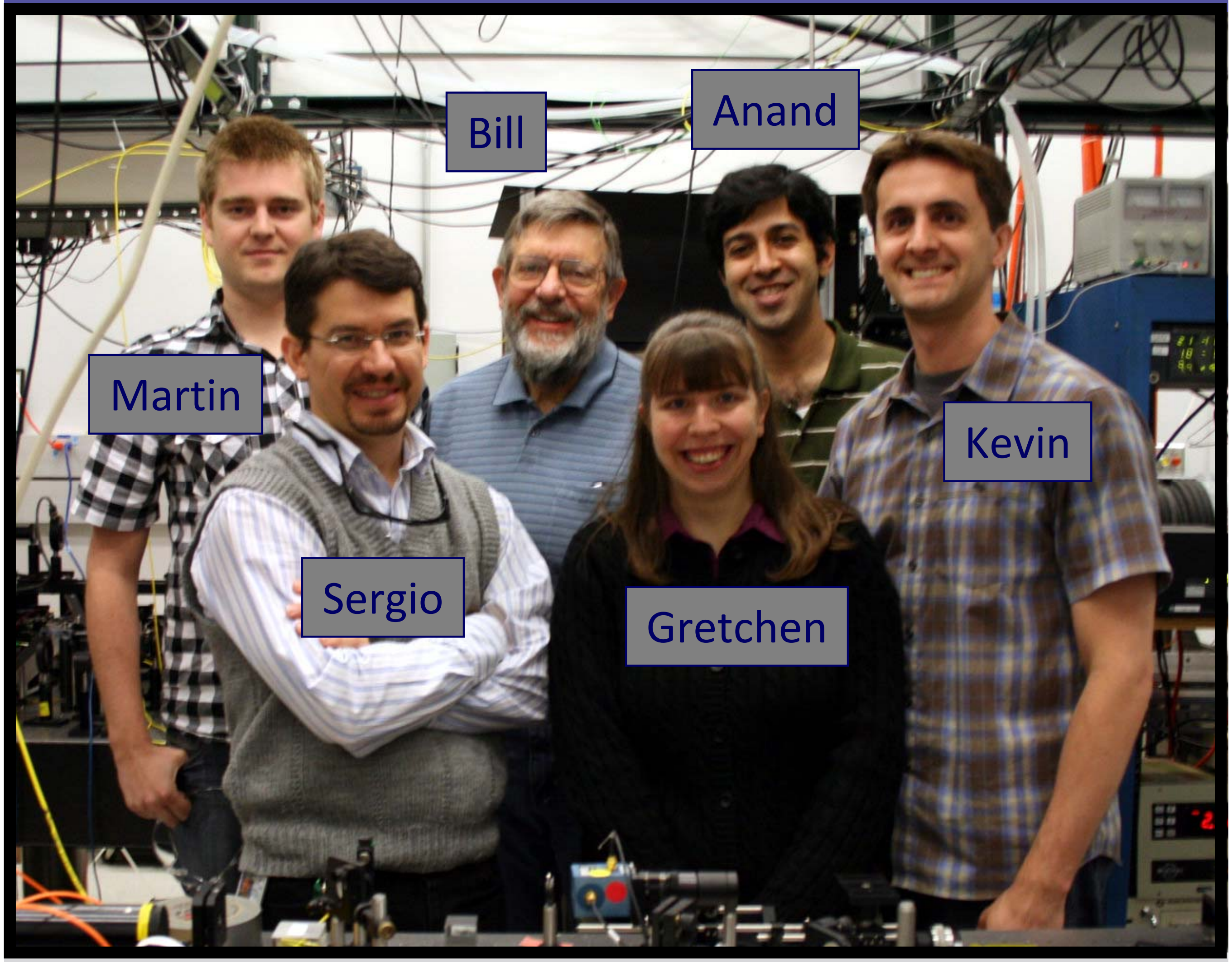
15 ms

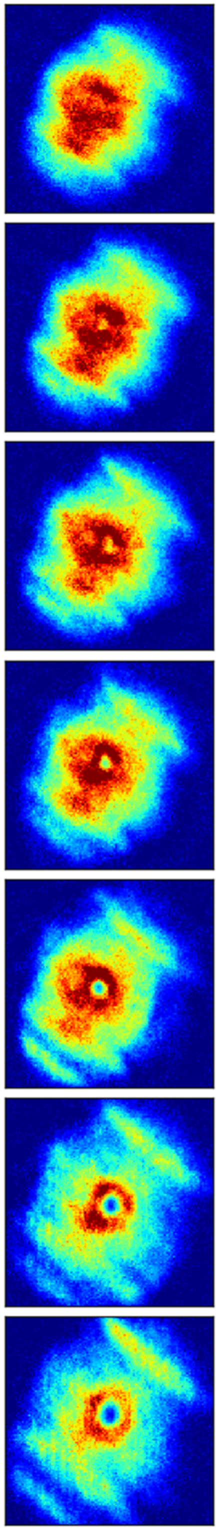


50 ms

The NIST Ring BEC Team

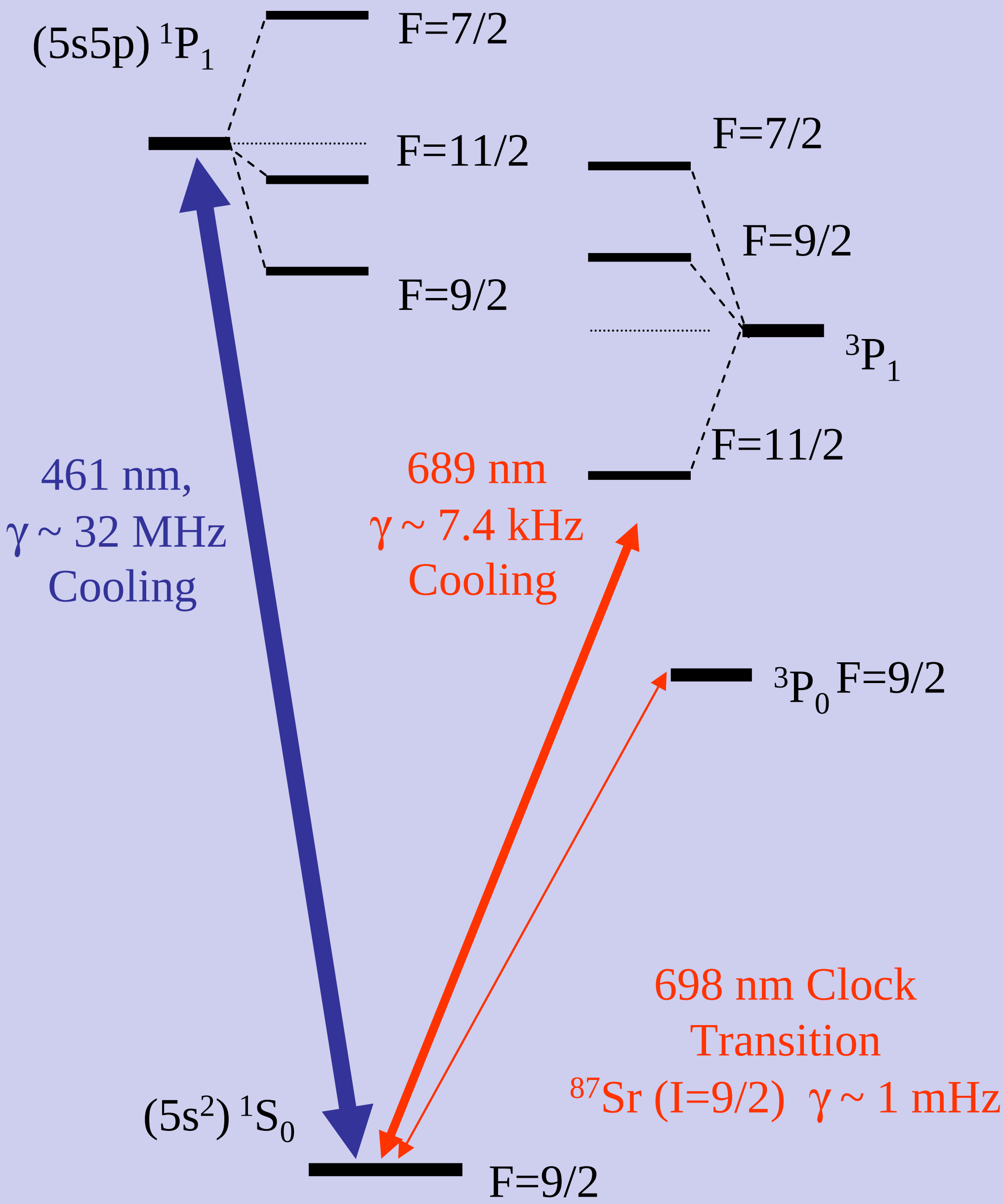






"One ring to rule them all..."

Alkaline earth atoms



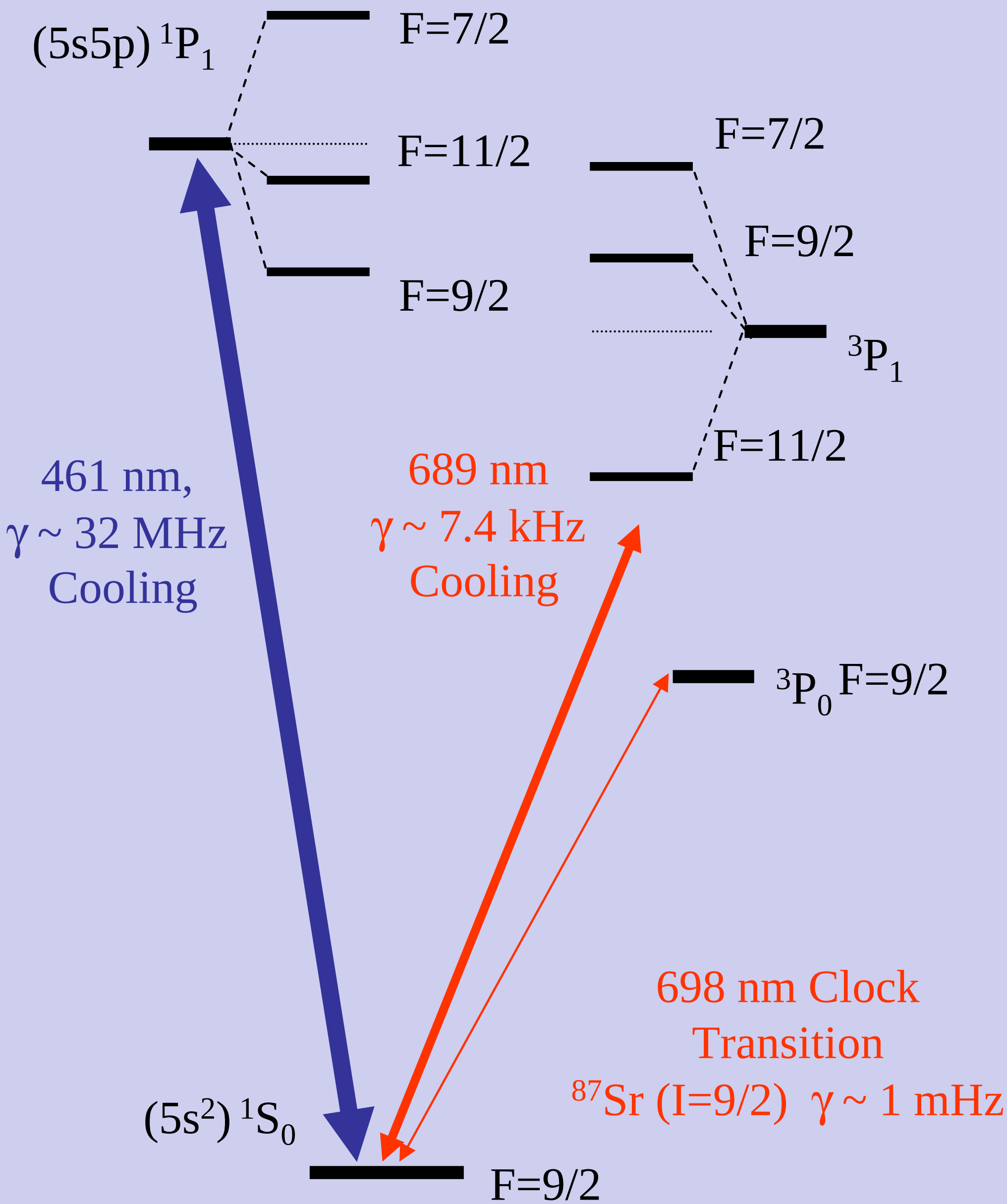
Strontium

^{84}Sr	0.56%	I=0
^{86}Sr	9.9%	I=0
^{87}Sr	7.0%	I=9/2
^{88}Sr	82.6%	I=0

^{87}Sr → Clocks, Quantum Optics, CMP

^{88}Sr → Interferometry

Alkaline earth atoms



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SU(10) Fermi System