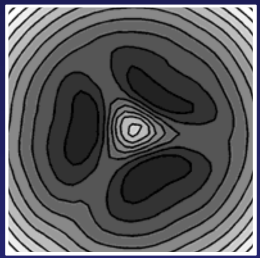
Bose-Einstein Condensation in Bumpy Potentials

ARO

NSF

EXPERIMENT

U. Arizona BEC group

Brian P. Anderson
Tyler Neely (PhD student)
Chad Weiler (PhD student)

David Scherer (PhD March 2007)

THEORY partners

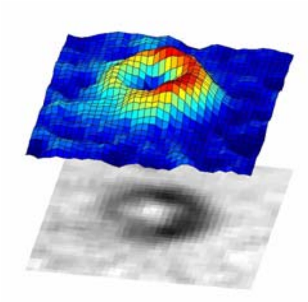
Condensation dynamics

Matthew Davis (UQ)
Ashton Bradley (UQ)

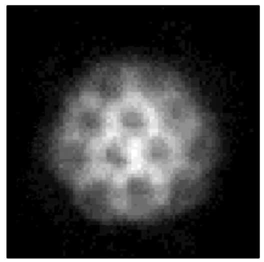
College of Optical Sciences
The University of Arizona

Vortices in BECs

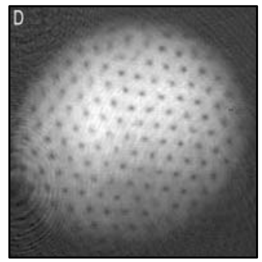
Various methods exist for making a BEC rotate…



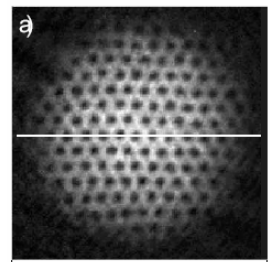
First BEC vortex (JILA)
M.R. Matthews *et al*, PRL 83, 2498 (1999).



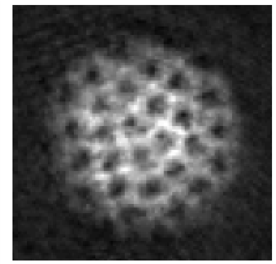
ENS, 1999



MIT, 2001



JILA, 2002



Arizona, 2007

Research question:

Can bumps in a trapping potential induce vortex formation (fluid rotation) during condensation?

Motivation

Vortices in superfluids
- Formation and trapping mechanisms

BECs in rough and disordered potentials
- Atom chips, fragmentation
- quantum phase transitions (Bose glass)
- properties of other superfluids

Quantum fluid mixing & merging
- atom-optical elements (beam combiners)
- Quantum-state engineering
- Superfluid turbulence
- Kibble-Zurek mechanism

Dynamics of condensation in bumpy potentials

Experiments

I. BEC in a 3-well trap

D R. Scherer, C.N. Weiler, T.W. Neely, and B.P. Anderson,
"Vortex Formation by Merging of Multiple Trapped Bose-Einstein Condensates," Phys. Rev. Lett. **98**, 110402 (2007).

[Simulations underway by P. Kevrekidis (UMass) and R. Carretero (SDSU)]

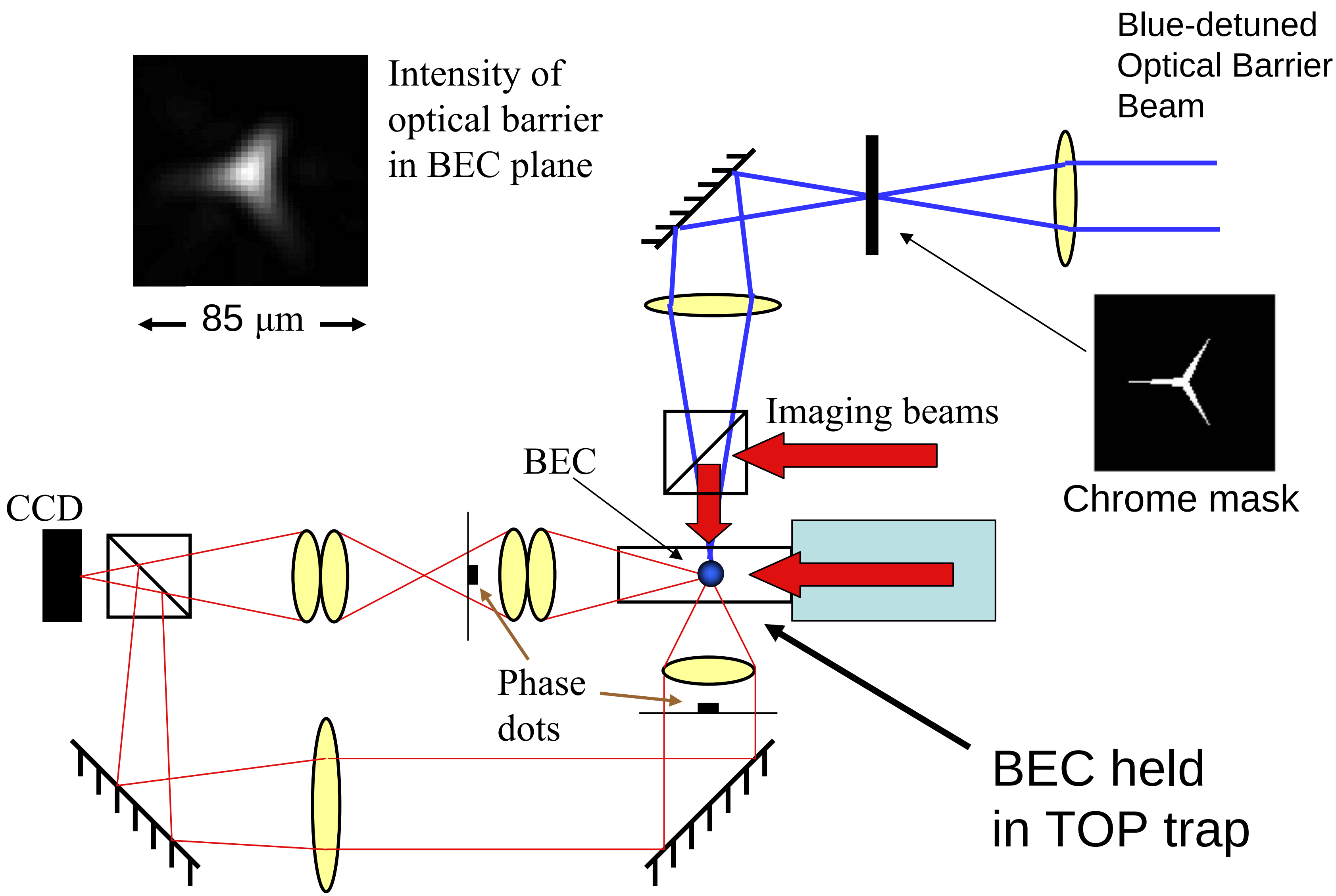
II. BEC in a toroidal trap

III. BEC in a spatially smooth trap

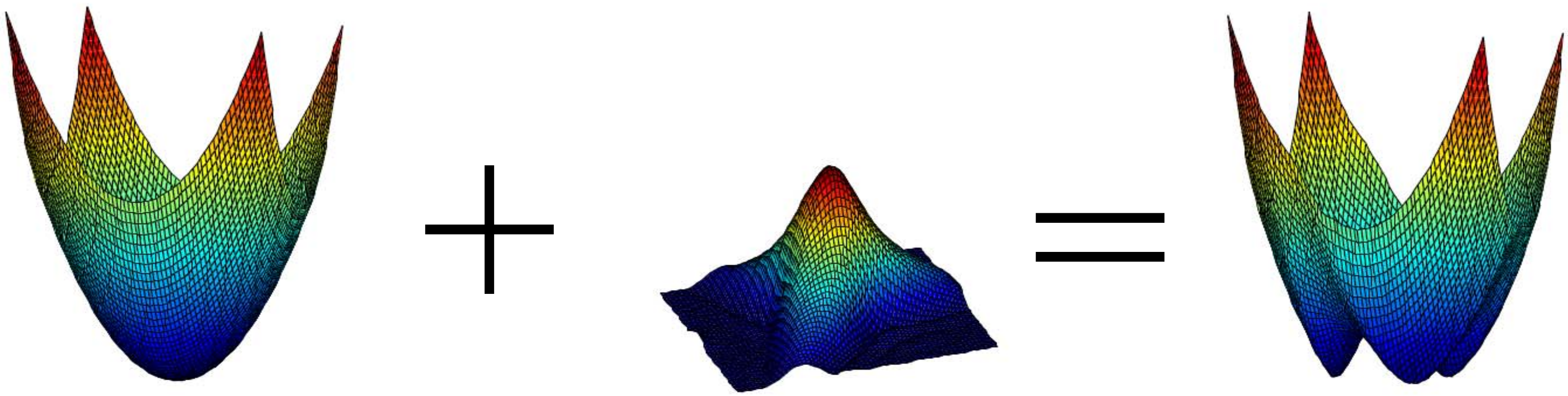
Common element: examining the **process of condensation**, rather than manipulation of a BEC

Partnering with **M. Davis, A. Bradley** to understand the dynamics of condensate formation in these experiments.

I. BEC in a 3-well trap



The 3-well trap

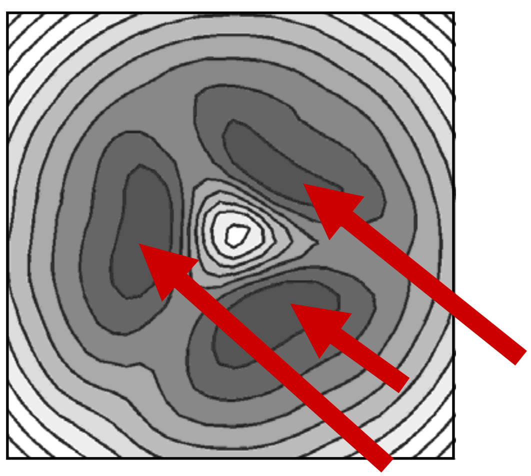


Magnetic potential
(TOP trap)

Optical Potential

3-Well Potential

Top-down view

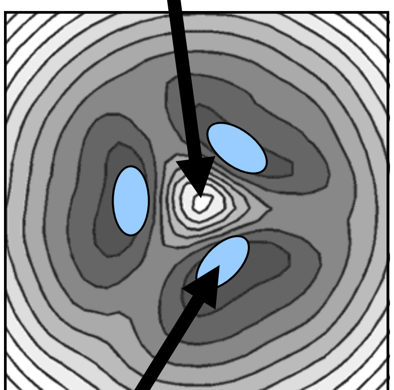


Isolated BECs start forming in 3 wells during evaporative cooling

BECs merge during growth

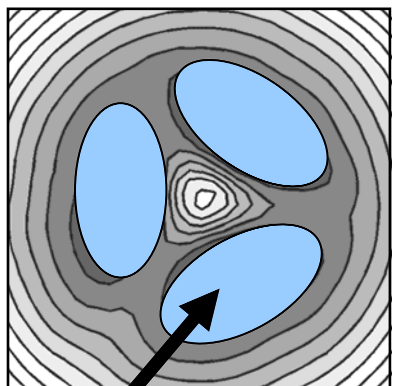
(1) 3 independent BECs start forming from common thermal cloud.

Barrier energy E_B



Single-particle ground-state energy $\mathbf{E_0 << E_B}$

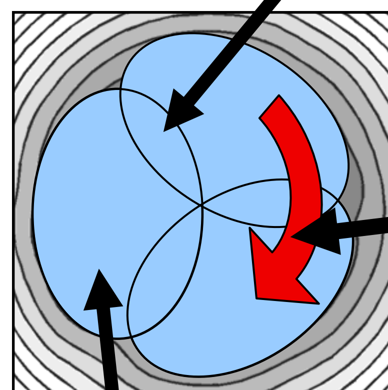
(2) BECs grow during continued evaporative cooling.



Chemical potential $\boldsymbol{\mu < E_B}$

(3) BECs merge together. Interference between matter waves leads to directional fluid flow.

Interference region



Final chemical potential $\boldsymbol{\mu > E_B}$

Fluid flow?

Depends on phase gradients and ***relative phases.***

Fluid flow

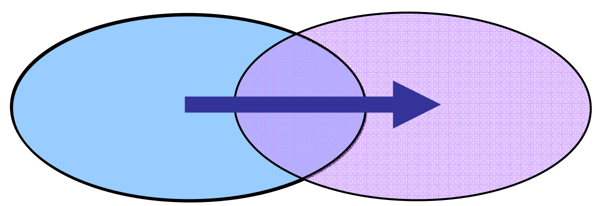
Slow merging of two condensates

Neglect phase gradients, assume constant phase profiles:

$$\Psi(\vec{r},t) = \sqrt{n_1(\vec{r}_1,t)} + \sqrt{n_2(\vec{r}_2,t)}\,e^{i\delta\phi}$$

Current density:

$$J(x) = \frac{\hbar}{2im}\left[\Psi^* \frac{\partial \Psi}{\partial x} - \frac{\partial \Psi^*}{\partial x}\Psi\right]$$

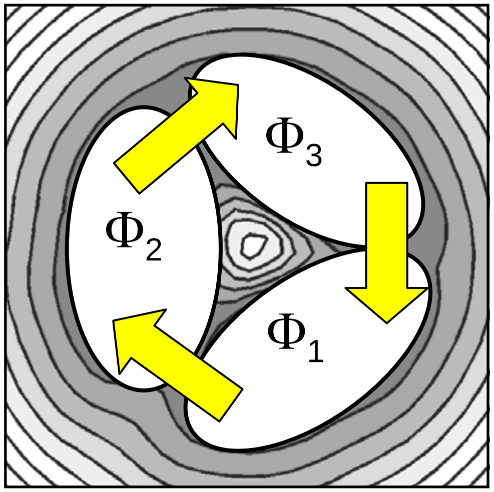


$$J(x=0) \propto \sin(\delta\phi)$$

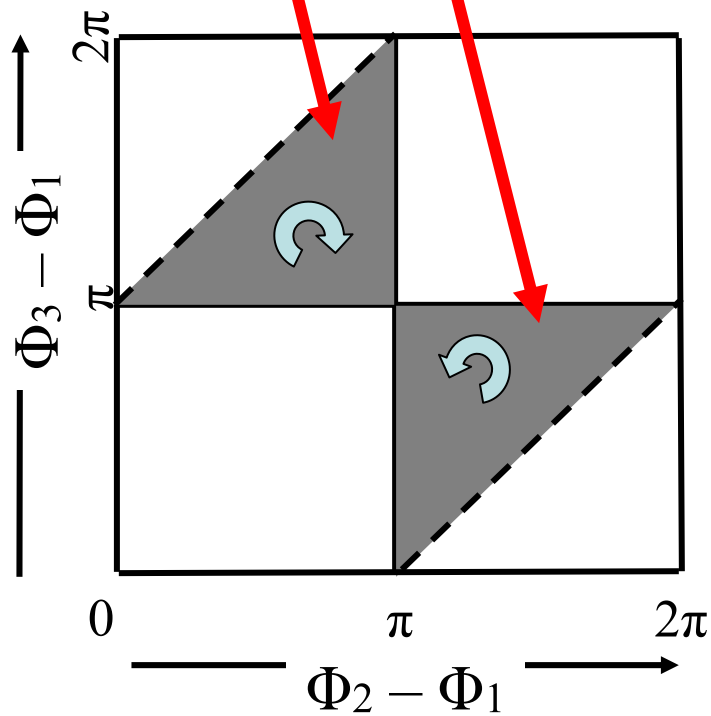
Direction of fluid flow at overlap depends on relative phase.

Not known *a priori* !

Vortices from slow BEC merging



Given random relative phases, conditions for vortex nucleation can occur up to 25% of the time.



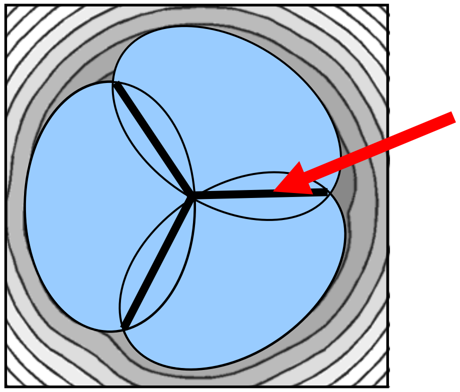
Conditions for circular flow

Clockwise Circulation	Counter-Clockwise Circulation
$\Phi_3 - \Phi_2 < \pi$	$\Phi_3 - \Phi_2 > \pi$
$\Phi_2 - \Phi_1 < \pi$	$\Phi_2 - \Phi_1 > \pi$
$\Phi_1 - \Phi_3 < \pi$	$\Phi_1 - \Phi_3 > \pi$

denotes *relative* phase

Probability of a vortex forming: ***P_v = 0.25***

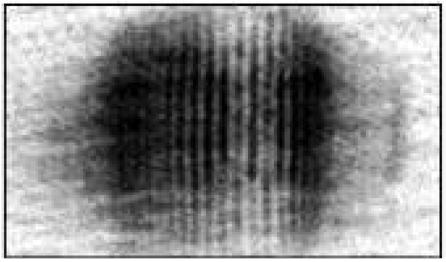
Fast Merging: interference fringes



Interference fringes from quickly merged **but still trapped** BECs.

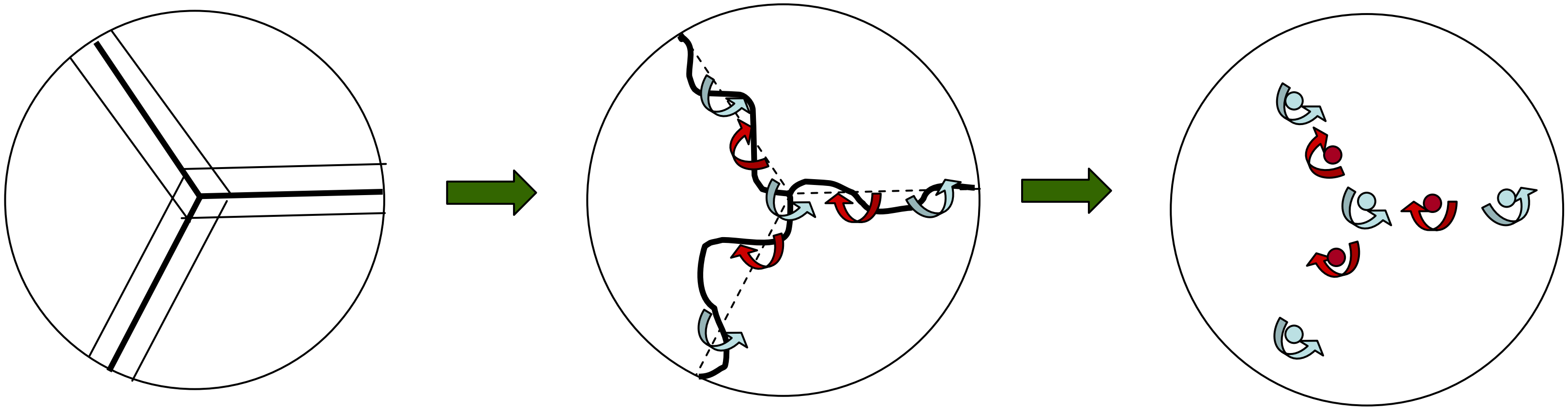
Estimate of fast merge time: ~500 ms.

Untrapped & expanding BECs



M.R. Andrews *et al.*, Science 275, 637 (1997).

Nonlinear dynamics (“snake” instability):
fringes decay to vortices and antivortices in a trapped BEC.

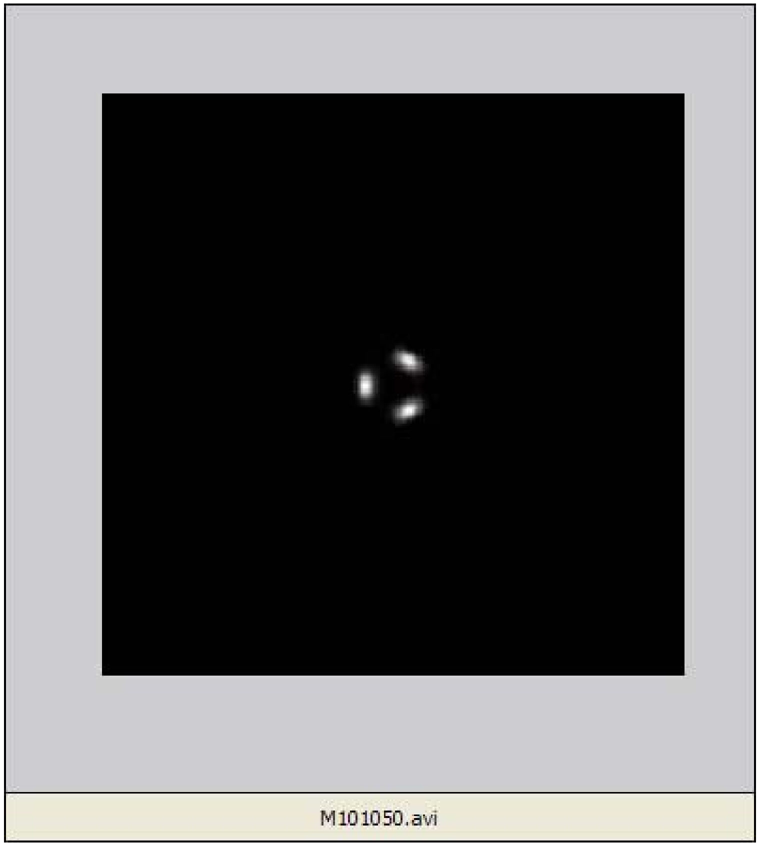


$P_v > 0.25$ for fast merging.
($P_v = 0.25$ for slow merging)

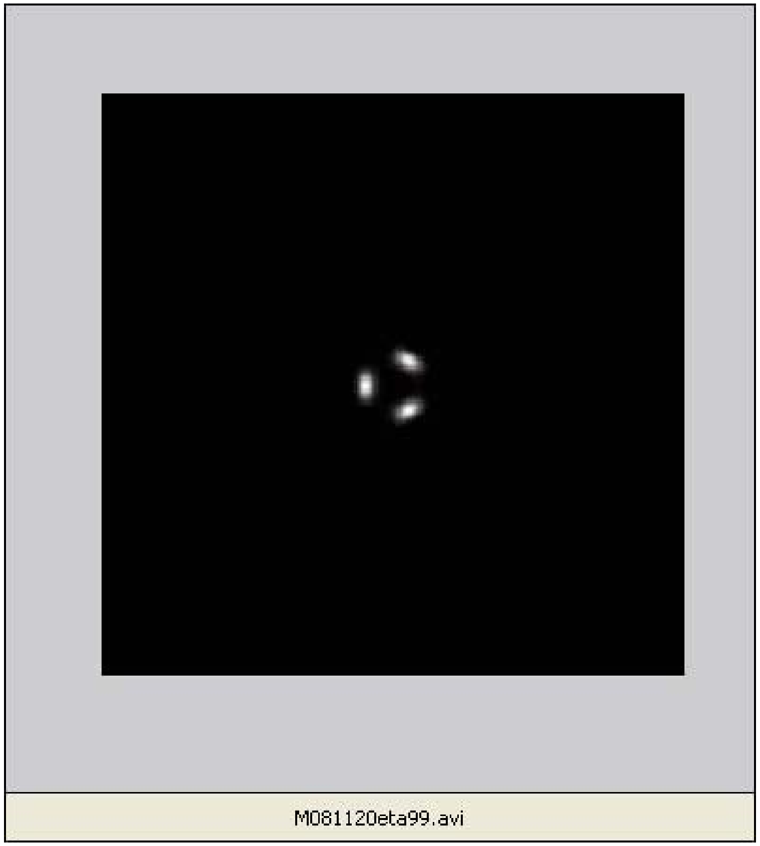
Simulations

2D GPE, no damping. Model of growth of BEC's physical size by increasing scattering length with time (only a simple approximation!).

2π/3 relative phases (ideal case)



Fast merging, with non-ideal phases

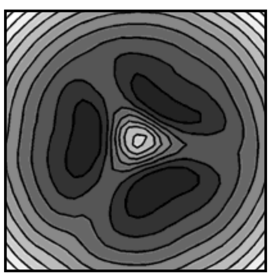


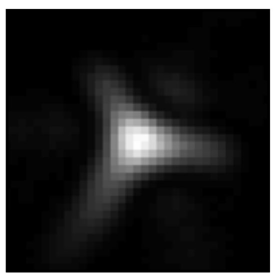
Experiment sequence

With no Optical Barrier:

- 4×10^5 atoms in ~7 Hz (radial) x 14 Hz (axial) trap
- **$\mu \sim k_B \times 8$ nK**

1. Turn on barrier beam
2. Make BECs by evaporative cooling
3. BECs merge
4. Turn off trap, cloud expands (vortex cores expand)
5. Image cloud (by absorption)





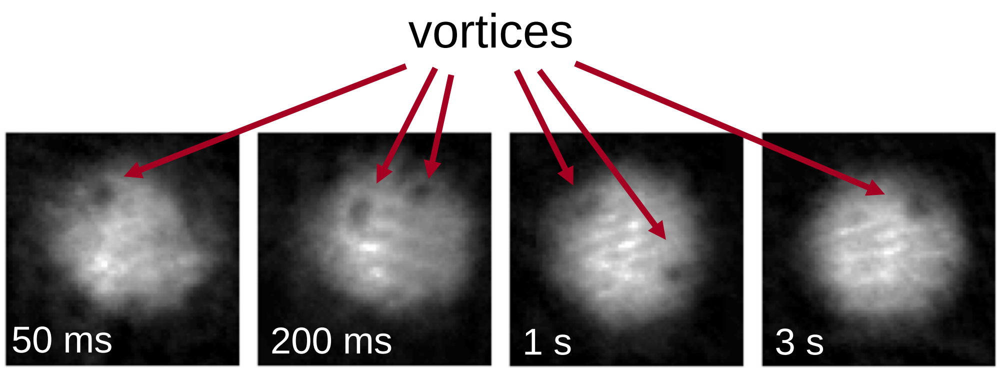
Optical barrier

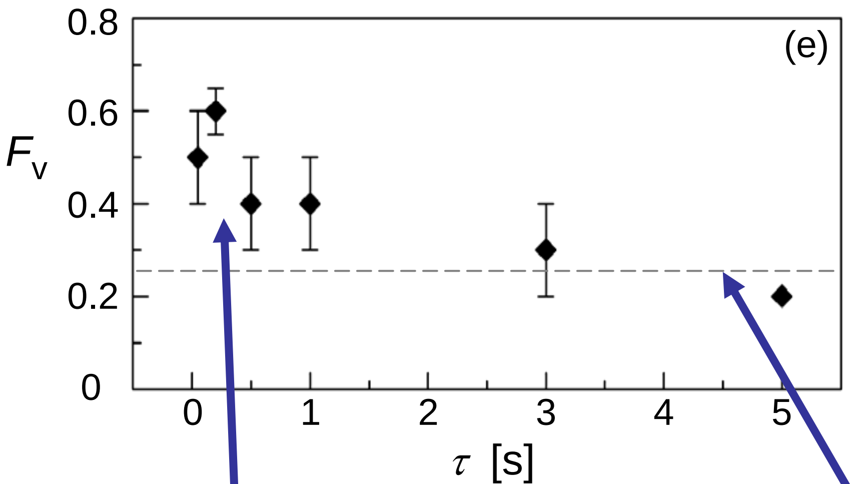
Test #1:
Strong barrier
170 μW, $k_B \times 26$ nK
Merge by lowering barrier

Test #2:
Weak barrier
45 μW, $k_B \times 7$ nK
BECs merge during growth

Test #1: Merge 3 BECs by lowering barrier

Example images:





Data:

F

$\boldsymbol{F_v}$: fraction of images that have *at least one* vortex. $\boldsymbol{F_v \sim P_v}$ **?**

τ: Time to ramp down barrier after BECs created

$\boldsymbol{F_v > 0.25}$, as expected for fast merging.

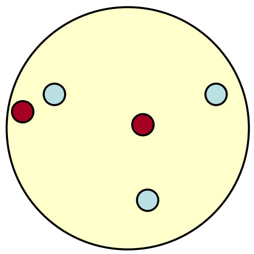
$\boldsymbol{F_v \sim 0.25}$, as expected for slow merging.

College of Optical Sciences
The University of Arizona

Multiple vortices

200 ms barrier ramp to zero: multiple vortices and (presumably) antivortices in final BEC.

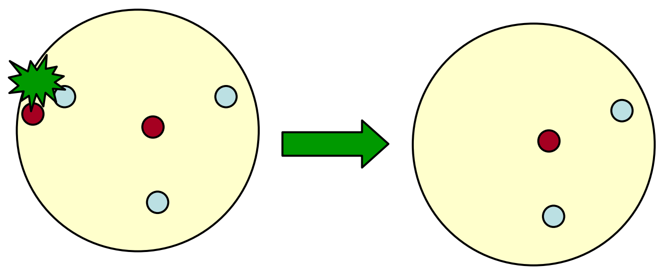
Average # of vortex cores per image: **2.1**



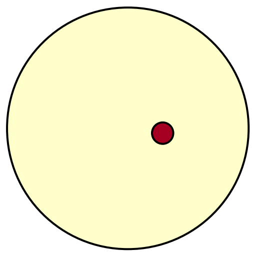
Add extra 100-ms hold time *after* ramp, but *before* expansion.

Average # of vortex cores per image: **0.7**

Vortex-antivortex annihilation?



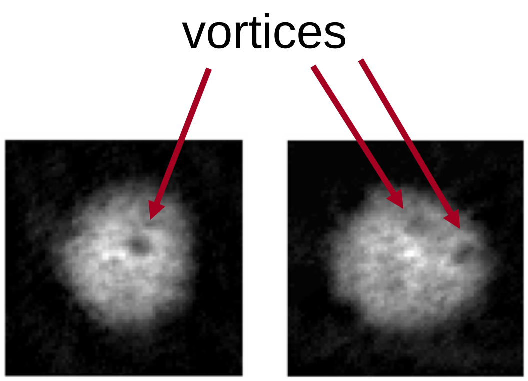
Single vortices observed for at least 5 s extra hold time: relatively long vortex lifetime.



3D, T=0 GPE modeling for 3 BEC merging underway by P. Kevrekidis (UMass) and R. Carretero (SDSU).

Test #2: merge during growth

? Do vortices form during BEC growth in a bumpy potential? ?



YES! Vortices seen in single BECs created in a bumpy potential.

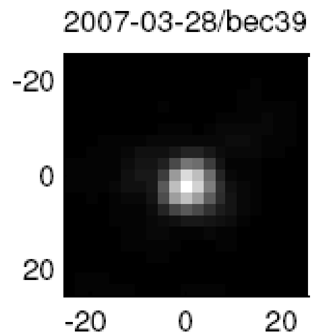
$F_v \sim 0.6$

Condensate growth rate is “fast”.

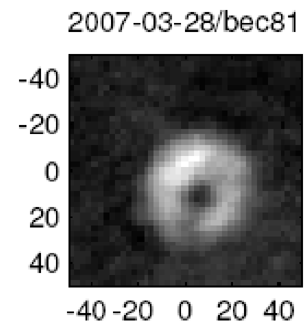
II. BEC in toroidal potential

Instead of 3-armed Optical Barrier, use tightly focused Gaussian beam (optical plug).

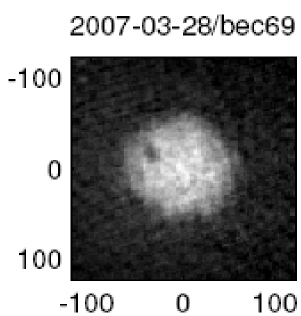
Toroidal trap in the limit of large beam intensity.

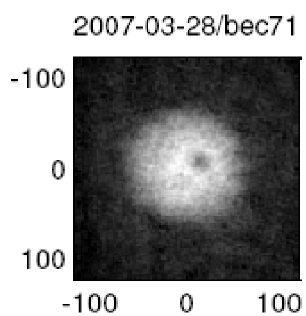


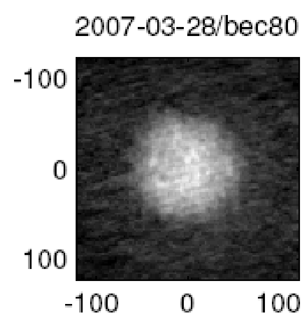
Then condense…

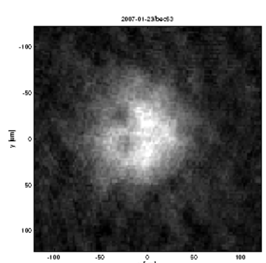


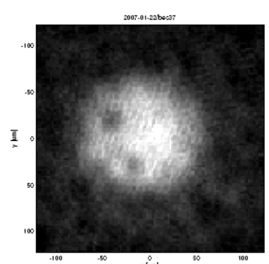
Remove beam + expand + image

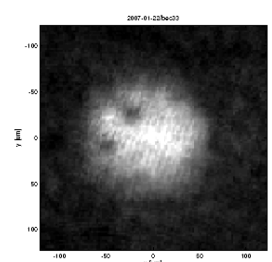












Measuring the angular momentum

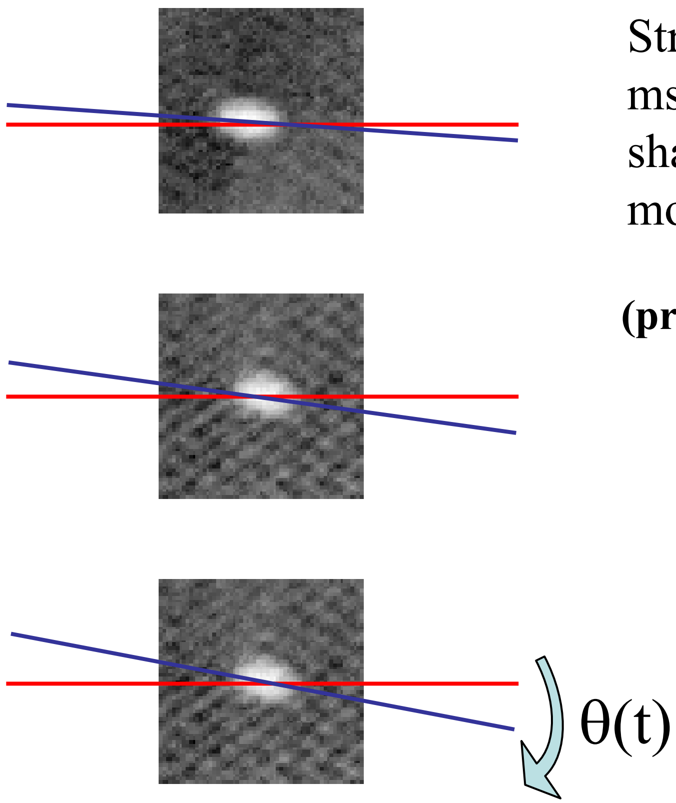
t = -50 ms to
t = 0

Squeeze trap, induce quadrupolar oscillations of BEC.

t = 40 ms

t = 130 ms

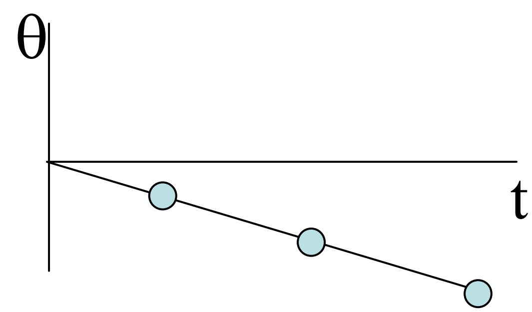
t = 220 ms



Strobe the oscillations (90 ms period). Precession of shape if BEC has angular momentum.

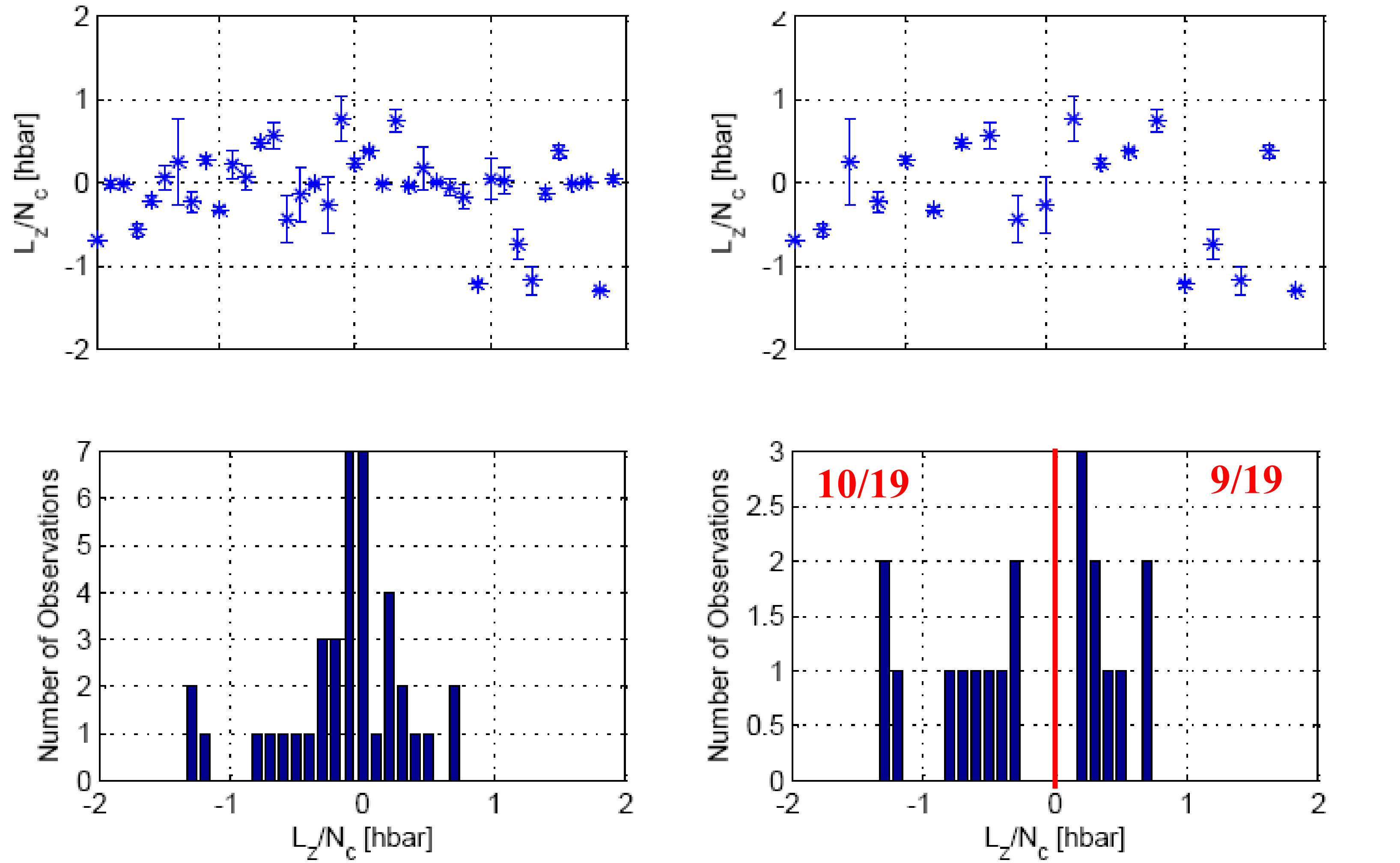
(prev. used at ENS, JILA, Oxford, …)

Slope = angular momentum



Angular momentum measurements

Full data set | **Rotations only**



What's going on?

Kibble-Zurek mechanism in a toroidal trap (spontaneous persistent currents)?

- defect trapping in a quenched phase transition

Kibble, J Phys A 9, 1387(1976),
Zurek, Nature 317, 505 (1985),
Anglin and Zurek, PRL 83,1707 (1999)

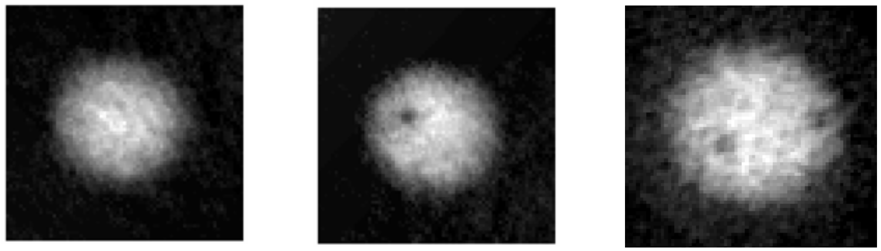
SGPE simulations by Matt Davis and Ashton Bradley, U. Queensland

Movie:
3D SGPE with Optical plug

toroid1Small.mov

III. Evaporative cooling in a smooth trap

Harmonic trap: **optical barrier beam is absent**.



Spontaneous vortex formation?
A single vortex observed **up to 30%** of the time!

Spontaneous formation of vortices in BEC during evaporative cooling:

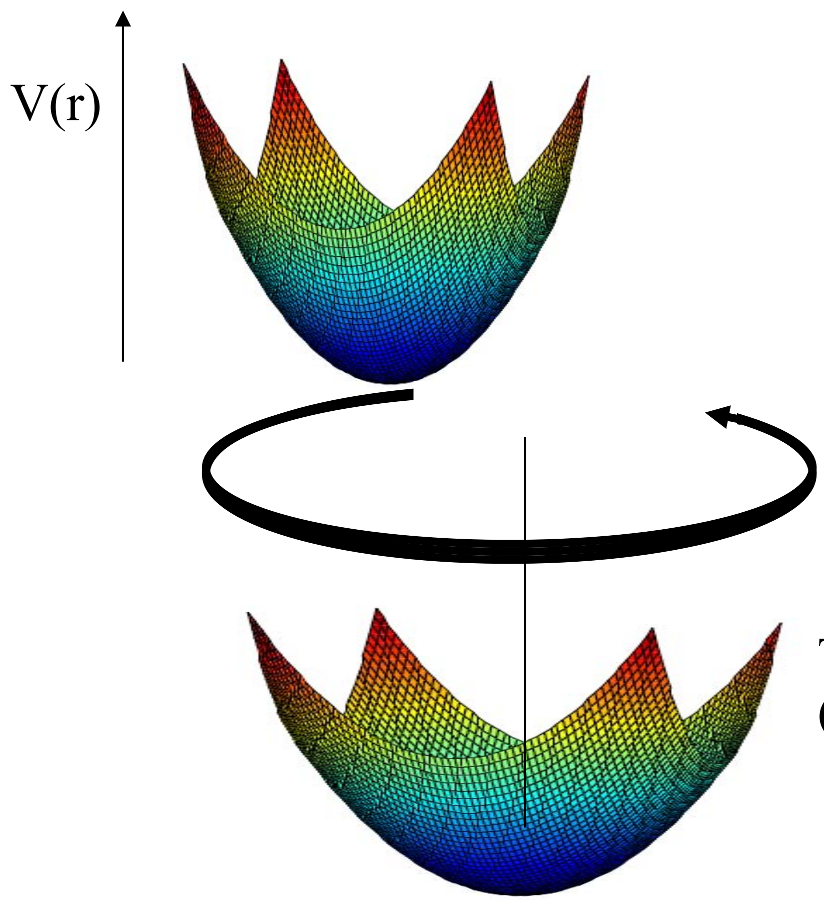
Marshal, New, Burnett, and Choi, PRA 59, 2085 (1999),
Drummond and Corney, PRA 60, R2661 (1999).
Spin vortices, experiment: Stamper-Kurn group (Nature, 2006)

Kibble-Zurek mechanism in a smooth trap?

Something else altogether (ie, turbulence)?

TOP trap

TOP trap is ***dynamic***. Our TOP trap has an instantaneous radial harmonic potential (due to gravitational sag).

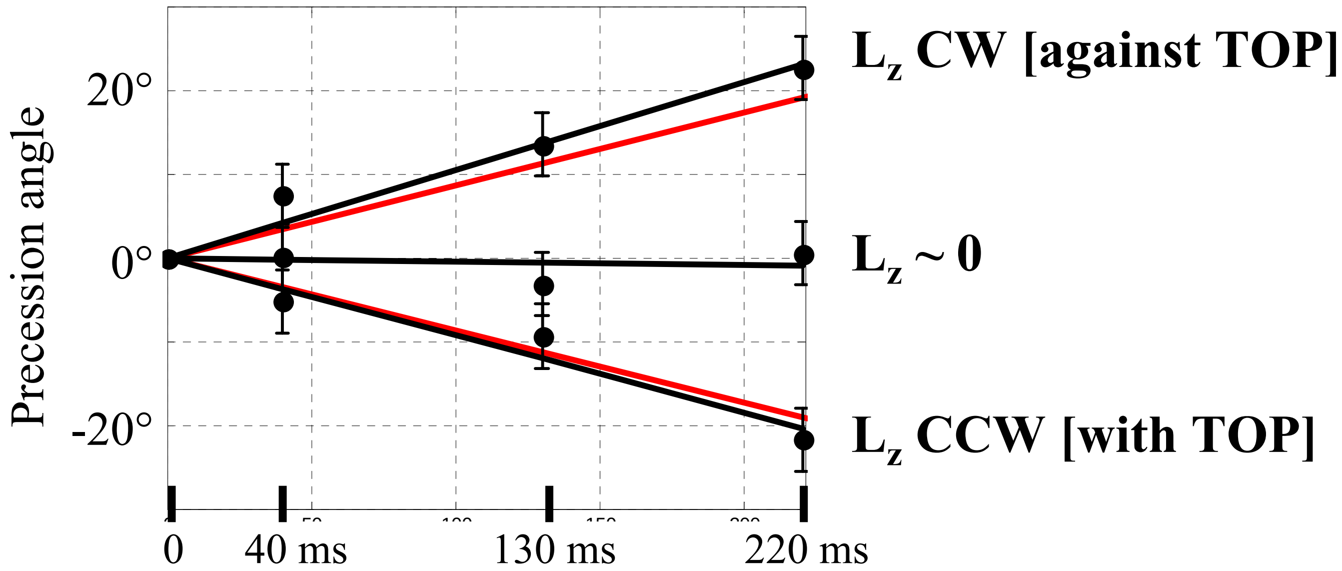


Rotating bias field shifts trap center around a circle.
2 kHz rotation frequency.

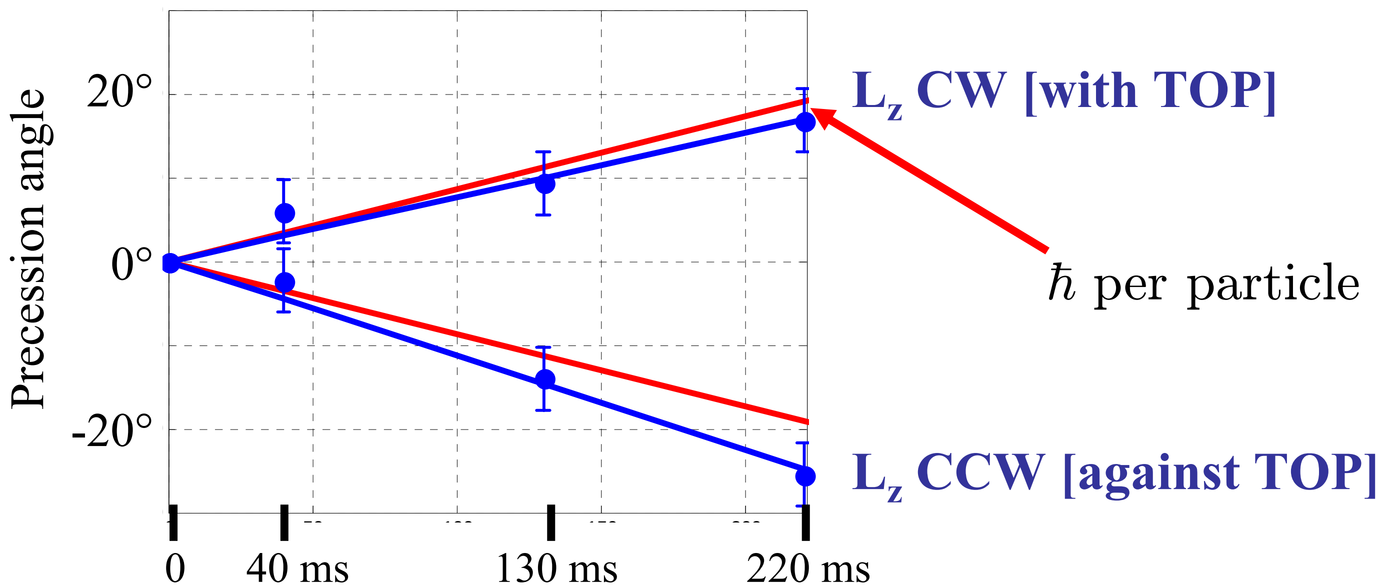
Time-averaged potential (harmonic)

Do vortices depend on TOP?

TOP CCW



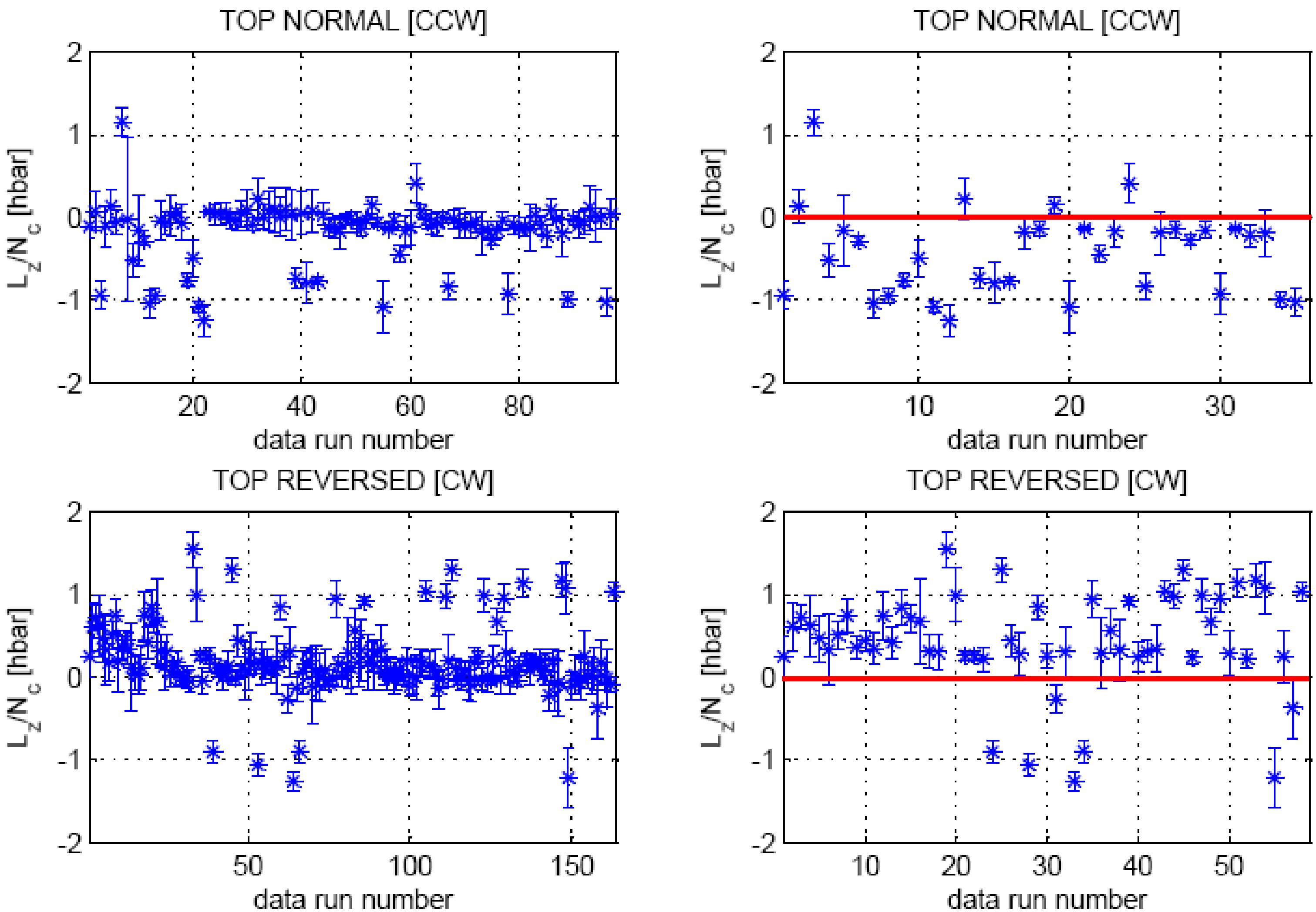
TOP CW



TOP does bias angular momentum of vortices!

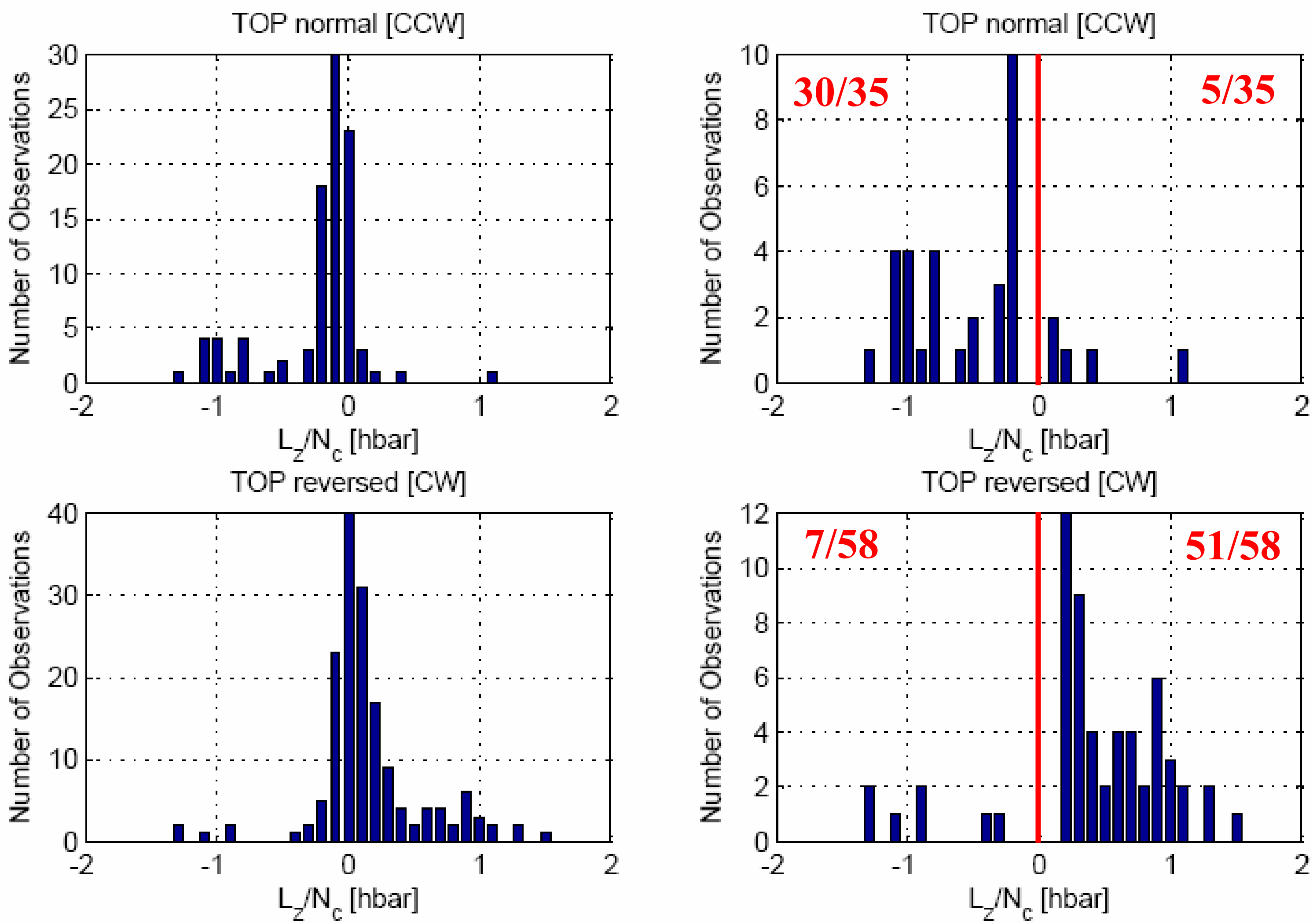
TOP CCW

TOP CW



TOP CCW

TOP CW



Summary

I. 3-well experiments

1. **Single Vortices created via slow merging of BECs.**

2. **Multiple Vortices (vortex pairs?) created via fast merging of BECs.**

3. **Vortices created simply by making a single BEC in a 3-well potential**

II. Toroidal trap

4. **Persistent currents are created by condensing in toroidal potential.**
   Can also be seen in SGPE simulations.

III. Smooth TOP trap

5. **Vortices appear after condensation in smooth TOP trap, with direction strongly biased in TOP rotation direction, though not all are in TOP direction.**