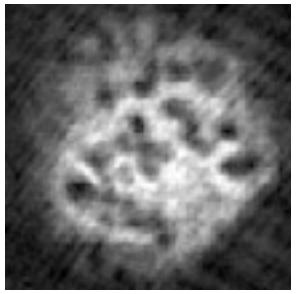
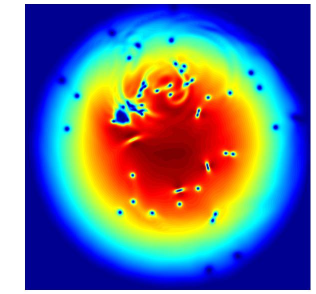


Two-dimensional Quantum Turbulence in Bose-Einstein condensates



Brian P. Anderson
College of Optical Sciences
University of Arizona

Experiments *(U. Arizona)*
T.W. Neely *(now at U. Queensland)*
Z.L. Newman
E.C. Samson *(now at Ga. Tech.)*
K.E. Wilson
BPA

Theory and Computation
A.S. Bradley *(U. Otago)*
R. Carretero-González *(San Diego S. U.)*
M.J. Davis *(U. Queensland)*
P.G. Kevrekidis *(U. Mass. at Amherst)*
K.J.H. Law *(U. Warwick)*
S.J. Rooney *(U. Otago)*
E.M. Wright *(U. Arizona)*

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TE PŪTEA RANGAHAU A MARSDEN

the ROYAL SOCIETY of NEW ZEALAND
TE APĀRANGI

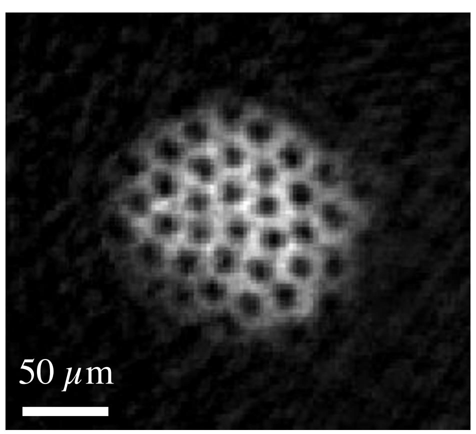
Australian Government
Australian Research Council

Vortices in BECs: Experiments

Over 10 years of experiments with vortices in BECs

Resource Article: Experiments with Vortices in Superfluid Atomic Gases
B. P. Anderson, JLTP 161, 574 (2010)

Lots of work on quantum state engineering, rotating BECs and vortex lattices



Until now there has been relatively little study of

- far-from-equilibrium phenomena
- turbulence
- highly oblate and 2D systems
- vortex manipulation
- vortex dynamics
- persistent currents

All topics of emphasis in current BEC vortex experiments

Studies of 2D vortex turbulence in superfluids are sparse in comparison to 3D superfluid turbulence: lots still to understand

- What vortex distributions arise in 2DQT ?
- What spectral signatures exist for vortex distributions in 2DQT?
- Can an inverse energy cascade be observed? A double cascade? Is there any connection to an enstrophy cascade?
- Can large-scale flow develop from small-scale forcing?
- Can vortices cluster together, or will annihilation dominate?

Goals

To understand the range of vortex dynamics and spectra that can occur in forced 2DQT.

Learn a wide range of experimental tools for generating, observing, and manipulating vortices and 2DQT

Progress so far

- Many ways to generate 2DQT
- Stirring with laser beam: low excitation 2DQT *(expt/num)*
  - simulations: energy spectra, vortex aggregation, suppression of vortex annihilation *(num)*
  - development of large-scale flows *(expt/num)*
- Demonstrated new ways to generate and manipulate vortices *(expt)*

Why BECs ?

Adjustable trapping geometry: 2D is straightforward
Vortex visualization techniques
Vortex manipulation techniques
Dilute superfluid: modeling, theoretical approaches
Compressible: vortex and/or wave turbulence

Tunable interactions
Single or multiple component wavefunction
...

Why *not* BECs (?)

Microscopic
 ... but much bigger than vortex size
Short lifetimes / loss of atoms
 ... but lifetime can greatly exceed vortex dynamics timescales
Few vortices
 ... but plenty to show complex, turbulent, chaotic dynamics
Heating
 ... can be minimized with optimal forcing

BECs are not as limiting as they might at first appear.

I. Experimental methods for 2DQT

preprint (available by request, soon to be on arXiv)

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K.E. Wilson, C.E. Samson, Z.L. Newman, T.W. Neely, B.P. Anderson

II. 2DQT in a BEC: stirring with a laser beam

arXiv: 1204.1102

Characteristics of Two-Dimensional Quantum Turbulence in a Compressible Superfluid

Neely, Bradley, Samson, Rooney, Wright, Law, Carretero, Kevrekidis, Davis, Anderson *Experiment and simulations*

III. On-demand vortex generation and manipulation

in preparation

On-demand vortex generation and manipulation

C.E. Samson, K.E. Wilson, Z.L. Newman, B.P. Anderson

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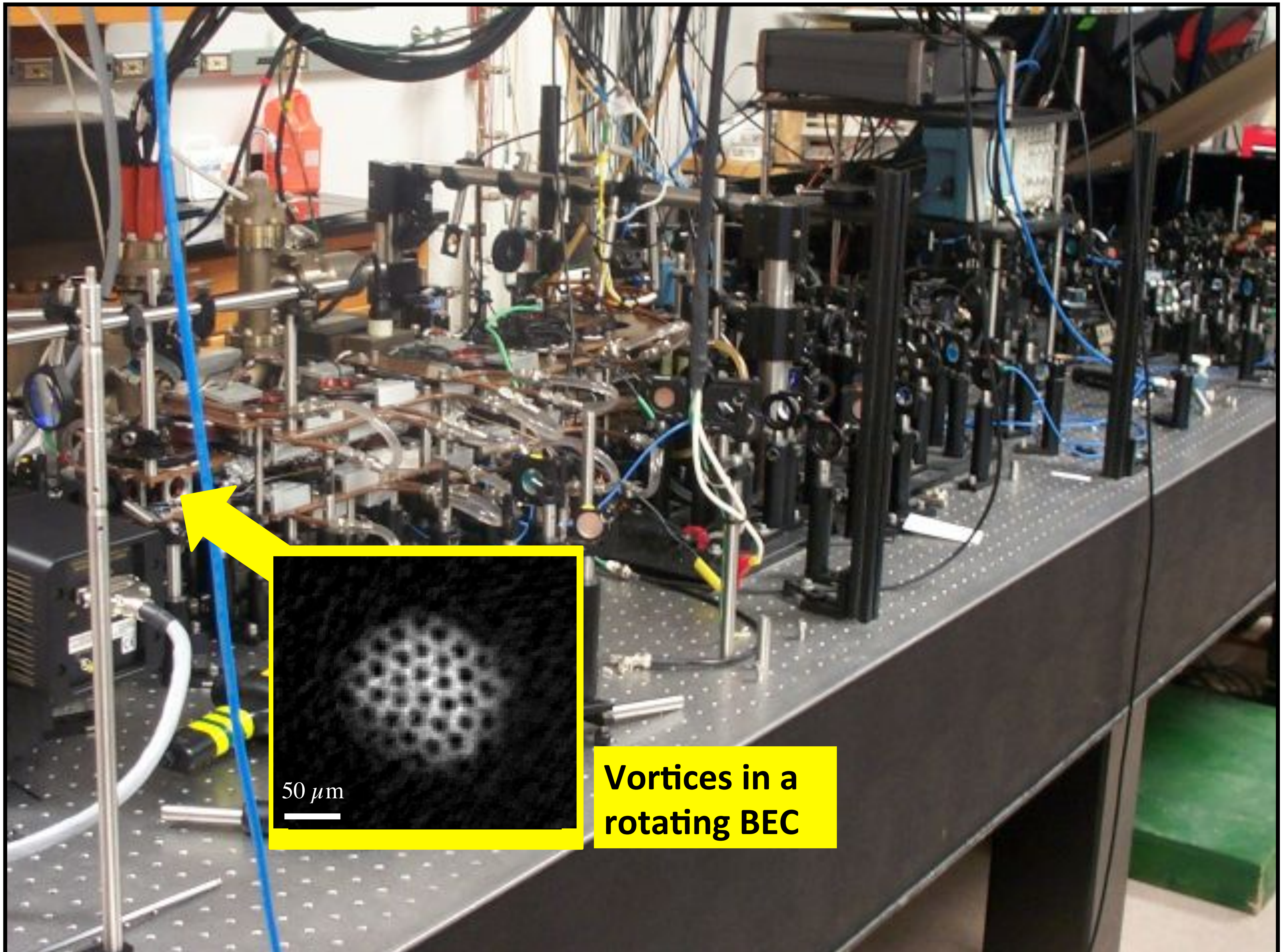
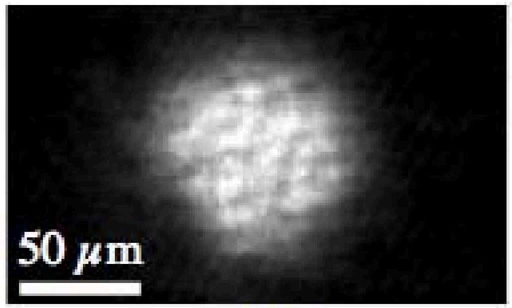
Arizona BEC lab

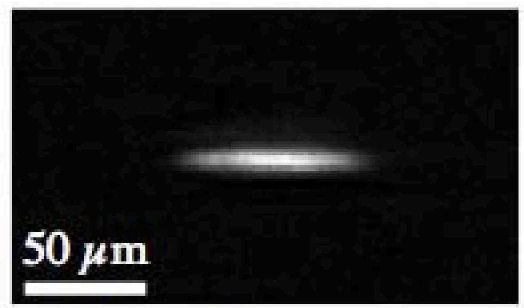


Magnetic trap (TOP) + **laser light sheet**

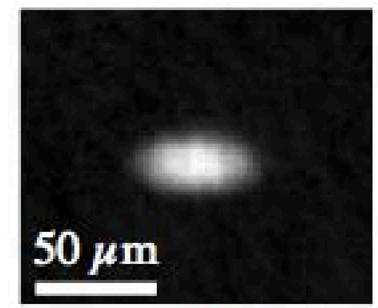
top view



side view



Side view of TOP trap
(2:1 aspect ratio, *not* highly oblate)

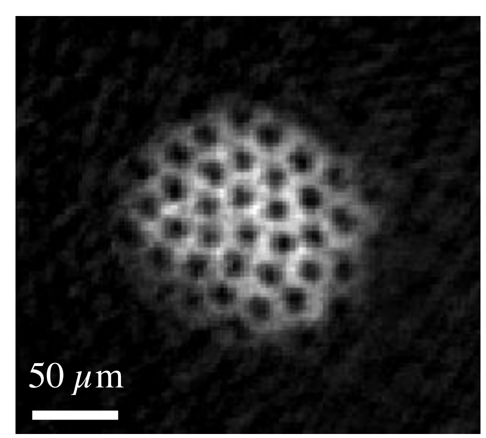


Vortex bending, tilting inhibited:
2D vortex dynamics

Atom: ^{87}Rb (F=1, m_F=-1)
$N_c = 2 \times 10^6$
$T_c \sim 100$ nK
$\omega_r = 2\pi \times 8$ Hz
$\omega_z = 2\pi \times 90$ Hz
$\mu = 8\,\hbar\omega_z$ **(not Q2D, no BKT!)**
lifetimes ~ 50 sec

$\xi \sim 0.4$ μm
R ~ 50 μm

R/ξ ~ 100
Not as limited as it appears from images
- expansion, dimensionality



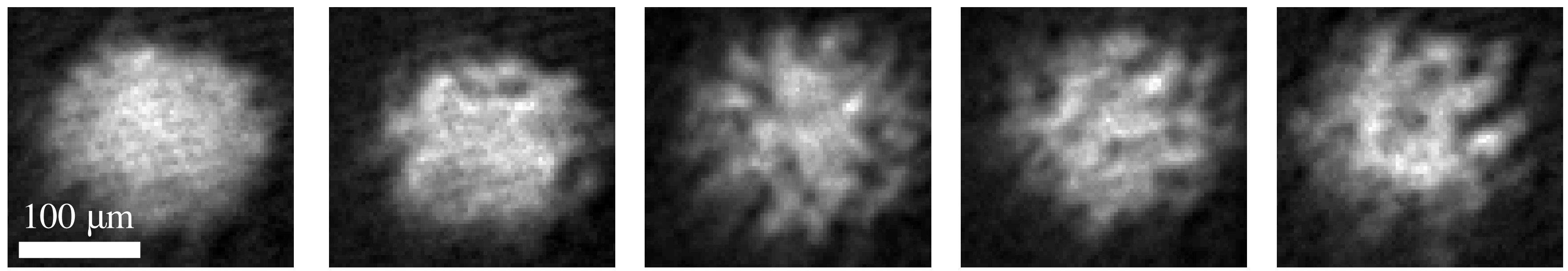
Expansion!!!

Modulate the trapping potential (trap frequency modulation)

Decay of surface waves?

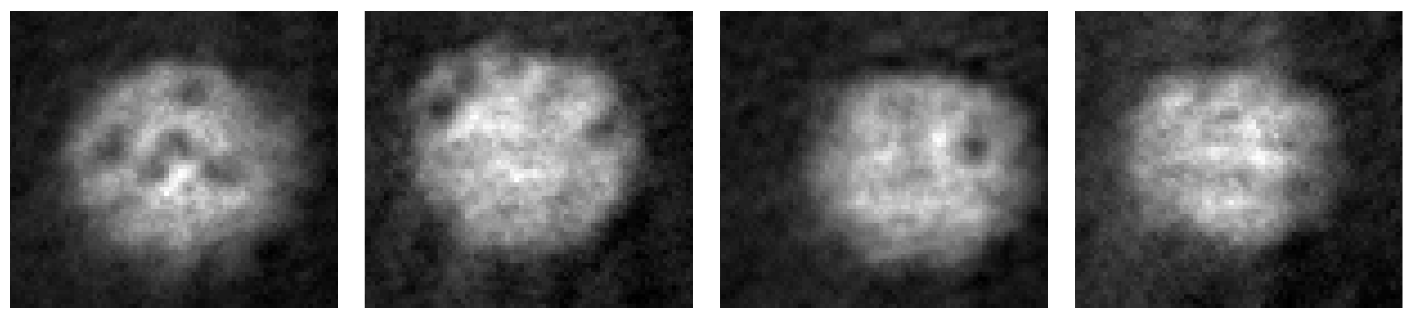
Harmonic trap

(a)



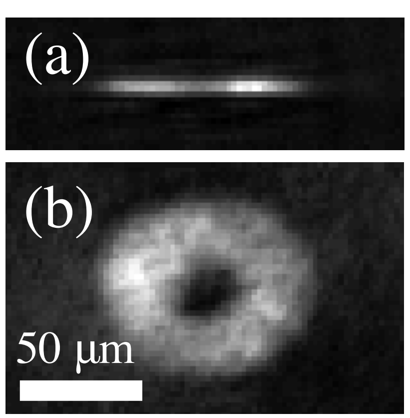
$t_{mod} = 0.2$ s $t_{mod} = 0.4$ s $t_{mod} = 0.6$ s $t_{mod} = 1$ s $t_{mod} = 1.5$ s

(b)

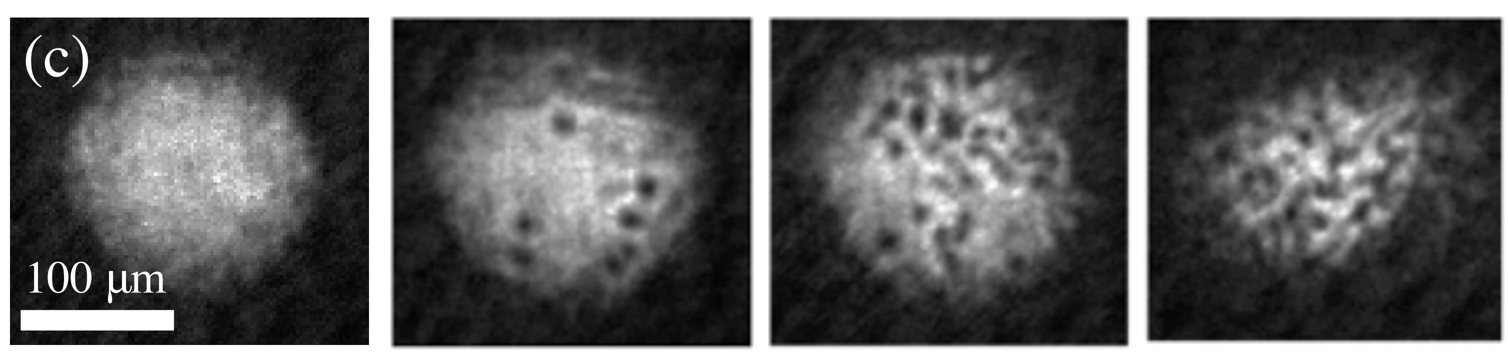


$t_h = 1$ s $t_h = 2$ s $t_h = 4$ s $t_h = 8$ s

Toroidal trap

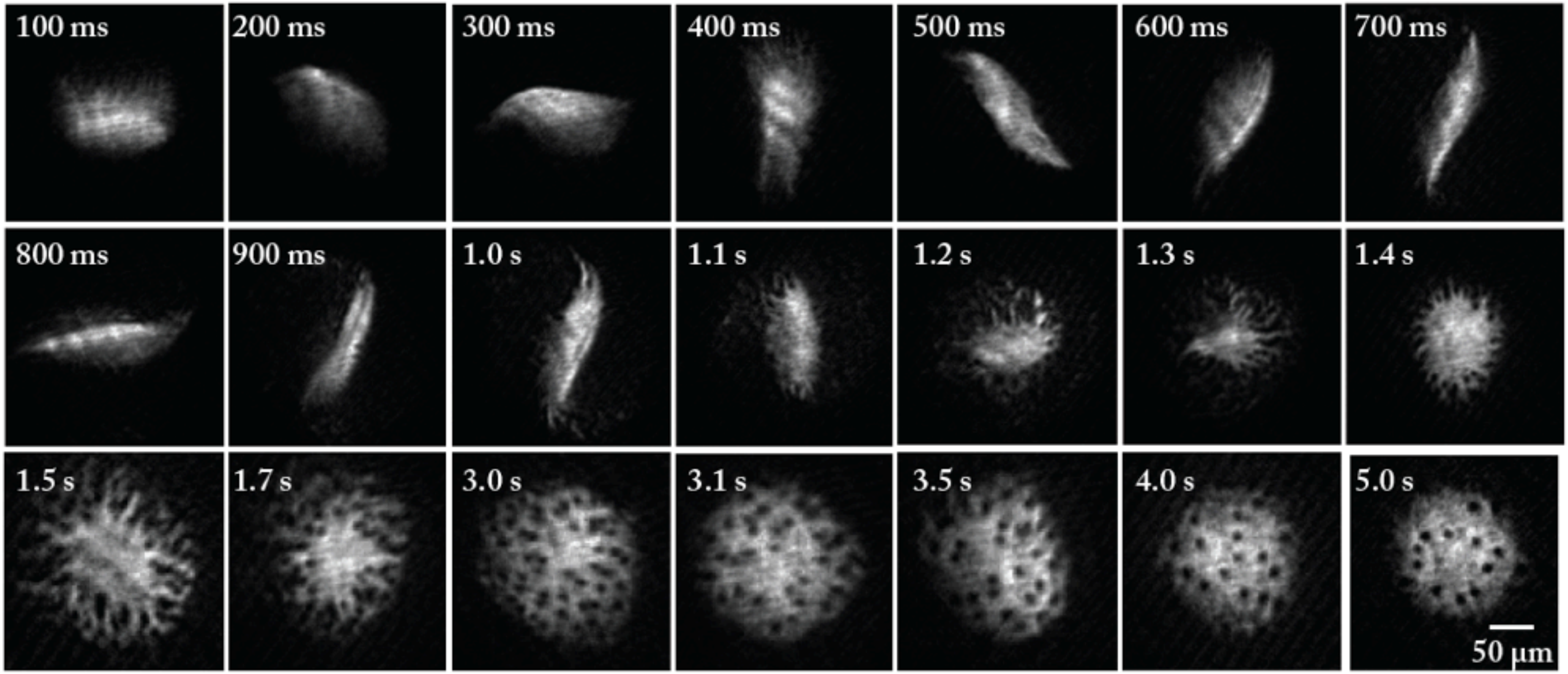


No surface excitation. Vortices nucleated within BEC



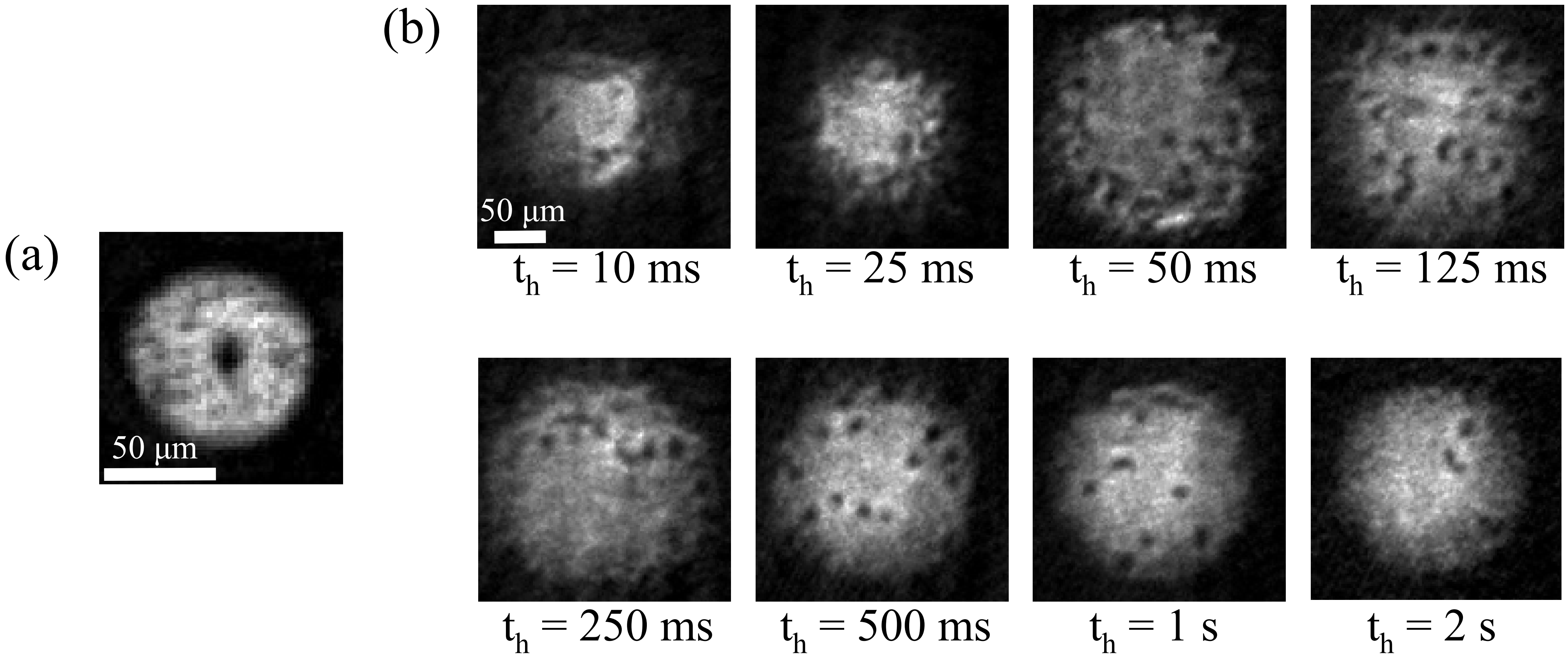
$t_{mod} = 0$ s $t_{mod} = 10$ ms $t_{mod} = 50$ ms $t_{mod} = 250$ ms

Spin the highly oblate trap (slightly elliptical)

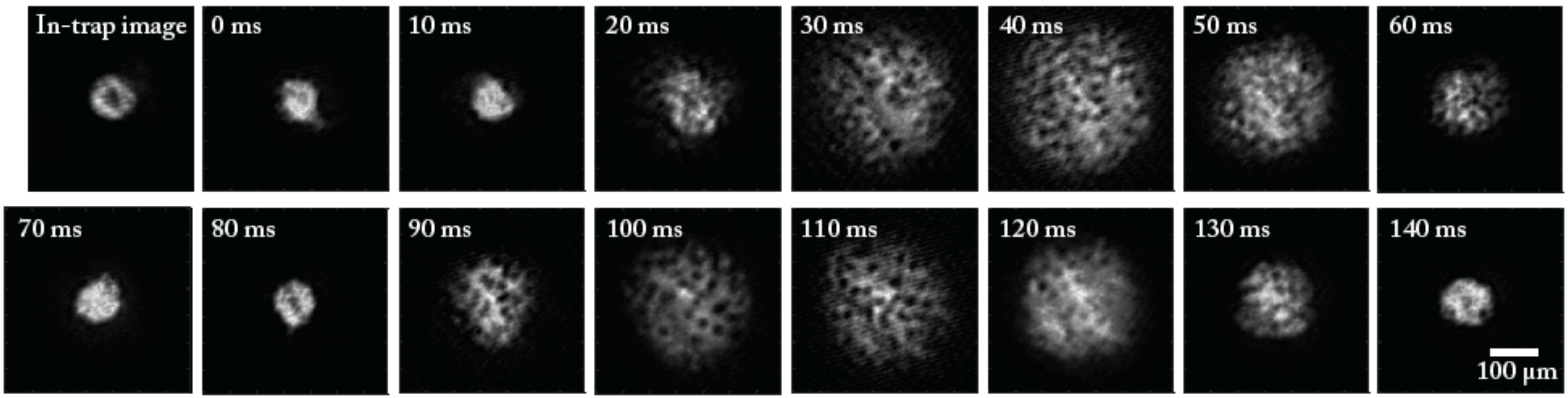


Blasting the BEC with a laser

Blast BEC with focused laser beam



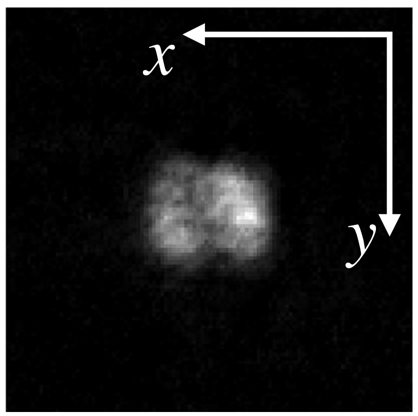
3 cycles of amplitude modulation, 2 x ω_r, 1/2 μ



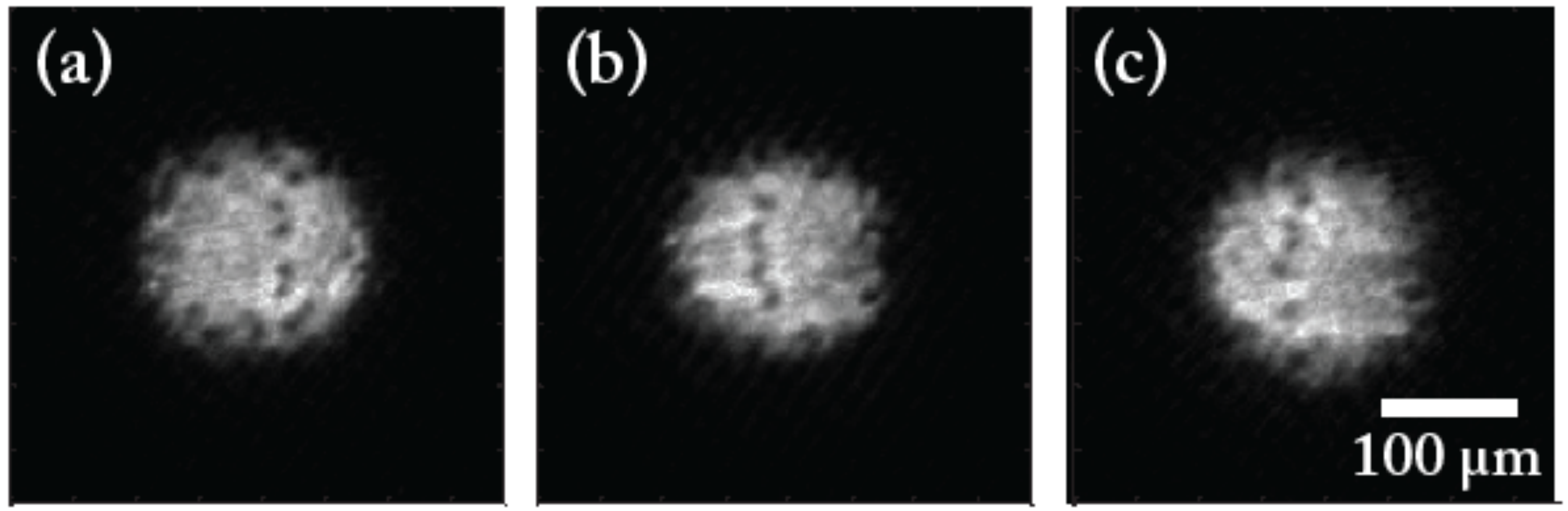
Where do the vortices come from?

Local excitation

Elongated laser beam



One period modulation, 2 x ω_r



Origin of vortices?

Making vortices, generating 2DQT turns out to be surprisingly easy!

Hard parts:

- understanding what is going on
- minimizing other excitations, shape oscillations, sound
- reaching a continuous injection of energy, vortices
- understanding the injection mechanisms

I. Experimental methods for 2DQT

preprint (available by request, soon to be on arXiv)
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K.E. Wilson, C.E. Samson, Z.L. Newman, T.W. Neely, B.P. Anderson

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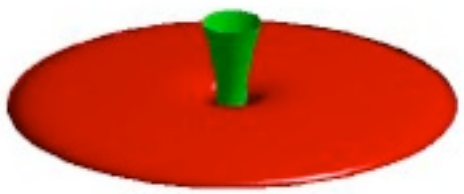
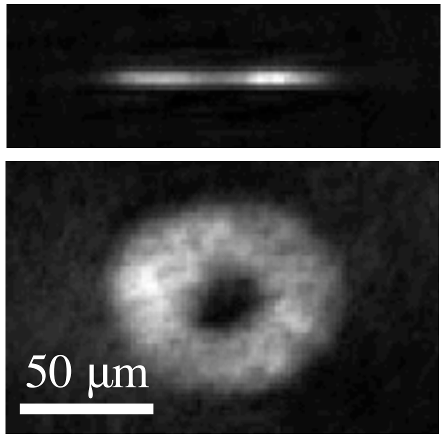
III. On-demand vortex generation and manipulation

in preparation
On-demand vortex generation and manipulation
C.E. Samson, K.E. Wilson, Z.L. Newman, B.P. Anderson

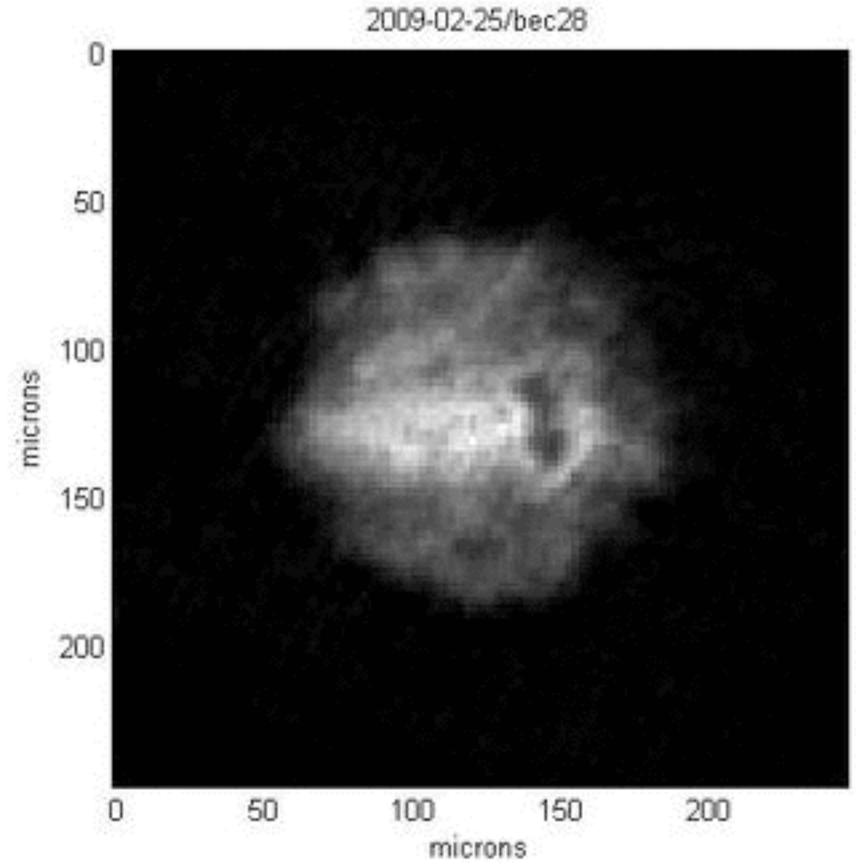
Stirring the BEC with a laser beam: vortex dipoles



BEC in trap (not expansion)



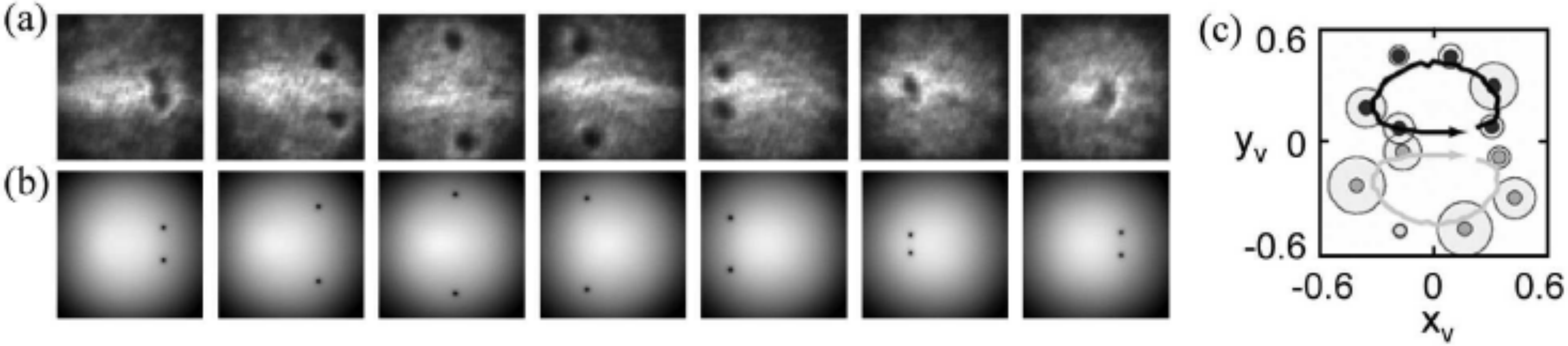
Beam swipes through BEC to the right. Above a critical velocity (~0.1 c) a vortex dipole forms.



200 ms between images, ~1.25 sec orbital period

(1 orbit shown, continuous loop)

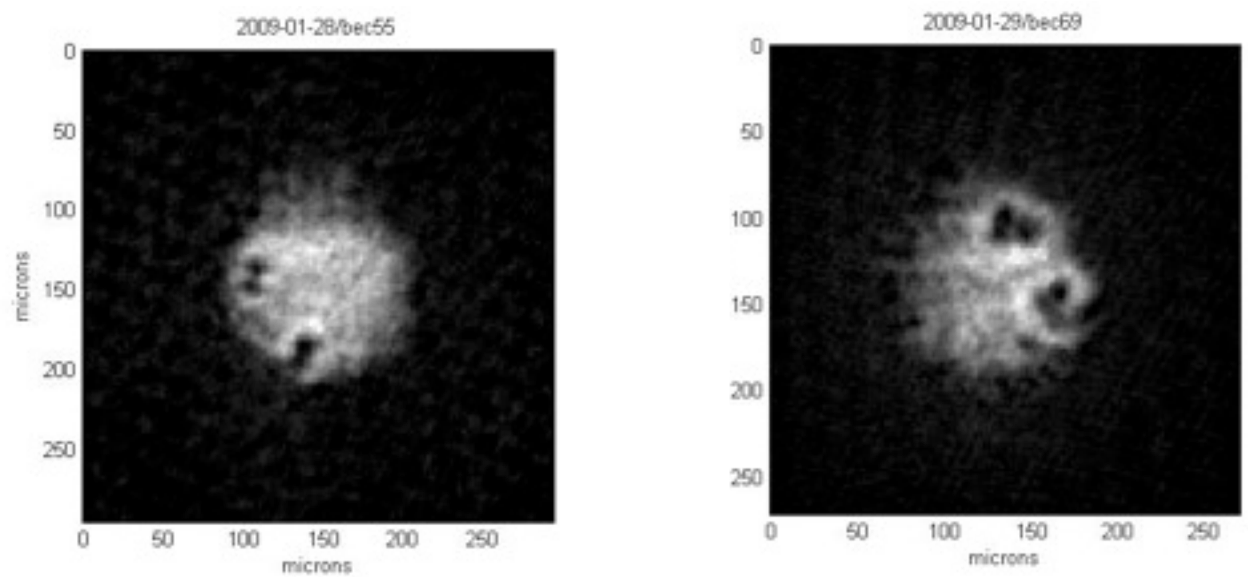
Observation of Vortex Dipoles in an Oblate Bose-Einstein Condensate
Neely, Samson, Bradley, Davis, Anderson
PRL 104, 160401 (2010)

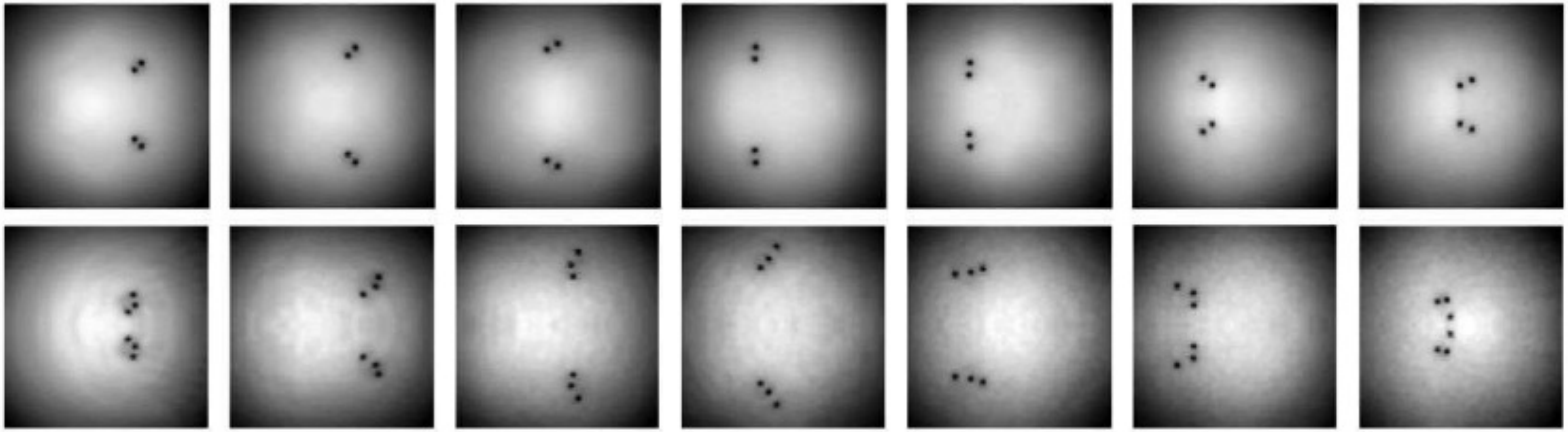


Faster swipes: vortex clusters *can* be supported in BEC and may stick together for long times

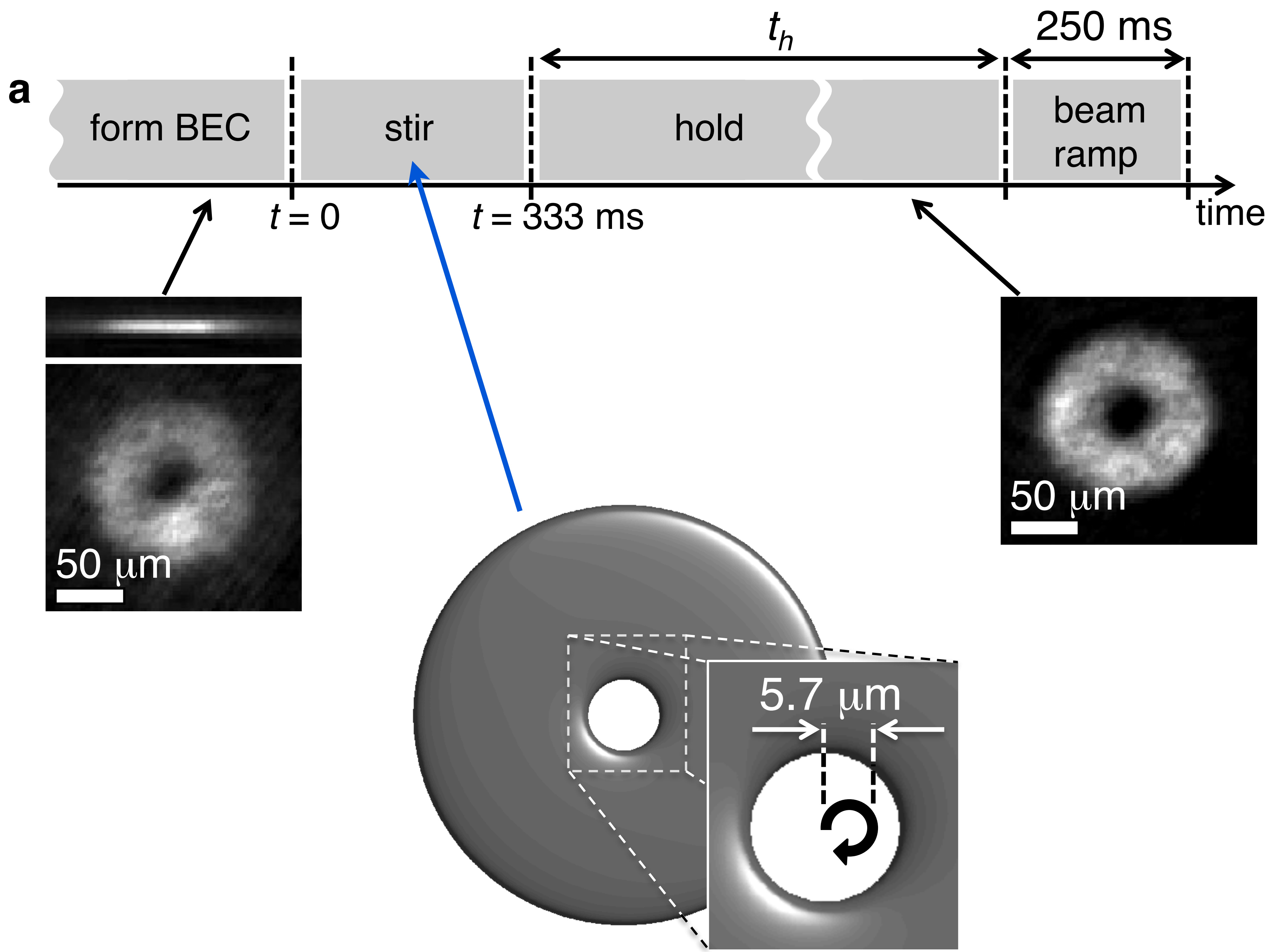
2 vortex pairs

3 pairs





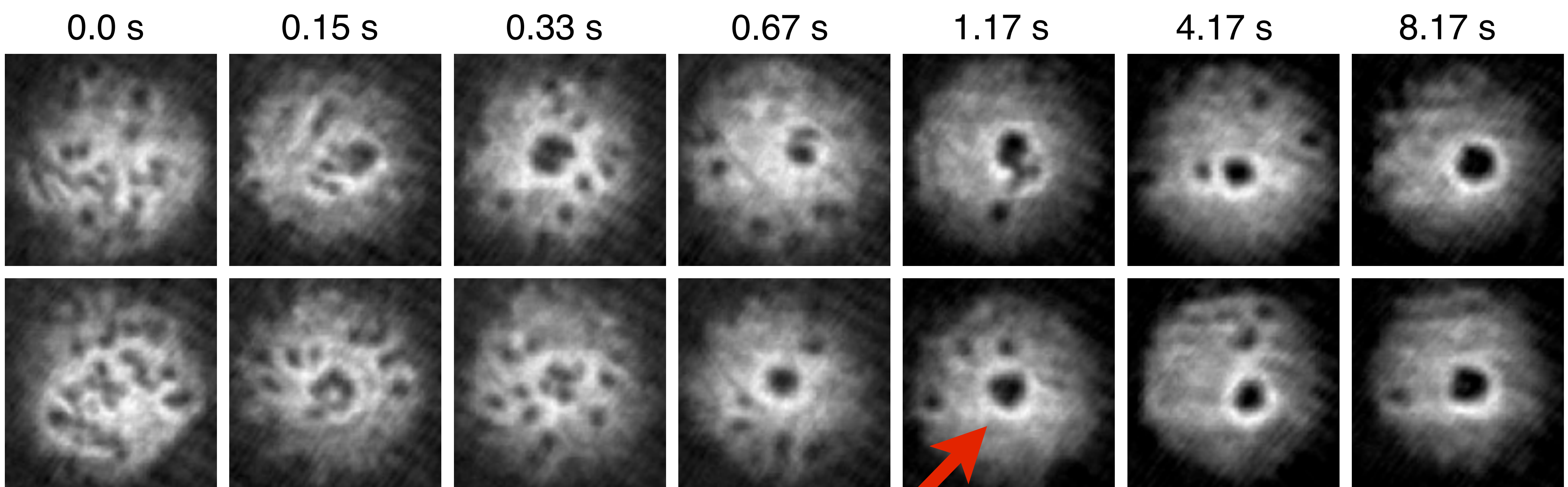
Inject more vortices: use circular stir



Decay of 2DQT - Formation of large-scale flows (persistent currents)

Hold after end of stir

EXPT
- ramp off beam
- expand



2DQT

Large fluid-free hole
= large vorticity
= flow at large length scale

large-scale flows

- Experimental generation of 2DQT from small-scale forcing.
- Development of large-scale flows during decay.

- Can not (yet)
  - determine circulation direction of vortices
  - measure energy spectra
  - determine vortex dynamics (image method is destructive)

Simulation: Stir using Damped GPE

1. Initial condition: BEC in ground state of toroidal trap
2. Stir, as in the experiment
3. Hold, then observe vortex distribution

Two-Dimensional Quantum Turbulence

T. W. Neely, A. S. Bradley, E. C. Samson, S. J. Rooney, E. M. Wright,
K. J. H. Law, R. Carretero-González, P. G. Kevrekidis, M. J. Davis, B. P. Anderson

Movie S1

DPGPE simulation parameters

Trap frequencies $(\omega_r, \omega_z) = 2\pi \times (8, 90)$ Hz
Scattering rate $\gamma = 8 \times 10^{-4}$
Chemical potential $\mu = 34\hbar\bar{\omega}$
Gaussian potential height $U_0 = 58\hbar\bar{\omega}$
Gaussian potential half width $\sigma_0 = 16.3\ \mu$m
Stirring radius $r_0 = 2.85\ \mu$m

College of Optical Sciences
THE UNIVERSITY OF ARIZONA

SAN DIEGO STATE UNIVERSITY

Decay of 2DQT - Formation of large-scale flows (persistent currents)

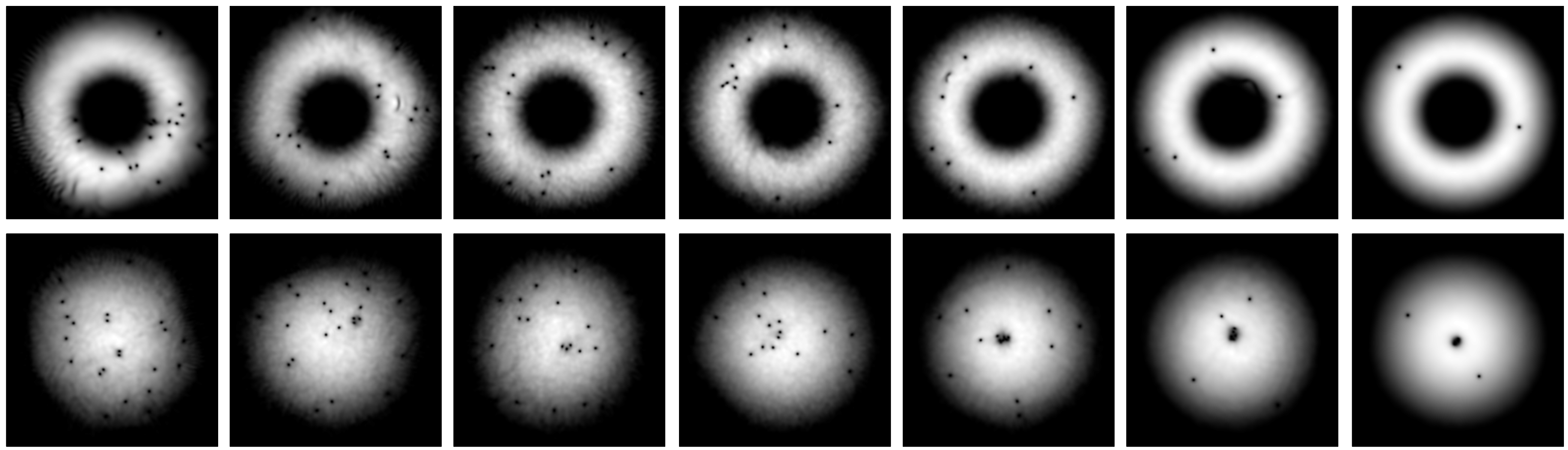
Hold after end of stir

SIMS

0.0 s | 0.15 s | 0.33 s | 0.67 s | 1.17 s | 4.17 s | 8.17 s

toroidal trap

beam ramped off

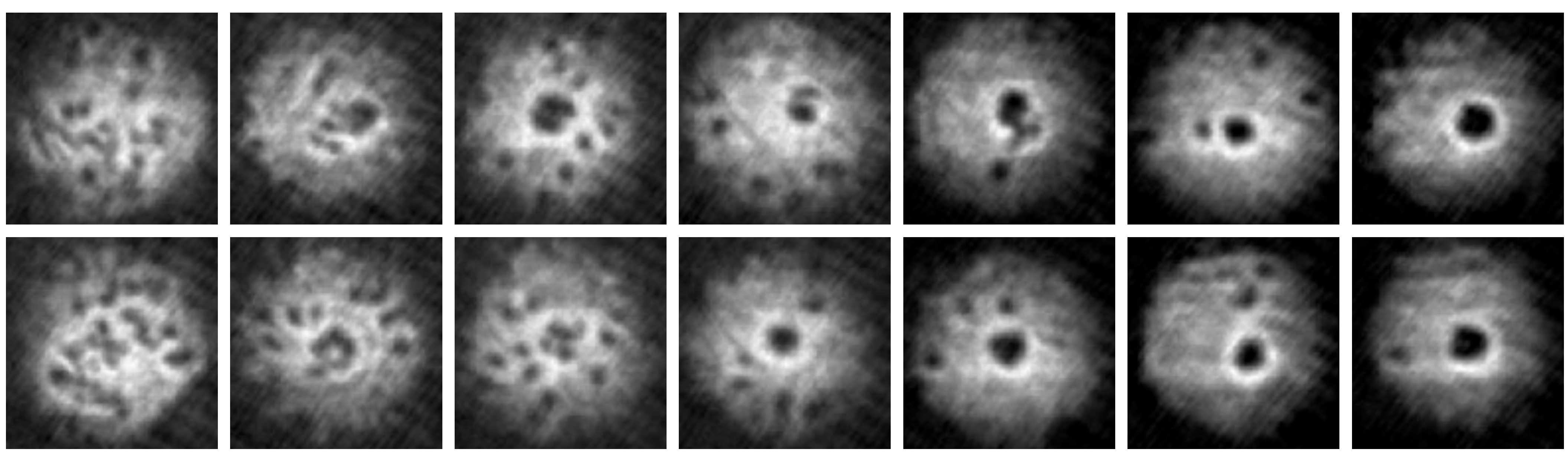


2DQT

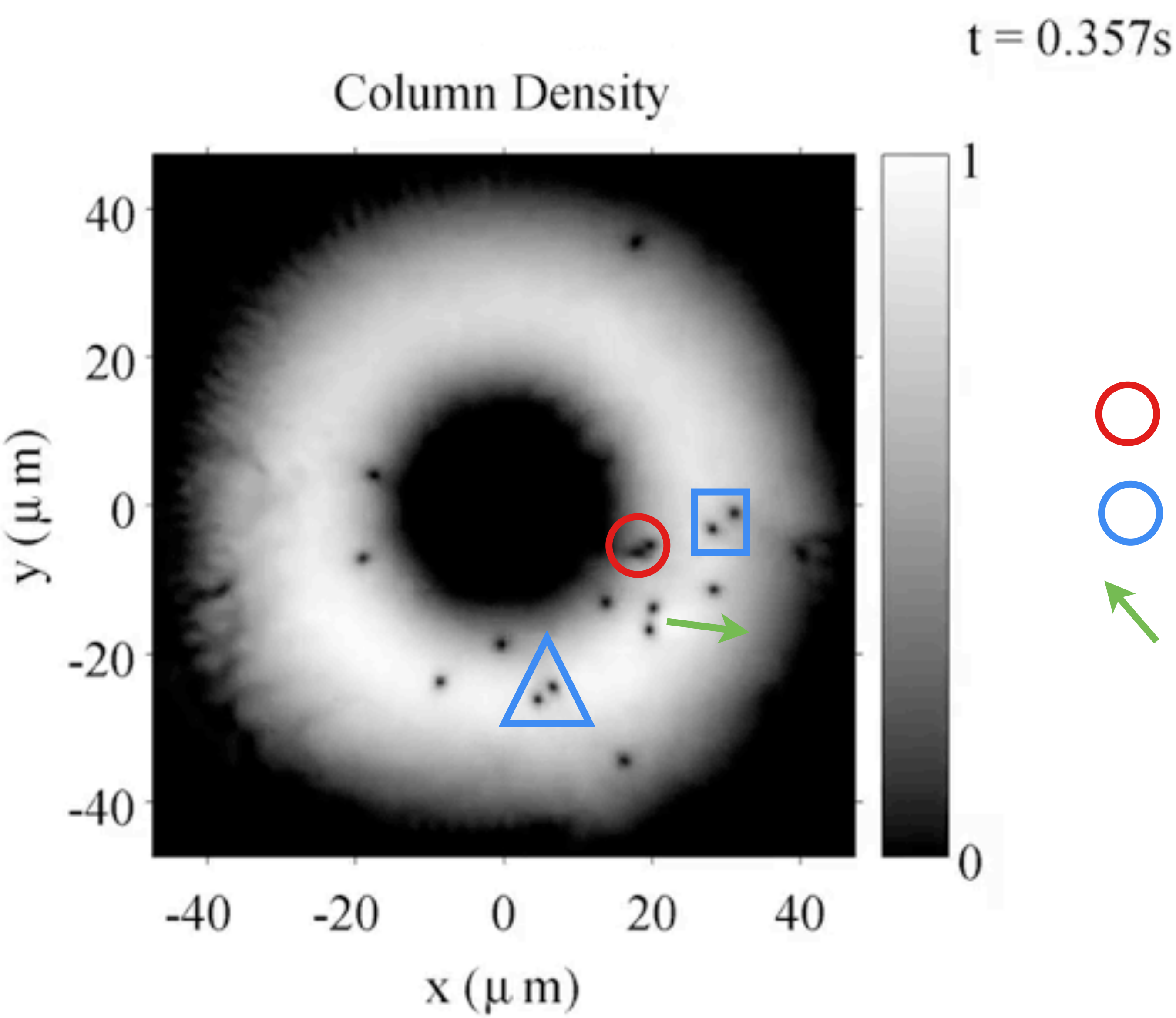
large-scale flows

EXPT

- ramp off beam
- expand



Vortex clusters



Vortex cluster with *clockwise* rotation

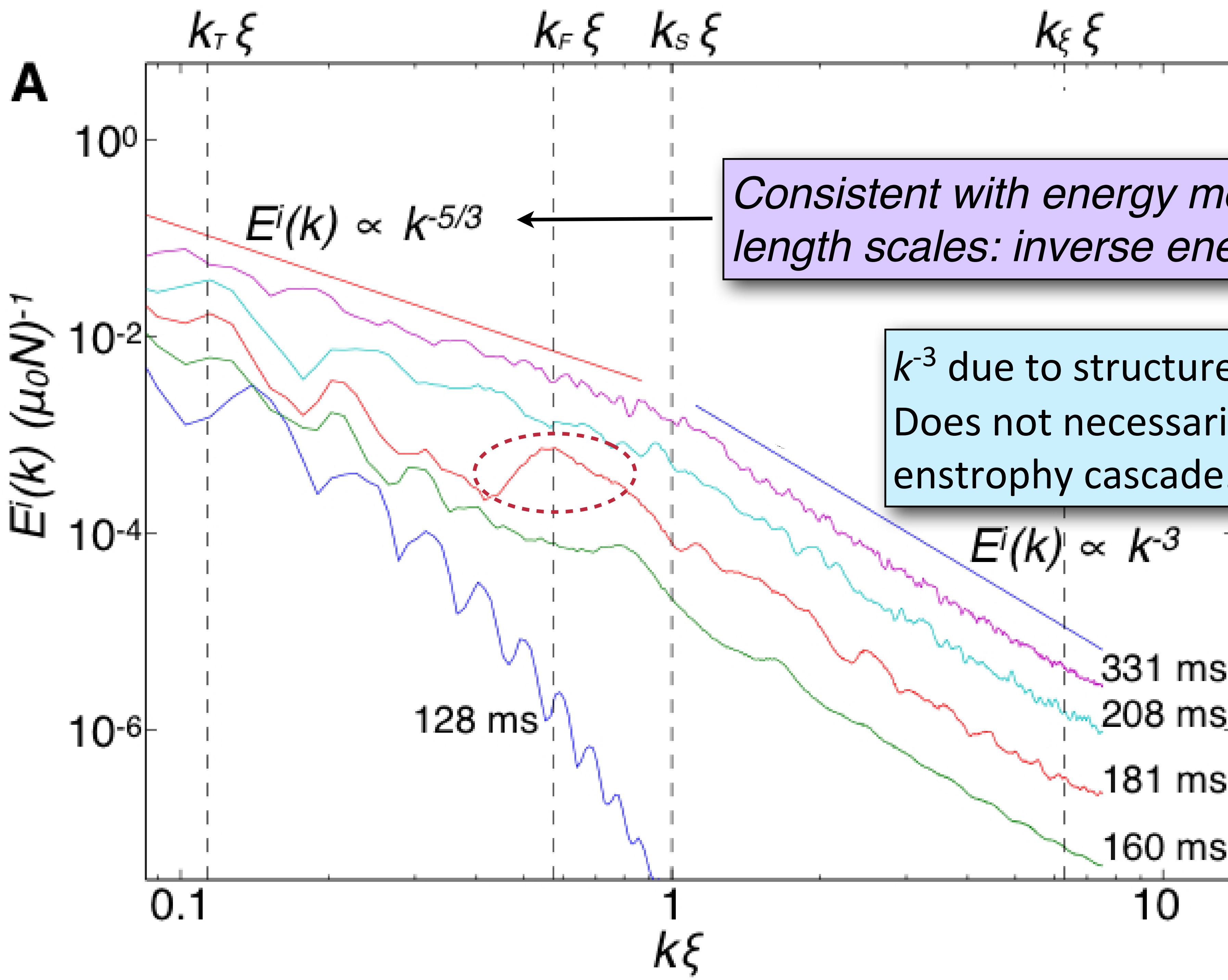
Vortex cluster with *anticlockwise* rotation

Linear momentum of vortex dipole

Vortex pair lifetime: over 600 ms, ~15x longer than turnover time

- Observation of vortex clusters in numerics
- Observed suppression of vortex annihilation (vortex number stays constant immediately after stirring)

Kinetic Energy spectrum (incompressible component)



Consistent with energy moving to ***larger*** *length scales: inverse energy cascade*

k^{-3} due to structure of vortex core! Does not necessarily imply enstrophy cascade.

End of stir

Forcing: breakdown of sound into vortices.
Injection of vortices separated by ~10ξ

Summary of 2DQT stirring project

2DQT in a BEC seems to share striking similarities with 2D classical turbulence

- Experimental generation of 2DQT.
- Development of large-scale flows from small-scale forcing.

- Observation of vortex clusters in numerics
- Observed suppression of vortex annihilation (vortex number stays constant immediately after stirring)

- $k^{-5/3}$ energy spectrum for large length scales (k < forcing scale)
- k^{-3} energy spectrum for short length scales (k > forcing scale)
- Observed suppression of vortex annihilation (vortex number stays constant immediately after stirring)

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in preparation
On-demand vortex generation and manipulation
C.E. Samson, K.E. Wilson, Z.L. Newman, B.P. Anderson

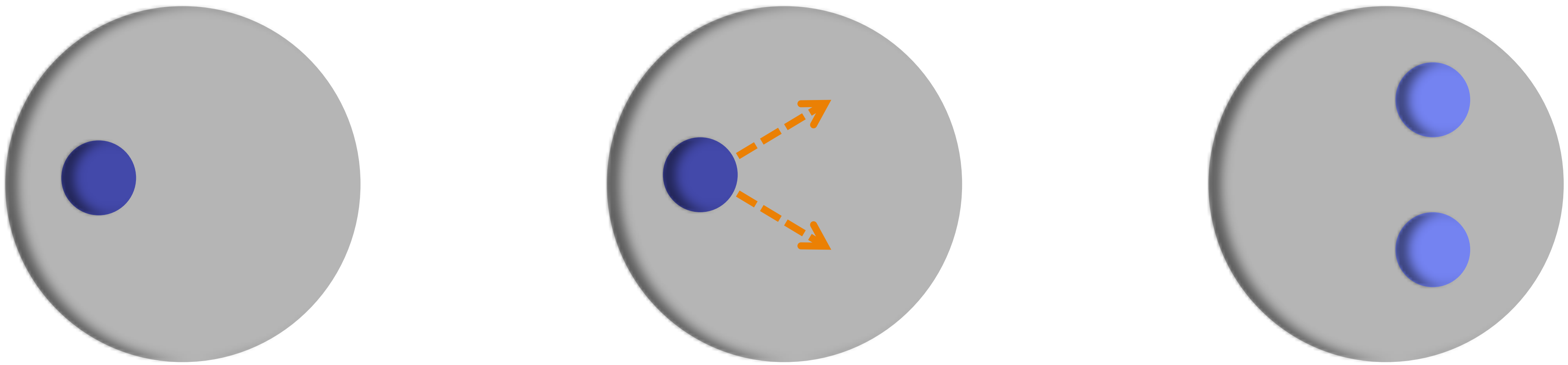
Precision studies of 2DQT ?

Goal: Build up vortex distributions one by one.
A bottom-up approach to vortex dynamics, turbulence.

Investigate:
- dynamics of vortex structures,
- interactions between vortices,
- roles of impurities and trap shape,
- roles of dimensionality of trap
- effects of temperature/thermal bath

Initial goals: demonstrate
(1) On-demand vortex generation
(2) Manipulation of vortices with laser beams (pinning)
(2) Control of winding number of pinned vortices

(1) On-demand vortex generation

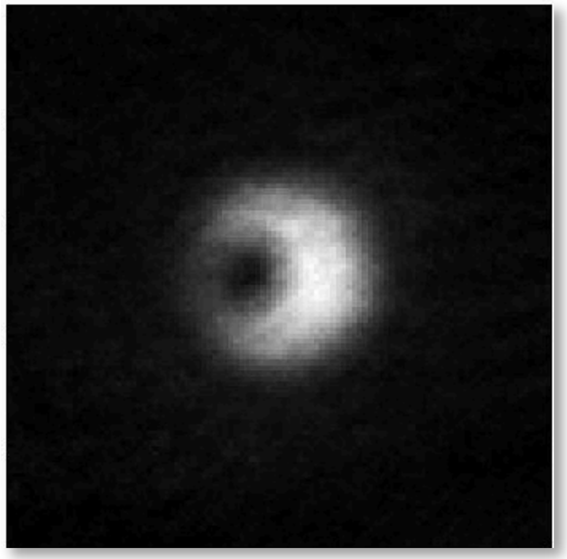


Two coincident laser beams | Separate beams | Final positions

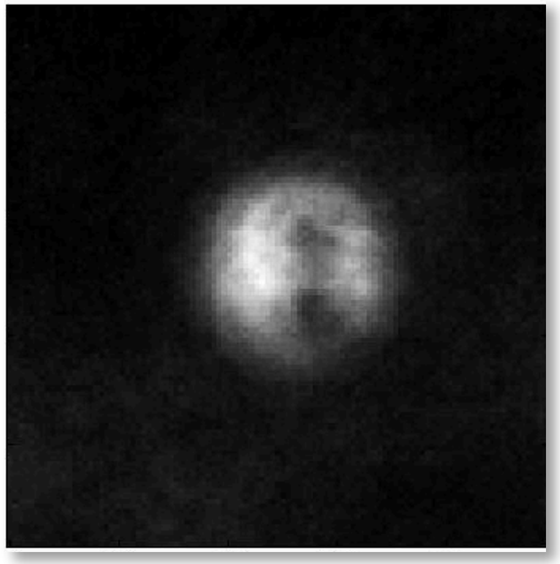
Slow linear swipe, ~40 um/s

About 25% of critical velocity for vortex dipole nucleation (180 um/s)

Prior to swipe

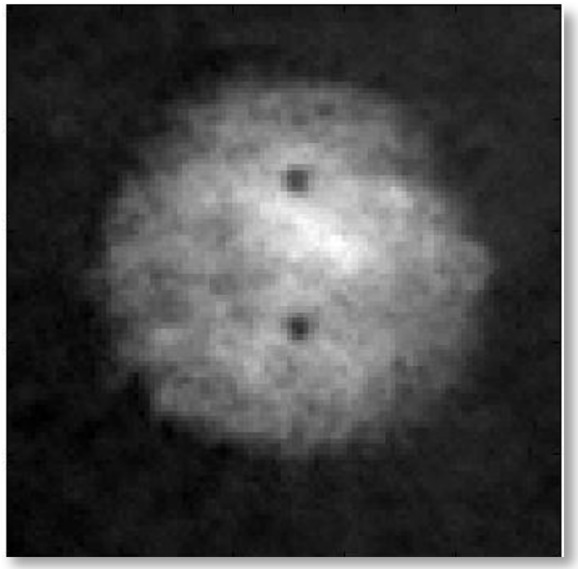


Final beam positions

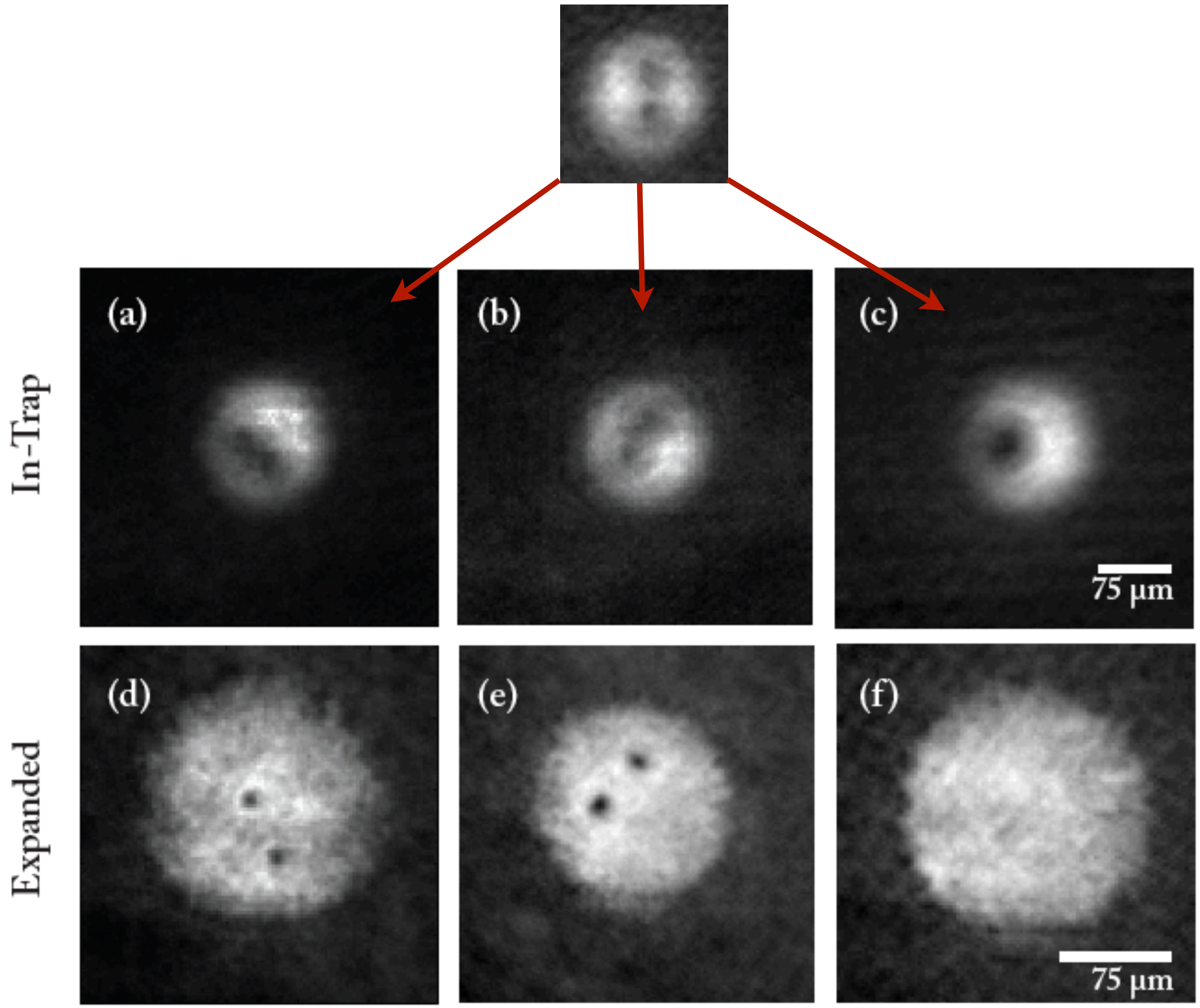


Trapped BECs

Expanded BEC with vortices



(2) Vortex manipulation



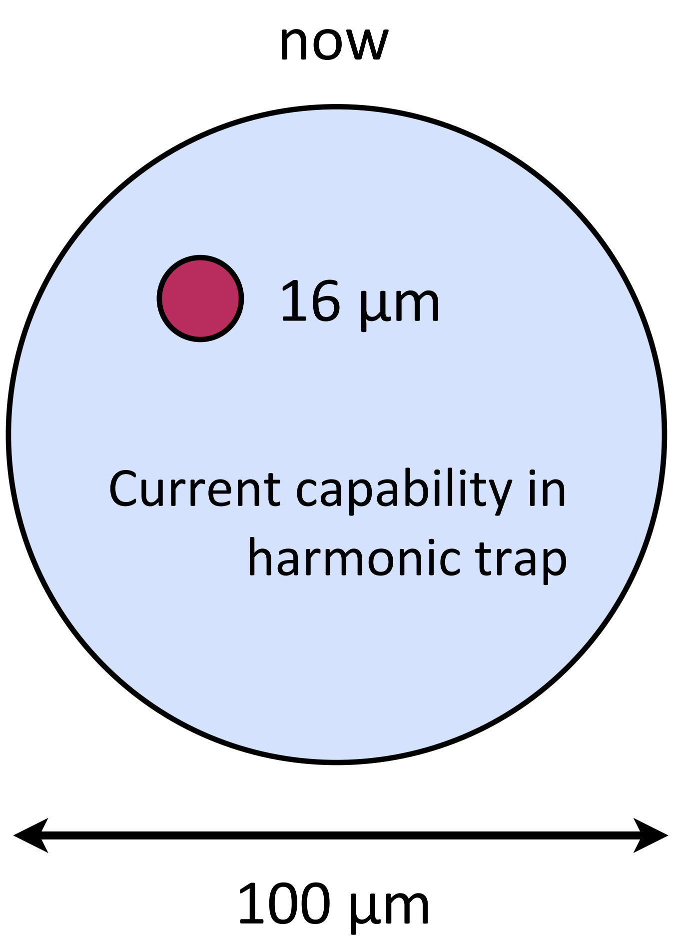
Next to do:

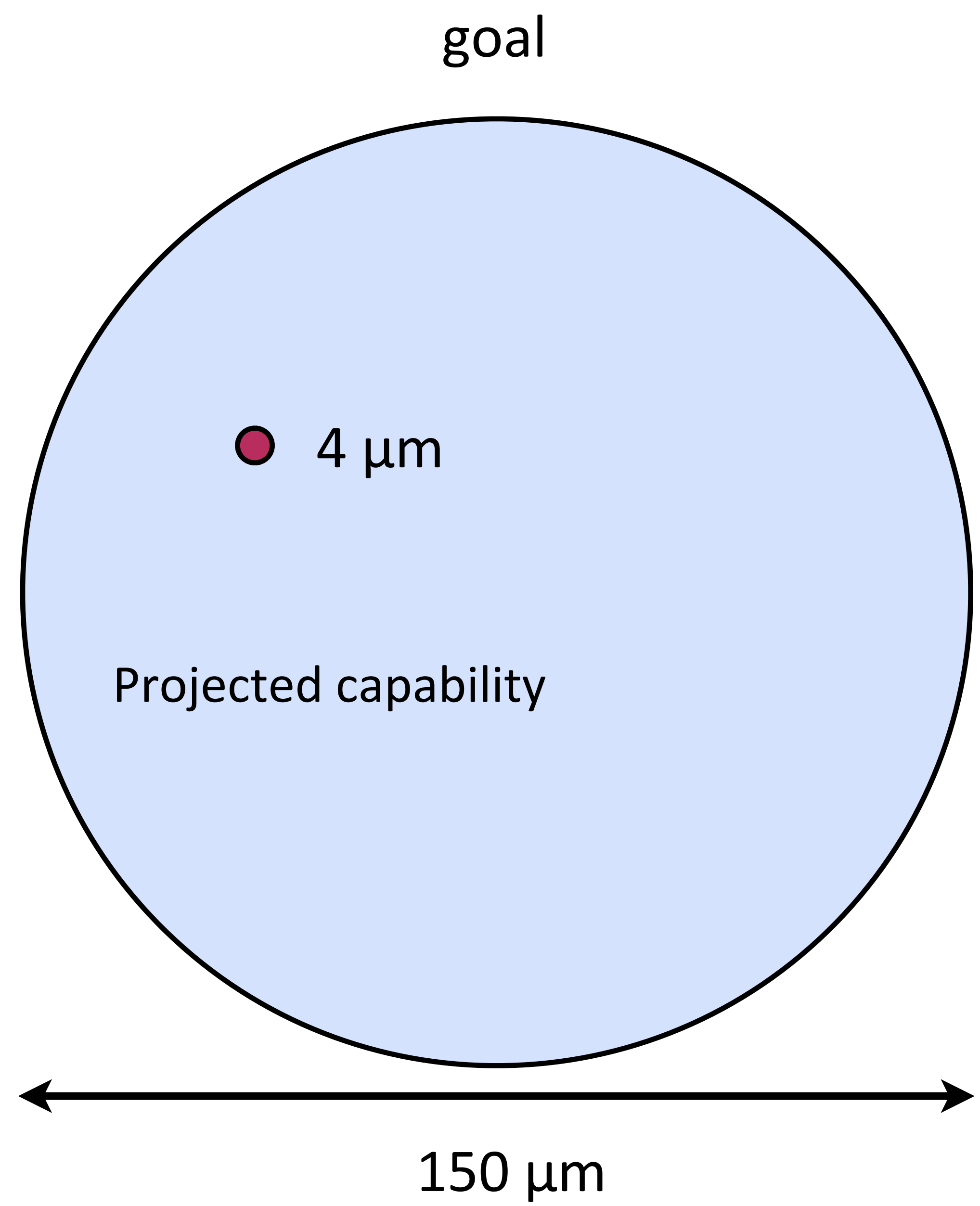
- remove one beam (and one vortex) from system
- transfer a vortex to another pinning site
- generation of more vortices

Optimized vortex manipulation: projection

High-resolution microscopy: vortex manipulation

BEC size - laser spot size comparison

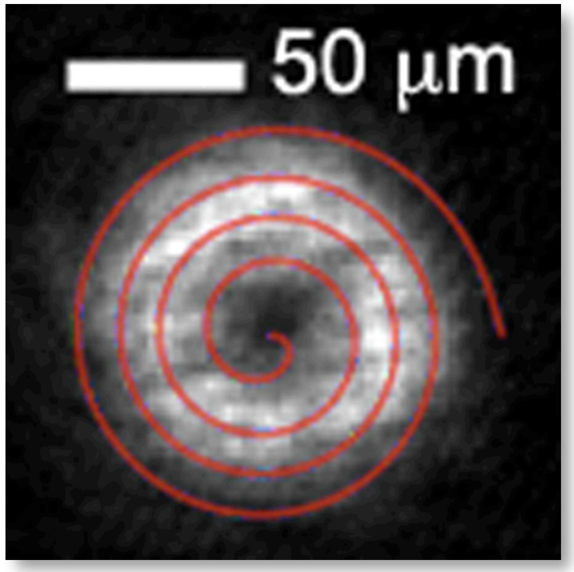




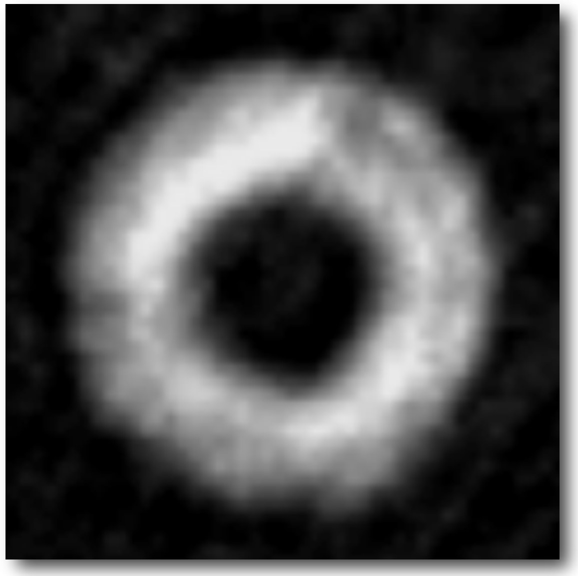
An array of individual focused laser beams is probably not the ideal solution for many-vortex manipulation.

Alternative: spatial light modulator, transfer vortices to stationary sites

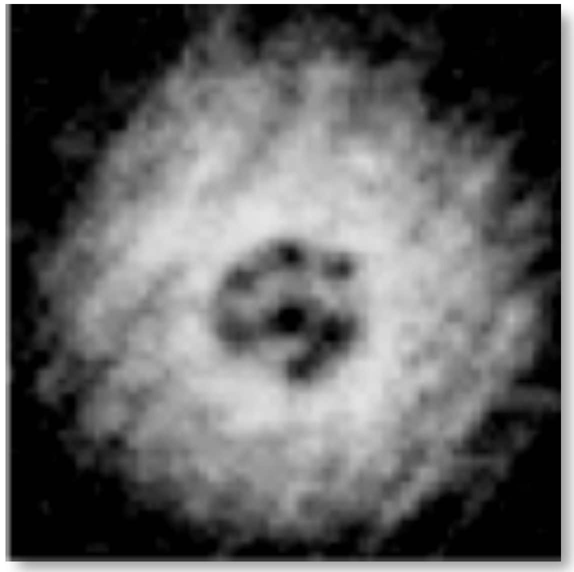
(3) Winding number control



Spiral trajectory of laser beam



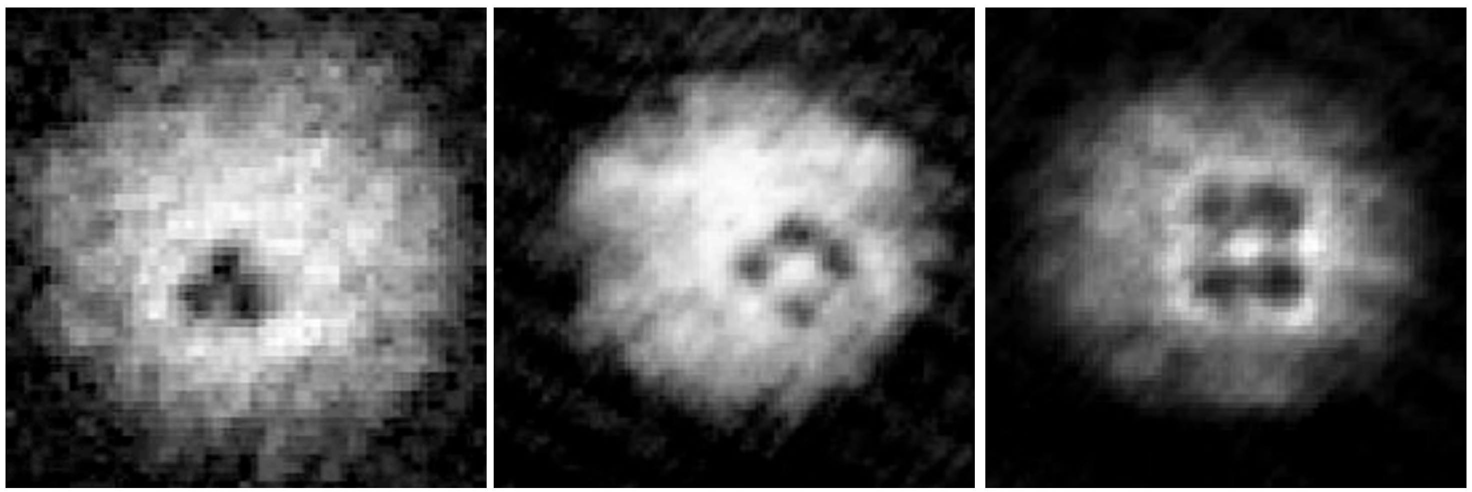
Large pinned circulation



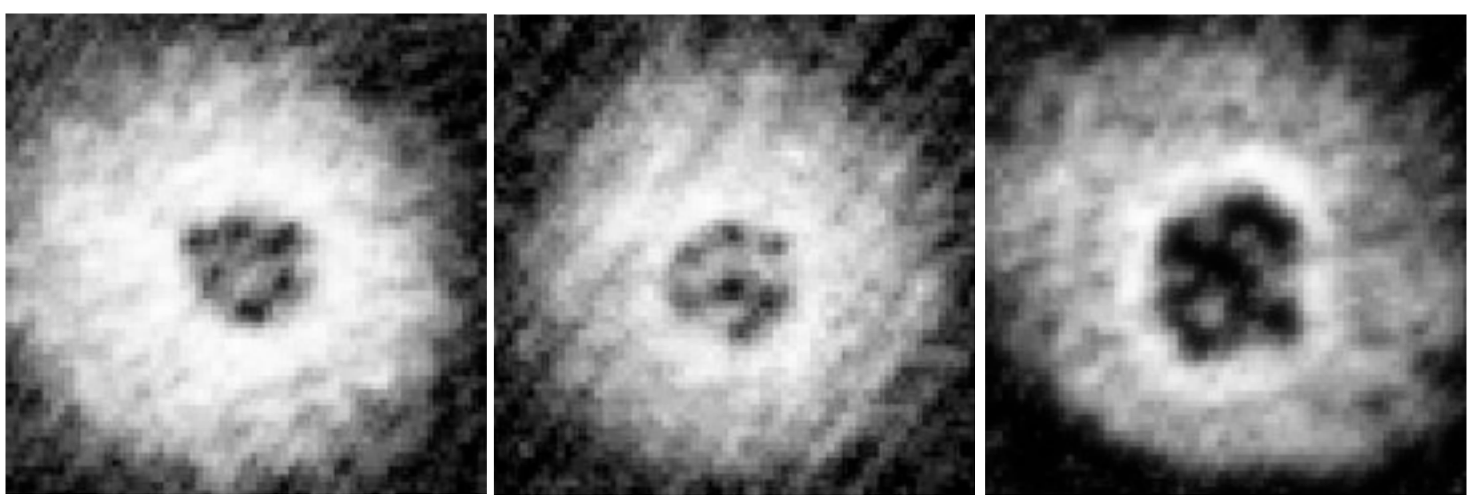
Vortices separate with extra hold time (160 ms)

Vortex crystals/bundles

3 4 4



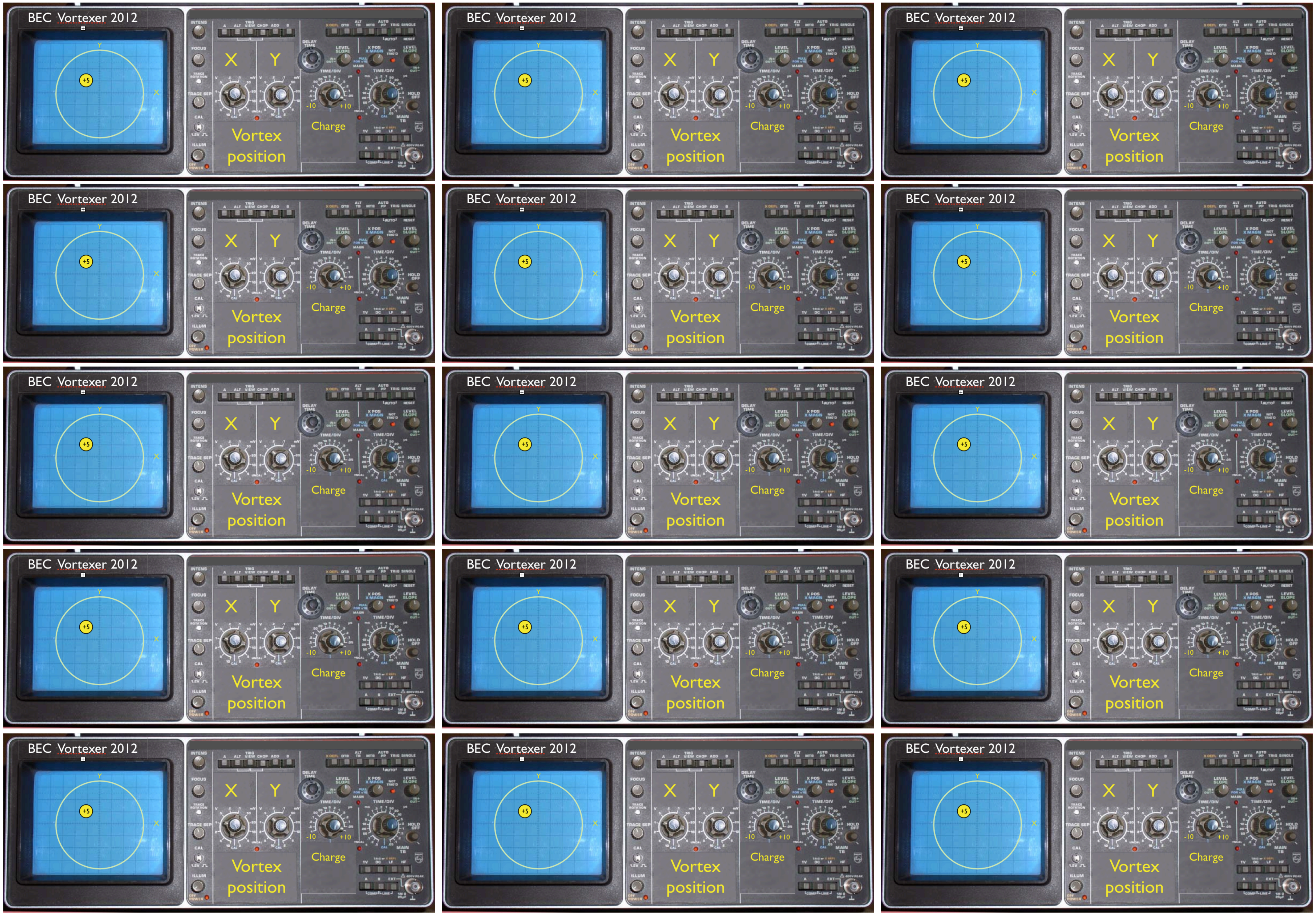
6 7 8?



(Images from various vortex generation techniques)

2 pinning sites is feasible: **release of vortex bundles into BEC (2D or 3D BEC)**

Maybe some day



Experimental challenges

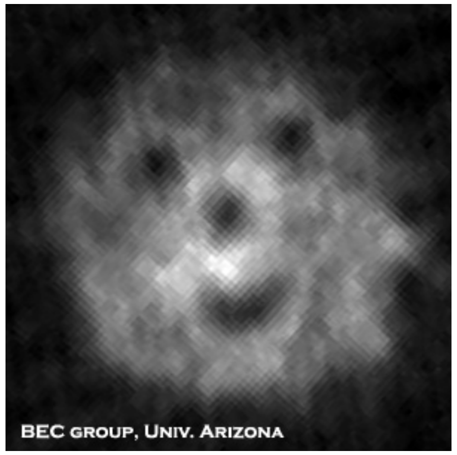
Sustaining a turbulent state

- steady-state forcing and dissipation
- minimal heating, atom loss, and excitation of BEC

Multiple-image *in situ* vortex imaging

- watch the inverse energy cascade in real time (clustering of vortices)
- measure chaotic dynamics of few-vortex systems
- characterize vortex interactions with impurities
- characterize vortex-antivortex annihilation and generation

Eventually: Real-time imaging, generation, and manipulation of vortices will lead to precision experimental studies and control of 2D quantum turbulence!



arXiv: 1204.1102
Characteristics of Two-Dimensional Quantum Turbulence in a Compressible Superfluid
T.W. Neely *et al.*   *Experiment and simulations*

preprint (available by request, soon to be on arXiv)
Experimental Methods for Generating Two-Dimensional Turbulence in Bose-Einstein Condensates
K.E. Wilson, C.E. Samson, Z.L. Newman, T.W. Neely, B.P. Anderson

arXiv: 1204.1103 (not discussed)
Energy Spectra of Vortex Distributions in Two-Dimensional Quantum Turbulence
A.S. Bradley and B.P. Anderson.   *Analytical approach*

Resource Article: Experiments with Vortices in Superfluid Atomic Gases
B. P. Anderson, JLTP 161, 574 (2010)

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