Formation of Vortices and Vortex Clusters from Matter-wave Interference in BECs

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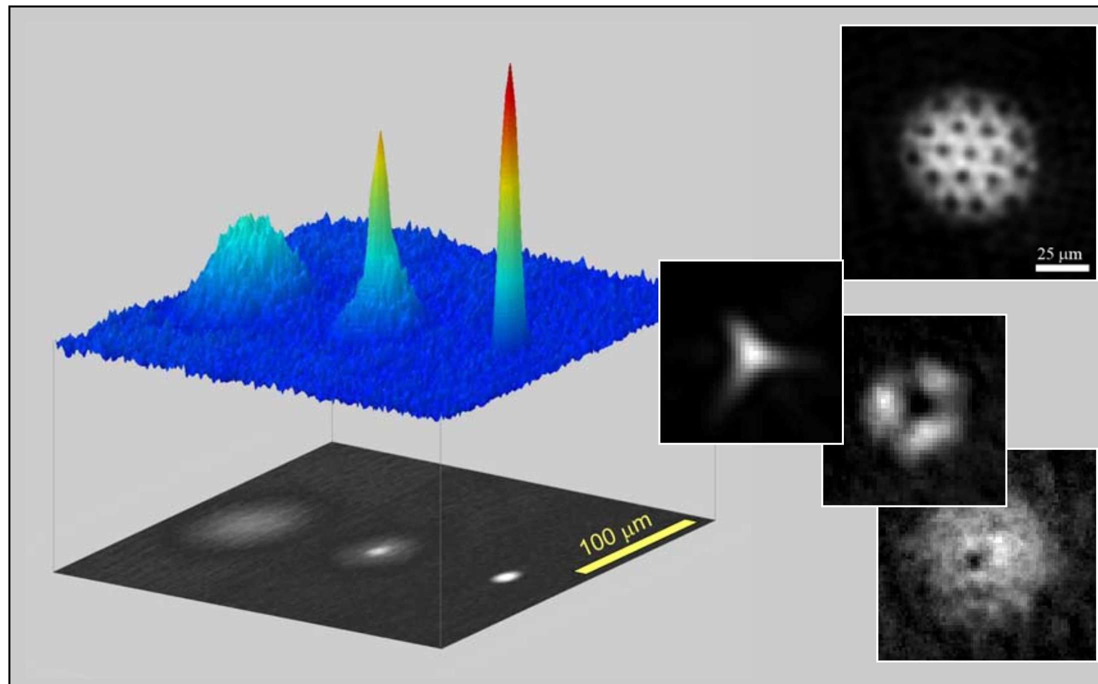

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Main Objective

To understand how the role of **defects and roughness** in a confining potential affects the formation and dynamics of BECs, and superfluids in general.

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Interference,
Turbulence,
Vortices

Motivation and Importance

- **Condensed-matter physics**: better understanding of the establishment of superconducting, superfluid states. BEC is a model system, easier to study "dirty" effects (i.e., defects) by starting with a "clean" system such as achieved with BECs.

- **Applications**: BEC transport in waveguides, atom-optical elements (ex: beam-combiners)

- **New topics in BEC**: Characterizing superfluids in disordered potentials

- **Fundamental issues**: fragmentation, onset of condensation, **symmetry-breaking transitions.** "Can a BEC form in an excited state of a potential?"

- **Quantum (*non*)-control**: Means for (possibly undesired) excitations to enter system: vortex formation and pinning. BEC dynamics based on indeterminate initial conditions.

- **Matter-wave interference**: fundamental link to turbulence, generation of vortices, vortex clusters.

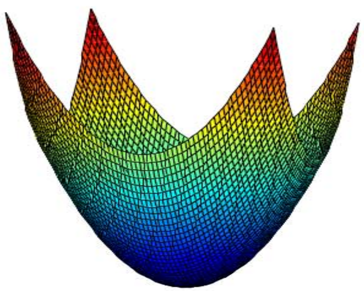
- **Quantum-state engineering**: possible new methods of state preparation

How do quantum fluids merge together?

Experiment Idea

1. **Approximate a “rough” potential with a weak bump in the middle of a harmonic oscillator potential.**

- Negligible effect on thermal cloud
- Just one BEC in the overall potential at the end of evaporative cooling



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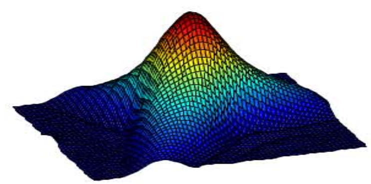

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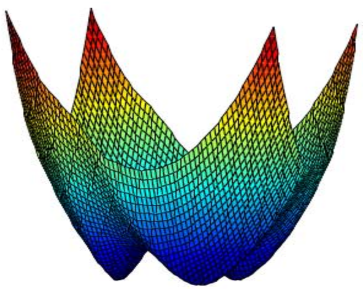
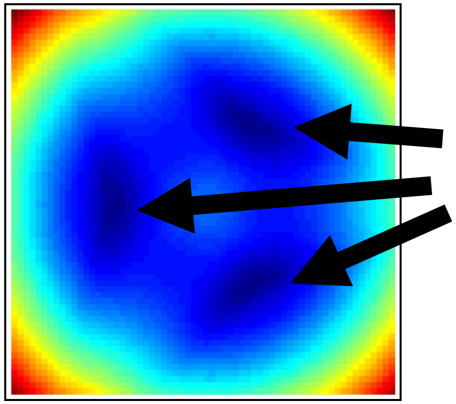


A trap with 3 wells

2. **Make a BEC in this new potential well.**

Top-down view:



“Seed” BECs start to form in 3 places, **but they merge together as they grow**

Approach, & Talk Outline

Theory

1. **Concept:** Build an understanding of how the mixing of quantum fluids may produce vortices.
2. **Numerics:** Use GPE to model the growth of a (quasi-2D) BEC in a bumpy potential

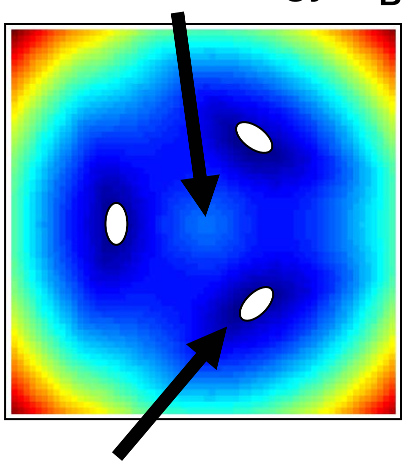
Experiment

3. **Optical barrier:** Shape a blue-detuned laser beam, add to a weak TOP trap to make bumpy trap
4. **Condense:** Create ^{87}Rb BECs in the bumpy trap
5. **Measurements:** Look for vortices

Concept: Growth of a BEC

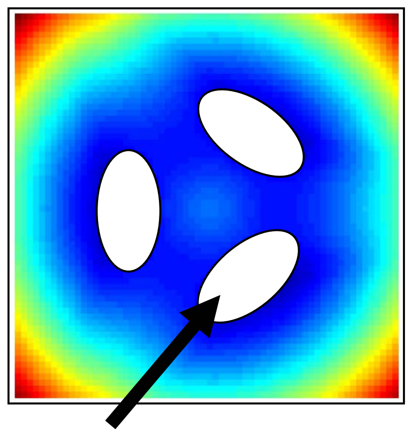
(1) 3 independent seed BECs start forming from common thermal cloud.

Barrier energy $\mathbf{E_B}$



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

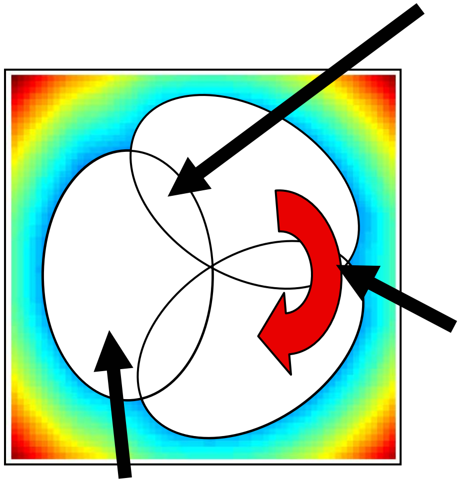
(2) Seed BECs grow, merge, establish relative phases (random), first by tunneling, then above-barrier transport.



Chemical potential μ **<** $\mathbf{E_B}$

(3) BECs merge together into one final BEC. Interference leads to fluid flow, excitations.

Interference region



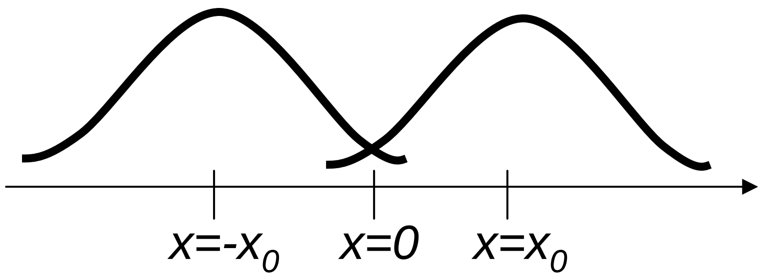
Fluid flow? Depends on phase gradients **and relative phases.**

Final chemical potential μ **>** $\mathbf{E_B}$

Fluid flow over barriers

Assume a symmetric superposition state with variable phases ϕ_1 and ϕ_2

$$\Psi = \sqrt{n_1(x+x_0)}e^{i\phi_1} + \sqrt{n_2(x-x_0)}e^{i\phi_2}$$



Current density:

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

$$J(x=0) = \frac{\hbar n_2(x=0)}{m}\sin(\phi_2-\phi_1)$$

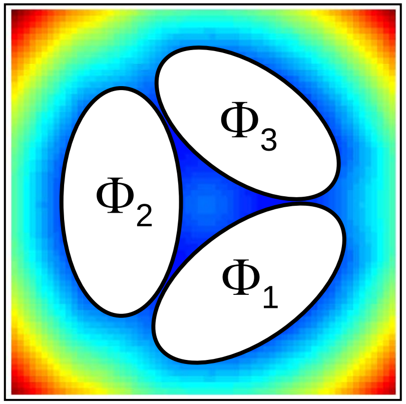
(assumes $n_1 = n_2$, $dn_1/dt = -dn_2/dt$)

Mass current (fluid flow) direction depends on phase difference: true for Josephson Effect **and** above-barrier transport.

Neglects phase gradients, potentially very important, may lead to interference ***fringes*** in the growing BEC.

A Vortex from matter-wave interference

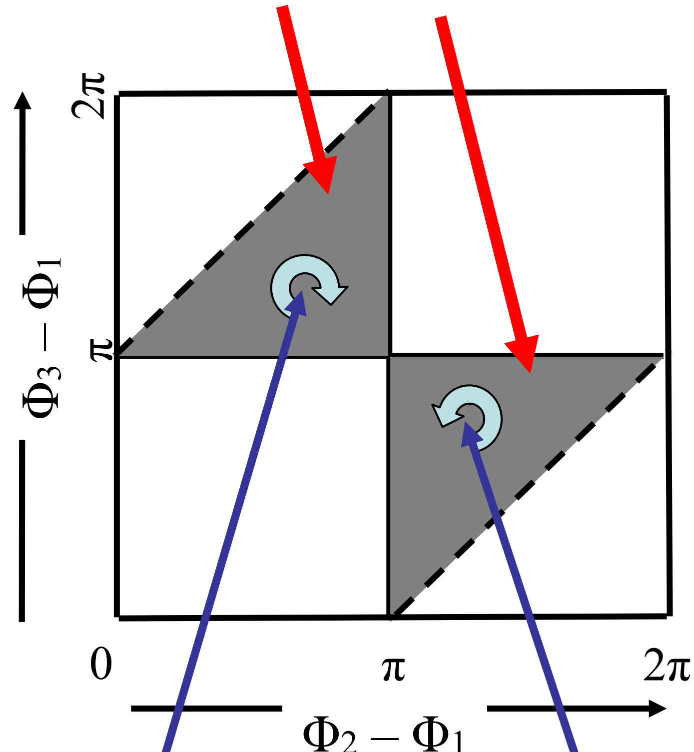
$$J \sim \sin(\phi_2 - \phi_1)$$



For ease of discussion, artificially assign phases to the 3 growing BECs.

(There are really **only two independent phase variables**.)

Given random relative phases, **vortex nucleation might occur up to 25% of the time.**



"Ideal" phases:

Φ_1=0, Φ_2=2π/3, Φ_3=4π/3

Φ_1=0, Φ_2=4π/3, Φ_3=2π/3

Conditions for circular flow
(all phase differences between 0 and 2π)

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

Numerics

To model the growth of 3 independently-formed seed condensates:

GPE

T=0, quasi-2D, split-step Fourier transform method

Initial conditions

- Generate 3 independent condensates in segmented trap
- fixed number of atoms
- scattering length $a_s = 0$
- assign phase differences

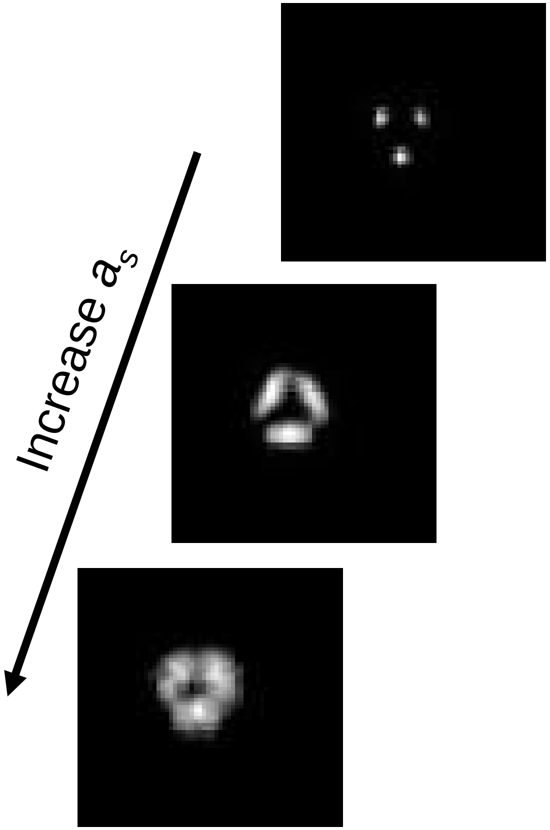
Growth

- Increase a_s (or increase atom number)

Main Variables

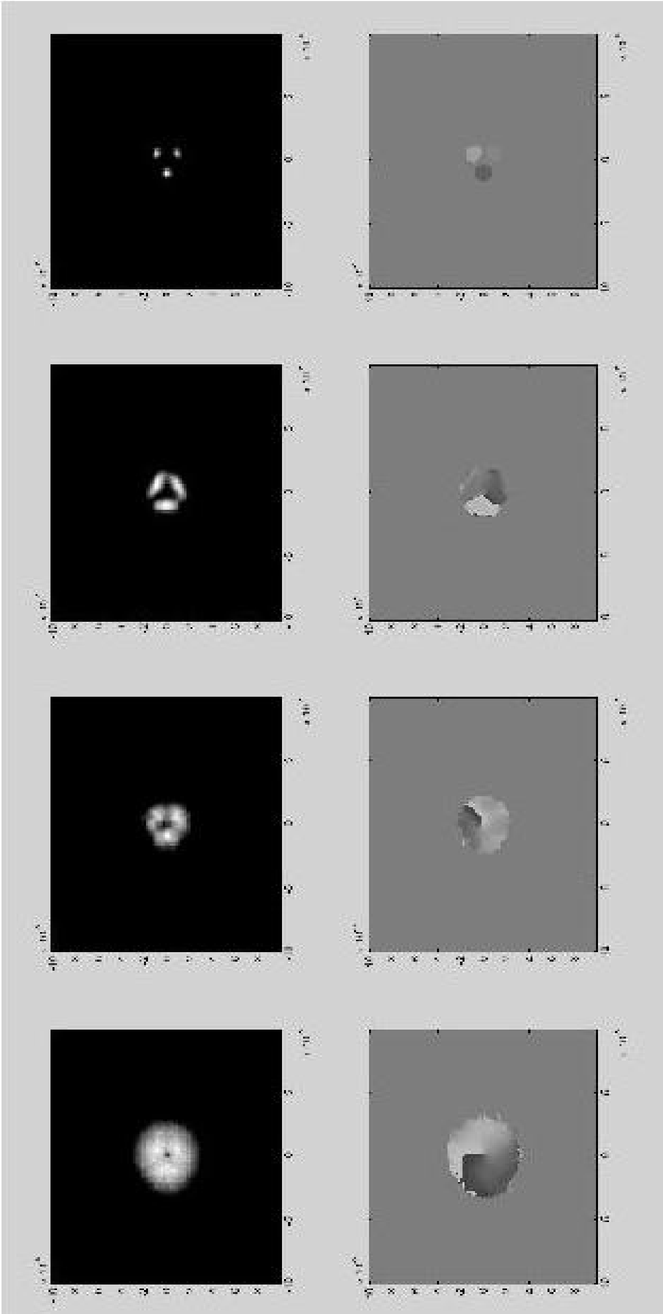
- **Rate of increase of a_s**
- **Initial phase differences** (random in experiment)
- Barrier height, shape

Simulated data



Simulation Sequence

Density Phase



3 seed BECs are generated.
Phases assigned.

Condensates grow in number, size

Atoms flow over barriers

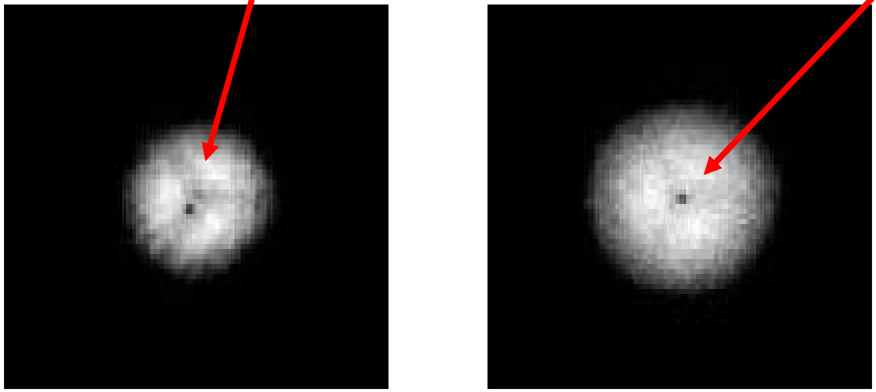
A vortex core is formed and pinned at the central barrier

Increasing time, a_s

Does a vortex always form?

No. Given **random** relative phase differences, about 25% of the time (depends on growth rate) will the relative phases be appropriate to establish a vortex, though not always on-center. However...

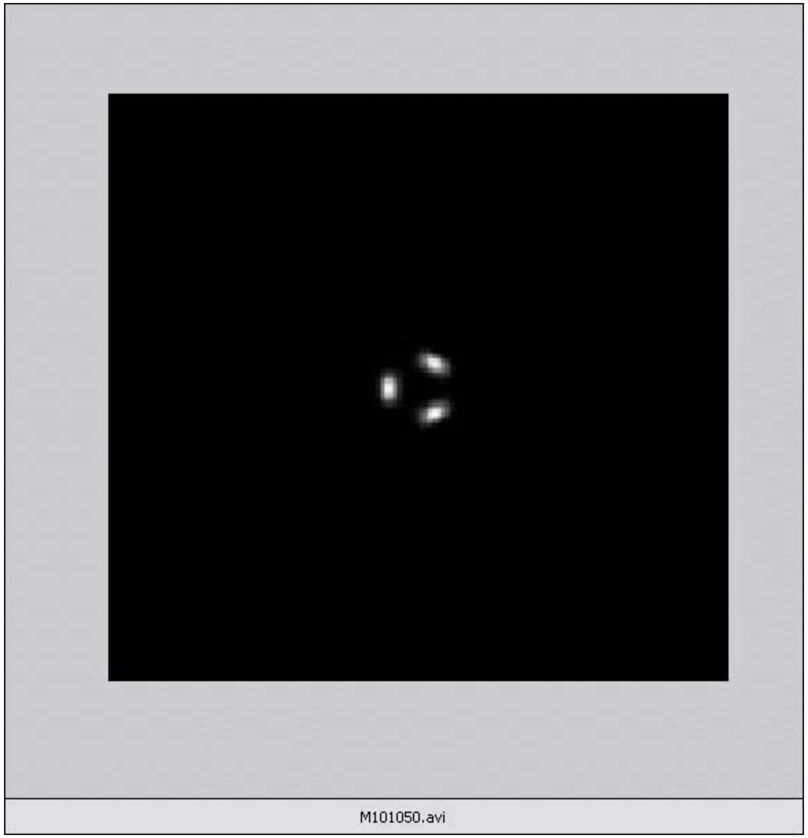
...**a vortex core that forms off-center can drift towards the center** and be pinned at the barrier.



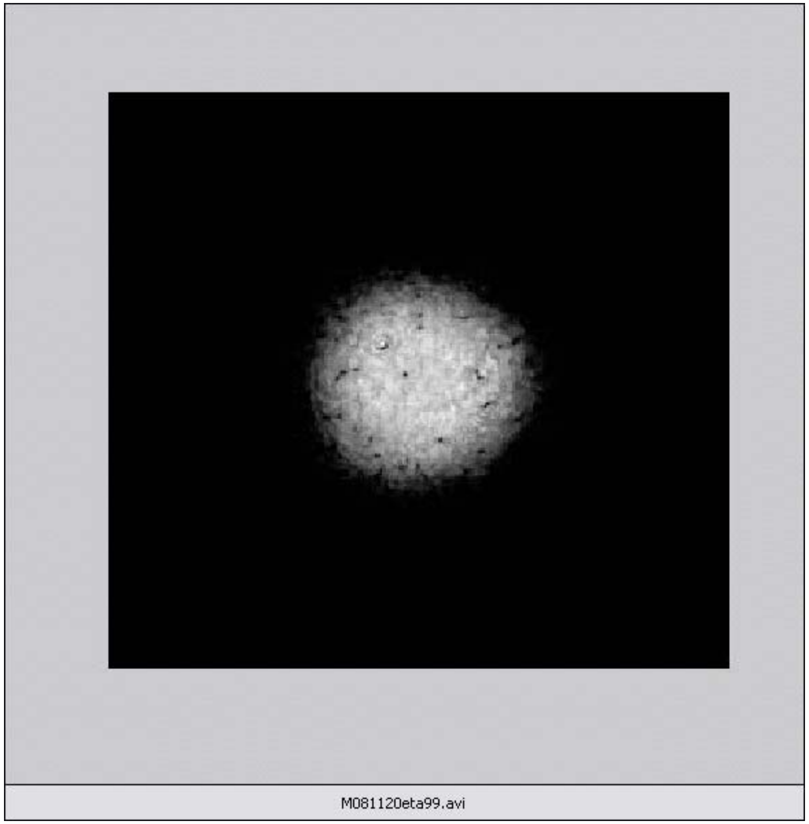
Simulation results

Even when the barrier height is too low to poke a hole in the BEC, the barrier preferentially displaces atoms from the center. The vortex core is pulled to the center to displace the least number of atoms.

Simulation movies



2π/3 relative phases (ideal case)



faster formation, with non-ideal phases (note “turbulence vortices”)

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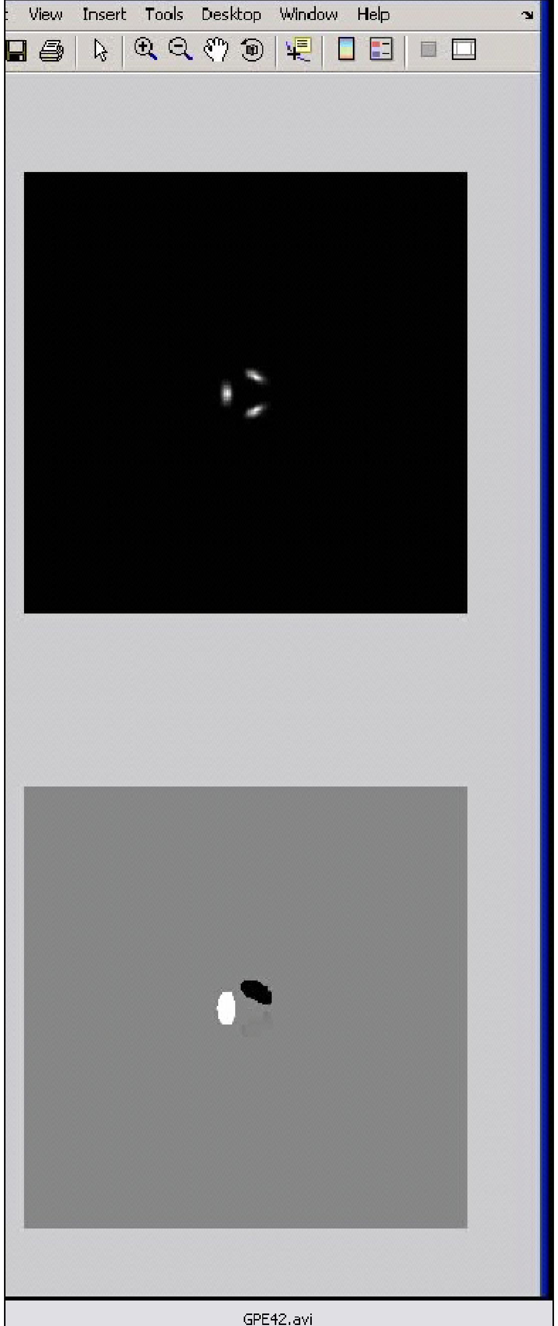
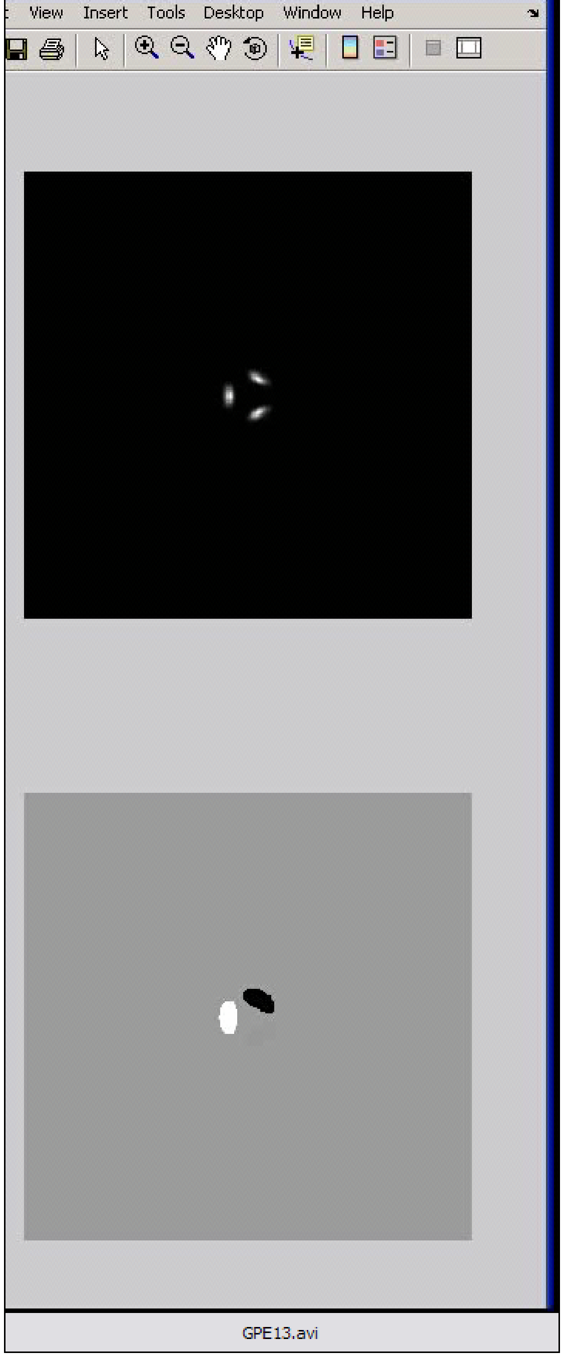


0,2π/3,4π/3
phase split,

5.0 s BEC growth

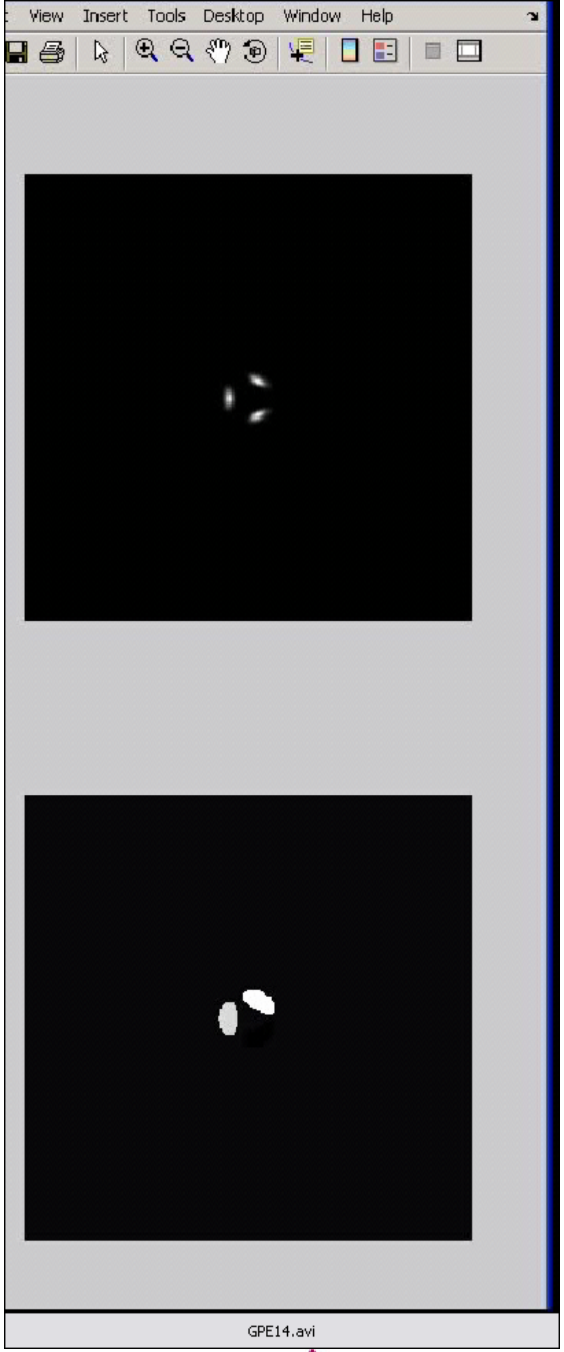
0,2π/3,4π/3
phase split,

1.0 s BEC growth



0,2π/3,(0.8)*4π/3 phase split,

1.0 s BEC growth



0,2π/3,(0.6)*4π/3 phase split,

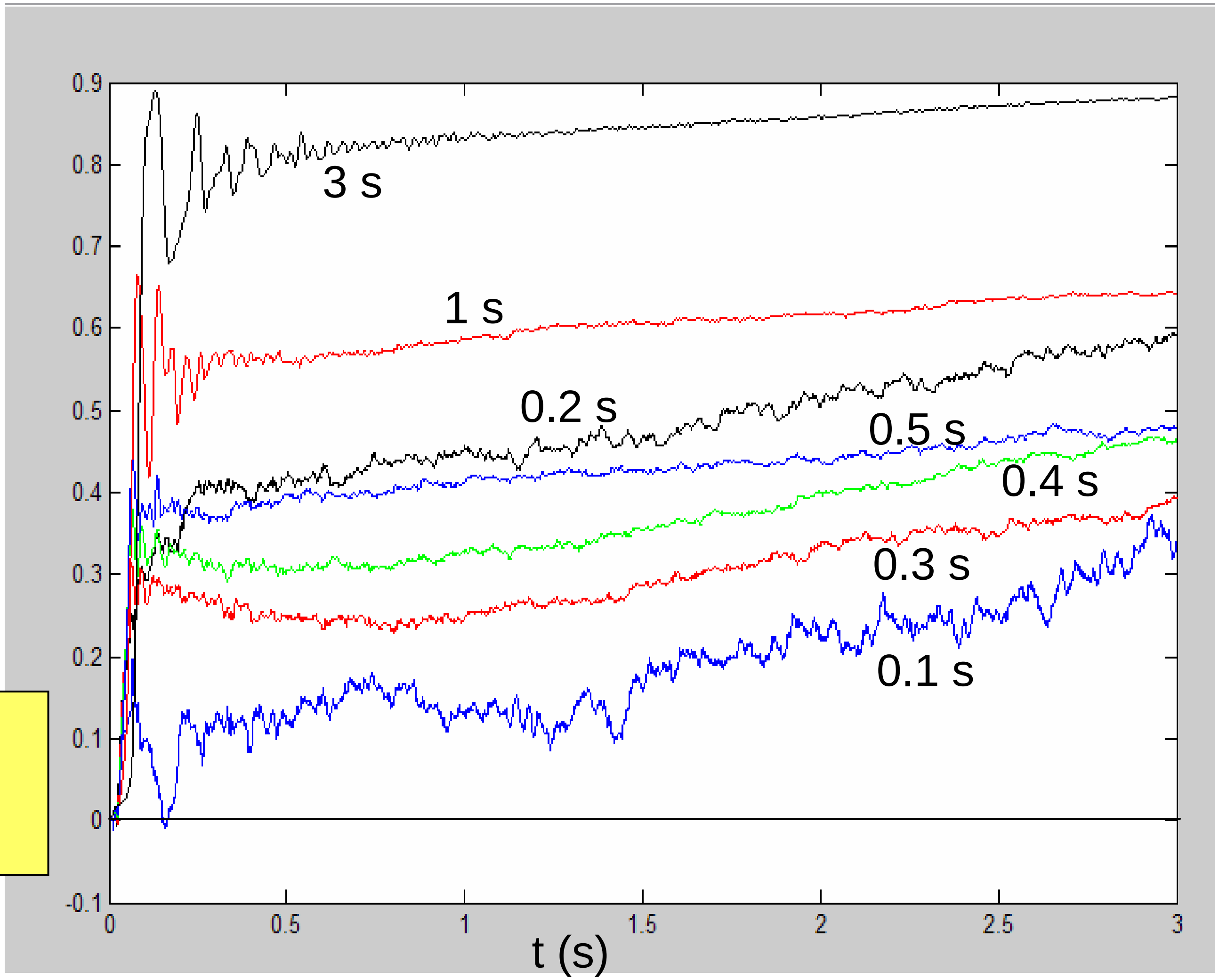
1.0 s BEC growth

Angular momentum

Time dependence of angular momentum per atom, varying time to increase a_s.
3 seconds of dynamics for each case.

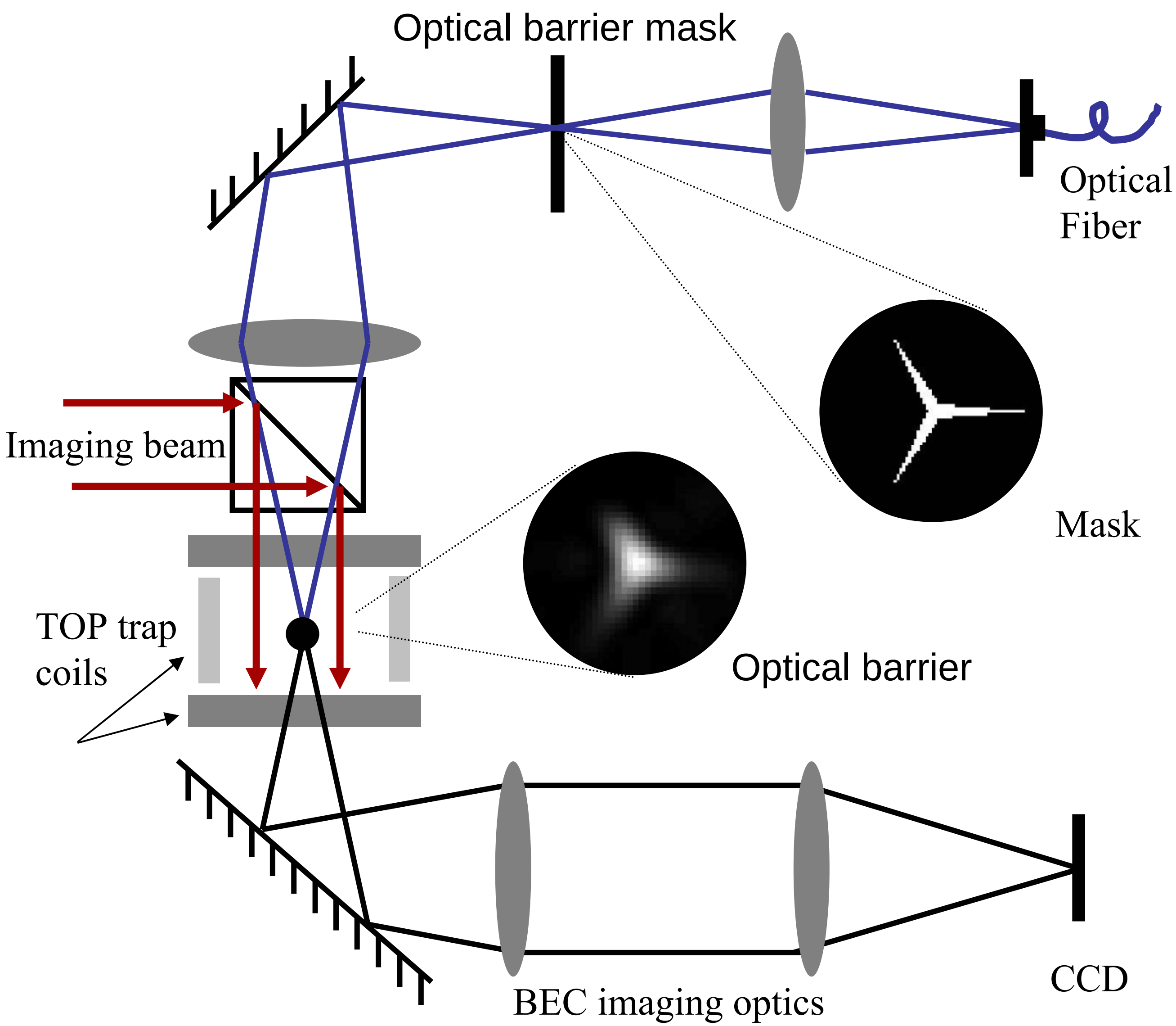
$$\frac{1}{N\hbar}\left\langle \hat{L}_z \right\rangle$$

$$\hat{L}_z = -i\hbar\left[x\frac{\partial}{\partial y} - y\frac{\partial}{\partial x}\right]$$



Slower = more angular momentum, and fewer "turbulence vortices".

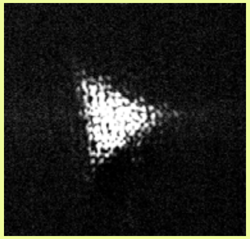
Experiment: Optical Barrier and BEC imaging



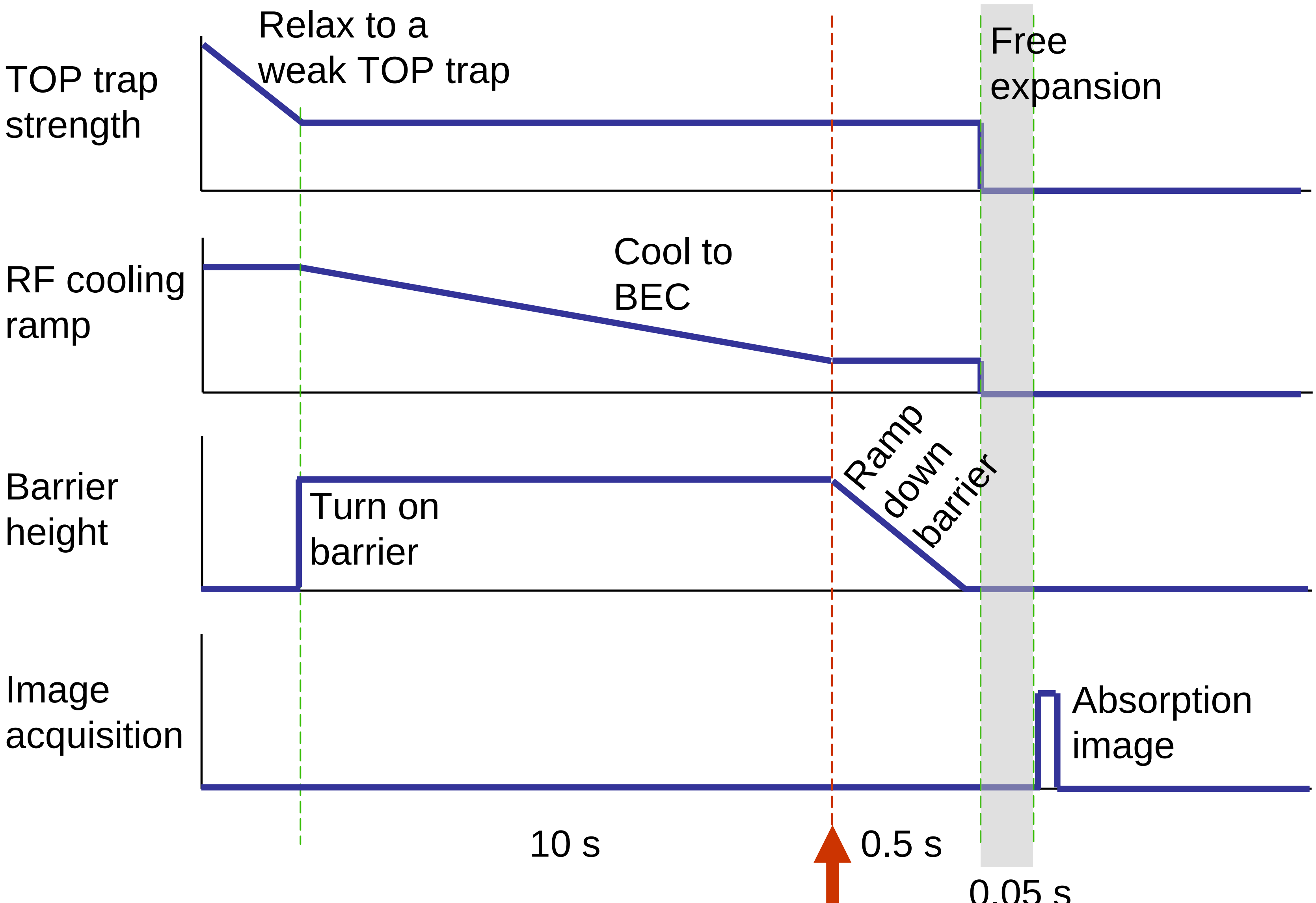
Maskless Lithography Tool
Prof. Tom Milster
College of Optical Sciences

(1) **Direct Imaging**
-Chrome transmission mask

(2) **Computer-Generated Hologram**
-Phase holograms etched from photoresist



Experiment sequence



Final state of BEC: depends on Barrier Height

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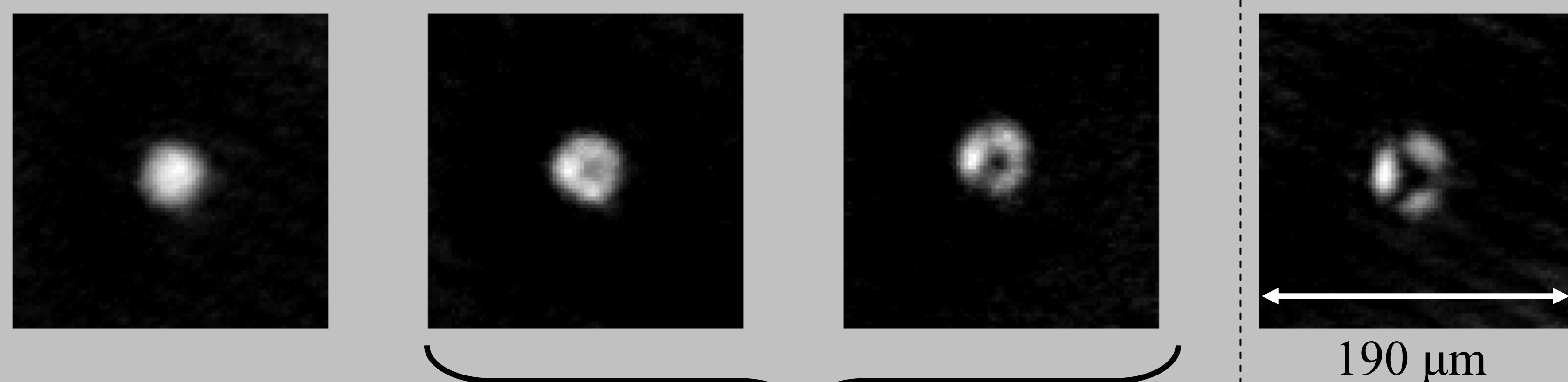
Condensation in the presence of the barriers

Experimental data: In-trap, phase contrast images of fully formed BECs.

Increasing power in the optical beam



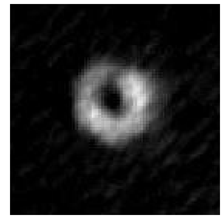
No Barriers.
TF radius ~ 30 μm

Ramp down medium-power barriers: **look for vortices due to BEC growth**

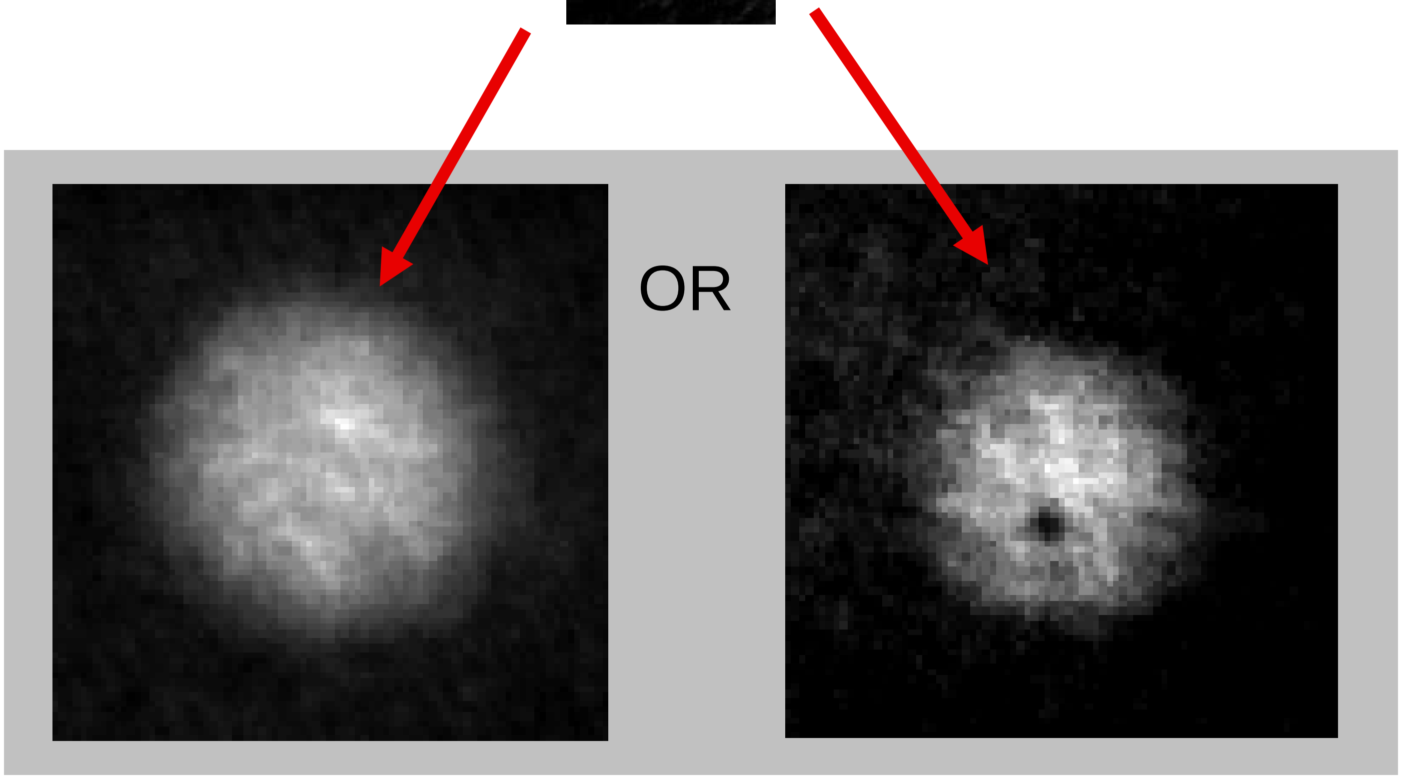
Ramp down high-power barriers: **look for vortices due to ramp-down**

Barrier beam

Experimental Results

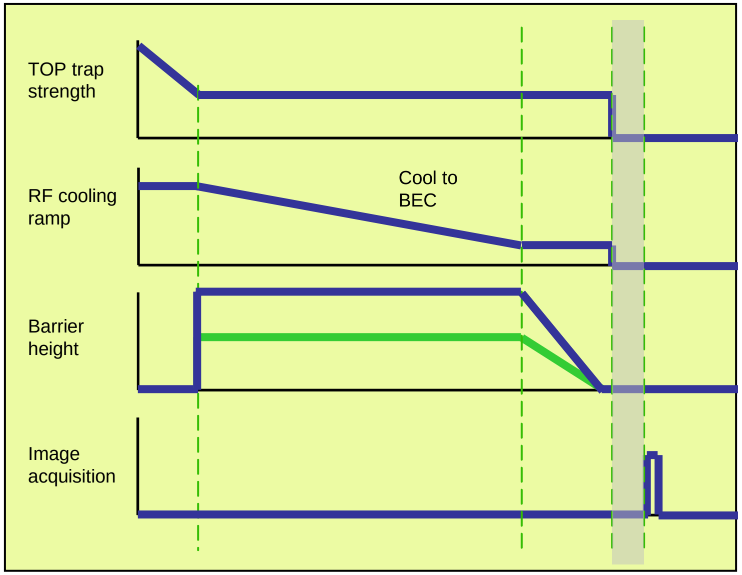


In-trap, phase-contrast image
(with barrier on)



Absorption images after ballistic expansion

Results summary



Experimental conditions

- 10 second final RF ramp to create BEC.
- Medium-intensity optical barrier (a final merged BEC).
- 100-500 ms ramp down of optical barrier

Results

Observation of at least one vortex core: ~40%

>25%: **turbulence, BEC growth rate is probably important**

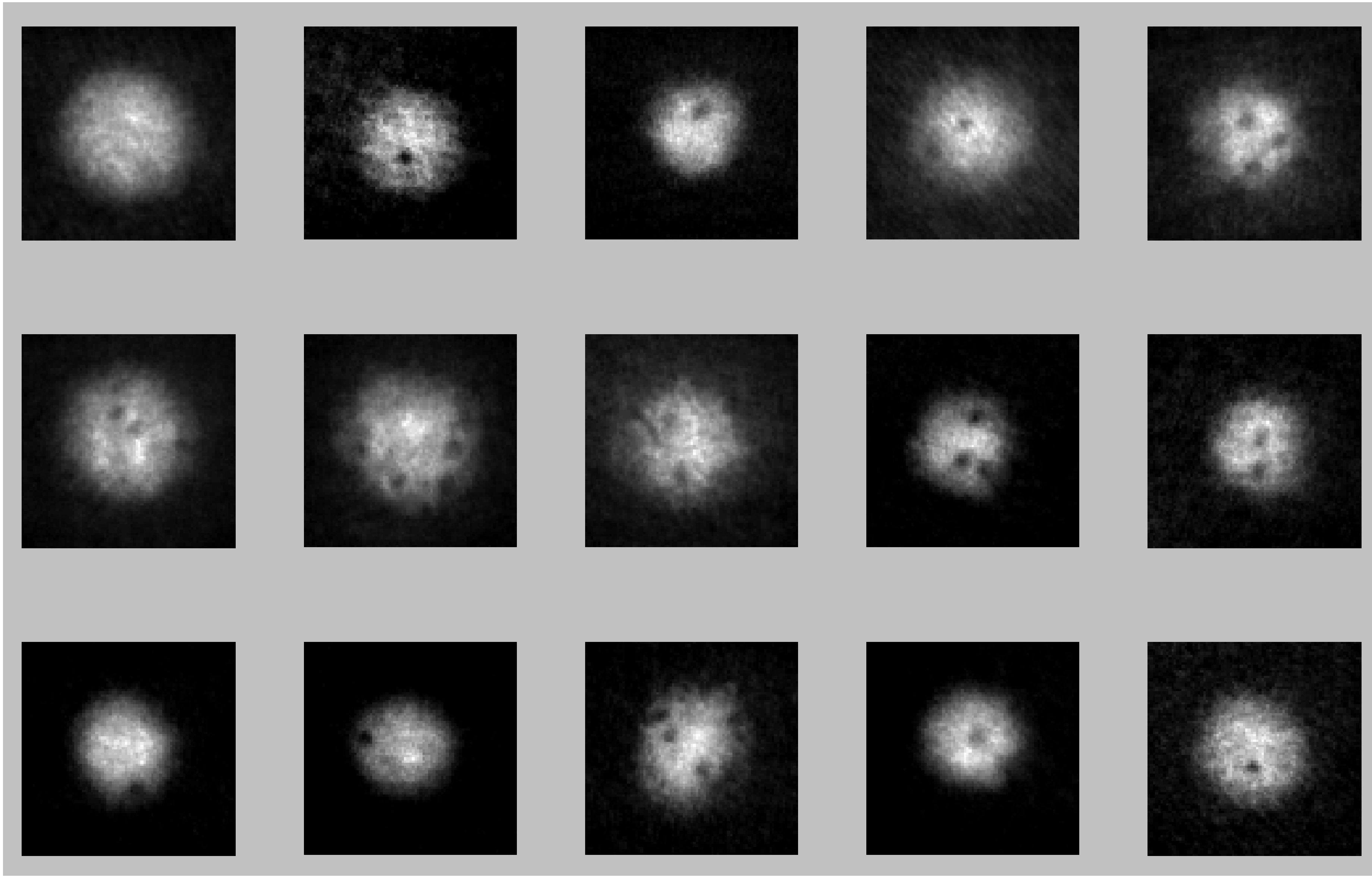
Add up to 1 s. before barrier ramp down, vortex observation probability drops to 0%.

Vortices form during BEC growth, not during barrier ramp

***Instead*, use high-intensity barriers so that 3 final BECs form:**

- up to **60%** probability of vortex observation
- **Vortices form during ramp**
- Vortex observation probability unaffected by extra time before ramp down
- multiple vortices often seen
- faster ramp = more vortex cores
- short (<100 ms) vortex lifetime

Image Gallery



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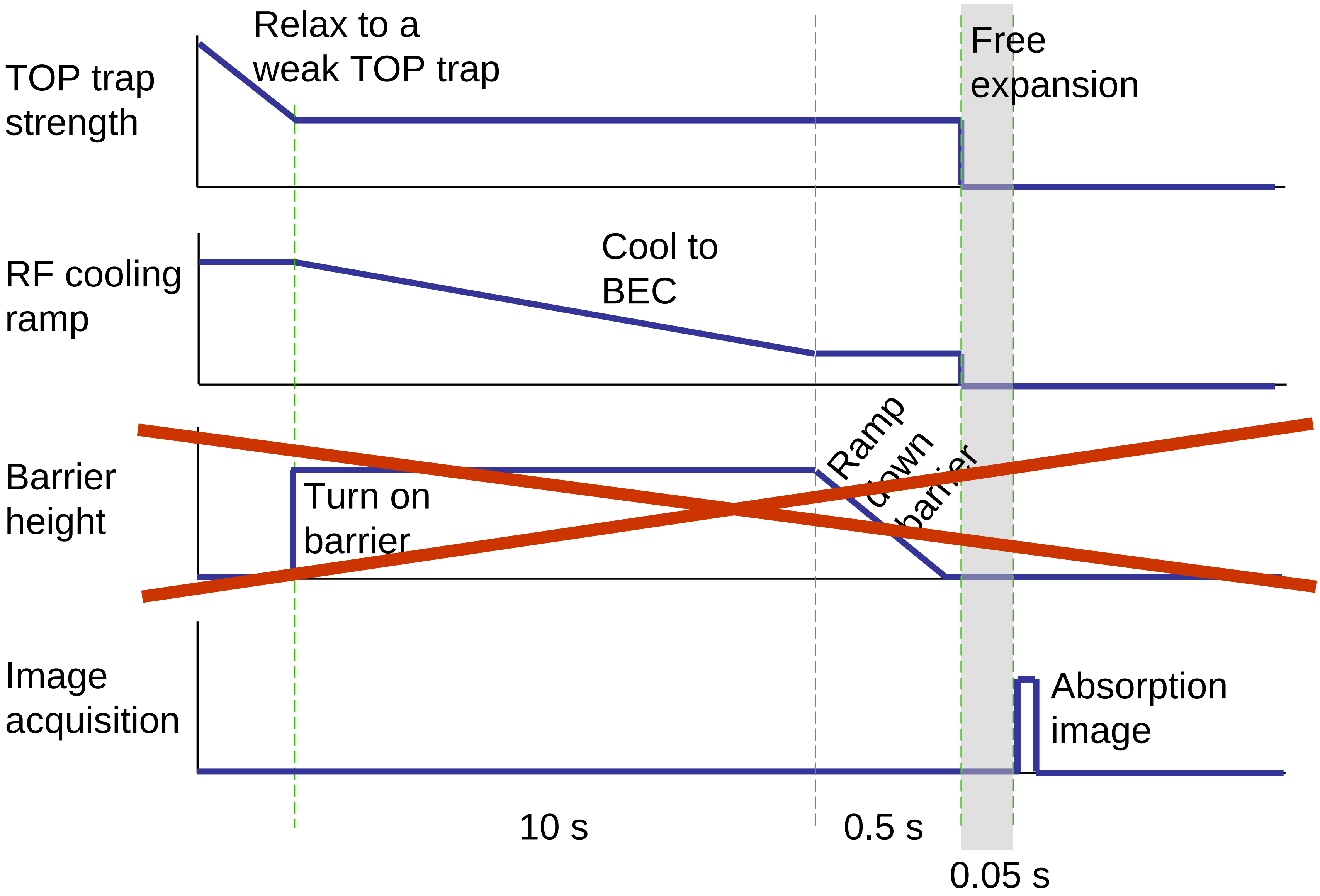
A more basic experiment sequence



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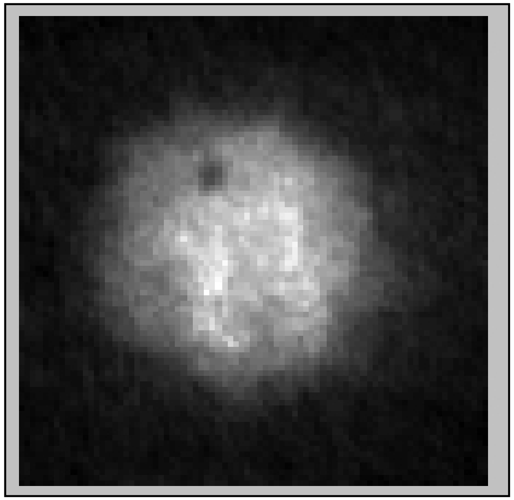
Spontaneous Formation of Vortices by Evaporative Cooling



A single vortex observed **up to 10%** of the time, just by evaporative cooling in 3D trap (optical barrier beam is absent)!

Spontaneous symmetry breaking in a temperature quench? Proposals by Kibble, Zurek for CM systems and BEC, models for the dynamics of the early universe.

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

Spontaneous formation of vortices in BEC during evaporative cooling, also predicted by:

Marshal, New, Burnett, and Choi, PRA 59, 2085 (1999),
Drummond and Corney, PRA 60, R2661 (1999)

Conclusions

• **When BECs merge and interfere, turbulence and vortices may result. Can happen by intentionally merging BECs, or by condensing in a bumpy potential.**

• Vortices may be used as tools for examining fragmentation, phase dynamics.

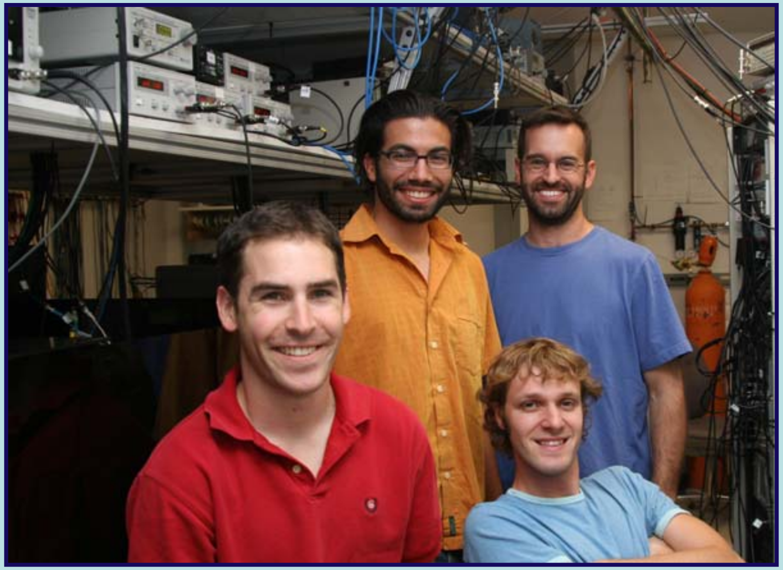
• Further work may aid in studying superfluids in more "dirty" systems (*eg.*, random defects in superconducting systems), and in disordered systems.

• Direct phase imprinting of a split BEC might be used to controllably create vortex states.

• Vortices can spontaneously form during evaporative cooling. Spontaneous symmetry breaking during a temperature quench?

Next Steps:

• Vary time scales for BEC growth in both smooth and bumpy potentials
• Quasi-2D geometry (optical trap)
• Add more roughness to potential well
• Better examination of early stages of BEC formation?



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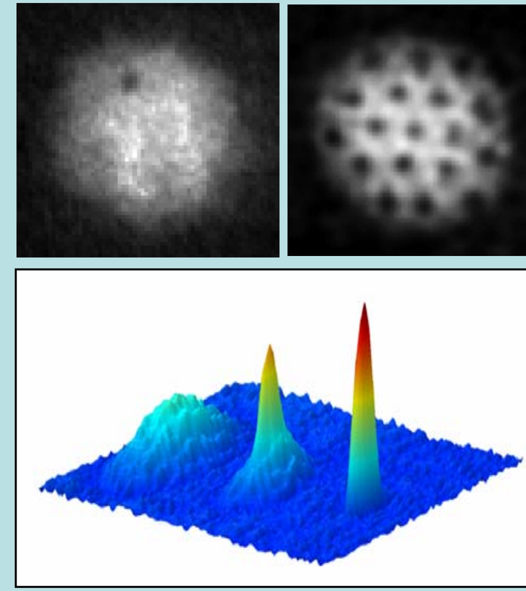

… continuing an old Tucson tradition of vortex research