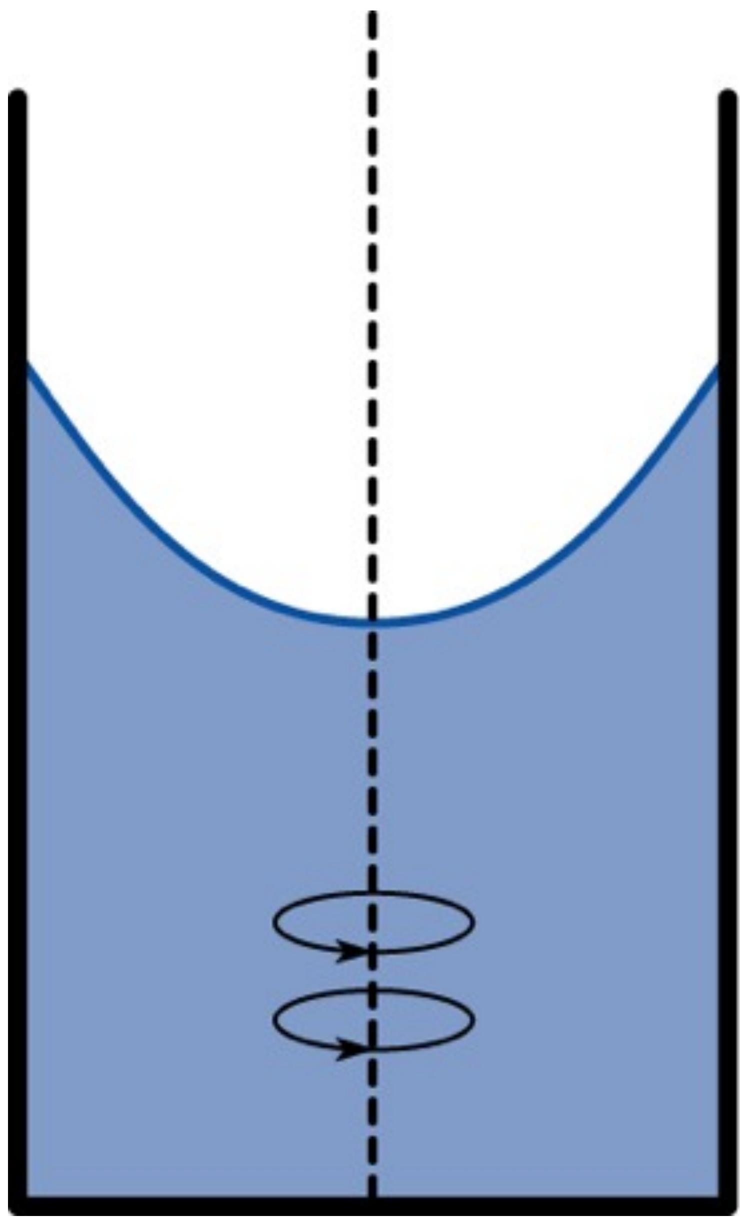
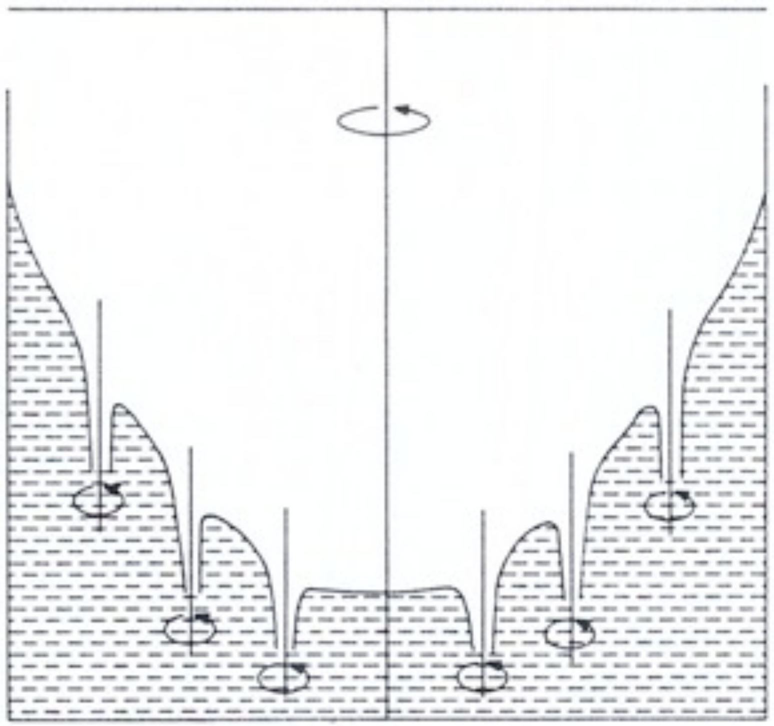
Rotating a Classical Fluid



Surface of the fluid is shaped like a parabola !

Rotating a Quantum Fluid

e.g. Rotating bucket experiment in He II

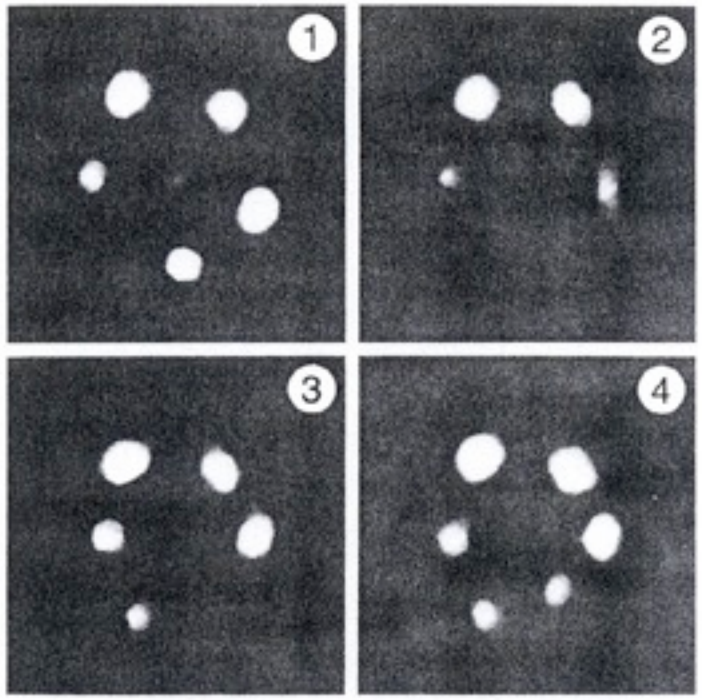


Below a critical angular velocity the quantum fluid remains in rest.

Above a critical angular velocity one or more singular lines appear in the fluid.

Vortices

The circulation around such singular lines is quantized.



These vortex lines can be detected via trapping of electrons on the vortex cores !

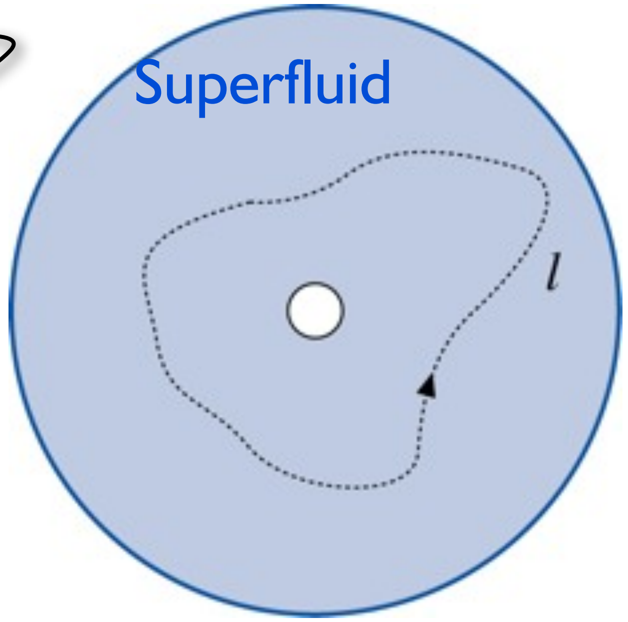
Yarmchuk and Packard (1982)

Quantization of Circulation

Definition of Circulation: $$\kappa = \int \mathbf{v} d\mathbf{r}$$

$$\mathbf{v} = \frac{h}{m} \nabla \theta(\mathbf{r})$$ Velocity field of the order parameter

$$\kappa = \frac{h}{m} \Delta\theta$$



Superfluid occupying a multiply connected region. Contour path ***l*** within the superfluid.

The order parameter has to be single valued !

$$\hookrightarrow \Delta\theta = n \cdot 2\pi$$

$$\kappa = n \cdot \frac{h}{m}$$

Circulation is quantized !

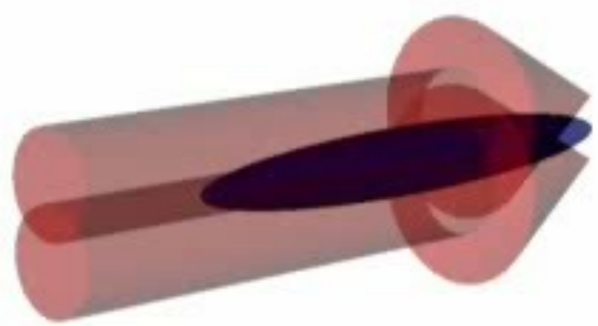
Stirring a Bose-Einstein Condensate

Magnetic trapping potential: $V(r) = \frac{1}{2} m(\omega_\rho^2 x^2 + \omega_\rho^2 y^2 + \omega_z^2 z^2)$

Use light beams to create a deformation of the potential that can be rotated !

$$V_{dip}(r) = \frac{1}{2} m\left(\varepsilon_X \omega_\rho^2 X^2 + \varepsilon_Y \omega_\rho^2 Y^2\right)$$

X,Y basis is rotated with an angular velocity Ω.



Hamiltonian in the co-rotating frame

$$H_{rot} = H - \Omega L_z$$

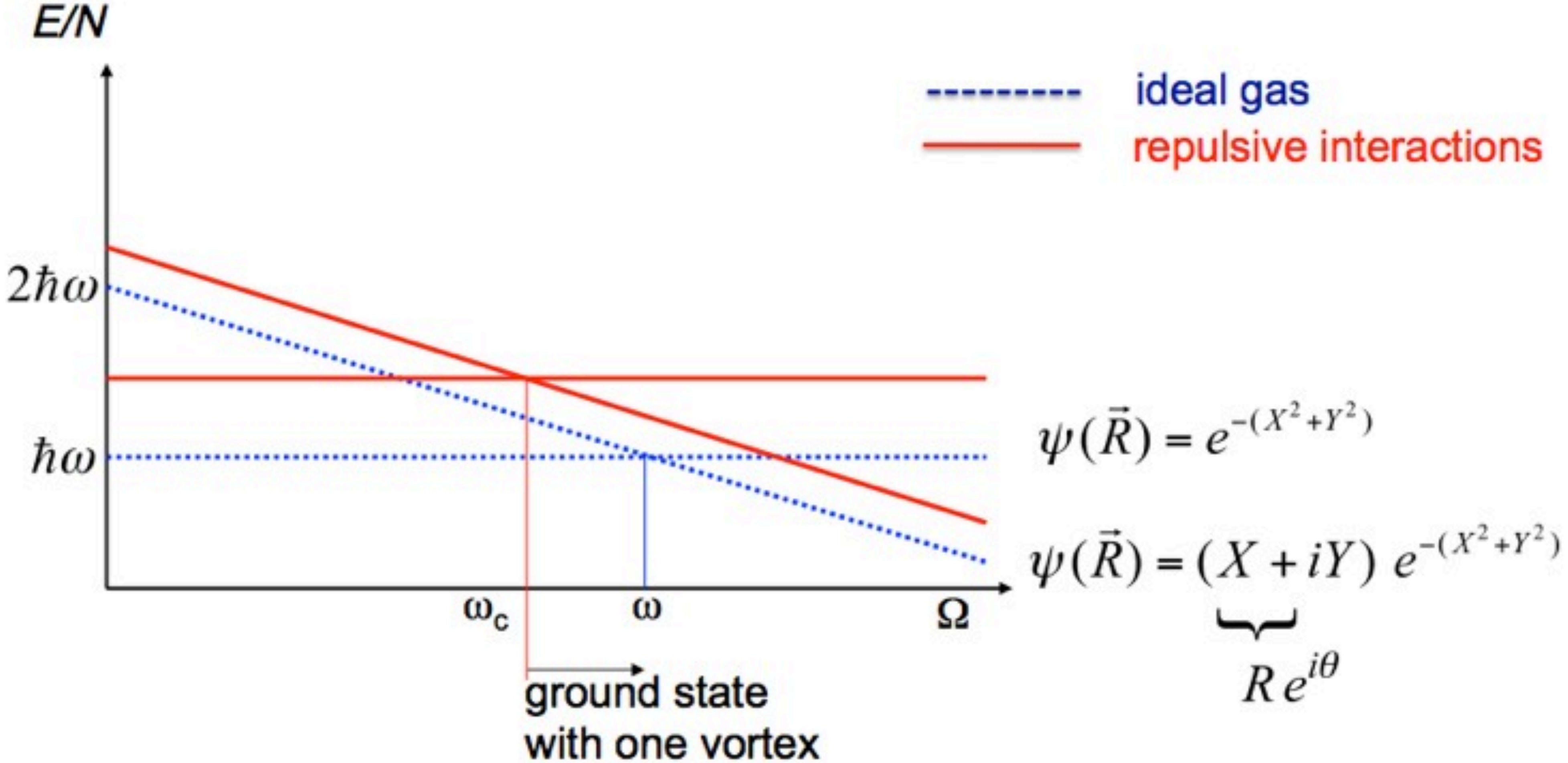
Vortex state raises energy

Vortex state lowers energy

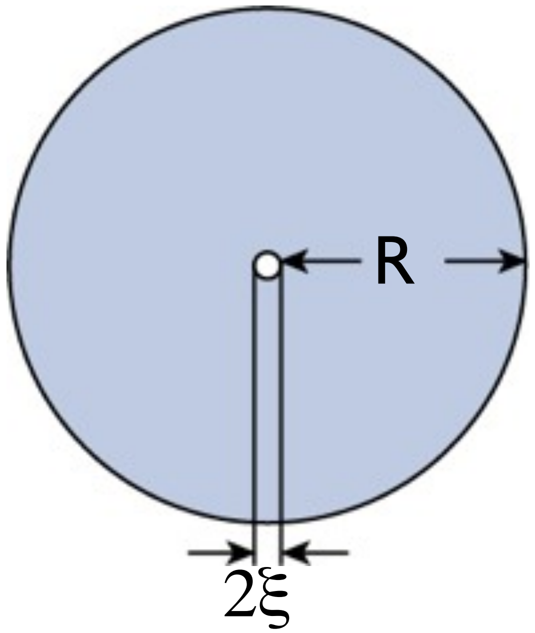
Vortices as a Ground State of the New Hamiltonian

Neglect for simplicity the term in ε

single-particle Hamiltonian in rotating frame: $H = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 r^2 - \Omega L_z$



Vortices in a Gaseous BEC

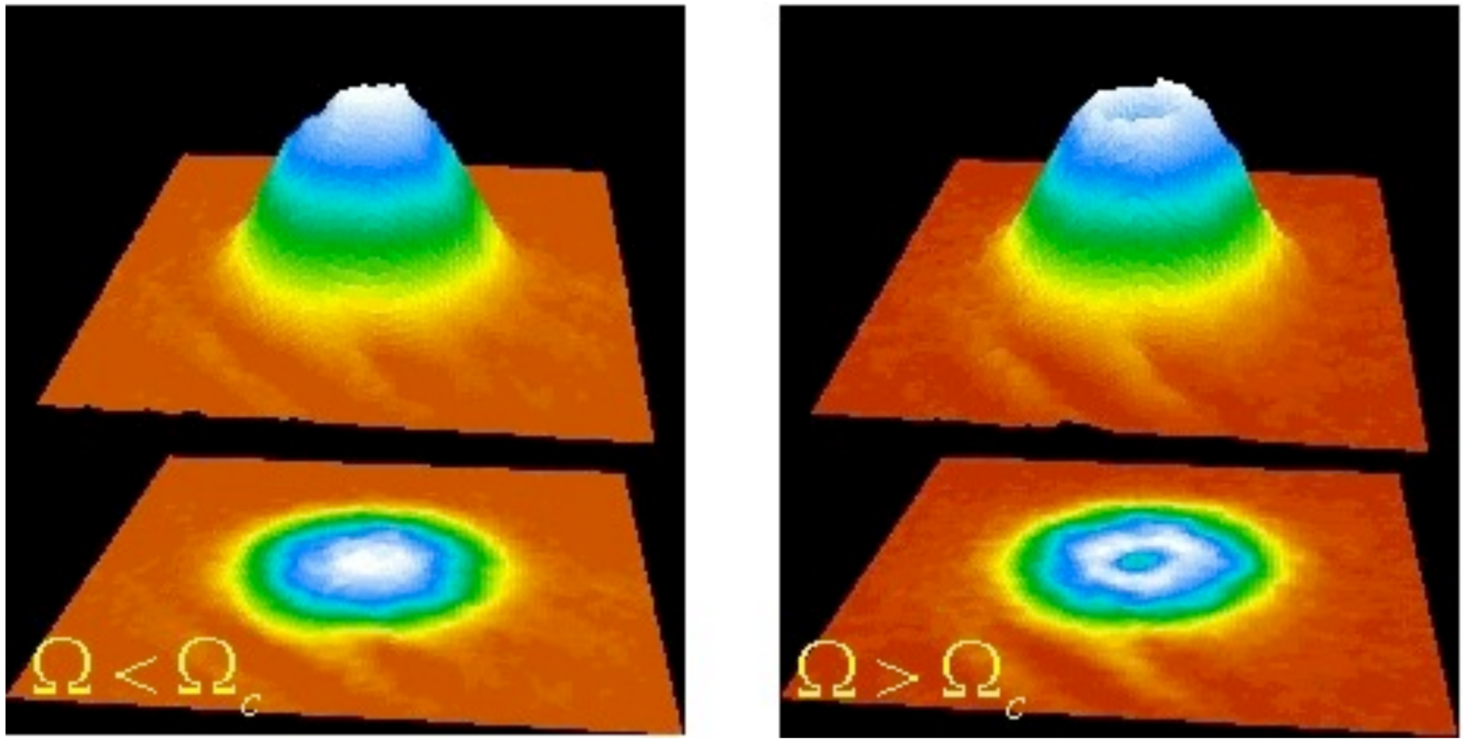


Vortex core size is given by the healing length:

$$\xi = \frac{1}{\sqrt{8\pi n a}} \approx 200\,\mathrm{nm}$$

Too small to be imaged directly in the trap !

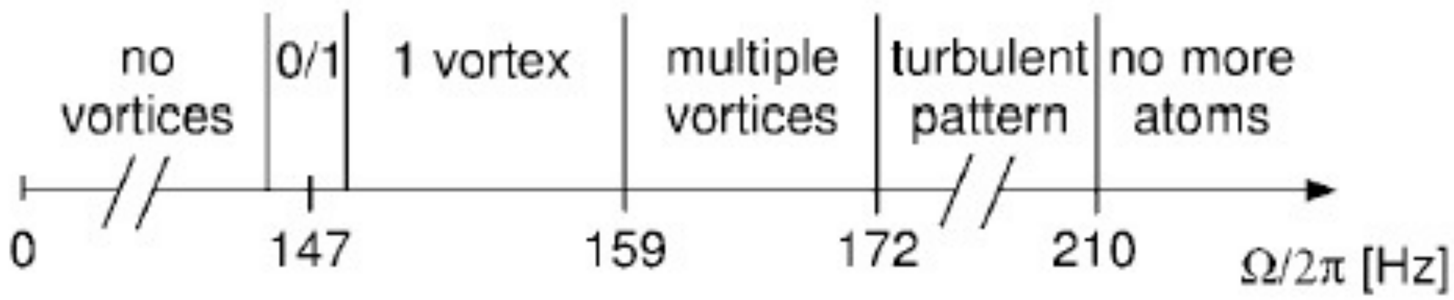
Solution: Use TOF expansion such that all dimensions are expanded by a factor $\sqrt{1+\omega_\rho^2 T^2}$



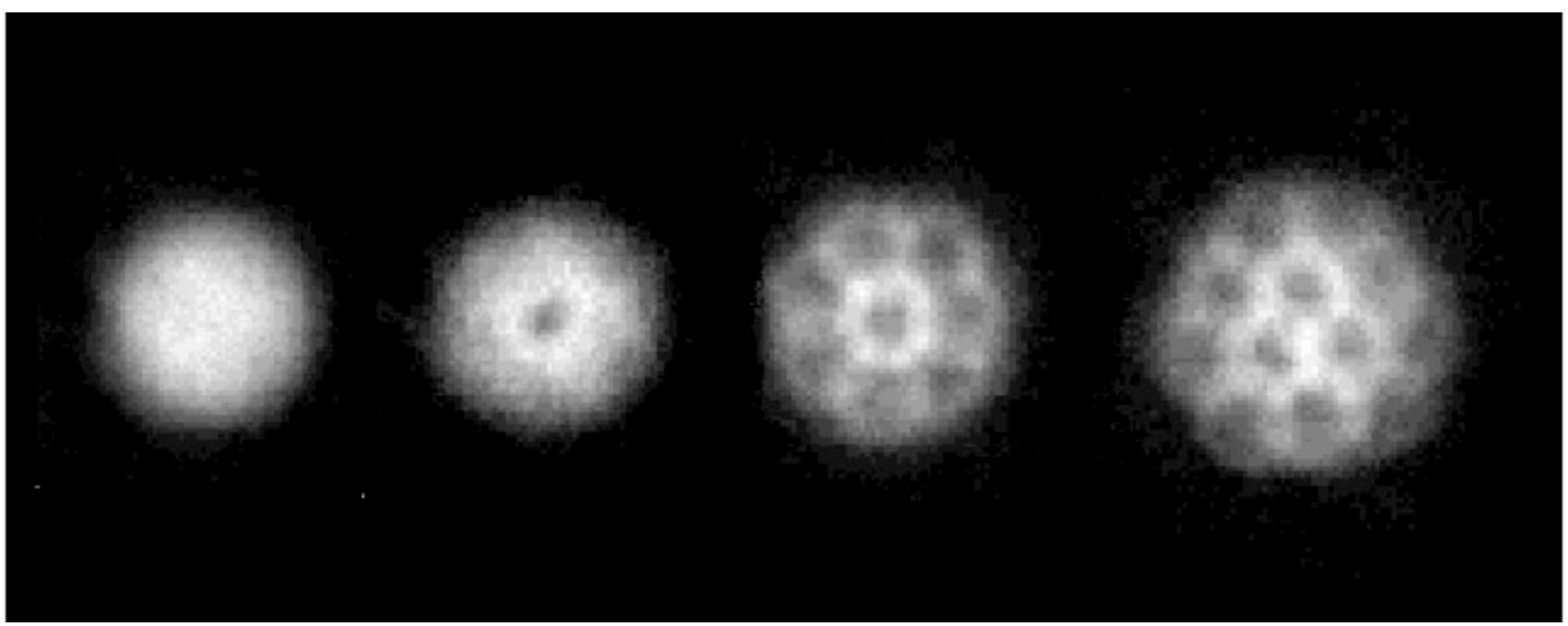
K. W. Madison et al. (2000)

Abrikosov Vortex Arrays (1)

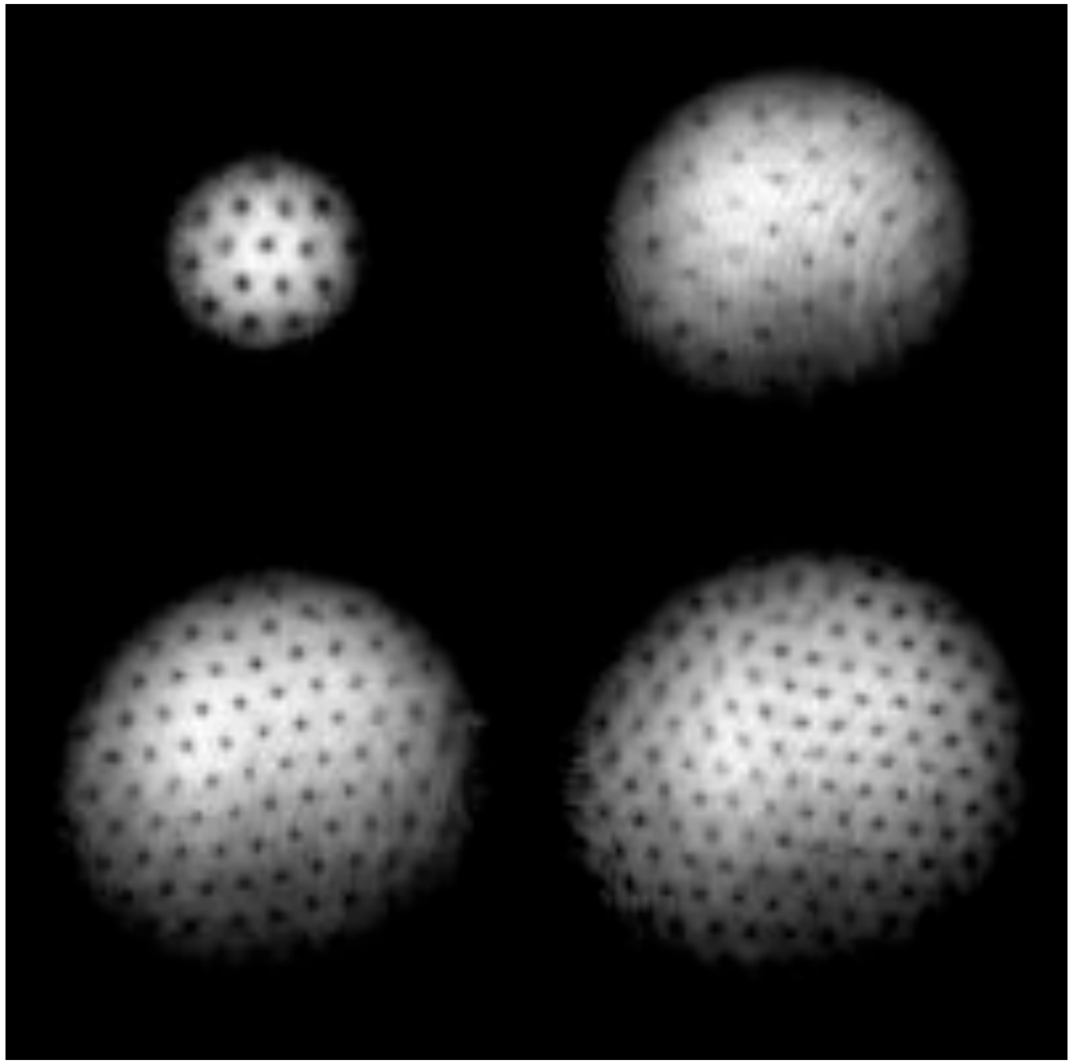
Phase diagram of vortex nucleation

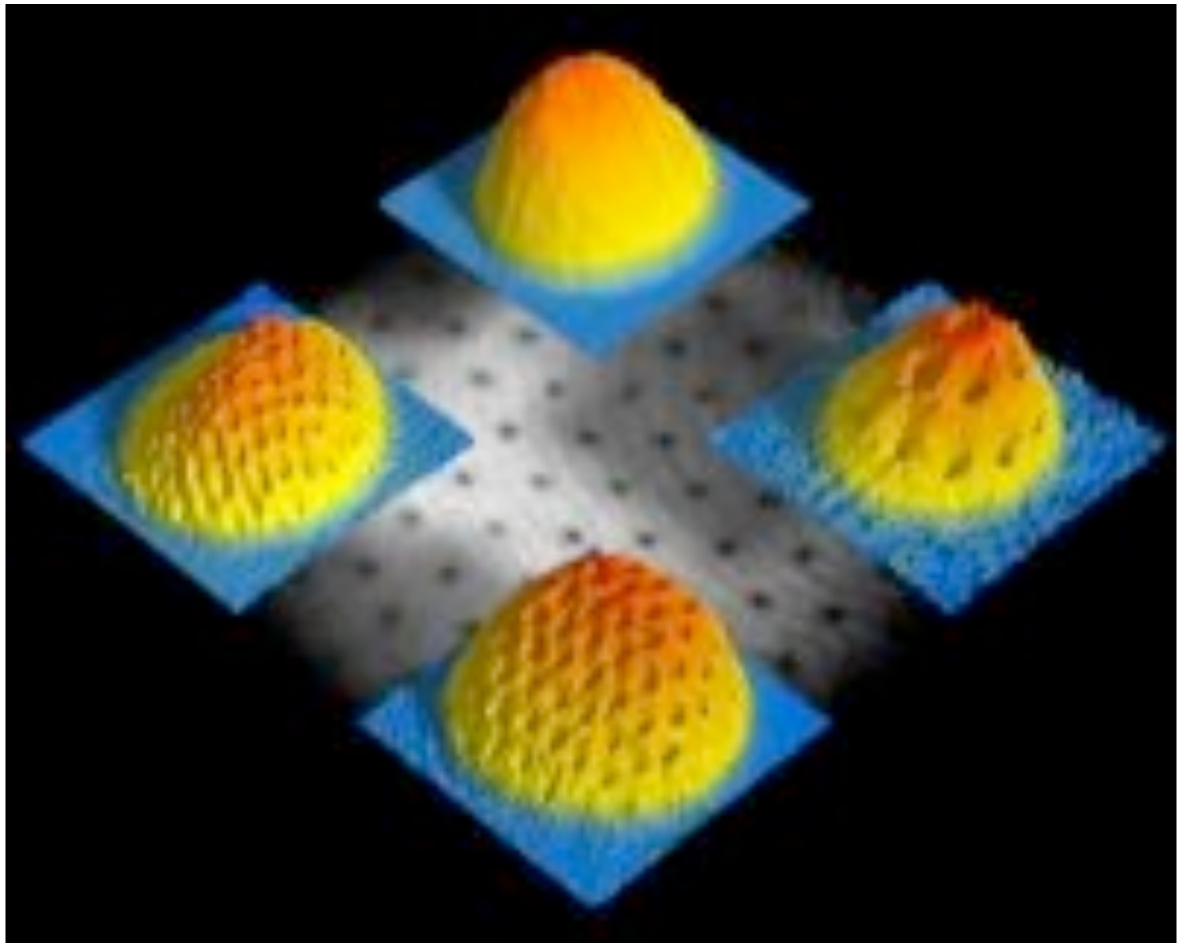


# of vortices: 0 1 8 12



Large Abrikosov Vortex Lattices

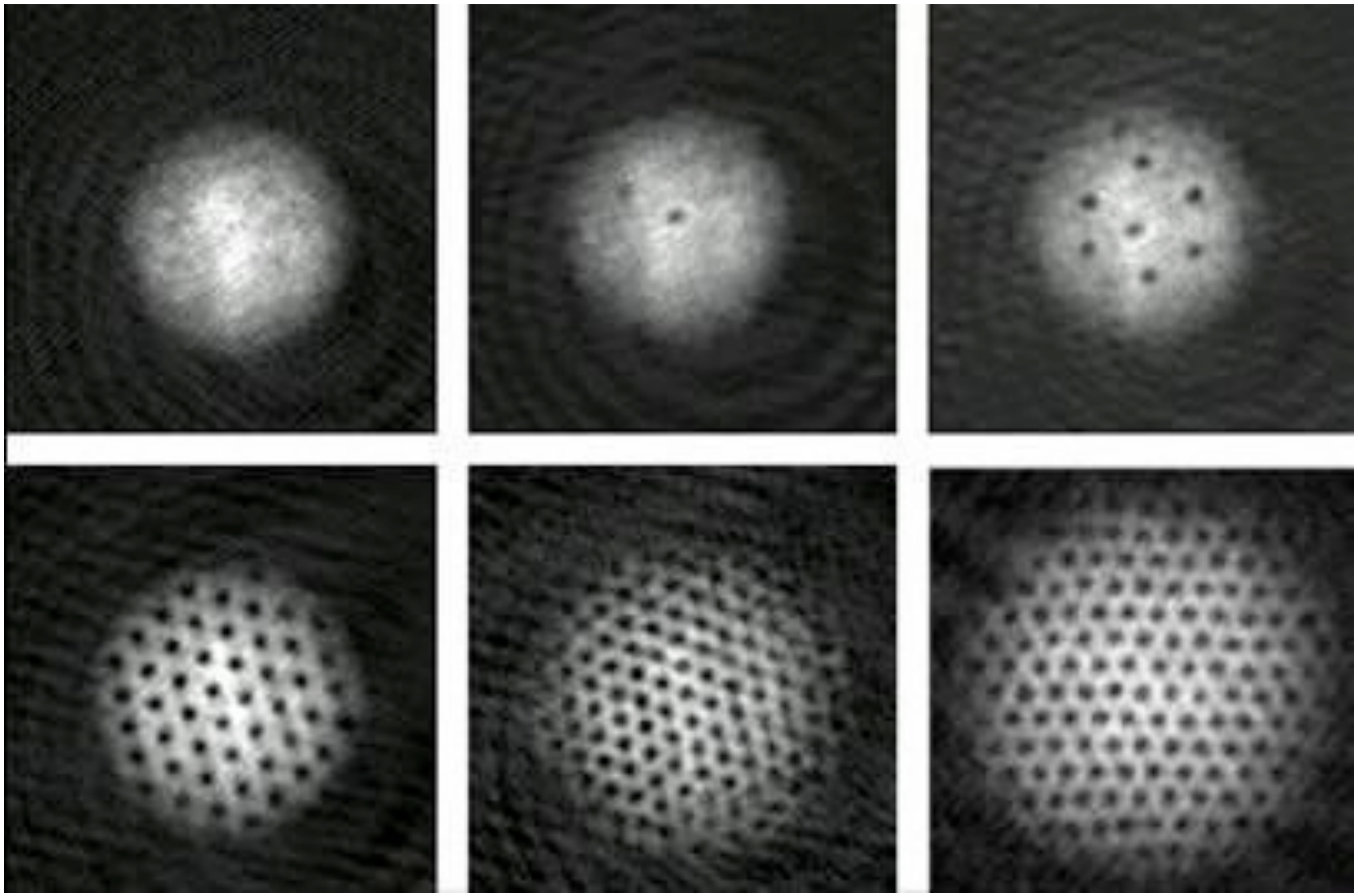




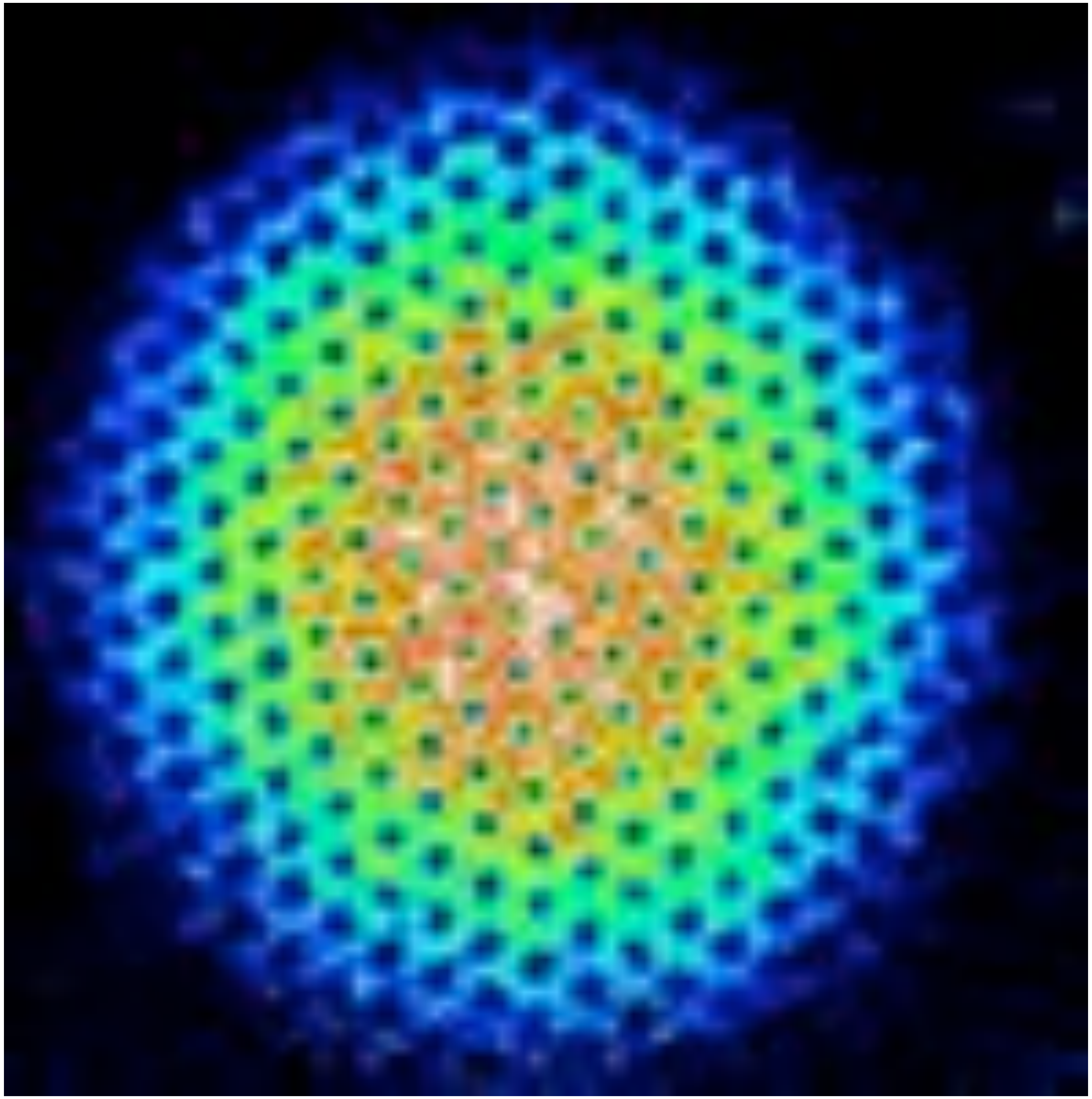
J. R. Abo-Shaeer et al. (2001)

Up to 150 vortices !

More Vortices



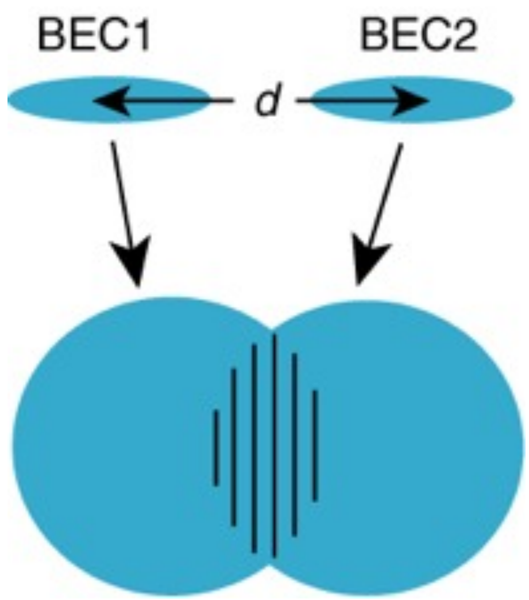
Even More...



Interference between two Bose-Einstein Condensates

Trapped
BECs

BECs after
expansion time t



$$\lambda = \frac{h}{m\Delta v} = \frac{ht}{md}$$

Interference between two Bose-Einstein Condensates

Trapped
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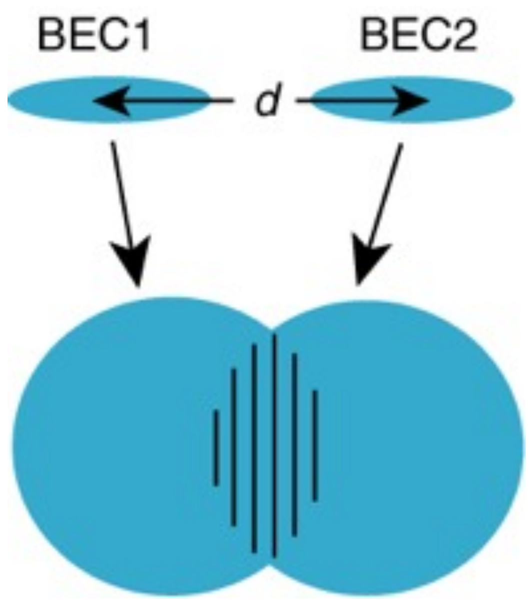
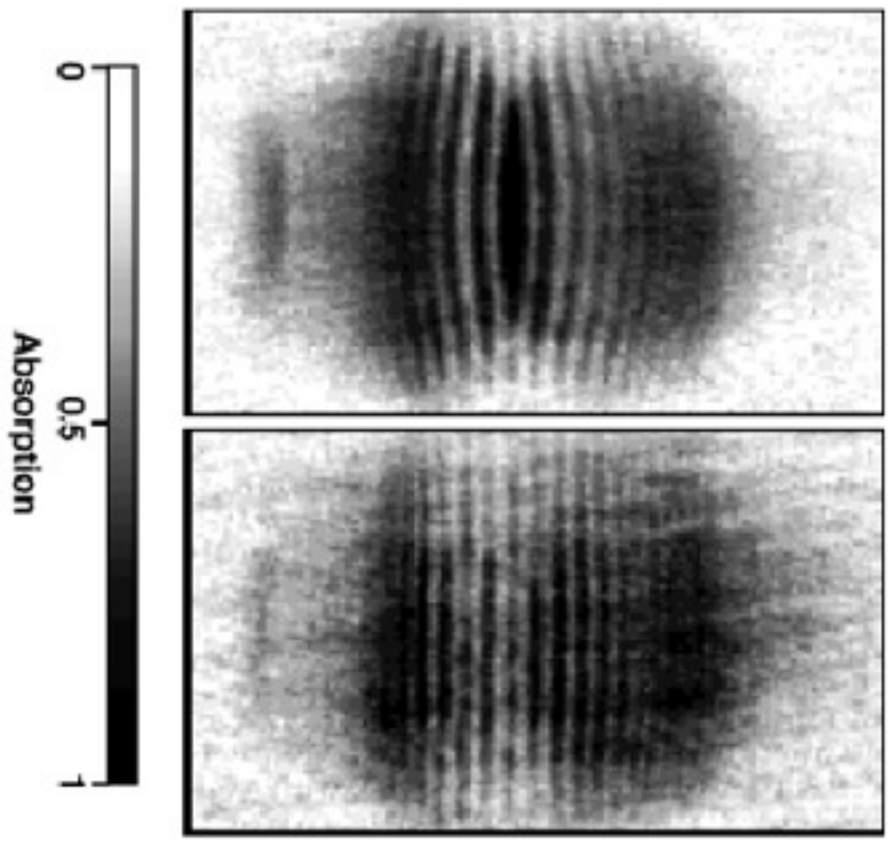
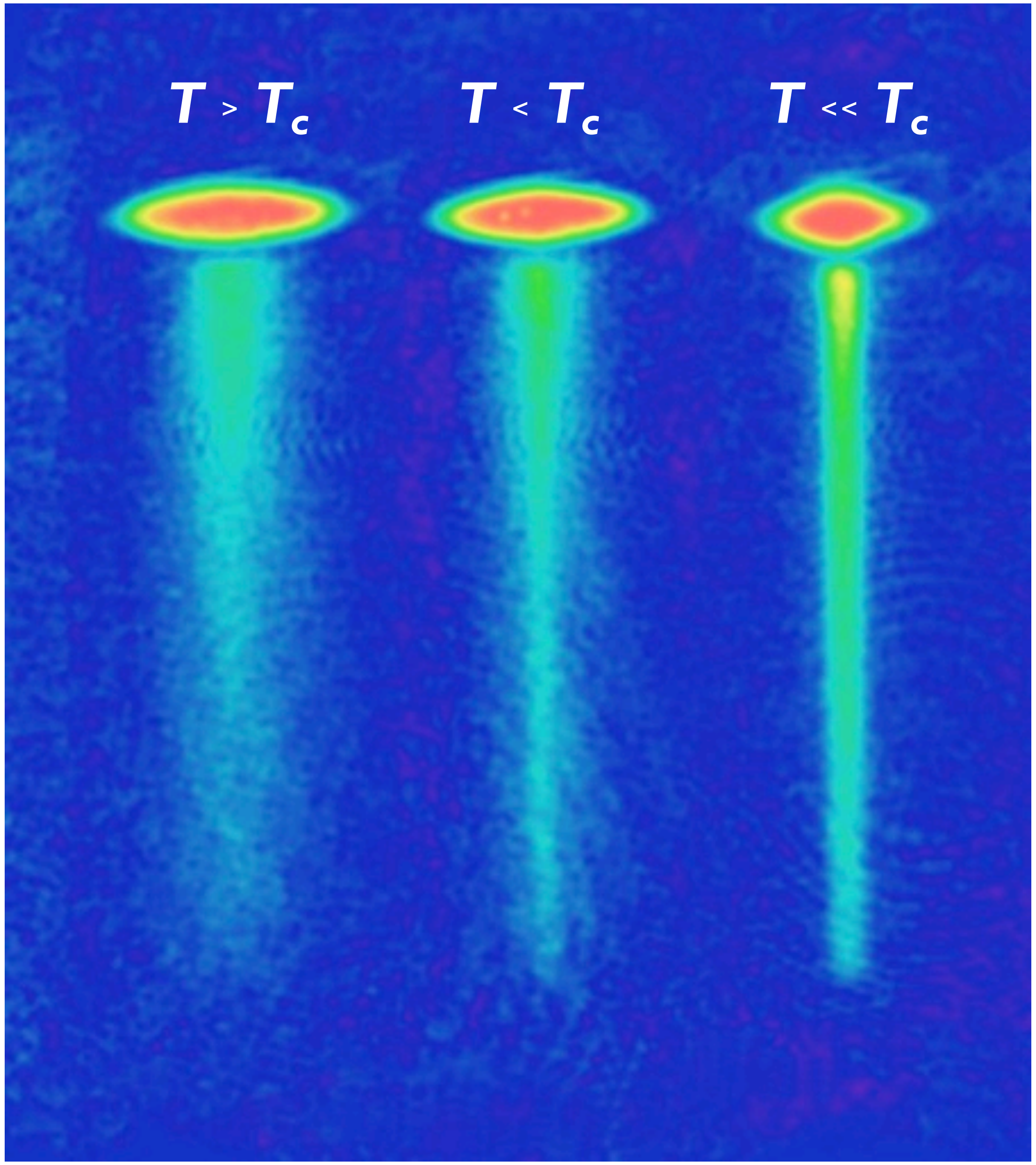


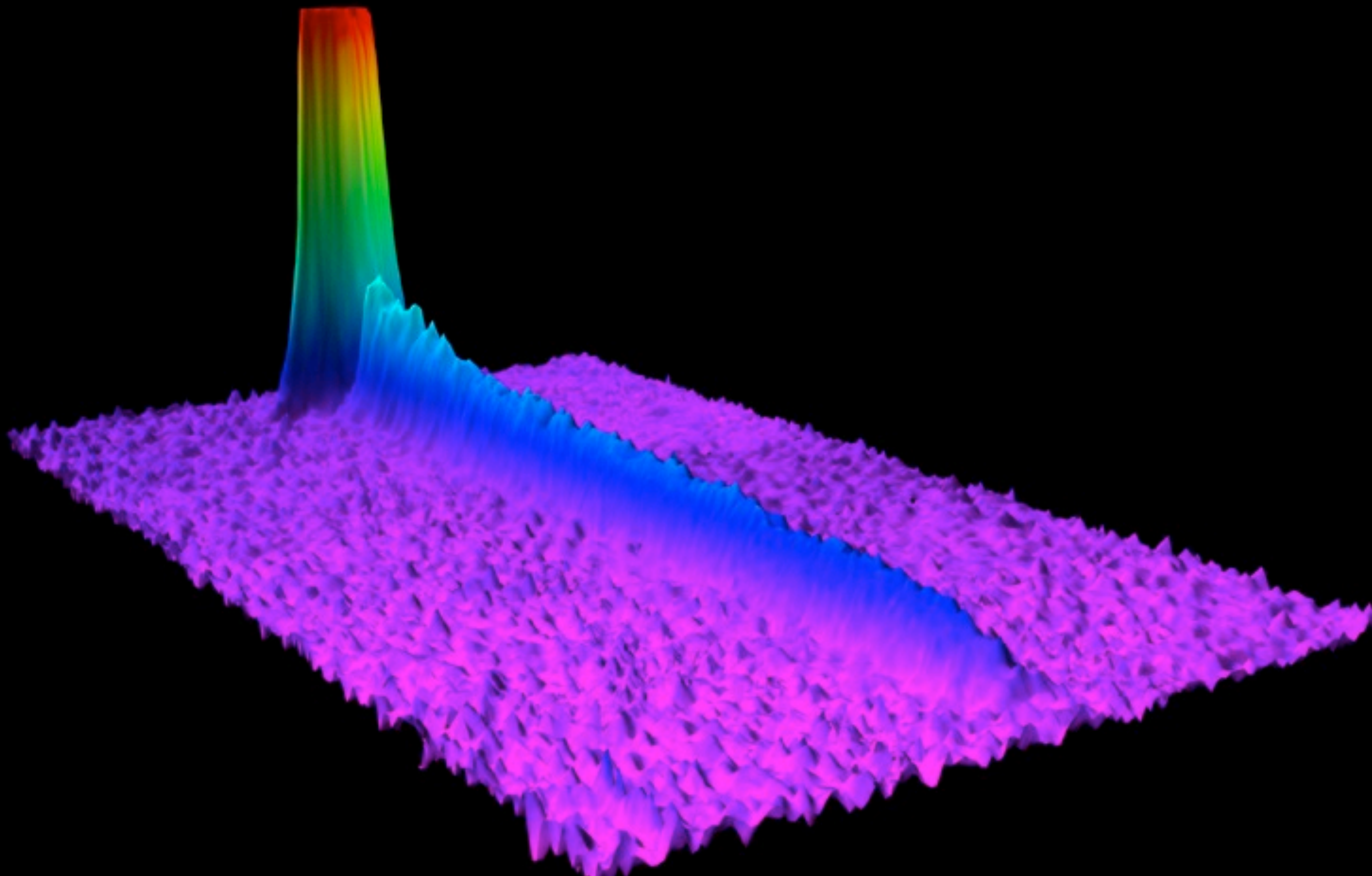
$$\lambda = \frac{h}{m\Delta v} = \frac{ht}{md}$$

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



Atomlaser am Phasenübergang





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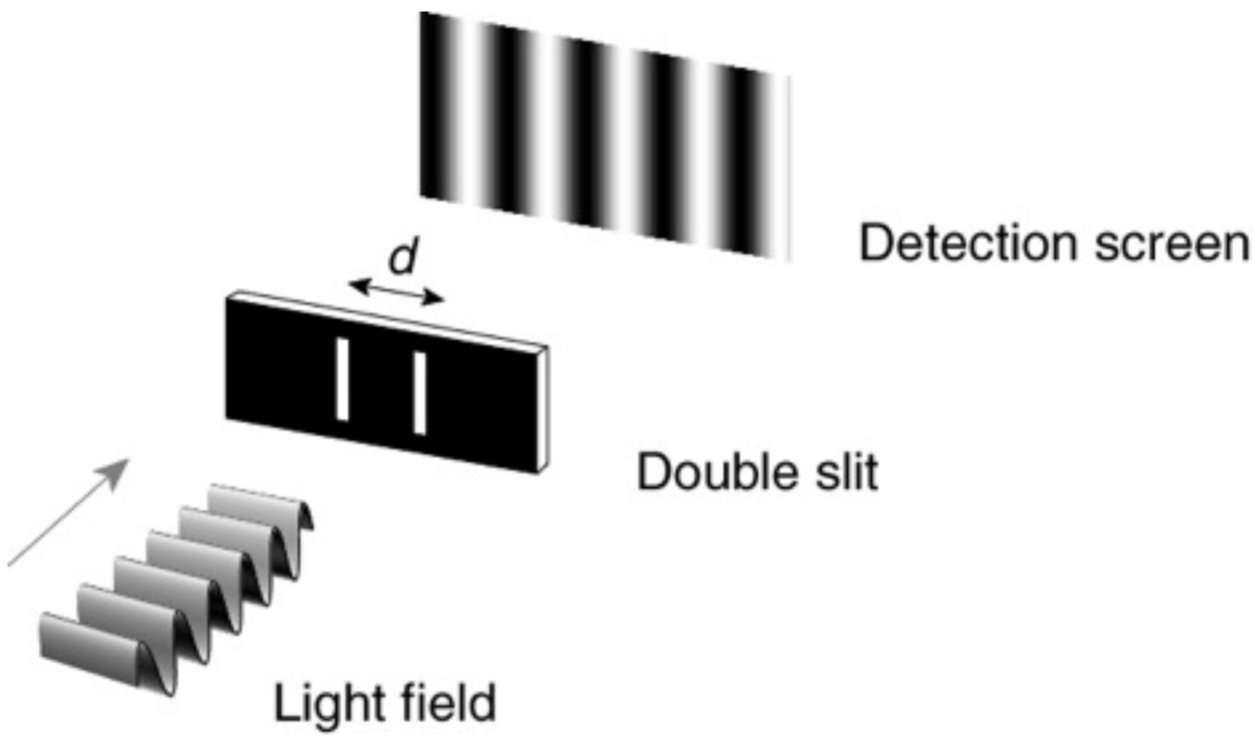
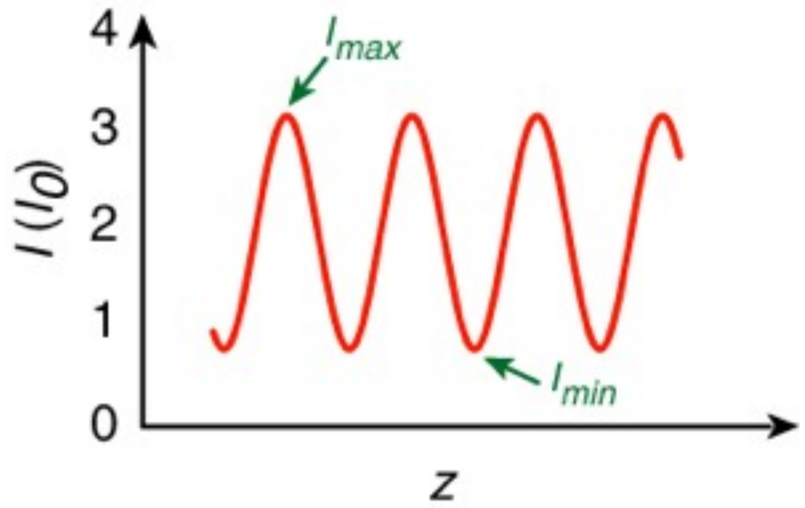
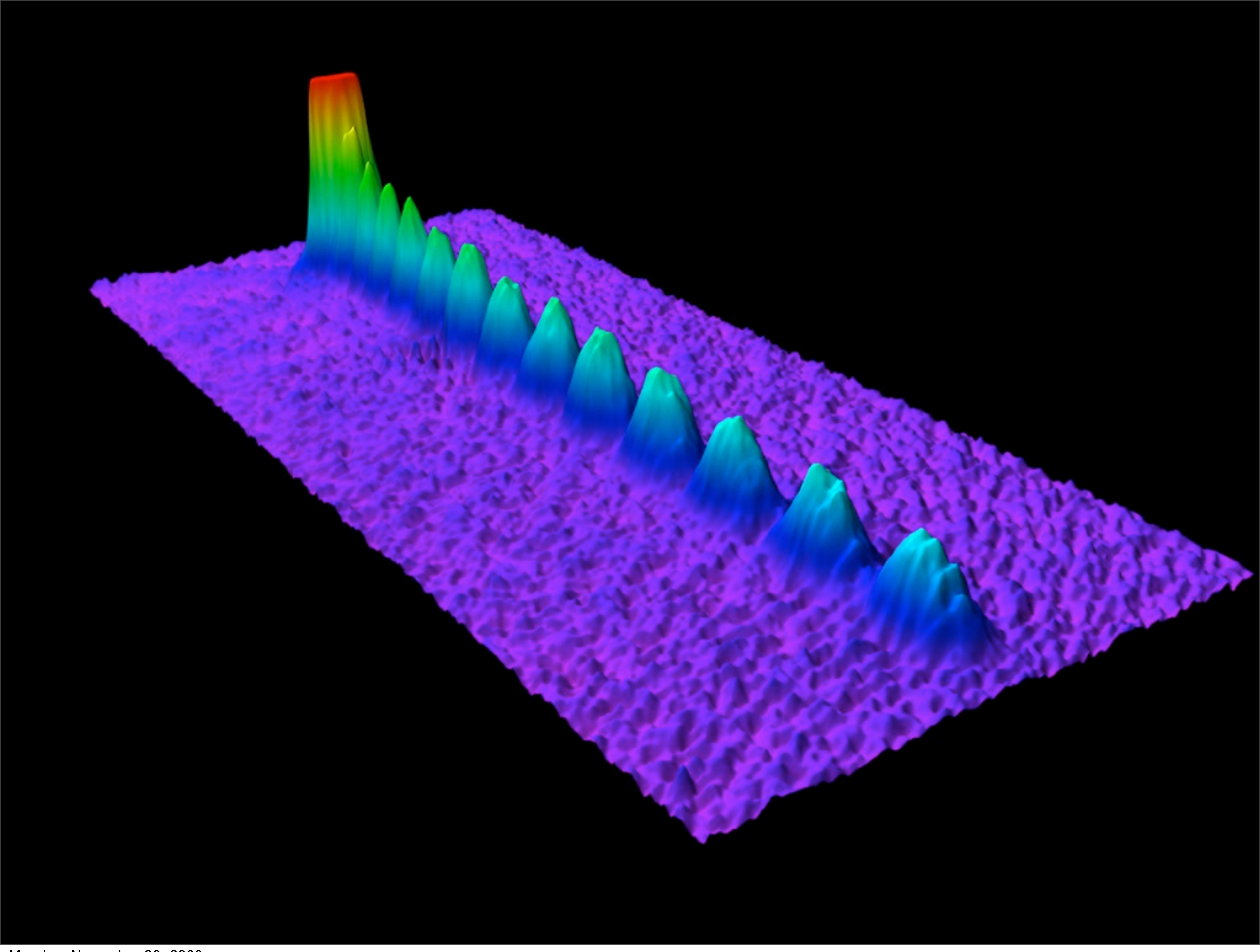
Doppelspaltexperiment mit zwei Atomlasern

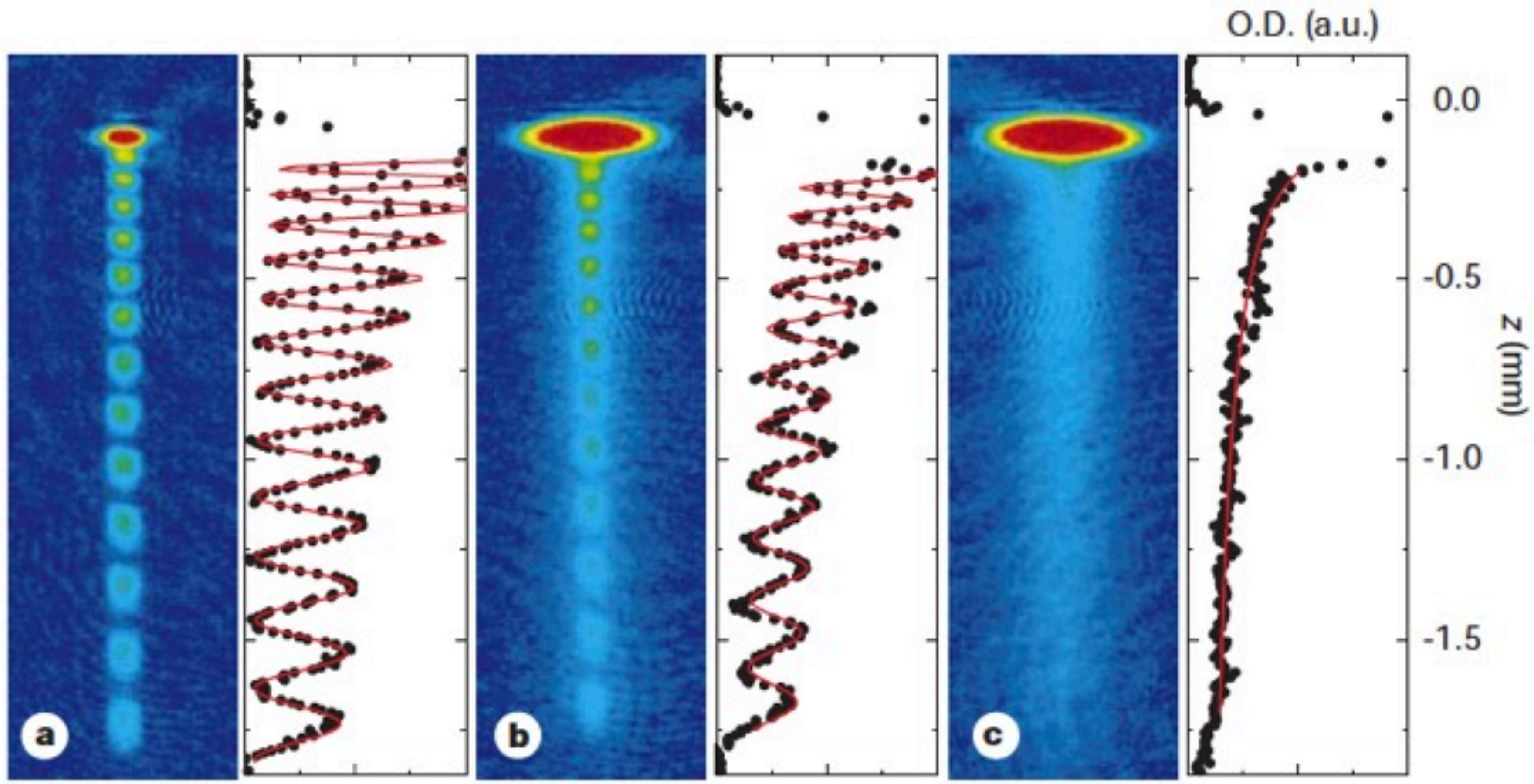




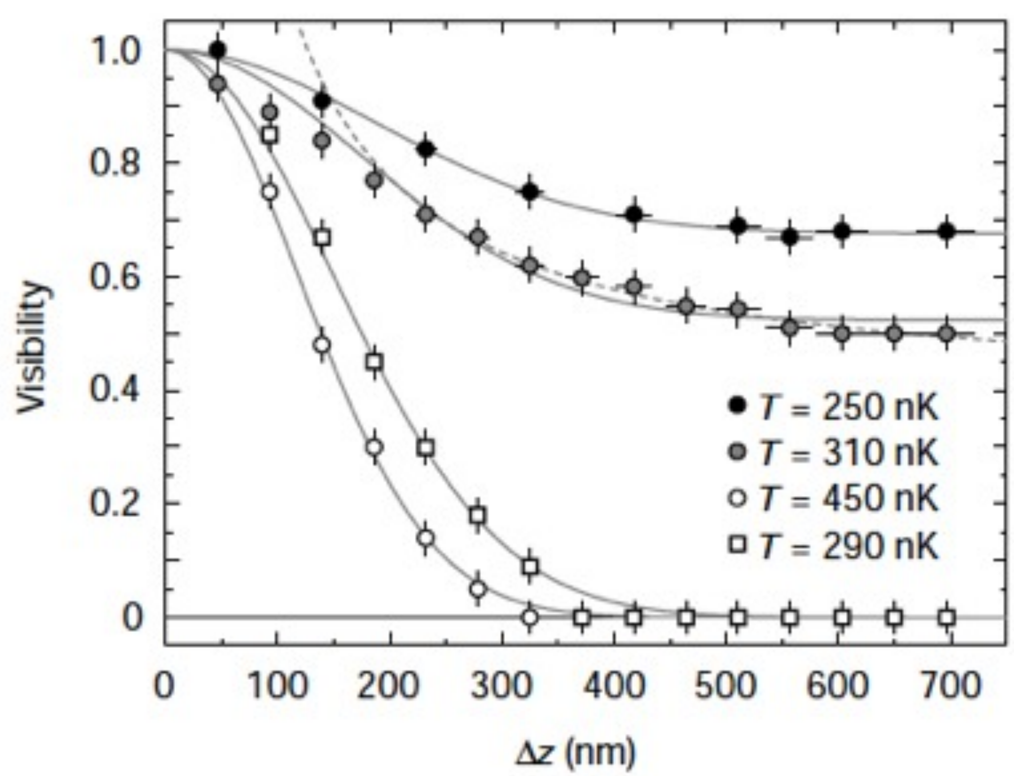
$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = g^{(1)}(\vec{r}_1, \vec{r}_2, \tau)$$



Measuring First Order Coherence



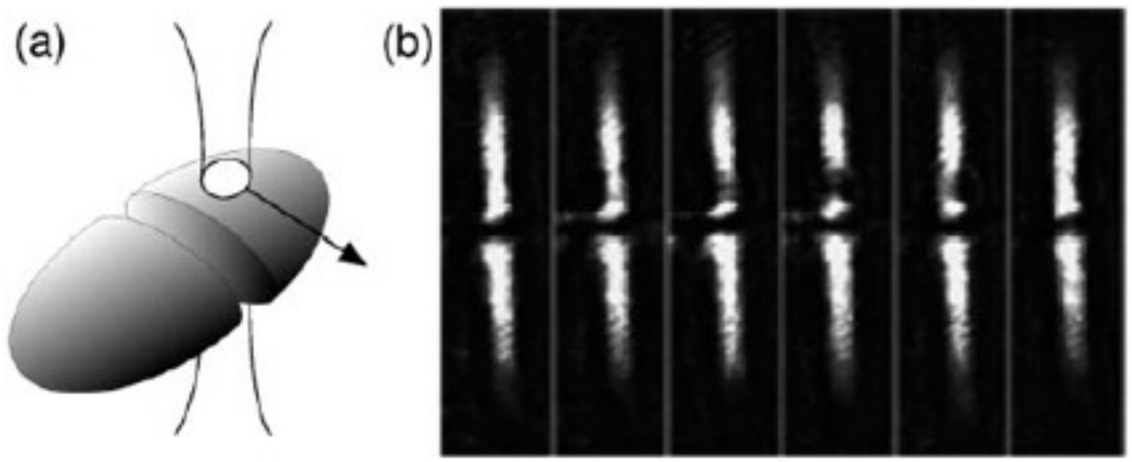
Interference pattern for fixed slit separation and variable temperature.



$$g^{(1)}(\Delta z) = \frac{\langle \hat{\psi}^{+}(0)\,\hat{\psi}(\Delta z)\rangle}{\sqrt{\langle \hat{\psi}^{+}(0)\,\hat{\psi}(0)\rangle}\sqrt{\langle \hat{\psi}^{+}(\Delta z)\,\hat{\psi}(\Delta z)\rangle}}$$

Condensate Shows Long Range Order (in 3D)

Detecting the Phase Singularity of a Vortex



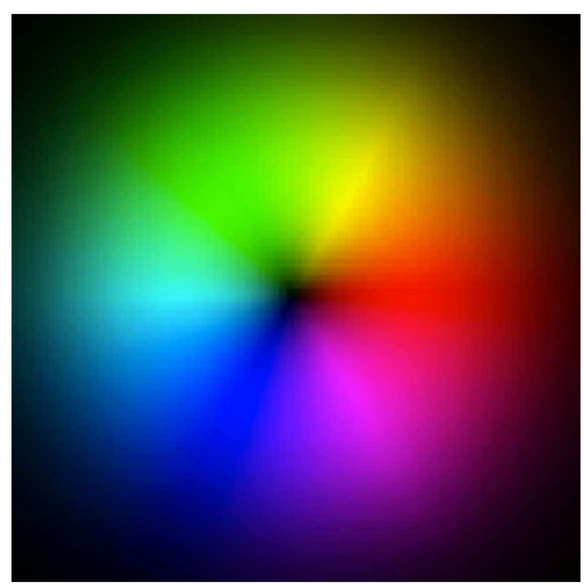
Make two condensates, one with a vortex and one without a vortex.

Let them interfere!

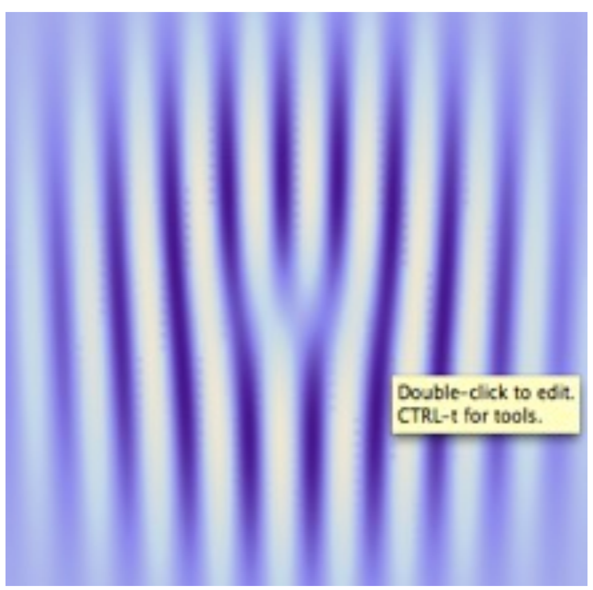
Expect Fork Dislocation in interference pattern, due to phase singularity!

Plane wave wavefunction

+

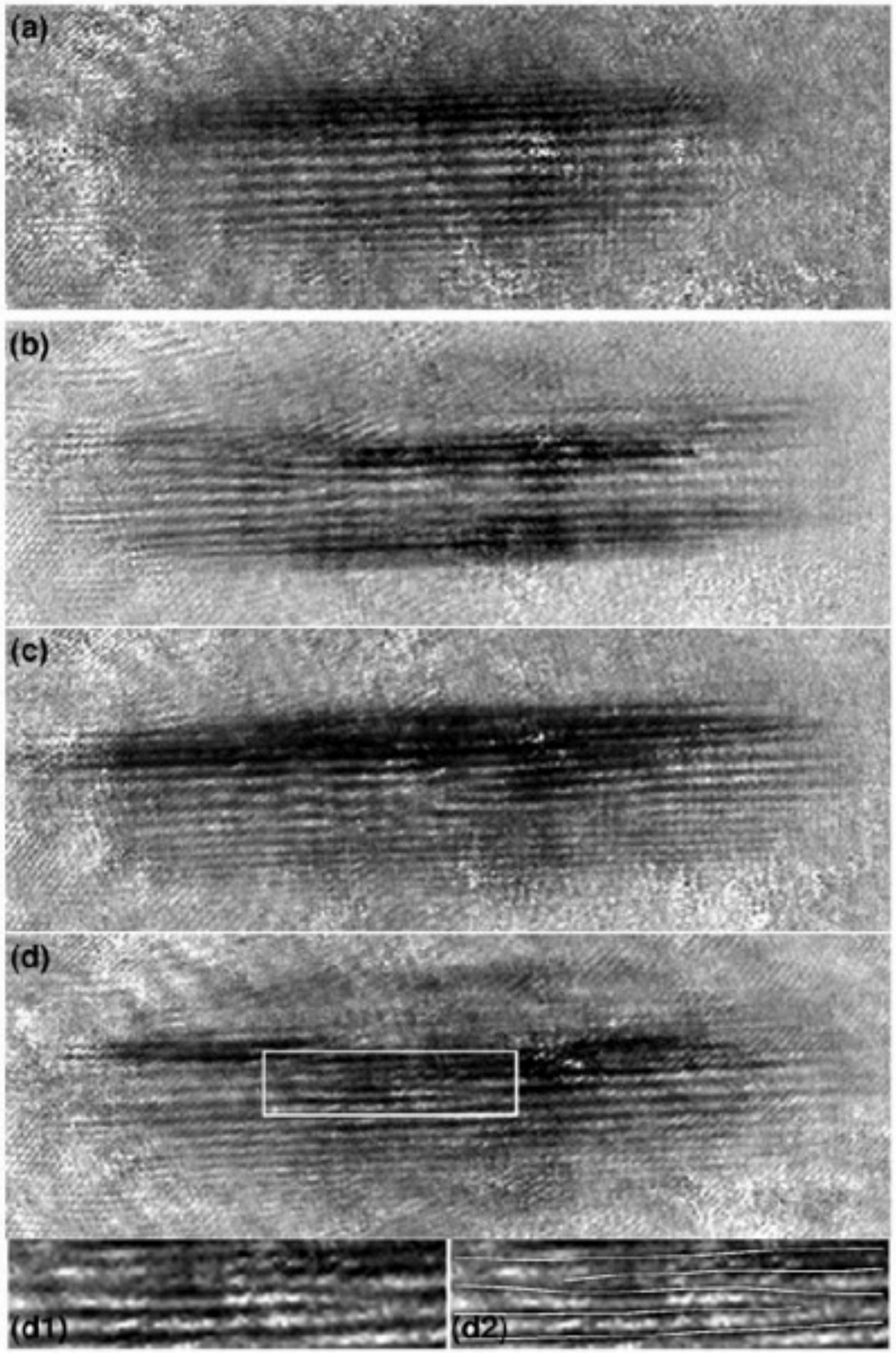


Vortex wavefunction



Interference pattern

Observing the Phase Singularity



from S. Inouye et al.: PRL 87, 080402 (2001)
see also: F. Chevy PRA 64, 031601 (2001)