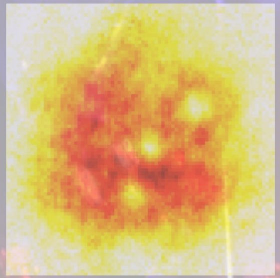
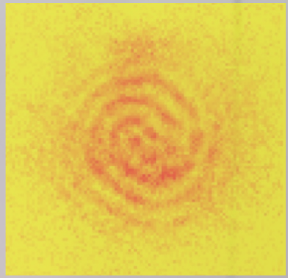
Vortices in two-dimensional atomic quantum gases: a review of experiments





Lauriane Chomaz,
Quantum-Fluid group,
University of Heidelberg.

STRUCTURES CLUSTER OF EXCELLENCE

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

18/04/2022

Intense vortex week, 12/09/2022

My Background

- **2010-2014:** PhD student

BEC group, Prof. Jean Dalibard, ENS Paris | Collège de France, Paris (France).

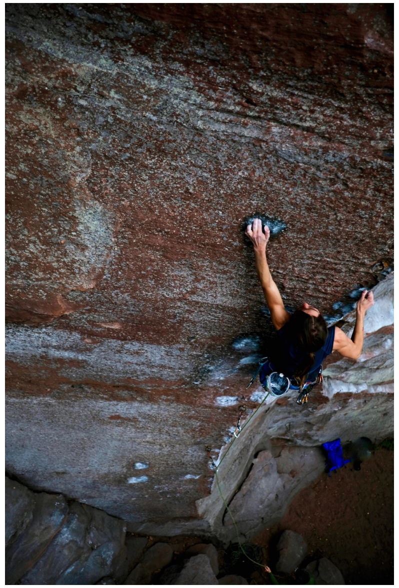
on experimental studies of the „dynamics and thermodynamics of two-dimensional Bose gases“

- **2015-2020:** Postdoc (including Marie Curie and Elise Richter fellowship)

Dipolar Quantum Gas group, Prof. Franscesca Ferlaino,

Innsbruck University (Austria).

on experiments probing many-body physics of dipolar gases.



- **Since February 2021:** Tenure-Track Professor,

Heidelberg University (Germany).

starting an experiment on two-dimensional dipolar gases.

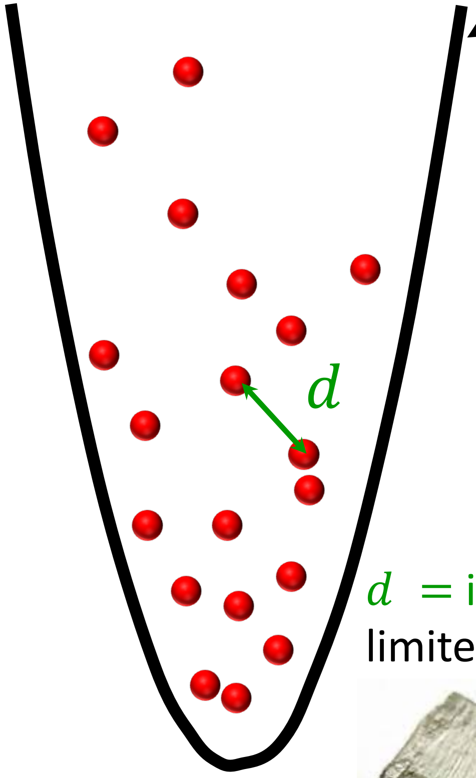
Outline

- **What are quantum atomic gases, what are vortices, and why two dimensions**
  - *ultracold gases, superfluids, and vortices for phase winding*
  - *vortices, rotation and excitations*
  - *specificity of vortices in 2D and 2D regimes: characteristic sizes*
- **How to image vortices in 2d gas experiments**
  - *vortex signature in the density: vortex core.*
  - *retrieving phase (charge) information : interferences between matter wave, time resolved dynamics, Doppler shifts*
- **How to generate vortices in 2d gases**
  - *spontaneous vortices in 2d, thermal proliferation and Beresinskii Kosterlitz Thouless mechanism*
  - *vortices as relics of out-of-equilibrium states, Kibble Zurek mechanism across phase transition…*
  - *vortices in turbulent systems…*

Quantum atomic gases

QUANTUM FLUIDS

Dilute gas of atoms



(Immaterial) trap (made of light or magnetic fields)

d = interparticle distance

limited by 3-body recombination:

Dy @wikipedia

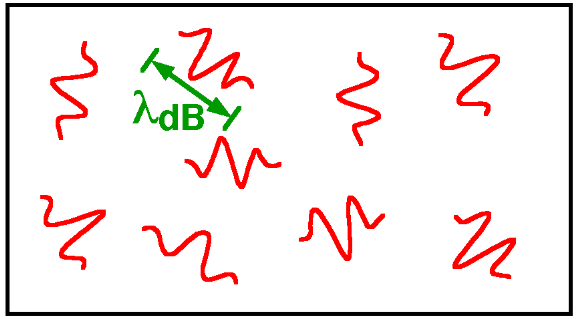
Gas = metastable state

lifetime ~ several seconds for:

$\Rightarrow$ density $n \approx 10^{20}\ \mathrm{m}^{-3}$

$\Rightarrow d \approx 100\ \mathrm{nm}$

T = gas temperature. need to be very small for quantum behavior:



Low Temperature T:

De Broglie wavelength

$\lambda_{dB} = h/Mv \propto 1/\sqrt{T}$

"Wave packets"

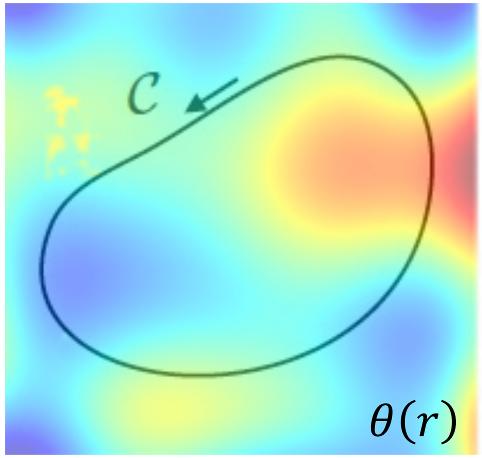
from "Making, probing and understanding Bose-Einstein condensates", Ketterle, Durfee, Stamper-Kurn (1999)

Winding of the phase and vortices

$\psi_0(\boldsymbol{r}) = \sqrt{\boldsymbol{n}(\boldsymbol{r})}e^{i\theta(\boldsymbol{r})}$

density **phase**

Circulation of the phase on a closed loop:



$\theta(r)$ should match up to multiple of 2π at all physical point

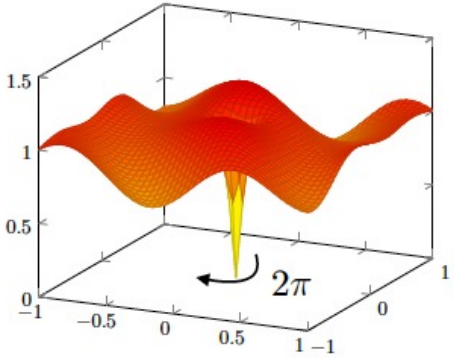
$$\oint_{\mathcal{C}} \boldsymbol{\nabla}\theta(r)\, dr = 2\pi \times m$$

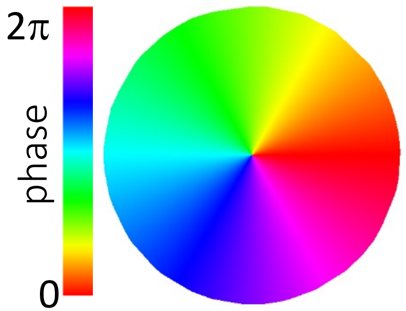
$\Rightarrow$ circulation quantified: $m \in \mathbb{Z}$

$\Rightarrow m \neq 0$ implies a **singular** point $\boldsymbol{r_0}$ *in the loop where* $\boldsymbol{\theta}$ ***is not defined*** $\Rightarrow$ $\boldsymbol{n}$ ***cancels***

$\Rightarrow m =$ "topological invariant". i.e. cannot be changed without introducing or removing a **singularity** (density hole, etc). "**charge" of the vortex.**

$\boldsymbol{n}(\boldsymbol{r_0}) = 0$





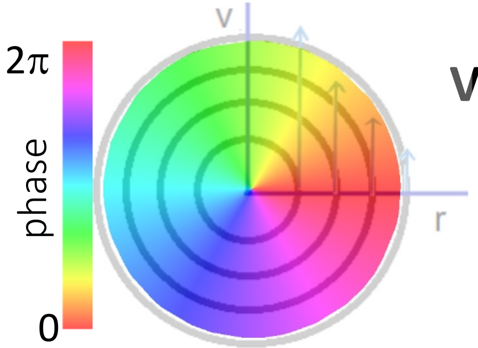
phase winds around $\boldsymbol{r_0} = \boldsymbol{0}$:
e.g. $\theta(\boldsymbol{r}) = m\varphi$

= "Vortex" — "Topological" defect.

Vortex and fluid rotation

$\psi_0(\boldsymbol{r}) = \sqrt{\boldsymbol{n}(\boldsymbol{r})}e^{i\theta(\boldsymbol{r})}$

Quantum gas dynamics $\Rightarrow$ $\frac{\hbar}{M}\boldsymbol{\nabla}\theta = \boldsymbol{v}$ = velocity field



Vortex: phase winding around $r_0 = 0$

$$\theta(\boldsymbol{r}) = m\varphi$$

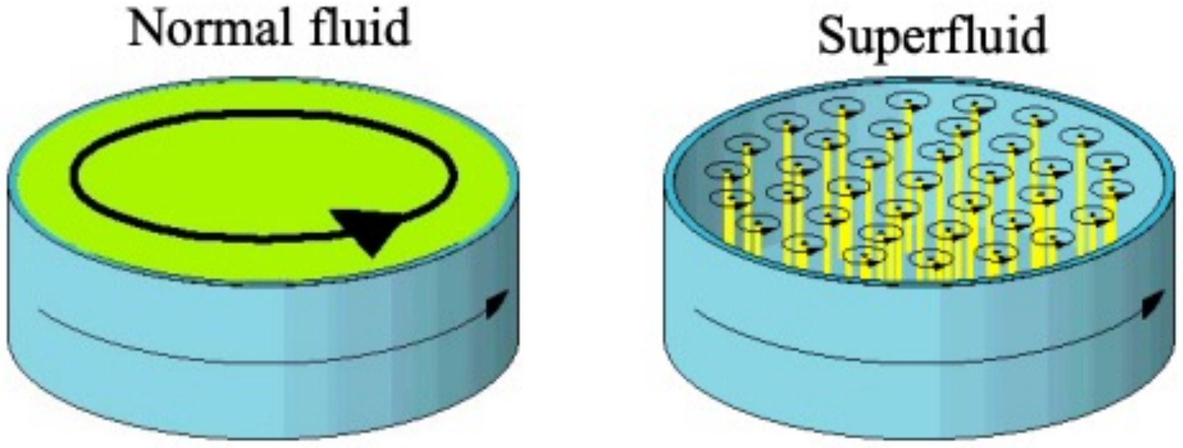
$\Rightarrow$ $\boldsymbol{v}(\boldsymbol{r}) = \frac{\hbar m}{M|r|}\boldsymbol{e_\theta}$ = **rotation** of the gas around $\boldsymbol{r_0}$

$\Rightarrow$ $n(r_0) = 0$: centrifugal effect

$\Rightarrow$ quantized angular momentum per particle $L_m = m\hbar$

$\Rightarrow$ particularity of quantum gas flow: $\boldsymbol{\nabla}\times\boldsymbol{v} = \boldsymbol{0}$! **Irrotational flow.**

rotation possible only via introduction of singularities = vortices



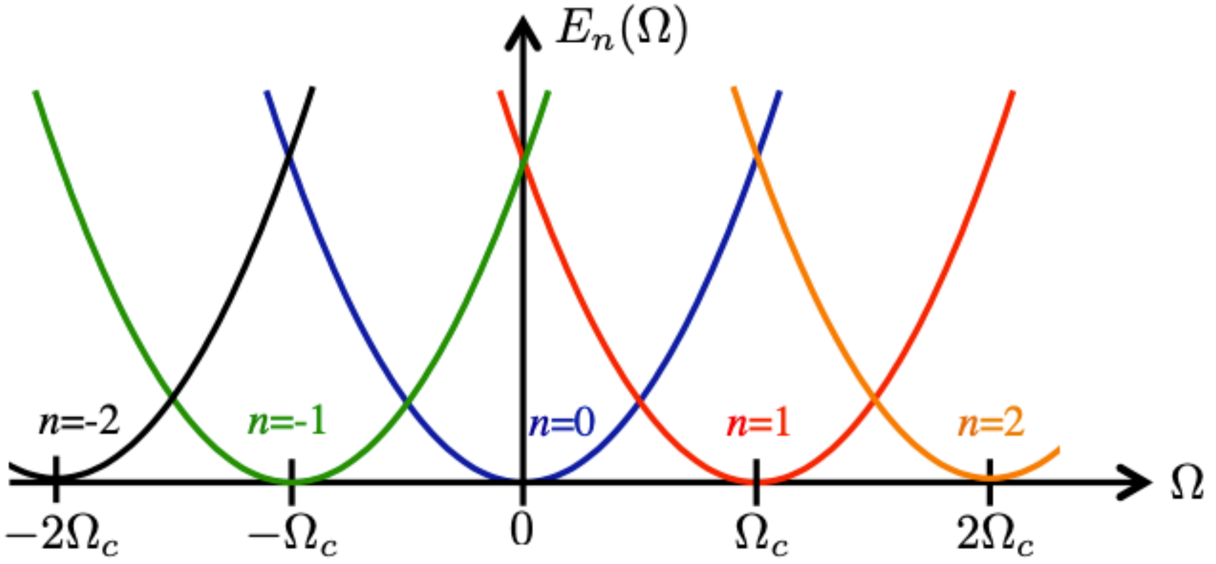
rotation of the superfluid
$\Rightarrow$ formation of vortex lattice

Vortex with and without net rotation

Under **(fast) rotation**, vortex or vortex lattices can be the **ground state** of the system.

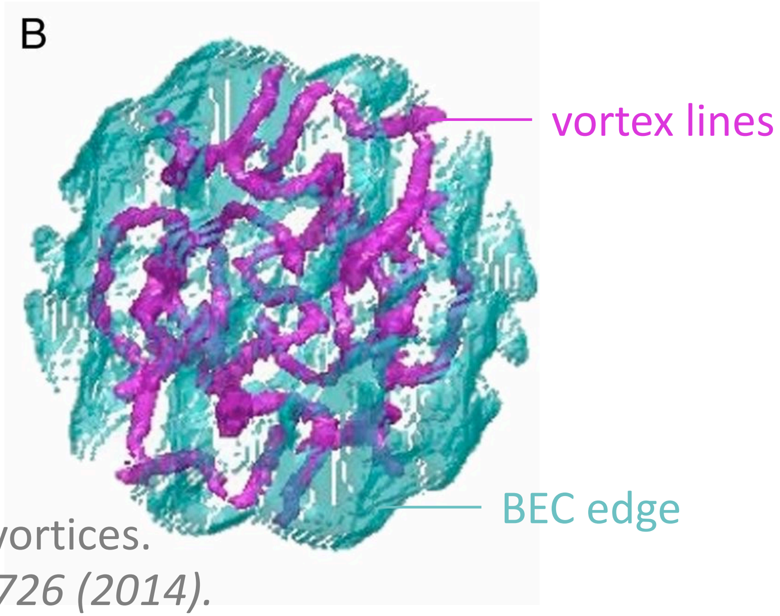
Ω : rotation frequency. Additonal energy term: $-L_z\,\Omega$

$E_m(\Omega)$: Energy of state with vortex of charge m for an annulus BEC.
from Dalibard CDF course, 2015.



In absence of rotation, **vortices = excitations**

- topologically protected $\Rightarrow$ long-lived (= persistence flow of a superfluid).
- decay of vortices still possible via:
  - ✓ dissipation through the thermal component of the fluid,
  - ✓ interactions with other vortices
  - ✓ excitations of the vortex lines (=Kelvon modes)



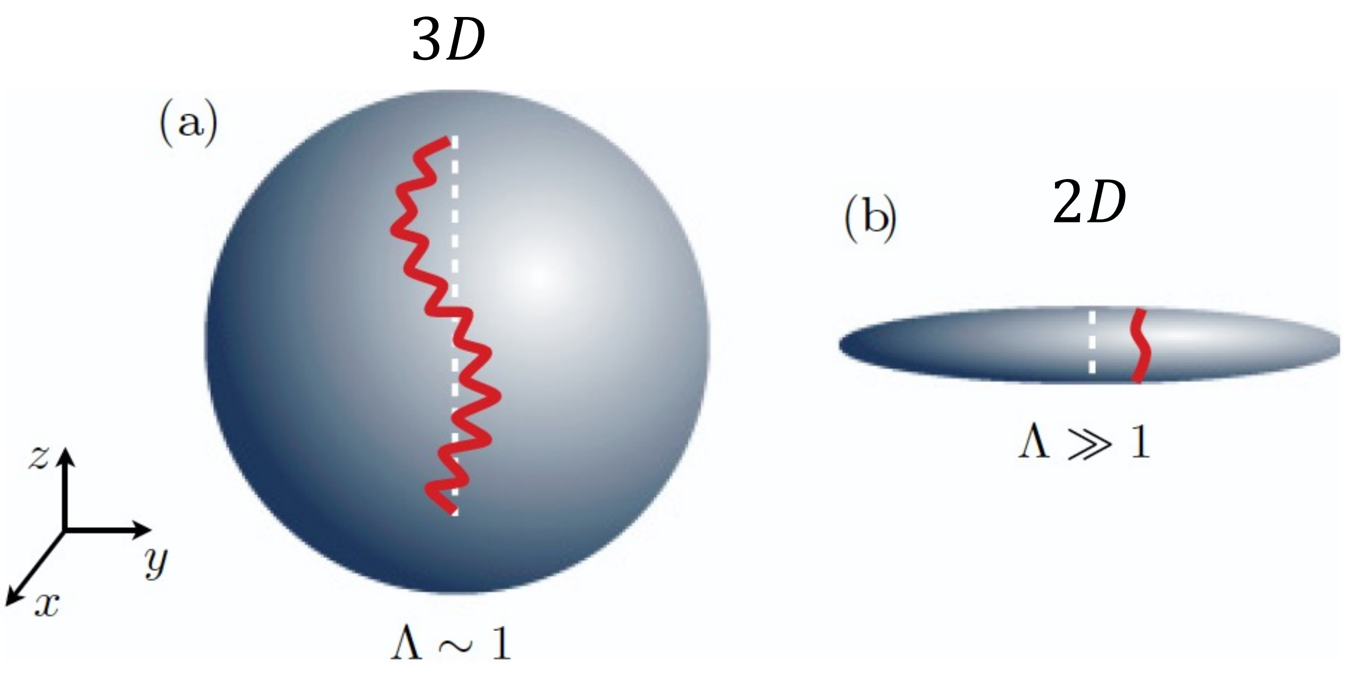
Evolved BEC after phase-imprinted lattice of straight vortices.
from White, Anderson & Bagnato, PNAS, 111, 4719-4726 (2014).

2D regime and vortices

Until now : no consideration of the gas geometry…

Yet the gas can be shaped and this influences the physics of vortices!

$\Rightarrow$ *proper description & definition to see just after!*



$\Lambda = \ell_{x,y}/\ell_z \approx$ Aspect ratio of the gas

$\ell_z <$ vortex core size $< \ell_{x,y}$

Interest of **“2D” regime for vortex physics:**

- **vortices align $\perp$ tight direction**

$\Rightarrow$ simpler dynamics and interactions but still rich

$\Rightarrow$ simpler to observe in experiments (all vortex are “aligned!’)

- **vortex = point like object**

$\Rightarrow$ simpler internal structures (no mode!)

- **long lifetime of vortices**

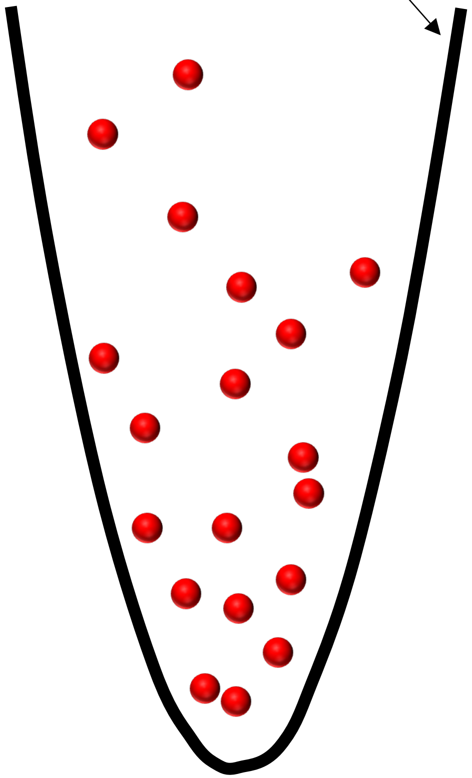
$\Leftarrow$ Kelvon excitations are suppressed.

from Rooney & al PRA 84, 023637 (2011)

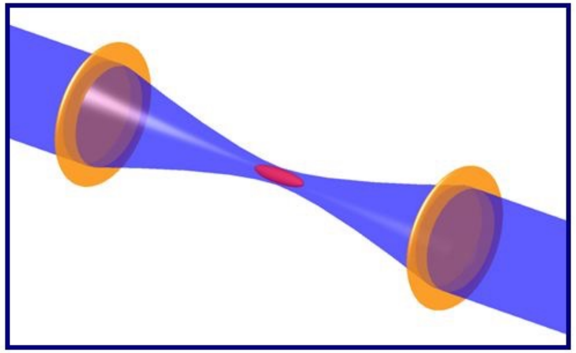
Tuning the geometry of quantum gases

Most common technique = Optical dipole trap

immaterial trap



$$U(\boldsymbol{r}) = \alpha\, I(\boldsymbol{r})$$



Atomic polarisability (at λ)

- $\alpha < 0$, atoms trapped at $\min[I]$
- $\alpha > 0$, atoms trapped at $\max[I]$

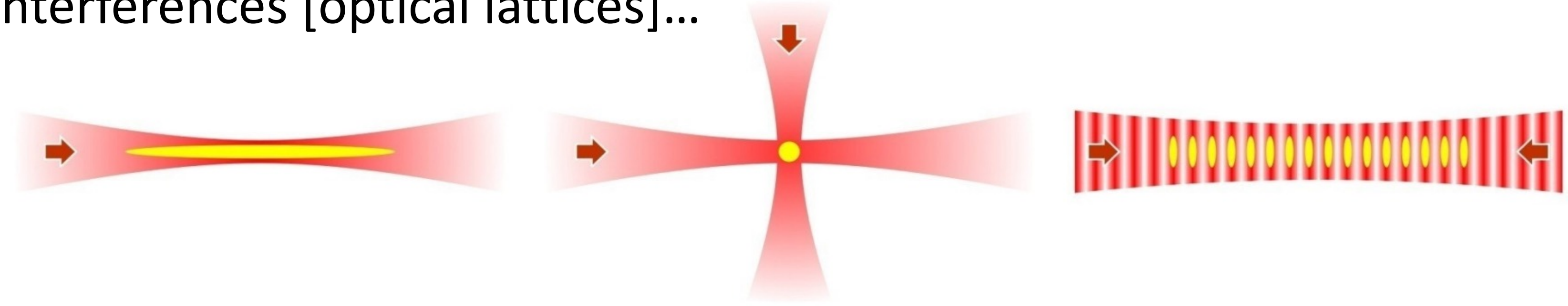
Intensity profile of laser beam, wavelength λ far-detuned to atomic transition

$\Rightarrow$ trap depth $U_0 = |\alpha|\,(\max[I] - \min[I])$

$\Rightarrow$ **trap shapping** by:

beam shapping (focussing, anisotropic waists, …).

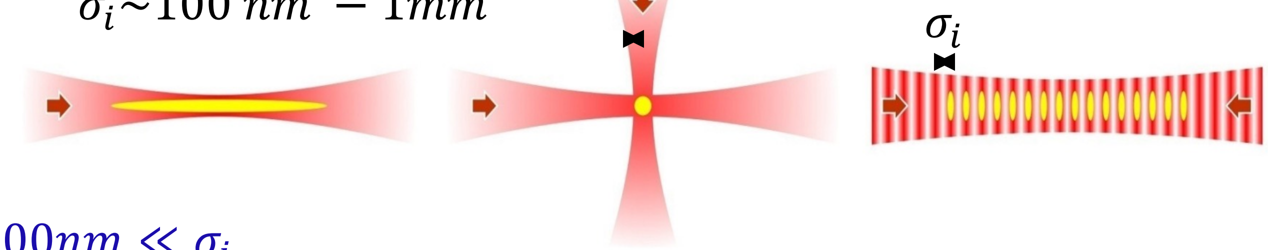
overlapping several beams, without [crossed dipole trap] or with interferences [optical lattices]…



Tuning the geometry of quantum gases, II

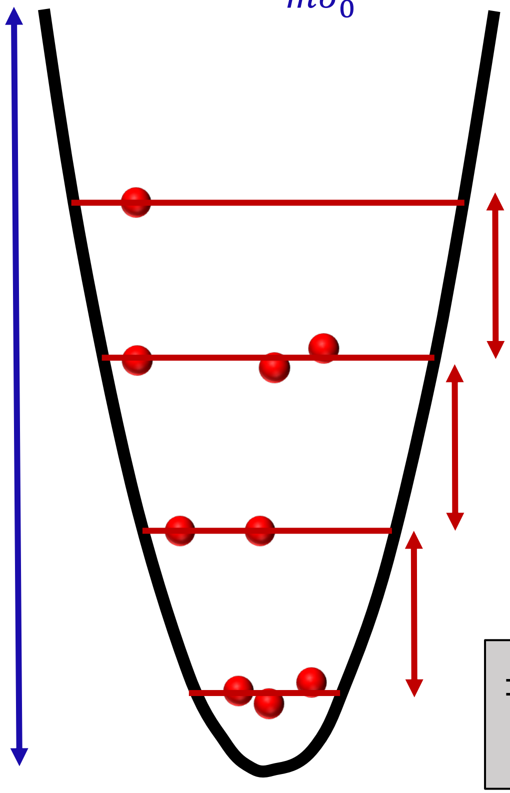
Shapping — Characteristic lengths of intensity profile (beam waist, rayleigh length, interference pattern wavelength):

$\sigma_i \sim 100\ nm\ - 1mm$



Shapping — tunable trap depth

$$U_0 = |\alpha| I_0 = \frac{\hbar^2}{m\sigma_0^2} \sim k_B \times [100nK\ - 10\mu K]\ ;\ \sigma_0 \sim 10\ nm\ - 500nm \ll \sigma_i$$



Harmonic approximation: $U(\boldsymbol{r}) \approx \sum_i \frac{m\omega_i^2 x_i^2}{2} - U_0$;

Shapping — tunable trap frequencies

$$\hbar\omega_i = \frac{\hbar^2}{m\ell_i^2} \sim k_B \times [0.5\ - 500]nK$$

$$\omega_i \approx \sqrt{\frac{2U_0}{m\sigma_i^2}} \sim 2\pi \times [10Hz\ - 10kHz]$$

$\Rightarrow$ size of harmonic oscillator states. : $\ell_i \sim \sqrt{\frac{\hbar}{m\omega_i}} = \sqrt{\sigma_i \sigma_0} = 50\ nm\ - 5\mu m < \sigma_i$

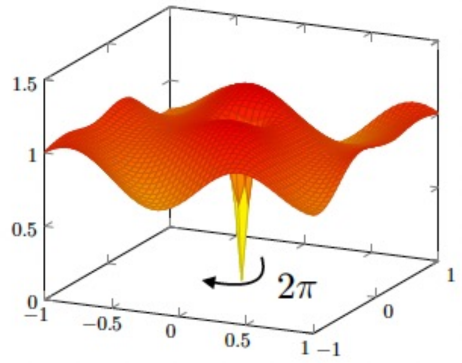
$\Rightarrow$ effective **reduced dimension for the atoms dynamics** along i: $\hbar\omega_i \gg k_B T, \mu (< U_0)$

Typically achieved with $\omega_i \approx 2\pi \times$ few kHz, in the quantum regime…

Vortex core and excitation sizes / interactions.

Vortex core size and typical excitations of the core = ***sharp density variations***

$\boldsymbol{n(r_0)} = 0$



$\Rightarrow \mathrm{E_{kin}} = \int dr \psi_0^*(r) \frac{\hbar^2 \Delta}{2m} \psi_0(r)$

sharp spatial variations of n : increased kinetic energy cost

$\Rightarrow \mathrm{E_{int}} = \frac{\mathrm{g}}{2} \int dr |\psi_0(r,t)|^4$ with $\mathrm{g} = \frac{4\pi\hbar^2 a_s}{m} > 0$ (**repulsive**) interaction strength.

tends to suppress spatial variations of n.

Healing length ξ = typical scale of variations of n for which kinetic cost = interaction energy

$$\frac{\hbar^2}{2m\xi^2} = g n_0 \Rightarrow \boldsymbol{\xi = 1/\sqrt{8\pi n_0 a_s}}$$

$n_0 \sim 10^{20} m^{-3}, a_s \sim 5nm \Rightarrow \xi \sim 1\ \mu m$

Note: without interaction, consider the typical size of $L = \hbar$ single particle state.

$\Rightarrow$effective **reduced dimension for vortices** along direction i: $\ell_i \ll \xi, \ell_j$

Typically achieved with $\omega_i \approx\ 2\pi\times$ few 100 Hz ...

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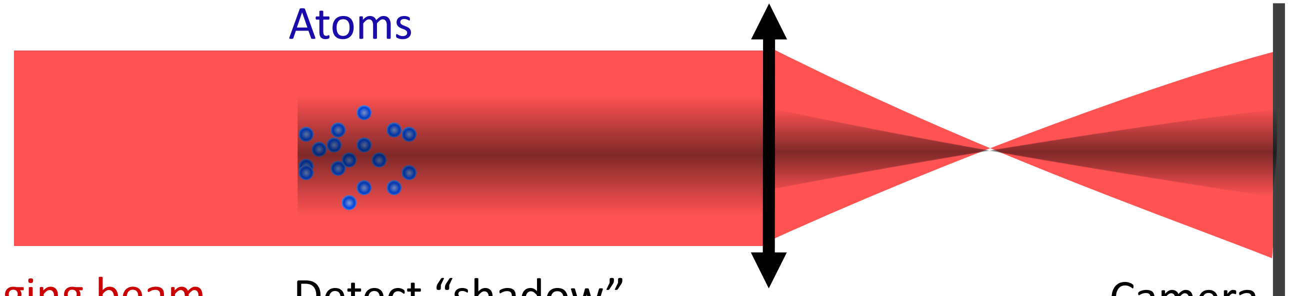
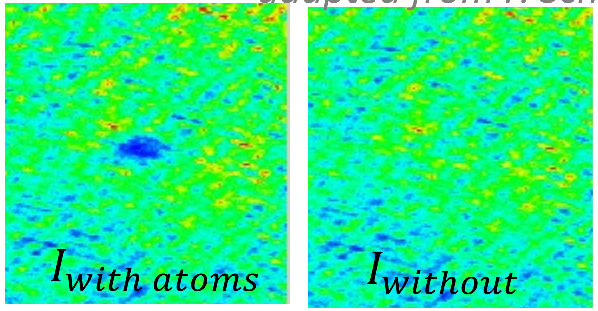
  - *vortices in turbulent systems…*

Atomic gas imaging : density sensitive

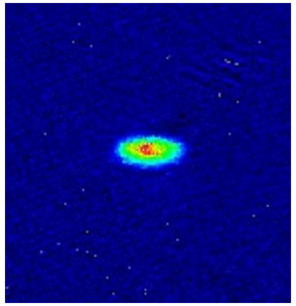
adapted from F. Schreck

Exemple of absorption imaging:





Measured intensity profiles



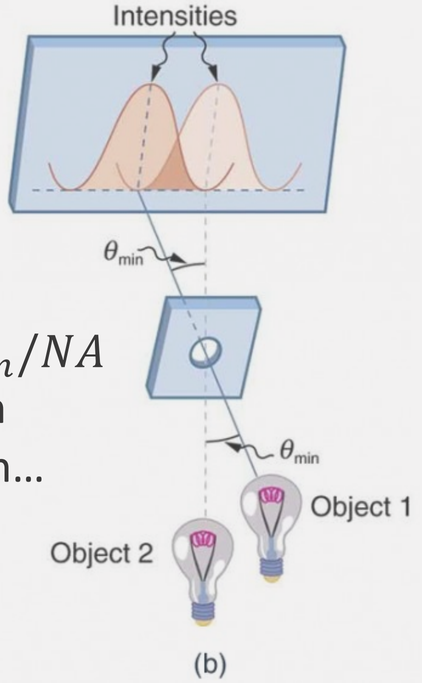
$$n_{int}(\rho) = \int n(\rho, z)dz$$
$$= -\ln\left(\frac{I_{with\ atoms}}{I_{without}}\right)/\sigma_{scatt}$$

Most standard techniques:

- absorption imaging
- fluorescence imaging
- phase contrast (dispersive) imaging…

$$NA = n \sin\theta$$

Resolution $= 0.61\lambda_{im}/NA$
typically >0.5µm
standard = few µm…



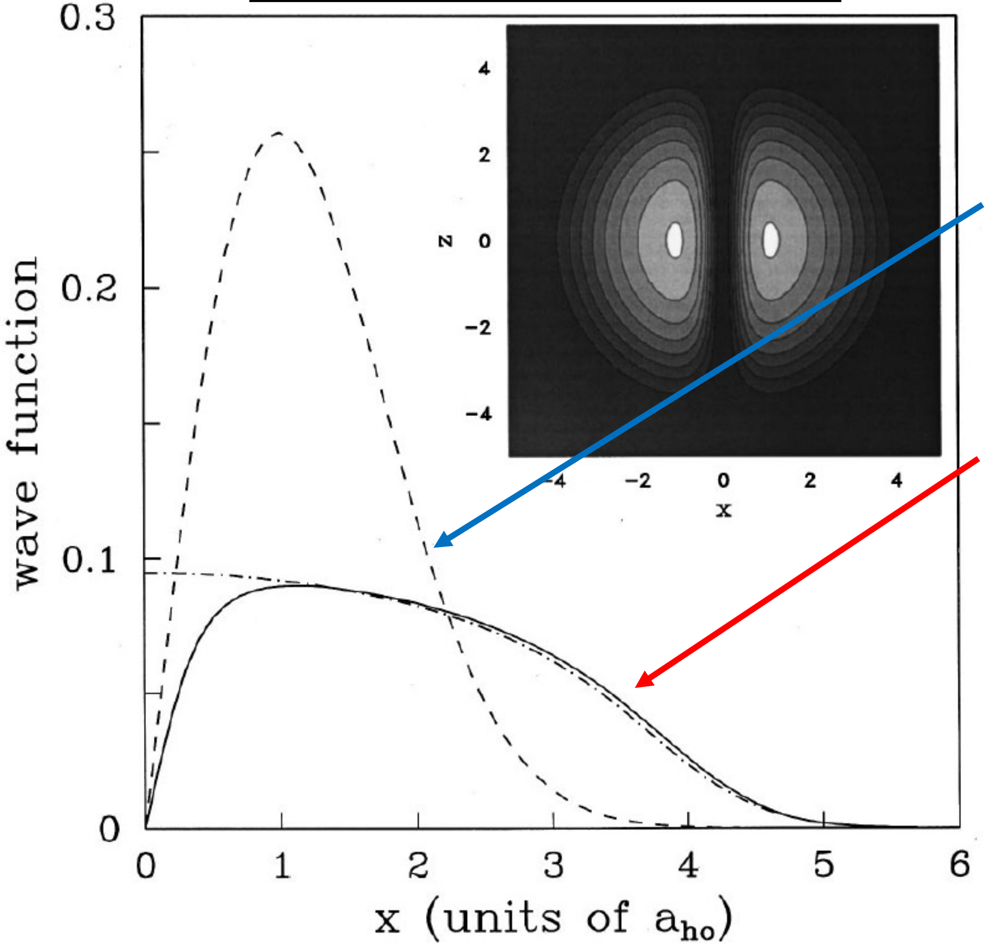
Imaging of quantum gases = ***sensitive to the (column) density*** *and mostly* ***not to the phase****….*

Vortex and density structure

Imaging of quantum gases = sensitive to the (column) density…

Vortex core = density signature of the vortex.

radial cut of wavefunction:



Advantage in 2D = all vortex cores aligned
& aligned ⊥ imaging axis!
$\Rightarrow$ all vortices detectable

non interacting BEC. m=1 single-particle state.
scale given by trap (or cloud size)along x:

$$\ell_x = \sqrt{\hbar / m\omega_x}$$

$\boldsymbol{\ell_x \sim 0.5 - 5\mu m}$

interacting BEC:
scale given by interaction (see previous discussion):

$$\xi = 1/\sqrt{8\pi n_0 a_s}$$

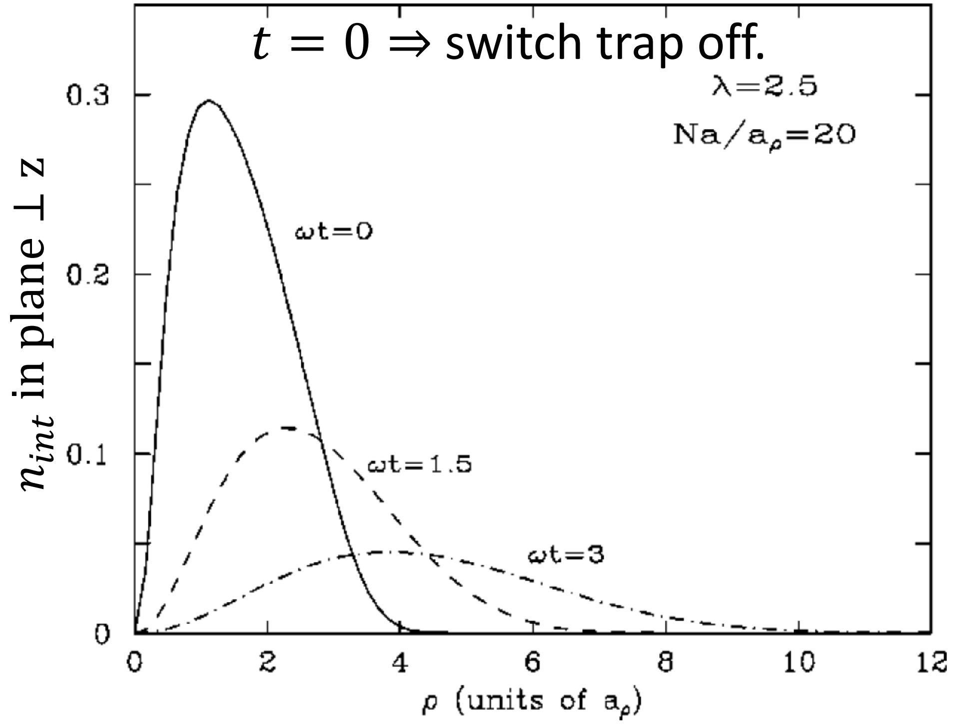
$\boldsymbol{\xi \sim 100nm\ - few\ \mu m}$

$\Rightarrow$ may be observed **insitu** with state-of-the-art technology
$\Rightarrow$ historically a **short time-of-flight** used to magnify the core

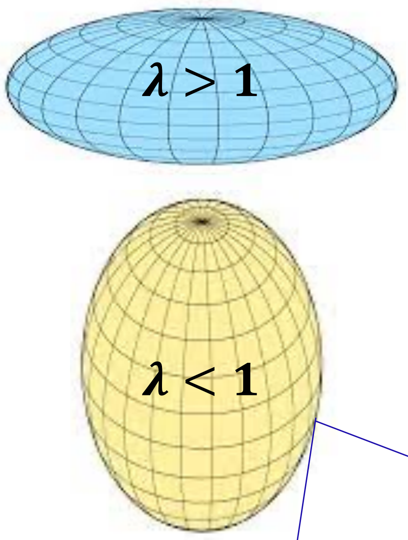
from Dalfovo & al. Rev. Mod. Phys., 71, 3 (1999)

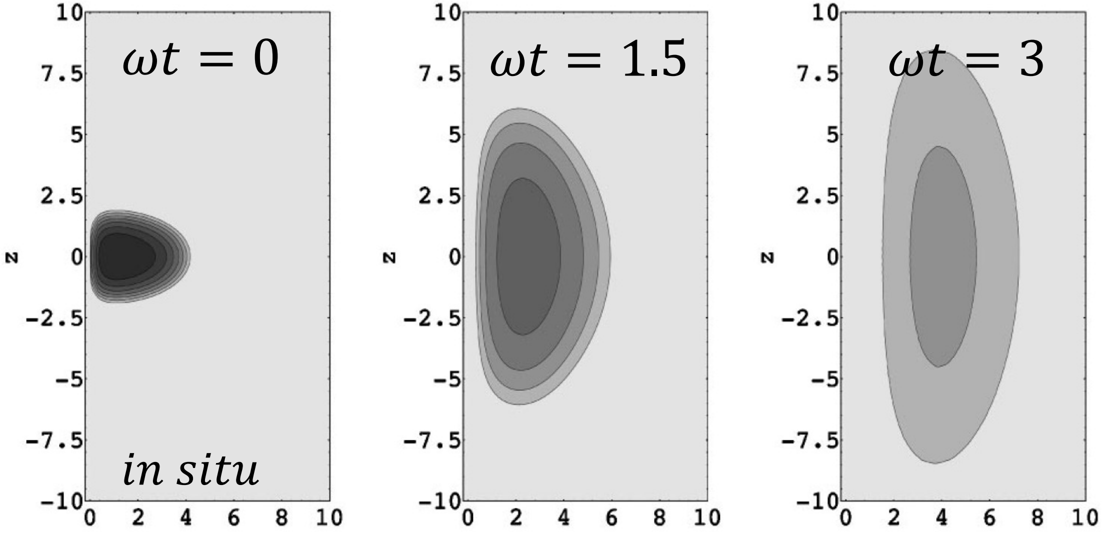
Free expansion, revealing vortex core.

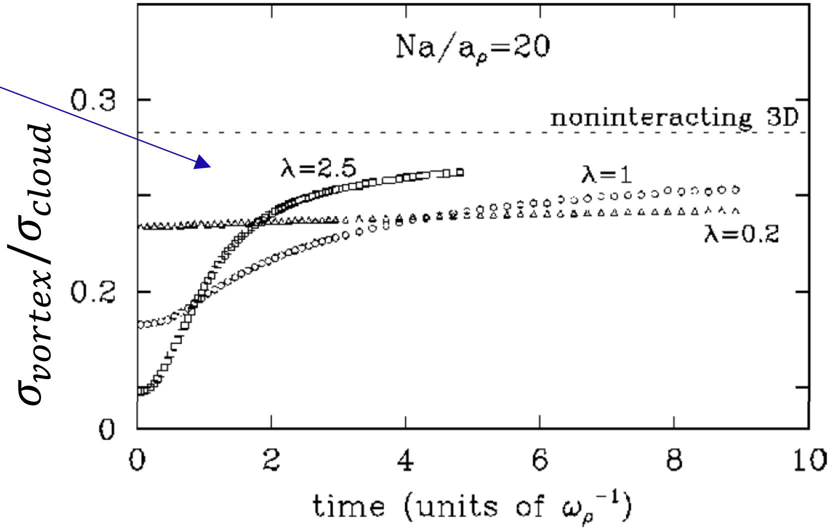
t = time of free expansion



trap anisotropy
$\boldsymbol{\lambda = \omega_z/\omega}$







$\Rightarrow$ cloud expands, density decreases.

$\Rightarrow$ vortex core **(topologically) preserved** during expansion

$\Rightarrow$ **vortex core expands**

in interacting gas, initially set by density decrease $\xi(t) = 1/\sqrt{n_t}$

$\Rightarrow$ vortex initially **expands faster** than cloud itself,

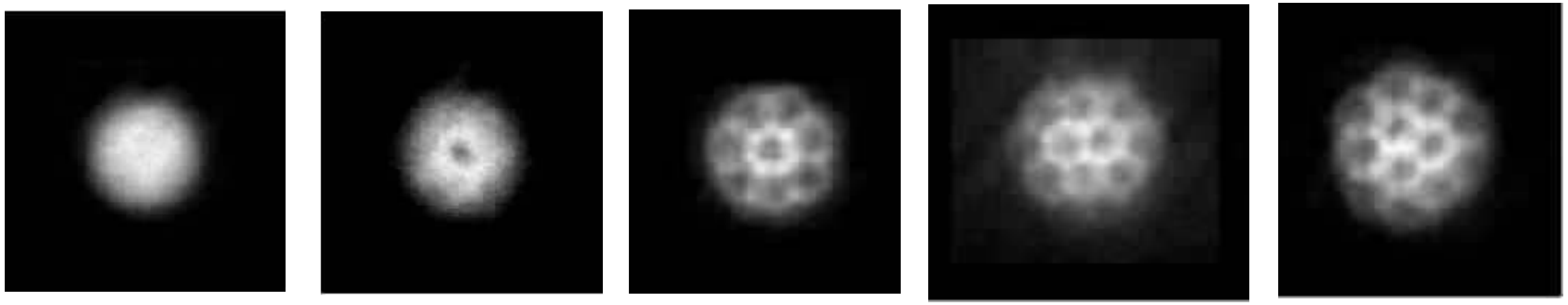
$\Rightarrow$ expansion difference most marked in **2D (large λ)**!

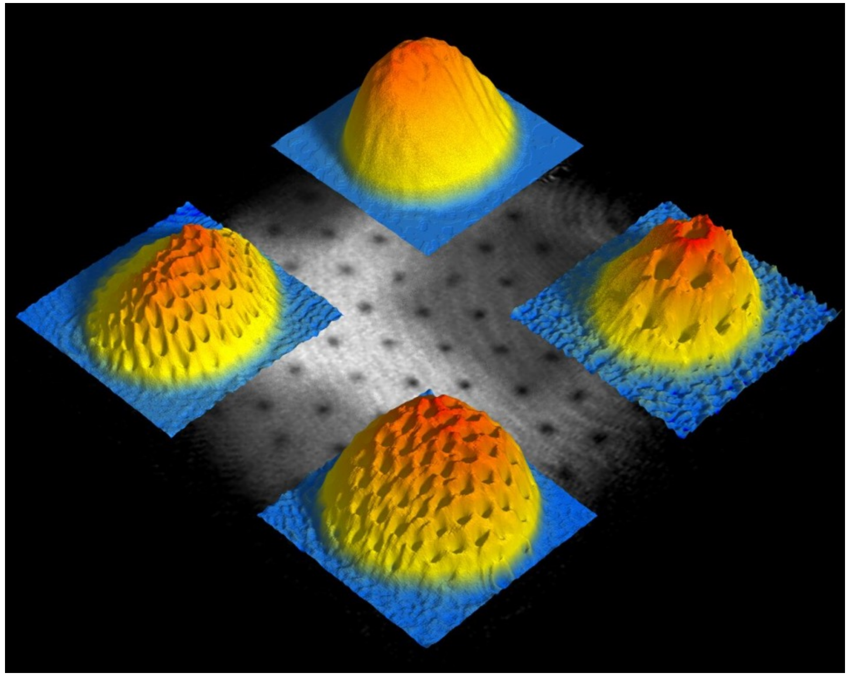
from Dalfovo & Modugno, PRA 61 023605 (2000)

Vortex core imaging in experiments

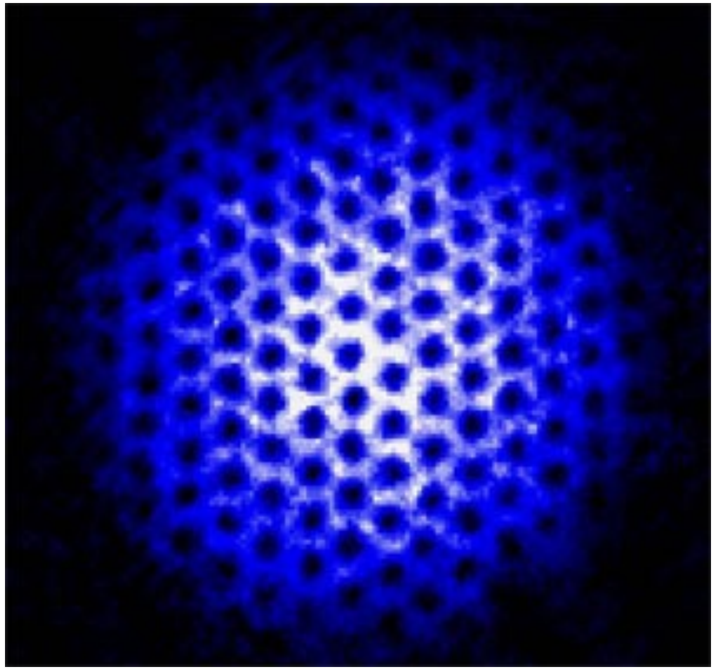
clouds put in rotation:

J. Dalibard et al., E.N.S., 2000





W. Ketterle group, MIT 2001

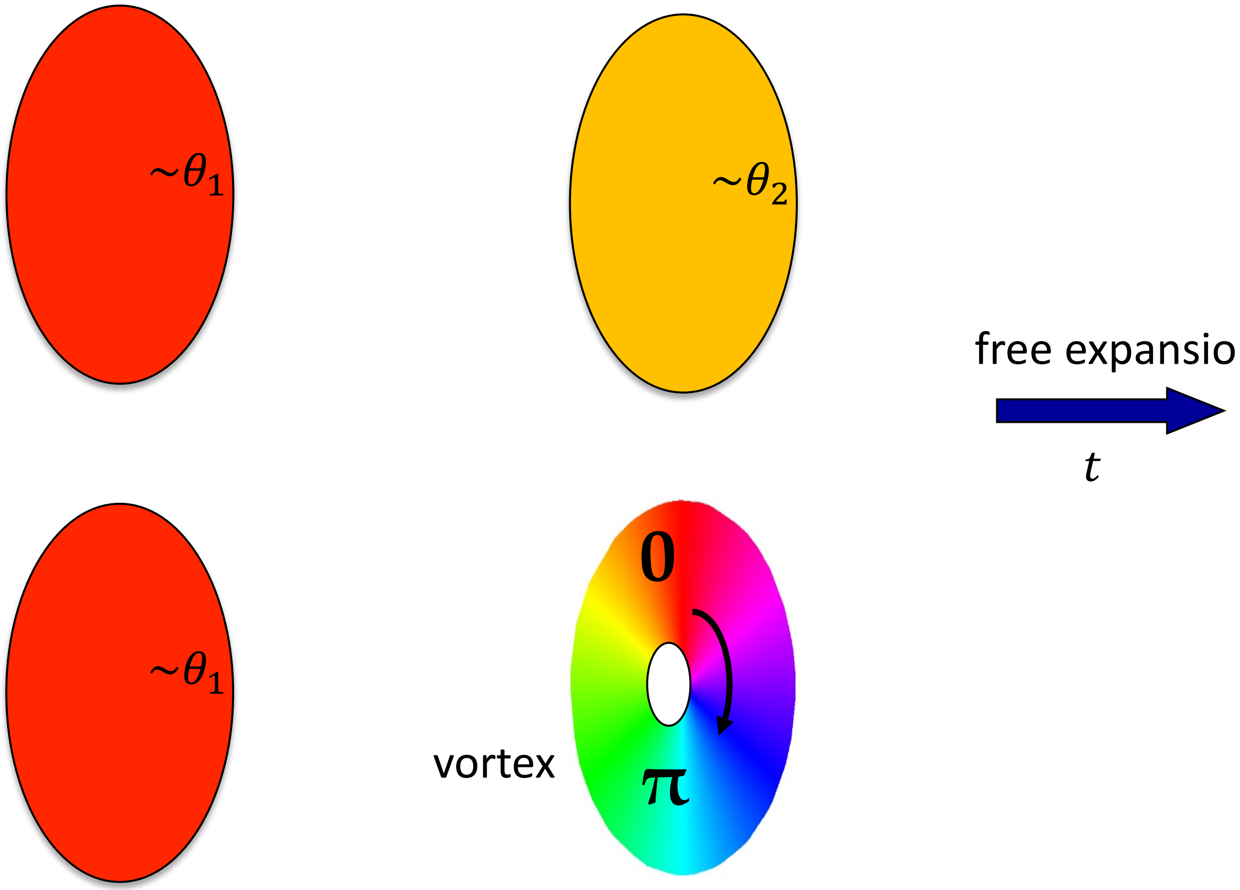


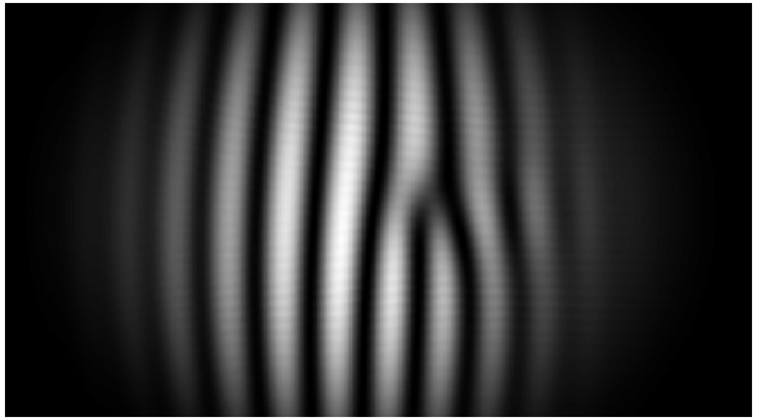
E. Cornell group, JILA 2001

Imaging the vortex phase?

Interference measurements reveal phase difference in density signal:

Interfering two (independent) gases:

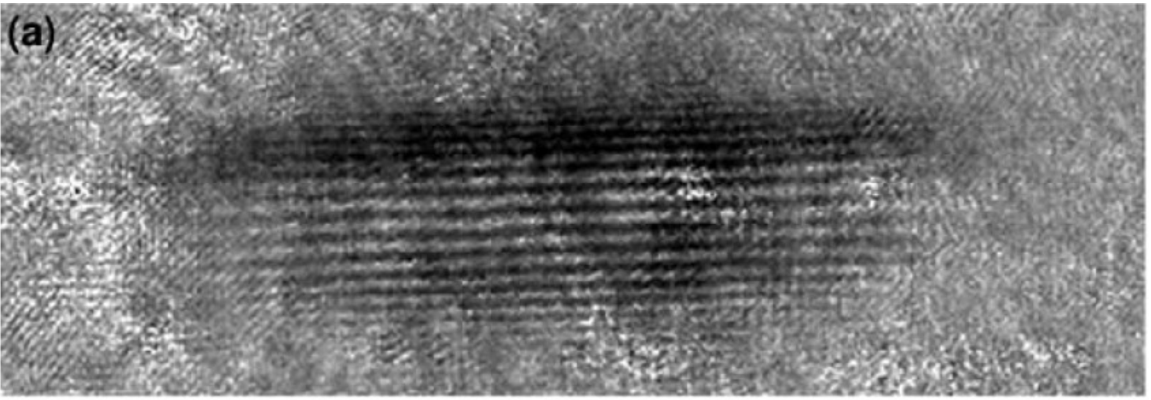


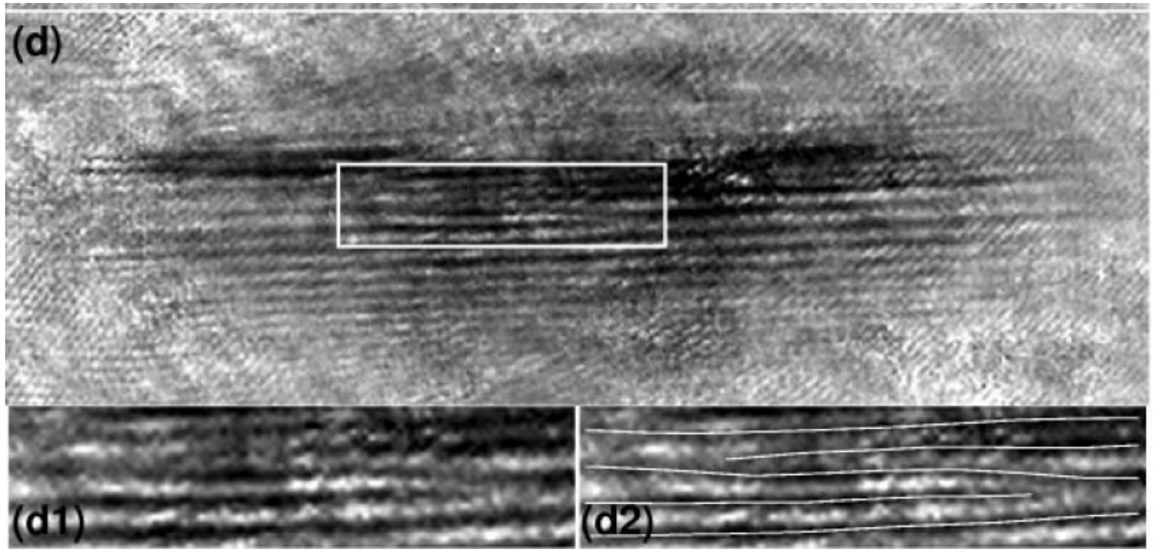


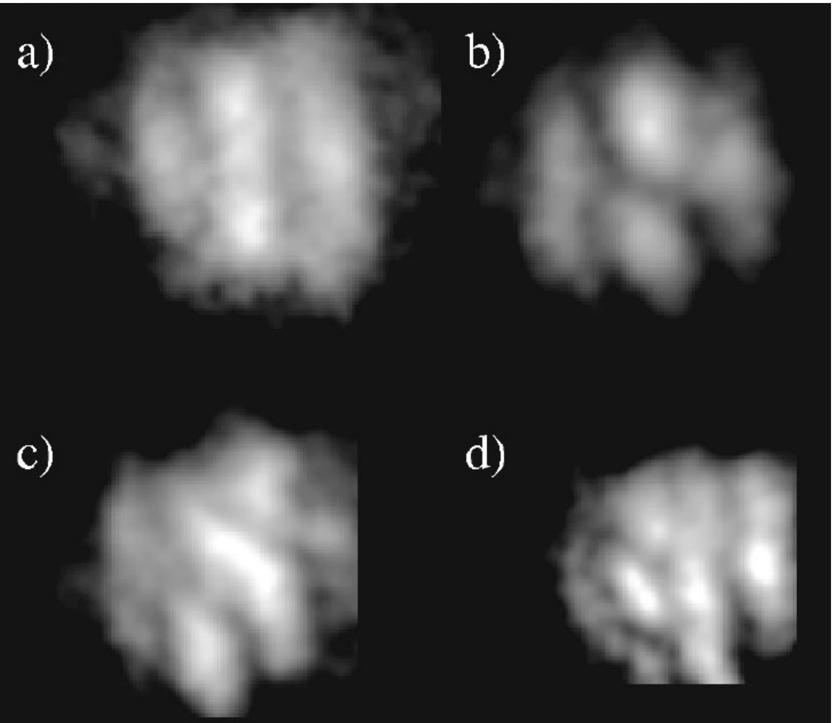
from Bolda & Walls, PRL 85 0031-9007 (2002)

Vortex interference imaging in experiments

Ketterle group, PRL 2001.
2 independent BECs

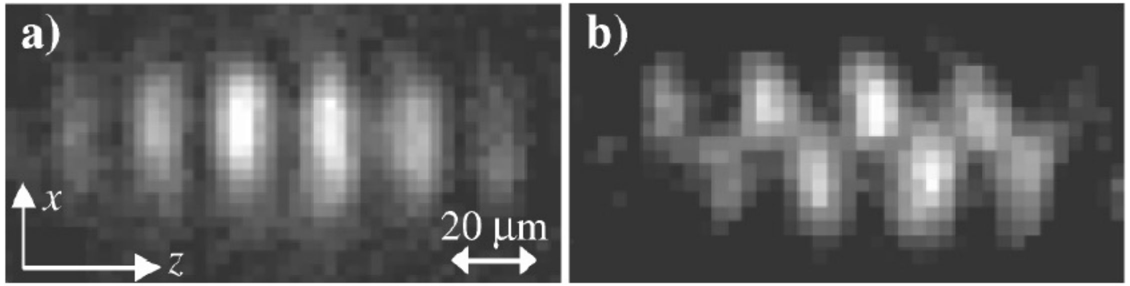


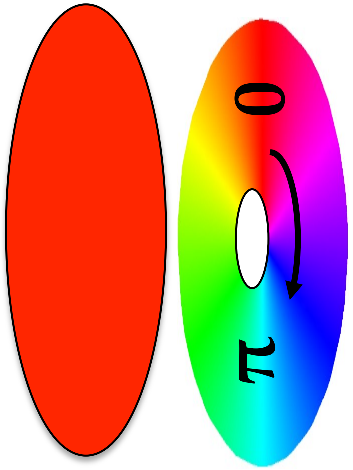




Dalibard group, PRA 2001.
self-interference of the BEC after splitting

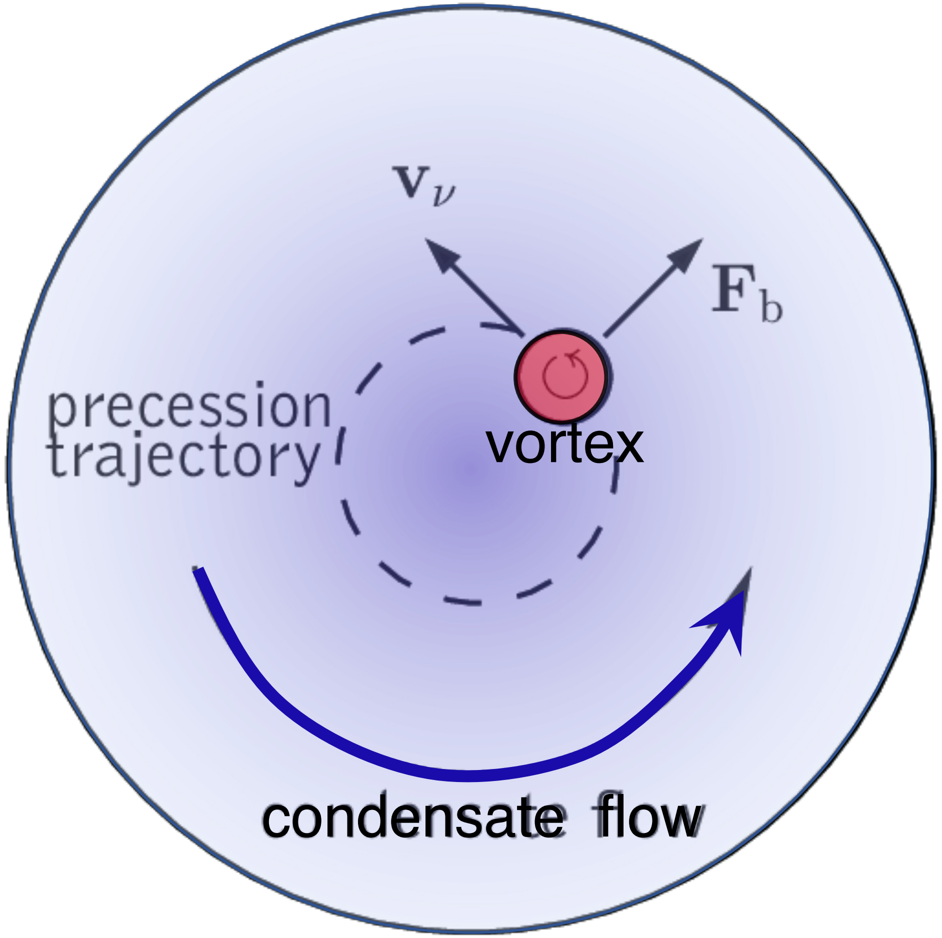
Dalibard group, PRL 2005. with 2 quasi-2D gases:





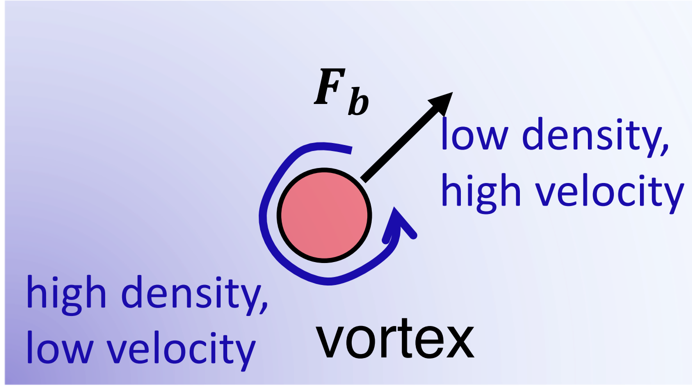
Vortex dynamics, precession

Vortex in a harmonic trap, **off-centered**
$\Rightarrow$anisotropic densities around the vortex



from T. Simula, PhD

Magnus force: effect of anisotropic flow in the fluid around a object (= vortex)



$\Rightarrow$ induces **precession** of the vortex.

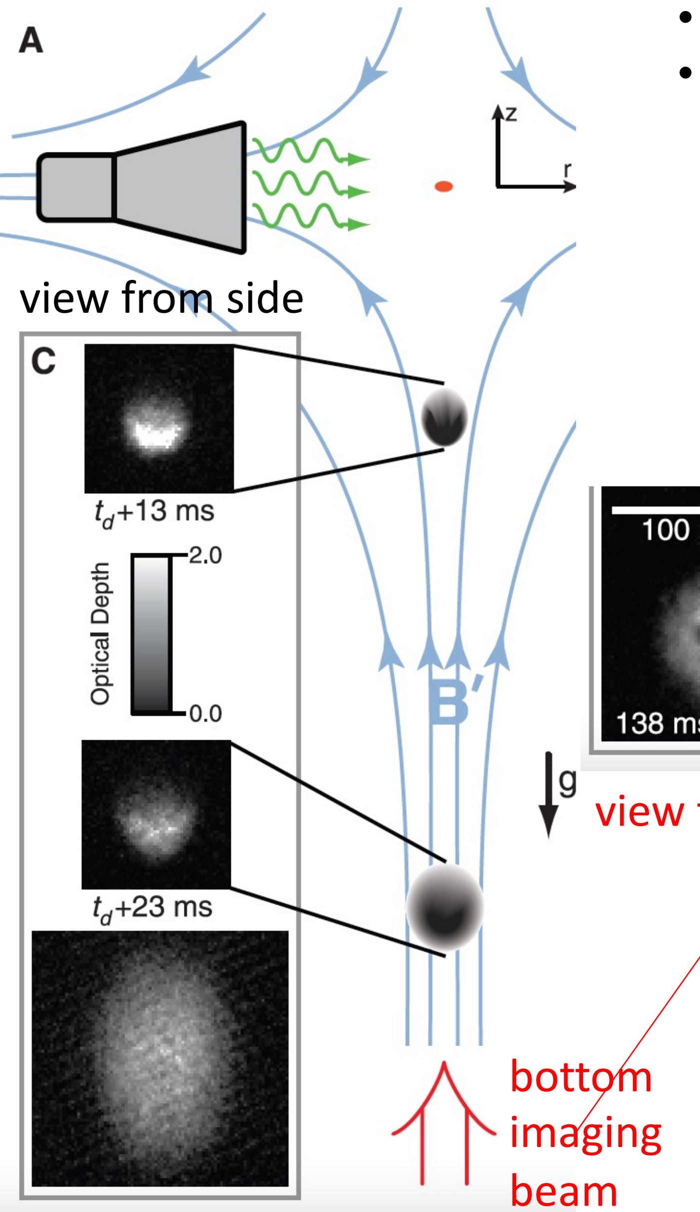
$\Rightarrow$ **direction** depends on vortex sign

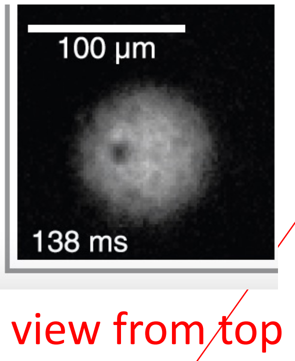
$\Rightarrow$ **speed** depends on:

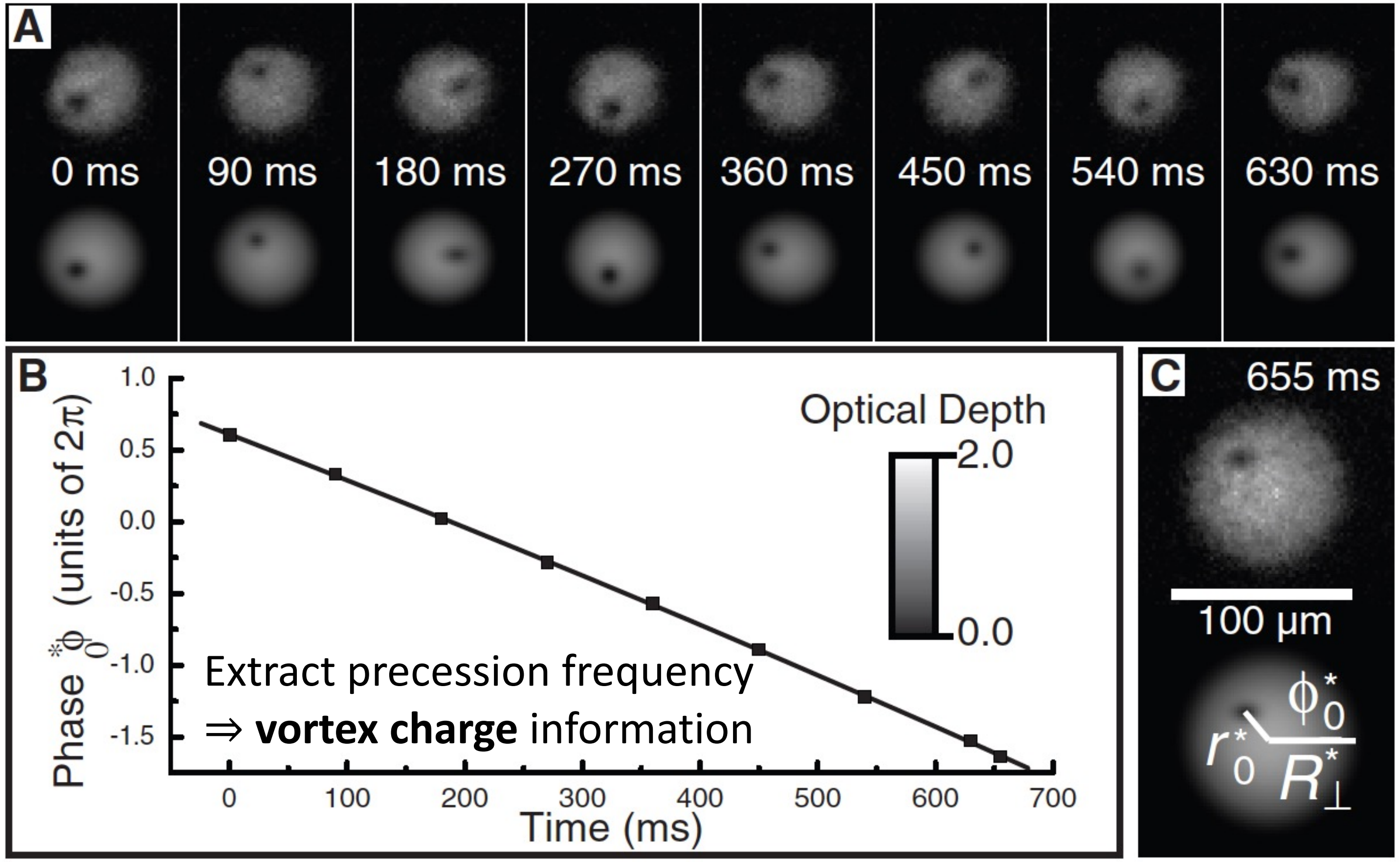
- charge of the vortex
- positon of the vortex /trap center
- trapping frequencies

Vortex dynamics, non-destructive imaging

- Extract **small fraction** of atoms to an untrapped state for **free-expansion + imaging**.
- Gas mostly unaffected by removal of small fraction. Let evolve and repeat.



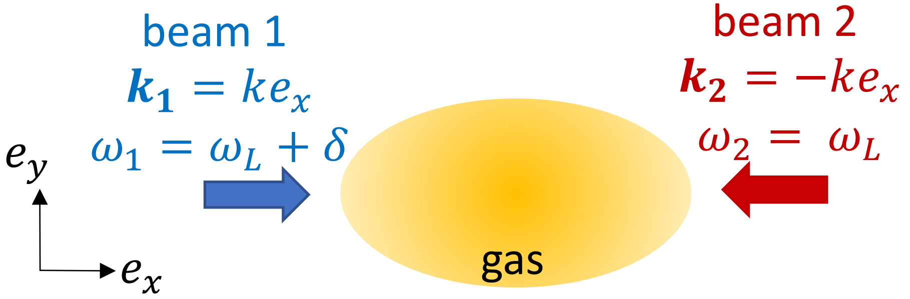




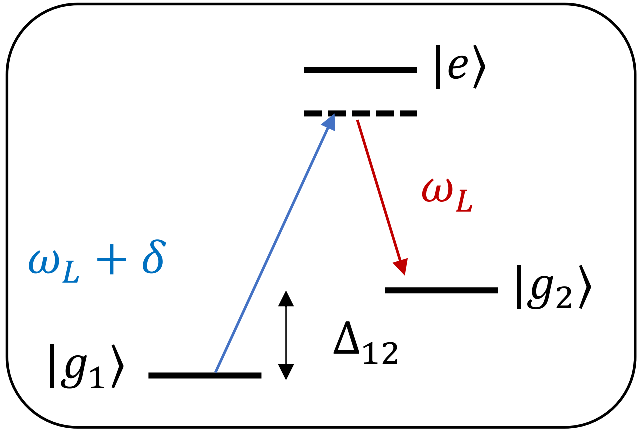
*from Hall group: Freilich, & al. Science, **329**, 1182 (2010),*
see also Cornell group PRL (1999) [+ Neely & al. , PRL 104, 160401 (2010).]

Bragg spectroscopy and Doppler effect

Bragg spectroscopy for probing Doppler shifts:



2-photon Raman process:



Resonnant for $\delta = \Delta_{12} = E_{g,2} - E_{g,1}$

!! 2-photon process implies a **momentum change** for the atom :

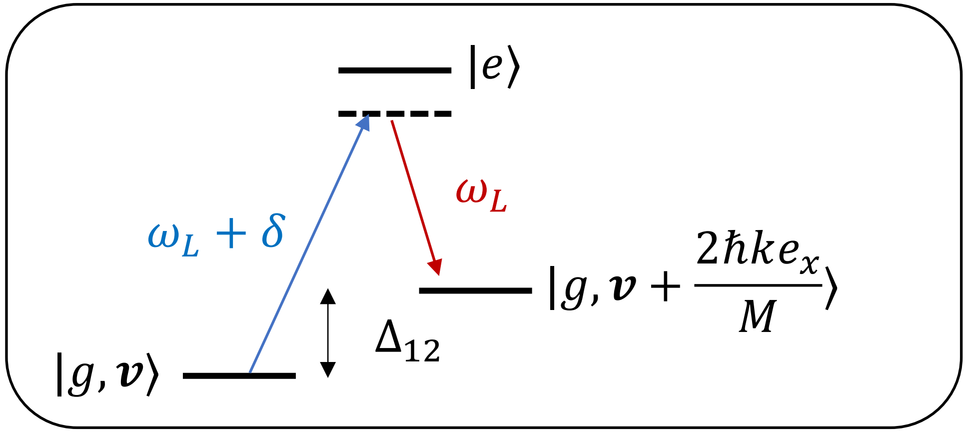
$$\Delta k_{atom} = \frac{\Delta v_{atom}}{M\hbar} = k_1 - k_2 = 2ke_x$$

$\Rightarrow$ used for **detection,** i.e. different positions after free expansion!!

!! Doppler effect: atom at velocity v see the beam i with a frequency

$$\omega_i + \boldsymbol{k_i . v_{atom}}$$

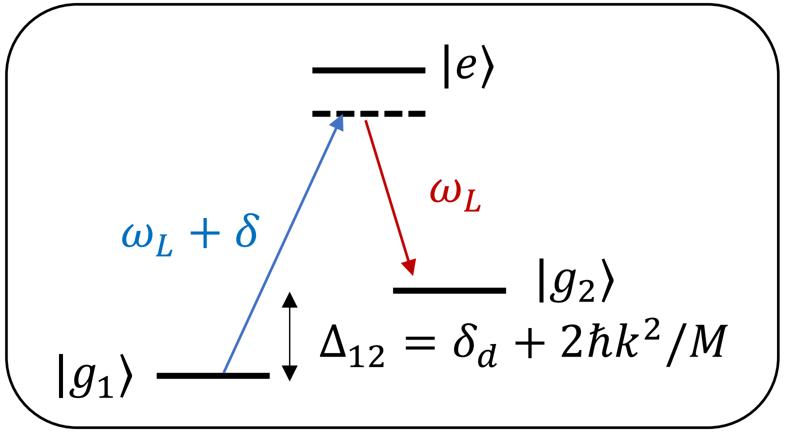
$\Rightarrow$ states $|g_1\rangle$ and $|g_2\rangle$ can be same internal state but ≠ velocities:



$$\Delta_{12} = 2k\left(v_x + \frac{\hbar k}{M}\right)$$

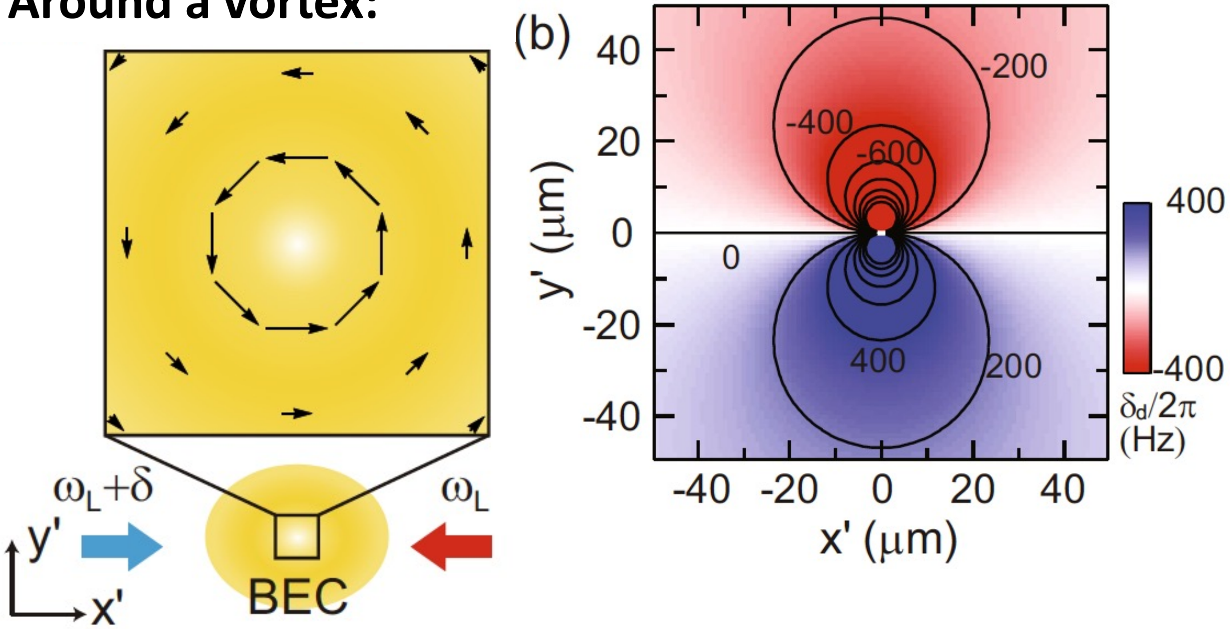
Bragg resonance position probe v_x !!

Bragg spectroscopy and vortex field

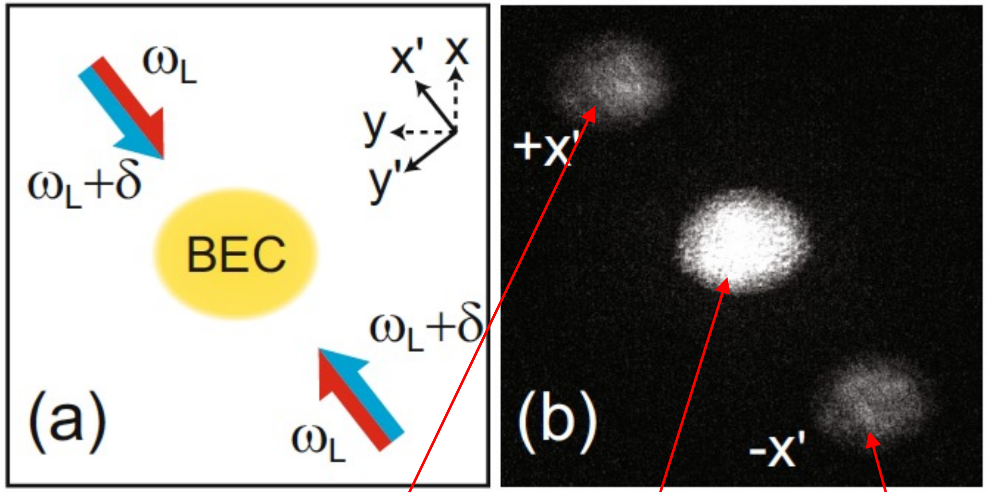


$\Rightarrow$ resonance condition probes $\delta_d = 2kv_x$

Around a vortex:



- In practice, use a set of 2 Bragg lasers to explore $\delta > 0$ and $\delta < 0$ simultaneous,
- Take absorption image after free expansion: 3 clouds.



atoms scattered at $+2ke_{x'}$

unscattered atoms

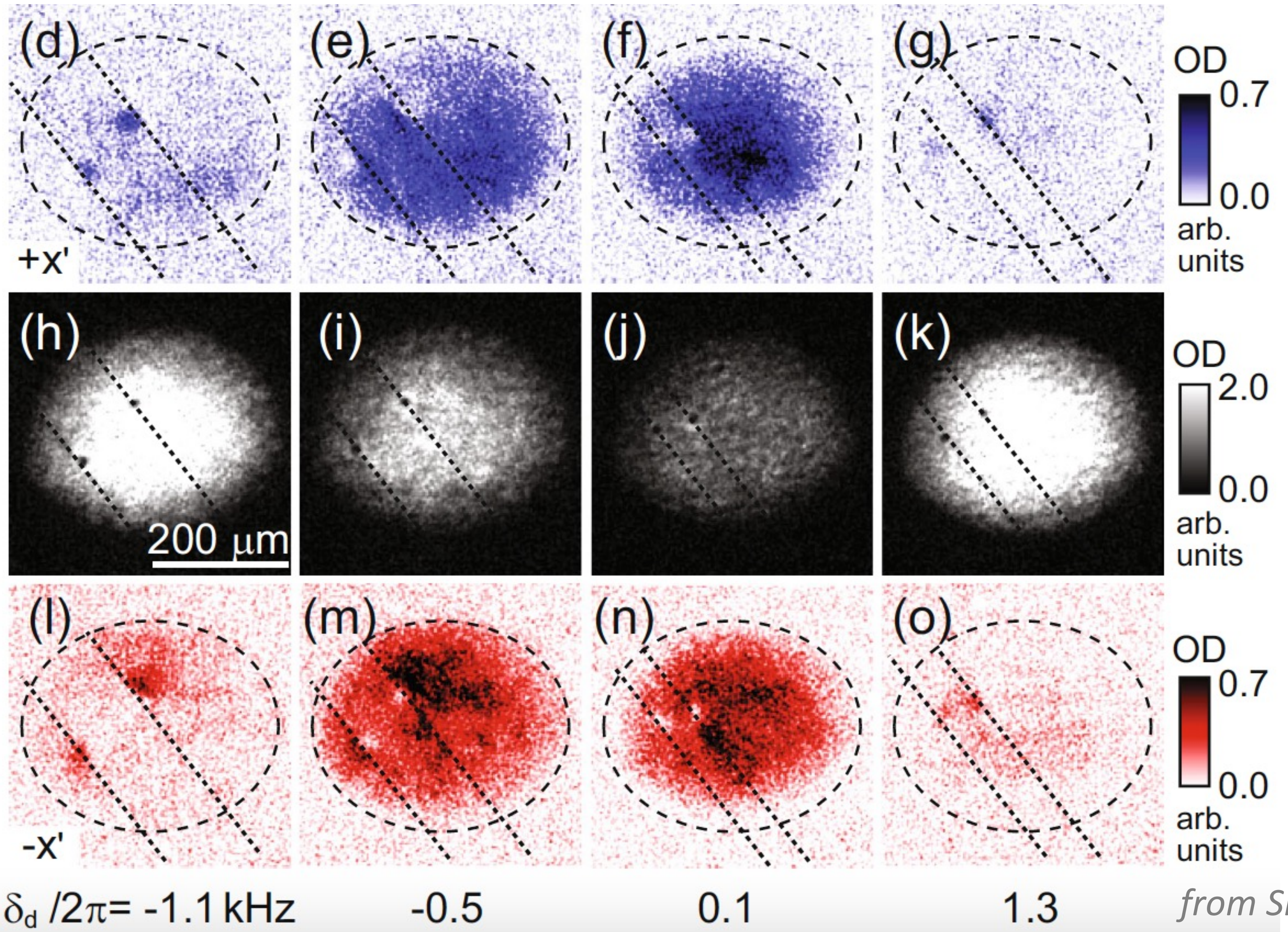
atoms scattered at $-2ke_{x'}$ (invert process)

from Shin group: Seo, & al. Scientific reports 7, 1 (2017)

velocity field spectroscopic imaging

QUANTUM FLUIDS

Compared unscattered and scattered density profiles for different detuning :



Protocol: *Create BECs with vortex dipoles (+1,-1) charges + probe via Bragg.*

atoms scattered at $+2ke_{x'}$
(resonant for $\delta_d = 2kv_x$)

unscattered atoms:
$\Rightarrow$ vortex core positions

atoms scattered at $-2ke_{x'}$
(resonant for $\delta_d = -2kv_x$)

from Shin group: Seo, & al. Scientific reports 7, 1 (2017)

Problem suggestions:

- in1D, estimate how the density of an interacting BEC is affect by “a wall” which imposes $n = 0$ at $r = 0$.

- Assume a pure BEC of sizes $(R, R, \Lambda R)$ and N atoms, estimate the size of a vortex insitu as a function of a_s, R and Lambda.
  + estimate how it would expand in free expansion, at short time.

- Estimate the interference pattern of 2 infinitely thin BEC separated by a distance d, with and without a phase slip of pi.

- Estimate an order of magnitude of the Doppler effect around a vortex for an laser light at $\lambda_L = 600nm$ and at a $distance = \xi = 1\mu m$

Outline

- **What are quantum atomic gases, what are vortices, and why two dimensions**
  - *ultracold gases, superfluids, and vortices for phase winding*
  - *vortices, rotation and excitations*
  - *specificity of vortices in 2D and 2D regimes: characteristic sizes*
- **How to image vortices in 2d gas experiments**
  - *vortex signature in the density: vortex core.*
  - *retrieving phase (charge) information : interferences between matter wave, time resolved dynamics, Doppler shifts*
- **How to generate vortices in 2d gases**
  - *spontaneous vortices in 2d, thermal proliferation and Beresinskii Kosterlitz Thouless mechanism*
  - *vortices as relics of out-of-equilibrium states, Kibble Zurek mechanism across phase transition…*
  - *vortices in turbulent systems…*

(no) long-range order in 2D

QUANTUM FLUIDS

Low-D (2D+1D) here =** motion frozen **for the atoms! $k_B T \ll \hbar\,\omega_z$

Order in 3D:

spontaneous symmetry breaking $\longleftrightarrow$ long-range order

order parameter s,
$G_1(r) = \langle s^*(r)s(0)\rangle \rightarrow \neq 0$

Low-D:

- Enhanced role of **fluctuations. Intuitively:** constraints imposed by neighbors are less.
- Prevent apparition of long-range order at finite T

no spontaneous breaking of continuous symmetry

$G_1(r) = \langle s^*(r)s(0)\rangle \rightarrow \; 0$

but at low T :

- quasi ordering: long coherence length
- \+ repulsive interaction: suppression of density fluctuations, only phase fluctuations remains

Mermin-Wagner-Hohenberg theorem (1966-67)

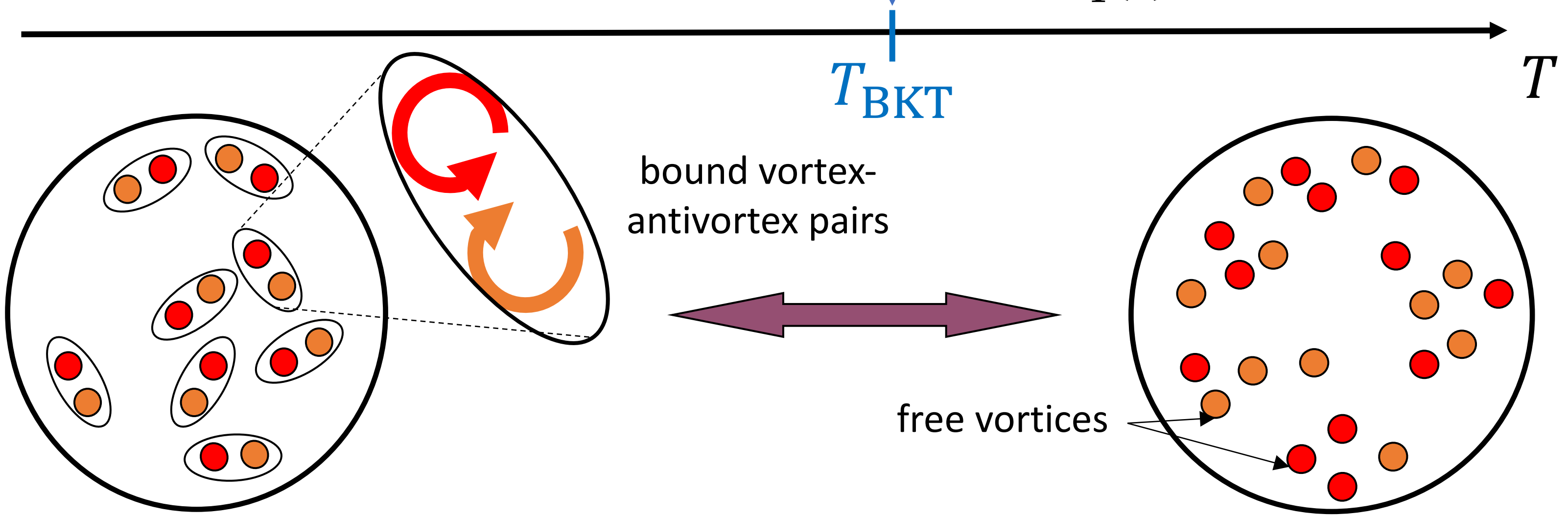
order in 2D & vortices

In 2D, in presence of interactions, there can be even more ordering appearing:

New transition mechanism *based on the* energetics of topological defects (= vortices for the superfluid case)

Universal jump: $\mathcal{D}_s = n_s \lambda_T^2 = 4$

$G_1(r) \propto r^{-1/n_s\lambda_T^2}$ $\qquad$ $G_1(r) \propto e^{-r/\ell}$



vortices free energy:

$F = E - TS$

$\log(R/\xi)$

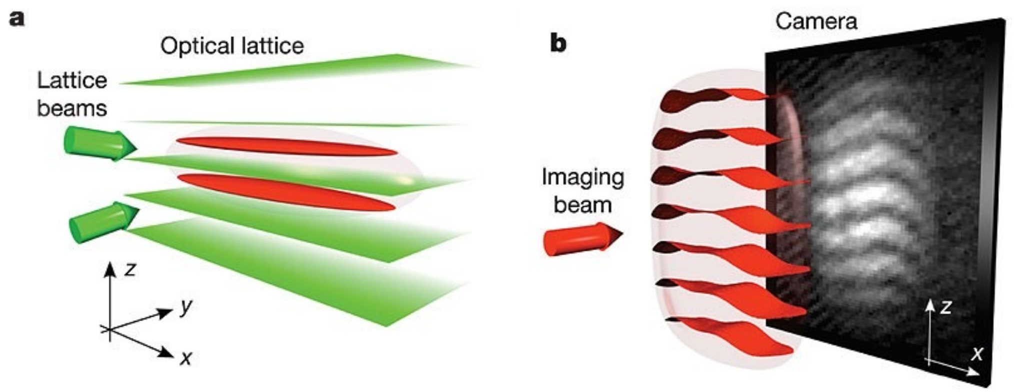
Uniform gas radius R with hollow core vortices radius ξ :

$$E \approx n_s \int_{\xi}^{R} \frac{1}{2}\left(\frac{\hbar}{mr}\right)^2 dr$$

$$S \approx k_B \ln(R^2\pi/\xi^2\pi)$$

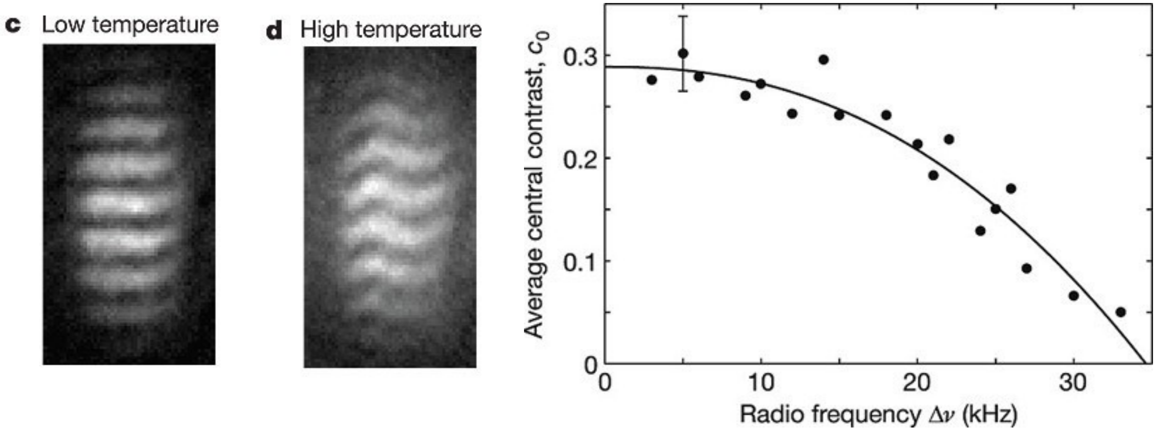
Berezinskii Kosterlitz Thouless (1971-73)

microscopic signature of the BKT mechanism

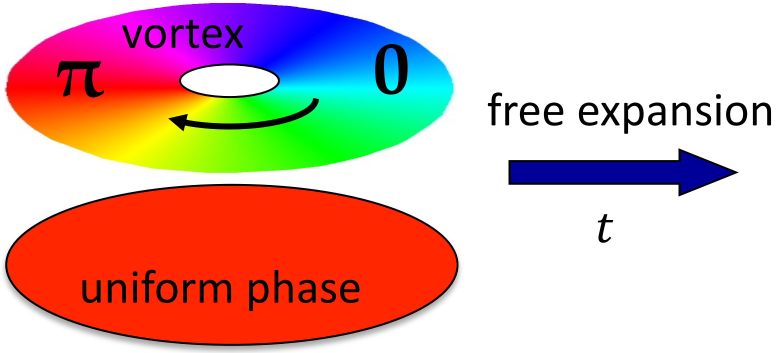


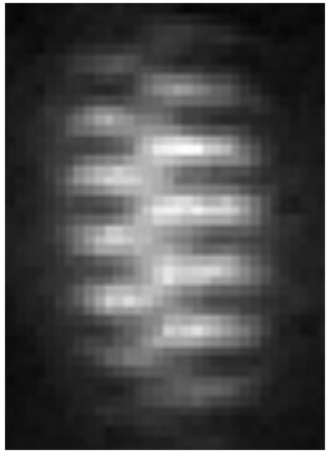
Protocol: create 2 independent 2D gases + make them interfere in time-of-flight.

+ repeat measurement for different temperatures.



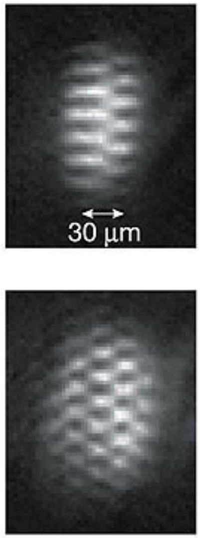
fringe contrast => access to $G_1(r) = \langle \psi^\dagger(r)\psi(0) \rangle$

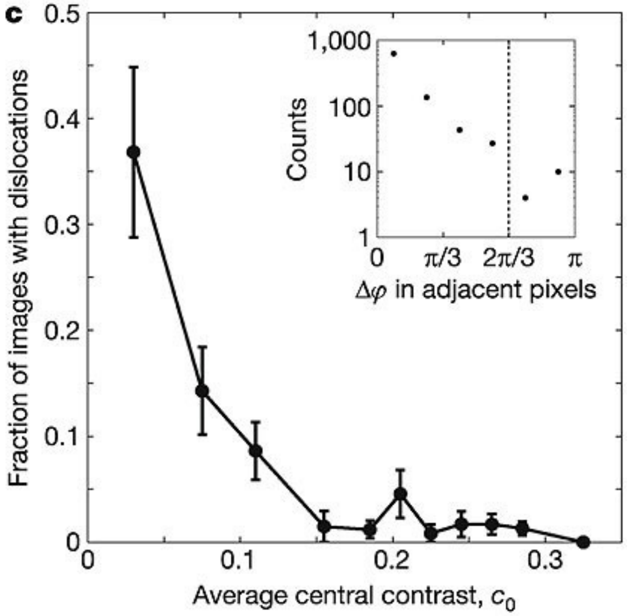




see previous section: vortices detected via dislocations in interferences.

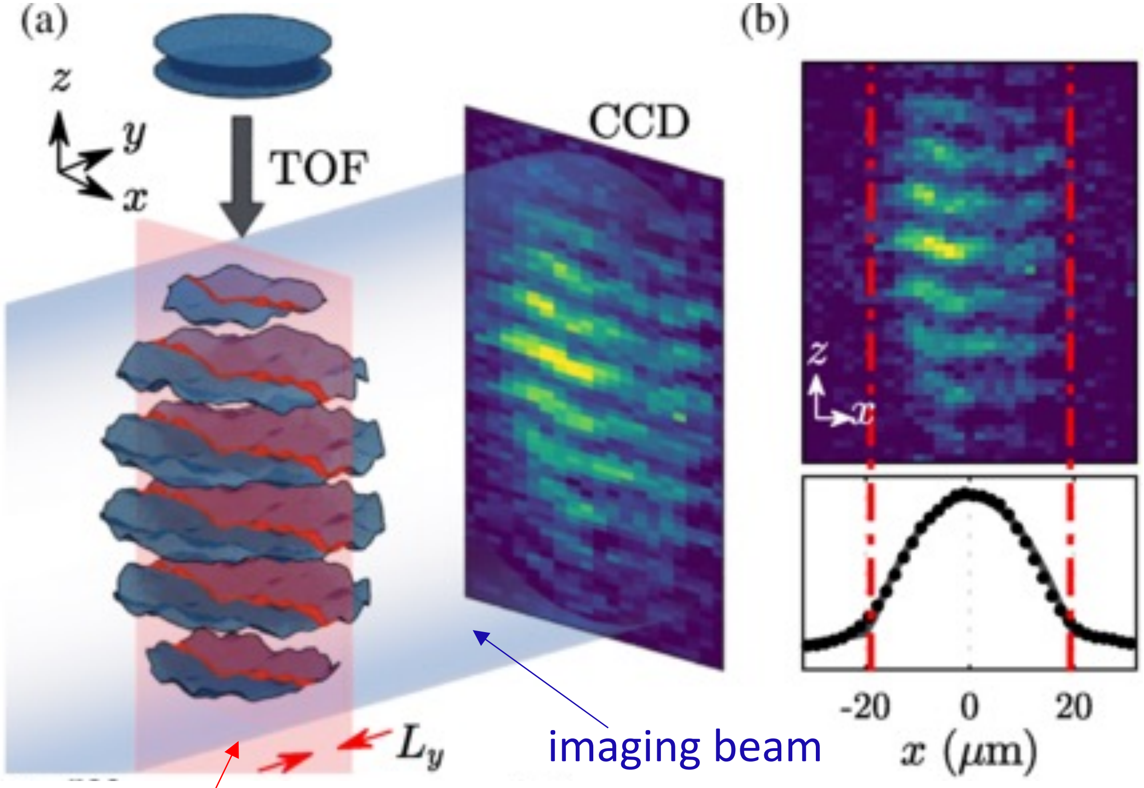
"Thermal activation" of vortices





Dalibard group : Hadzibabic et al, Nature **441**, 1118 (2006)

microscopic signature of the BKT mechanism

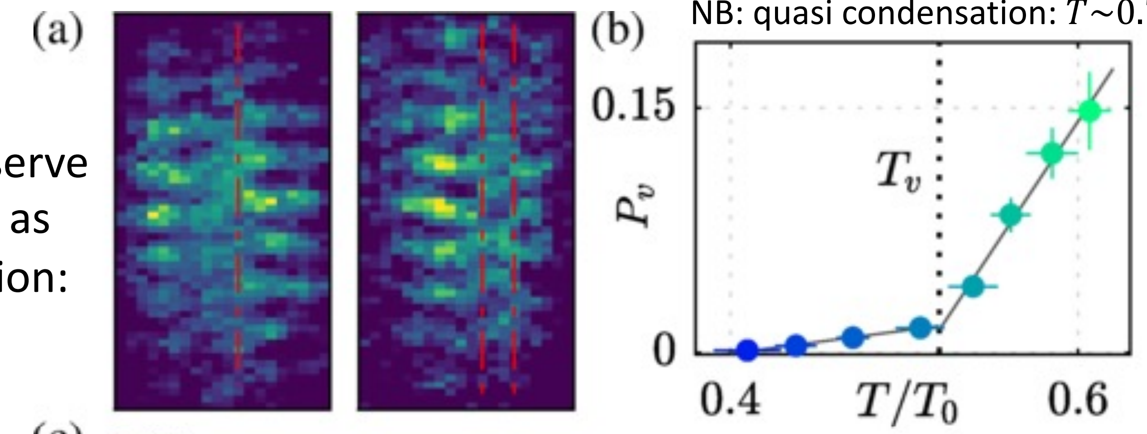


imaging beam

thin repumping laser beam
for selective imaging

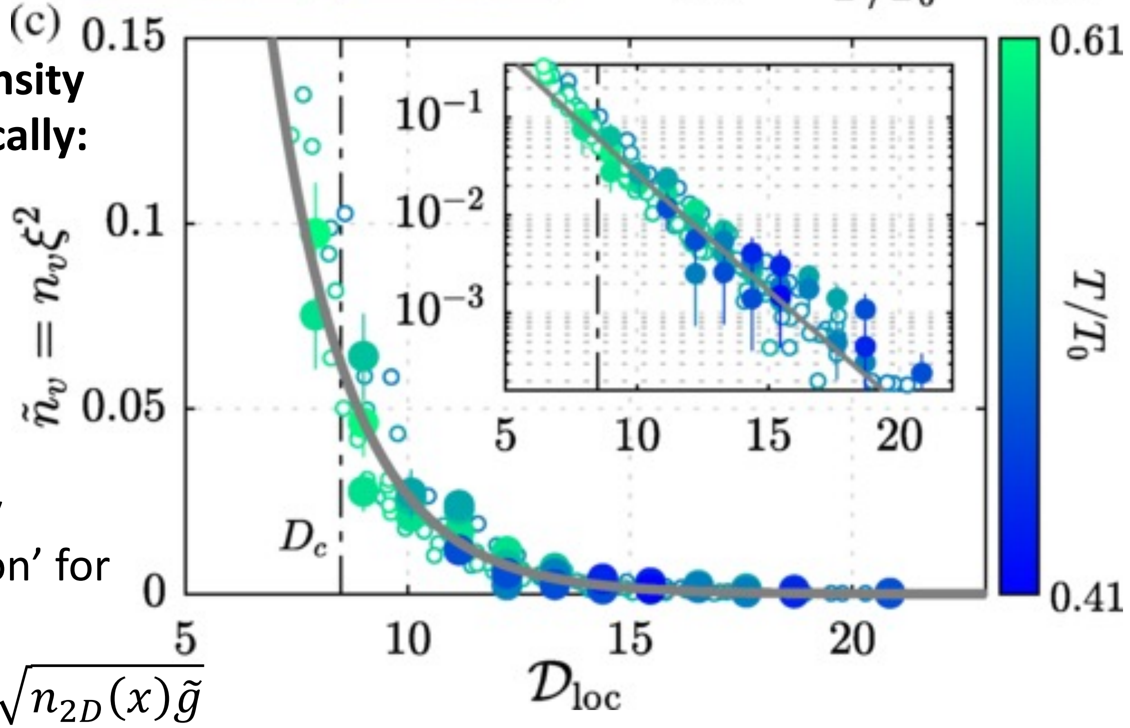
Similar protocol: create 2 independent 2D gases + make them interfere in time-of-flight.
But local probing of interference patterns: no integration along imaging beam!

also observe vortices as dislocation:



NB: quasi condensation: $T \sim 0.7 T_0$

vortex density known locally:



'local density approximation' for scalings:

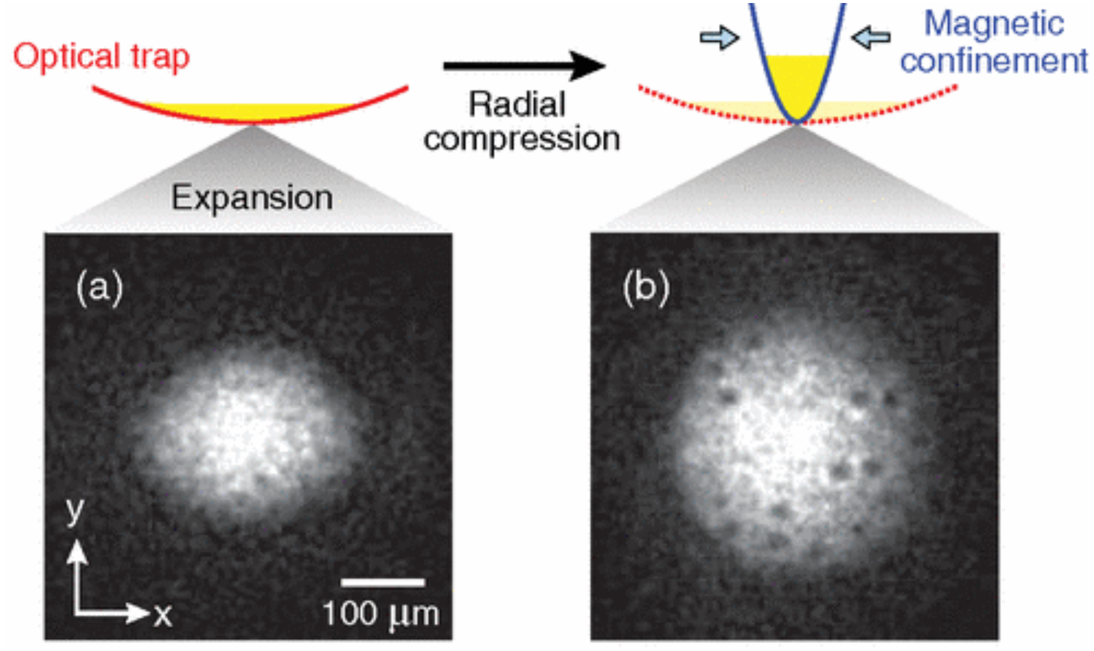
$$\xi(x) = 1/\sqrt{n_{2D}(x)\tilde{g}}$$

$$\mathcal{D}_{loc} = n_{2D}(x)\lambda(T)^2$$

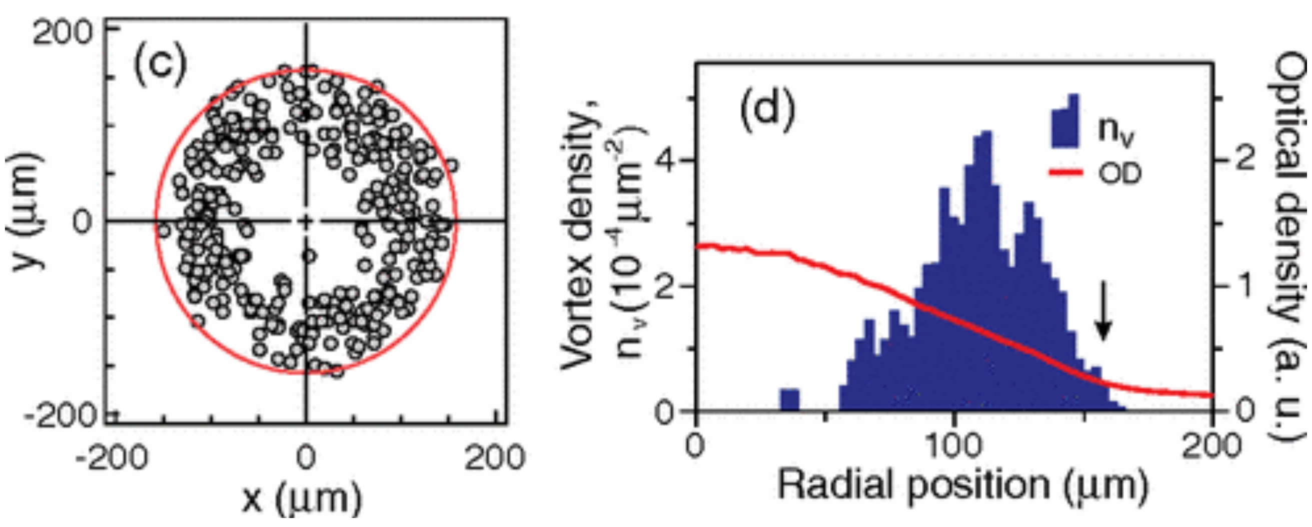
Foot group : Sunami et al, PRL **128**, 250402 (2022)

microscopic signature of the BKT mechanism, 2

Protocol: create single 2D gases. Detect vortices via vortex cores



Repeat same experimental condition "many" times (~20) and perform statistical analysis of positons
➔ free-vortex spatial density distribution / gas density profile



Apply a **special 2-step magnification technique** to remove phase fluctuations effects :

1) make the gas 3D via slow radial compression (remove phase fluctuations+ tightly bound pairs)
2) free expansion (reveal vortex cores of free or weakly bound pairs)

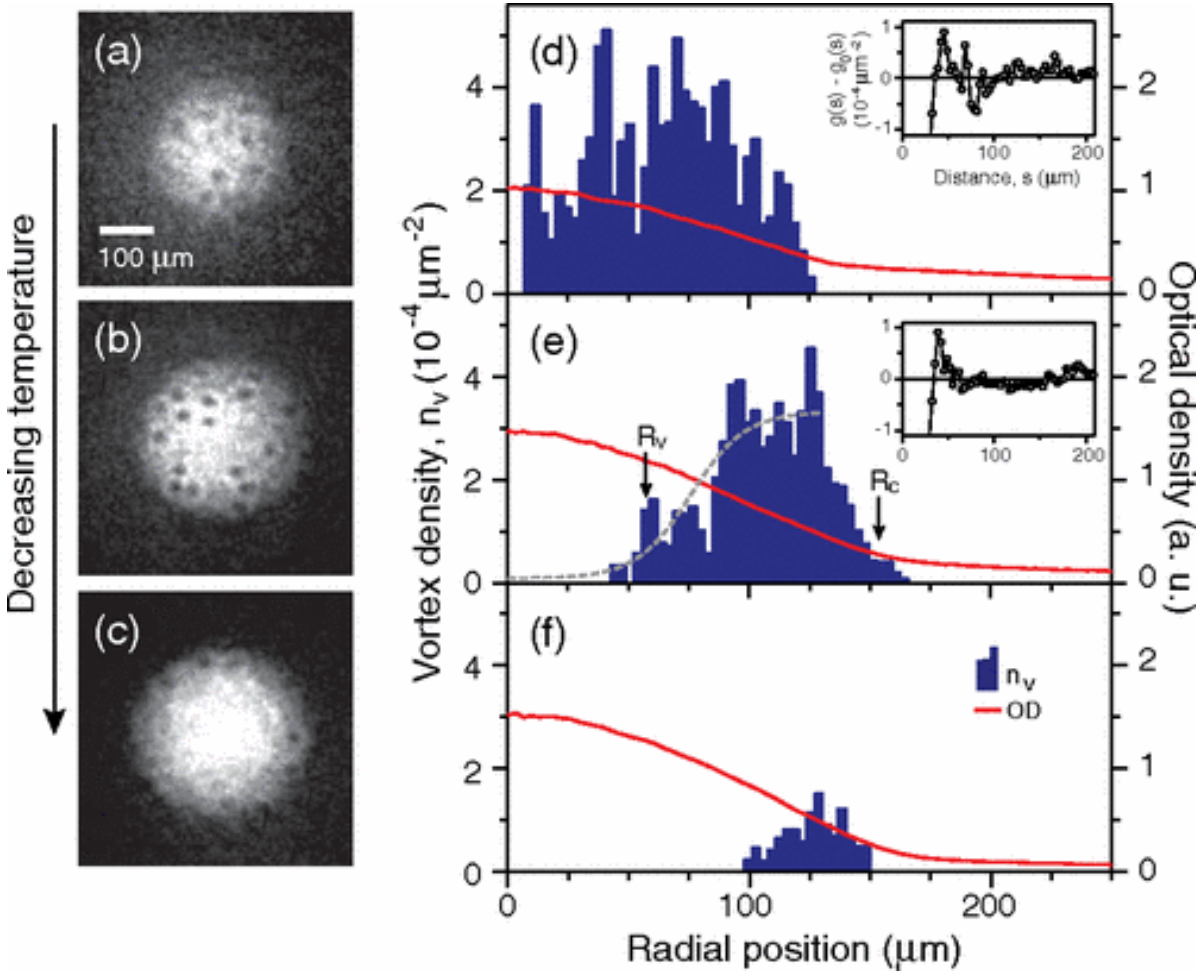
more vortices in the wings => 'local density approximation': lower phase space density

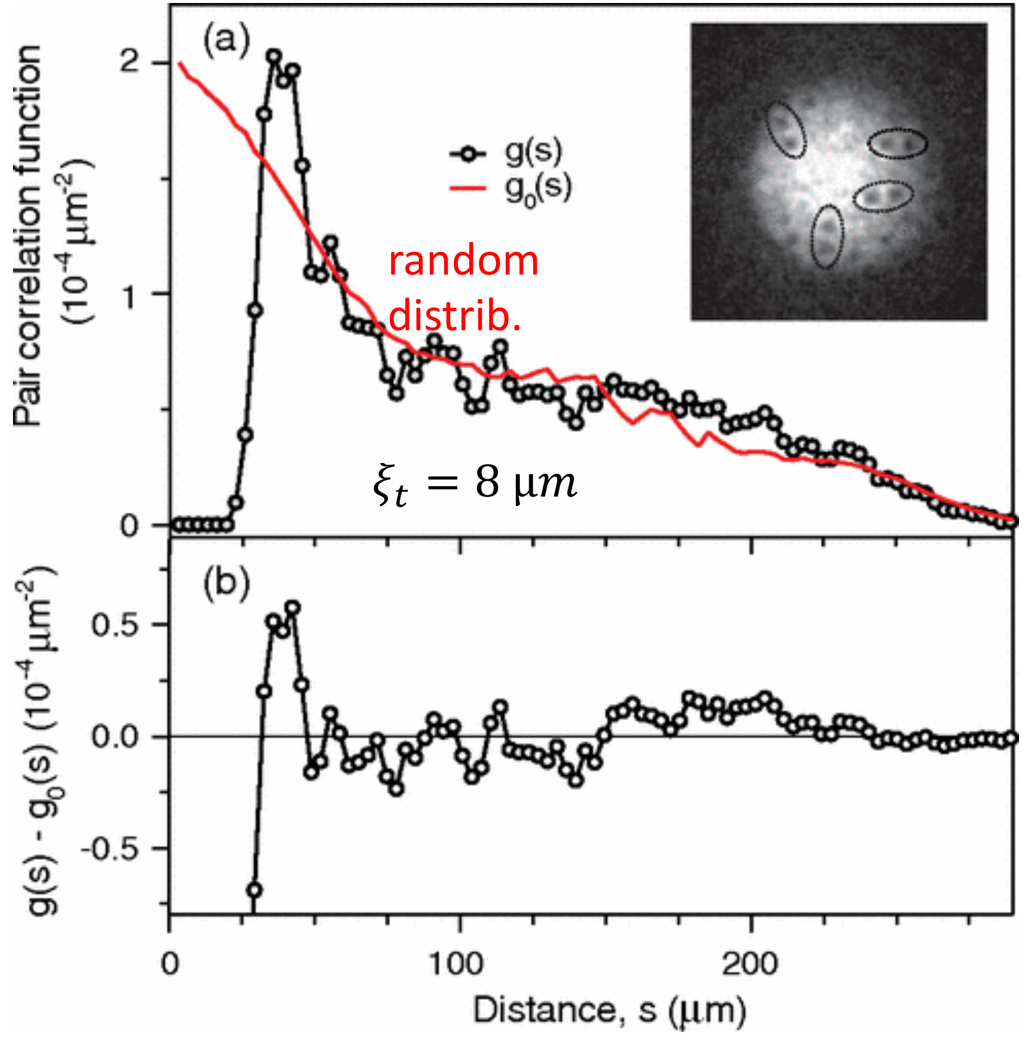
Shin: J. Choi et al, PRL **110**, 175302, (2013)
see also Cornell: Schweikhard et al., PRL 99, 030401 (2007)

microscopic signature of the BKT mechanism, 2

+ repeat measurement for different temperatures.

analysis of vortex pair correlation…





Number of vortices reduces with T + gets more to the wings => lower phase space density

Shin: J. Choi et al, PRL **110**, 175302, (2013)

Open questions of BKT vortices

- **BKT vortices beyond the bosonic superfluid order:**

  - **Fermions in the BEC-BCS crossover**. signature of BKT superfluid ordering observed but no microscopic signature of vortices proliferation yet.
  - **Beyond repulsive contact interaction:** role of anisotropic / longer range interacitons on the thermodynamics of vortices?
  - **Superfluid with (spontaneous) spatial density structures.** Supersolids, droplets, etc. Competition vortices/spatial order?

All of this can be access with ultracold atoms!

See also other talks in this week!

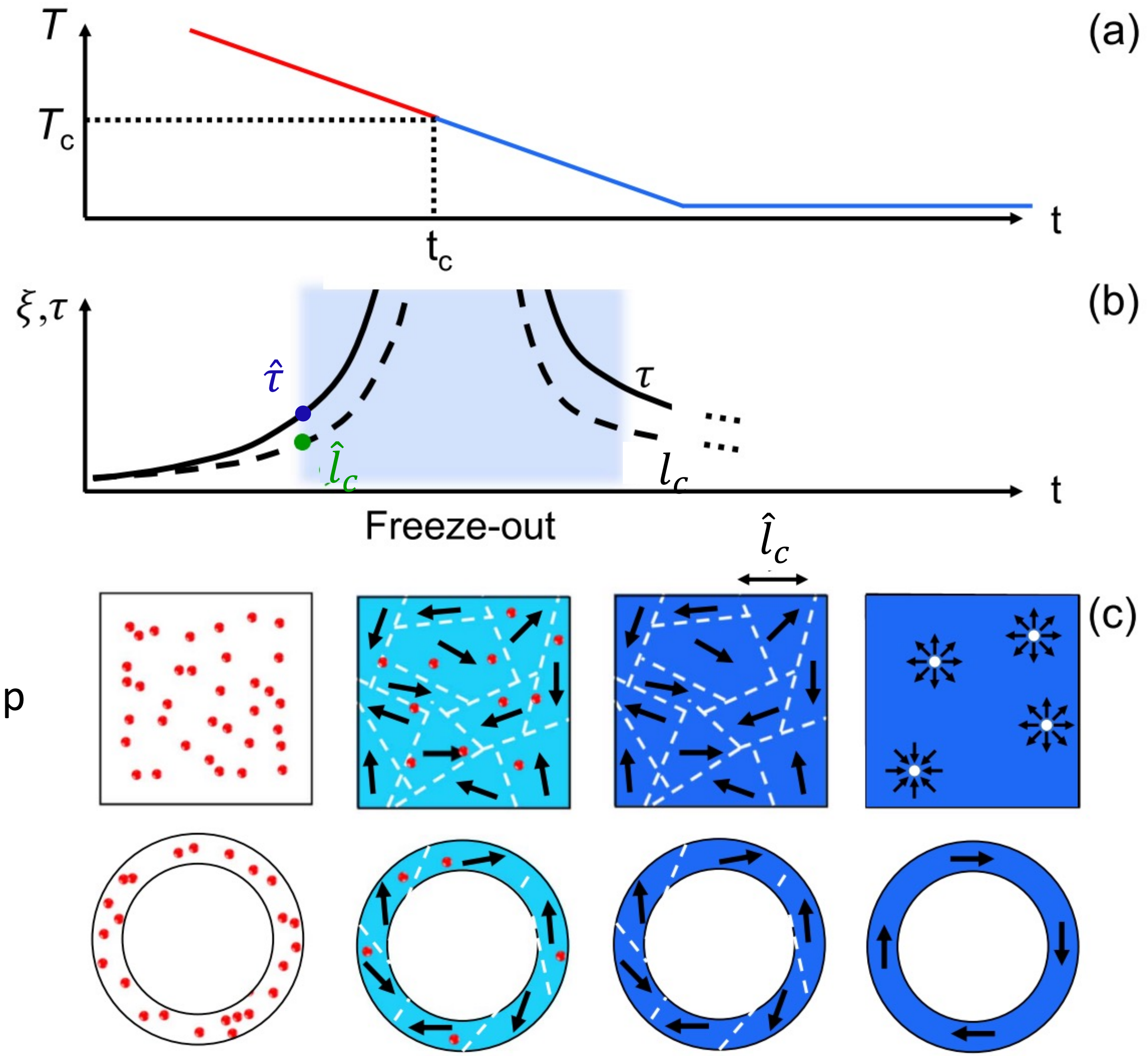
vortices, relics of transition. Kibble-Zurek mechanism

back to 3D (pancake shaped) gases.

phase transitions = discontinuous process.

$\Rightarrow$ divergence of :

- thermalisation time τ
- coherence length l_c



square trap

ring trap

In a dynamical crossing, e.g. $T(t)$. transition crossed at t_c

$\Rightarrow$ **'freeze-out** time':

$$\hat{\tau} \equiv \tau(t) = |t_c - t|$$

$\Rightarrow$ frozen correlation length: $\hat{l}_c$

(i) during freezing out: creation of domains of independent phases of size $\sim\hat{l}_c$

(ii) after transition, **"coarsening dynamics"**, phase domains merge.

if phase winding => topological defects are formed and survives!

from Beugnon &Navon J. Phys. B: At. Mol. Opt. Phys. ***50*** *022002 (2017) review*

Kibble (1976), Zurek (1985)

vortices, relics of transition. Kibble-Zurek mechanism

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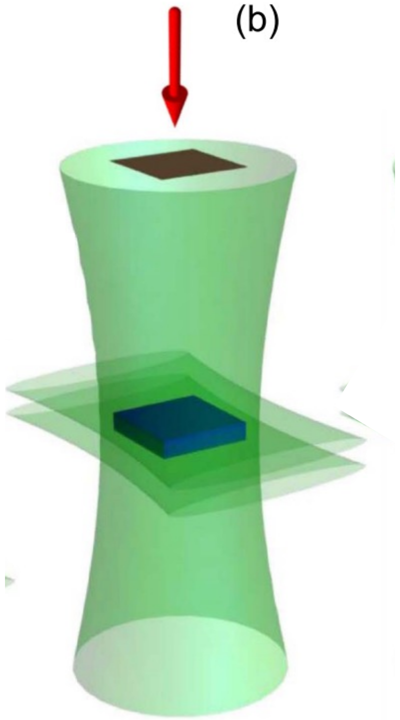
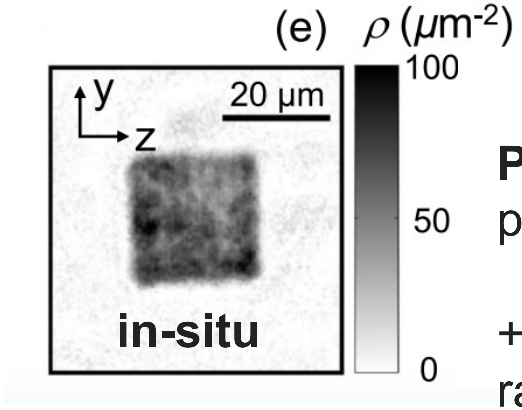
first experiment in 3D (transition = Bose Einstein condensates): Anderson group, Weiler & al. *Nature* 455, 7215 (2008), see also “vortex dynamics” experiment from Hall group

2014-2015, Dalibard group: experience in pancake shaped traps

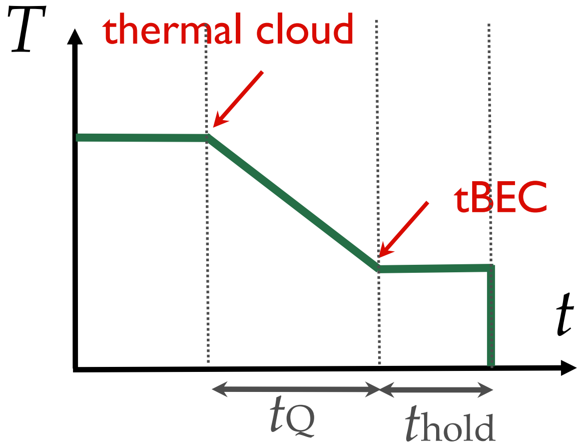
transition = transverse condensation (tBEC) = condensation in the tightly confined direction



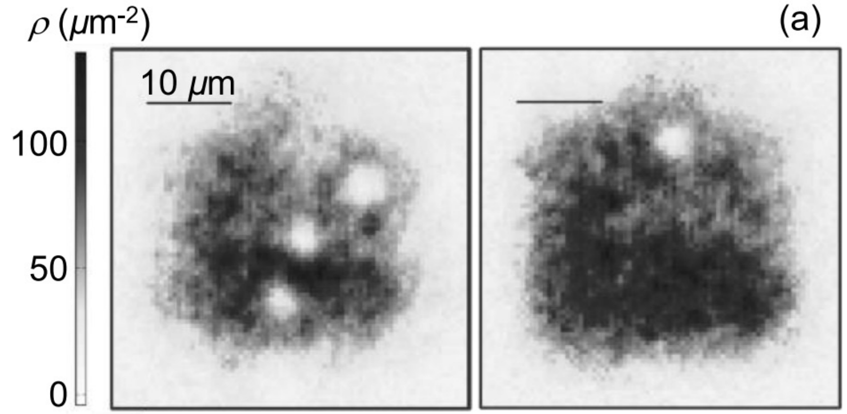


Protocol: trap gas in a pancake uniform trap.

+ perform evaporation ramp to tBEC



Observe vortex via vortex cores in short free-expansion



random number of vortices, changing with ramp speed.

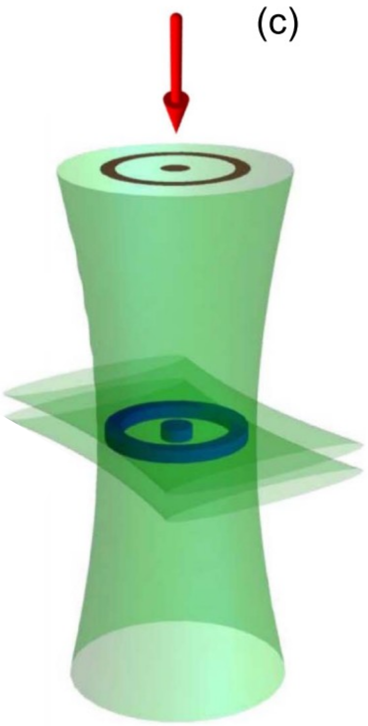
Chomaz & al., Nat. Commun. 6 6162 (2015)

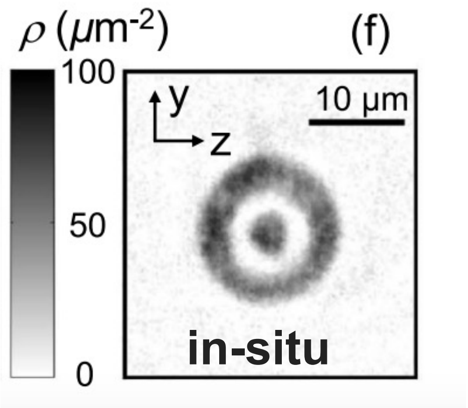
see also: Shin group. e.g. Ko & al., Nat. Phys. 15, 1227 (2019).

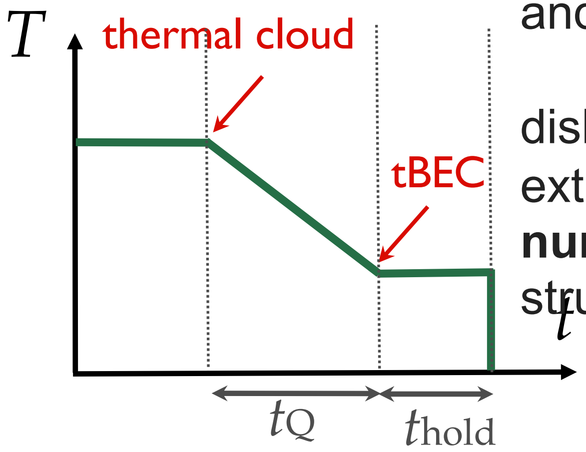
vortices, relics of transition. Kibble-Zurek mechanism

2014-2015, Dalibard group: experience in pancake shaped traps
transition = transverse condensation (tBEC) = condensation in the tightly confined direction

Also probing vortex charge via interference. here ring tBEC and small central phase reference.





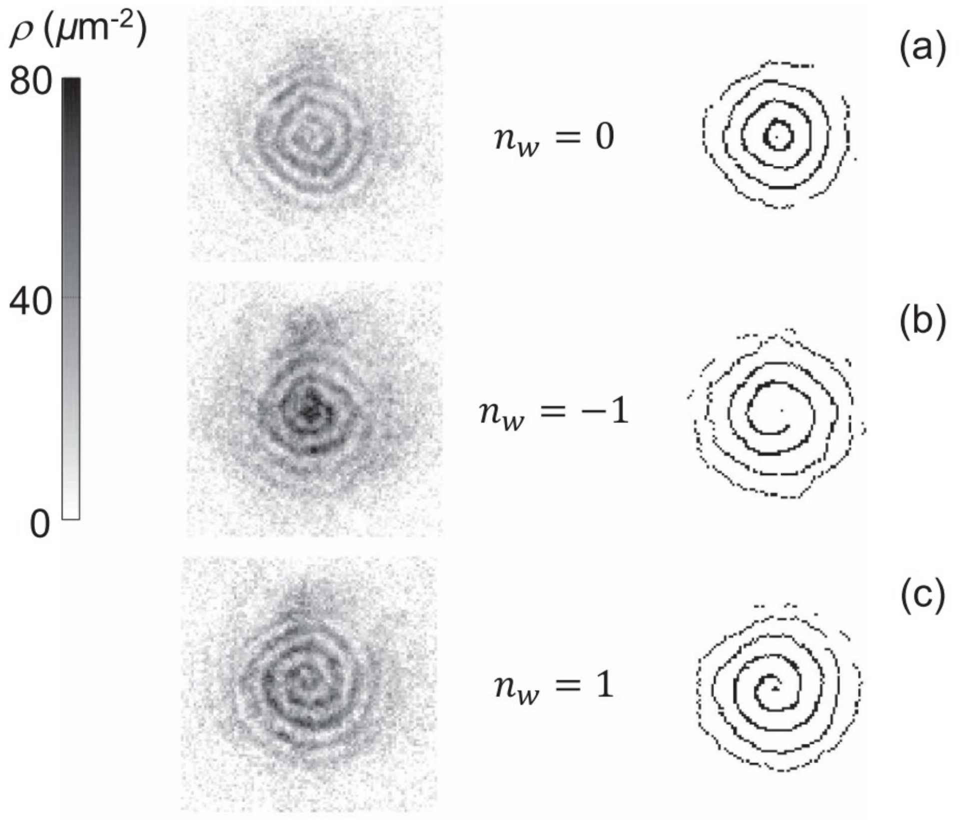


Protocol: trap gas in a ring + small central disk

perform evaporation ramp to tBEC

probe interference disk and ring in 2D expansion.

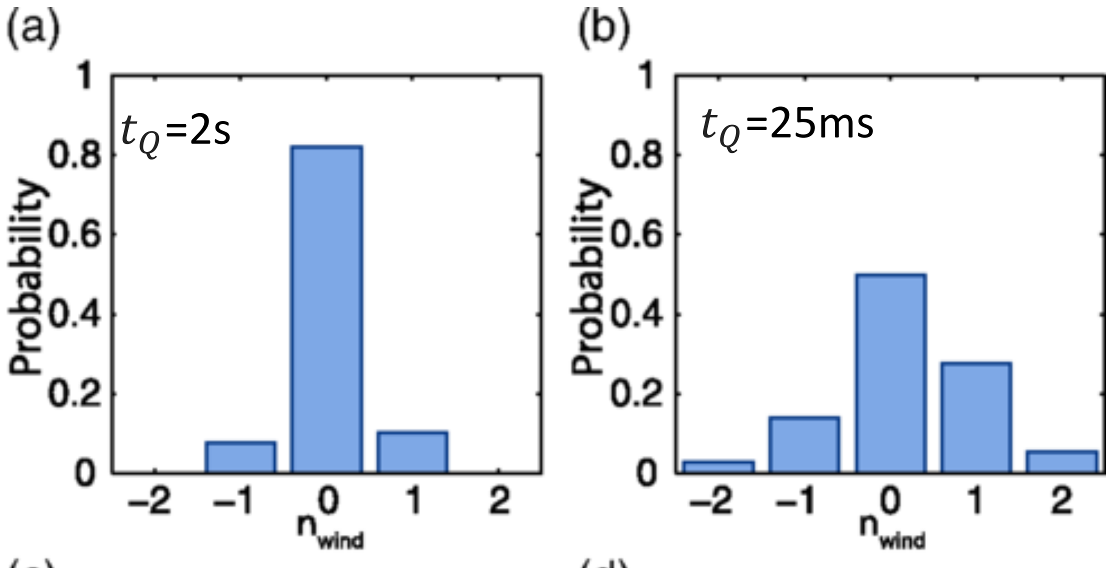
disk = phase-reference. extract **charged winding number** from pattern structure:



Corman, Chomaz & al., PRL (2014)

Vortices, relics of transition. Kibble-Zurek mechanism

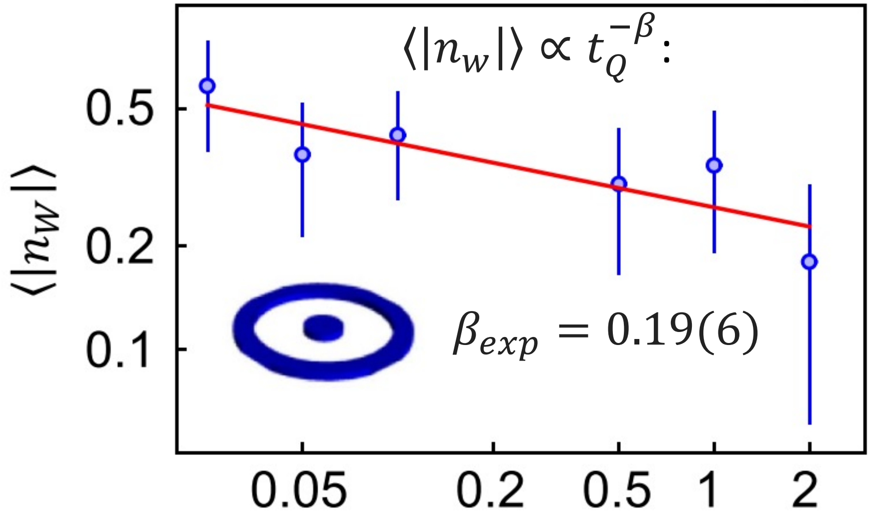
Many repetitions (~40) for different evaporation times
$\Rightarrow$ no net charge
$\Rightarrow$ increased number of vortices for small t_Q

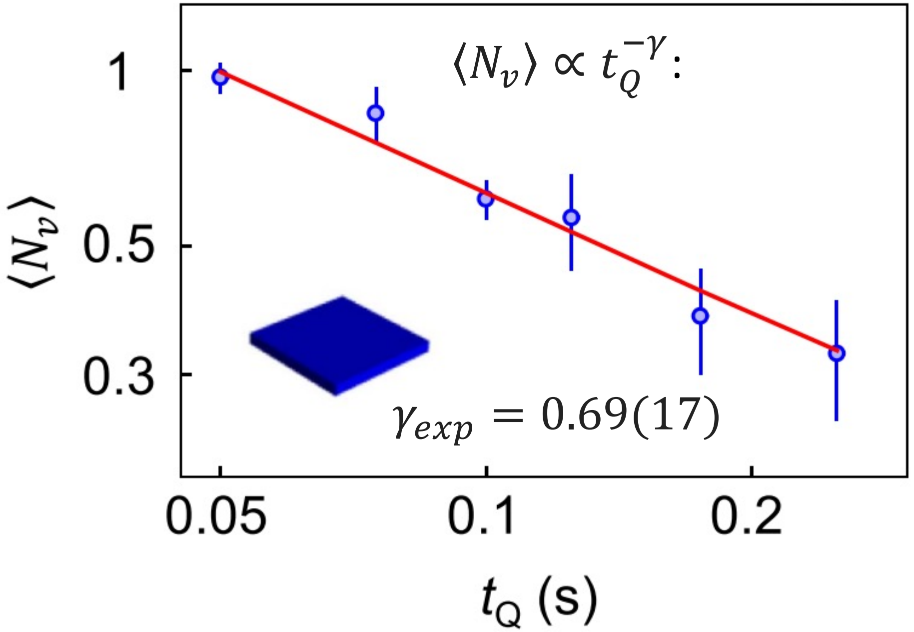


Number of vortices / t_Q: critical scalings (Universality classes)

$$\langle |n_w| \rangle \propto t_Q^{-\beta}: \beta_{MF} = 0.125, \beta_F = 0.167$$

$$\langle N_v \rangle \propto t_Q^{-\gamma}: \gamma_{MF} = 0.5, \beta_F = 0.67$$





Open questions of Kibble Zurek vortices

- **KZ vortices beyond the bosonic superfluid order:**

  - **BKT ordering!** very distinct universality class. still same mechanism predicted to hold… scaling not yet observed
  - **Also many more orders to be studied…**
  - **Critical dynamics and vortex relics beyond Unicversal sacalings.** Behavior in extreme conditions currently in focus.

See also other talks in this week!

Vortices, dynamics & turbulence.

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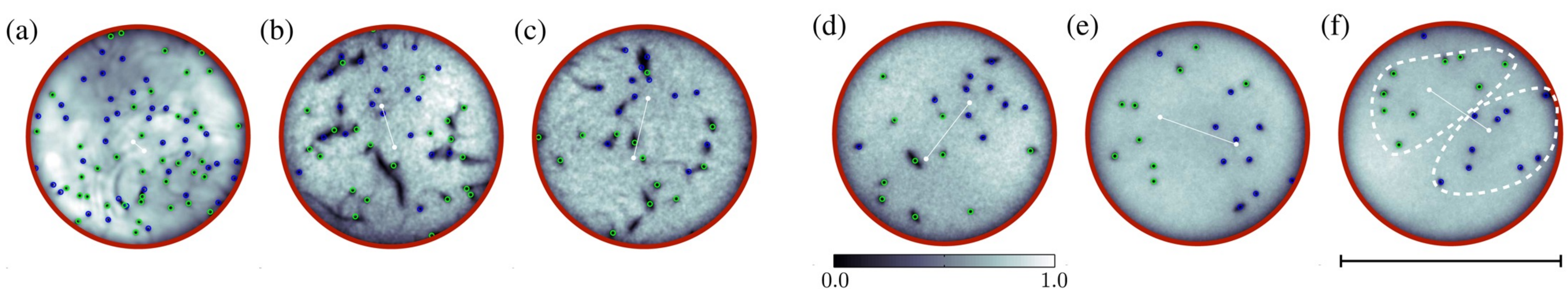
(Quantum) turbulence <= chaotic flow of a (super)fluid.

=> vortex assemblies (and their organisation/dynamics!)



from Simula, Davis, Helmerson, PRL 113, 165302 (2014)

Very active research in quantum gases!

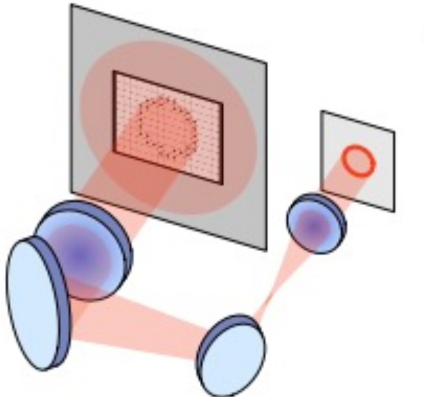
- How quantum turbulence decays:
  decay of a vortex assemblies (process for vortex-vortex annhilation, vortex pairs collisions, etc.)

- Possibility of “inverted cascade” in 2D (i.e. formation of large scale superflow structures):
  large-scale vortex clusters “Onsager cluster”

Turbulent Vortex Clusters

2013-2014, first experimental works but could not reach the clustering regimes...

2019, 2 experiments with improved modulation schemes based on programmable imprinting of arbitrary light potentials and using arrays of potentials

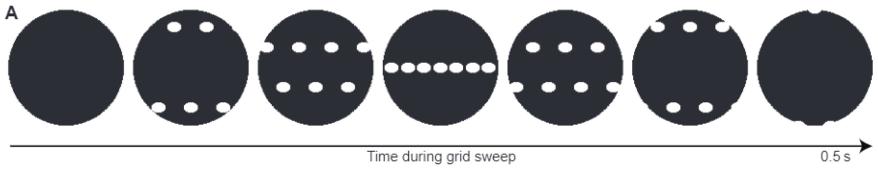


digital micromirror device (DMD)

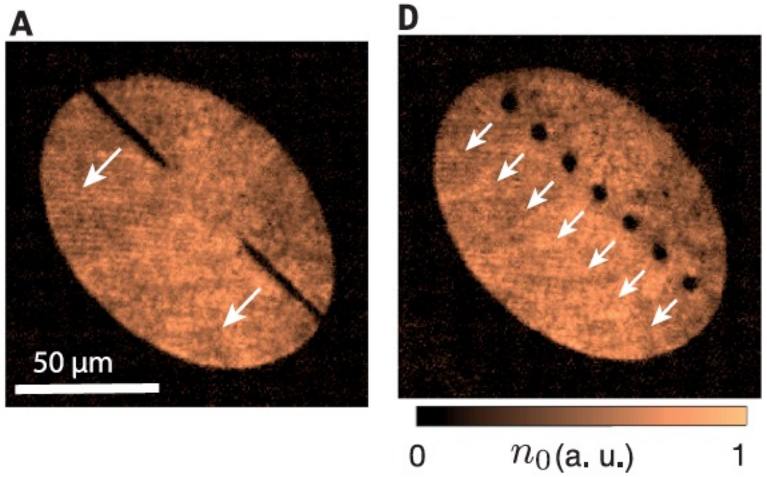
from Gauthier, &al, AAMOP 70, 1-101 (2022).

1) Create pancake shapped gases of uniform densities

2) Periodic driving by sweeping arrays of repulsive potentials:



3) Repeat with different defect sizes (control energy imparted)



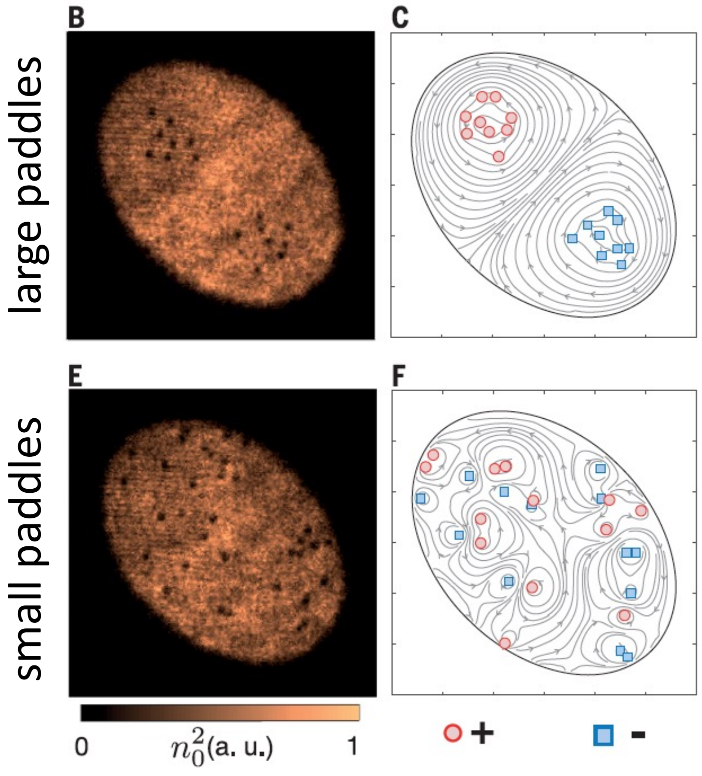
from Johnstone & al, Science 364, 1267-1271 (2019)
+ Gauthier & al, Science 364, 1264-1267 (2019)

Turbulent Vortex Clusters

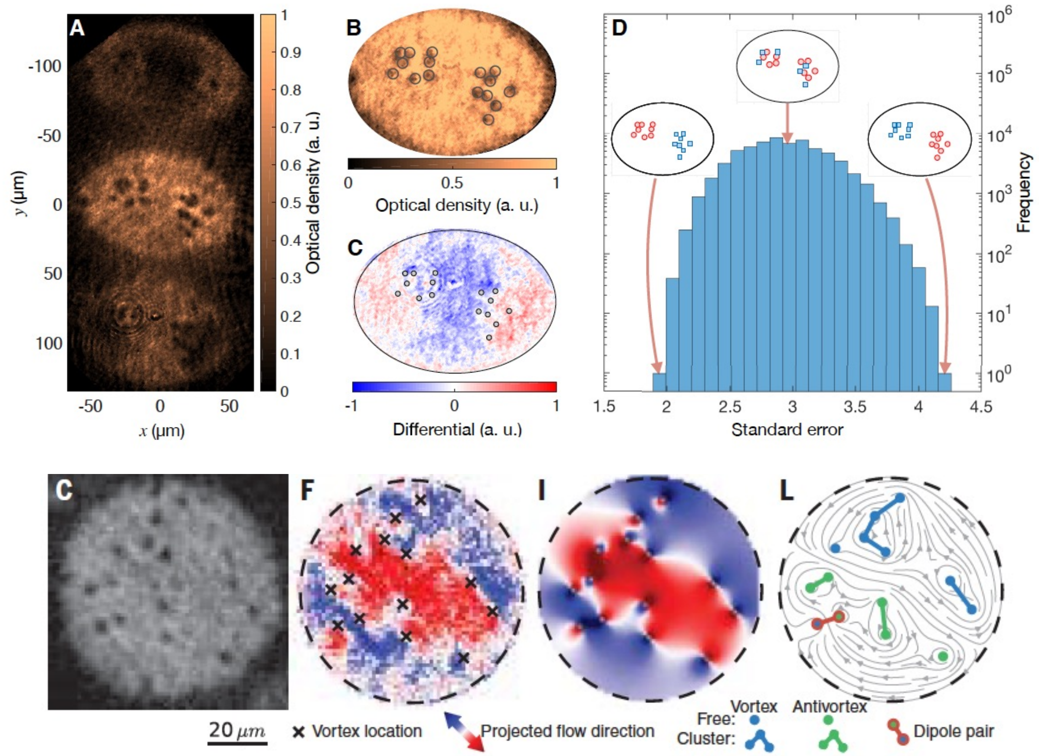
2013-2014, first experimental works but could not reach the clustering regimes...

2019, 2 experiments with improved modulation schemes based on programmable imprinting of arbitrary light potentials and using arrays of potentials.

- ➢ image vortex cores after short free exp.



- ➢ image vortex cores and velocity field via Bragg measurements:



from Gauthier & al, Science 364, 1264-1267 (2019) + Johnstone & al, Science 364, 1267-1271 (2019)

Much more on turbulence

- **Understanding the decay from elementary processes between vortices**
- **How does this decay processes connects to the critical scalings…**
- **Role of differents orderings, interactions, particles…**

See upcoming talks in this week!

Outline

- **What are quantum atomic gases, what are vortices, and why two dimensions**
  - *ultracold gases, superfluids, and vortices for phase winding*
  - *vortices, rotation and excitations*
  - *specificity of vortices in 2D and 2D regimes: characteristic sizes*
- **How to image vortices in 2d gas experiments**
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  - *spontaneous vortices in 2d, thermal proliferation and Beresinskii Kosterlitz Thouless mechanism*
  - *vortices as relics of out-of-equilibrium states, Kibble Zurek mechanism across phase transition…*
  - *vortices in turbulent systems…*

Thank you for your attention!

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