BEC experiments at JILA

Eric Cornell, {Carl Wieman}

NIST, N.S.F.

1) "Spin" 1/2 experiments { H. Lewandowski, J. McGuirk, D. Harber, J. Obrecht

2) Hypersonic shock

3) Rapidly rotating condensates

{ Peter Engels, Ian Coddington, Volker Schweikhard (*), Veronique Bogendorff, Shihkuang Tung

4) [Atom Chip] 5) [finite-T Casimir-Polder]

Old days 98-99 MIT, JILA spinor work

Now: Spinor BEC rebirth!

Thanks 1) C.M.P community

2) Beautiful new experiments (Sengstock, Chapman)

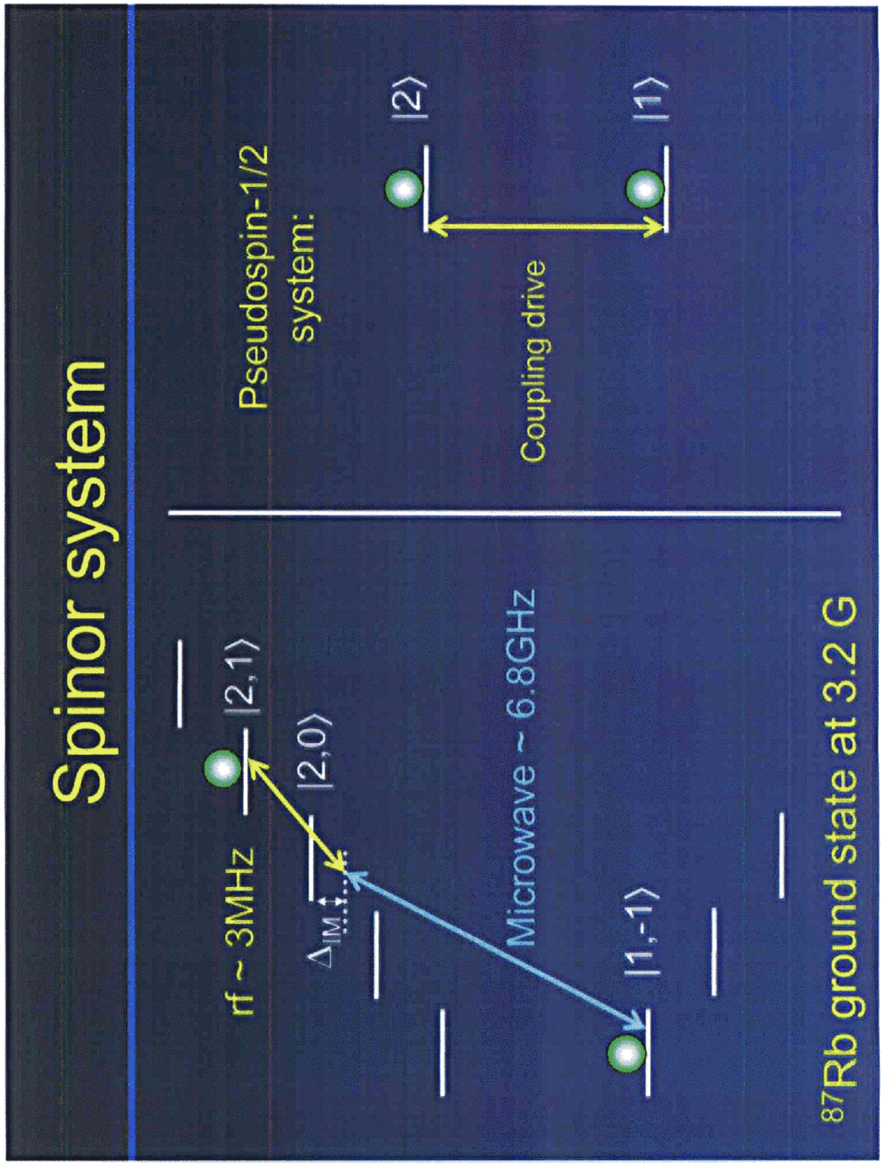
Na S=1 Ketterle

Rb S=1, S=2 } Sengstock, Chapman

Rb "S"=1/2 JILA

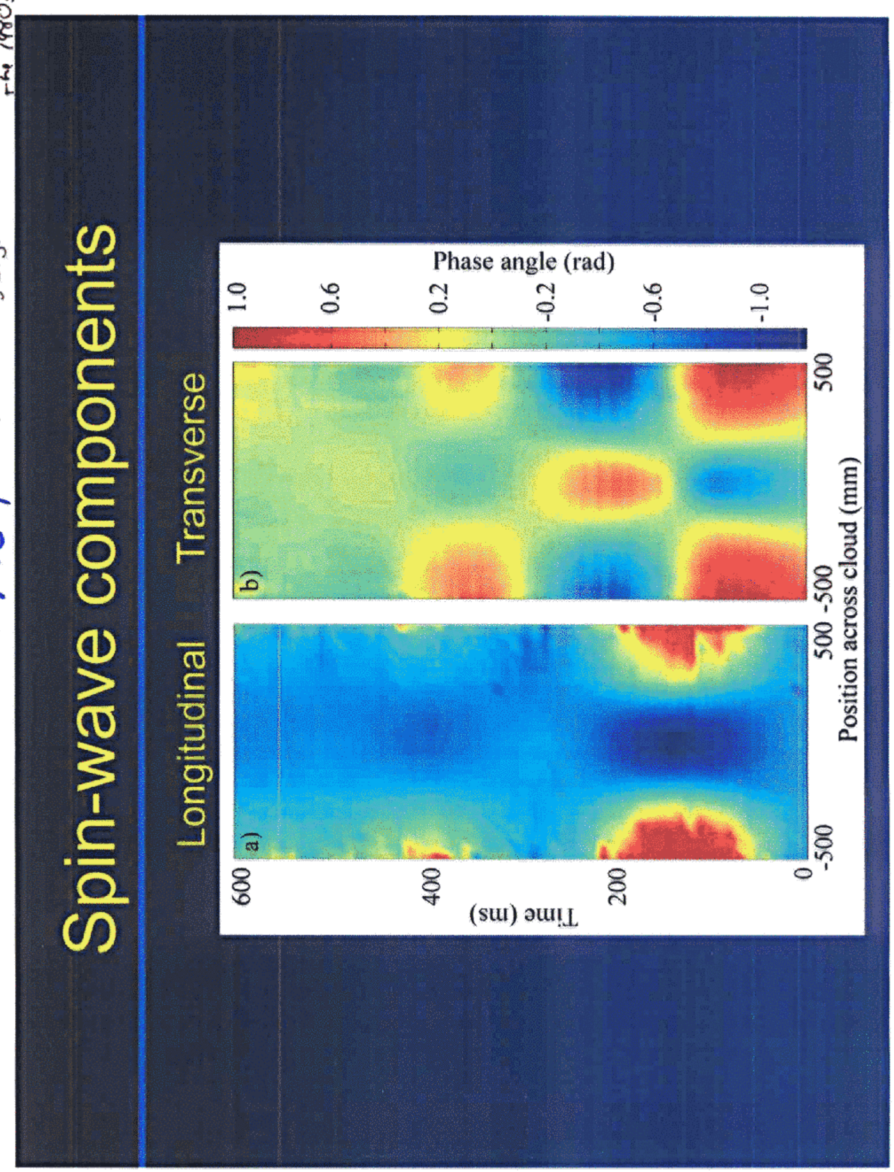
In general, S=1/2 system less rich.

But..



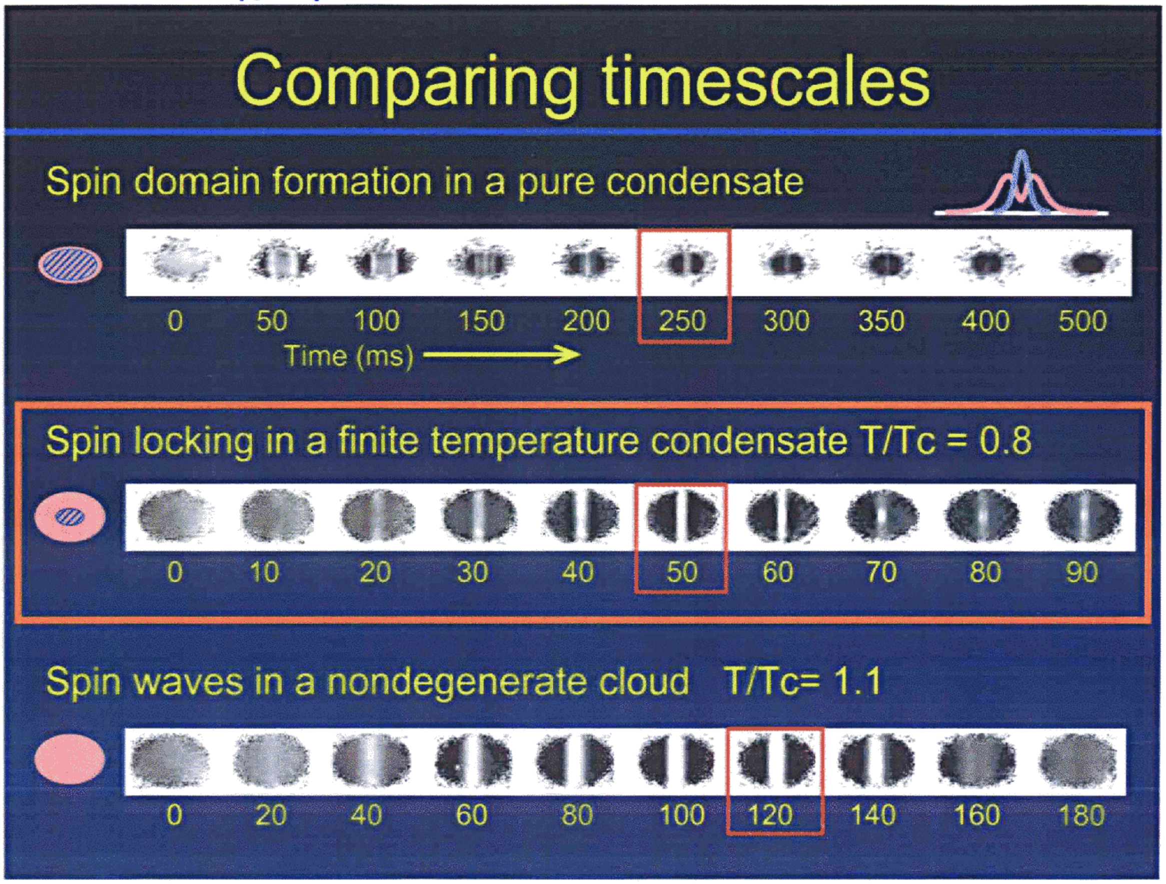
$\mu_1^{mag} = \mu_2^{mag}$ $|1\rangle = |\uparrow\rangle$ $|2\rangle = |\downarrow\rangle$

$T > T_c$ / Recall Lee, Bigelow work from the 1980s



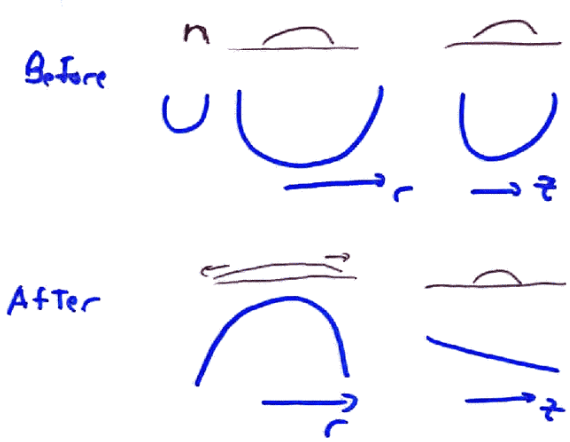
Early theory: Leggett, Ruckenstein, Lalöe / Recent theory Levitov, Williams + Nikuni, Lalöe

Note $U_{12} = \sqrt{U_1 U_2} \pm 0.5\%$ Separation driven by $U_{11} > U_{22}$



J.M. McGuirk PRL also cm/0306584

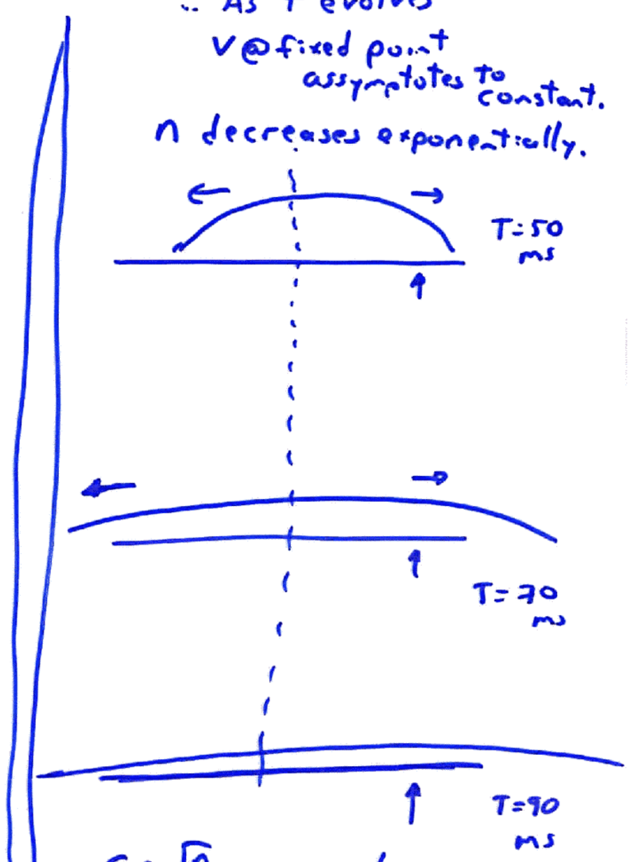
2-D Expansion



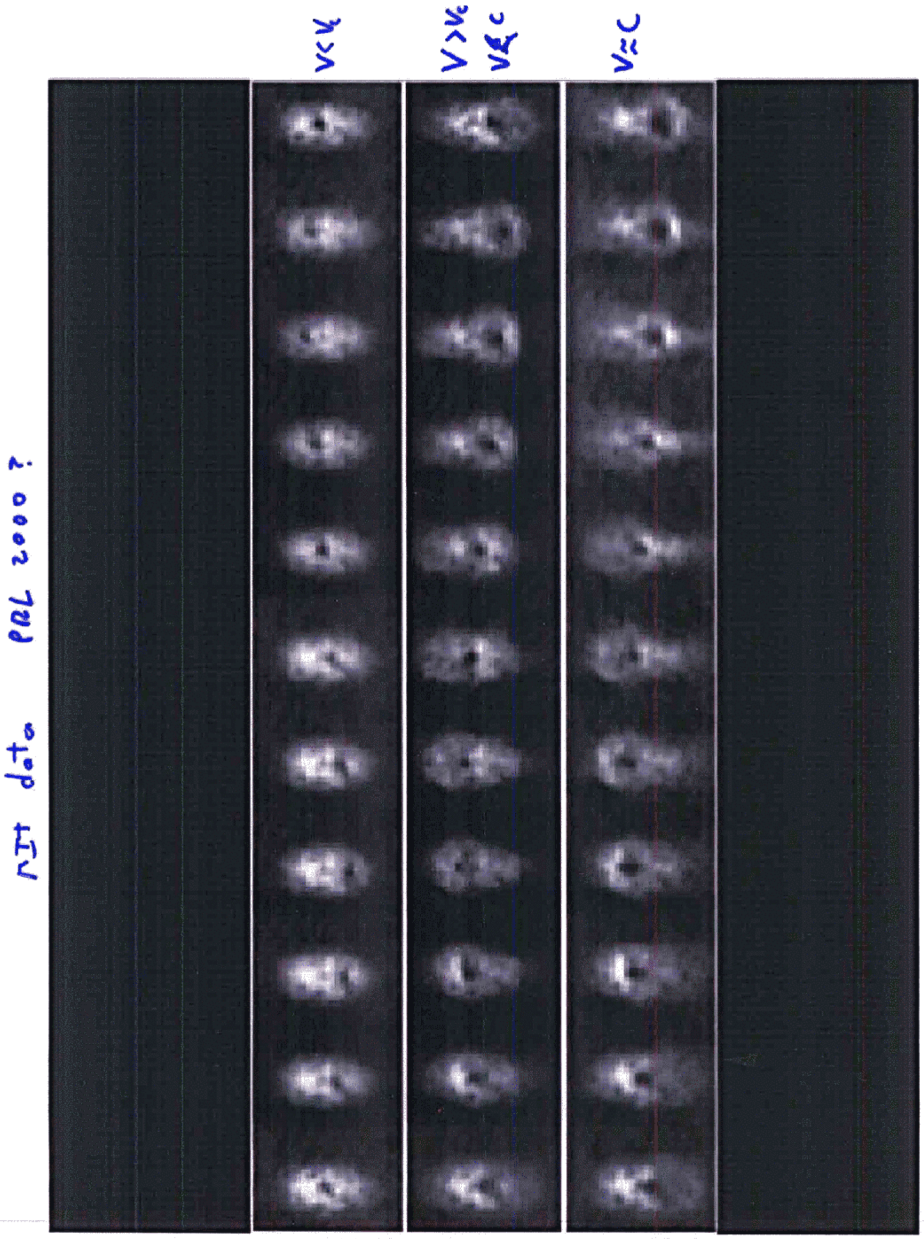
Good for viewing vortex lattices!

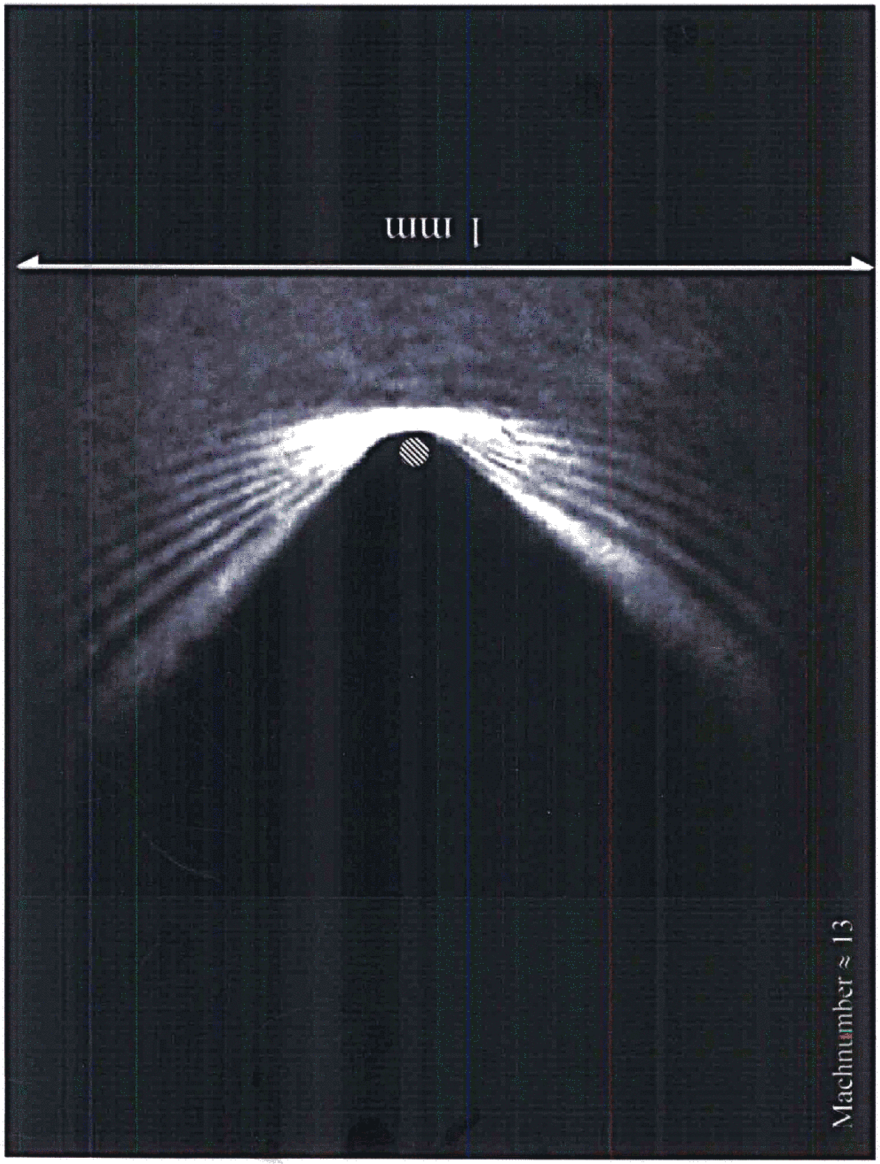
also..

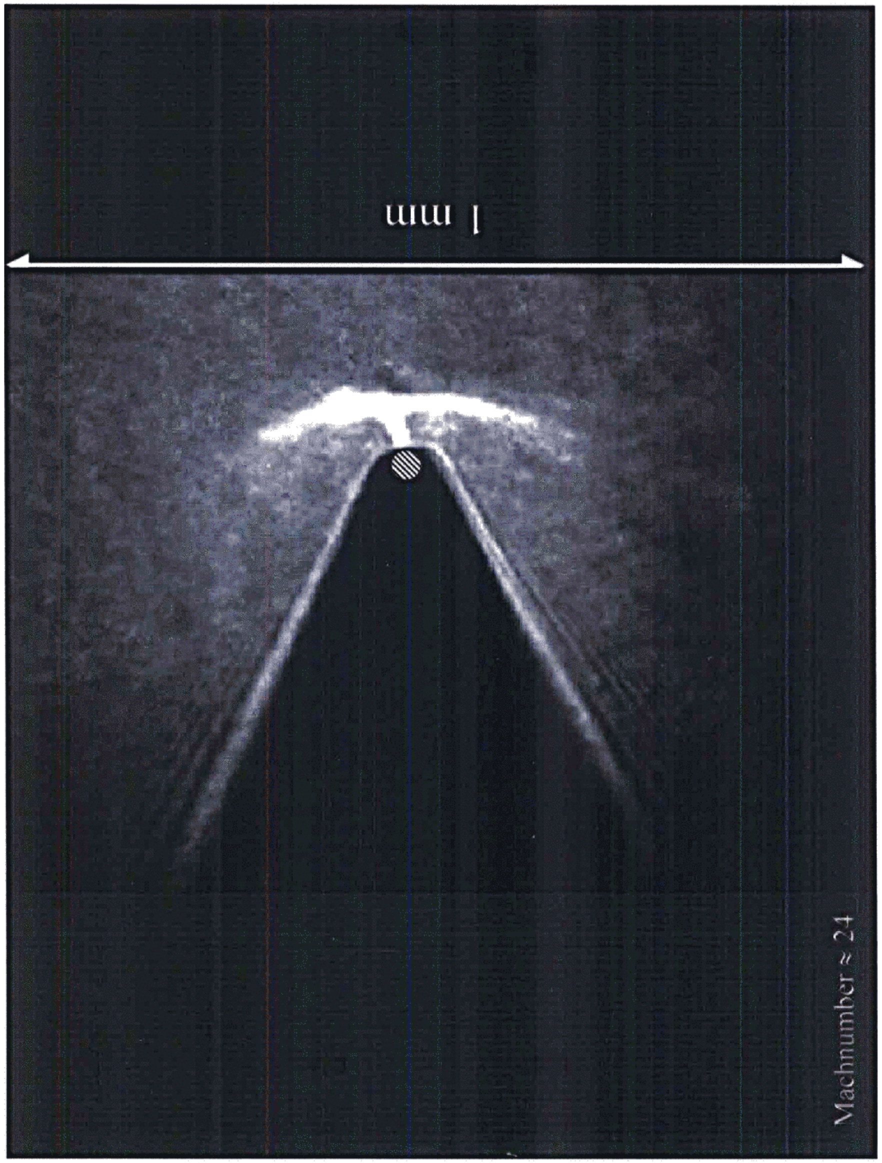
.. As t evolves
v @ fixed point asymptotes to constant.
n decreases exponentially.

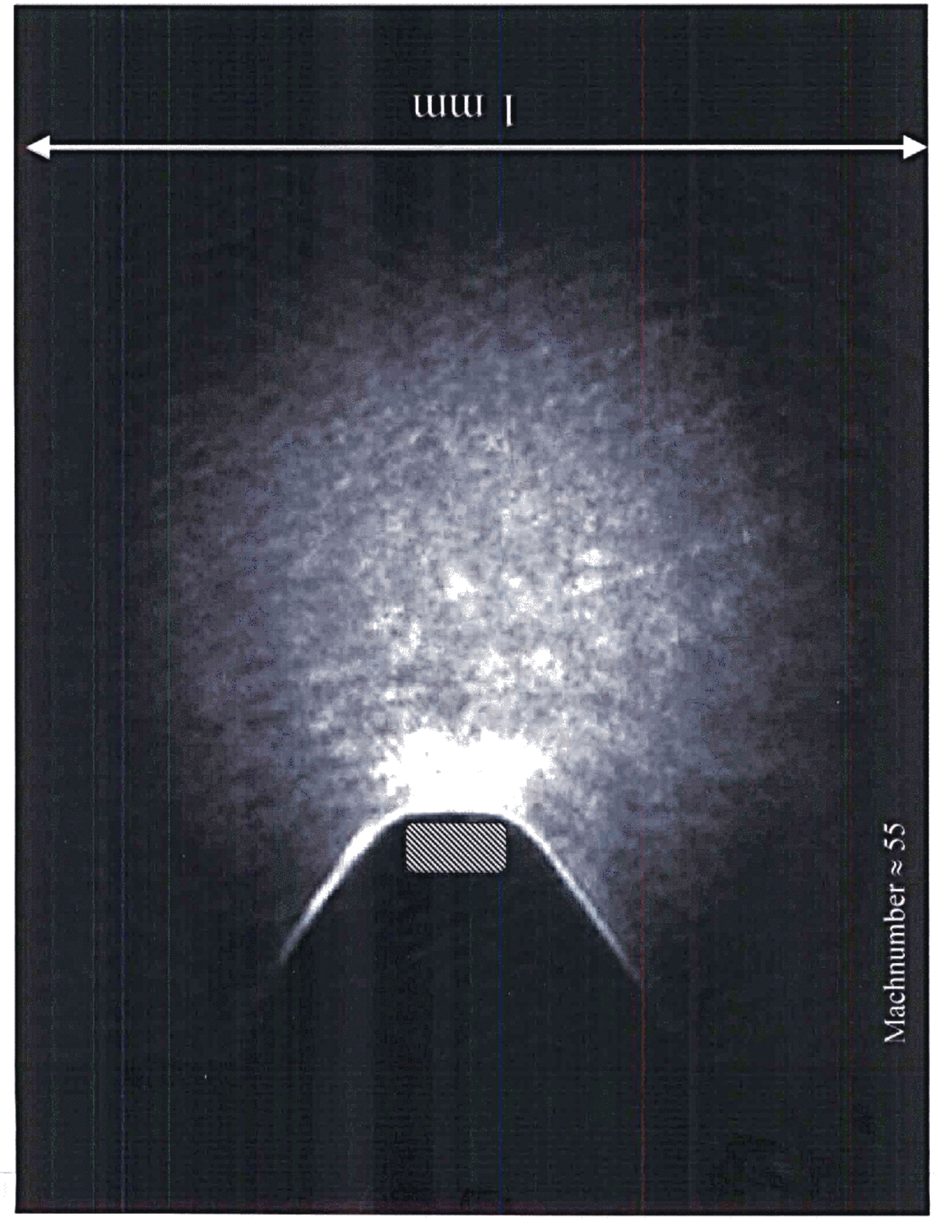


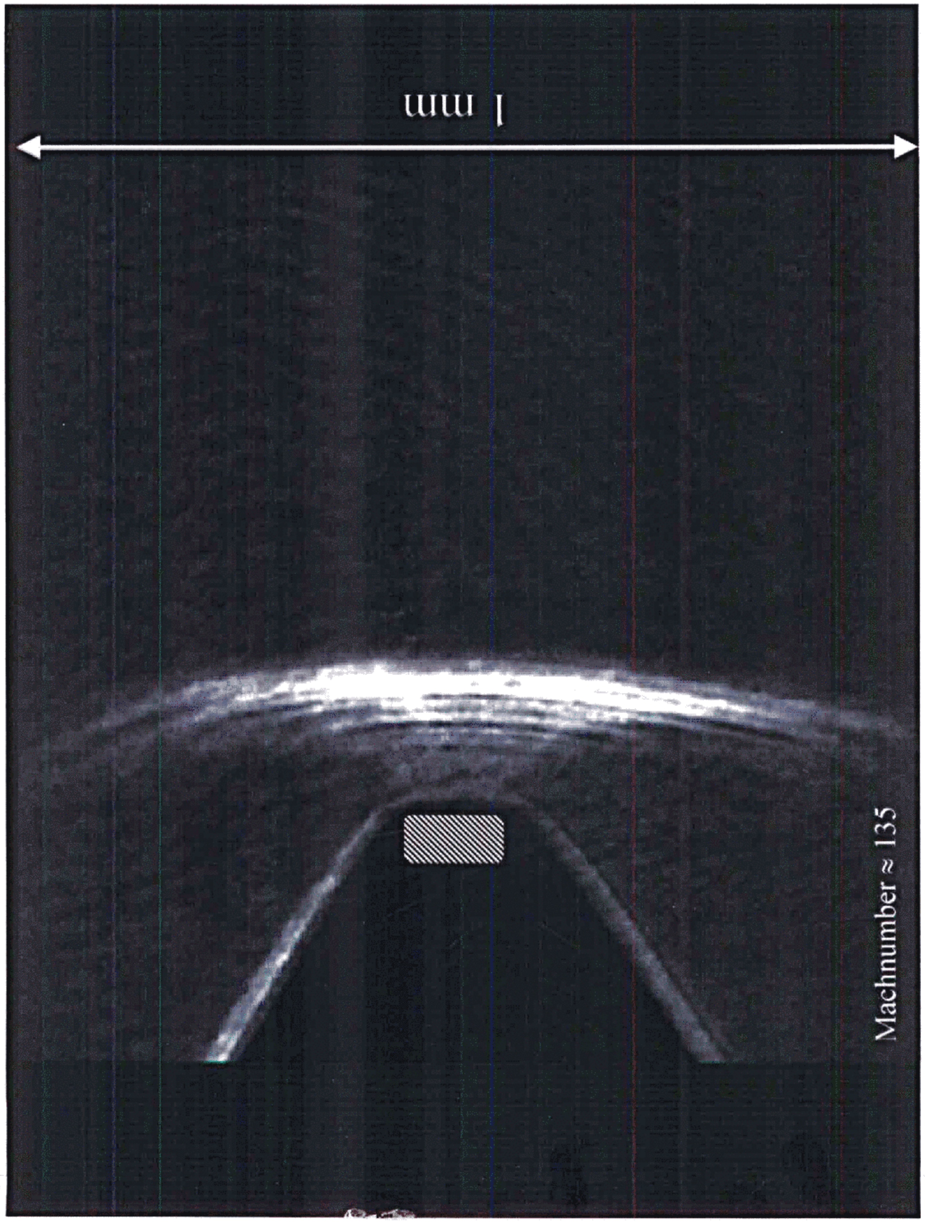
$c \sim \sqrt{n}$, so v/c gets huge

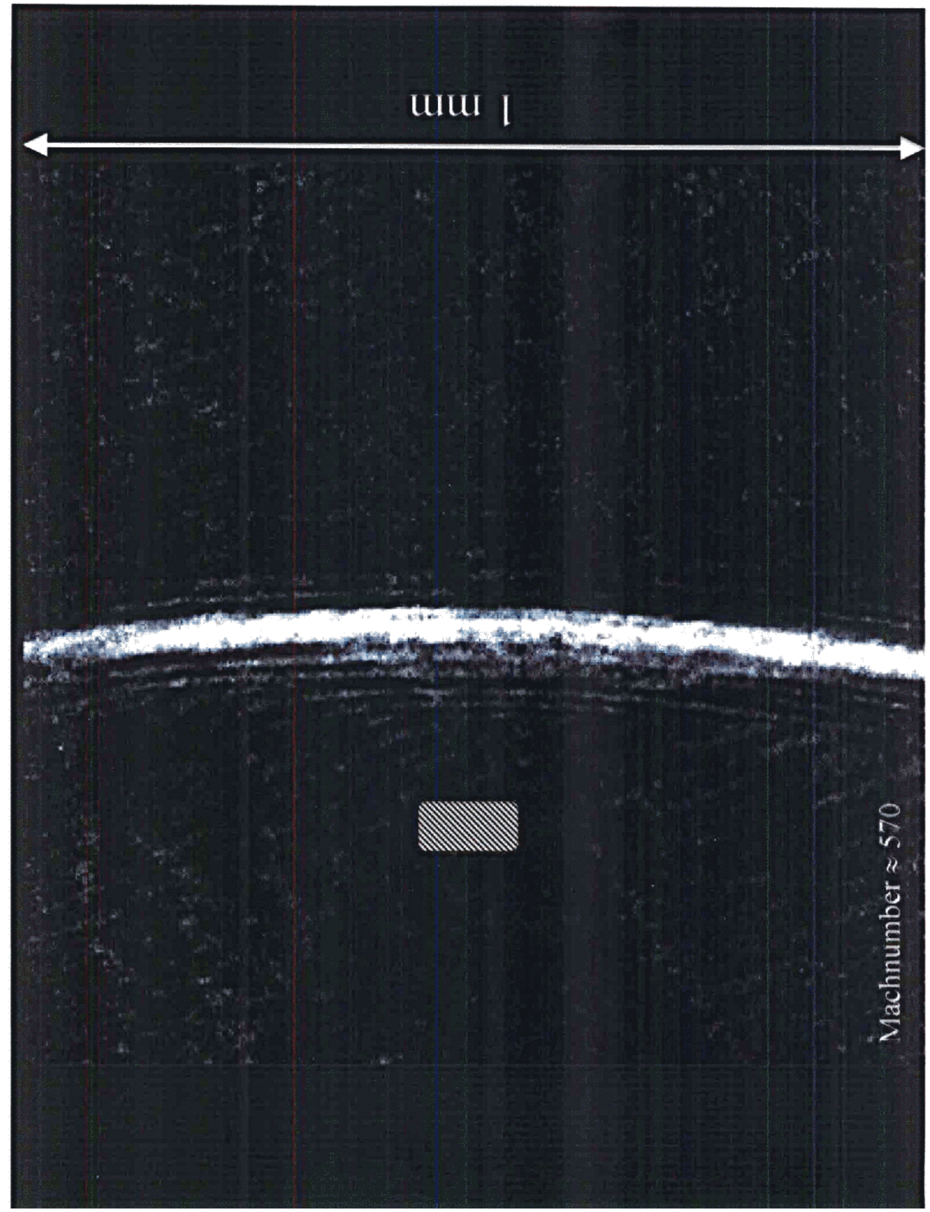

MIT data PRL 2000?

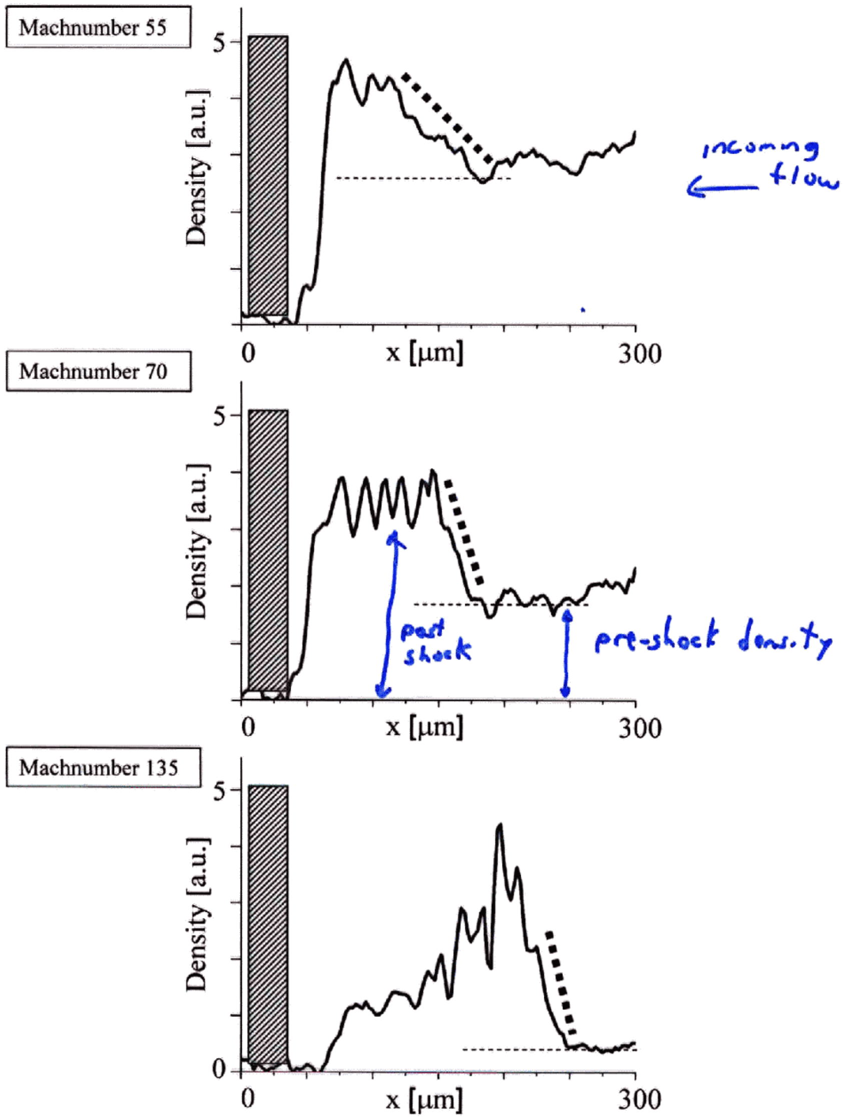

1 mm
Machnumber ≈ 13

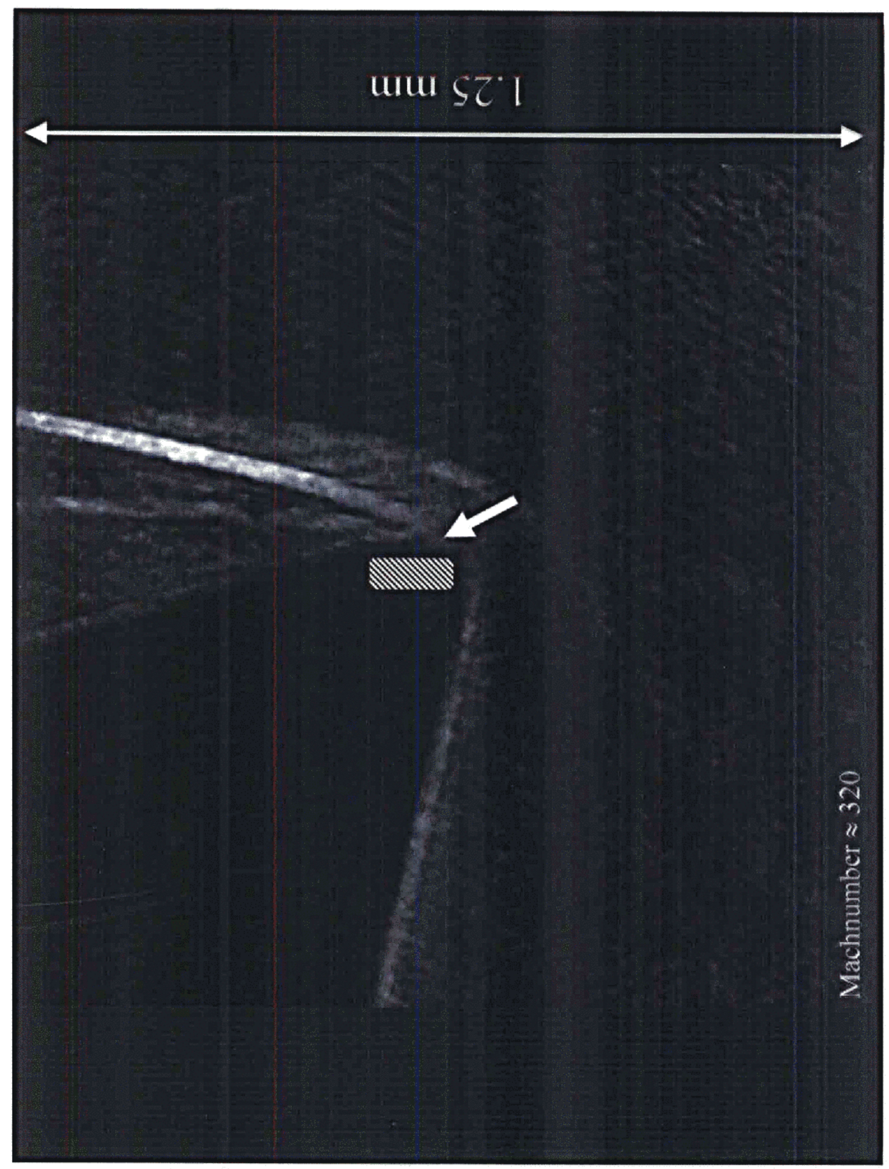

1 mm
Machnumber ≈ 24

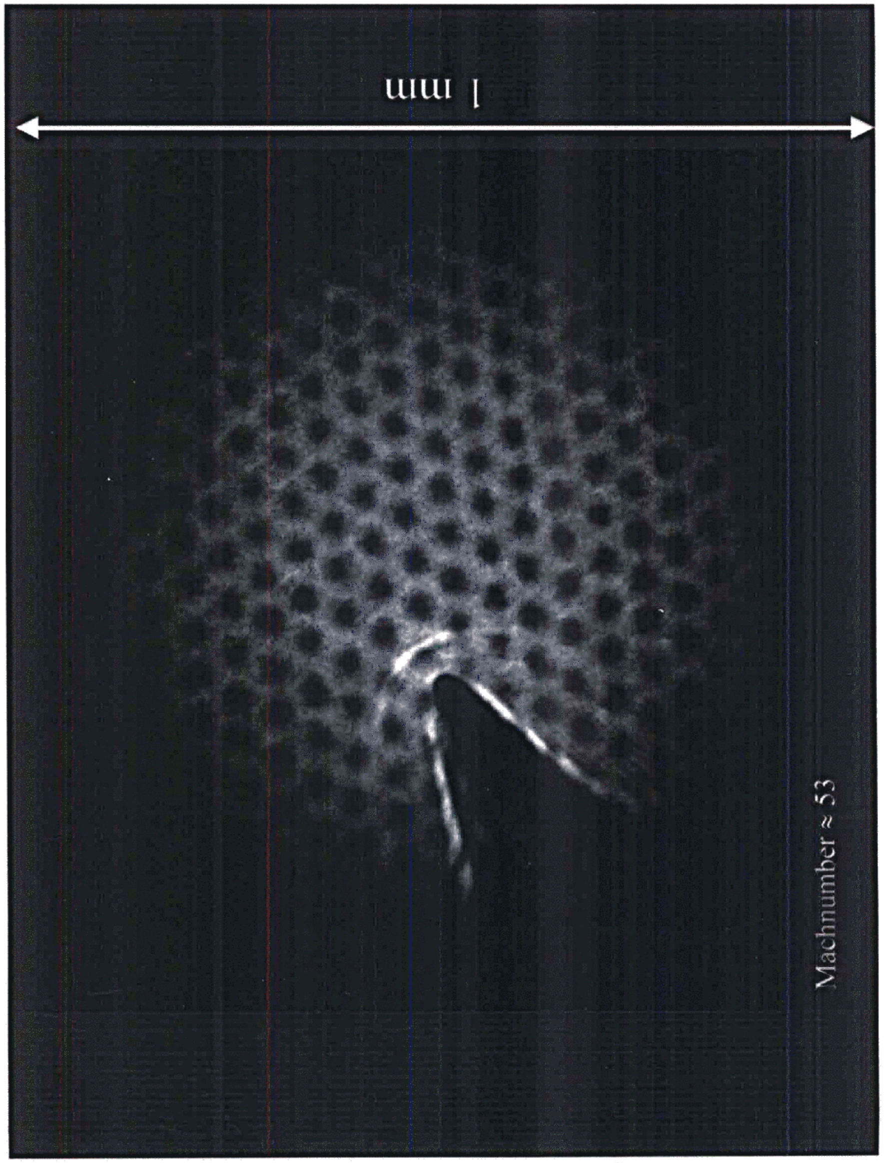

1 mm
Machnumber ≈ 55

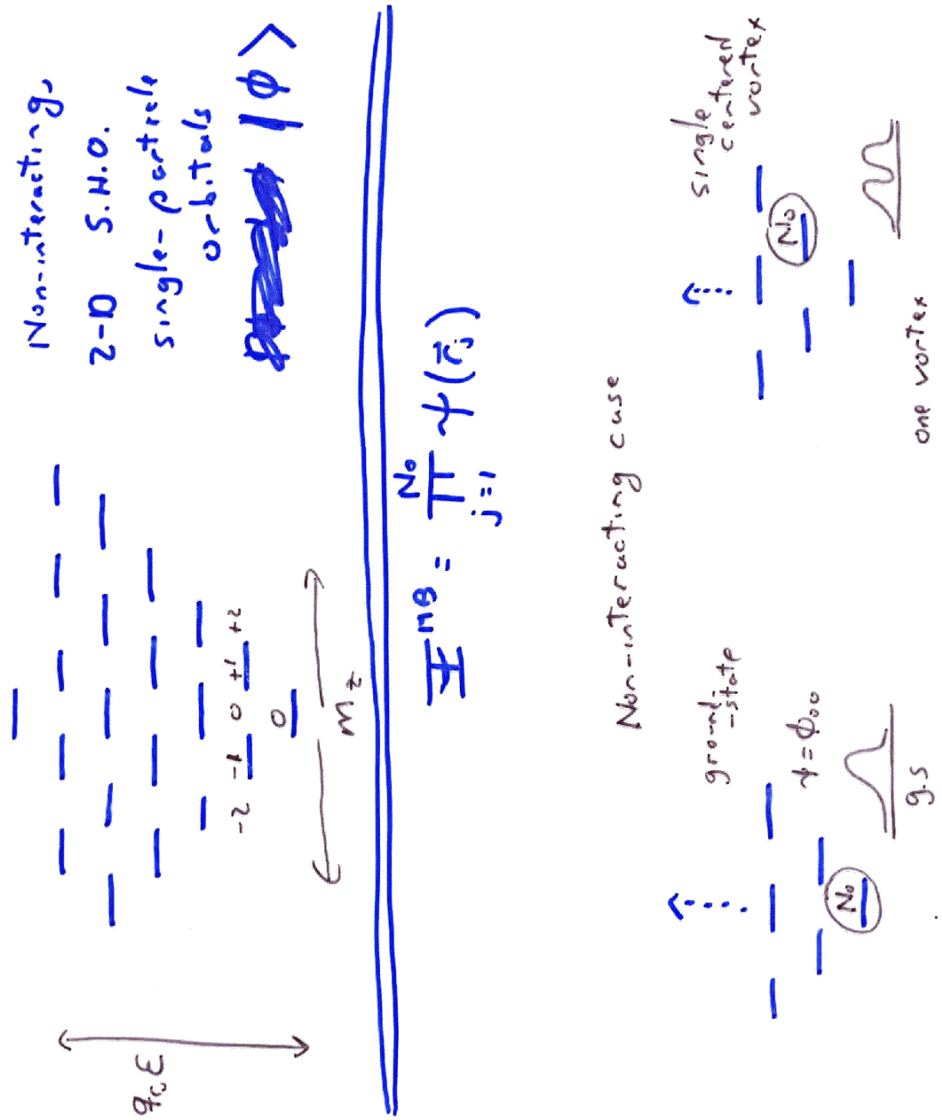

1 mm
Machnumber ≈ 135

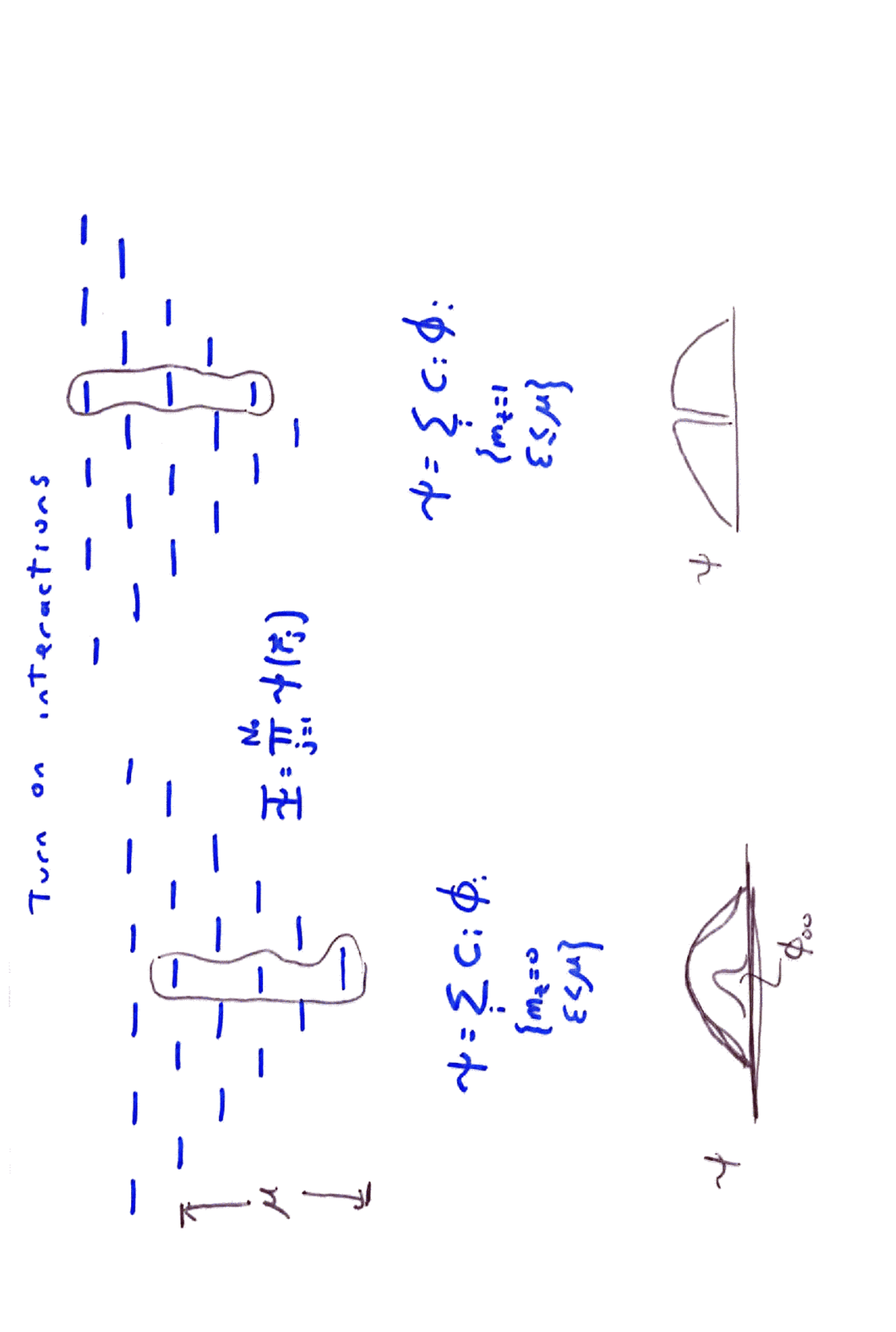

1 mm
Machnumber ≈ 570

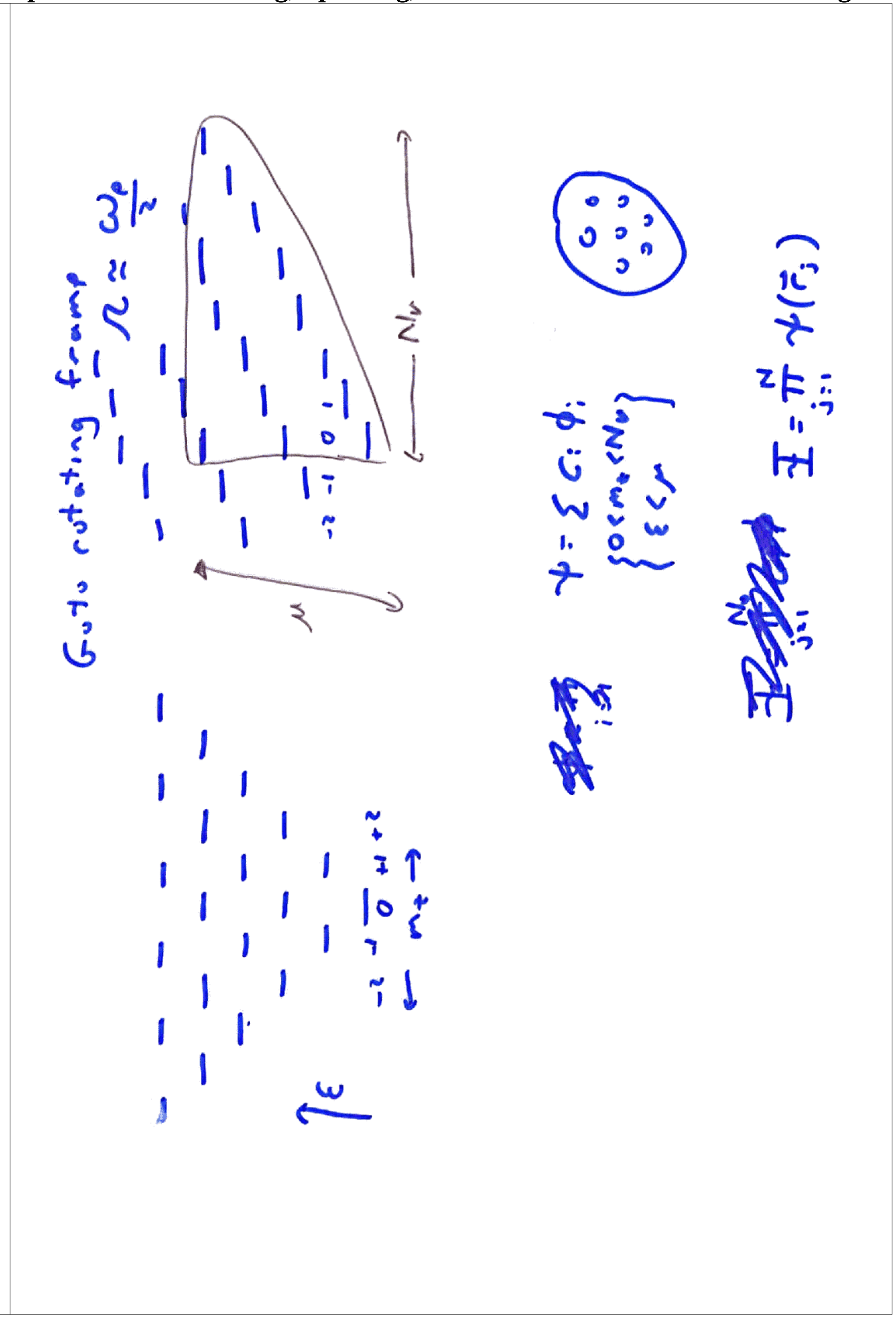

Machnumber 55
5
Density [a.u.]
0
x [μm]
300
incoming flow
Machnumber 70
5
Density [a.u.]
post shock
pre-shock density
0
x [μm]
300
Machnumber 135
5
0
Density [a.u.]
0
x [μm]
300


1.25 mm
Machnumber ≈ 320

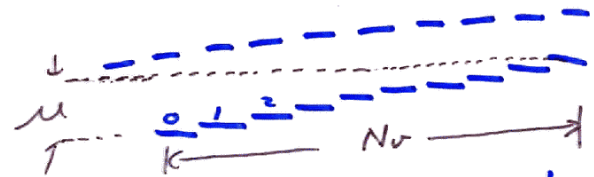

1 mm
Machnumber ≈ 53


Non-interacting, 2-D S.H.O. single-particle orbitals
Non-interacting case
ground-state
single centered vortex
one vortex


Turn on interactions
Ψ = ∏_{j=1}^{N_0} ψ(r_j)
ψ = Σ_i c_i φ_i {m_z=1, ε<μ}
ψ = Σ_i c_i φ_i {m_z=0, ε<μ}
ψ
φ_00
μ


Go to rotating frame Ω ≈ ω_ρ/2
N_v
μ
-2 -1 0 +1 +2
m_z
ε
ψ = Σ_i c_i φ_i {0<m_z<N_v, ε<μ}
Ψ = ∏_{j=1}^{N} ψ(r_j)

Rotating frame $\Omega = \omega_\rho \cdot f$



$\mu < 2\omega_\rho$

$\mu < 2\Omega$

$$\psi = \sum C_i \phi_i \quad \{LLL\}$$

$\dfrac{\#\text{particles}}{\text{single particle orbital}} = \dfrac{N_0}{N_v}$ (for fermions $\lesssim 1$) J. Ho

for bosons $\approx 10^4$

---

for bosons, if $\dfrac{N_0}{N_v} \lesssim 1$ $\left(\dfrac{N_0}{N_v} \overset{?}{\lesssim} 10\right)$

$\Psi \neq \prod_{j=1}^{N_0} \psi(\vec{r}_j)$ instead "Laughlinesque w.f."

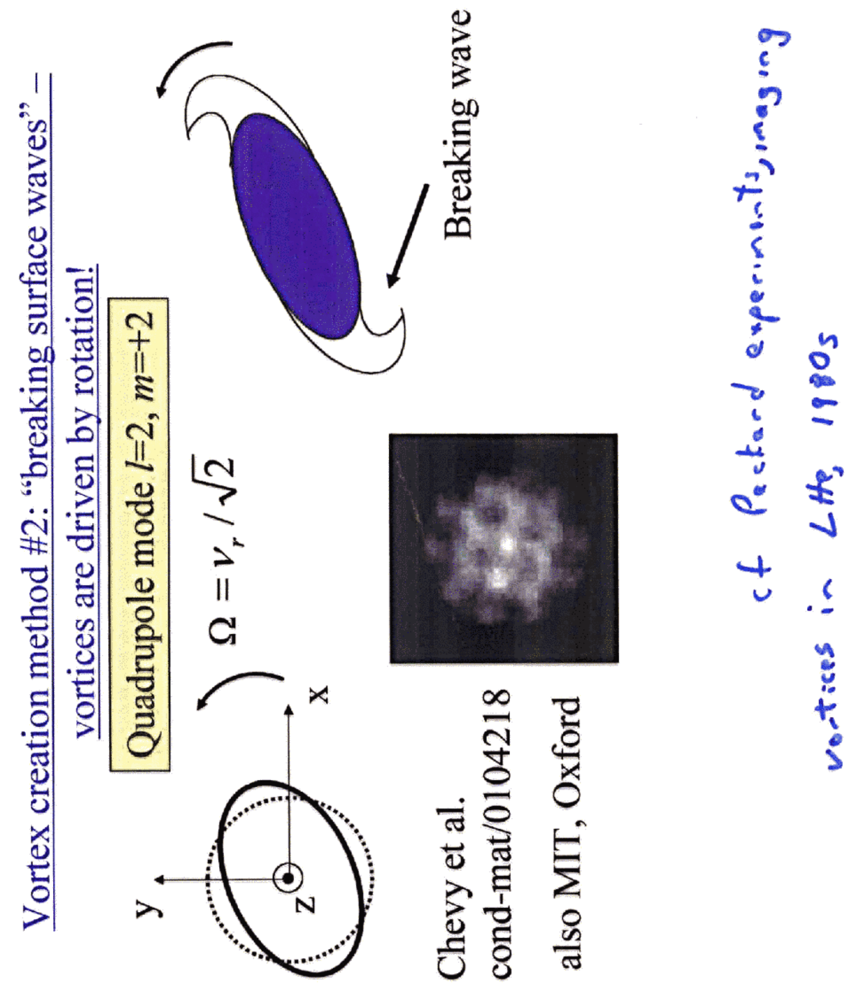
The LLLL figures of merit

$\Gamma_{2d} = \mu / 2\omega_z$ want $\lesssim 1$

$\Gamma_{LLL} = \mu / 2\Omega$ want $\lesssim 1$ "mean field LLL"

$\dfrac{N_0}{N_v} \approx$ "the occupation #" want ≈ 1 $\lesssim 10$ "Quantum Hall regime"

For all 3 figures-of-merit: Rotate Fast!!



Stir cloud @ Ω_z

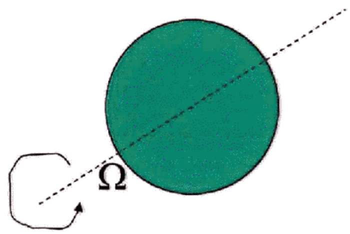
$0.995 \leq \Omega \leq 1.000$?

Prob 1: The thermal cloud is a drag

Prob 2 Stirring potential is very close to resonant with sloshing (c.o.m.) modes

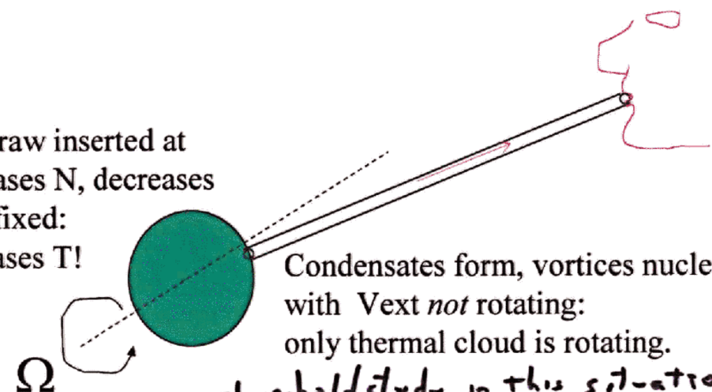
So we don't stir (except to get to Ω up to about 0.5

Floating blob of gas, rotating slowly. (Not condensed, yet)



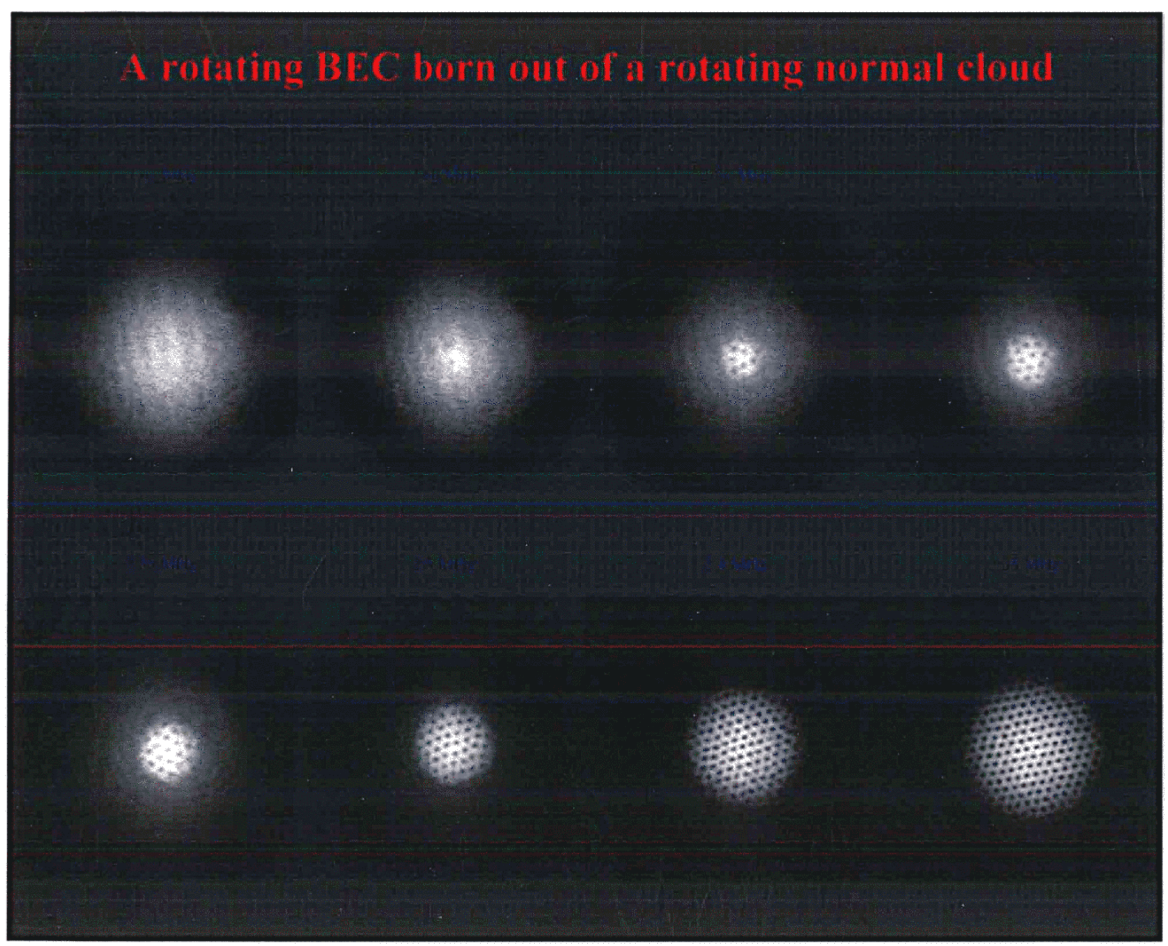
Paul Haljan, Ian Coddington,
Peter Engels and E.A. Cornell
cond-mat/0106362
"Driving Bose-Einstein condensate vorticity with a rotating normal cloud"

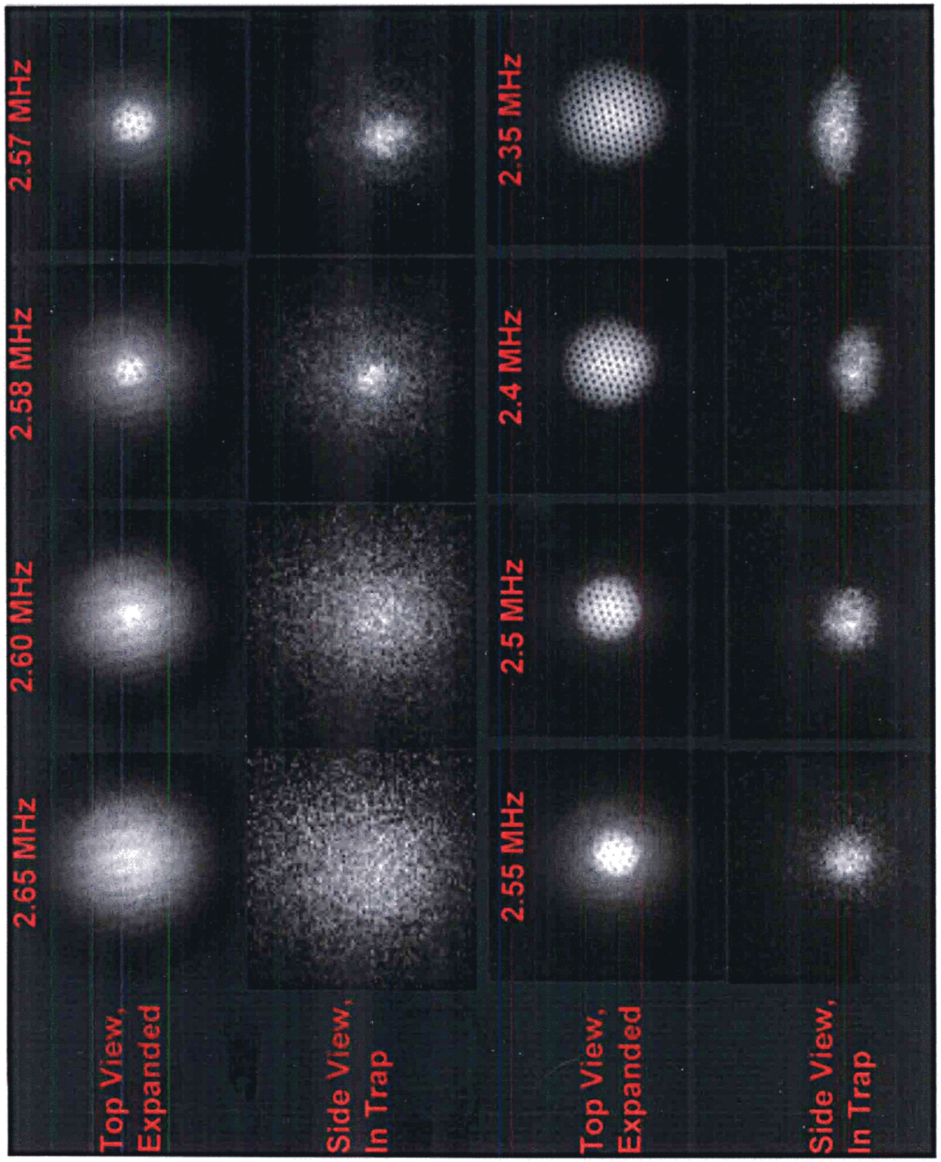
Sucking through straw inserted at "north pole" decreases N, decreases E (faster) keeps L fixed: increases Ω, decreases T!

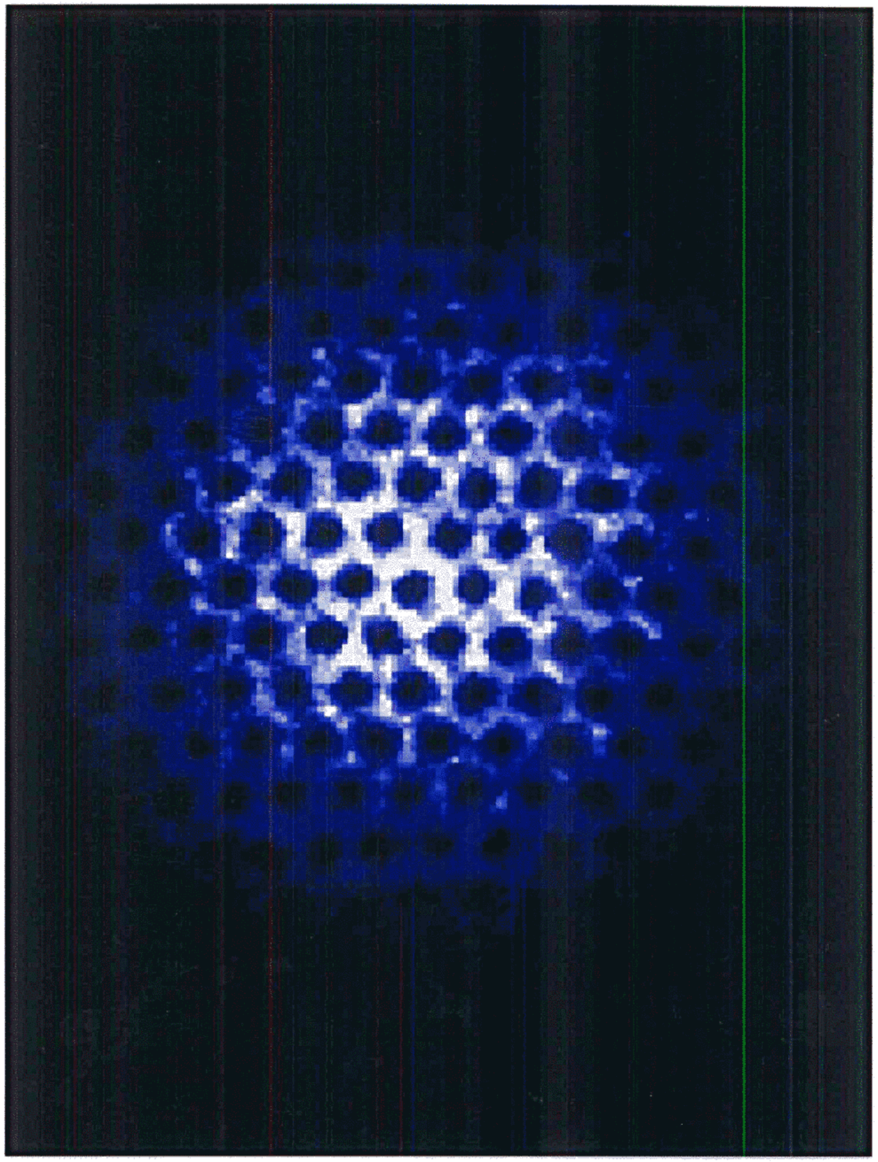


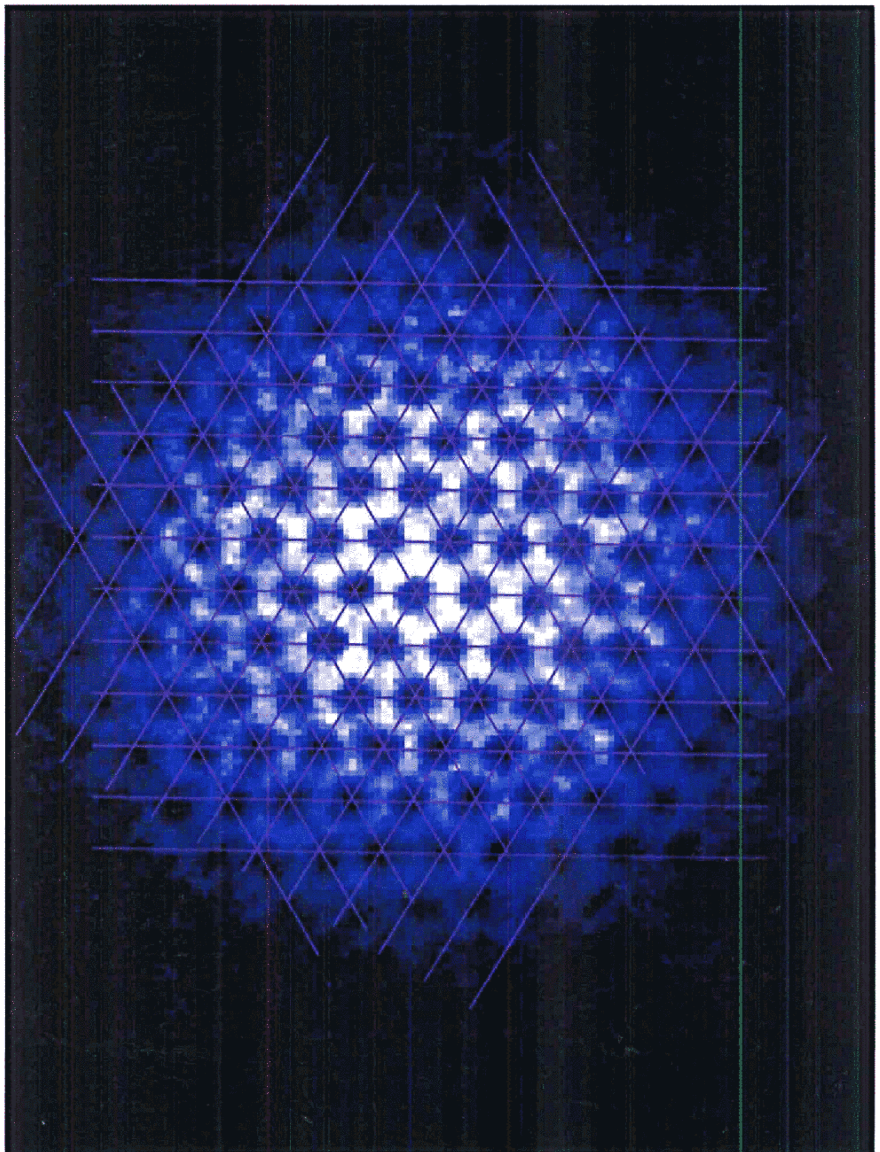
Condensates form, vortices nucleate, with Vext *not* rotating: only thermal cloud is rotating.

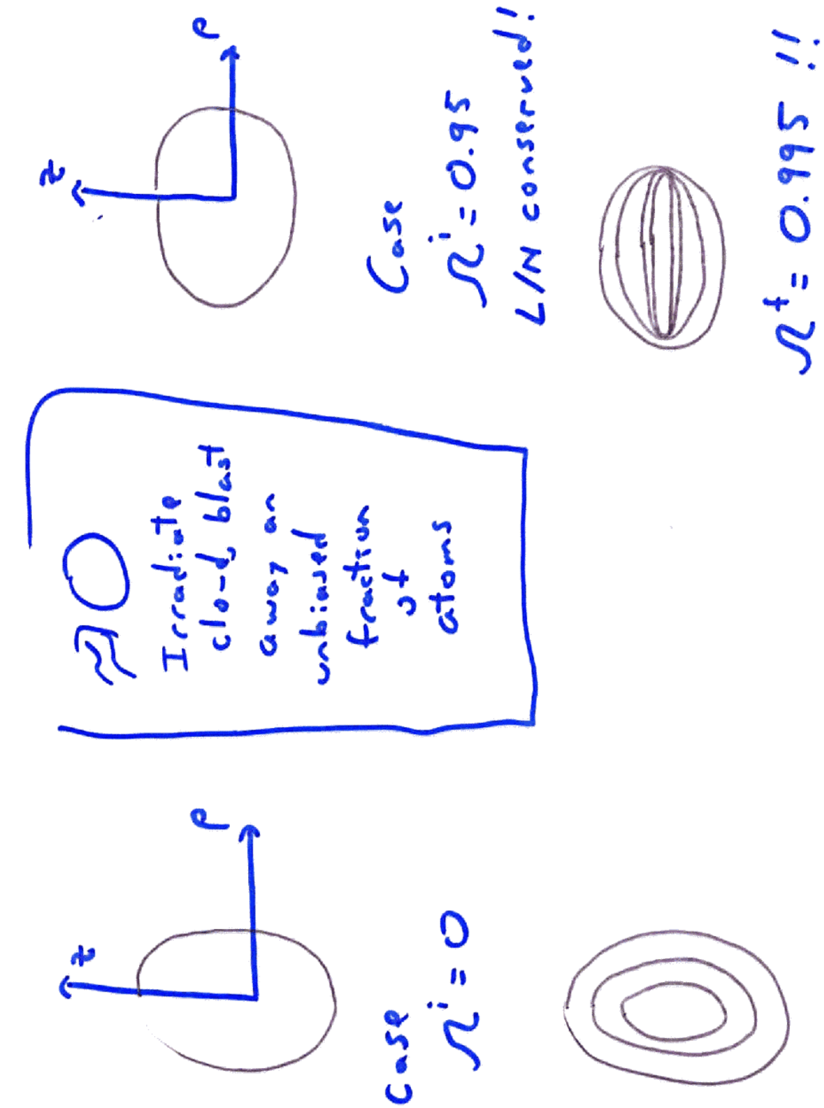
Threshold study in this situation
P. Engels poster



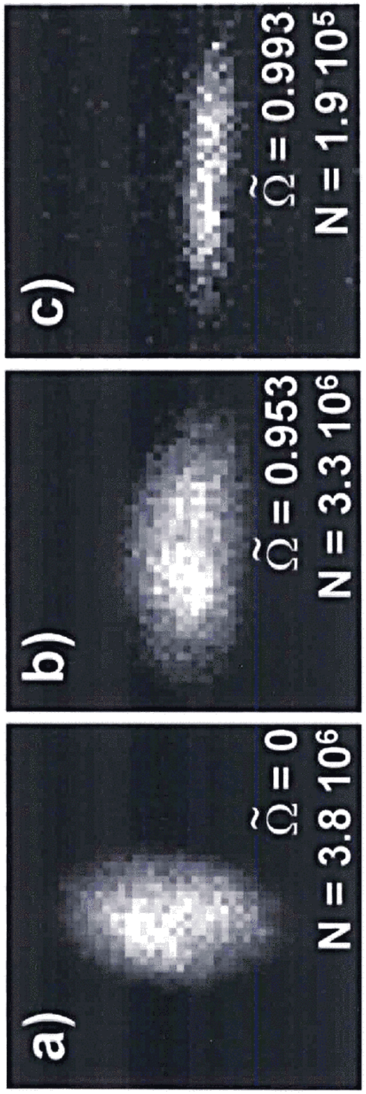

2.57 MHz
2.58 MHz
2.60 MHz
2.65 MHz
2.35 MHz
2.4 MHz
2.5 MHz
2.55 MHz
Top View, Expanded
Side View, In Trap
Top View, Expanded
Side View, In Trap

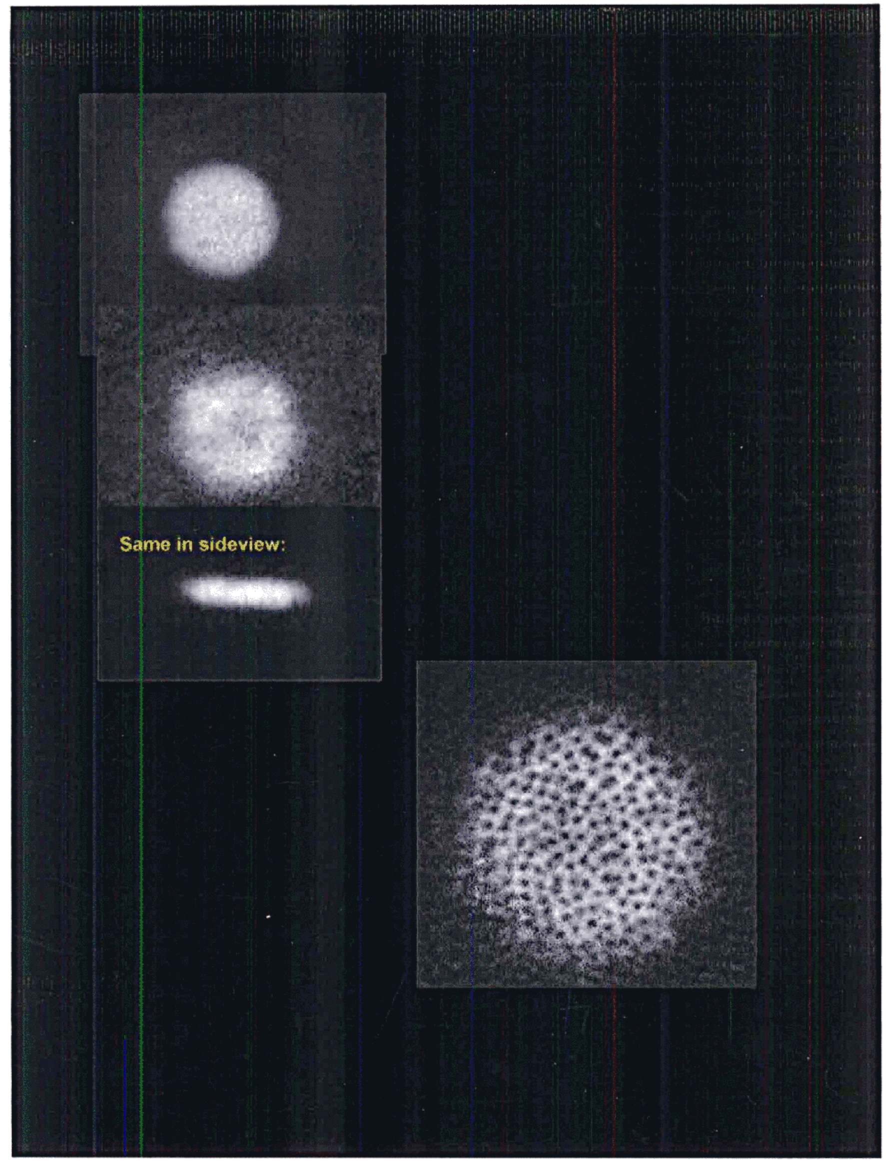




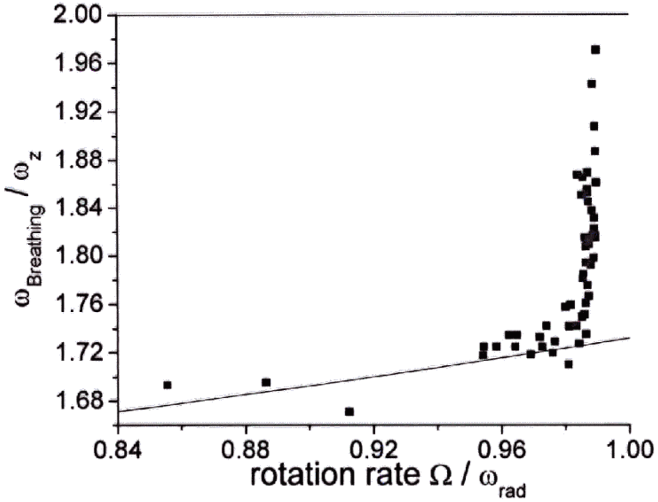


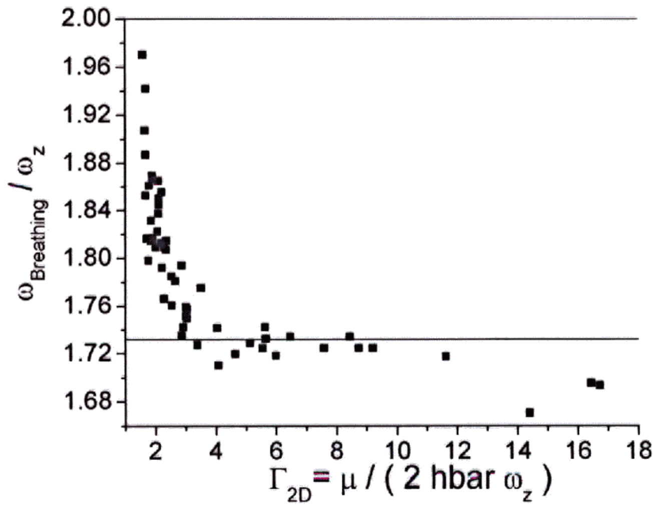
z
ρ
Case
Ω^i = 0.95
L/N conserved!
Ω^f = 0.995 !!
Irradiate cloud, blast away an unbiased fraction of atoms
Case
Ω^i = 0


a)
$\tilde{\Omega} = 0$
N = 3.8 10^6
b)
$\tilde{\Omega} = 0.953$
N = 3.3 10^6
c)
$\tilde{\Omega} = 0.993$
N = 1.9 10^5

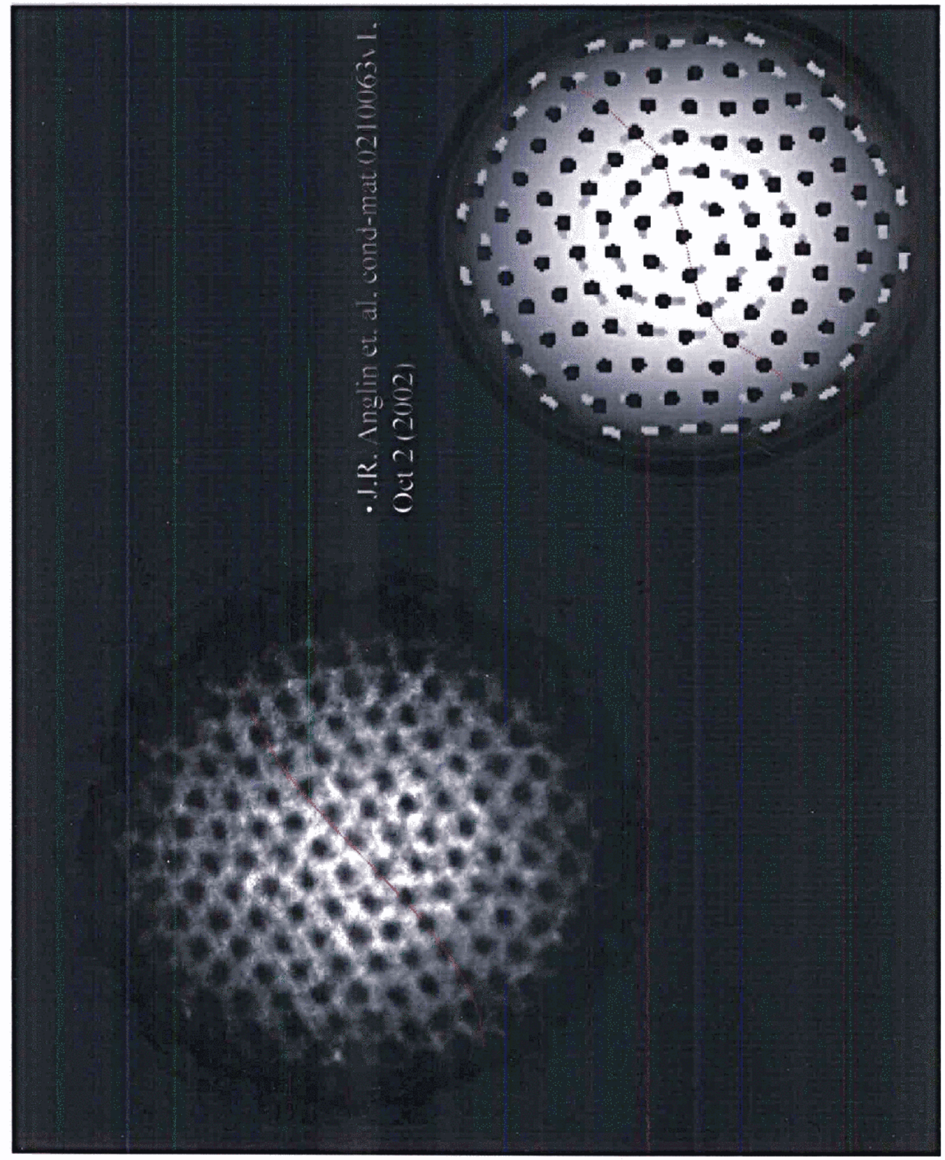

Same in sideview:

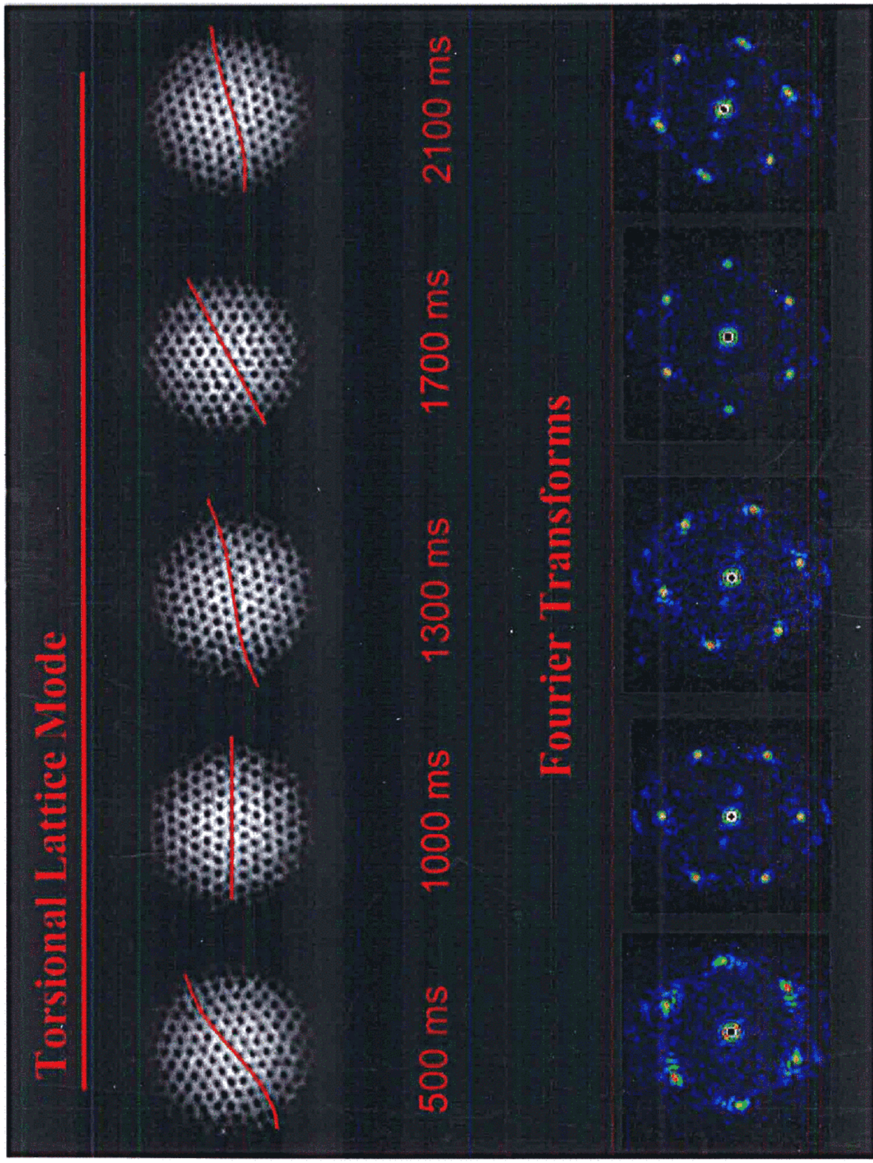
Cross-over in axial breathing mode



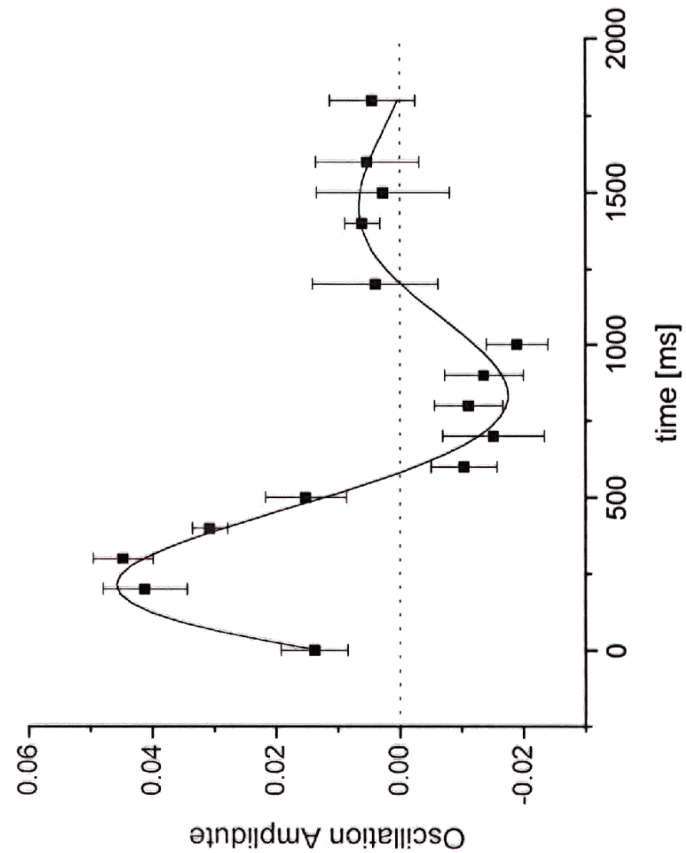


∴ we are into the 2-d limit.

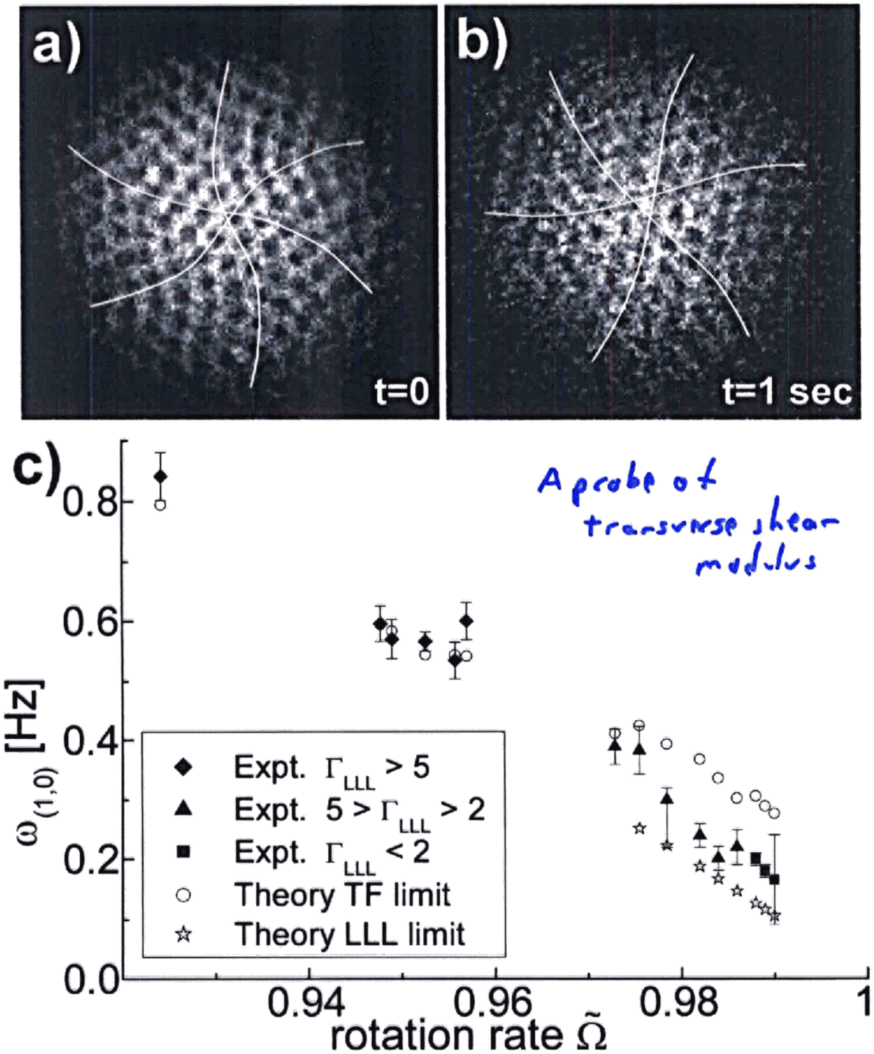




cond-mat/0305008

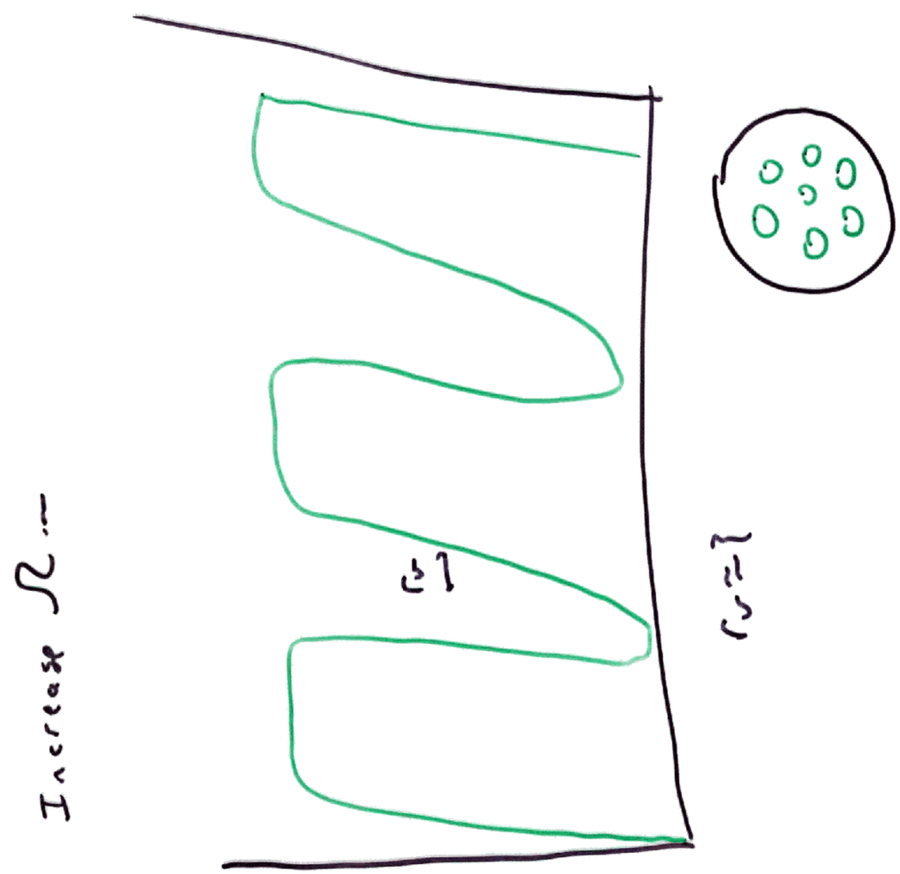


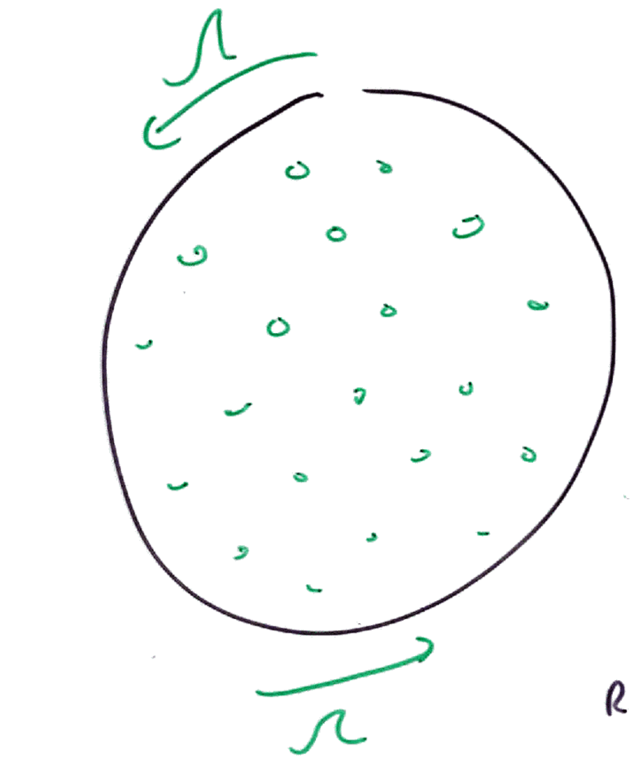
V. Schweikhard cm/0308582 also PRL



A probe of transverse shear modulus

Theory: Anglin, Baym





Area of one vortex

$A_v = \pi \xi^2 \approx \frac{\pi}{\alpha n}$

Areal density of vortices

$n_v \simeq \frac{m\Omega}{\hbar}$

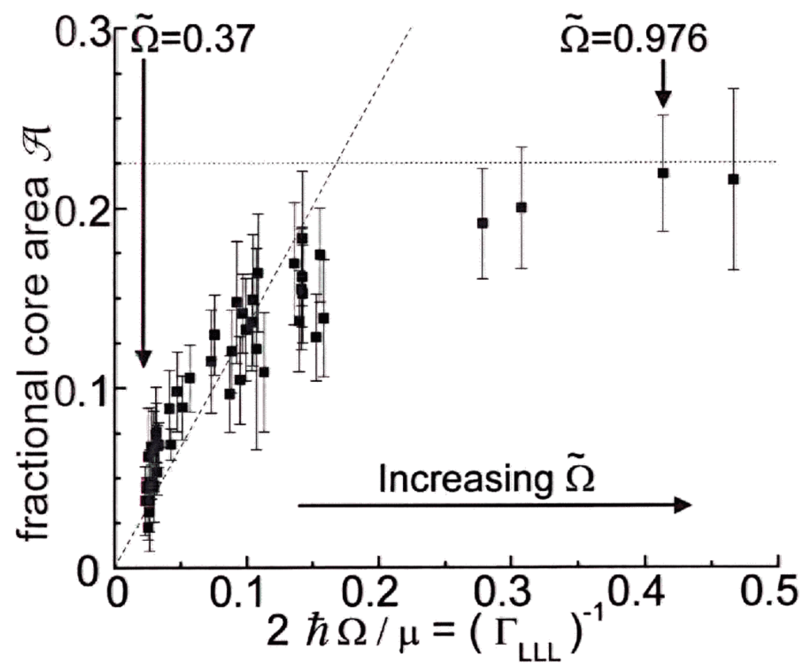
Rotate faster

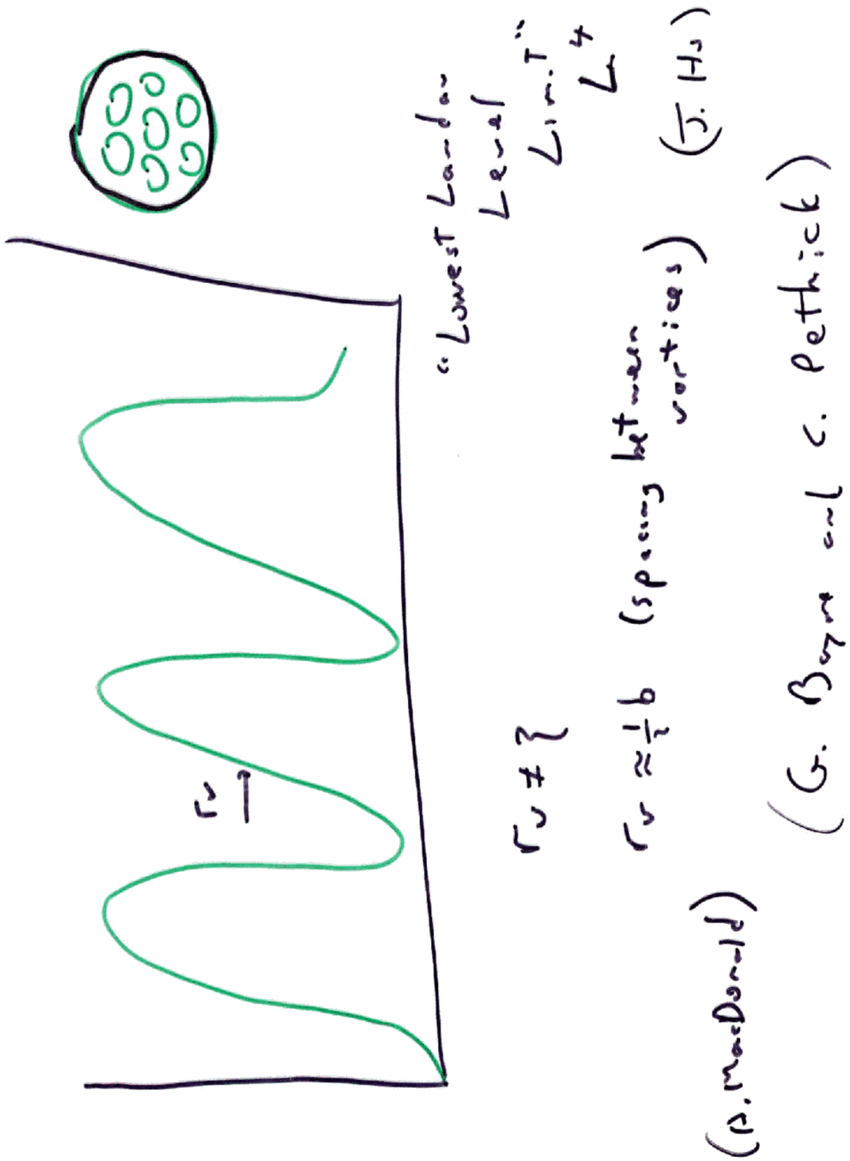
$\Omega \to$ bigger

$n \to$ smaller

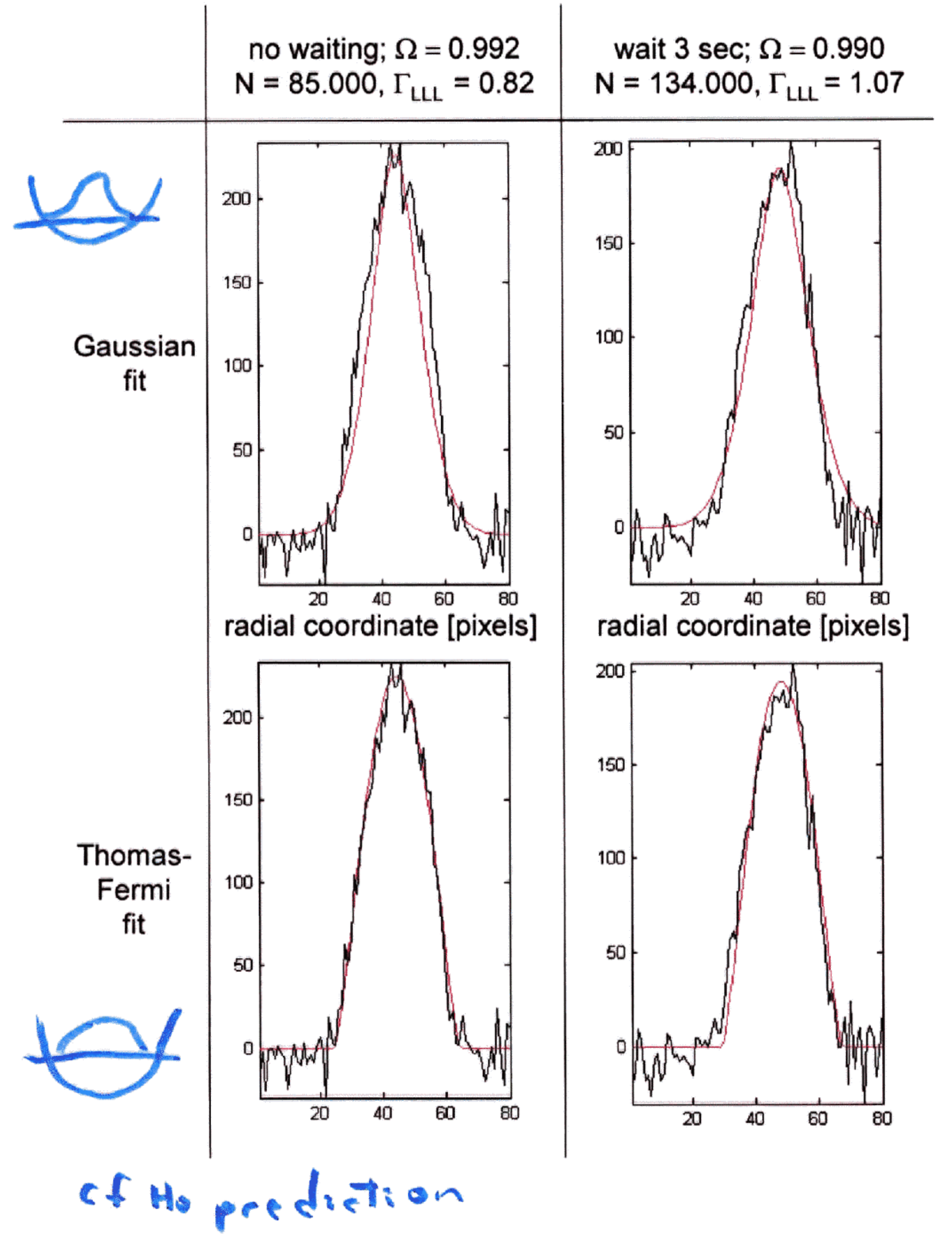
$n_v \to$ bigger

$\mathcal{A} = A_v n_v = \frac{\Omega}{\alpha n} \propto \frac{\Omega}{\mu} \approx \Gamma_{LLL}^{-1}$



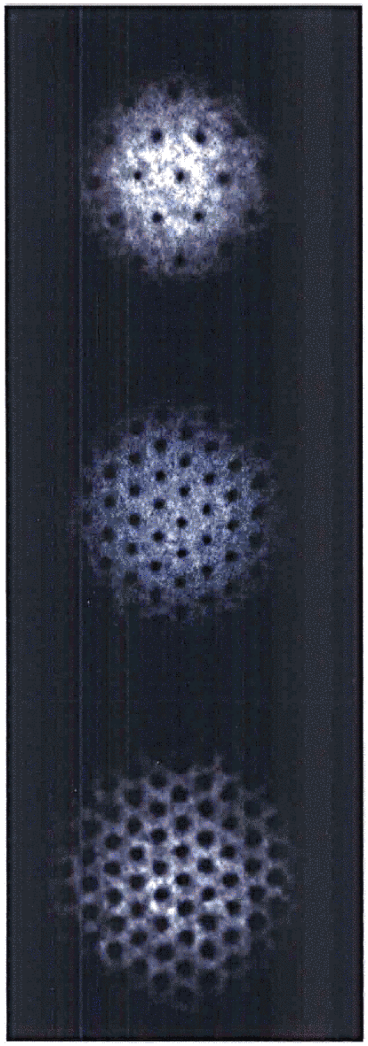


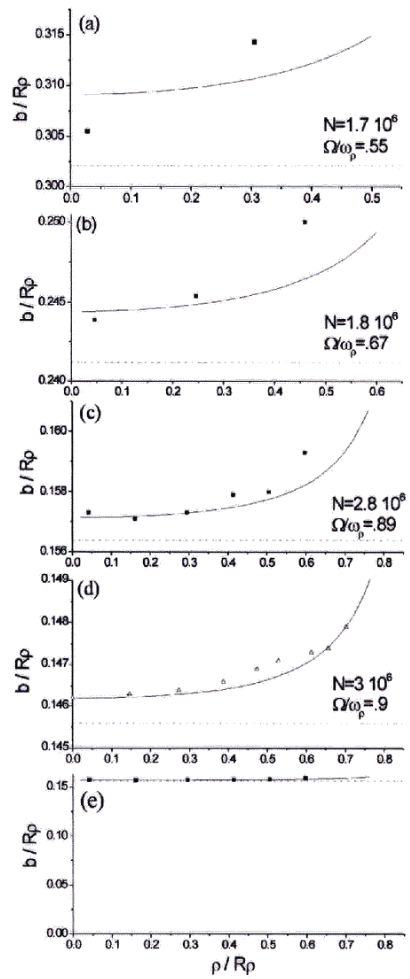
"Lowest Landau Level Limit"
(J. Ho)
r_v ≠ ξ
r_v ≈ ½ b (spacing between vortices)
(G. Baym and C. Pethick)
(A. MacDonald)



no waiting; Ω = 0.992
N = 85.000, Γ_LLL = 0.82
wait 3 sec; Ω = 0.990
N = 134.000, Γ_LLL = 1.07
Gaussian fit
Thomas-Fermi fit
radial coordinate [pixels]
radial coordinate [pixels]
cf Ho prediction

cond-mat/





- A. MacDonald
- Cooper + Read
- Baym + Pethick

} LLL

Sheehy + Radzihovsky thy for nonLLL regime

Ω	N_v	$\frac{\mu}{2\Omega}$	$\frac{\mu}{2\hbar\omega_z}$	$\frac{N_o}{N_v}$	Comments
0.97	100	10	15	10^4	Eventually, run out of thermal atoms
0.997	200	0.7	1	500	The LLLL! "mean-field" Shear modulus plunges towards zero, lattice too fragile to spin up further.

Anti-evap of Lot thermal atoms leads to →

Unbiased blasting of condensate atoms leads to

To Do: work on $\frac{a}{a_{ho}}$, combine Ω big, $S=1/2$