Superfluid Phases of a Fermi Gas with Unequal Spin Populations

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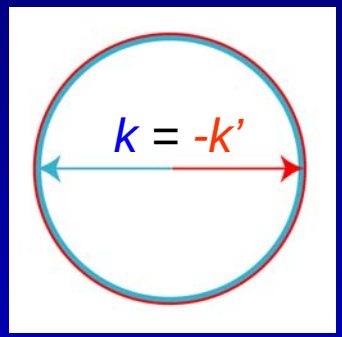
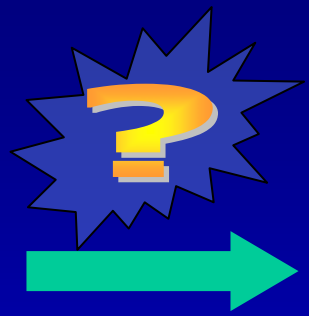
Special thanks to
Henk Stoof

RICE UNIVERSITY

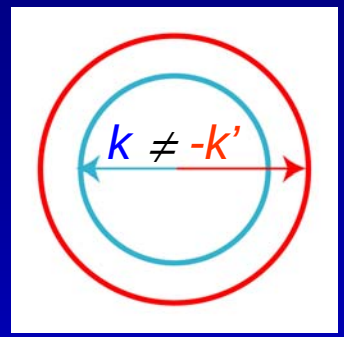
Pairing with Mismatched Fermi Surfaces

BCS





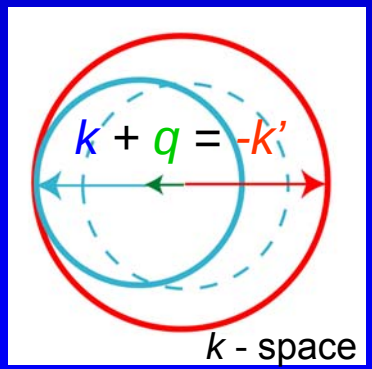
Mismatched



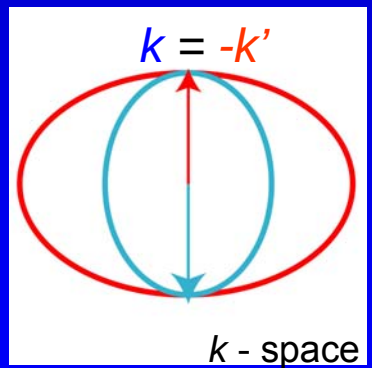
e.g. magnetized superconductor

Many predictions since 1963 (many recent cold atom theory papers):

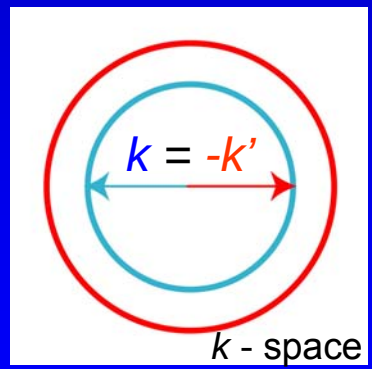
FFLO



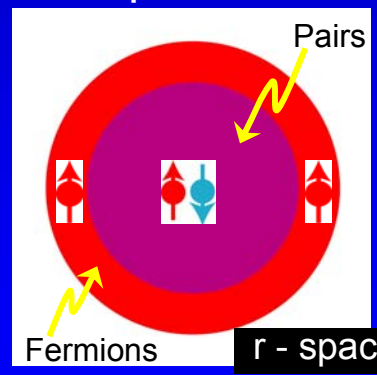
Deformed Fermi Surfaces



Sarma (Breached Pair)

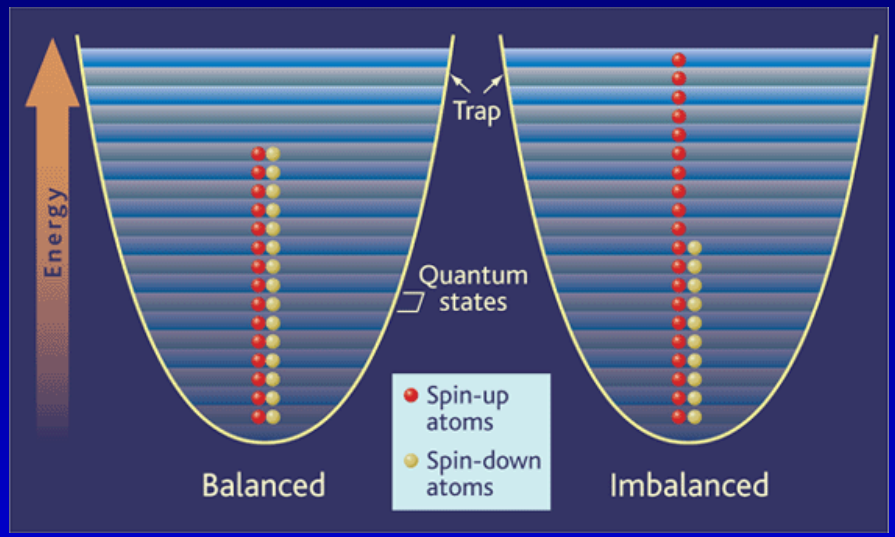


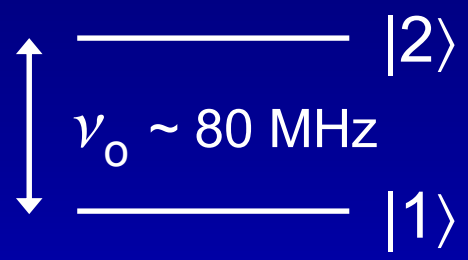
Phase Separation



- Fundamental incompatibility between magnetism and superconductivity
  - straightforward to make a polarized atomic gas
- Implications for nuclei, QCD, pairing of quarks in neutron stars

Unequal Spin Populations with Atoms





Use RF sweeps to transfer population between hf levels of ^{6}Li

Define polarization $P = (N_1 - N_2) / (N_1 + N_2)$

P controlled to be in the range $0 < P < 1$

Measure P by independent probes of $|1\rangle$ and $|2\rangle$

Experiments with ^{6}Li at MIT and Rice (*Science*, 2006)

Images Show Phase Separation - Unitarity

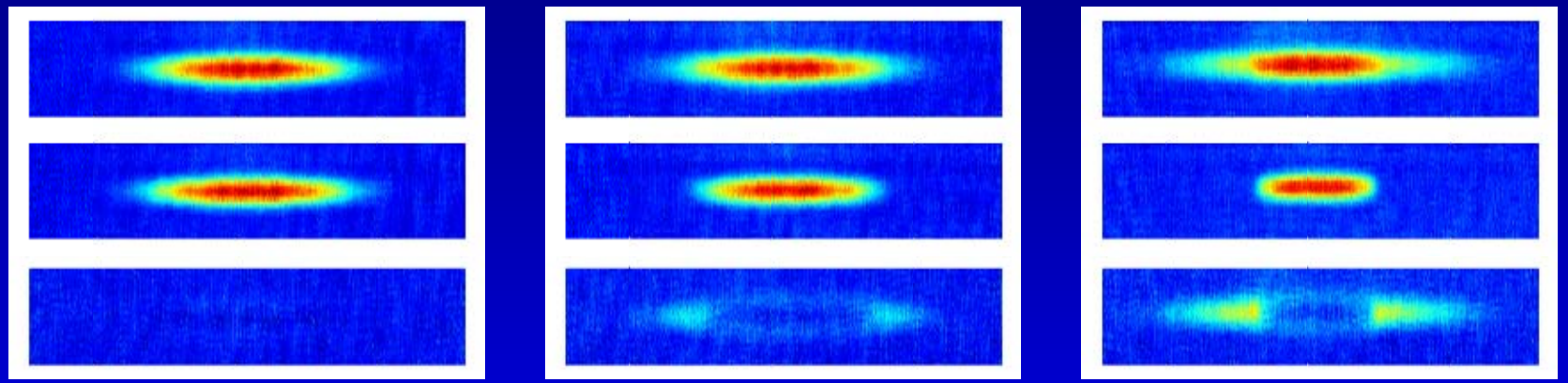
1. Paired core
2. Sharp phase boundaries
3. Core deformation

$P = 0$ $P = 0.18$ $P = 0.37$

$|1\rangle$

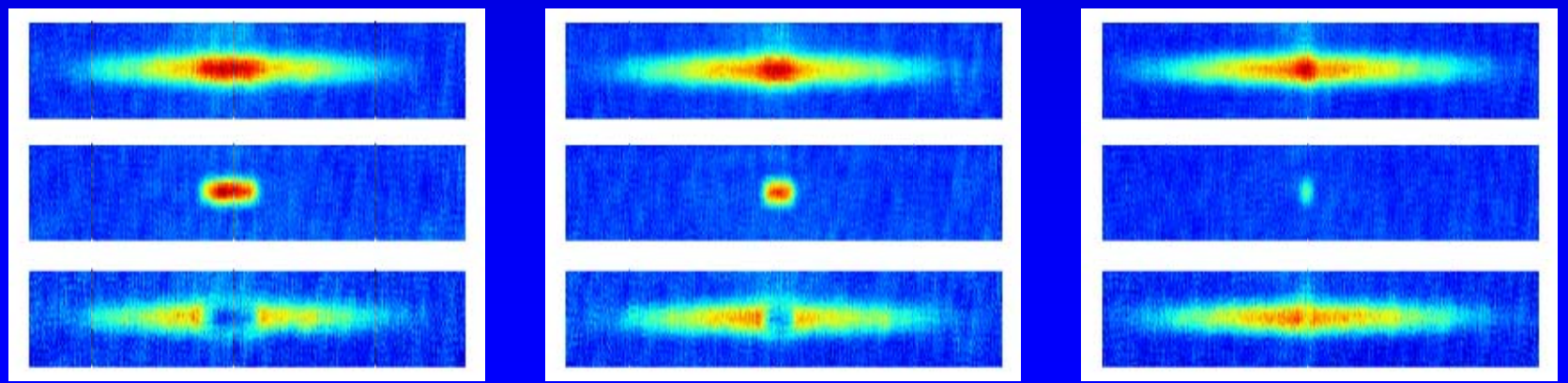
$|2\rangle$

$|1\rangle - |2\rangle$

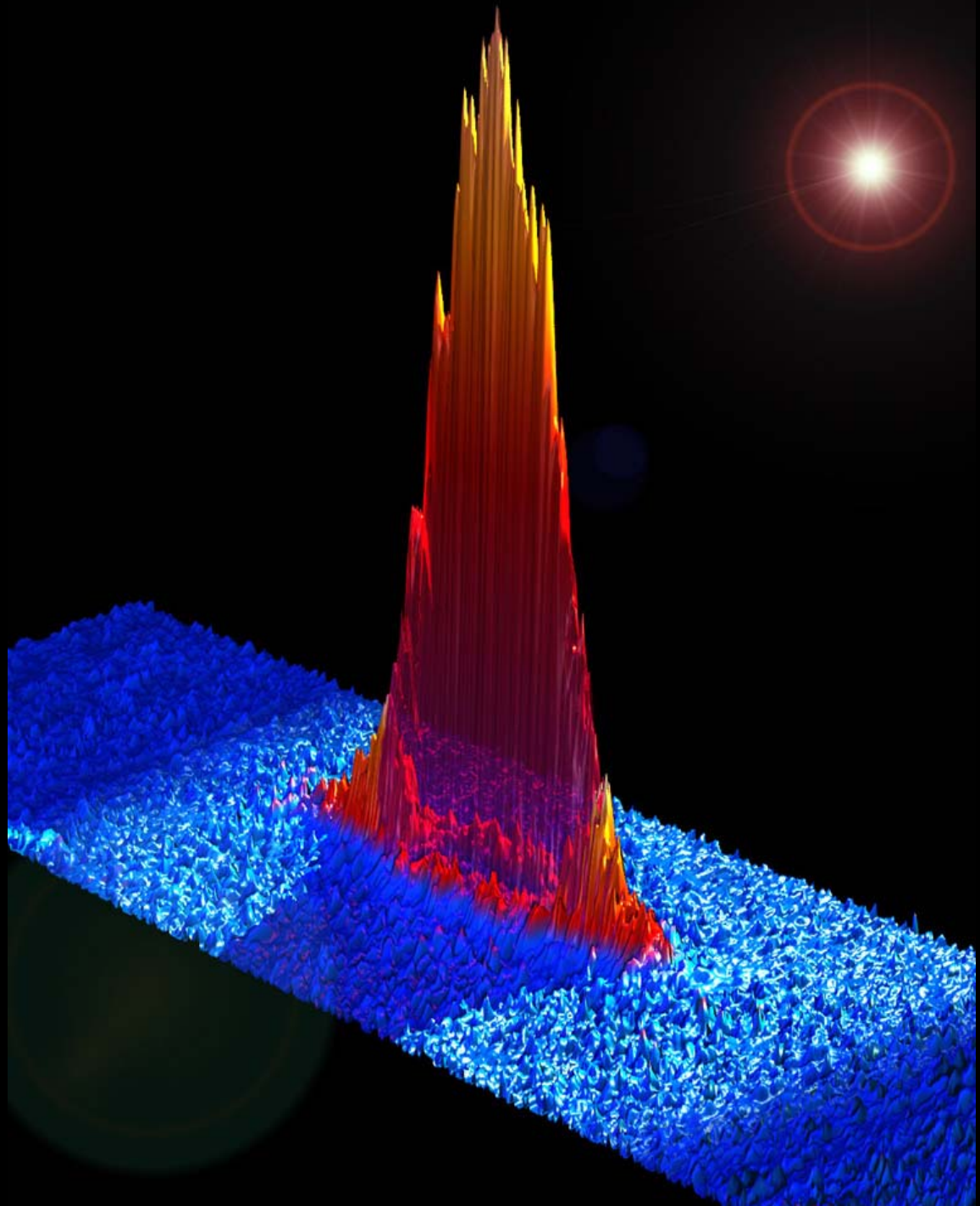


Dark center indicates paired core

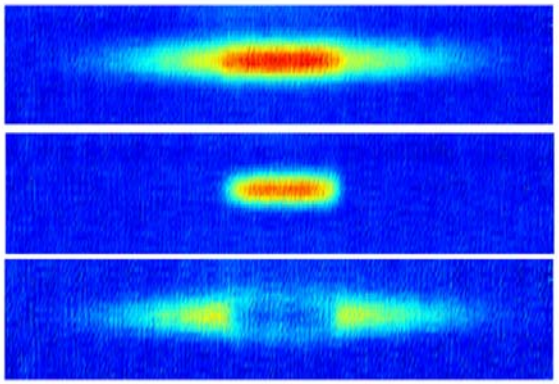
$P = 0.6$ $P = 0.79$ $P = 0.95$

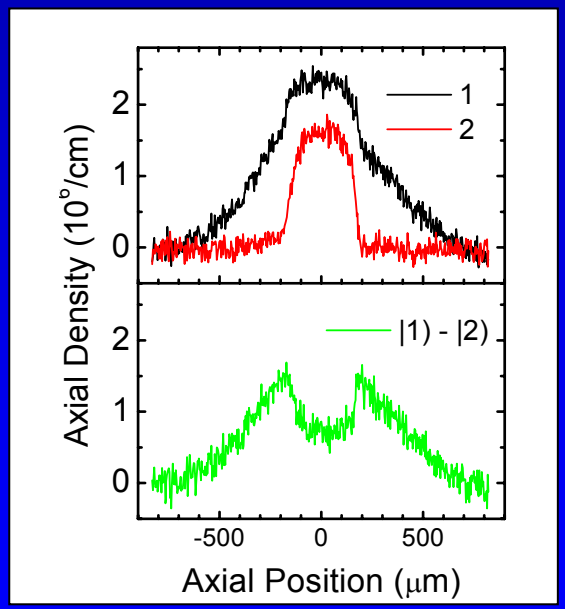


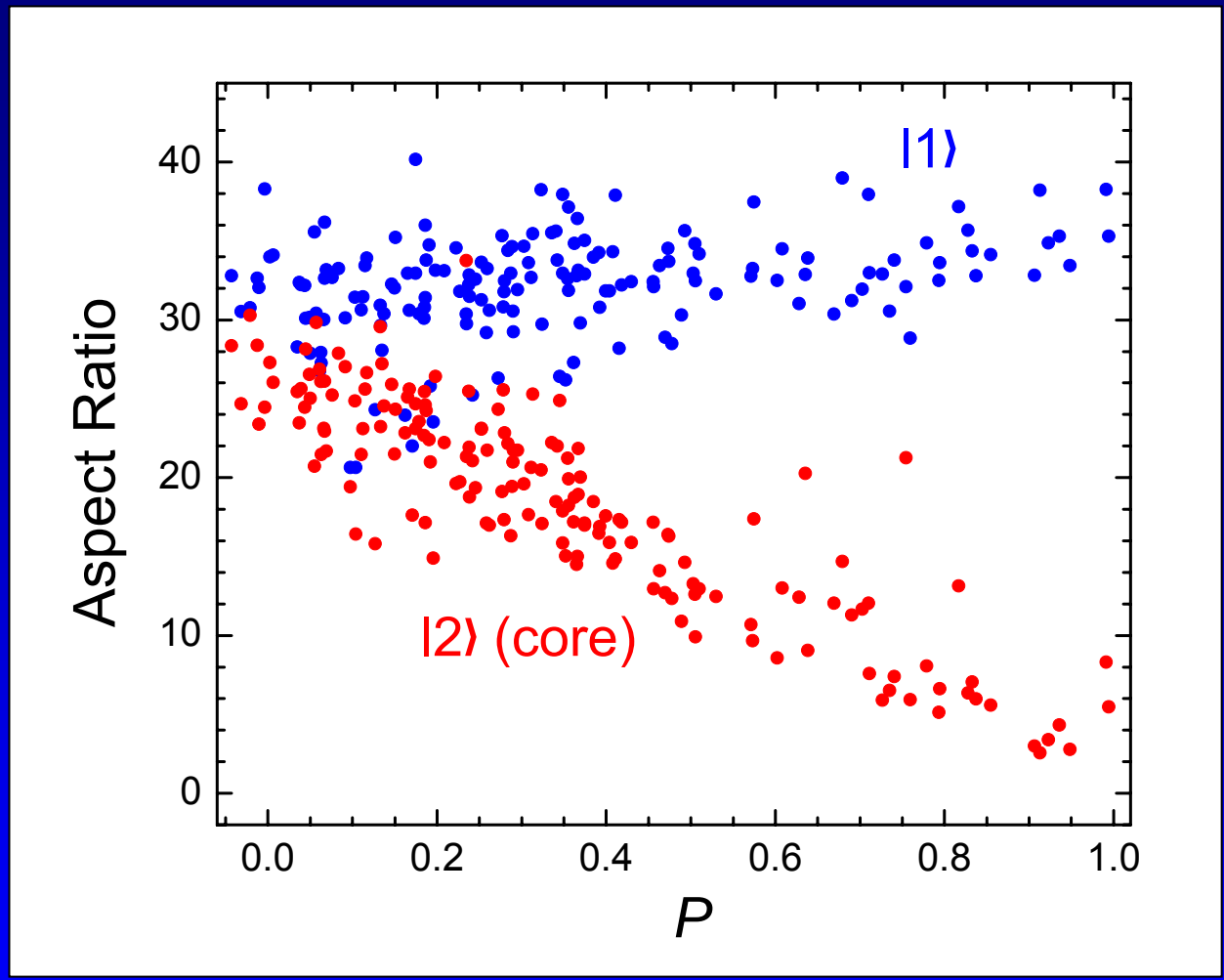
Partridge *et al.*, PRL **97**, 190407 (2006)



Deformation of Superfluid Core







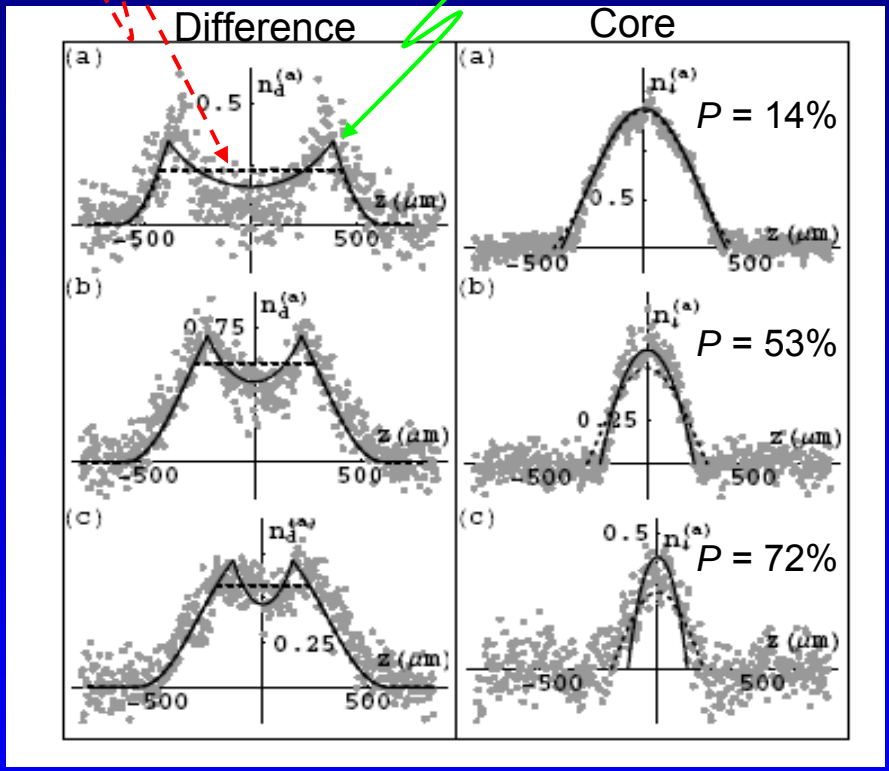
Deformation produces a characteristic dip in the axial difference distribution

The core is compressed axially with increasing *P*

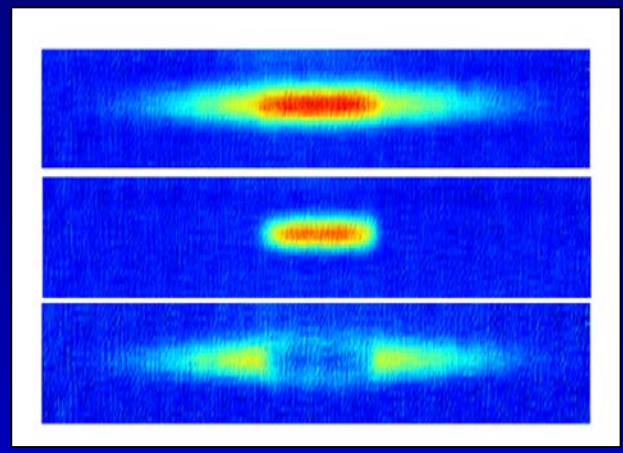
Deformation Produced by Surface Tension

Theory without surface tension

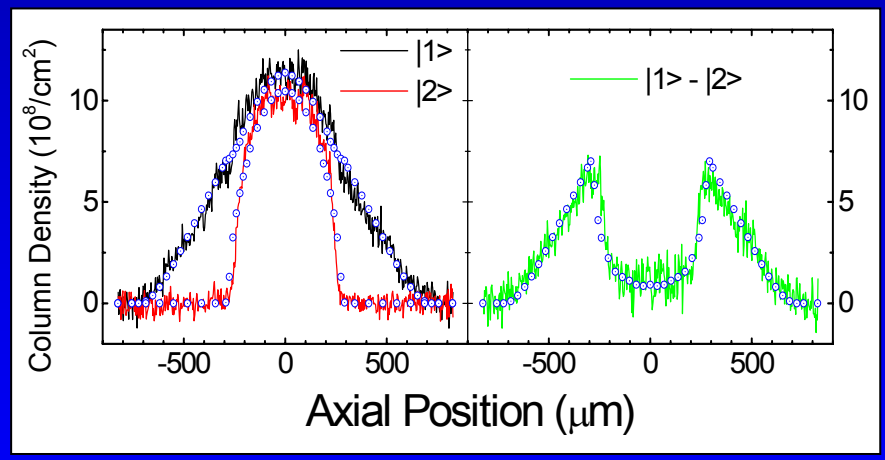
With surface tension



T.N. de Silva and E.J. Mueller, PRL **97**, 070402 (2006)



P = 50%

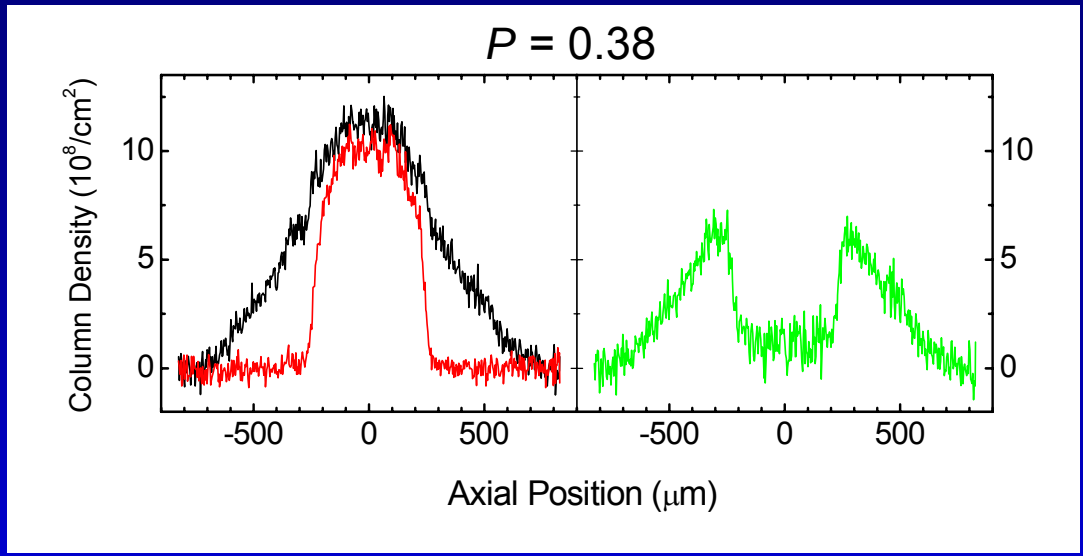


Calculation by M. Haque and H.T.C.Stoof

Deformation is produced by surface tension at the superfluid/normal phase boundary

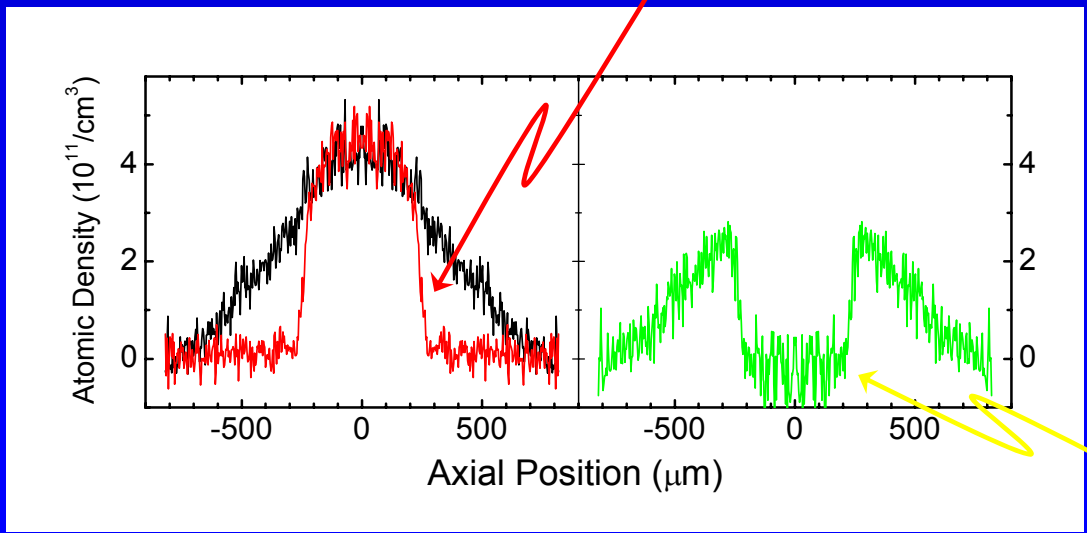
→ phase separation *requires* surface tension

3D Density Reconstruction – Atom Tomography



Column densities
(cut through image)

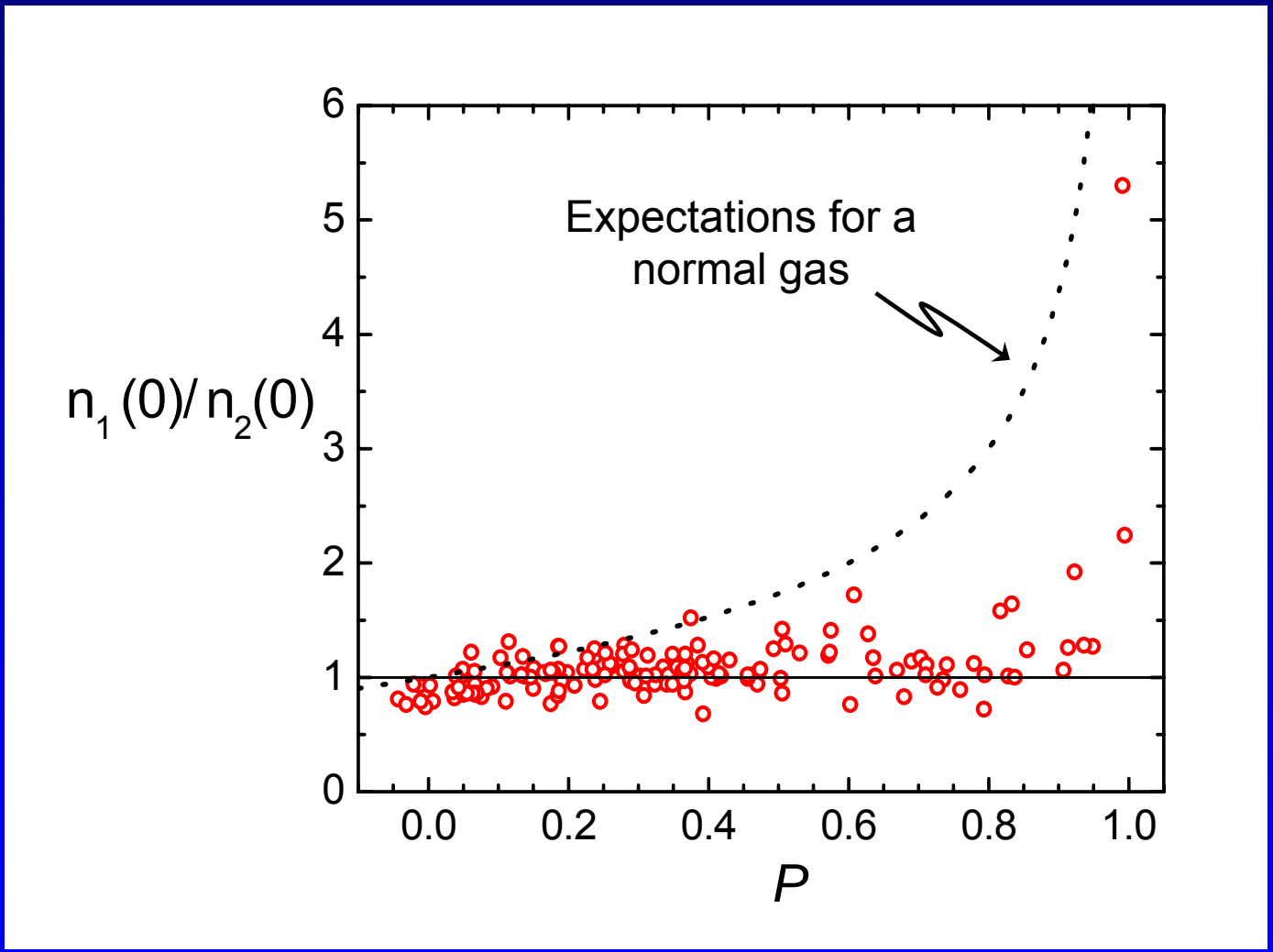
Phase boundary is very steep



Reconstructed real-space densities using Abel transform
(thanks to E. Mueller for code)

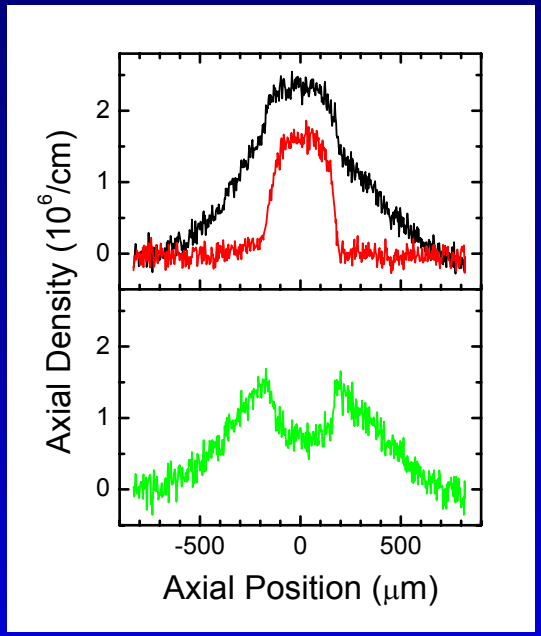
Central core is evenly paired

Central Core is Evenly Paired

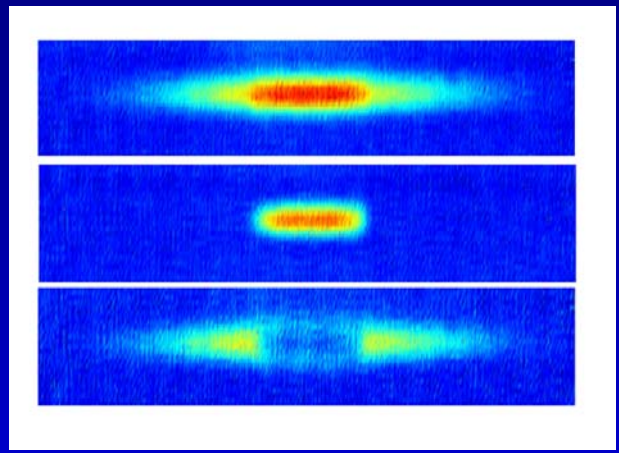


No Clogston limit: atoms paired even for $\Delta E_F > \Delta/2^{1/2}$

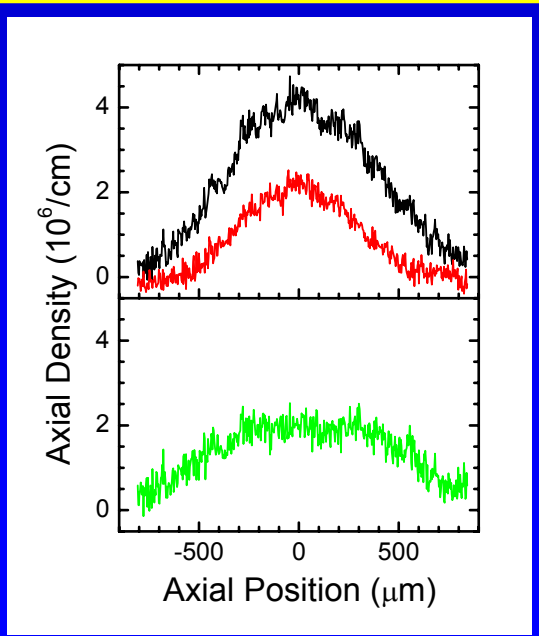
Temperature Dependence- 2 Regimes



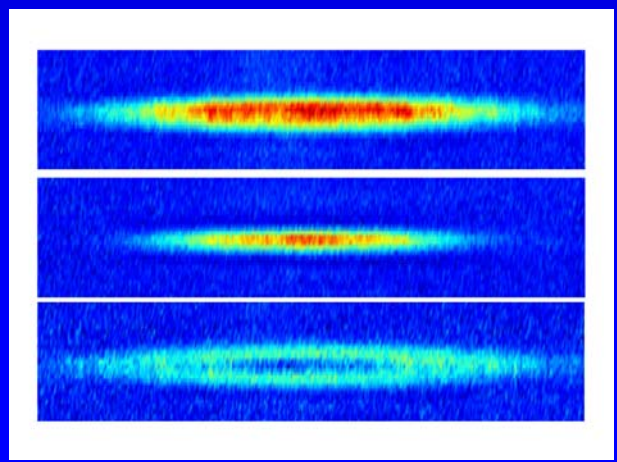
Low temperature: $T < 0.05\ T_F$



- distortion
- sharp phase boundary
- paired core for all P

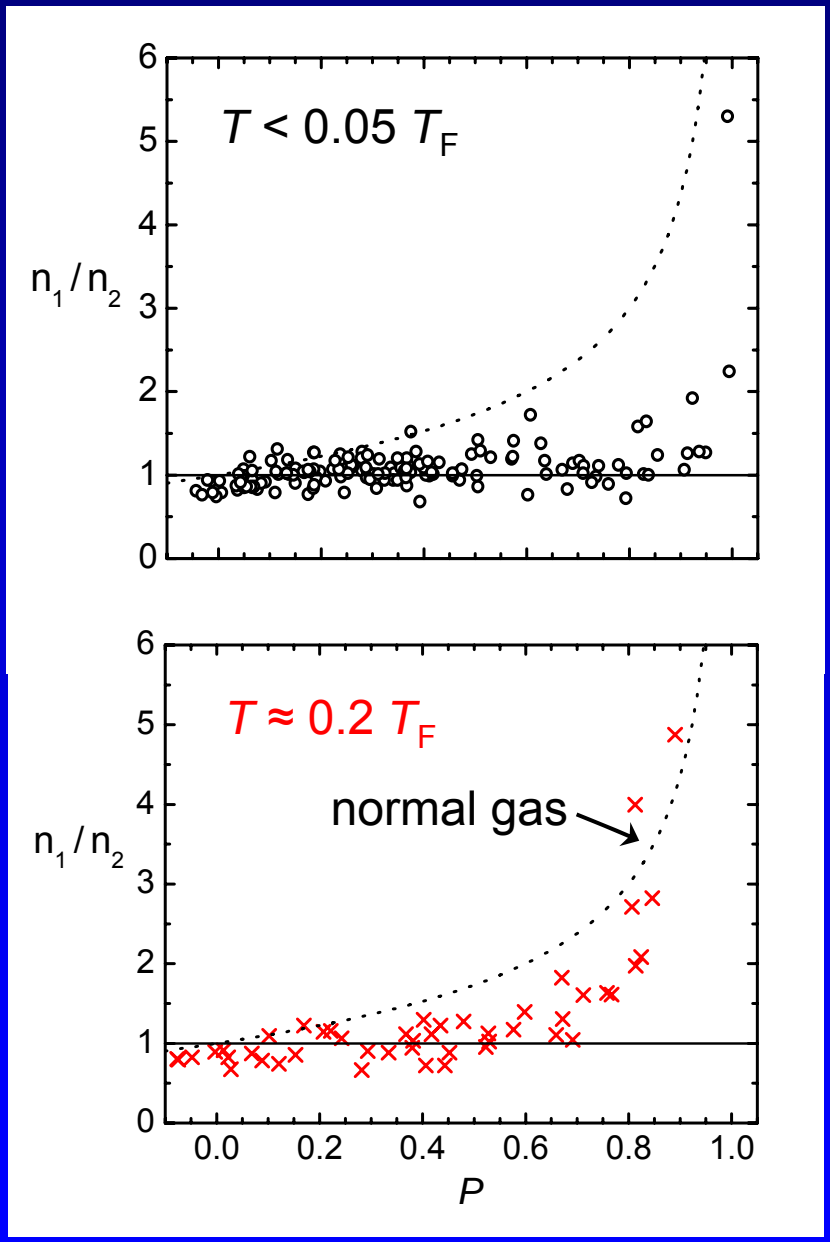


"High" temperature: $T \approx 0.2\ T_F$



- *no* distortion
- partially polarized shell
- *paired center* up to finite P

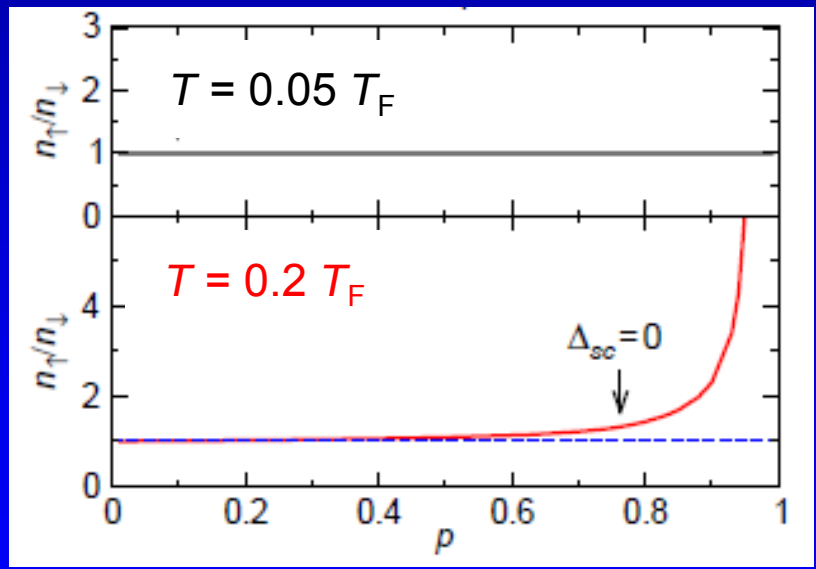
High T Phase also has Paired Center



Evenly paired for nearly all P

No Clogston limit

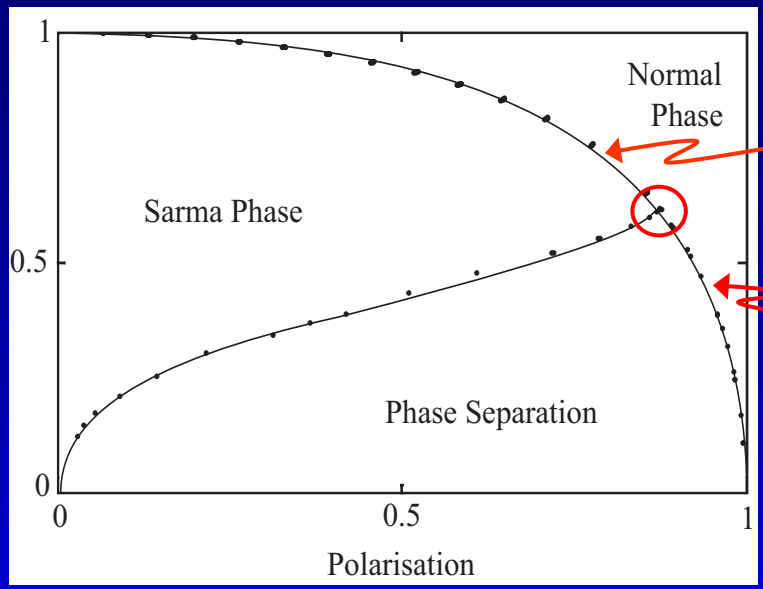
Theory by C-C Chien, Q Chen, Y He, and K Levin, cond-mat/0612103:



Center also paired for low P, but becomes unpaired for P > 60-70%

Clogston limit

Proposed Phase Diagram at Unitarity



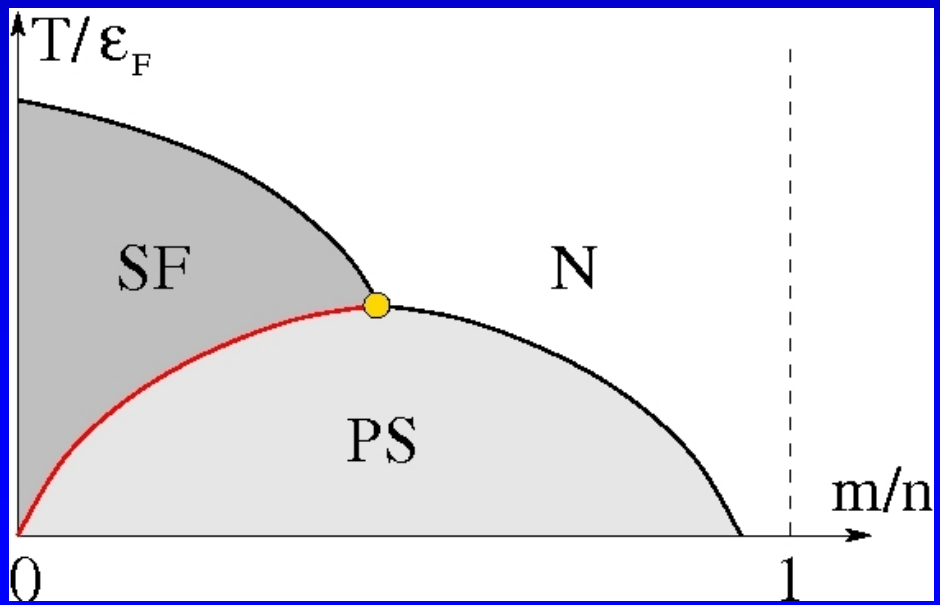
2nd order phase boundary

tricritical point

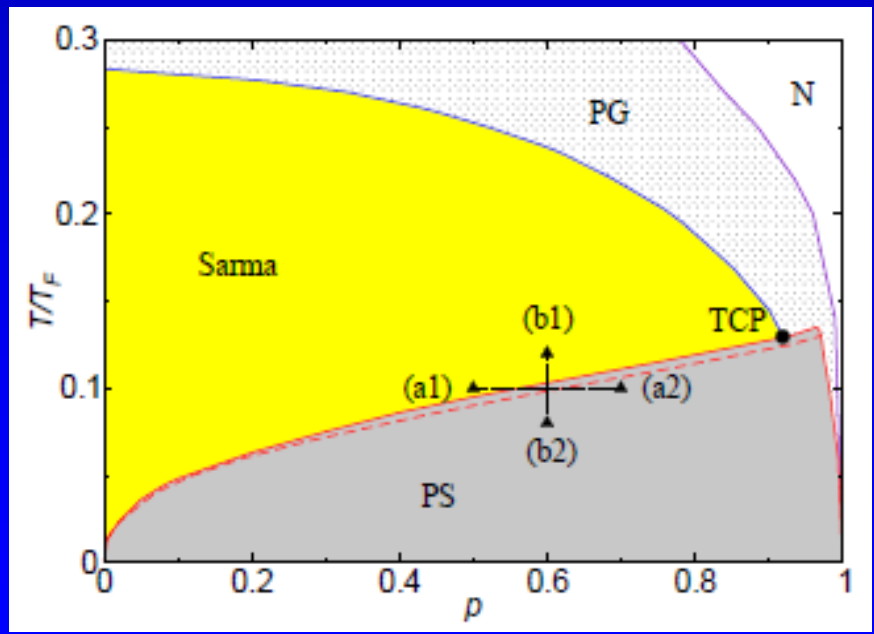
1st order phase boundary

- 2 superfluid phases
- did not consider FFLO or DFS

K Gubbels, M Romans, H Stoof, Phys Rev Lett **97**, 210402 (2006)

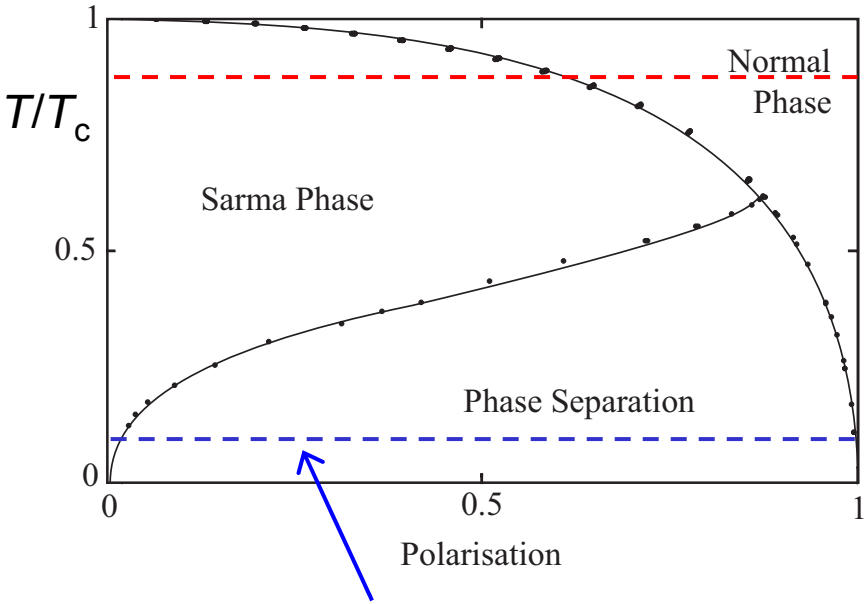


M. Parish *et al.*, Nature Phys. **3**, 124 (2007)

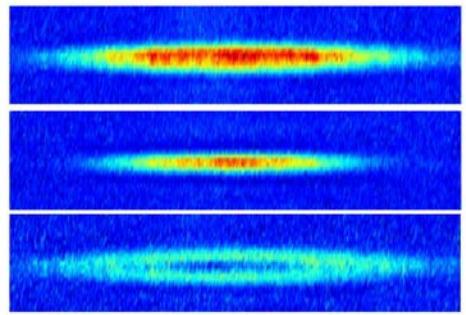


C-C Chien, Q Chen, Y He, K Levin, cond-mat/0612103

Proposed Phase Diagram at Unitarity

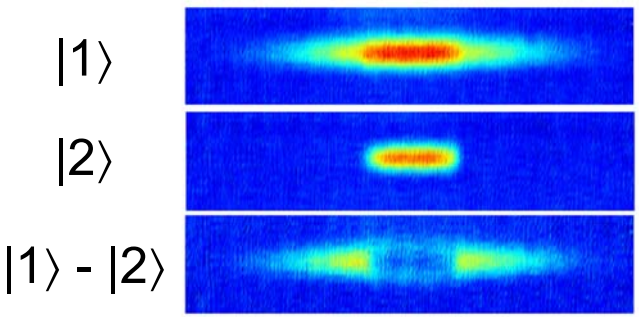


$T \approx 0.2\ T_F$



- diffuse phase boundary
- *no* distortion
- *paired center* up to $P \approx 60\%$

$T \leq 0.05\ T_F$



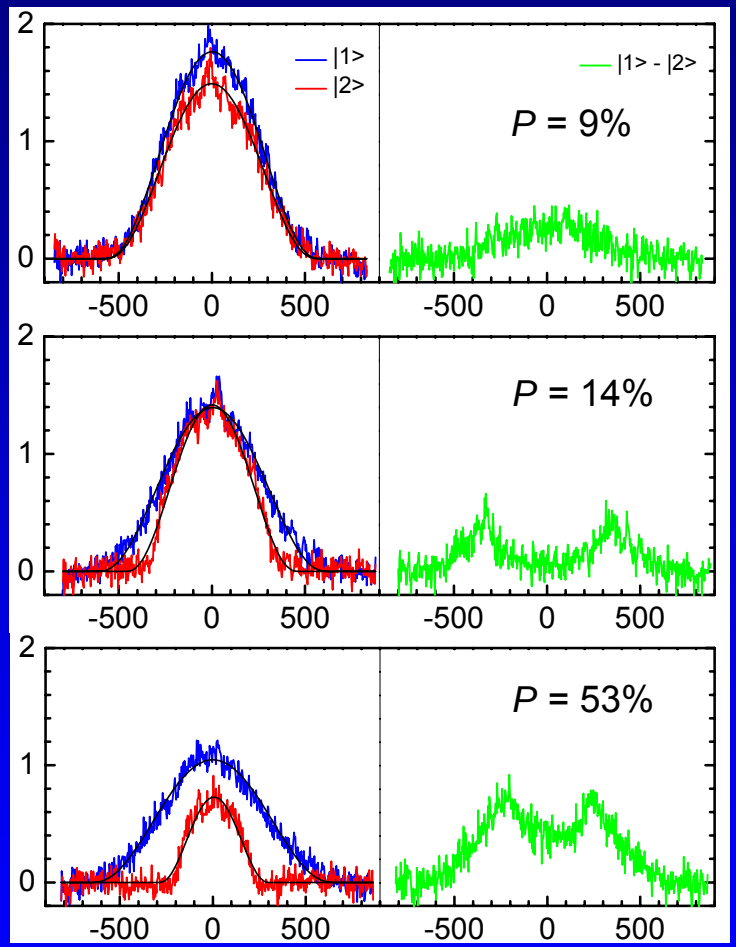
2 distinct superfluid phases

- sharp phase boundary
- distortions from surf. tension at phase boundary
- paired core for all P

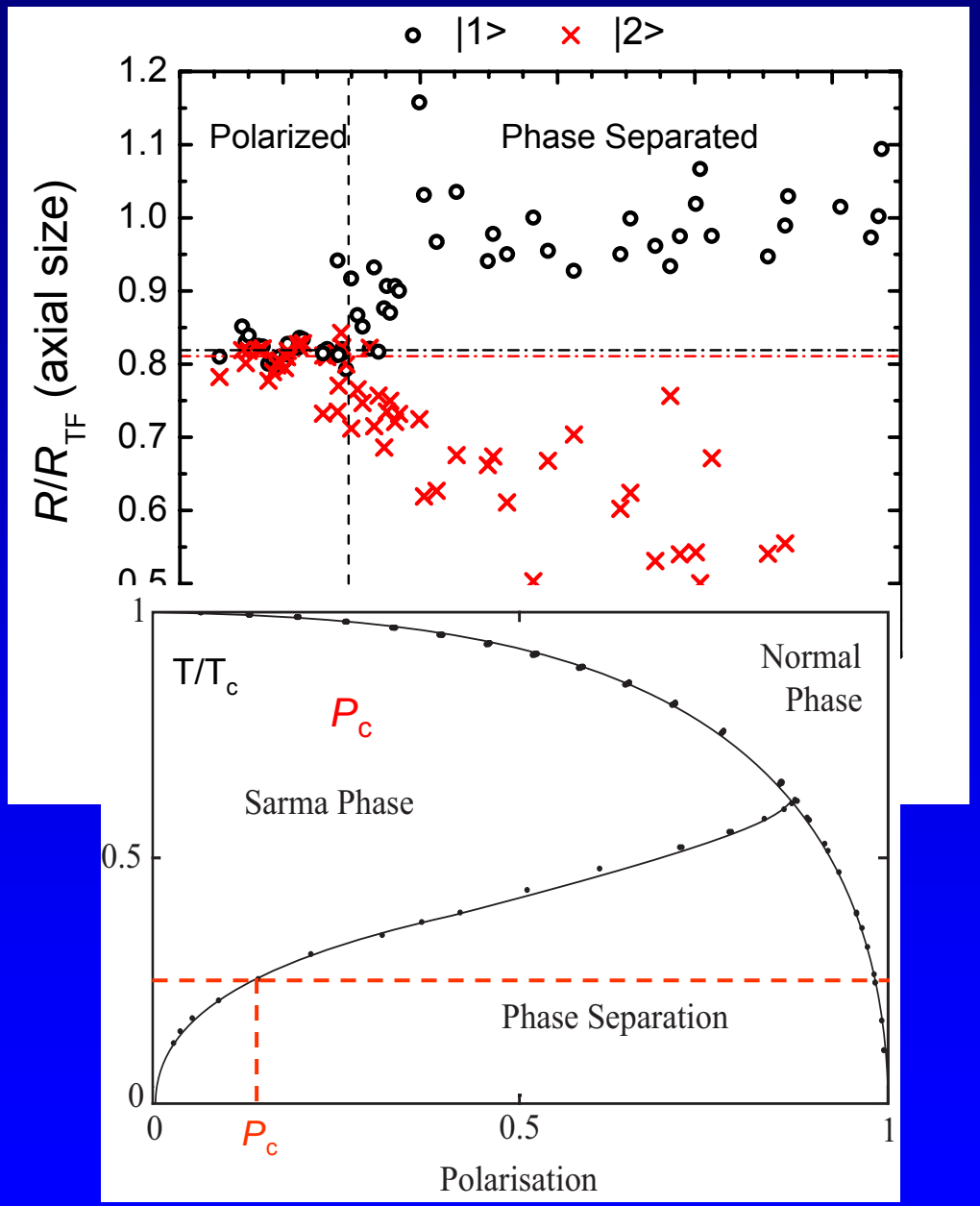
$$(N_1 - N_2)/ (N_1 + N_2)$$

Intermediate T - Phase Separation for $P > P_c$

$T \approx 0.1\ T_F$

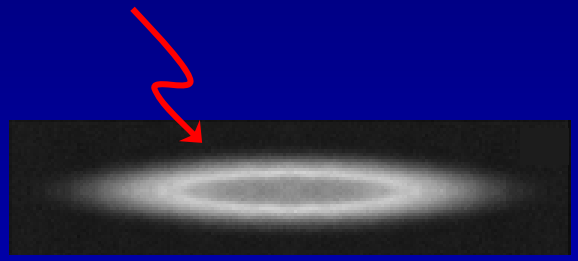


Partridge *et al.*, *Science* **311**, 503 (2006)

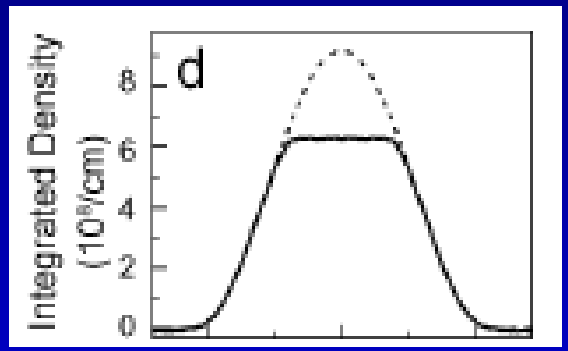


Comparison with MIT Data

Subsequent to our paper, MIT reported *in-situ* images showing paired core:

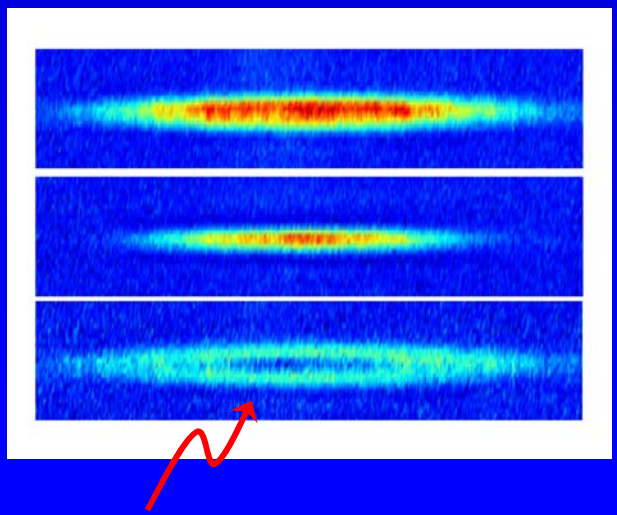


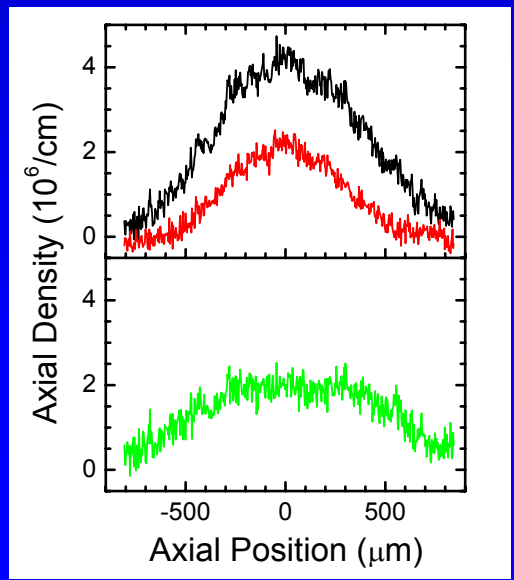
Shin, ..., Ketterle, PRL **97**, 030401 (2006)



- partially polarized shell
- no distortions
- fully paired center only to finite *P*

Compares with our high temperature data:



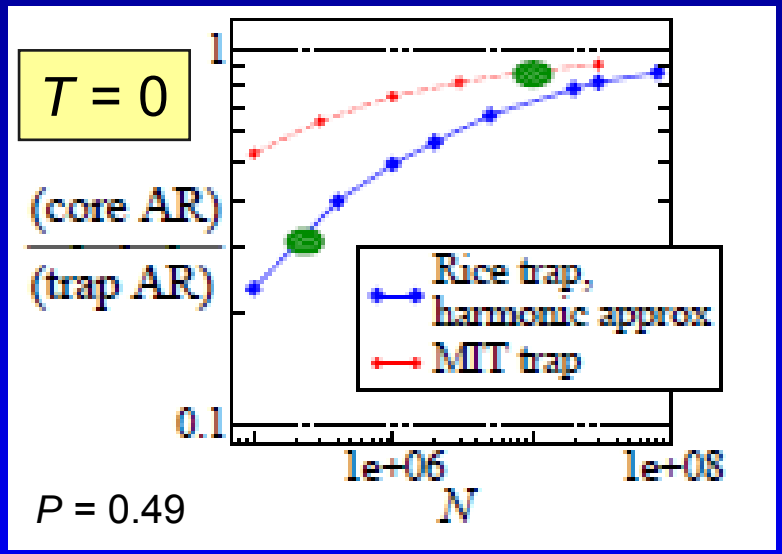


- partially polarized shell
- no distortions
- fully paired center only to finite *P*

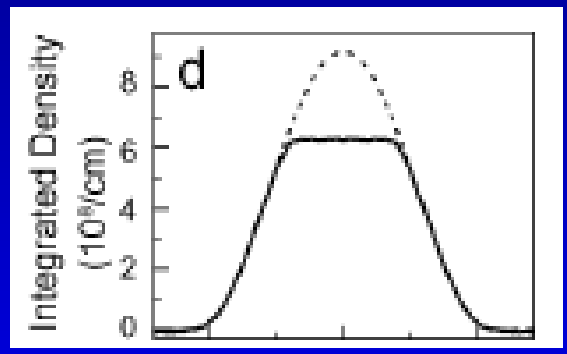
Surface Tension Effects Expected in MIT Expt.

Observation of Phase Separation in a Strongly Interacting Imbalanced Fermi Gas

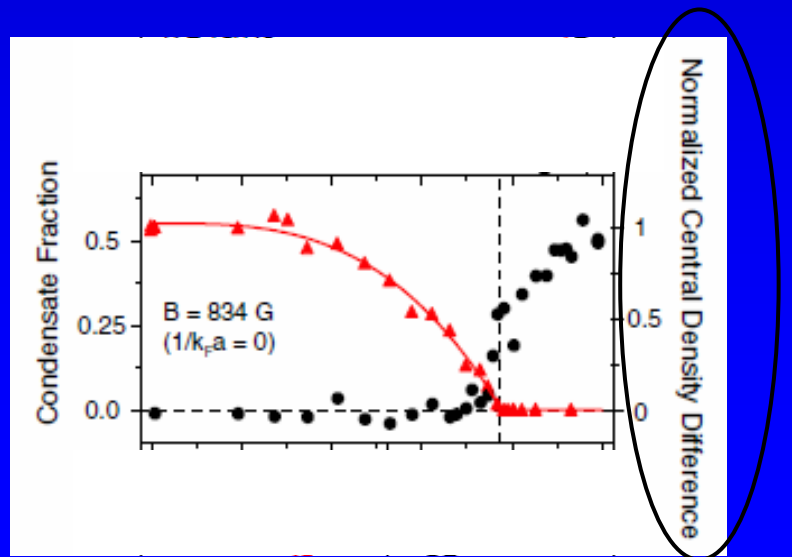
Y. Shin,* M. W. Zwierlein, C. H. Schunck, A. Schirotzek, and W. Ketterle
Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA
(Received 15 June 2006; published 18 July 2006; corrected 21 July 2006)



M. Haque and H.T.C. Stoof, cond-mat/0701464



No evidence of deformation

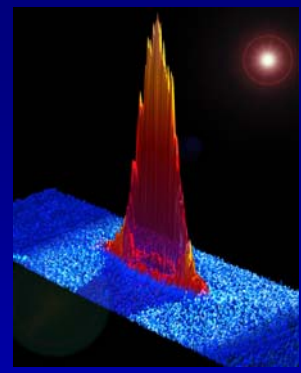


Evenly paired center does *not* prove phase separation

– property shared by the Sarma phase

Summary

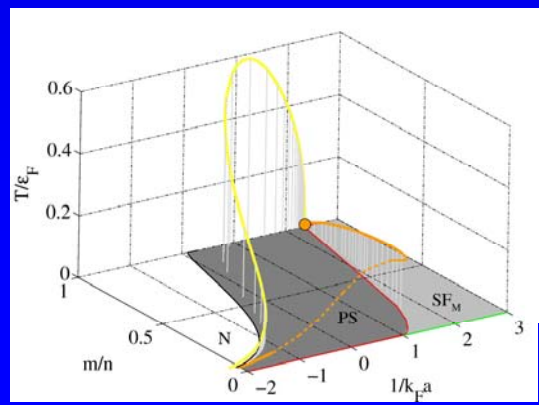
Yes	Phase separation	No Clogston limit
Maybe	Sarma phase	Clogston limit
No	FFLO	
No	DFS	



Surface tension between fully paired and fully polarized phases

→ *Smoking gun* for phase separation

- Open Questions
  - Why no Clogston limit in phase separated phase?
  - Is MIT data phase separated or Sarma? Why no surface tension?
  - Problems with MIT *T* fitting?
  - Geometry dependence?
- Future
  - map phase diagram vs. T, P, $k_F a$
  - search for FFLO phase



M. Parish *et al.*, Nature Phys. **3**, 124 (2007)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