The Abdus Salam
International Centre for Theoretical Physics

United Nations
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1859-27

Summer School on Novel Quantum Phases and Non-Equilibrium Phenomena in Cold Atomic Gases

27 August - 7 September, 2007

Experiments with Fermi gases in the BEC/BCS crossover - Part II

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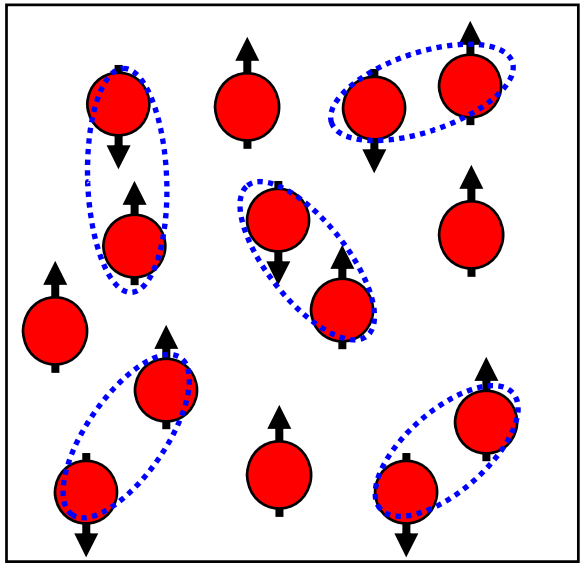
Fermion Pairing with Unequal Spin Populations

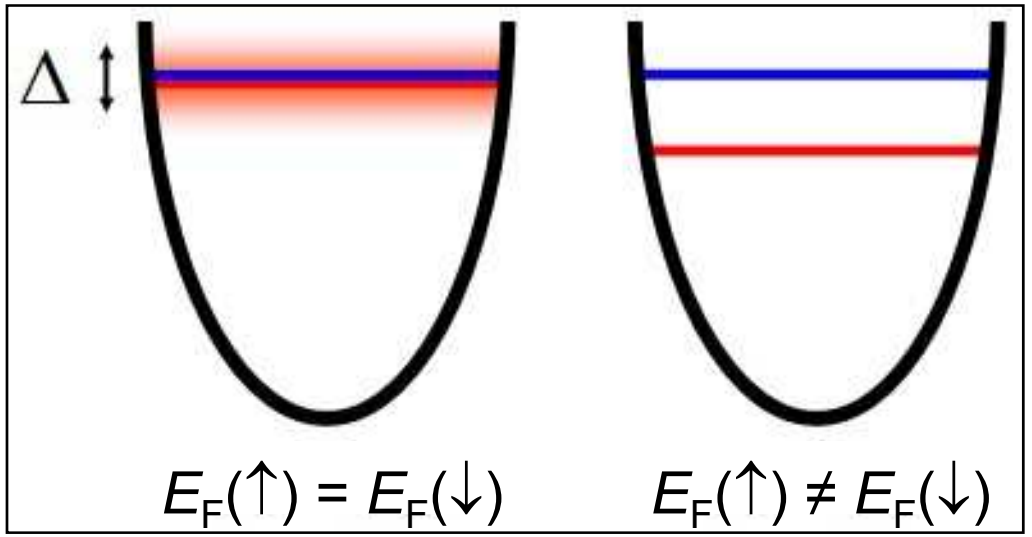
Guthrie Partridge
Yean-an Liao
Wenhui Li
Ramsey Kamar

Special thanks to
Henk Stoof

What Happens when the Fermi Energies are Mismatched?

In BCS, the Fermi energies of the two spins are equal:



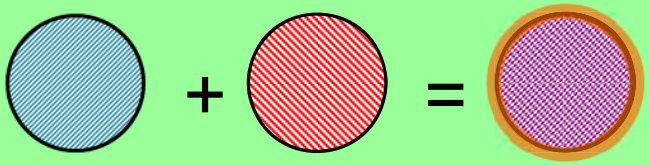


Mismatch may be created in:

- magnetized superconductors
- pairing of quarks in neutron stars
- cold atoms with unequal spin populations

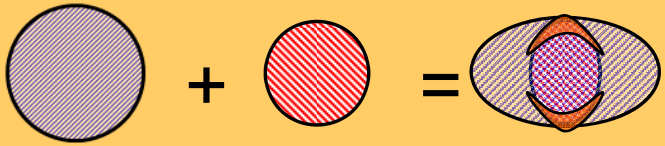
Proposed Pairing Mechanisms

In *k*-space:



BCS

FFLO
pairs have non-zero momentum



DFS
Deformed Fermi Surface

("Sarma")
Polarized Superfluid
$\mu_\uparrow - \mu_\downarrow < \Delta$: BCS
$> \Delta$: breached pair (gapless)

Phase Separation
(*real space*)

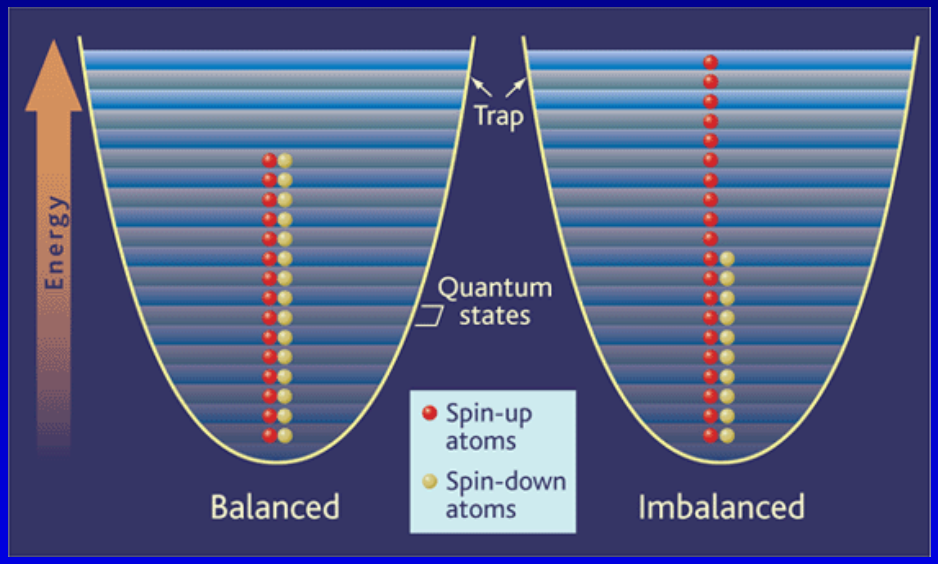
Majority Minority Paired State

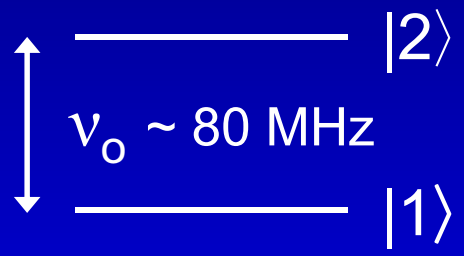
In a trap,
$\Delta = \Delta(r)$

Blue → pairs
Red → spin-up

Unequal Spin Populations with Atoms

- Fundamental incompatibility between magnetism and superconductivity
  - straightforward to make a polarized atomic gas





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 $0 < P < 1$

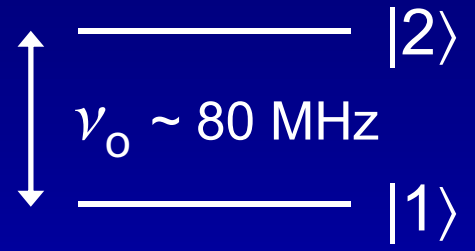
Measure P by independent probes of $|1\rangle$ and $|2\rangle$

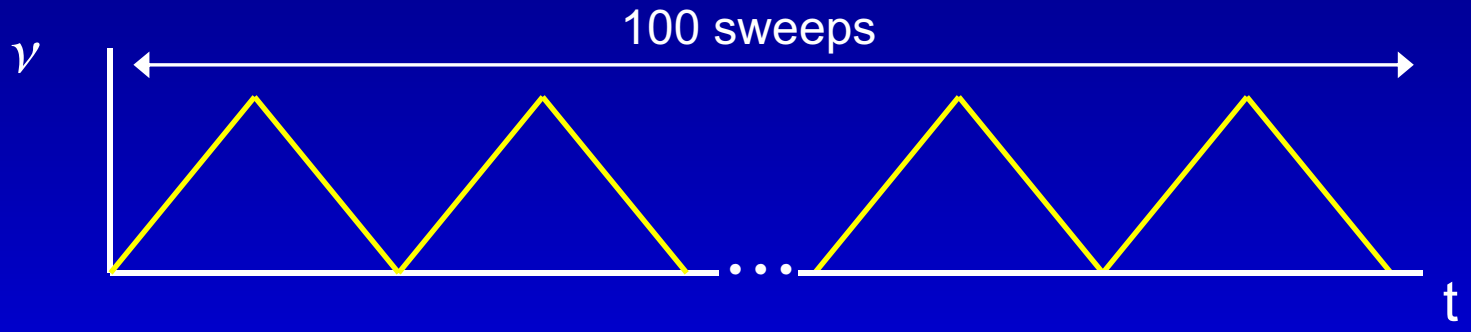
Experiments with ^{6}Li at MIT and Rice (*Science*, 2006)

Earliest cold atom theory papers: Combescot; Bedaque, Caldas, Rupak; Liu & Wilczek; Machida; Carlson; Sheehy & Radzihovsky; Sedrakian; K. Yang; Pieri & Strinati; Pao, Wu, Yip; Son; Cohen; Recati; Lobo; Chevy; Mueller; Stoof; Parish, Simons; Ho & Zhai; Hu & Liu; Torma; Chien & Levin; Bulgac; Duan; He

Making Polarized Mixtures

Use RF sweeps to transfer population





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

Initially, $N_2 = 0 \Rightarrow P = 1$ Finally, $0 < N_2 < N_1 \Rightarrow 0 < P < 1$

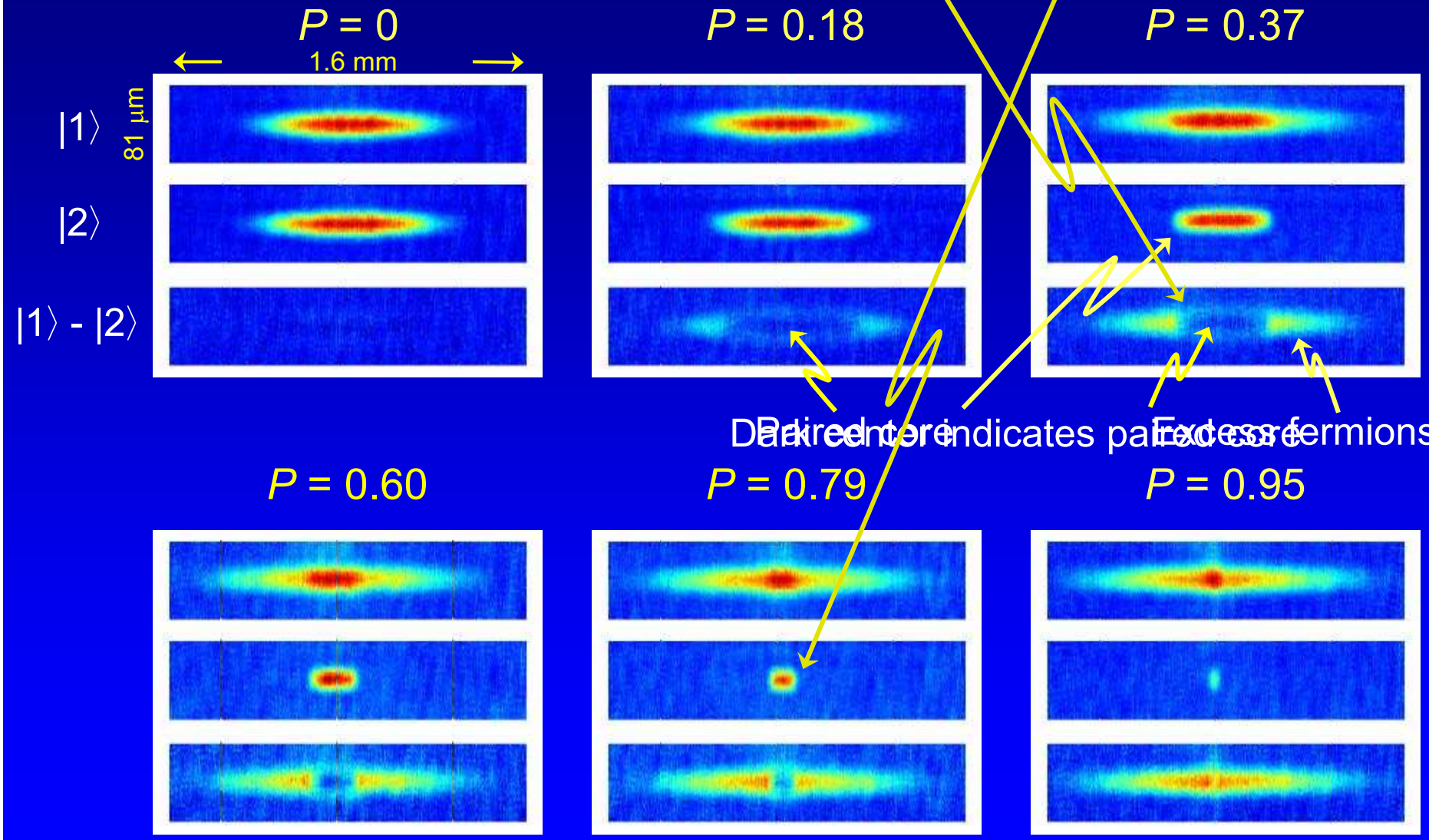
determined by RF power

$E_F \propto N^{1/3} \Rightarrow E_F(1) / E_F(2) = [(1 - P) / (1 + P)]^{1/3}$

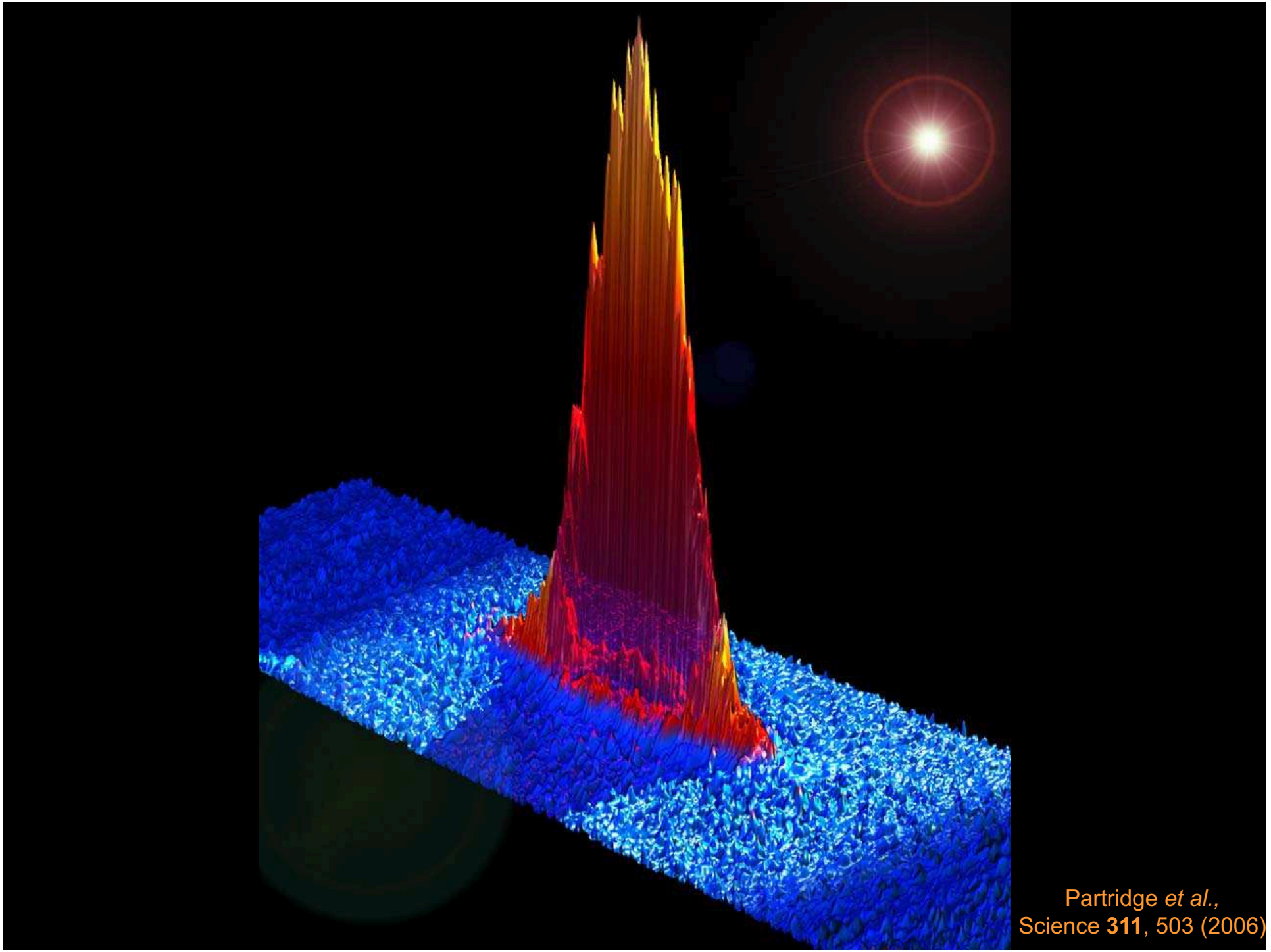
Measure P by independent probes of $|1\rangle$ and $|2\rangle$

Images at Unitarity Show Phase Separation

$P = (N_1 - N_2) / (N_1 + N_2)$ Paired core $1/k_F a = 0$, Sharp phase boundaries $T < 0.05\ T_F$ Core deformation

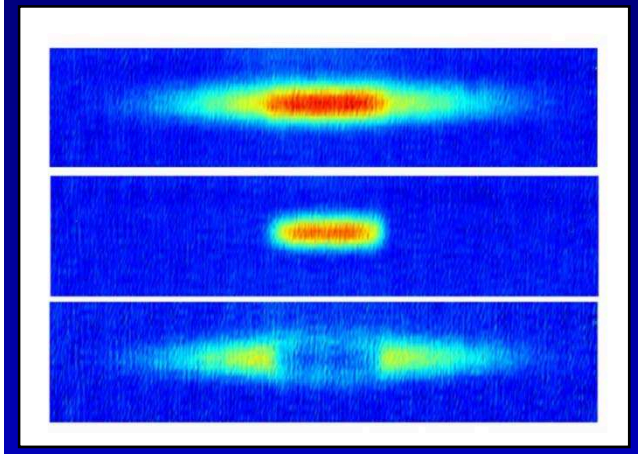


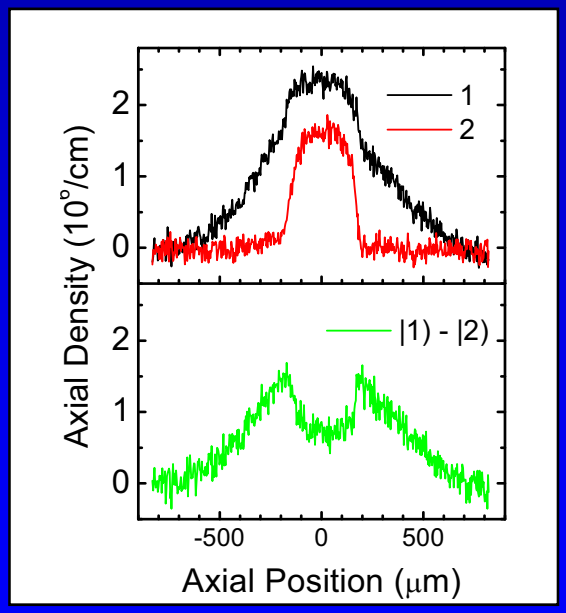
Partridge *et al.*, PRL **97**, 190407 (2006)

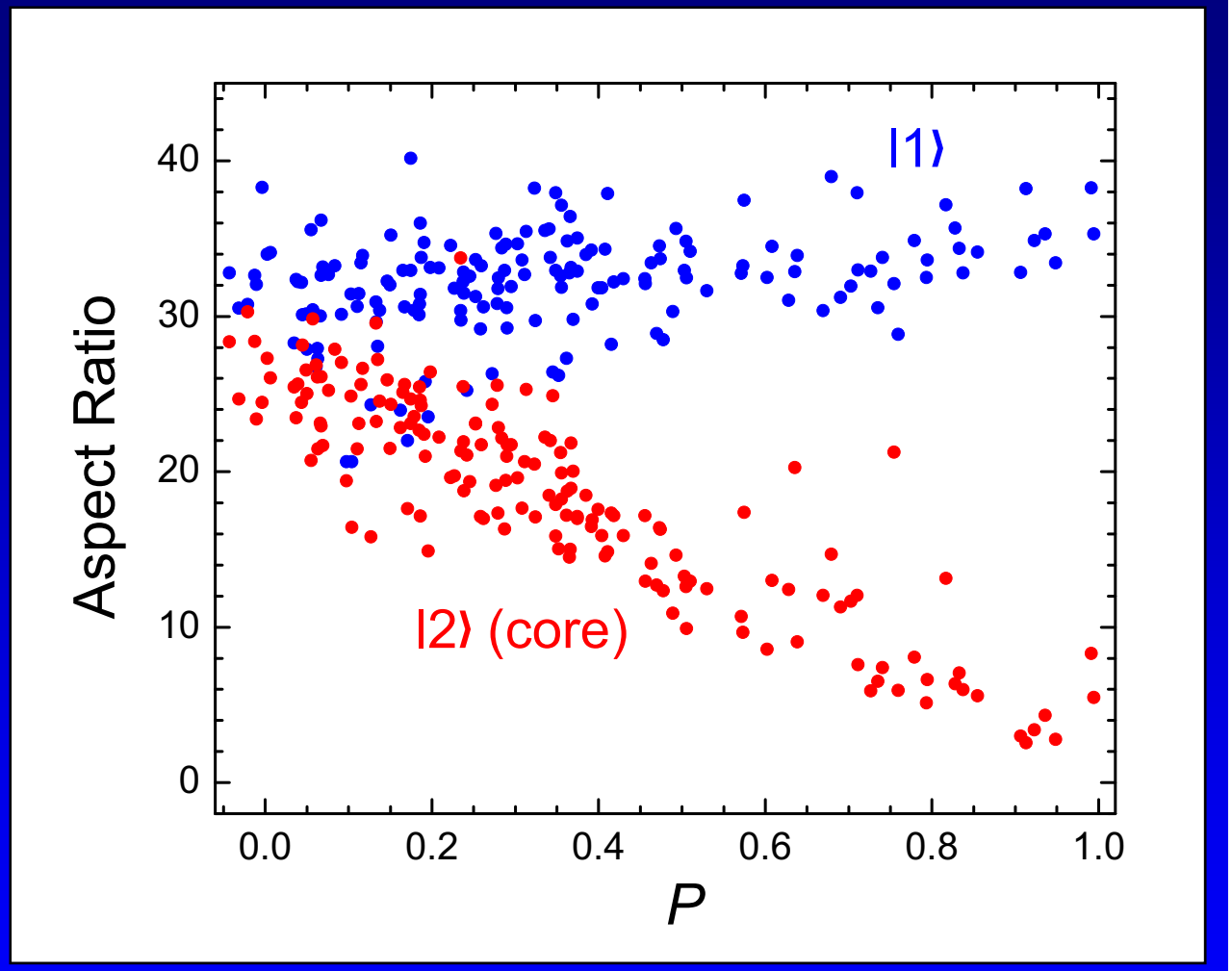


Partridge *et al.*,
Science **311**, 503 (2006)

Deformation of Superfluid Core







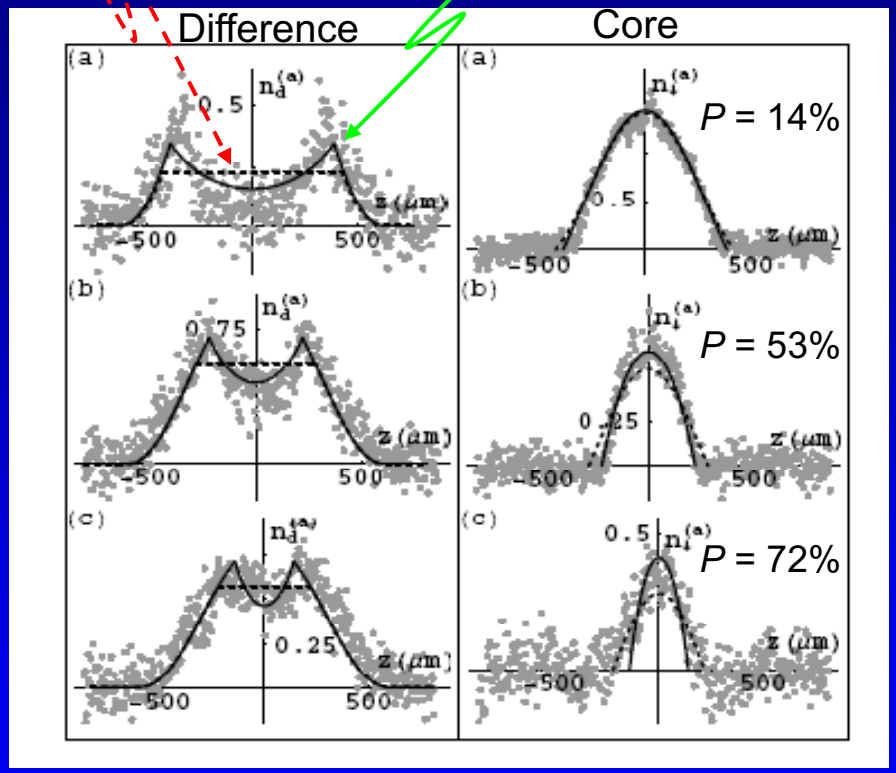
The core is compressed axially with increasing *P*

Deformation produces a characteristic dip in the axial difference distribution

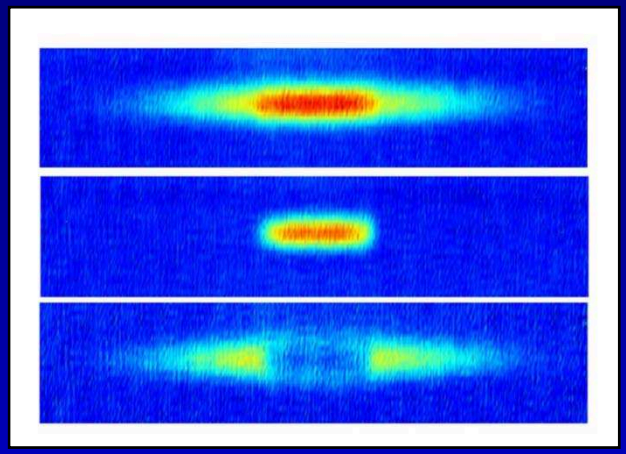
Deformation Produced by Surface Tension

Theory without surface tension

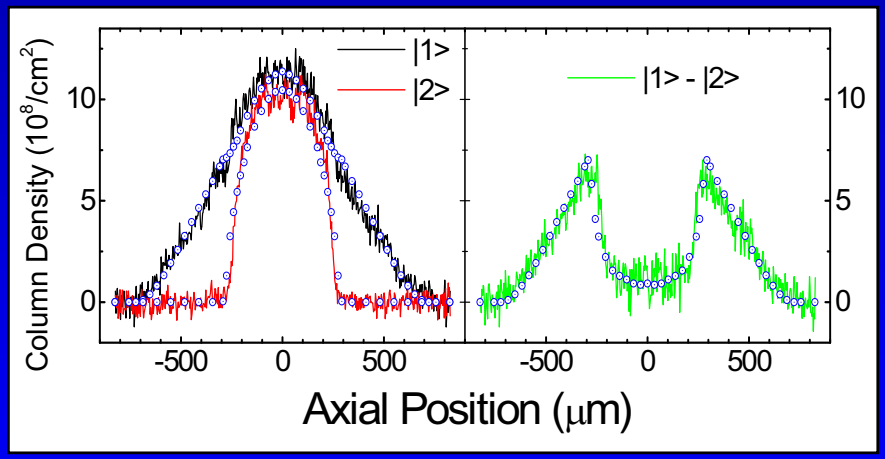
With surface tension



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



P = 50%



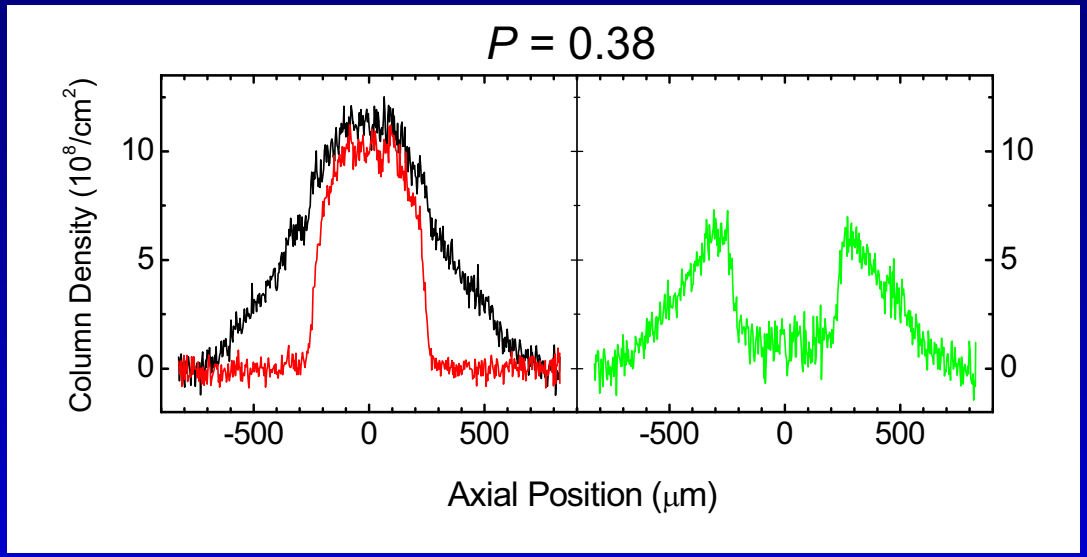
Calculation by M. Haque and H.T.C.Stoof
cond-mat/0701464

$E_s = \eta\, E_F/(\text{area})^2$

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

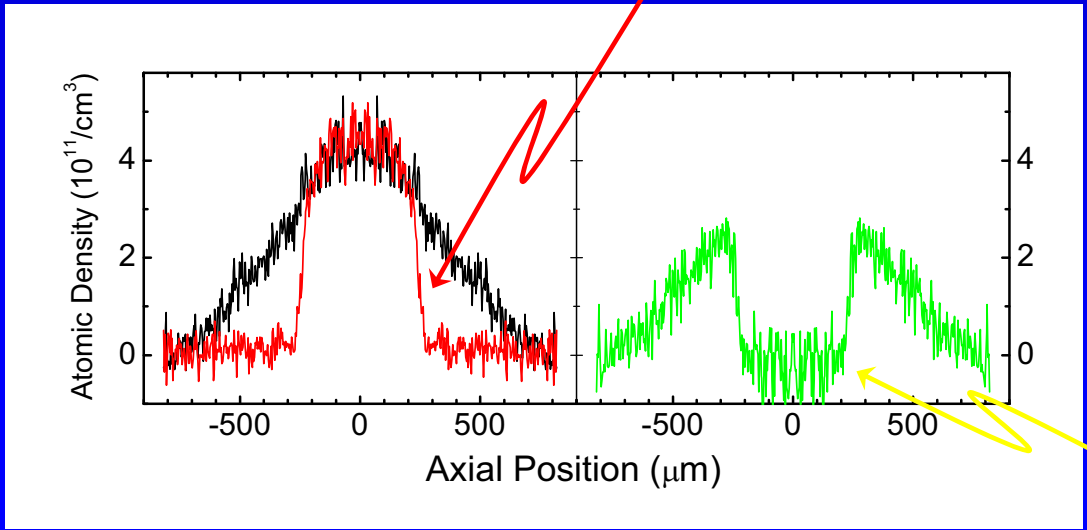
→ phase separation always results in surface tension

3D Density Reconstruction – Atom Tomography



Column densities
(cut through image)

Phase boundary is very steep



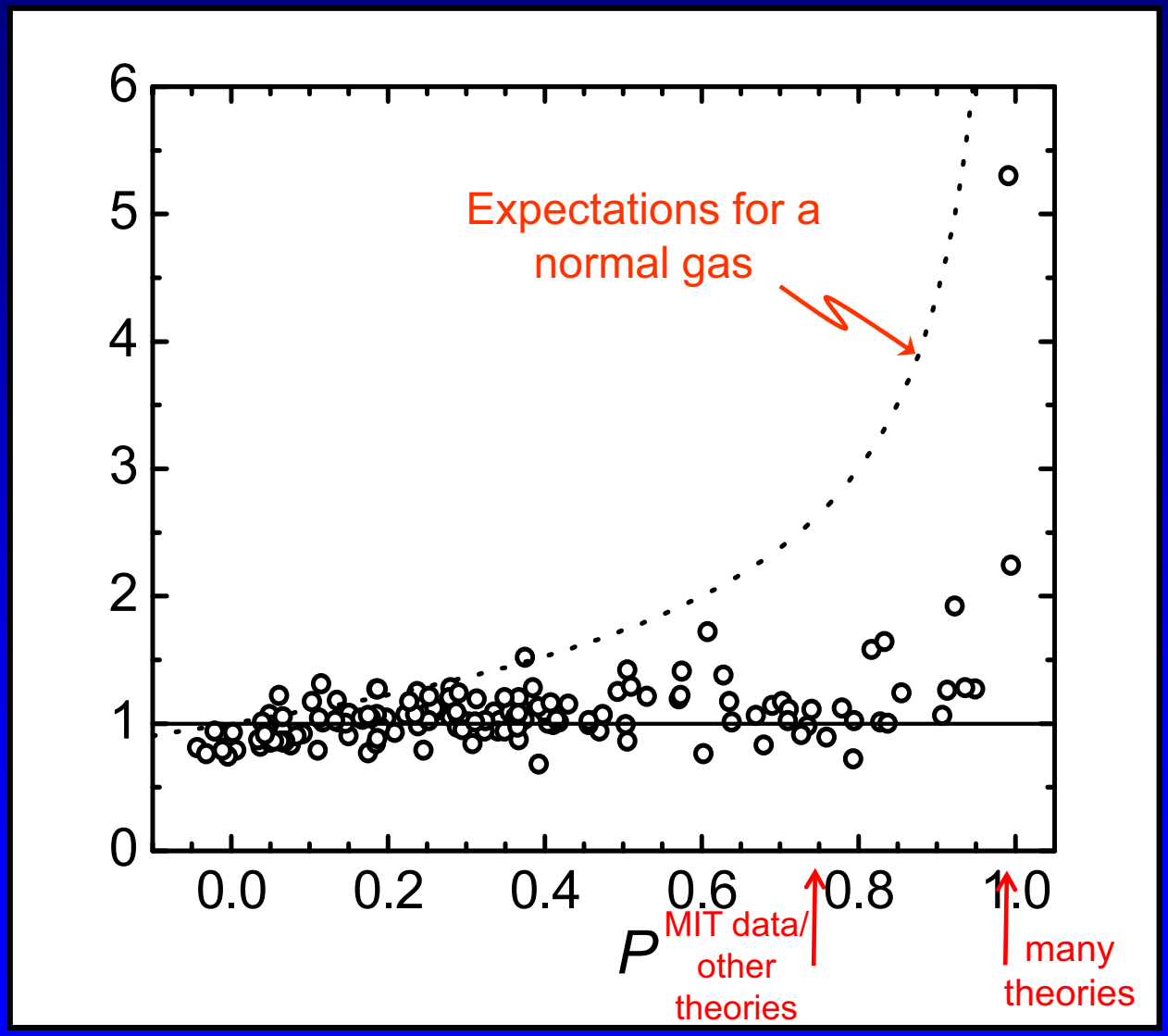
Reconstructed real-space densities using Abel transform
(thanks to E. Mueller for code)

Central core is evenly paired

Central Core is Evenly Paired

Ratio of central densities

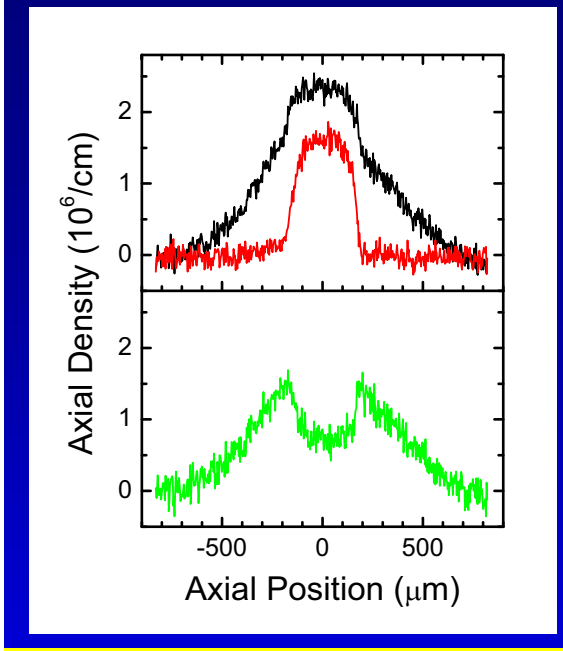
$n_1(0) / n_2(0)$



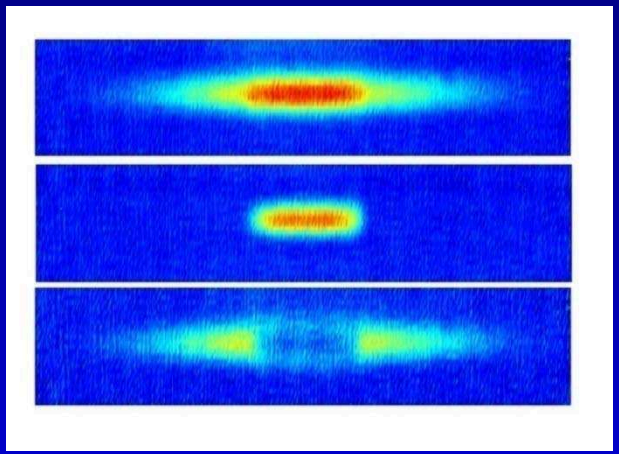
Theories do not account for violation of LDA

No Clogston limit: atoms paired even for $\mu_1 - \mu_2 > \Delta$

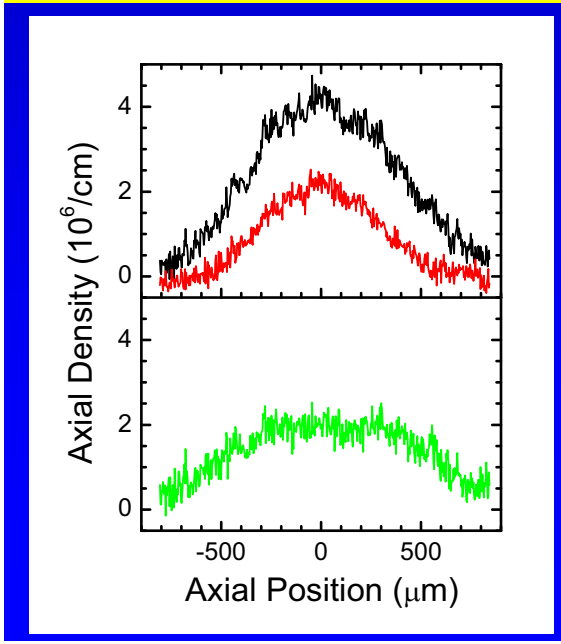
Temperature Dependence- 2 *Paired* Regimes



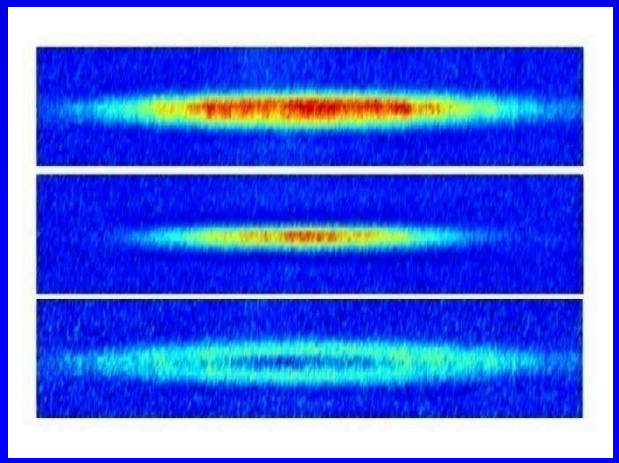
Low temperature: $T < 0.05\ T_F$



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

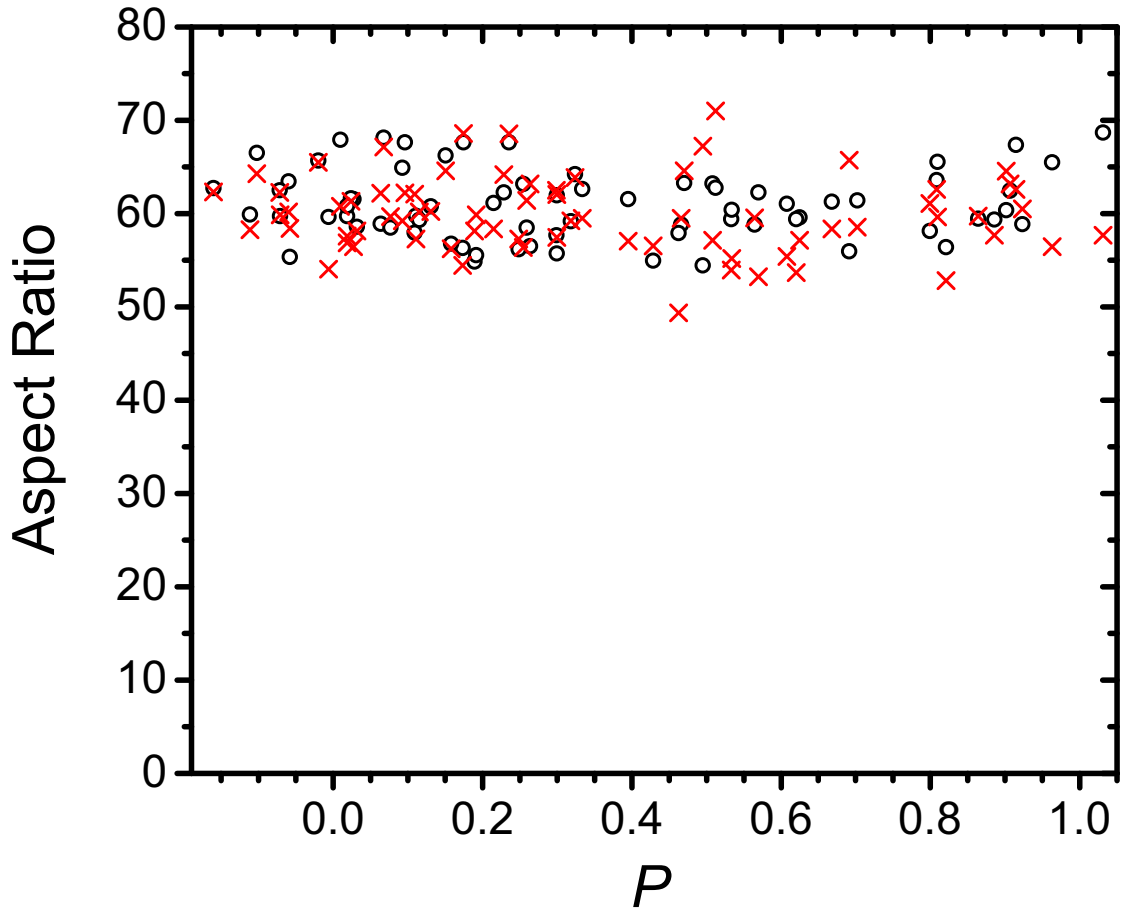


"High" temperature: $T \approx 0.2\ T_F$

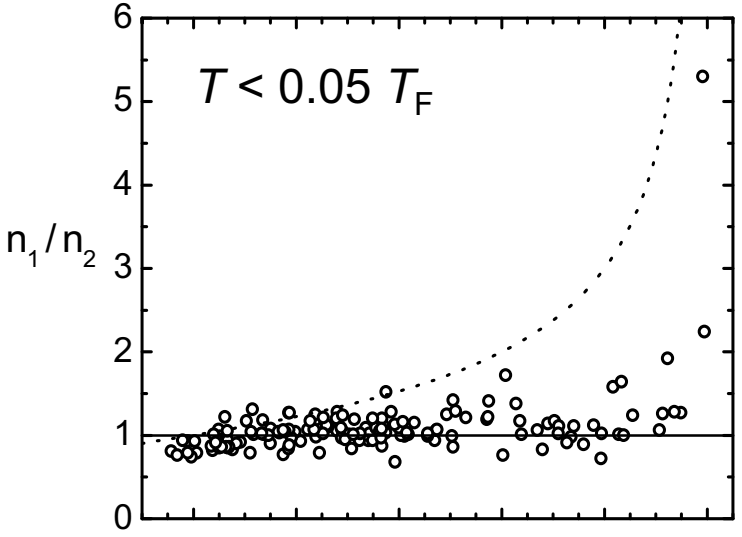


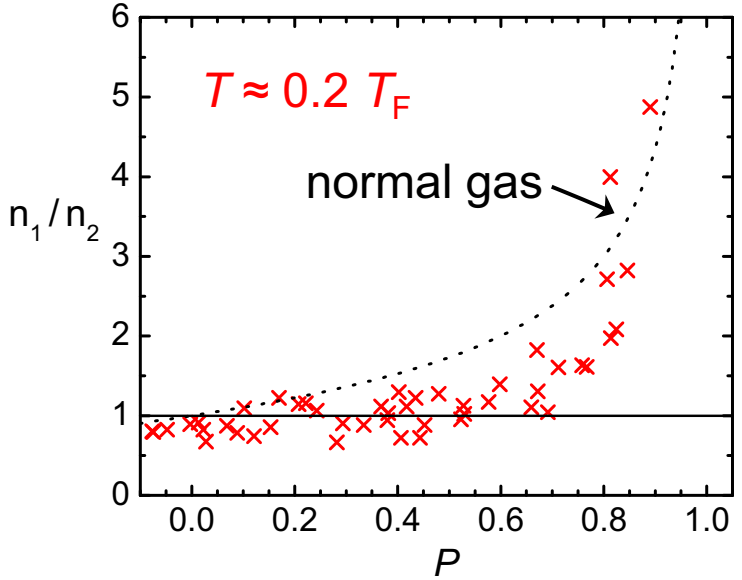
- *no* distortion
- partially polarized shell
- *paired center* up to finite *P*

$T \approx 0.2\ T_F$: No Distortion



High T Phase also has Paired Center

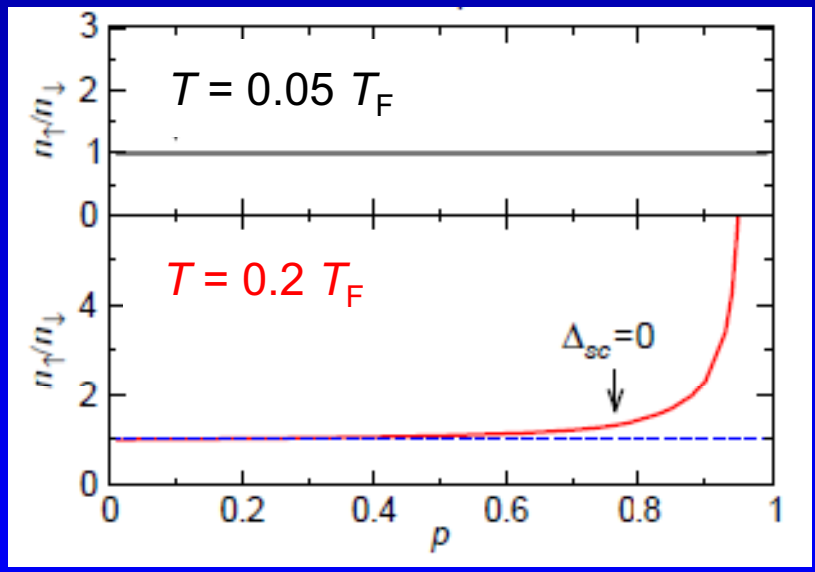




Evenly paired for nearly all P

No Clogston limit

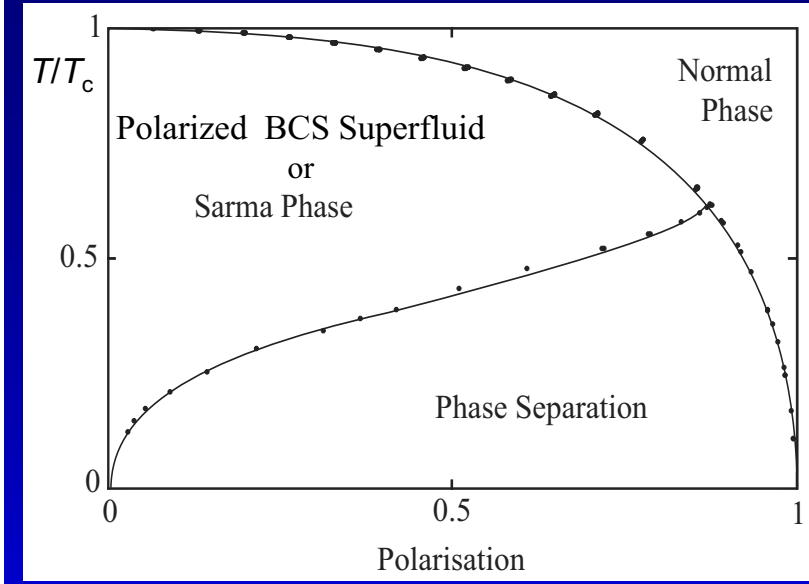
Theory by C-C Chien, Q Chen, Y He, and K Levin, cond-mat/0612103:



Center also paired for low P, but becomes unpaired for P > 70-80%

Clogston limit

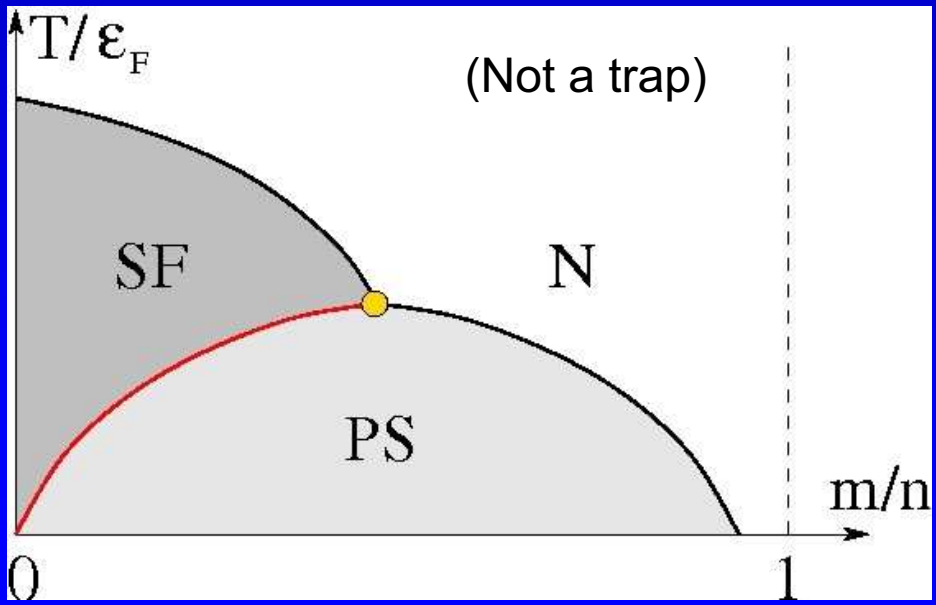
Proposed Phase Diagrams at Unitarity



- 2 superfluid phases
- did not consider FFLO or DFS

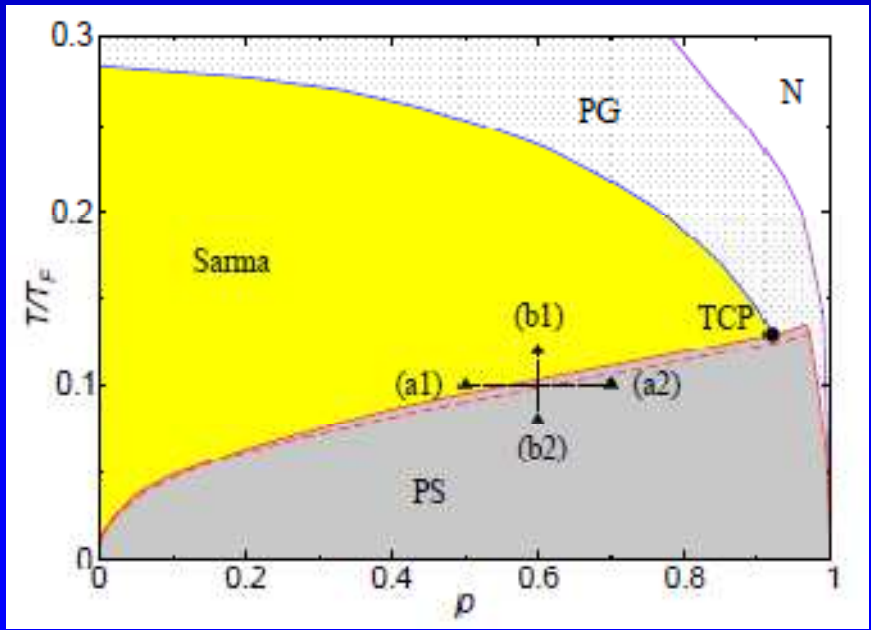
Trap

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



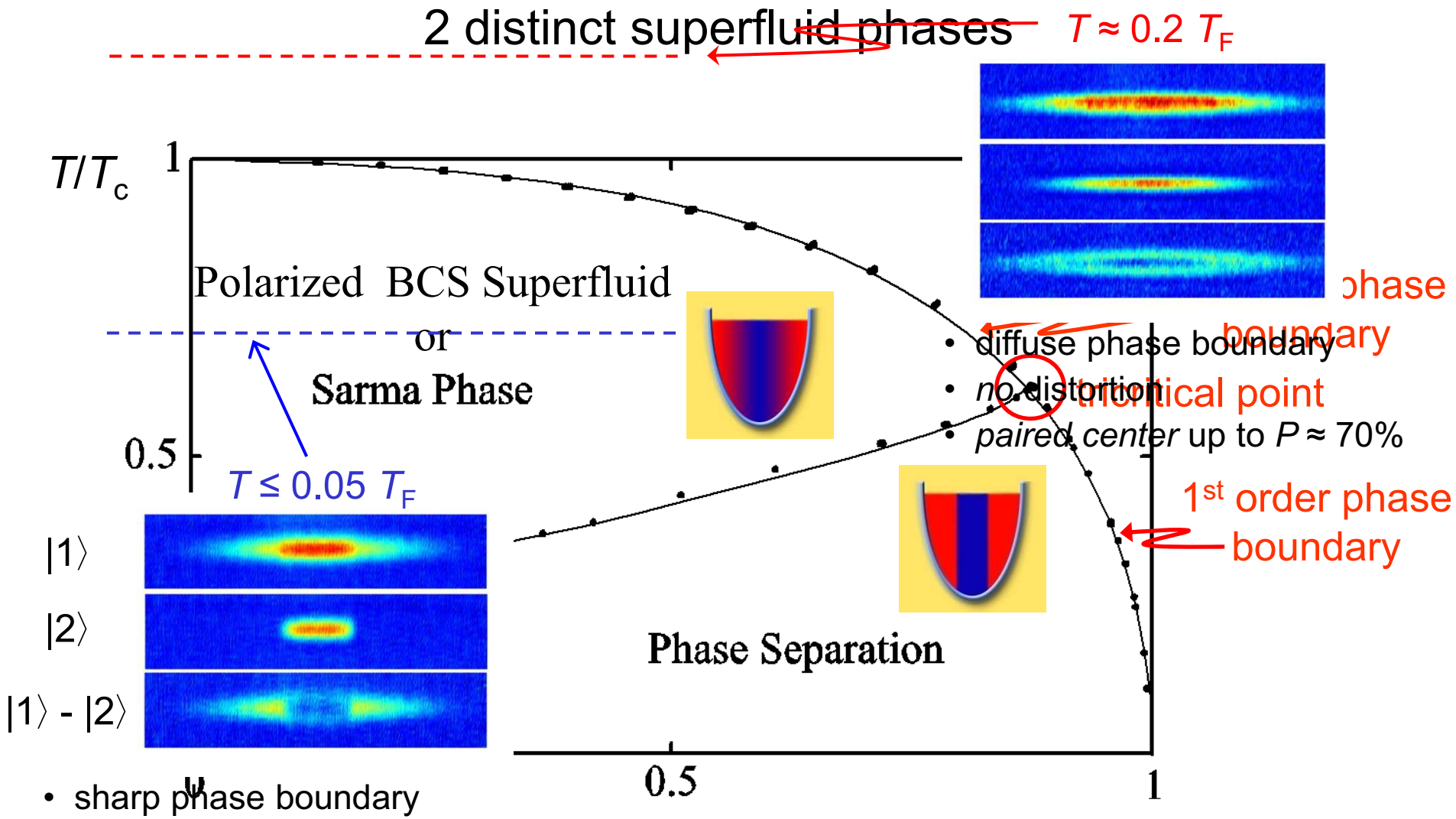
M. Parish *et al.*, Nature Phys. **3**, 124 (2007)

Trap



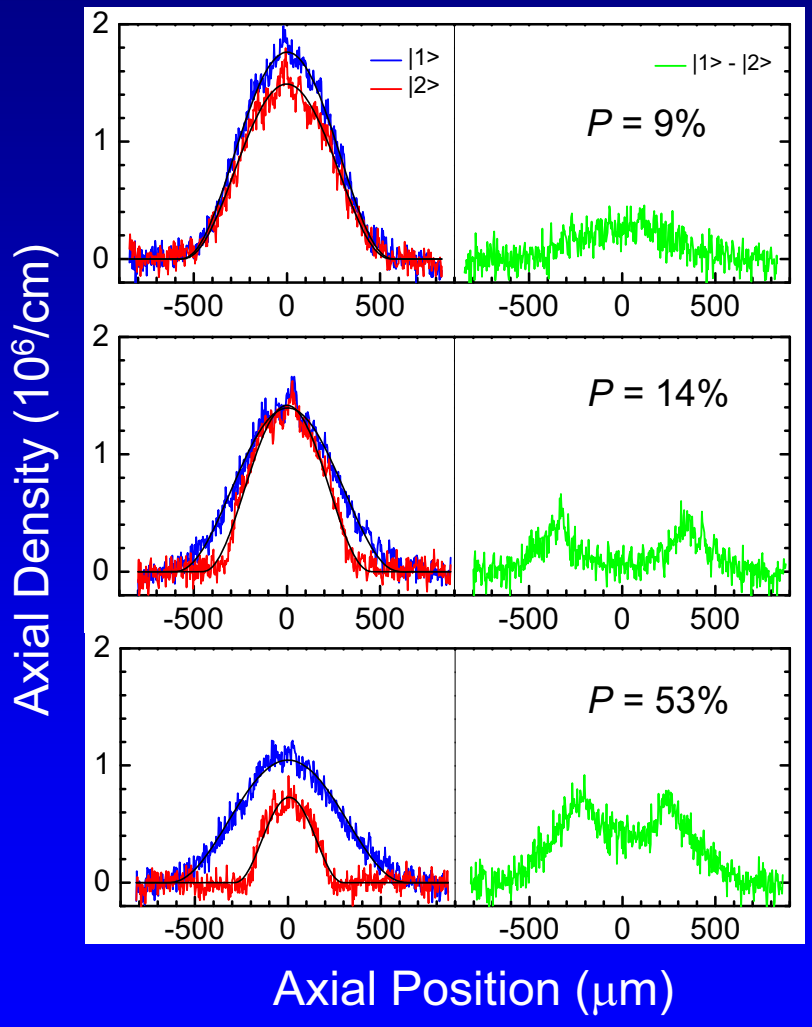
C-C Chien, Q Chen, Y He, K Levin, cond-mat/0612103

Proposed Phase Diagram at Unitarity

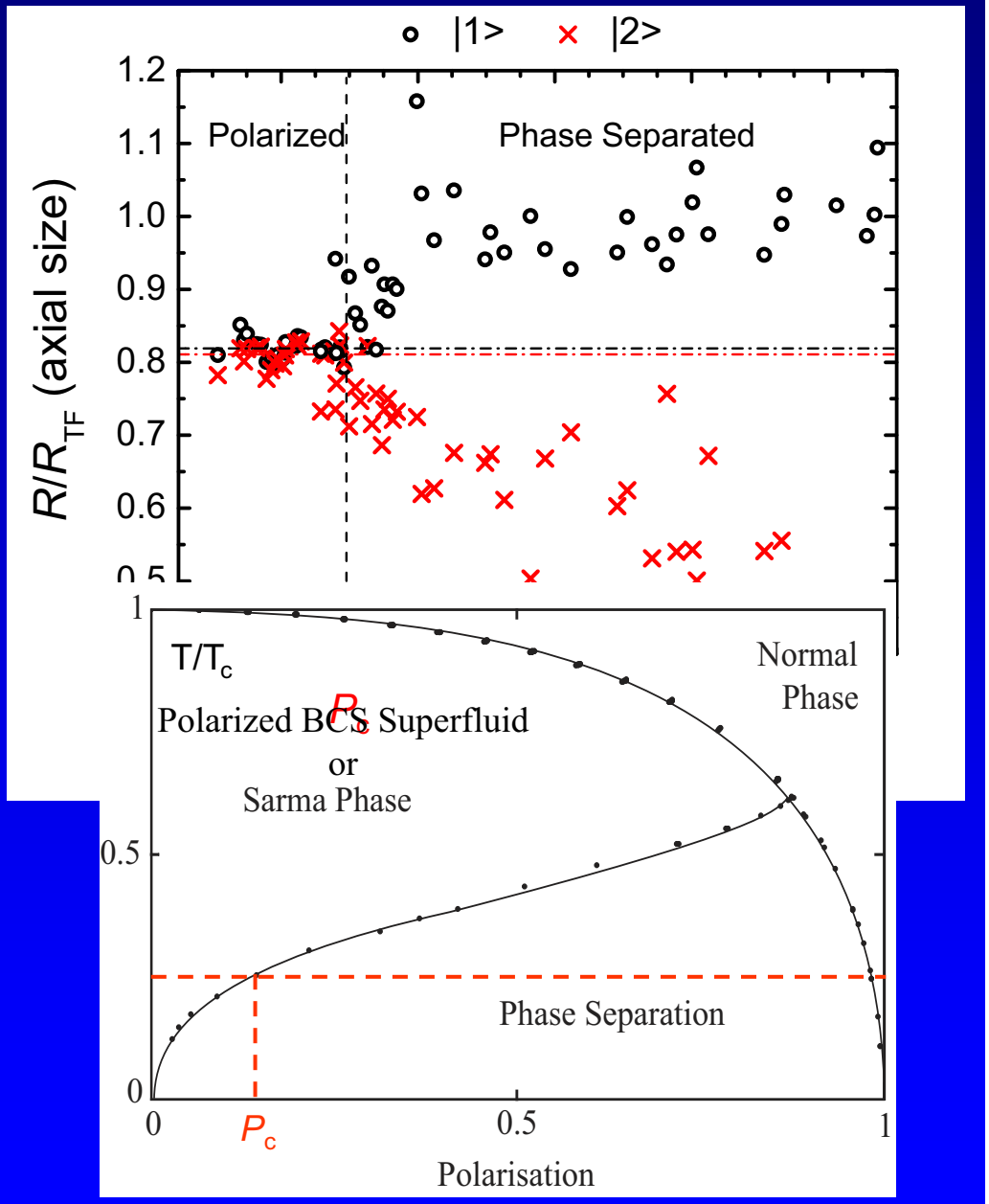


Intermediate T - Phase Separation for $P > P_c$

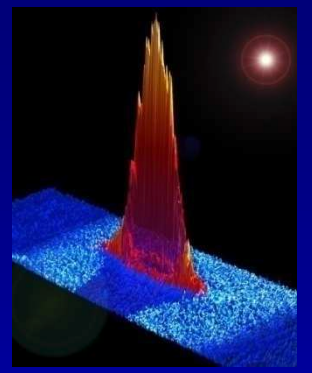
$T \approx 0.1\ T_F$



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



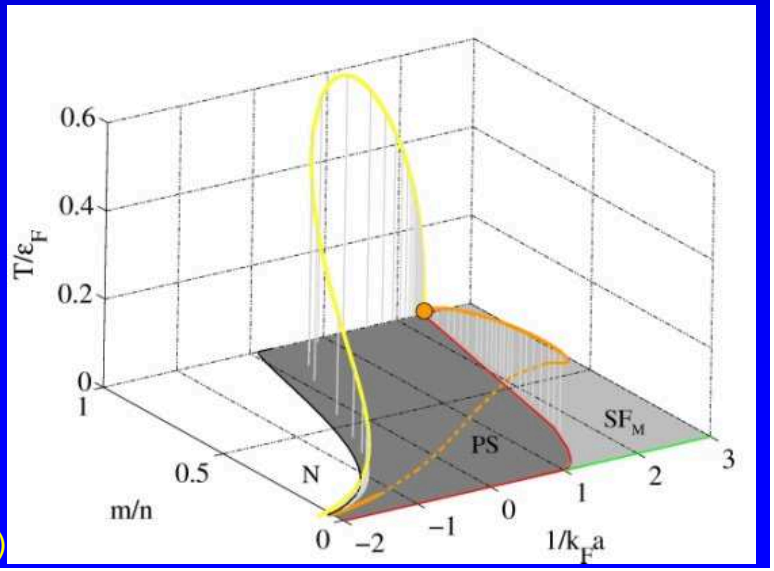
Summary



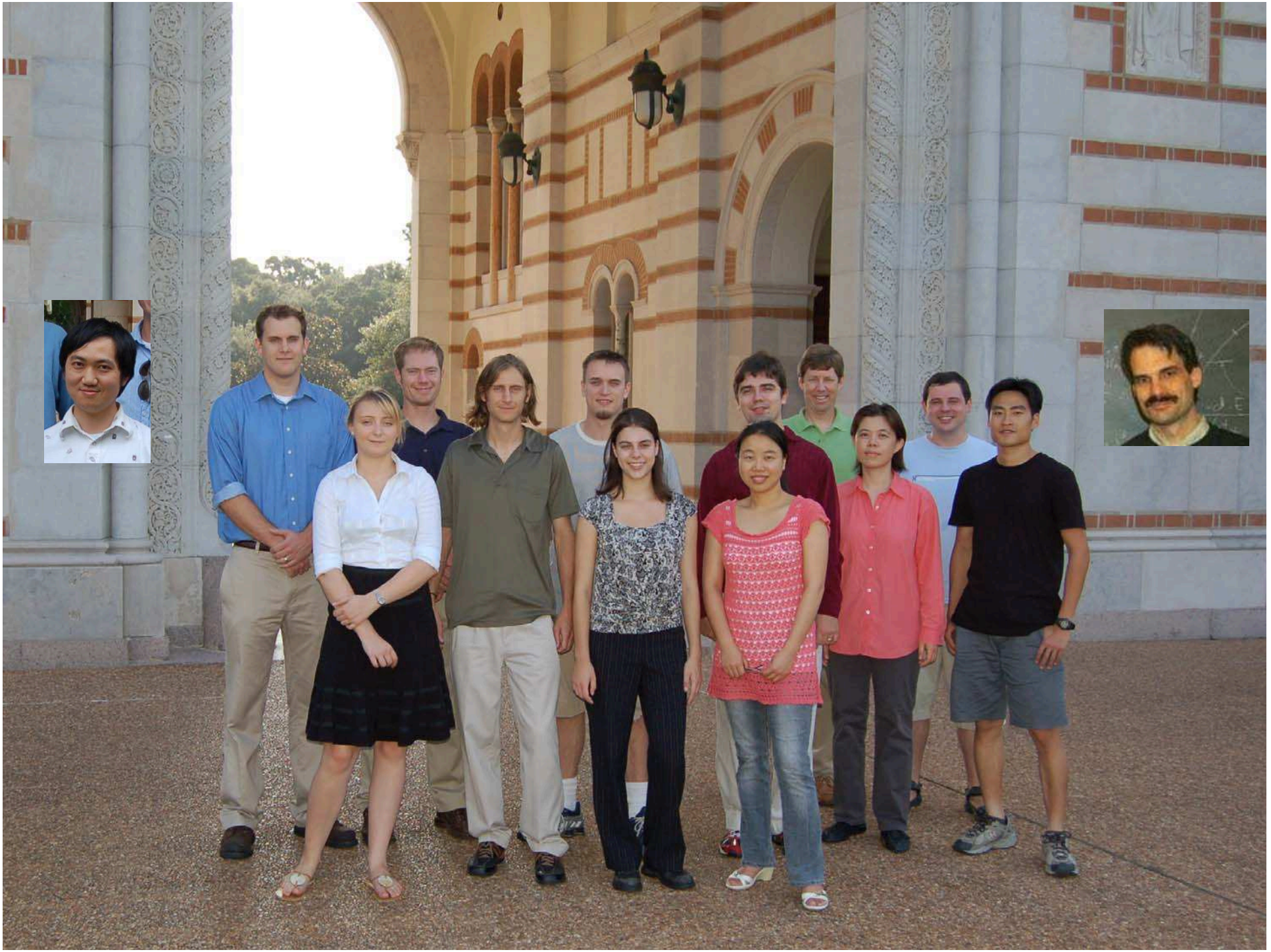
Yes	Phase separation	No Clogston limit
Maybe	Polarized BCS superfluid	Clogston limit
No	FFLO	
No	DFS	

Surface tension between fully paired and normal phases
→ Indicator of phase separation

- Is surface tension a finite size effect? ($N = 3\times10^5$)
  - YES: depends on surface area/vol ($N^{1/3}$ scaling)
  - NO: $E_F / \omega_r \sim 10$
- Clogston limit? H. Zhai cond-mat/0709.0388; Gubbels and Stoof
- Future
  - reduce aspect ratio
  - map phase diagram vs. T, P, $k_F a$
  - search for FFLO phase in 1D (Hu, Liu, Drummond; Orso)



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



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