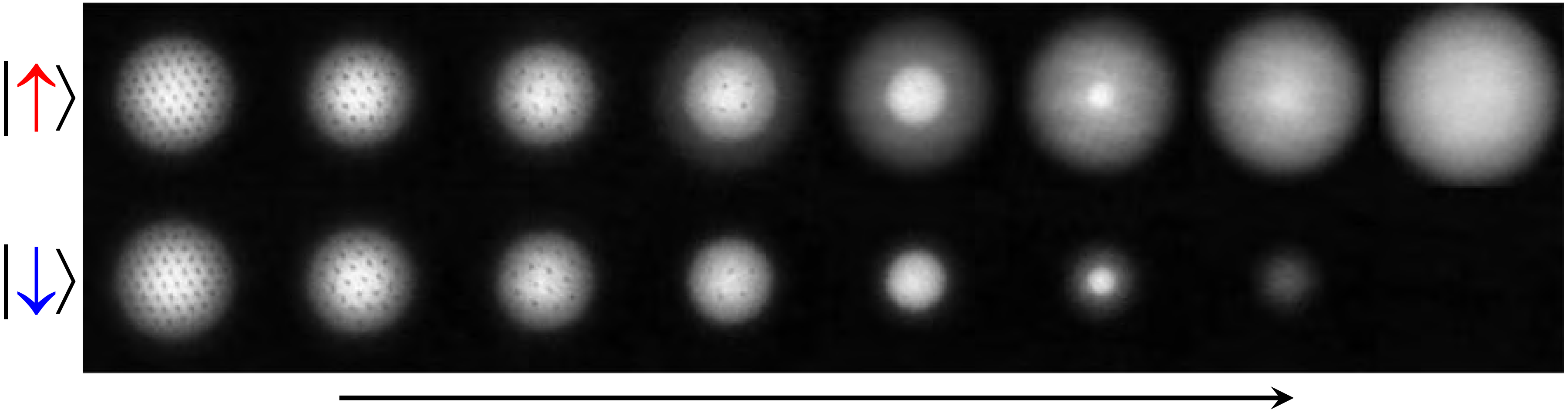
A. I. Larkin Memorial Conference, Landau Institute, Chernogolovka, Russia
June 24, 2007

The Ground State of Imbalanced Fermi Mixtures

Martin Zwierlein

MIT, Cambridge, USA and Johannes Gutenberg-Universität Mainz



Increasing Imbalance

Massachusetts Institute of Technology
Center for Ultracold Atoms at MIT and Harvard

$$$: NSF, ONR, NASA

Pairing and Superfluidity of Fermions

Ubiquitous Phenomenon

Condensed Matter Physics

Superconductivity

Superfluidity in ^{3}He

Nuclear Physics

Pairing inside nuclei

p-p, n-n, n-p(?)

Astrophysics

Early Universe: Dense quark matter

Neutron stars, Quark (Color) Superfluidity

Pairing and Superfluidity of Fermions

Atomic Physics: *Provides a Model System*

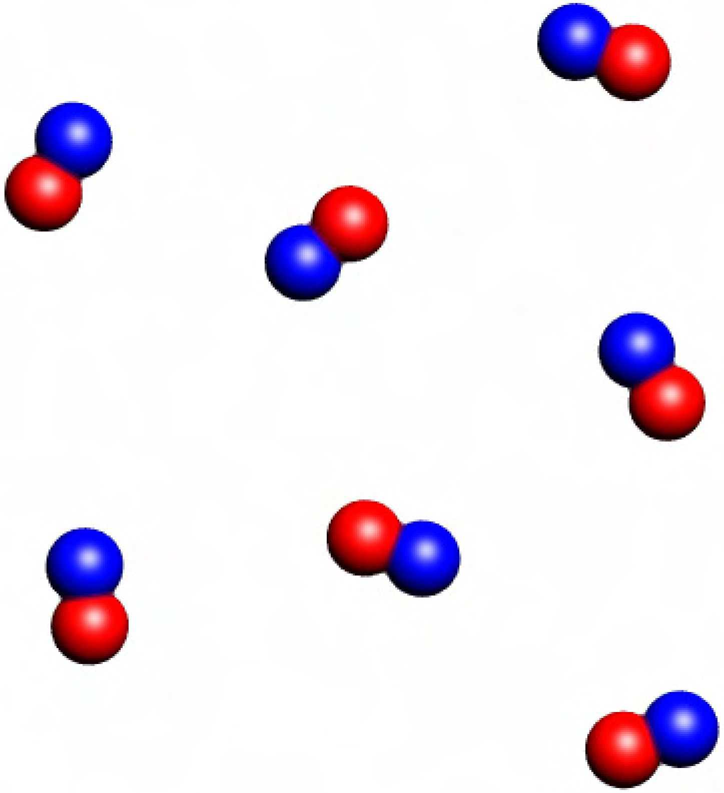
A mixture of fermionic atoms
strongly interacting fermionic atoms

Ultradilute

$n = 10^{11} \ldots 10^{15}\ \mathrm{cm}^{-3}$

Ultracold

$T_F = 0.1 \ldots 10\ \mu\mathrm{K}$



- No impurities
- Highly controllable:

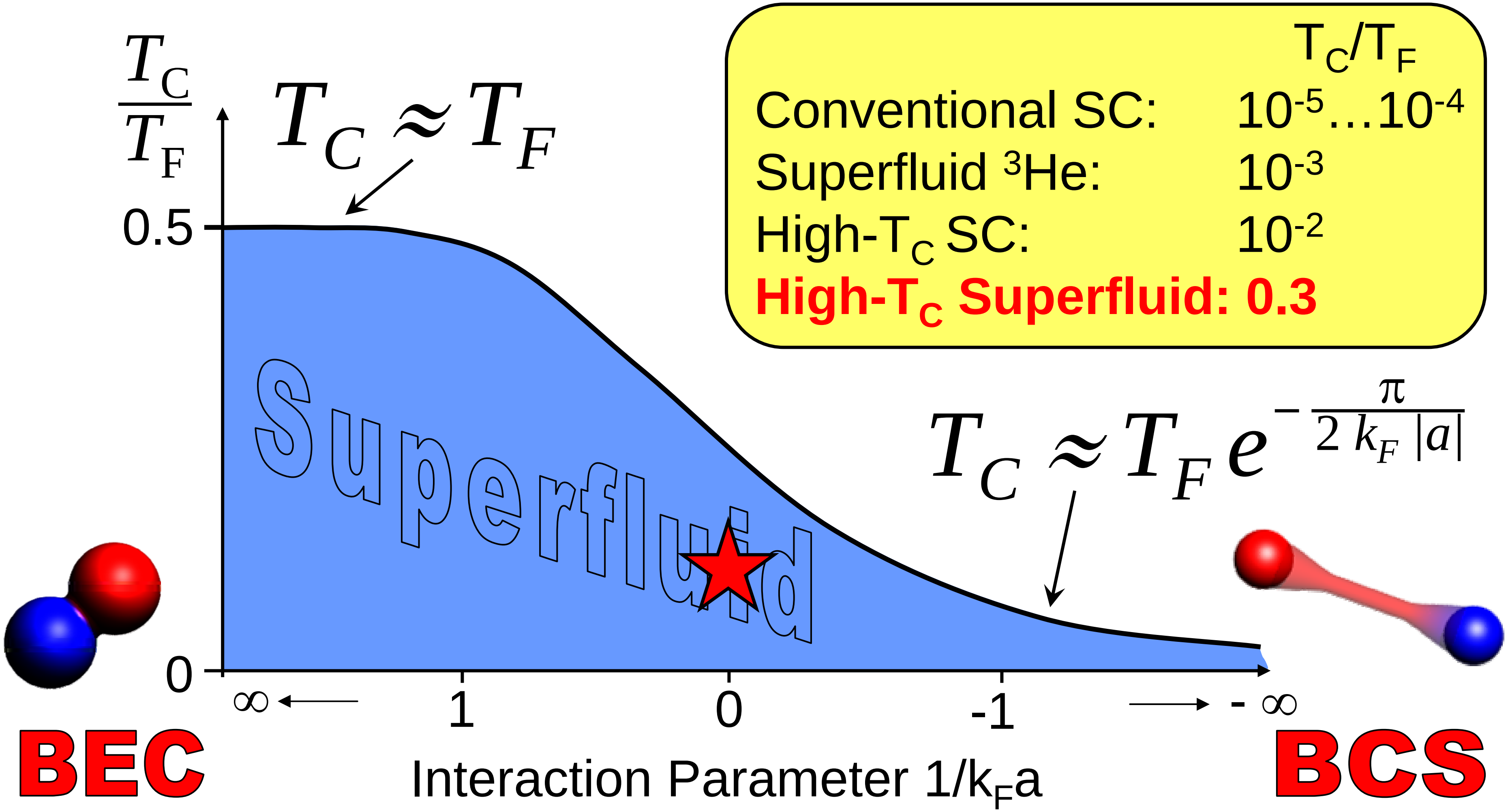
Density

Temperature

Dimensionality

Interaction strength → *High* T_C*!*

Critical Temperature for Fermionic Superfluidity



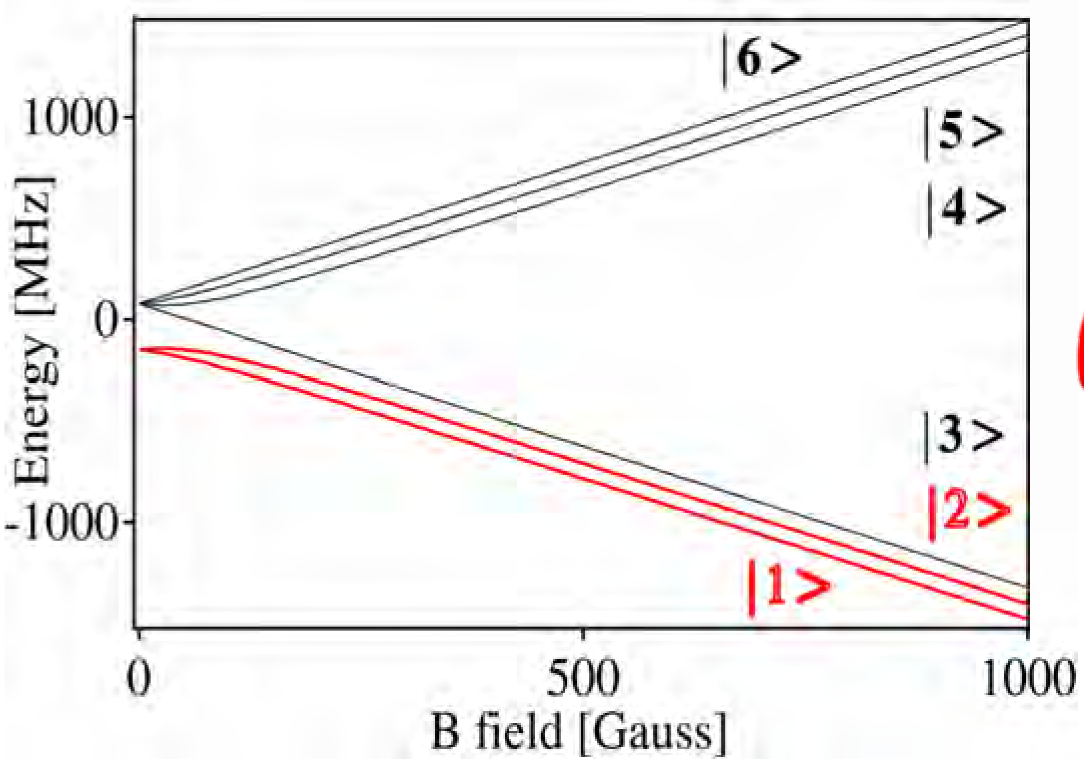
	T_C/T_F
Conventional SC:	$10^{-5} \ldots 10^{-4}$
Superfluid ^{3}He:	10^{-3}
High-T_C SC:	10^{-2}
High-T_C Superfluid:	**0.3**

Scaled to the density of electrons in solids:

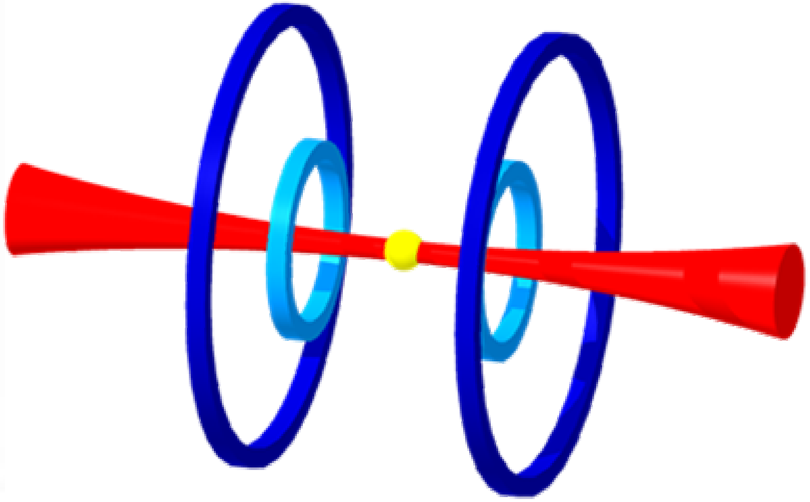
Superconductivity far above room temperature!

Preparation of an interacting Fermi system in Lithium-6

$$\left.\begin{aligned}|\uparrow\rangle &= |1\rangle \\ |\downarrow\rangle &= |2\rangle\end{aligned}\right\}$$ Lowest two hyperfine states of the ^{6}Li atom



Optical trapping @ 1064 nm



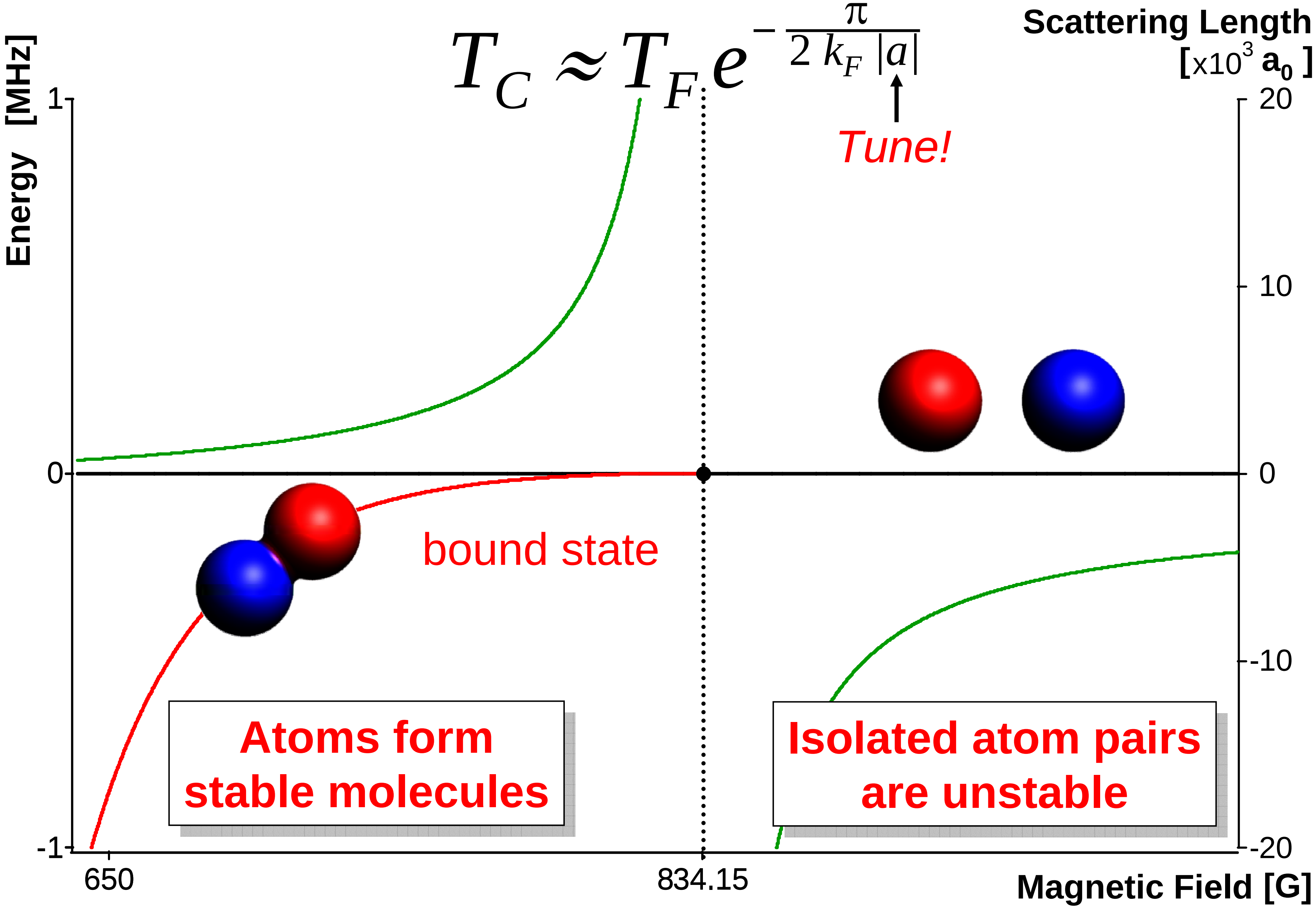
ν_{axial} = 10-20 Hz
ν_{radial}= 50–200 Hz
E_{trap} = 0.5 - 5 μK

At high fields, states |1> and |2> have large and negative scattering length

$$a_{12} = -2100\ a_0$$

High T_C !

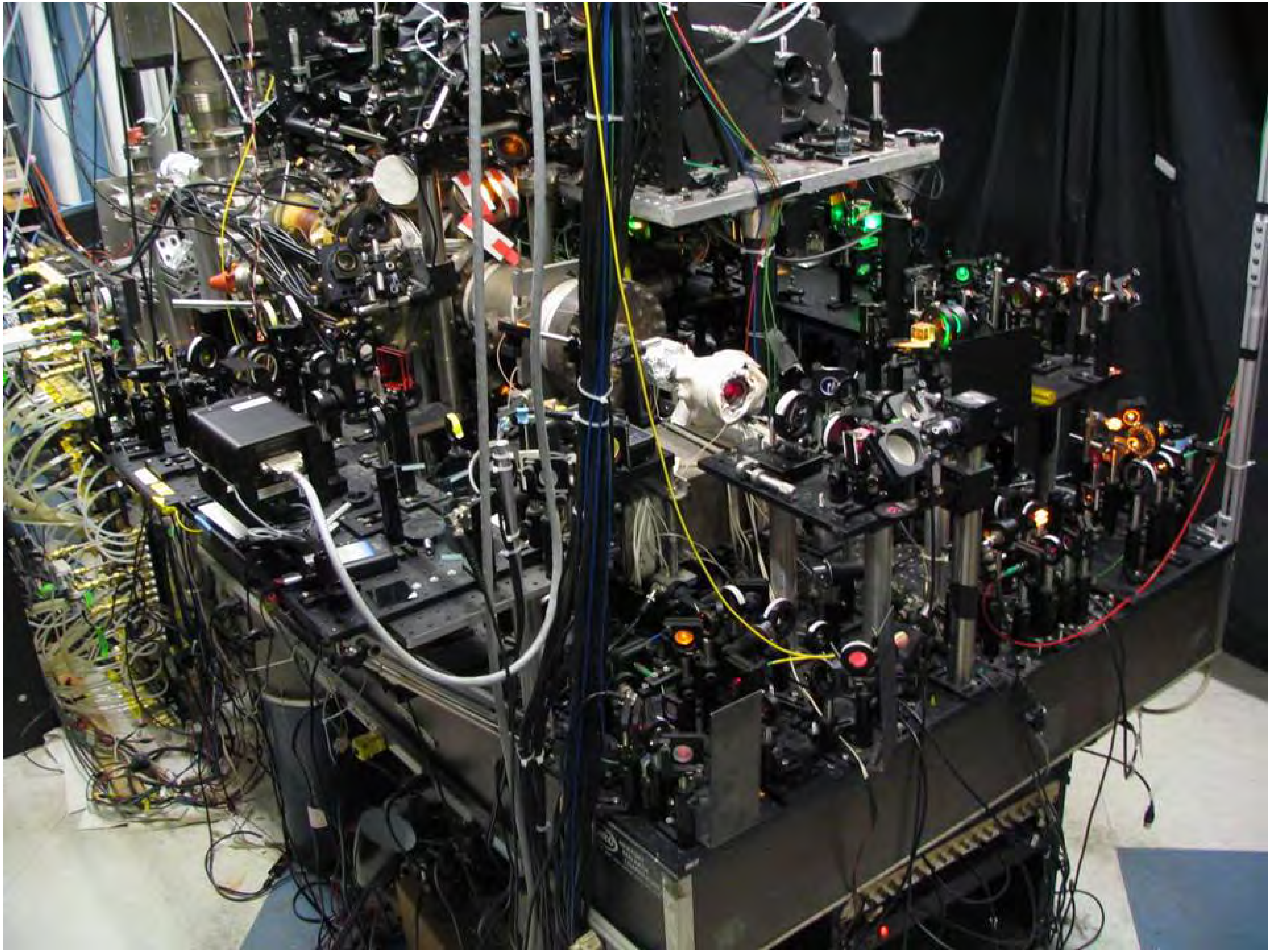
Feshbach Resonances



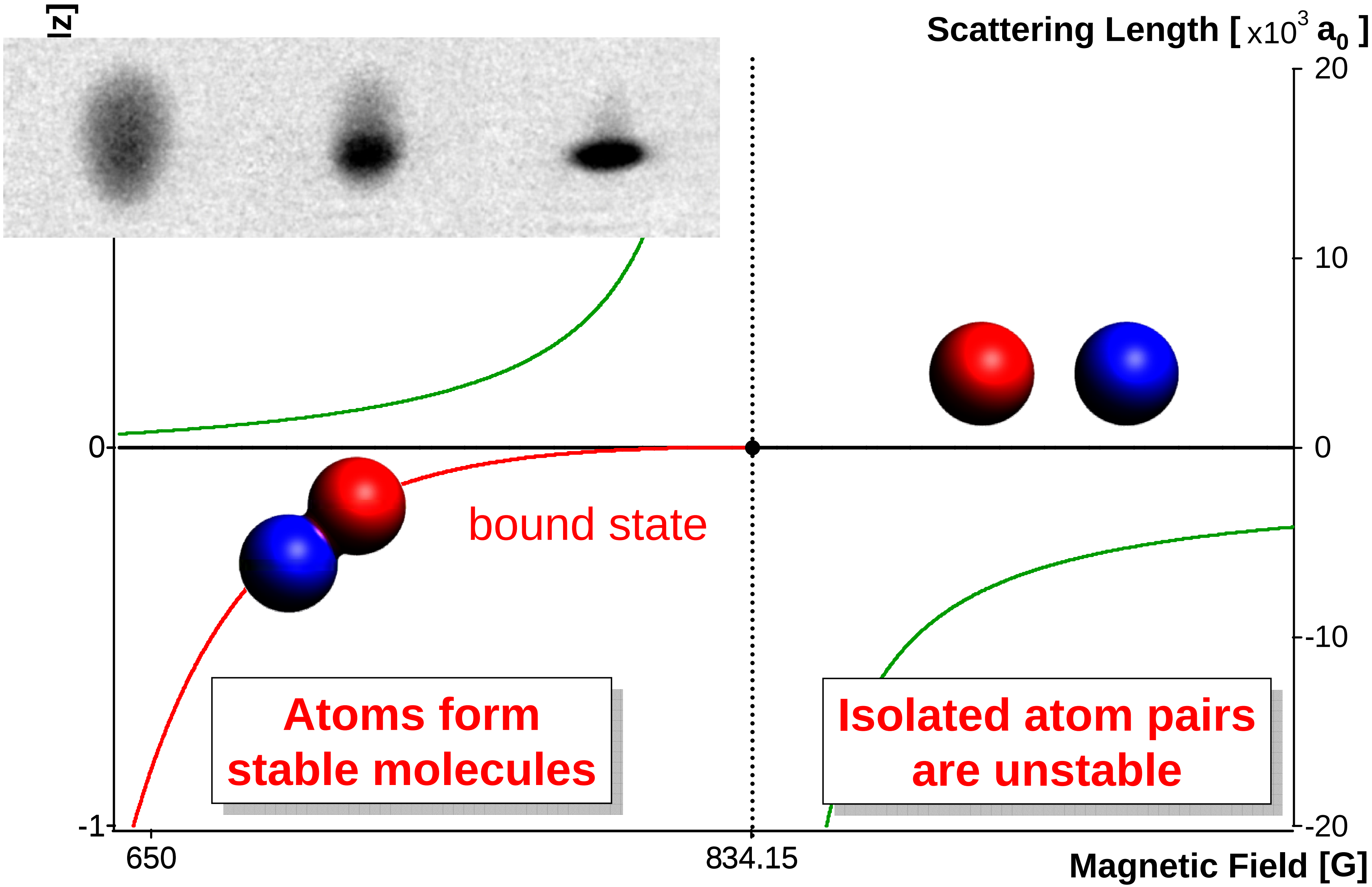
$$T_C \approx T_F\, e^{-\frac{\pi}{2 k_F |a|}}$$

Atoms form stable molecules

Isolated atom pairs are unstable



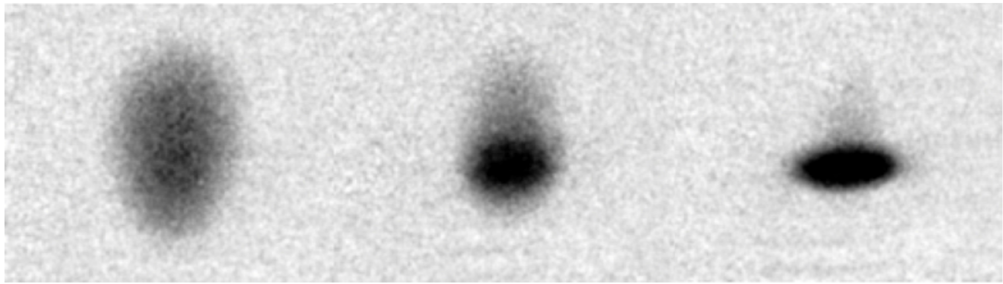
Feshbach Resonances



Atoms form stable molecules

Isolated atom pairs are unstable

BEC of Fermion Pairs (Molecules)

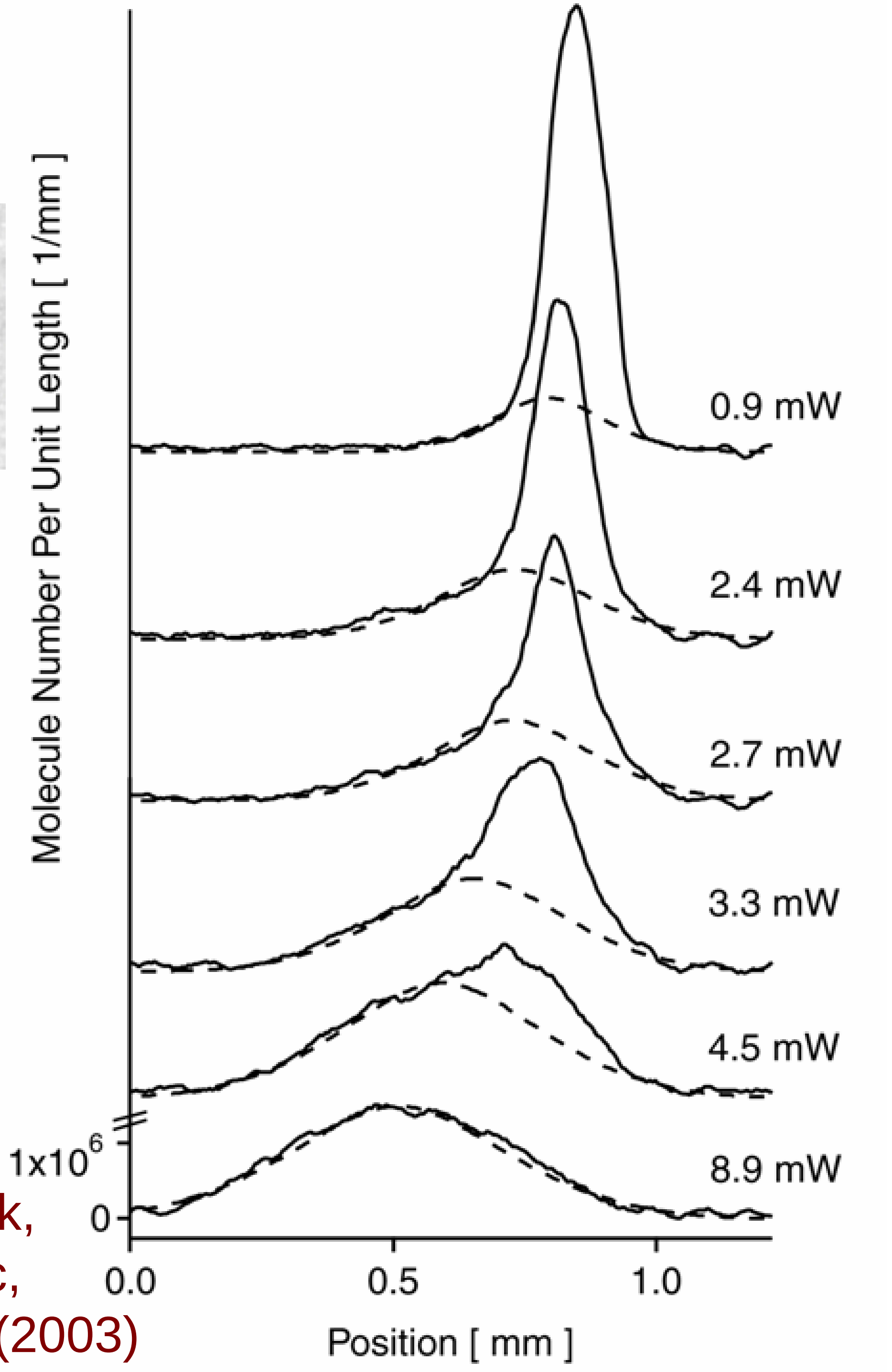


$T > T_C$ $T < T_C$ $T \ll T_C$

These days: Up to 10 million condensed molecules

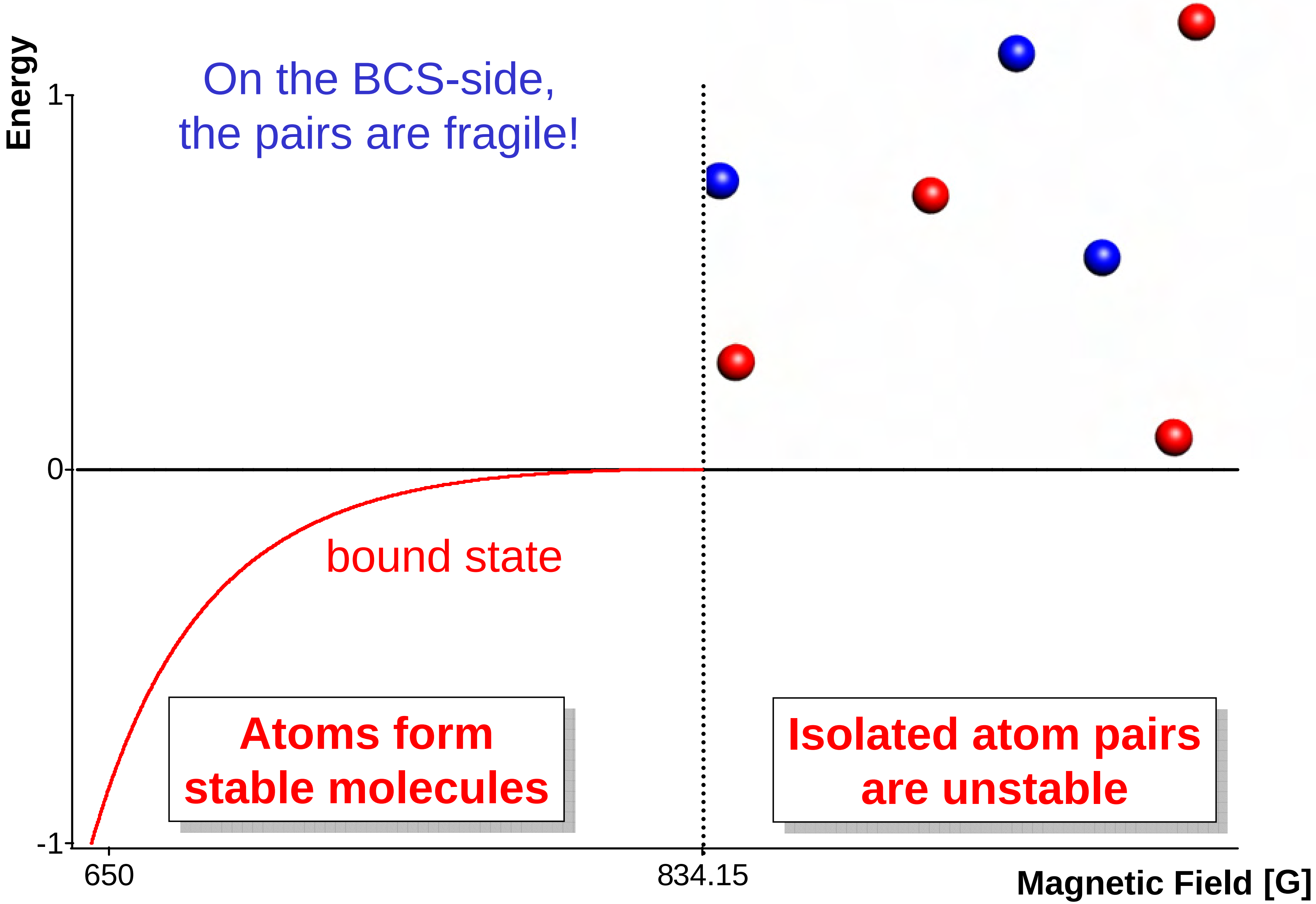
Boulder	Nov ‘03
Innsbruck	Nov ‘03, Jan ’04
MIT	Nov ’03
Paris	March ’04
Rice, Duke	

M.W. Zwierlein, C. A. Stan, C. H. Schunck, S.M.F. Raupach, S. Gupta, Z. Hadzibabic, W. Ketterle, Phys. Rev. Lett. 91, 250401 (2003)



Stabilizing Fermion Pairs

On the BCS-side,
the pairs are fragile!

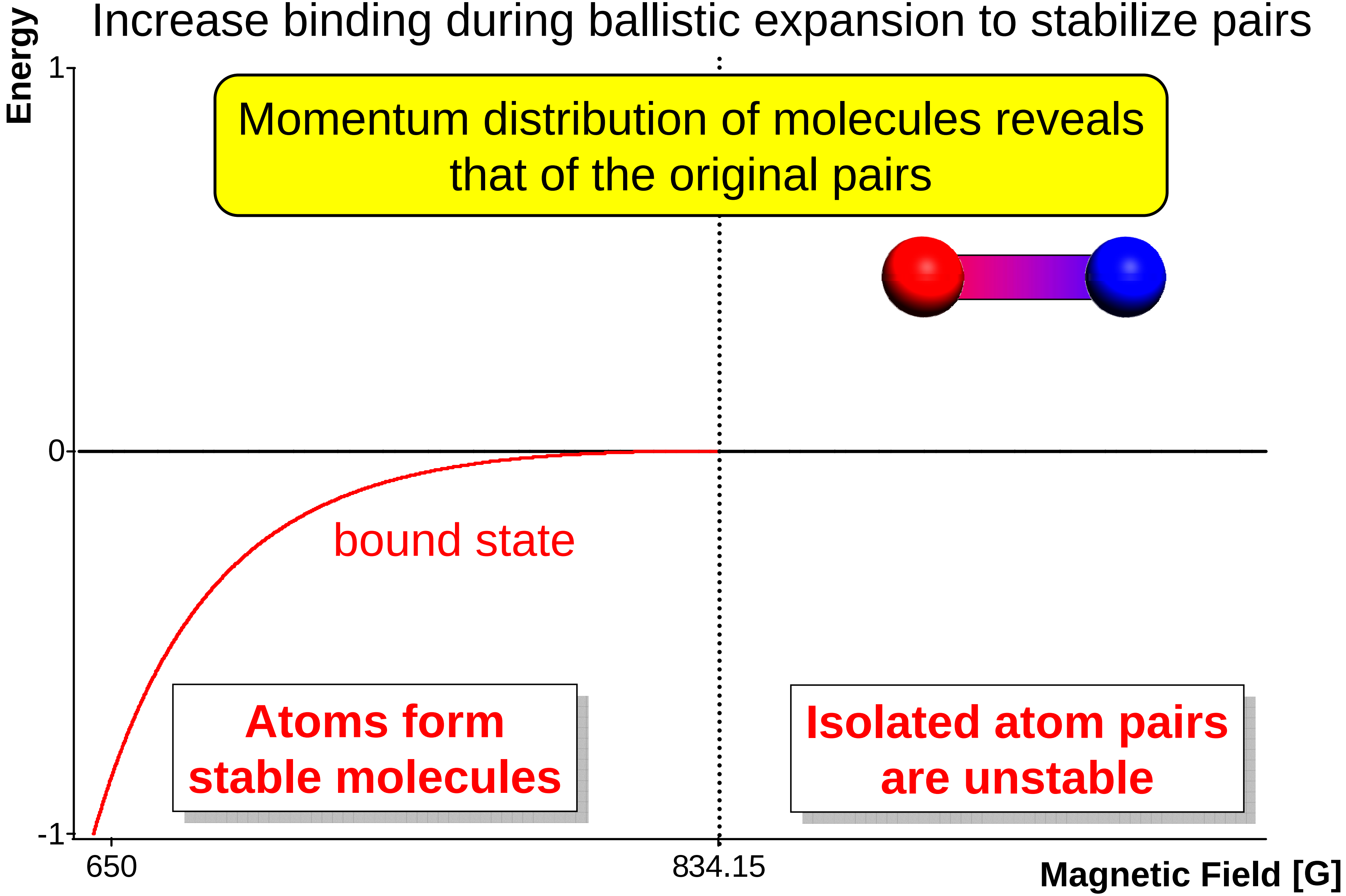


**Atoms form
stable molecules**

**Isolated atom pairs
are unstable**

Stabilizing Fermion Pairs

Increase binding during ballistic expansion to stabilize pairs



Momentum distribution of molecules reveals that of the original pairs

Atoms form stable molecules

Isolated atom pairs are unstable

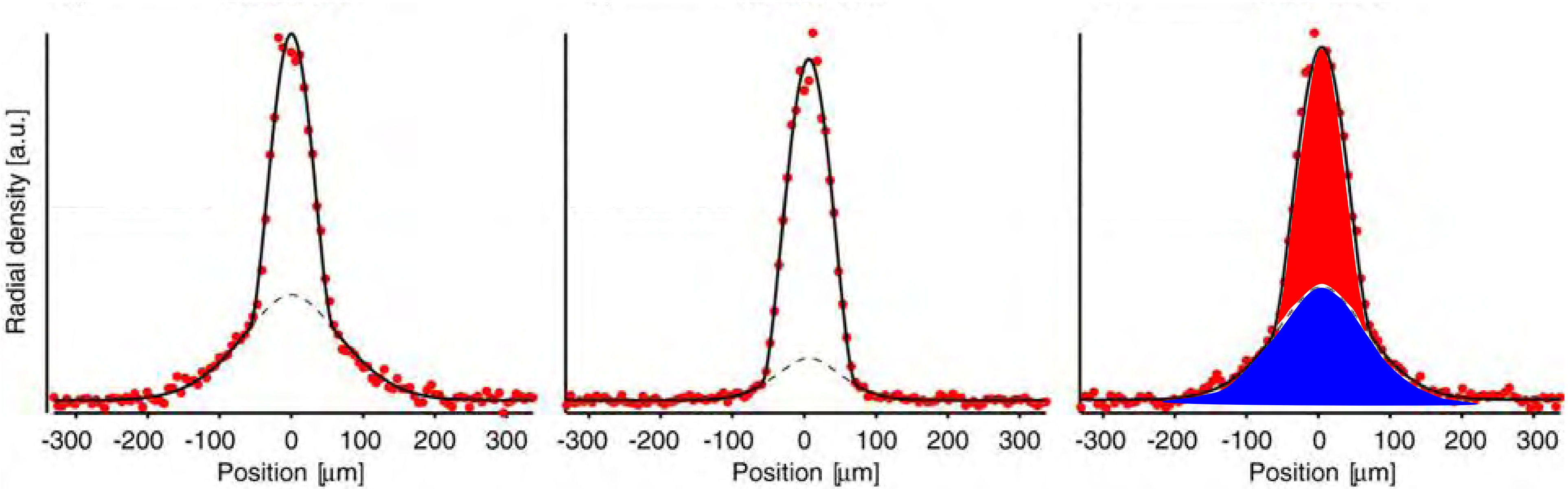
Observation of Pair Condensates

BEC-Side

Resonance

BCS-Side

(above dissociation
limit for molecules)

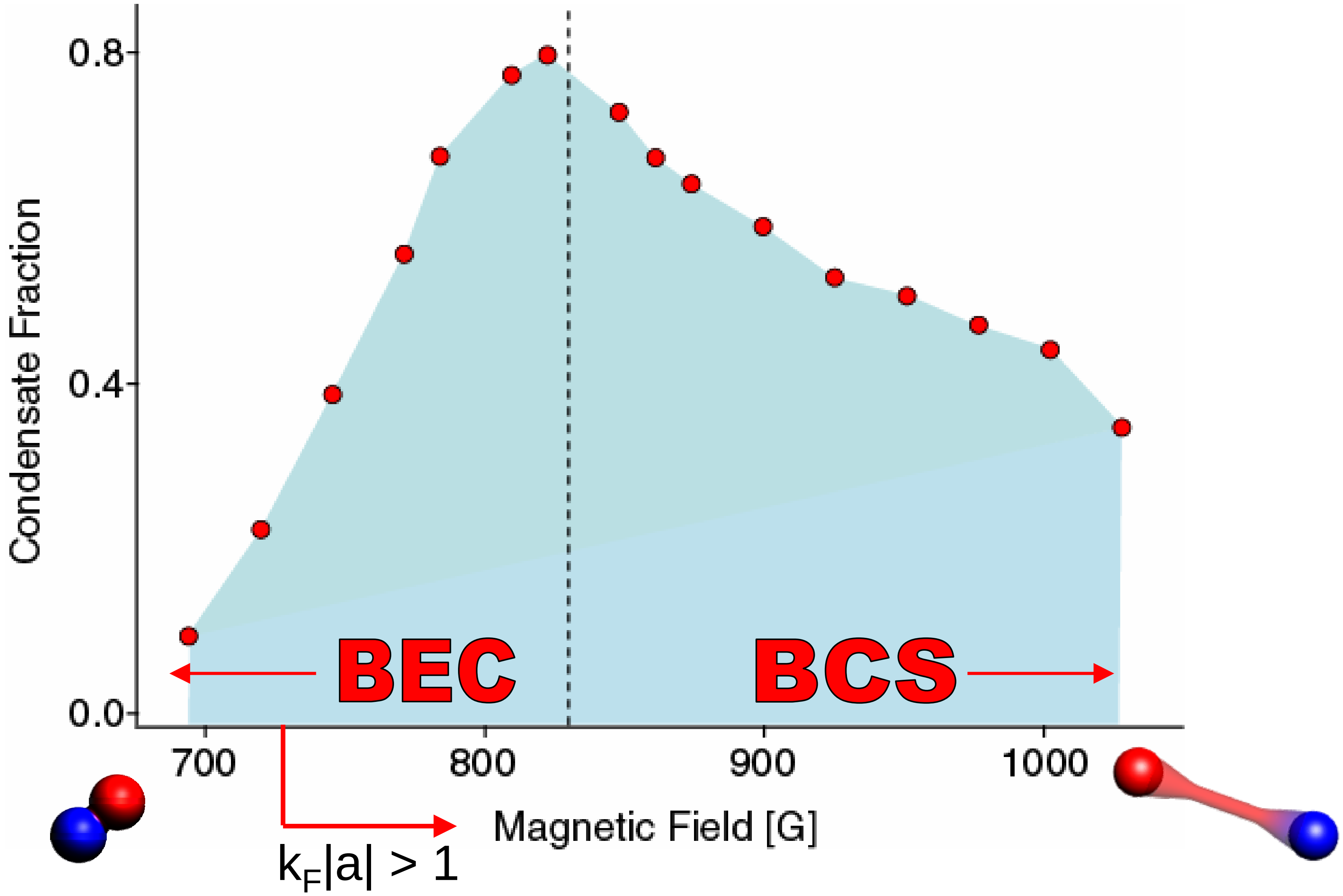


Thermal + condensed pairs

First observation: C.A. Regal et al., Phys. Rev. Lett. **92**, 040403 (2004)

M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman,
W. Ketterle, Phys. Rev. Lett. **92**, 120403 (2004).

Condensate Fraction vs Magnetic Field



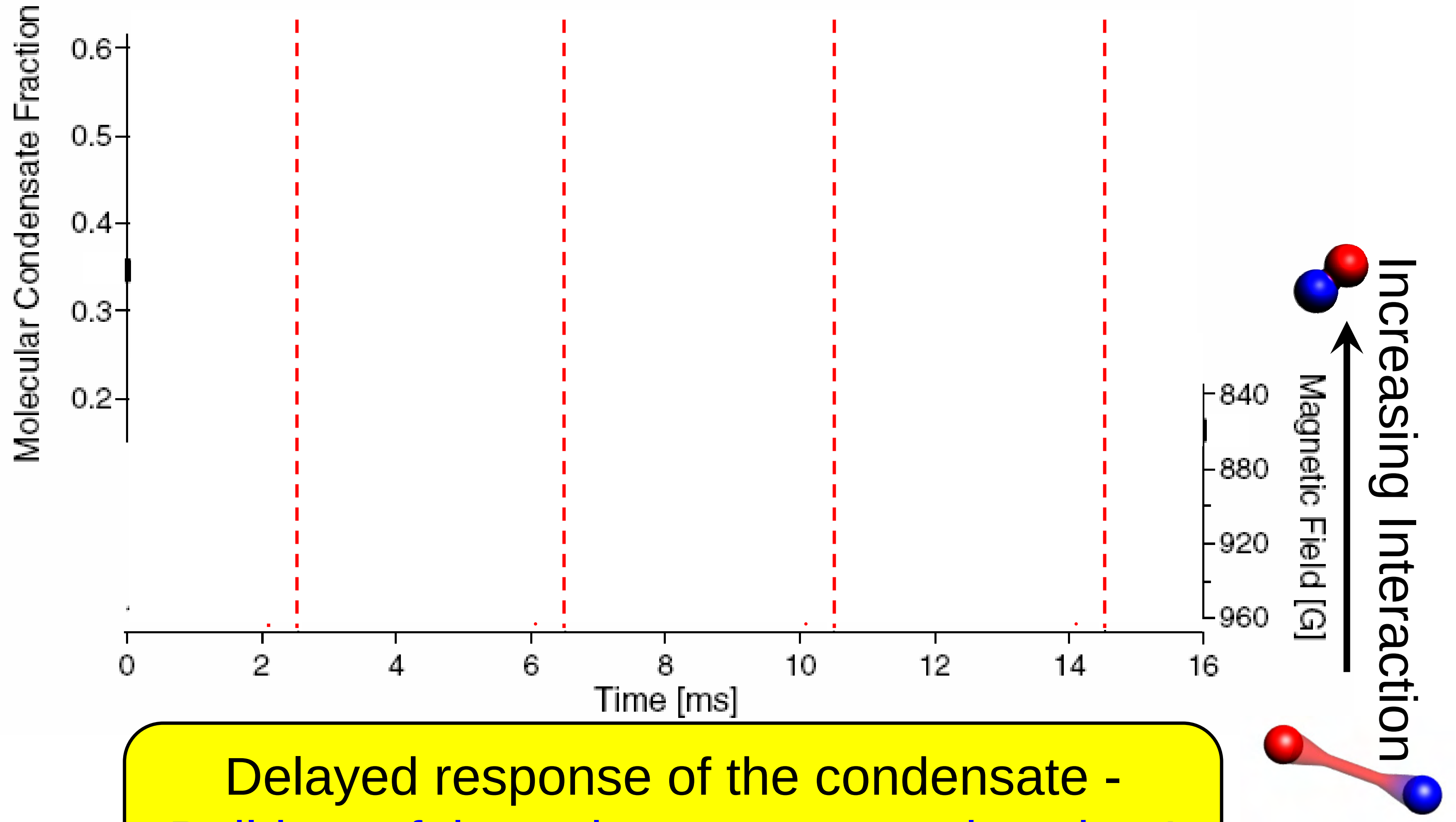
BEC

BCS

$k_F|a| > 1$

M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman, W. Ketterle, Phys. Rev. Lett. **92**, 120403 (2004).

Formation Time of the Condensate



Delayed response of the condensate -

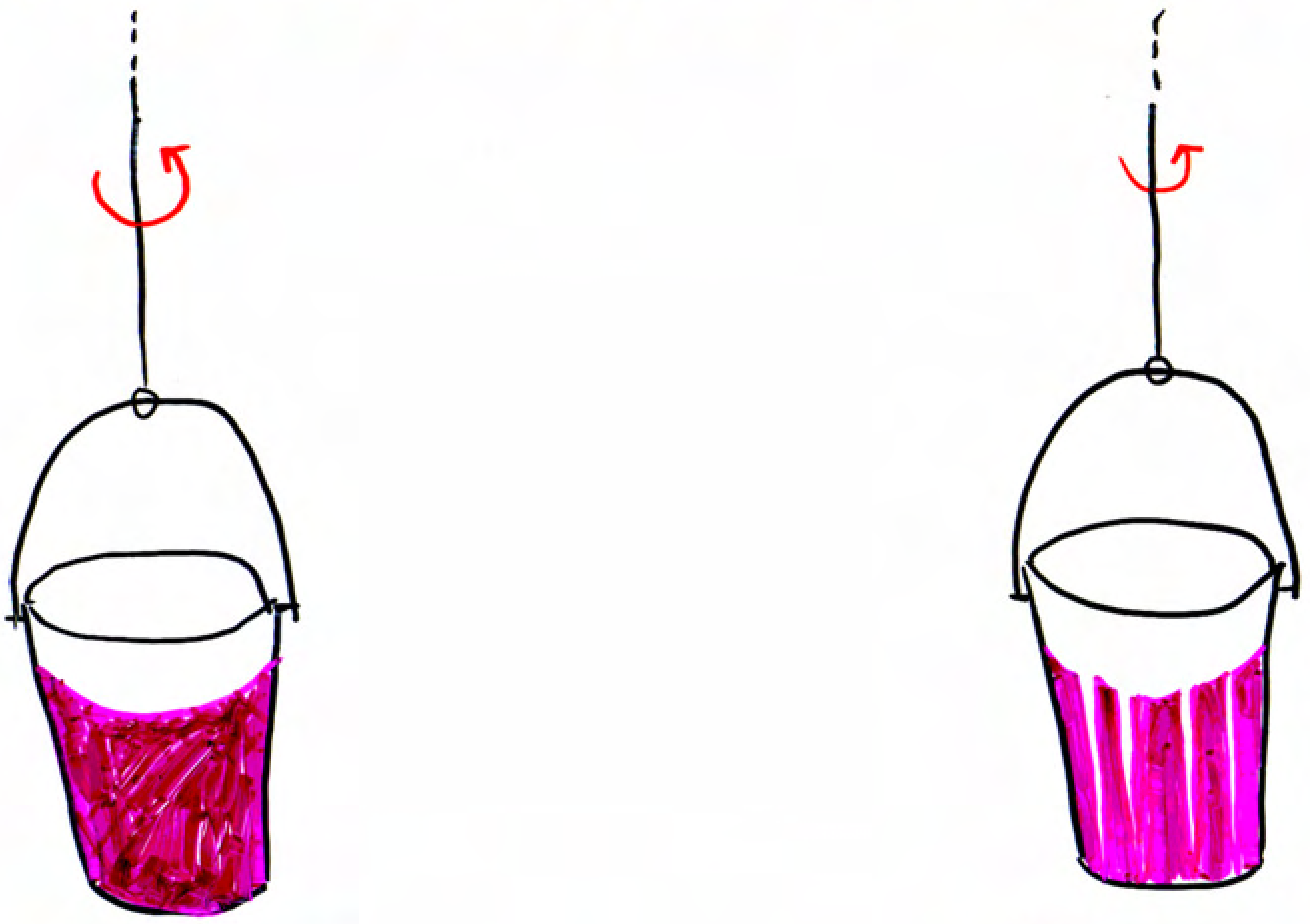
Build-up of the order parameter takes time!

Quasi-particle redistribution time: $\tau \approx \hbar E_F/\Delta^2$

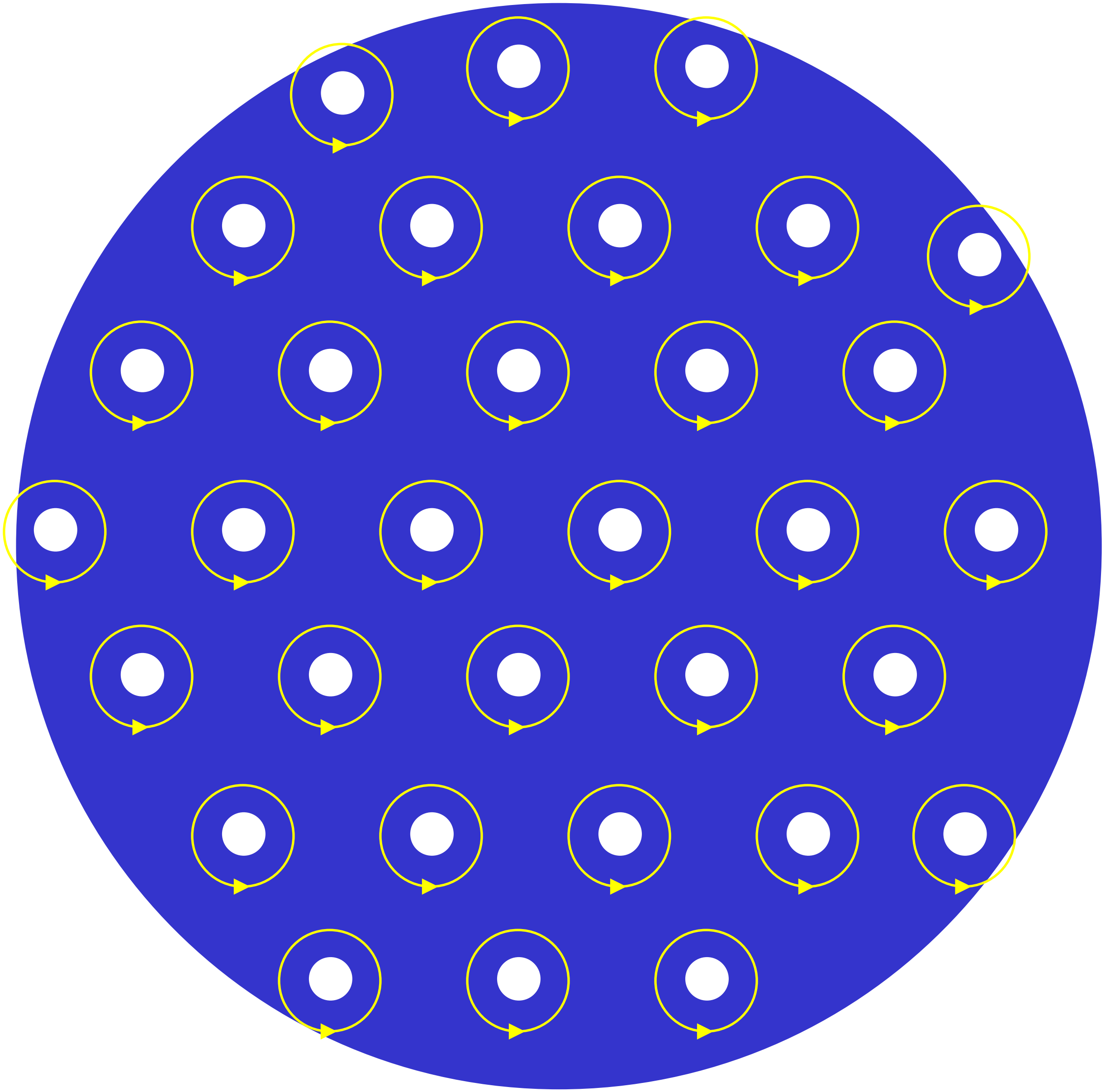
M.W. Zwierlein, C.H. Schunck, C.A. Stan, S.M.F. Raupach, W. Ketterle,
Phys. Rev. Lett. **94**, 180401 (2005).

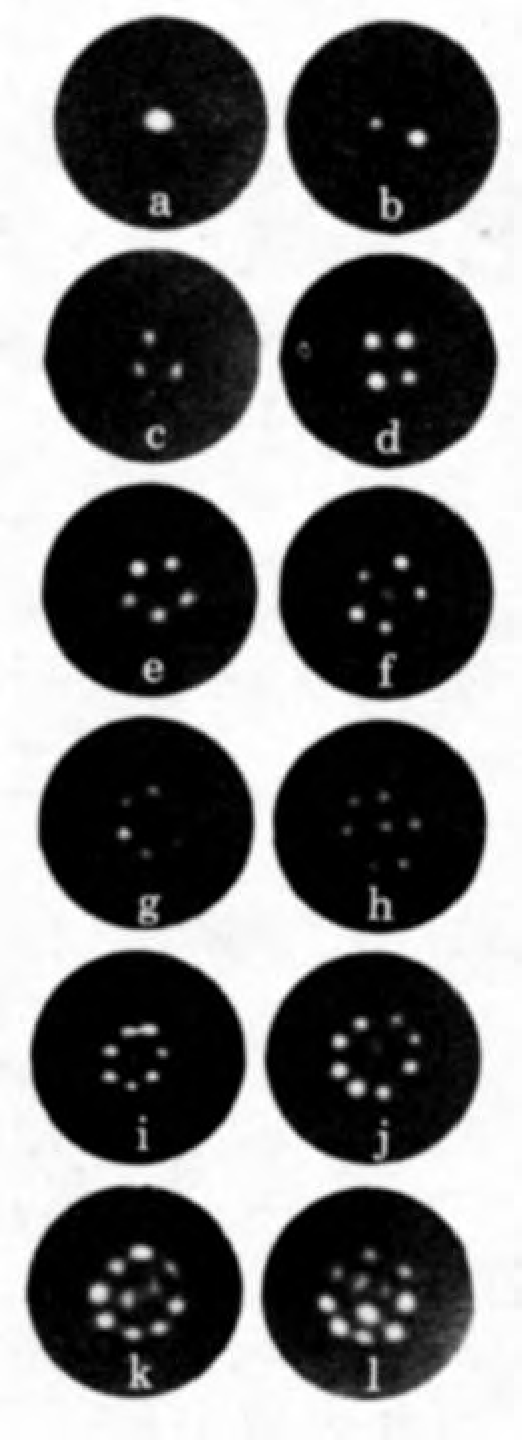
How can we show that these gases are superfluid?

Rotating Fluids



Abrikosov Lattice



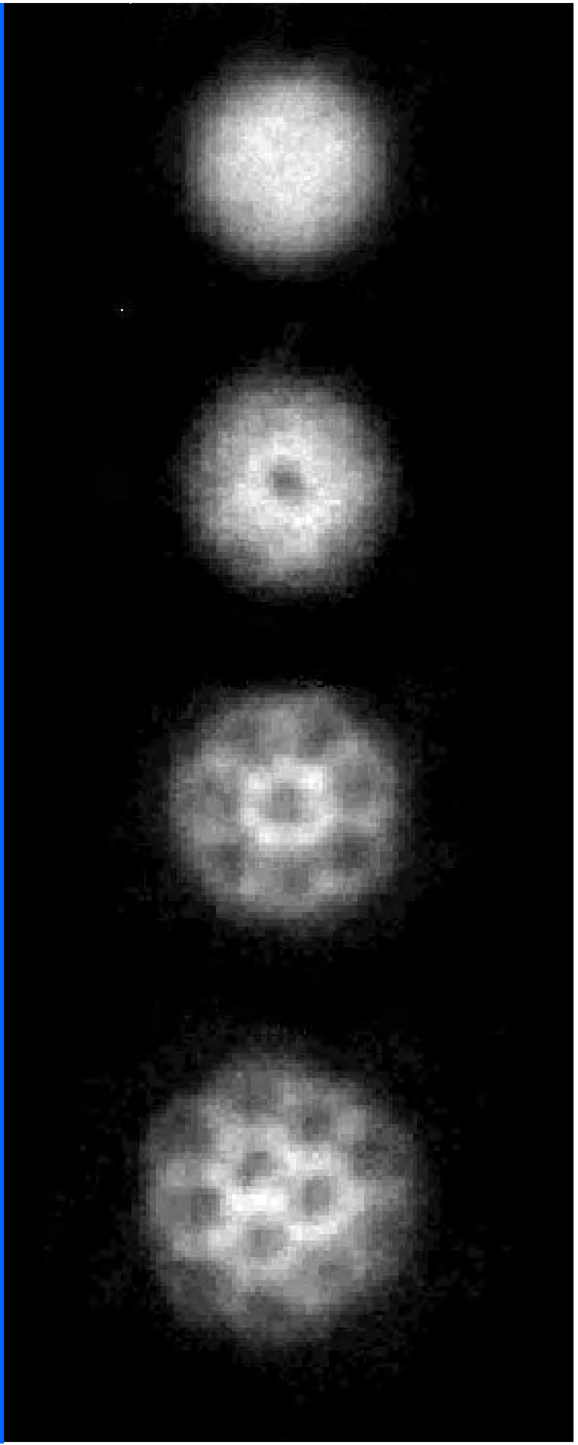


Vortex Arrays
in Bosonic Gases / Fluids

Berkeley
(R.E. Packard, 1979)
Helium-4

ENS
(J. Dalibard, 2000)
Rubidium BEC

Also: Phase engineering
of single vortices in BEC:
JILA (1999)



THE DIRECT OBSERVATION OF INDIVIDUAL FLUX LINES IN TYPE II SUPERCONDUCTORS

U. ESSMANN and H. TRÄUBLE
Institut für Physik am Max-Planck-Institut für Metallforschung, Stuttgart and
Institut für theoretische und angewandte Physik der Technischen Hochschule Stuttgart

Received 4 April 1967

Neutral superfluids under rotation

$$F = 2m\,(\mathbf{v} \times \mathbf{\Omega})$$

Coriolis force in rotating frame

$$\Leftrightarrow$$

Superconductors in magnetic field

$$F = q\,(\mathbf{v} \times \mathbf{B})$$

Lorentz Force

U. Essmann and H. Träuble,
Physics Letters A, **24**, 526 (1967)

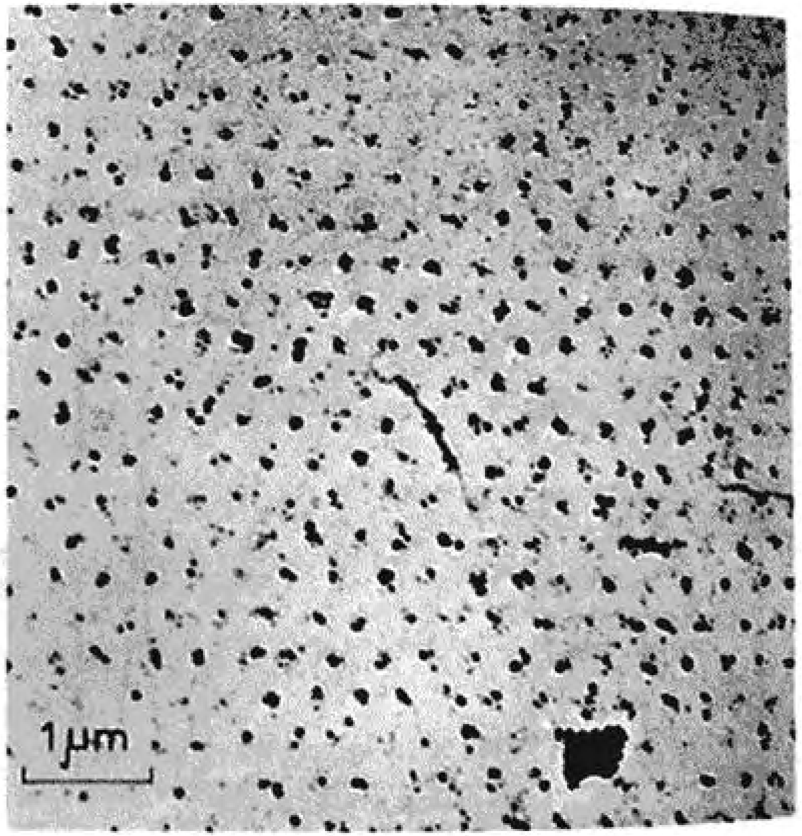
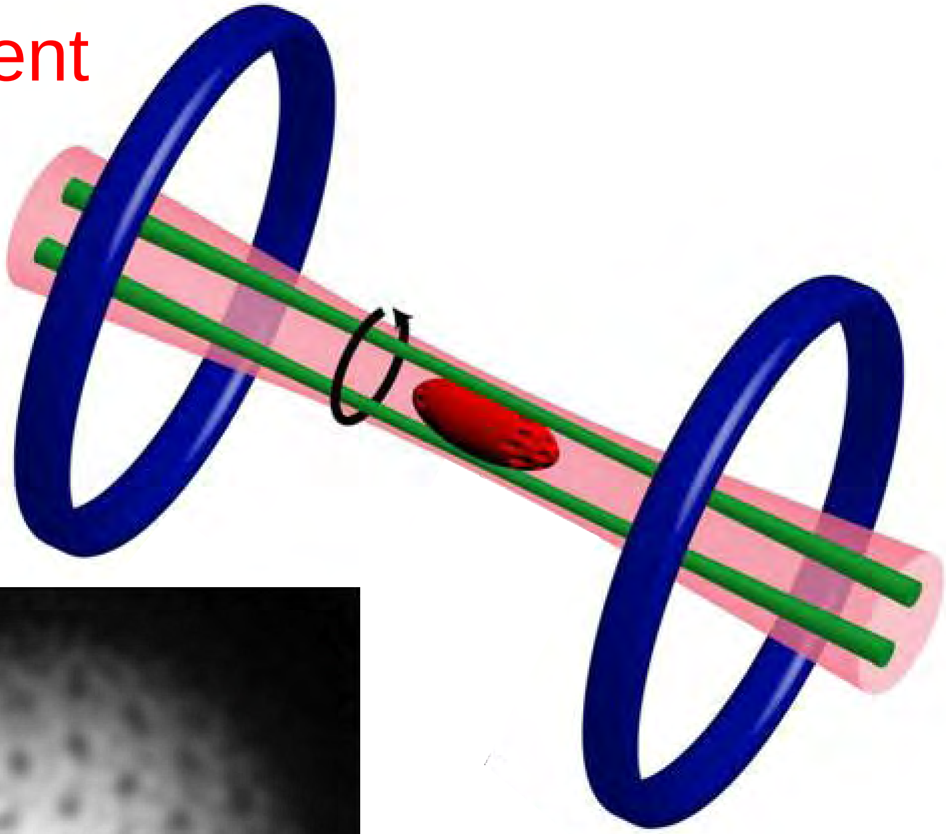
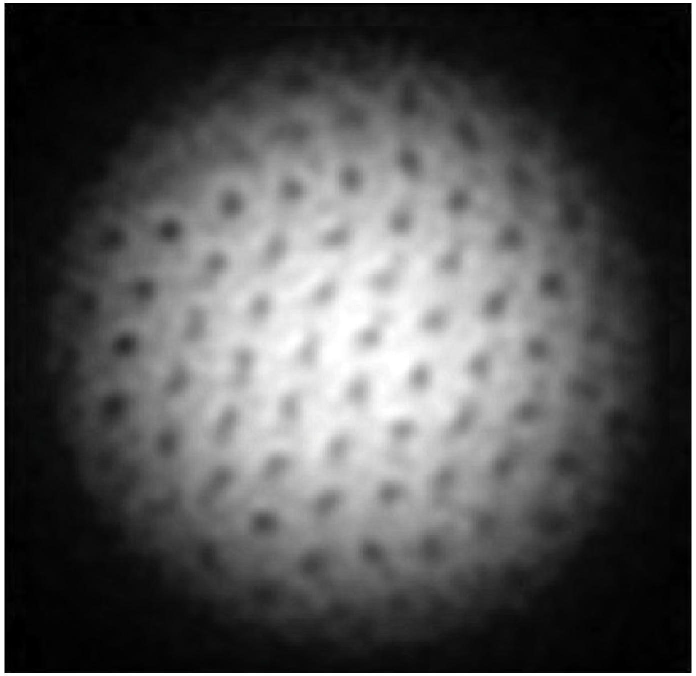


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Spinning a strongly interacting Fermi gas

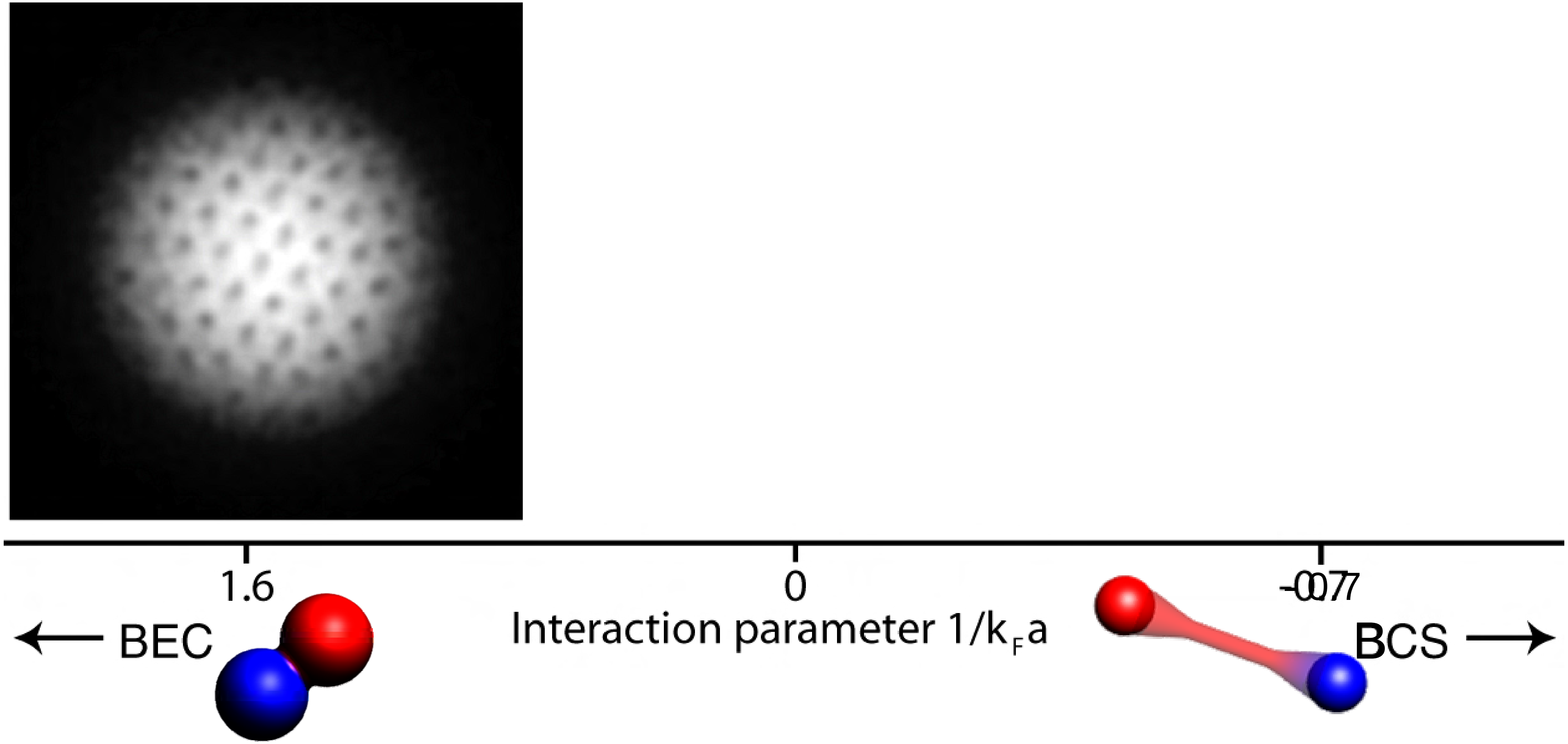
The rotating bucket experiment with a strongly interacting Fermi gas, a million times thinner than air





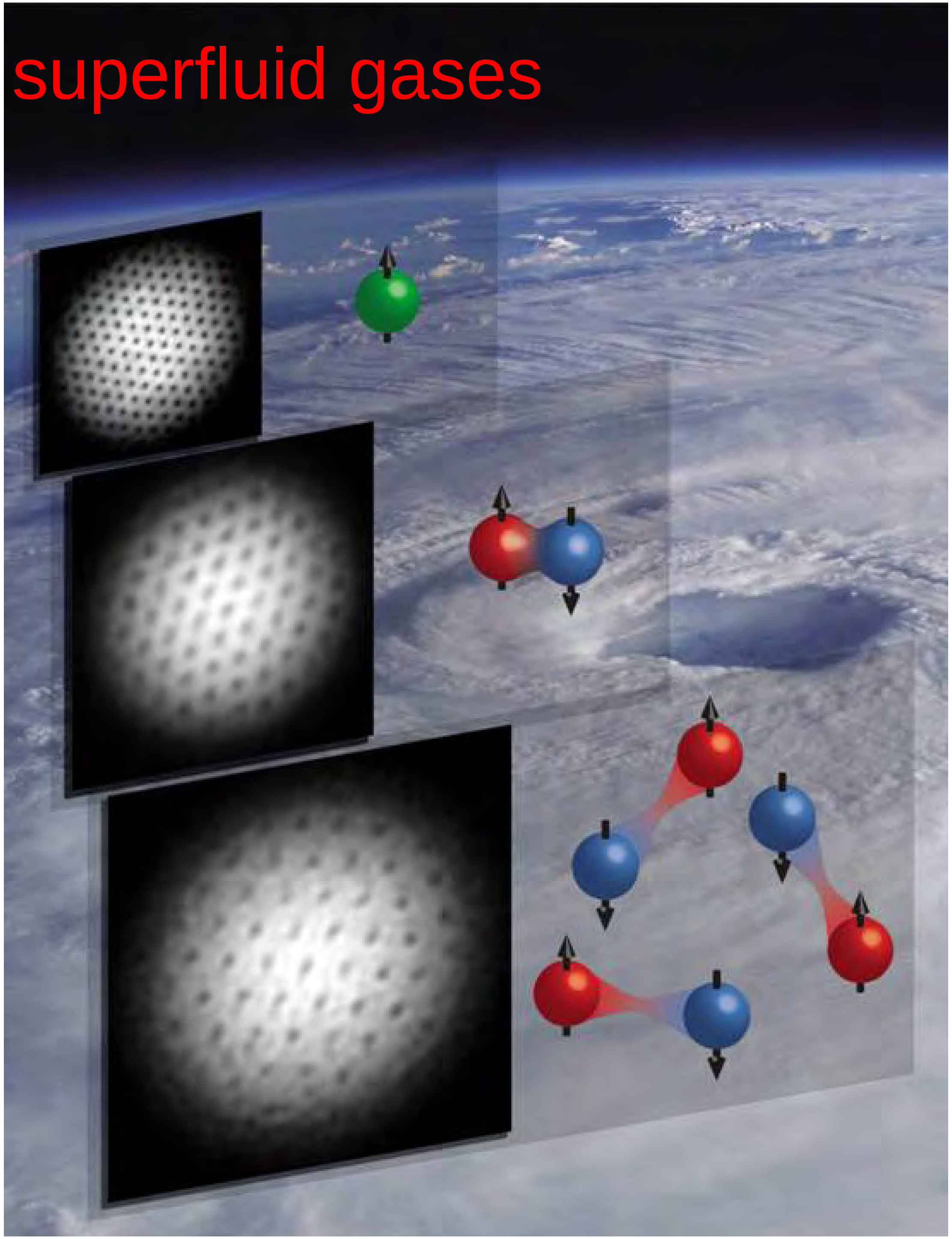
Vortex lattices in the BEC-BCS crossover

Establishes *superfluidity* and *phase coherence*
in gases of fermionic atom pairs



M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle,
Nature 435, 1047-1051 (2005)

Gallery of superfluid gases

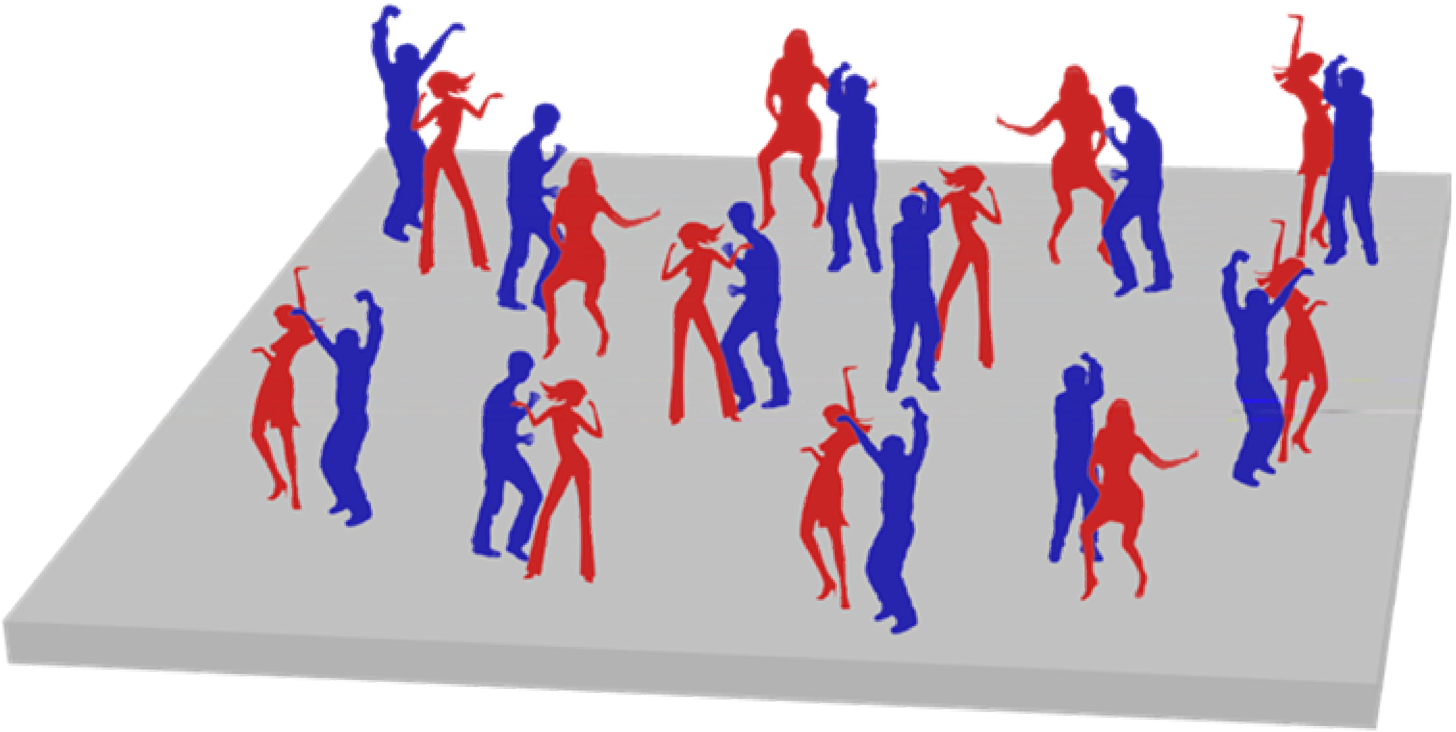


Atomic Bose-Einstein condensate (sodium)

Molecular Bose-Einstein condensate (lithium $^6Li_2$)

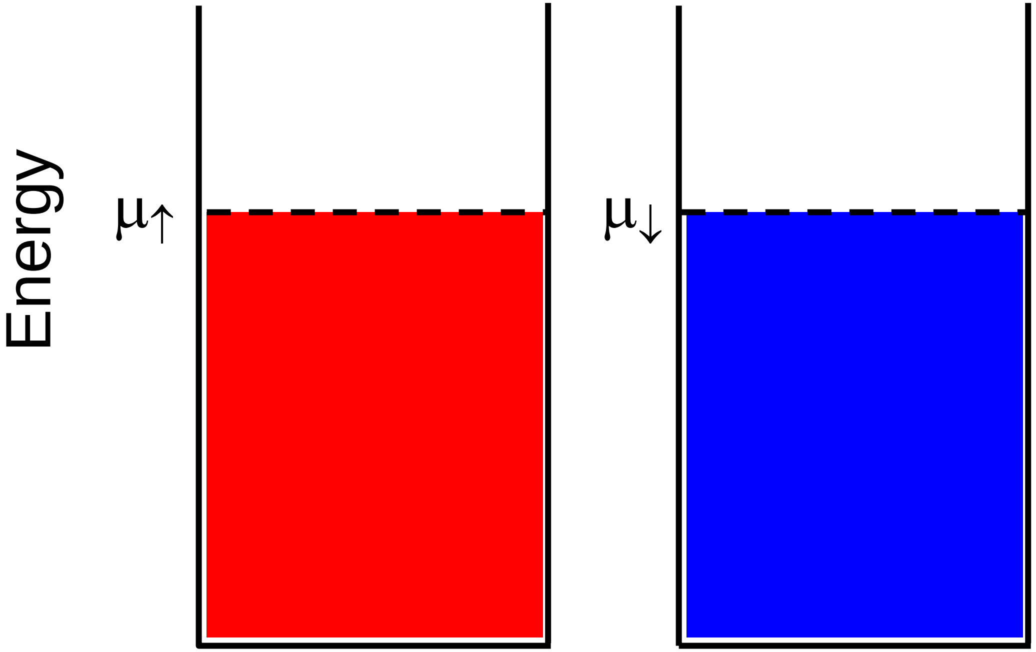
Pairs of fermionic atoms (lithium-6)

Fermionic Superfluidity with Imbalanced Spin Populations



What if there are more boys then girls…?

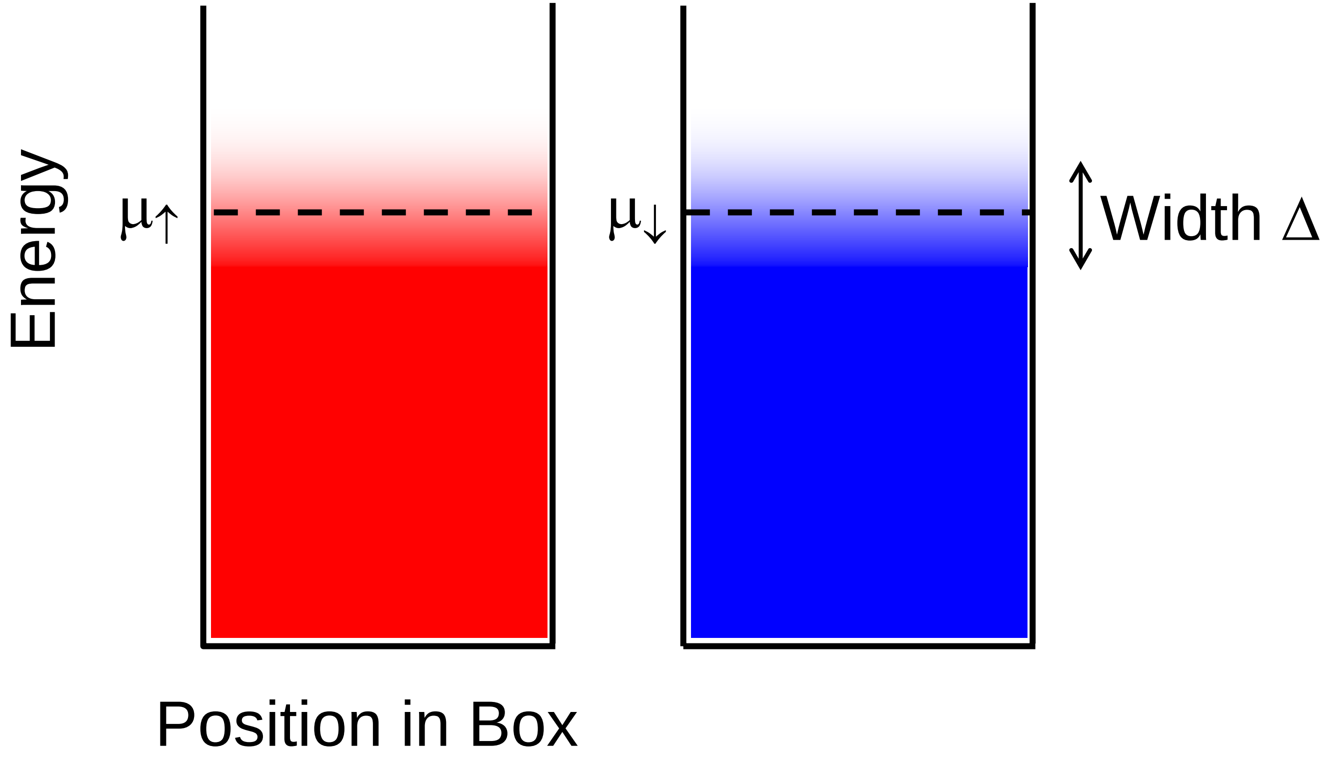
BCS Pairing of Fermions



BCS Pairing of Fermions

Pairing costs kinetic energy,
but there is gain in potential energy

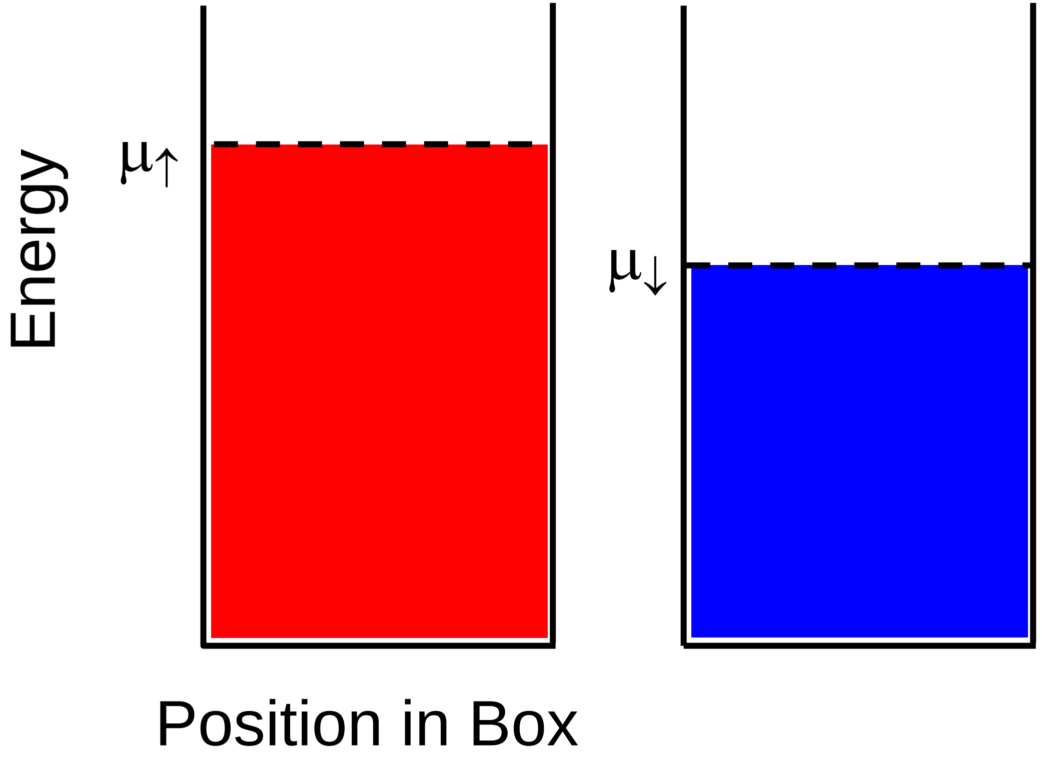
Pairing energy Δ



BCS Pairing of Fermions

Unequal Fermi surfaces, non-interacting case
(example: Apply magnetic field to a normal conductor)

"Magnetic Field" $\delta\mu = \mu_\uparrow - \mu_\downarrow$

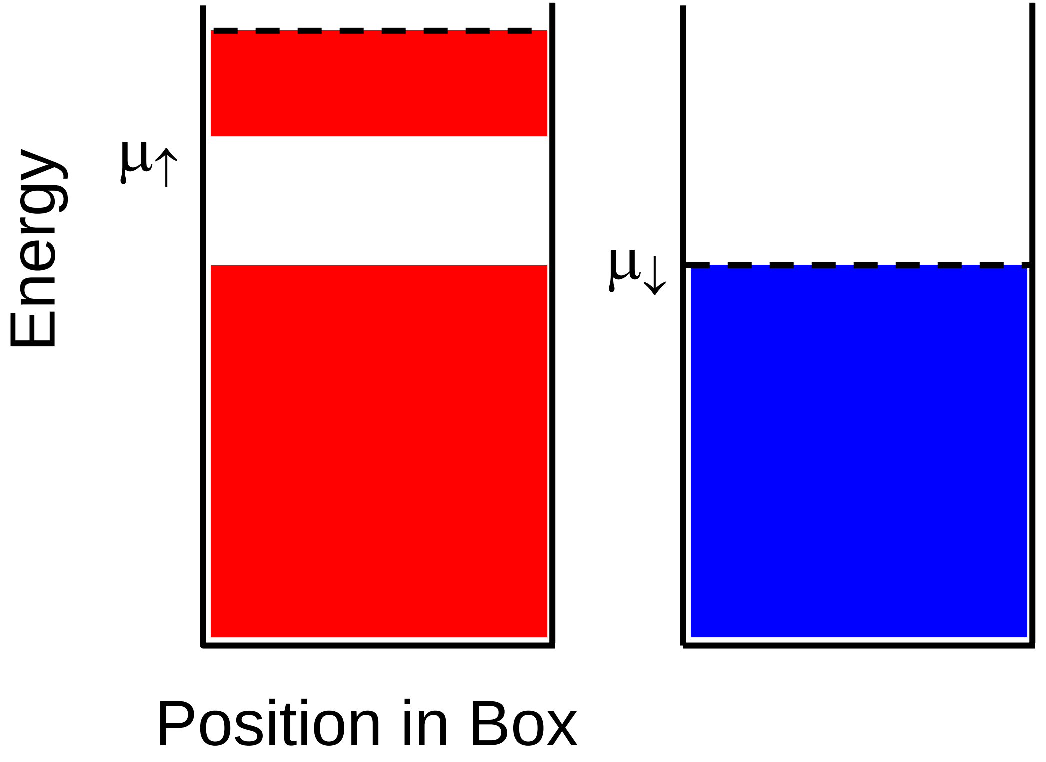


BCS Pairing of Fermions

Interacting case:

Sarma Phase (Sarma 1962), Breached Pairing Phase

Energy cost: $N \frac{\delta\mu}{E_F} \Delta$



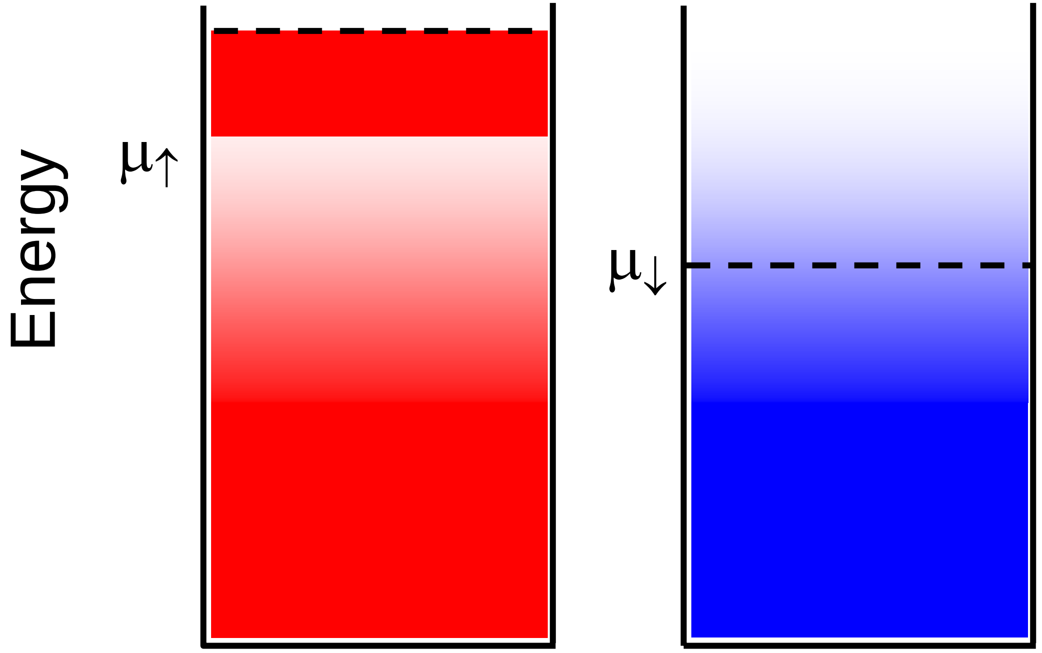
BCS Pairing of Fermions

Interacting case:

Sarma Phase (Sarma 1962), Breached Pairing Phase

Energy cost: $N \frac{\delta\mu}{E_F} \Delta$ Energy gain: $N \frac{\Delta}{E_F} \Delta$

Breakdown when: $\delta\mu > \Delta$



Position in Box

BCS Pairing of Fermions

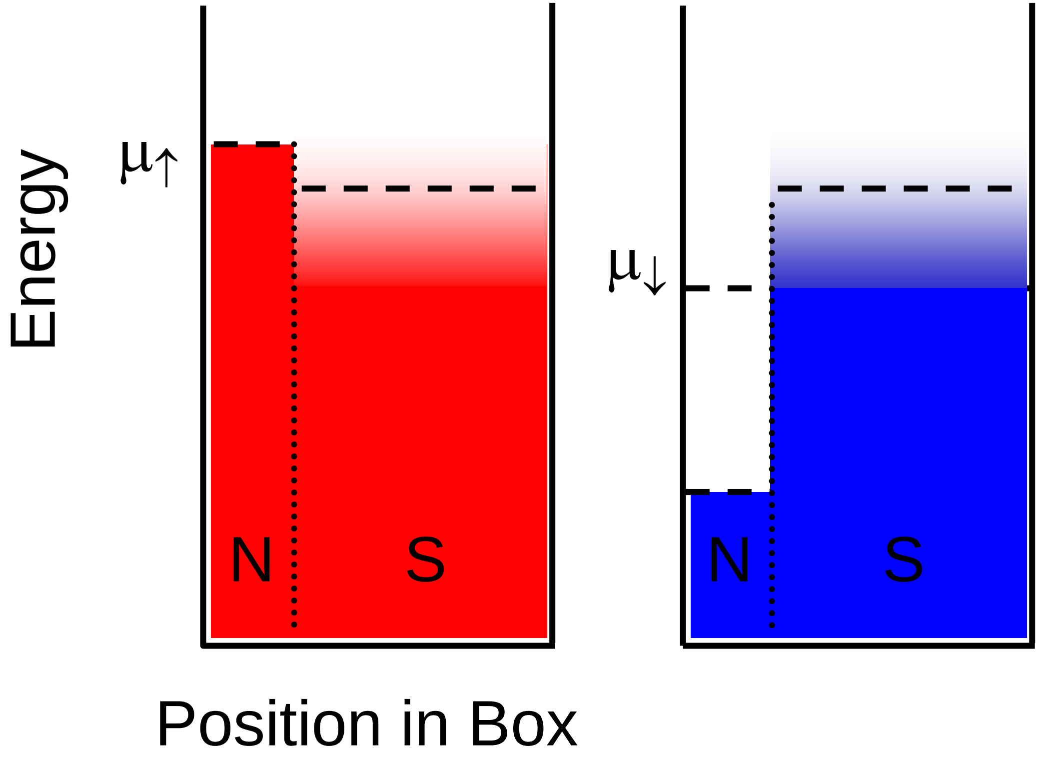
Energetically favorable solution:

Phase separation! (Bedaque, Caldas, Rupak 2003)

A fraction $x = \frac{\delta\mu}{\Delta}$ of the gas is a normal, polarized mixture

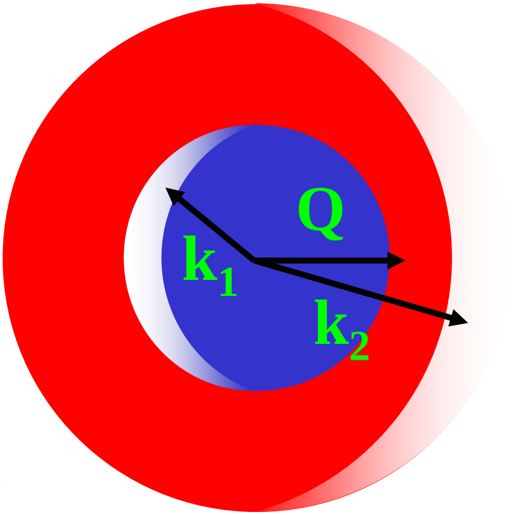
Breakdown of the BCS state when $\delta\mu > \Delta$

Chandrasekhar, Clogston 1962



Superfluidity with unequal Fermi energies

- Superfluidity in quarks involves unequal Fermi surfaces
  due to different quark masses, charges
  and hence different densities

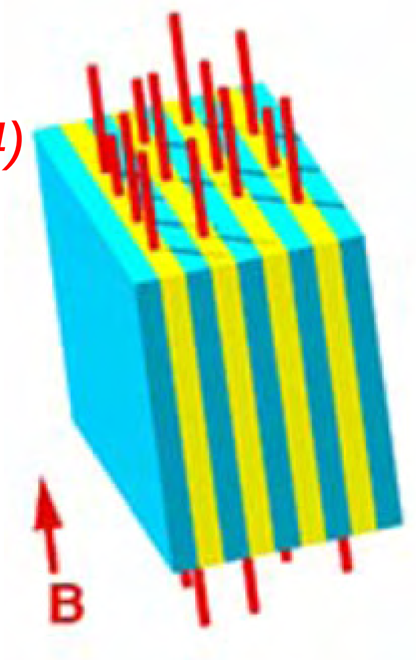


- New superfluid states predicted:
  e.g. Larkin-Ovchnnikov, Fulde-Ferrell–state
  Cooper pairs with non-zero momentum
  Generally: Inhomogeneous order parameter

A. I. Larkin, Yu. N. Ovchinnikov, "Inhomogeneous state of superconductors", Zh. Eksp. Teor. Fiz. ***47****, 1136 (1964)*

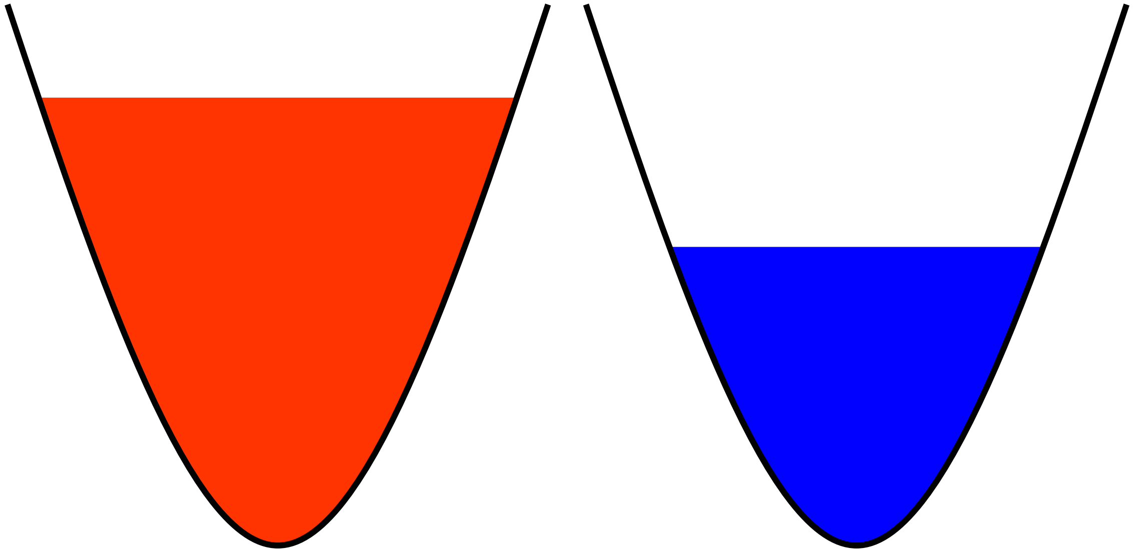
- Possible novel superconducting states
  in systems where vortices are suppressed:

  ex.: Heavy fermion superconductor $CeCoIn_5$
  Bianchi et al., PRL ***91****, 187004 (2003)*
  Radovan et al., Nature ***425****, 51 (2003)*



Trapped, Imbalanced Fermi Mixture

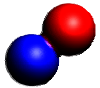
- Two spin states trapped in a 3D harmonic potential
- Population imbalance (or *Polarization*): $P = \dfrac{N_2 - N_1}{N_2 + N_1}$



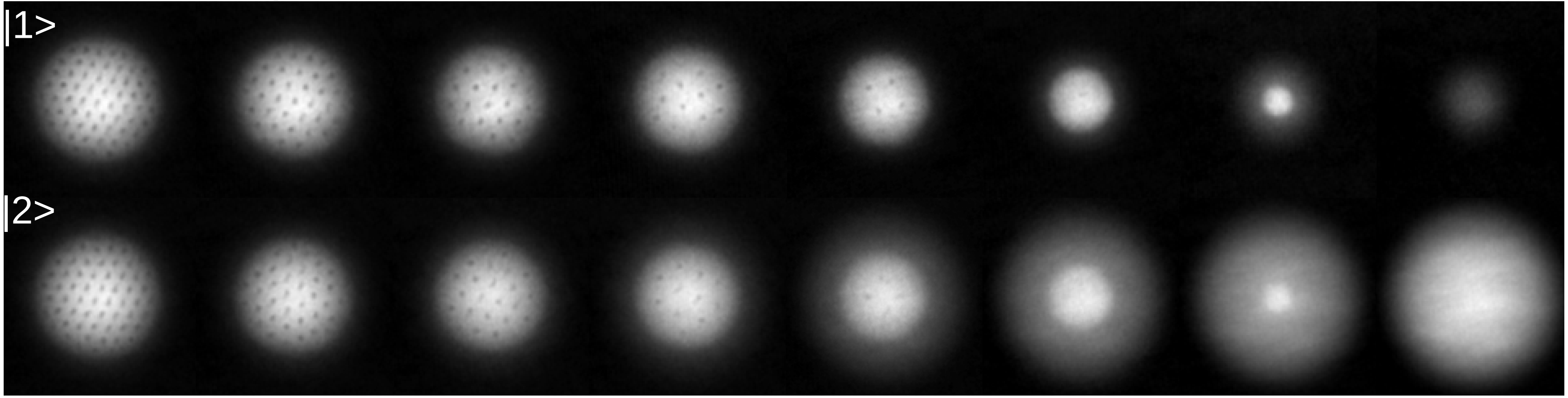
Can we have superfluidity?

Fermionic Superfluidity with Imbalanced Spin Populations

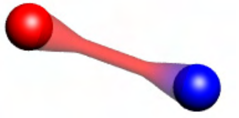
BEC-Side



$1/k_F a = 0.2$

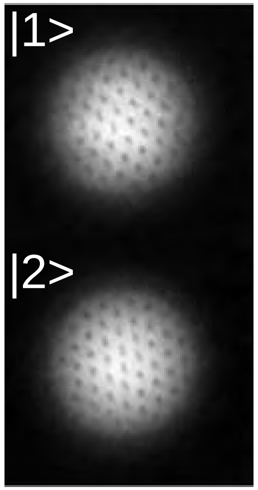


0% 6% 12% 22% 30% 56% 90% 94%



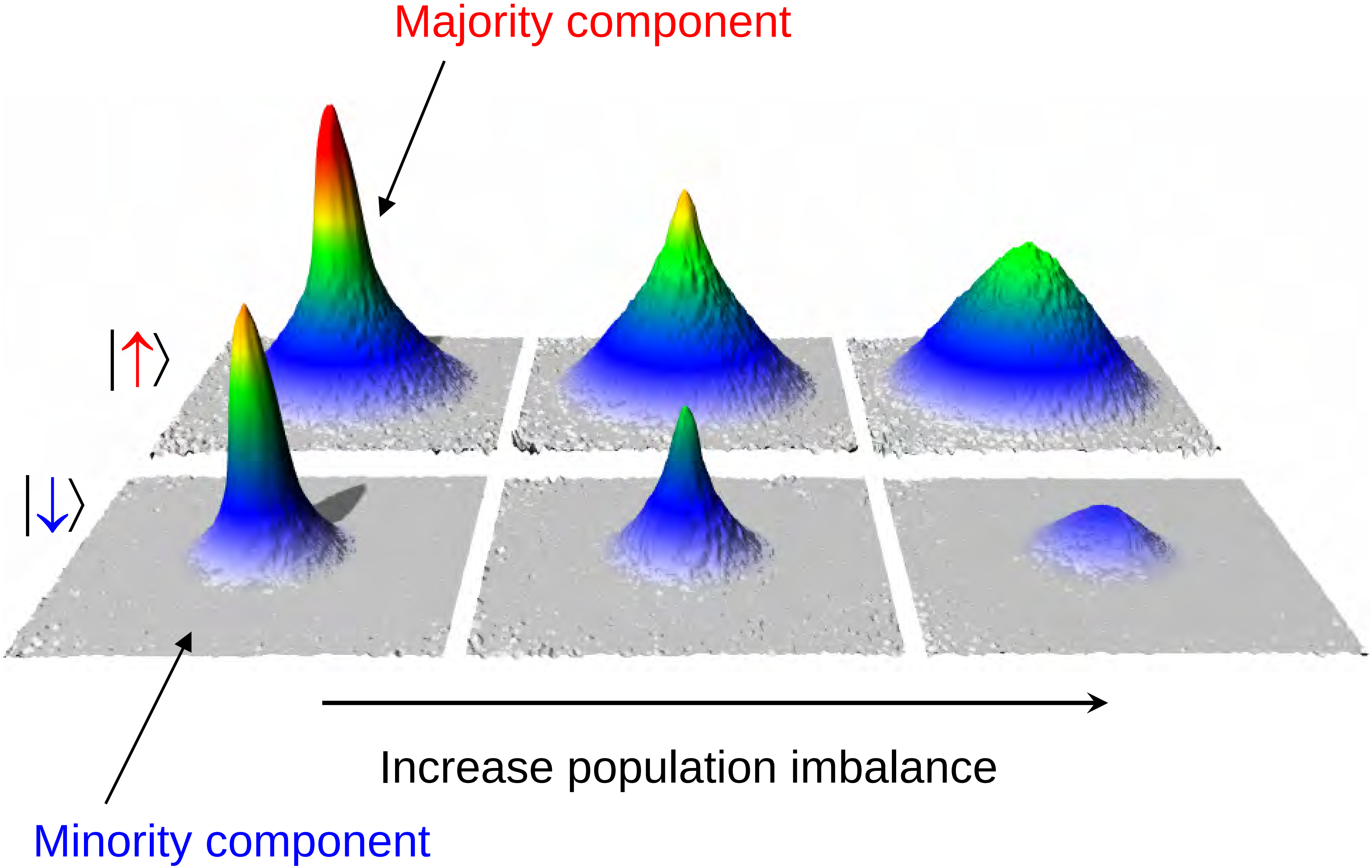
BCS-Side

$1/k_F a = -0.15$

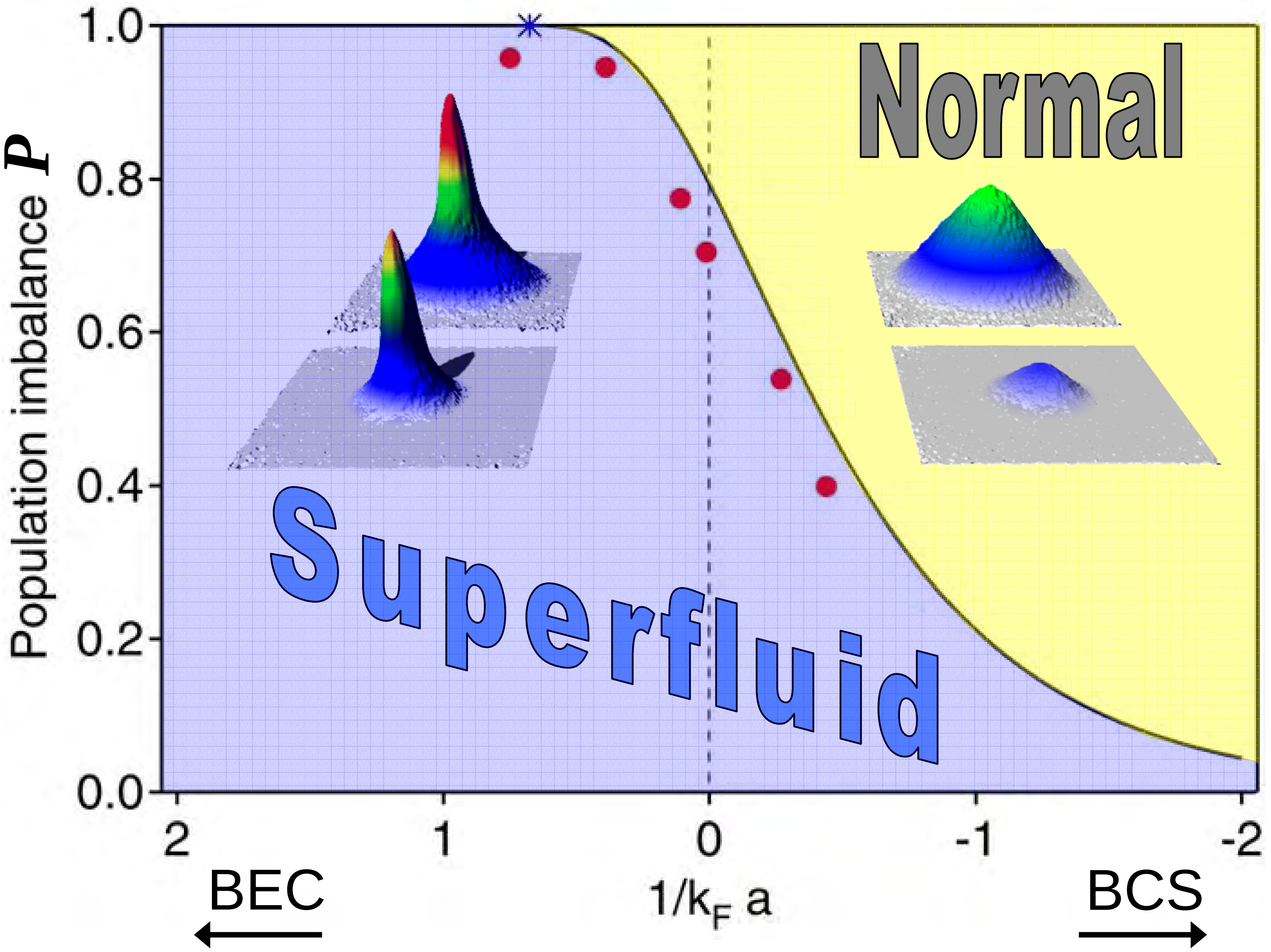


0%

The Clogston-Chandrasekhar limit



Phase Diagram for Unequal Mixtures



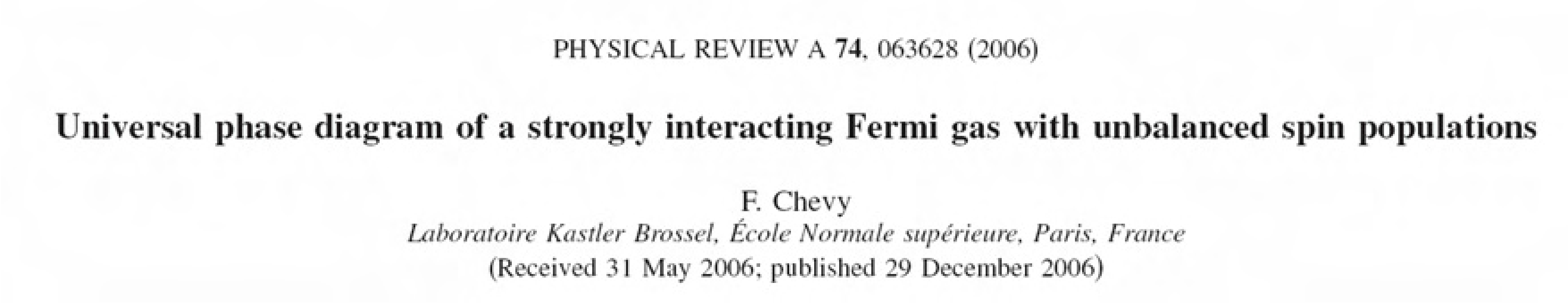
Breakdown: Critical polarization $P_c \propto$ Gap Δ

M.W. Zwierlein, A. Schirotzek, C.H. Schunck, W. Ketterle,
Science 311, 492 (2006)

Critical Polarization

Breakdown: Critical polarization $P_c \propto$ Gap Δ

Critical Polarization on resonance (experiment): $P_c = 0.74\ (5)$

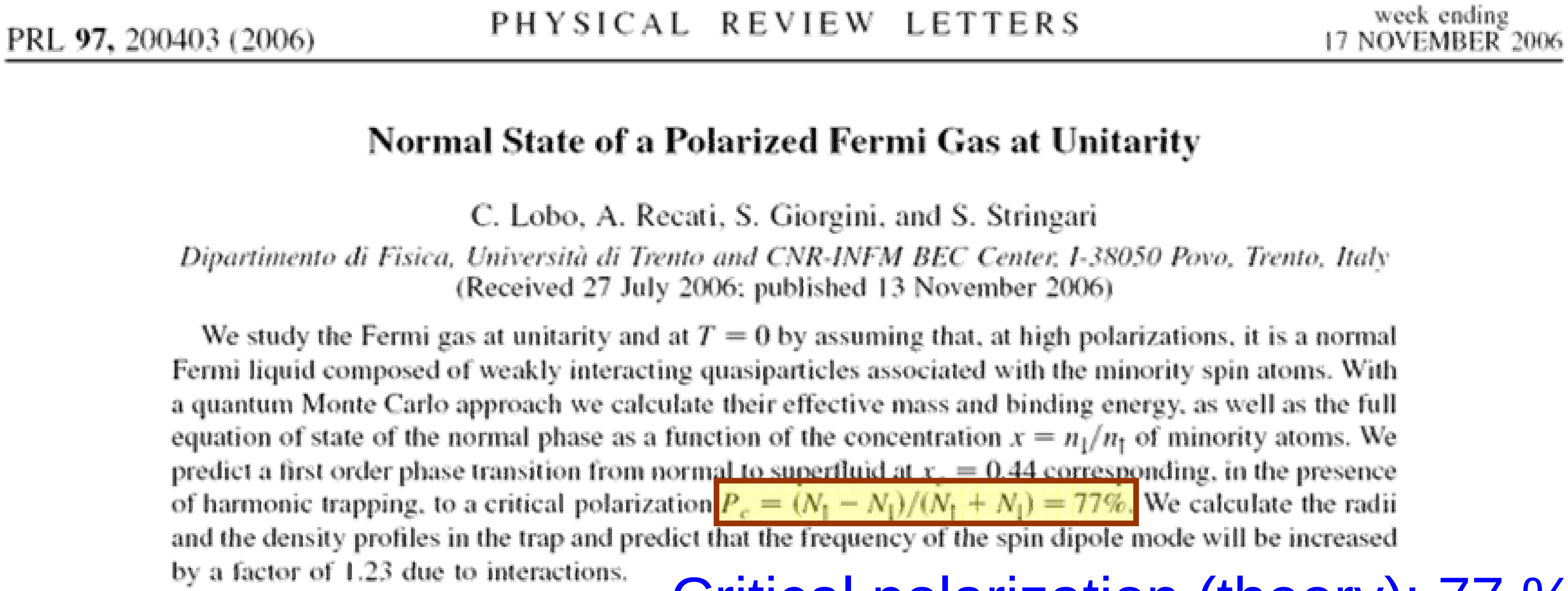


PHYSICAL REVIEW A **74**, 063628 (2006)

Universal phase diagram of a strongly interacting Fermi gas with unbalanced spin populations

F. Chevy
Laboratoire Kastler Brossel, École Normale supérieure, Paris, France

(Received 31 May 2006; published 29 December 2006)



PRL **97,** 200403 (2006) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2006

Normal State of a Polarized Fermi Gas at Unitarity

C. Lobo, A. Recati, S. Giorgini, and S. Stringari
Dipartimento di Fisica, Università di Trento and CNR-INFM BEC Center, I-38050 Povo, Trento, Italy

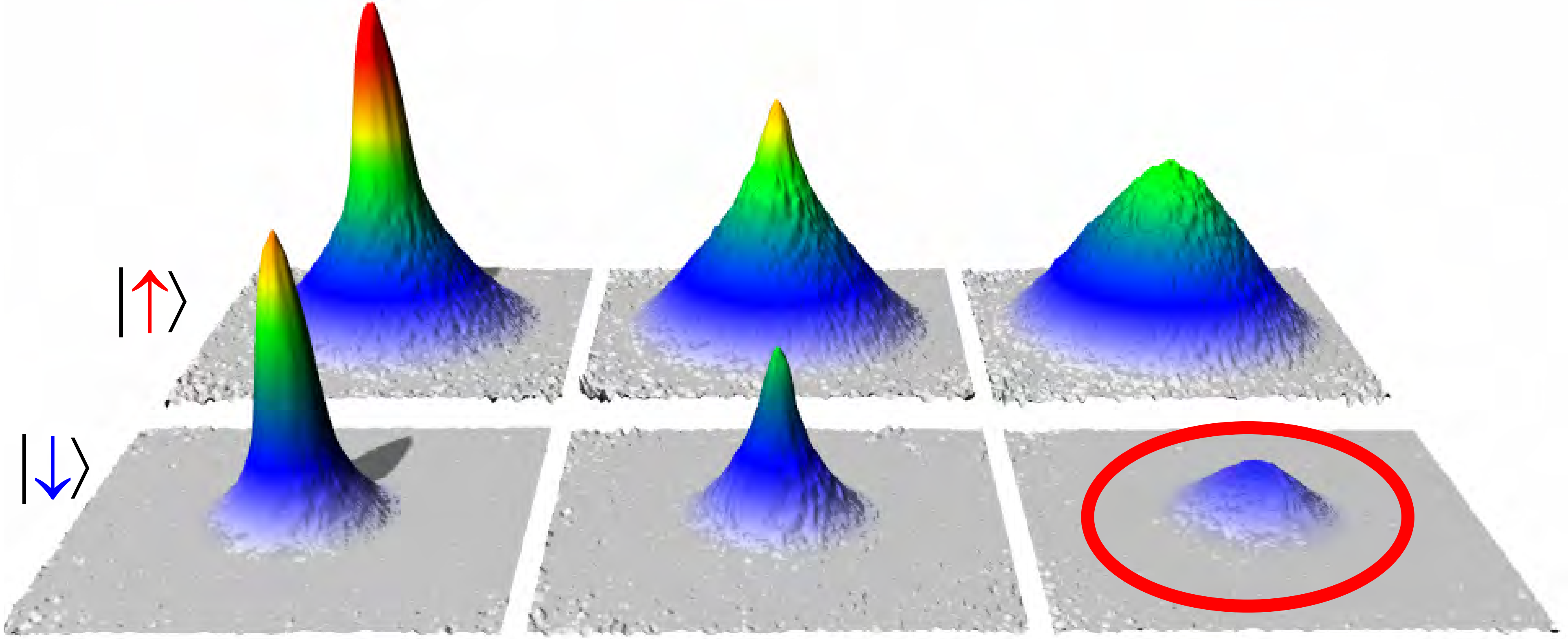
(Received 27 July 2006; published 13 November 2006)

We study the Fermi gas at unitarity and at $T = 0$ by assuming that, at high polarizations, it is a normal Fermi liquid composed of weakly interacting quasiparticles associated with the minority spin atoms. With a quantum Monte Carlo approach we calculate their effective mass and binding energy, as well as the full equation of state of the normal phase as a function of the concentration $x = n_\downarrow / n_\uparrow$ of minority atoms. We predict a first order phase transition from normal to superfluid at $x_c = 0.44$ corresponding, in the presence of harmonic trapping, to a critical polarization $\boxed{P_c = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow) = 77\%.}$ We calculate the radii and the density profiles in the trap and predict that the frequency of the spin dipole mode will be increased by a factor of 1.23 due to interactions.

Critical polarization (theory): 77 %

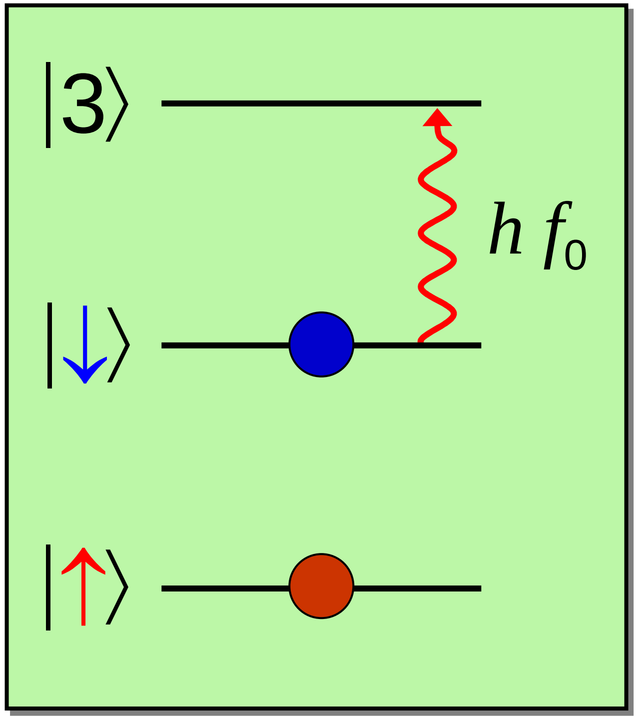
What happens at the Clogston-Chandrasekhar limit?

Also called the “Pauli pair breaking limit”

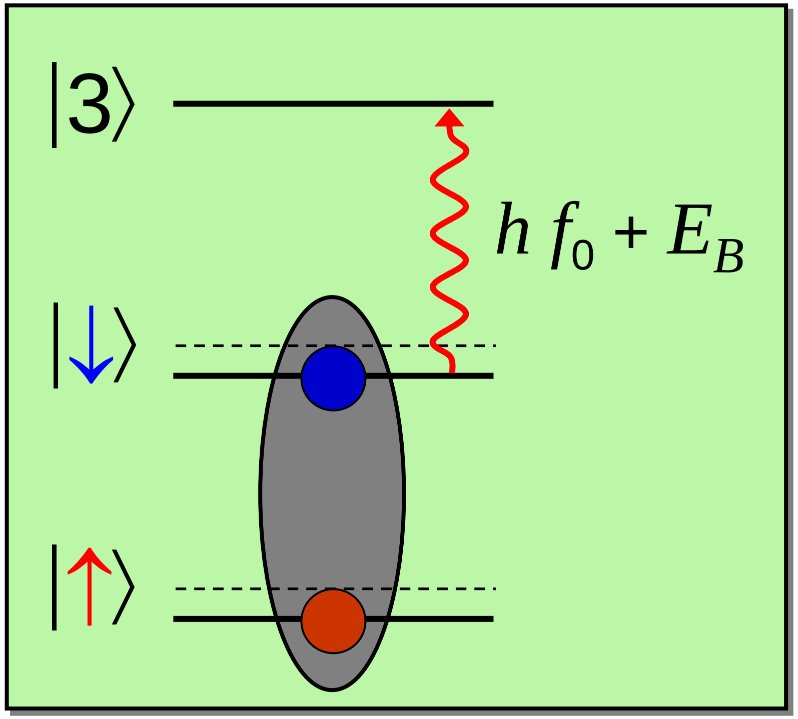


RF spectroscopy in a Fermi mixture

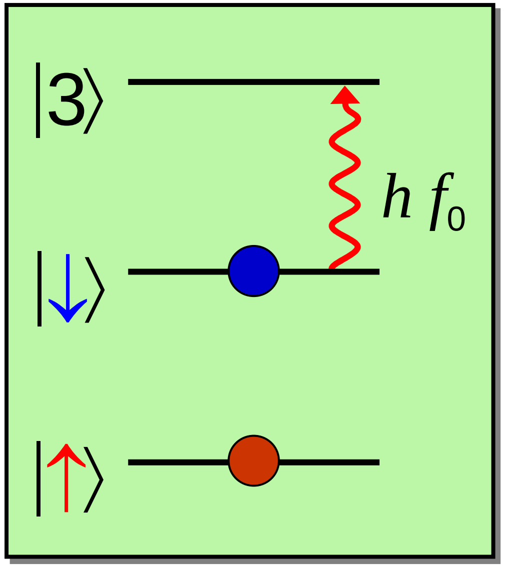
No interactions



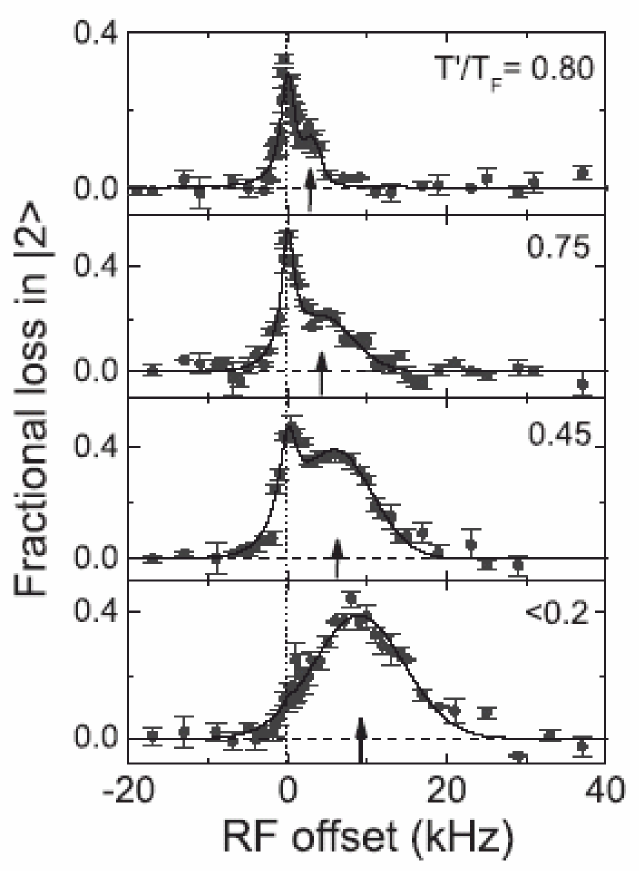
Pairing



Observation of a pairing gap in a *balanced* Fermi mixture



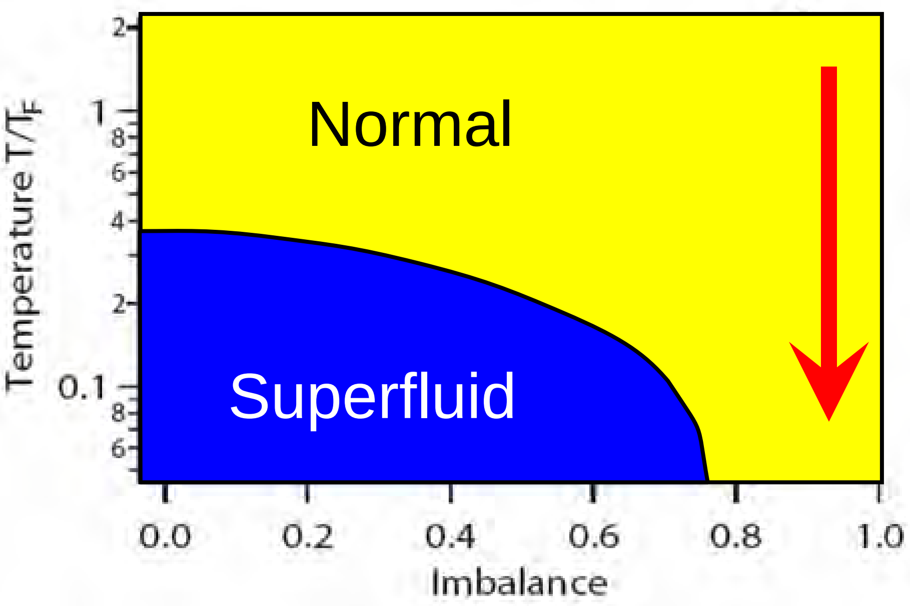
In balanced mixture:

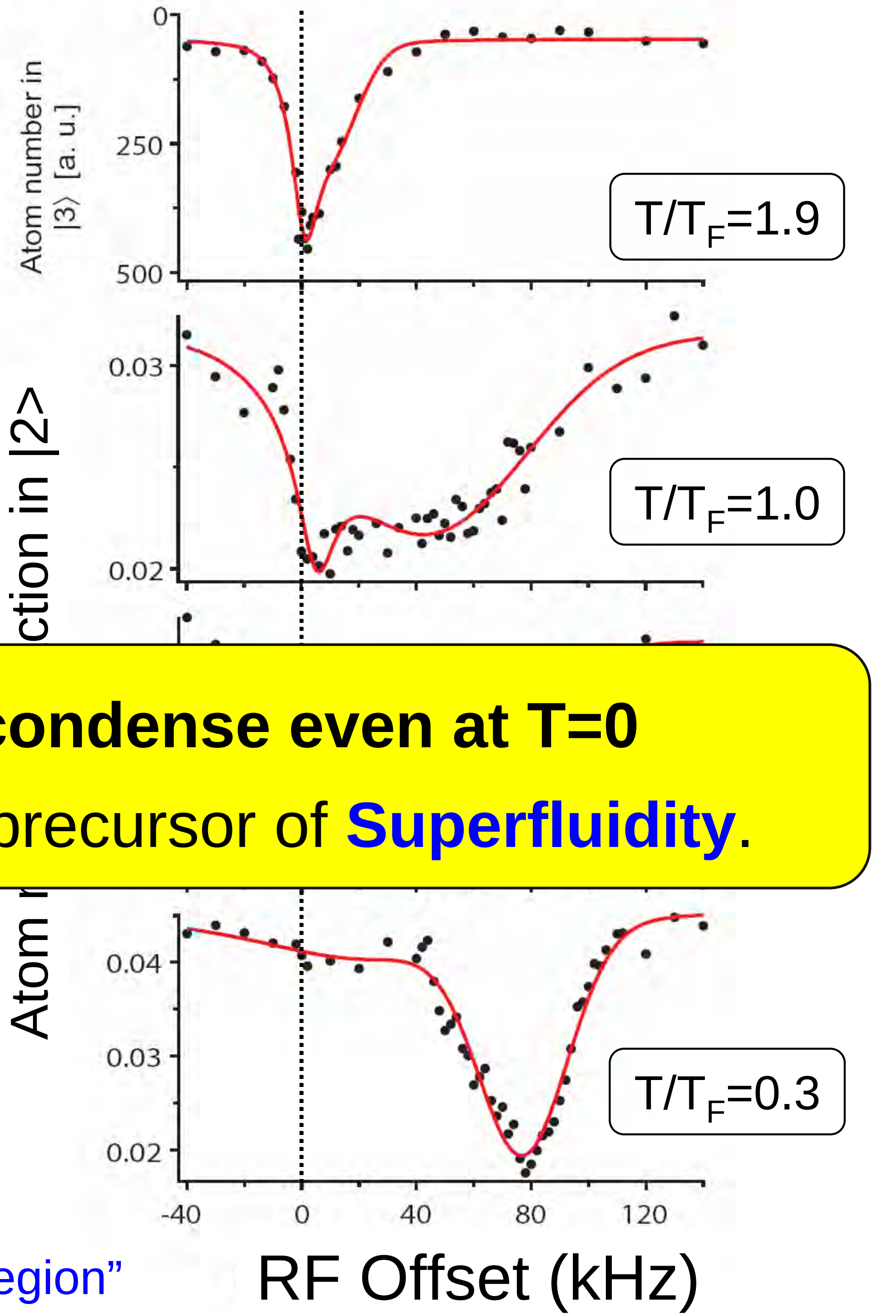


C. Chin et al., Science **305**, 1128 (2004)

Double peak structure indicates the presence of pairing.

RF spectroscopy in an *imbalanced* Fermi mixture





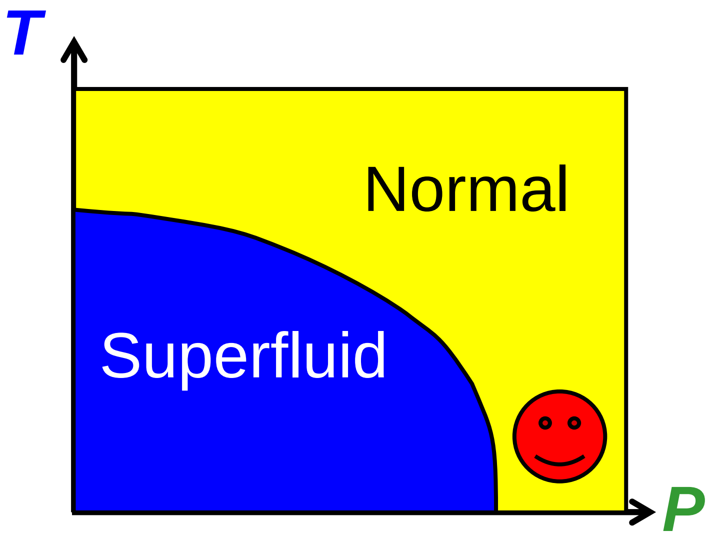
Fermion pairs *cannot* condense even at T=0

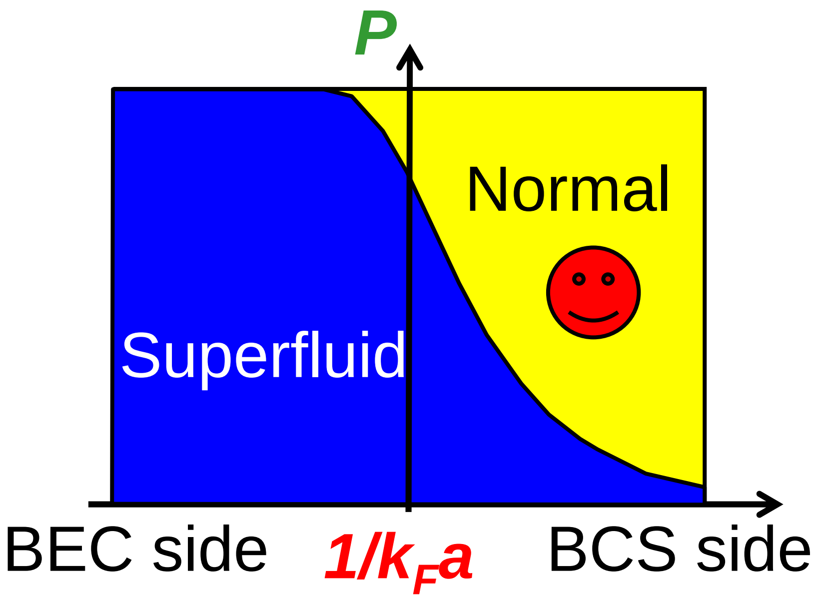
Pairing is *not* necessarily a precursor of **Superfluidity**.

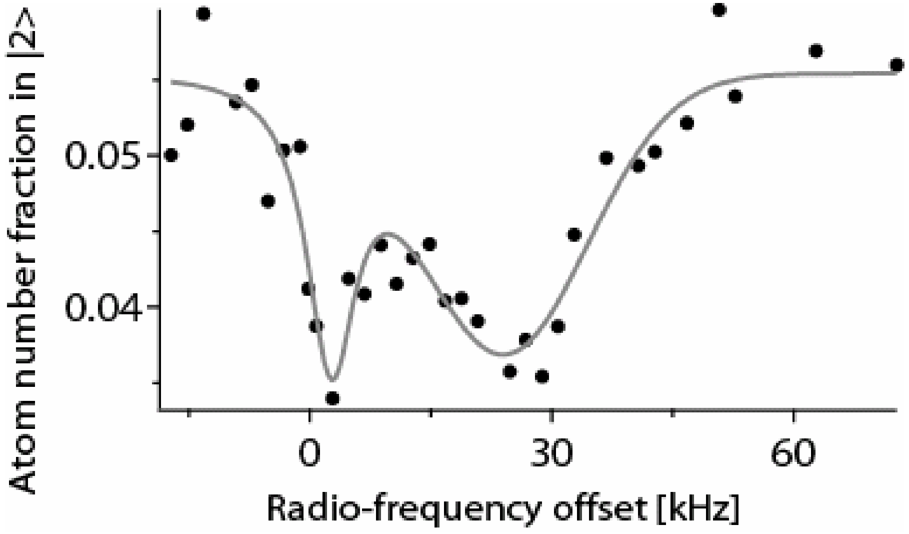
C.H. Schunck, Y. Shin, A. Schirotzek,
M.W. Zwierlein, and W. Ketterle,
Science **316**, 867 (2007)

I. L. Aleiner, B. L. Altshuler,
Phys. Rev. Lett. 79, 4242 (1997):
Fermion pairs exist “far above the transition region”

Pairing without Superfluidity







On the BCS side (936G)

Imbalance P ~ 90%

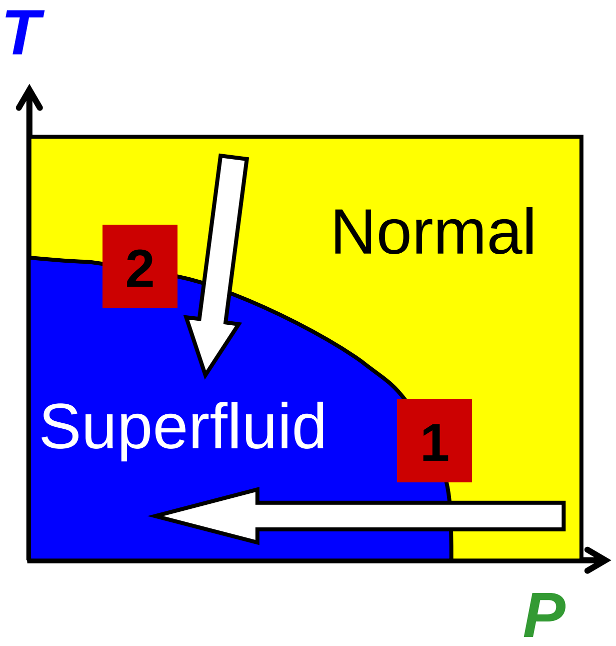
T/T_F ~ 0.3 **E_F/h ~ 280 kHz**

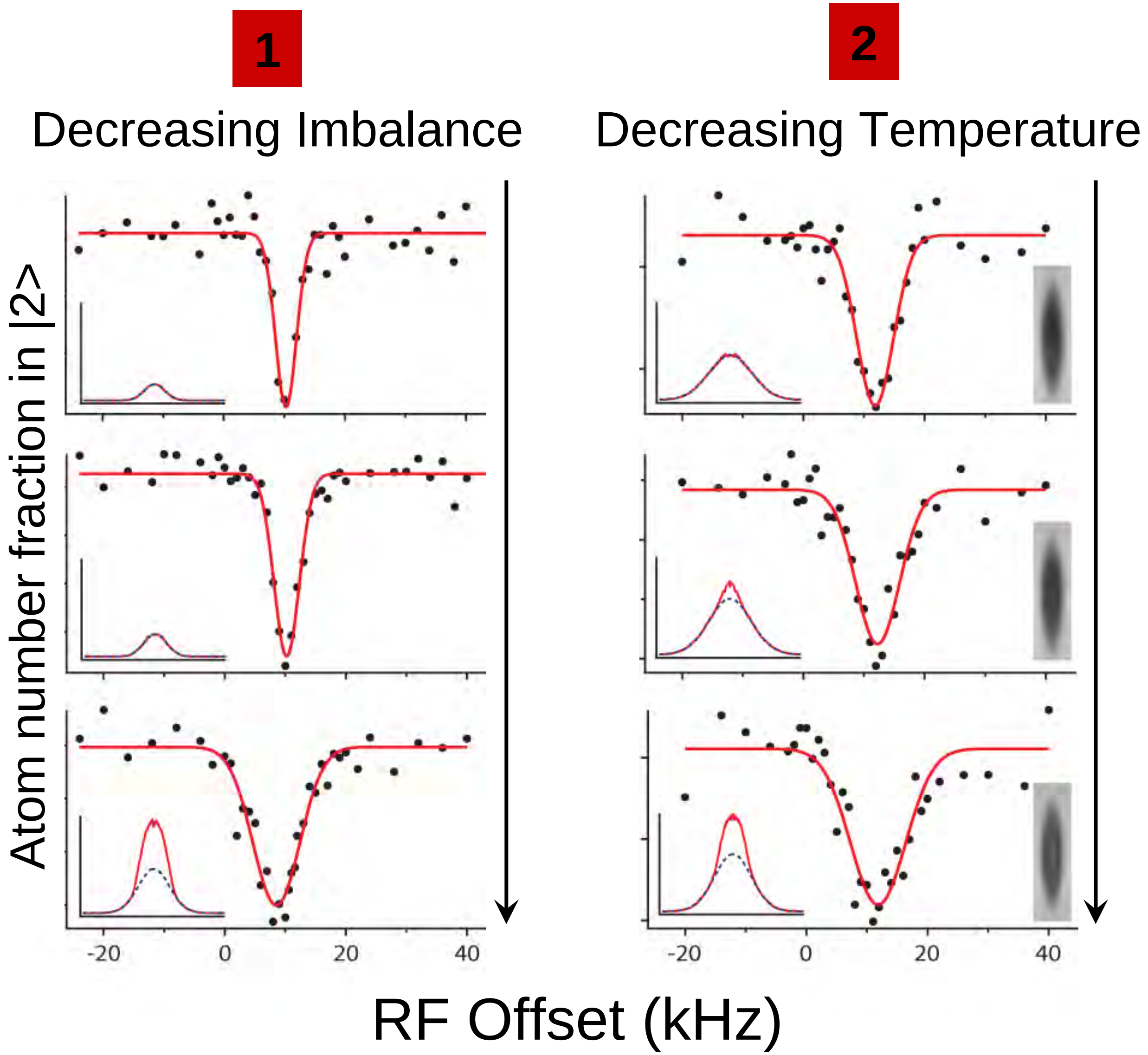
$1/k_F a = -0.18$

$P_{c,exp}$ ~ 60%

C.H. Schunck, Y. Shin, A. Schirotzek, M.W. Zwierlein, and W. Ketterle, Science 316, 867 (2007)

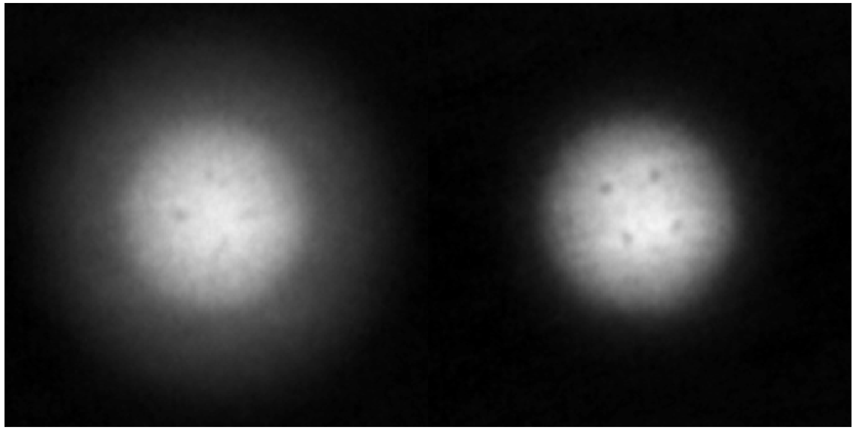
Rf spectroscopy across the phase transition

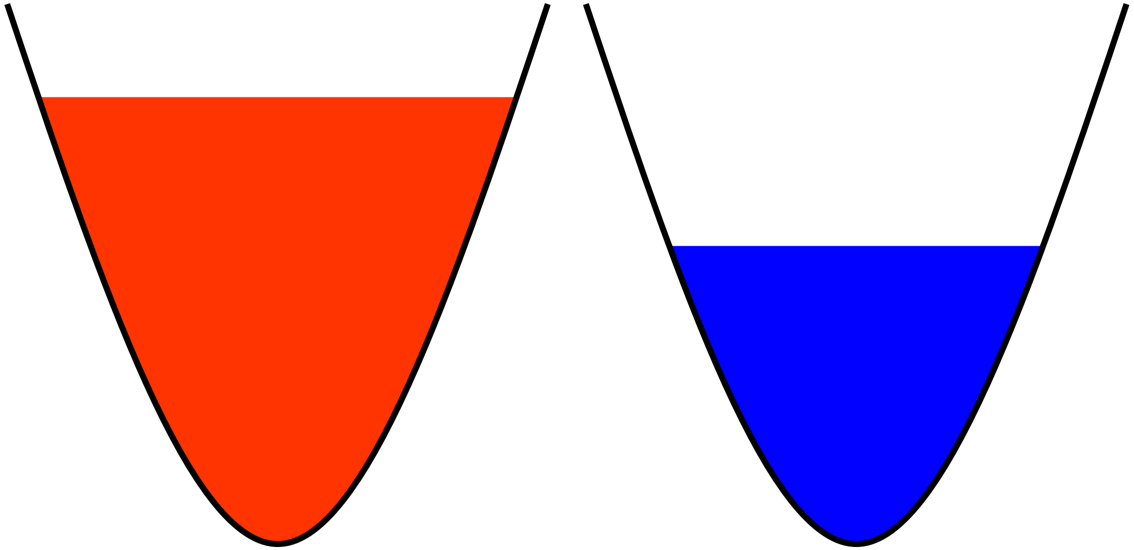




Rf-spectroscopy does not reveal superfluidity

What is the Nature of the Superfluid State?

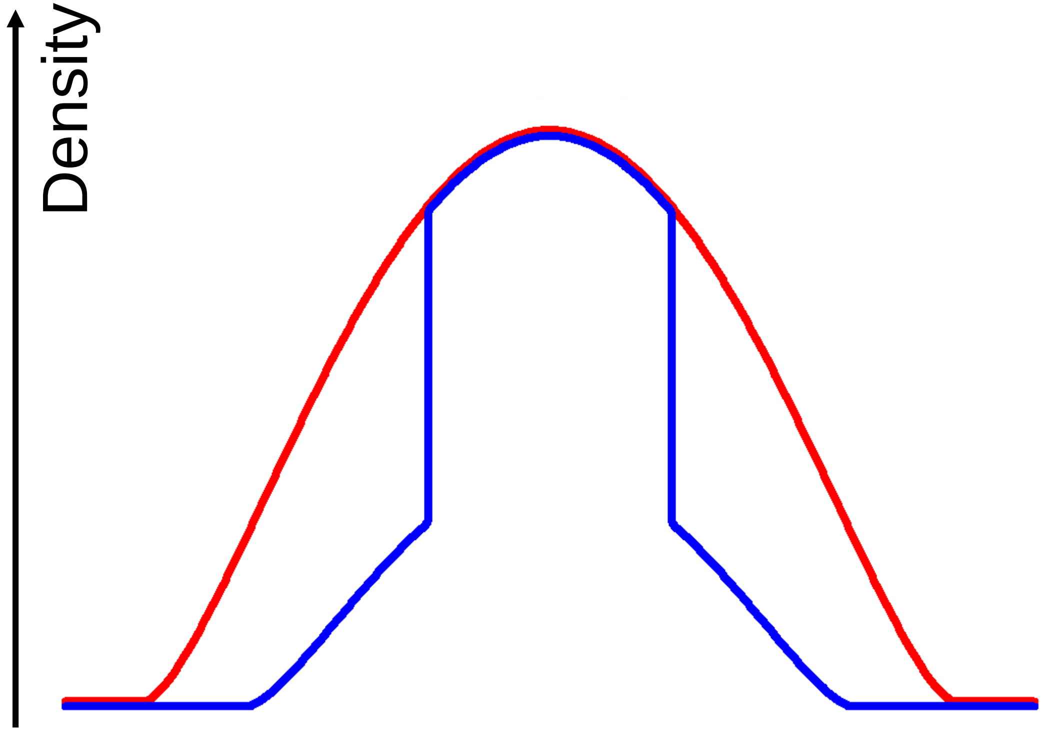




Density distribution of *unequal* mixtures

Normal state: unequal densities

Superfluid: needs equal densities (Phase separation scenario)

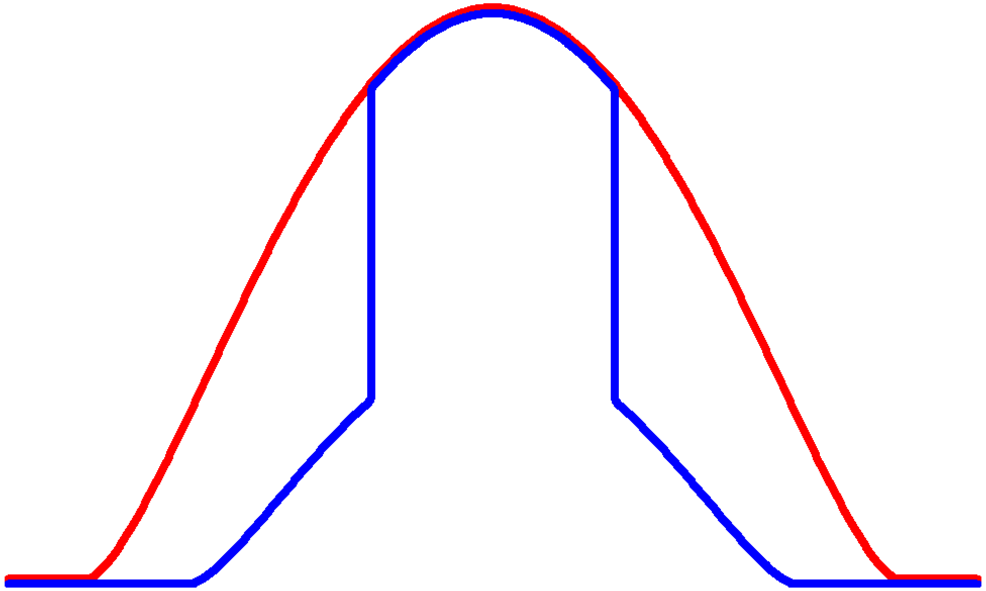


At the Normal – Superfluid – Transition:

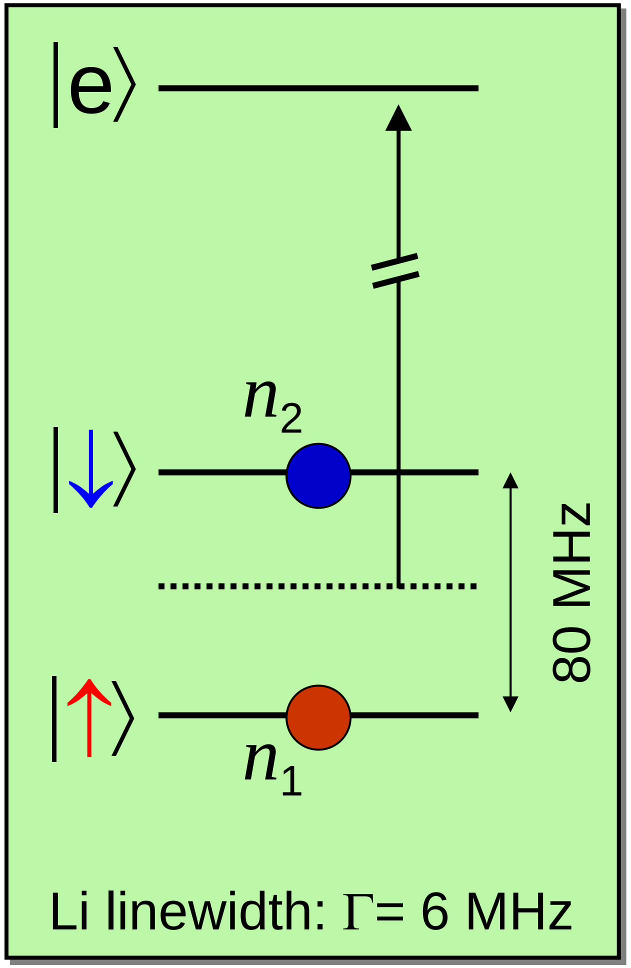
Density discontinuity or “kink” in the profiles!

M.W. Zwierlein, C.H. Schunck, A. Schirotzek, W. Ketterle,
Nature 442, 54 (2006)

How to image the density *difference*?



Phase Contrast Imaging



- Imaging beam red-detuned for $|\uparrow\rangle$
  blue-detuned for $|\downarrow\rangle$

- Phase shift $\propto$ Density difference

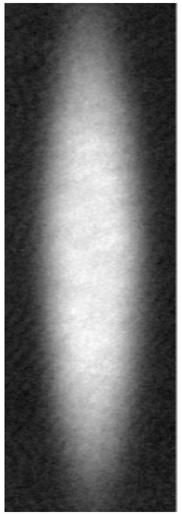
$$\Delta n = n_2 - n_1$$

In-trap images

Direct observation of the Phase transition

Cooling Down

Normal → Superfluid



Shell structure: A hint for phase separation

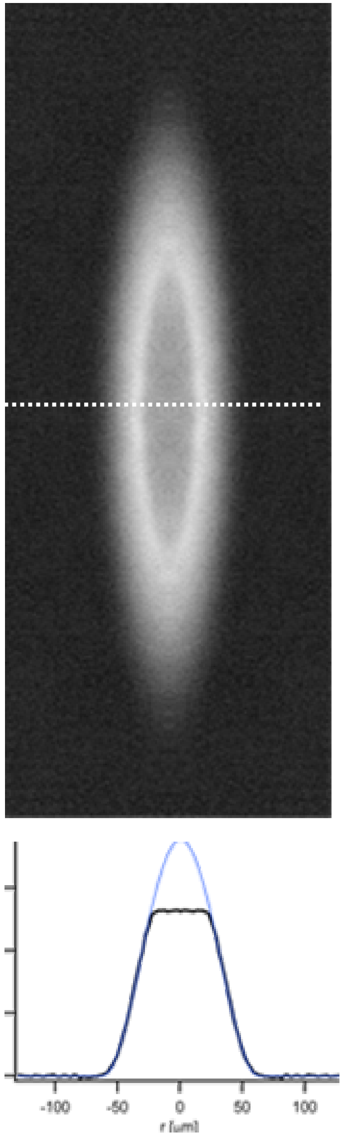
Y. Shin, M.W. Zwierlein, C.H. Schunck, A. Schirotzek, W. Ketterle,
PRL 97, 030401 (2006)

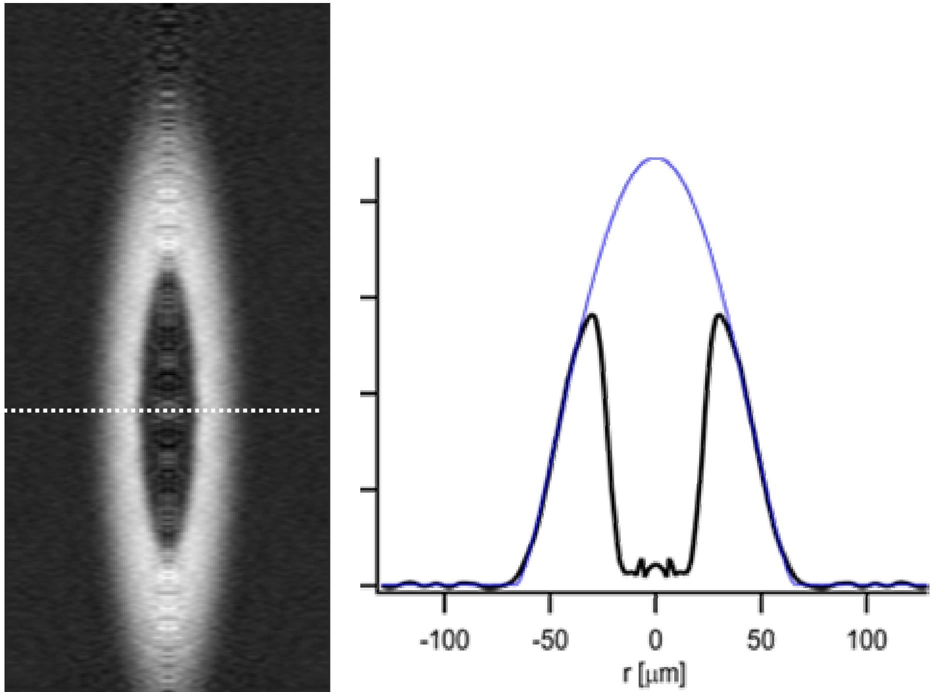
see also: M.W. Zwierlein, A. Schirotzek, C.H. Schunck, and W. Ketterle
Science **311**, 492 (2006)
Nature **442**, 54 (2006)
G. B. Partridge *et al.*, Science **311**, 503 (2006)

Reconstruction of 3D density profile

- Column density profile → 3D density profile
- Only assumes cylindrical symmetry

$P = 0.6$

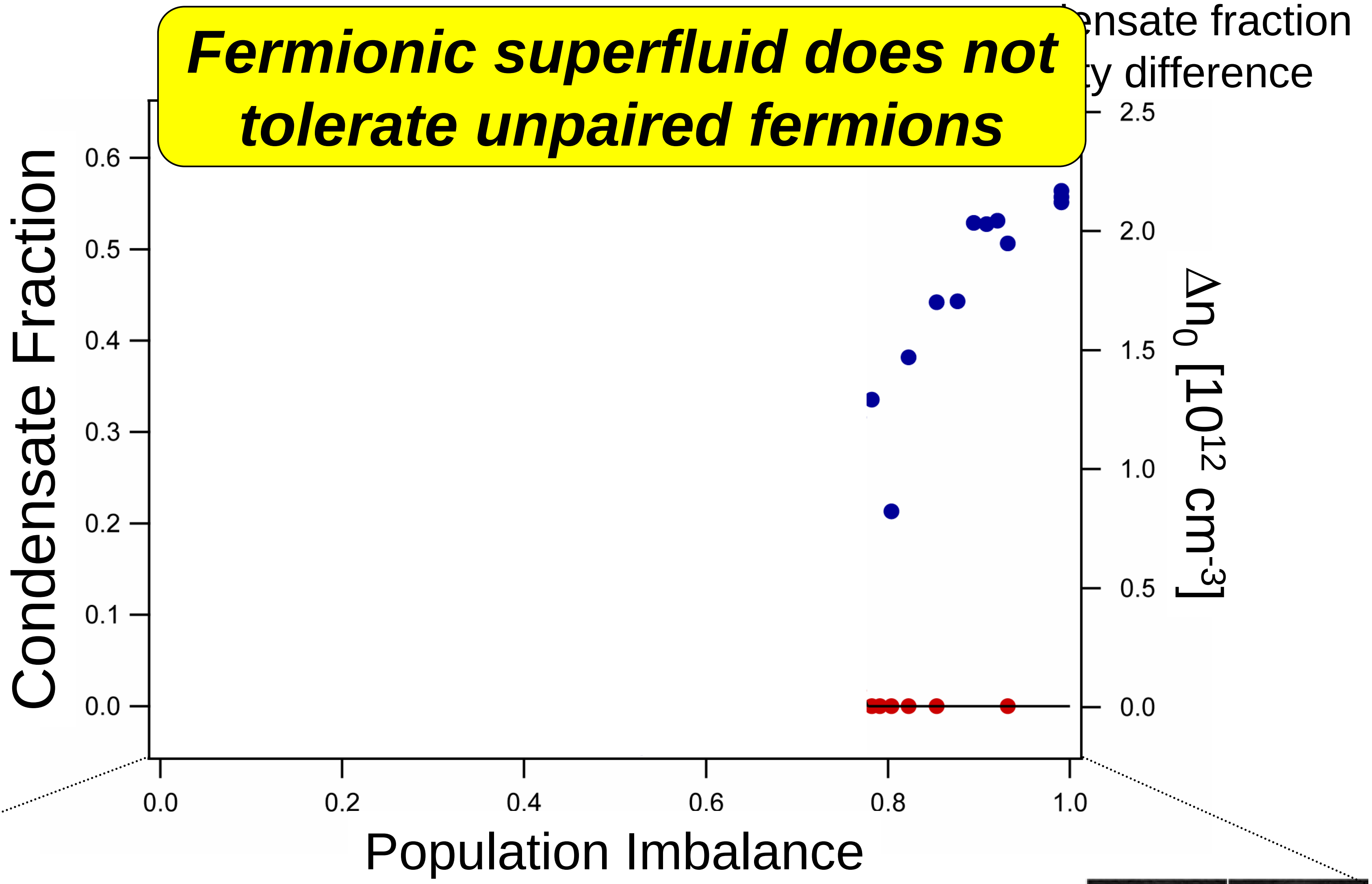


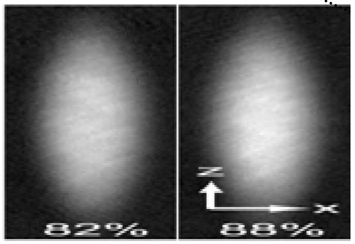


Observation of Phase Separation

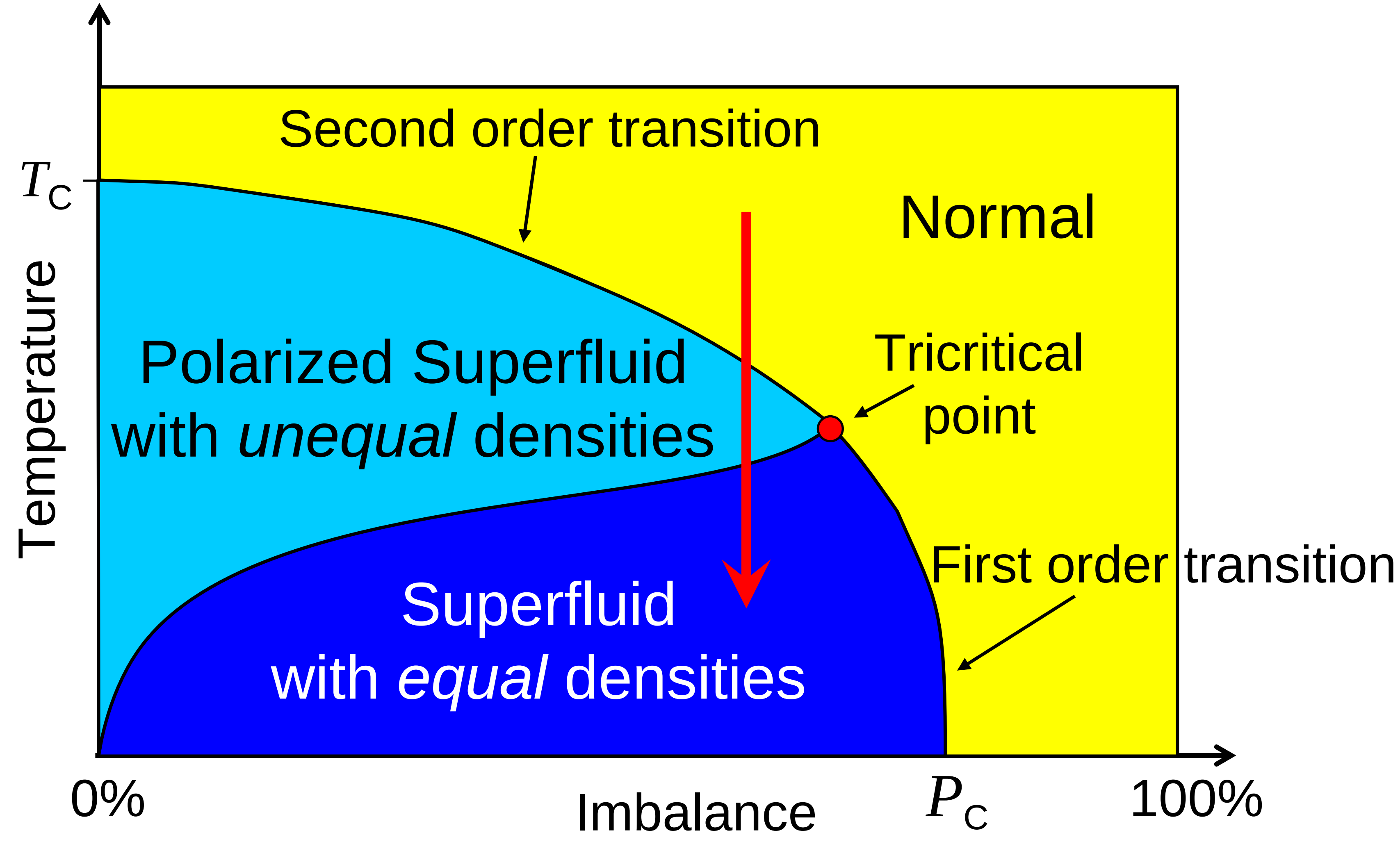
Phase Separation in an Imbalanced Fermi Gas

Fermionic superfluid does not tolerate unpaired fermions



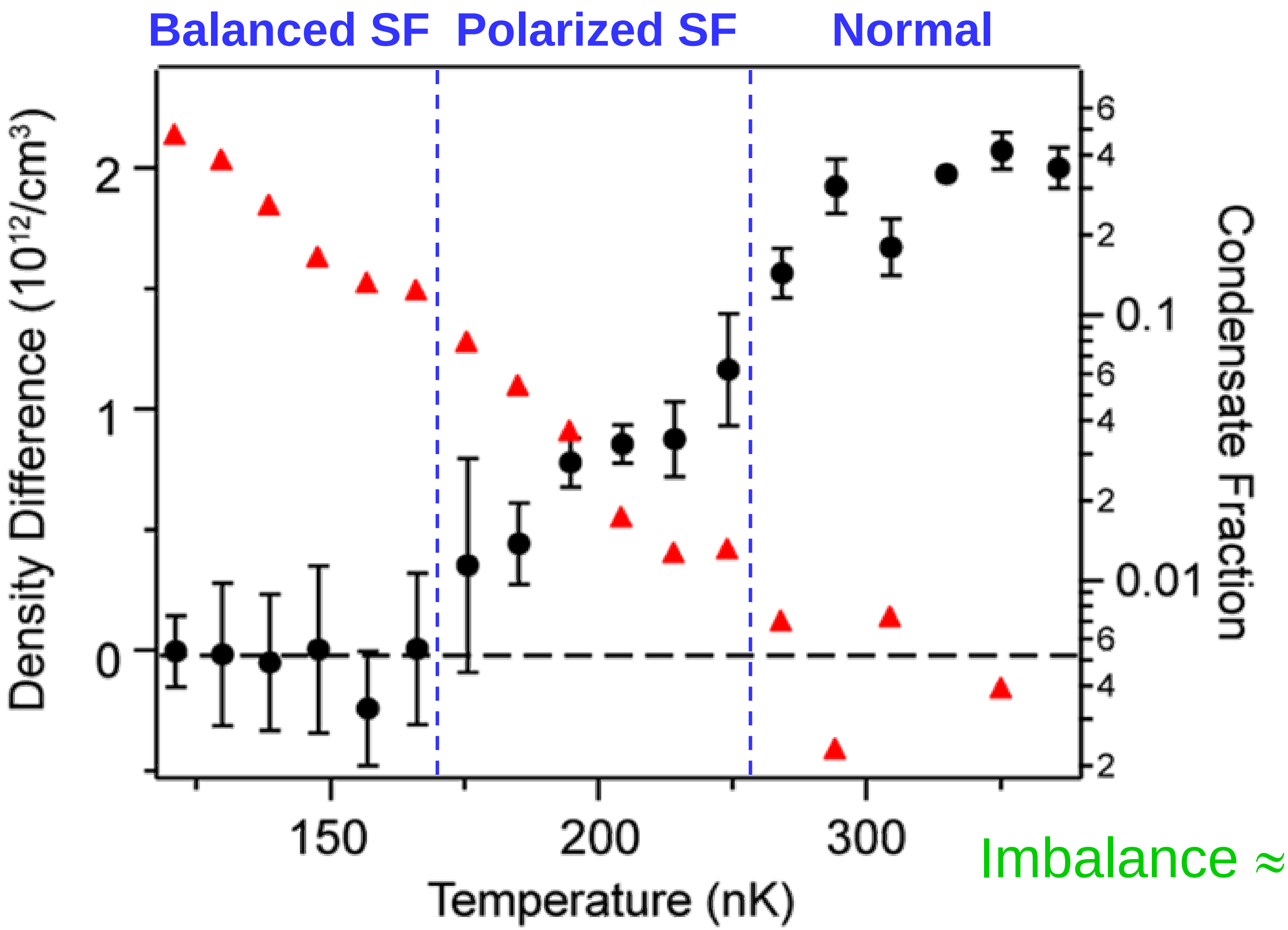


Finite Temperature Phase diagram



Proposed finite-T. phase diagrams:
Machida et al., PRL **97**, 120407 (2006), Liu and Hu, Eur.Phys.Lett. **75**, 364 (2006),
Gubbels et al., PRL 97, 210402 (2006), Parish et al., Nature Physics **3**, 124 (2007),
He et al., PRA **75**, 021602 (2007), Duan et al., cond-mat 0706.1253 (2007),…

Finite Temperature Effects

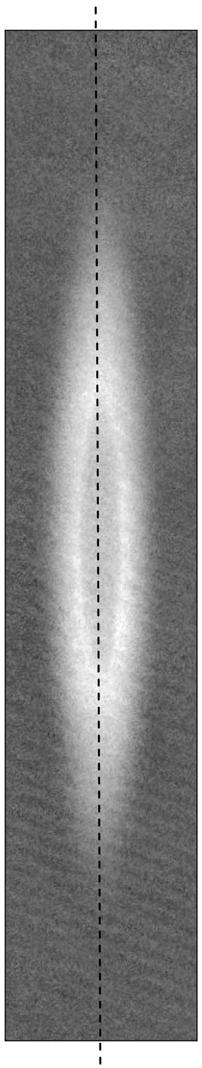


Imbalance ≈ 55 %

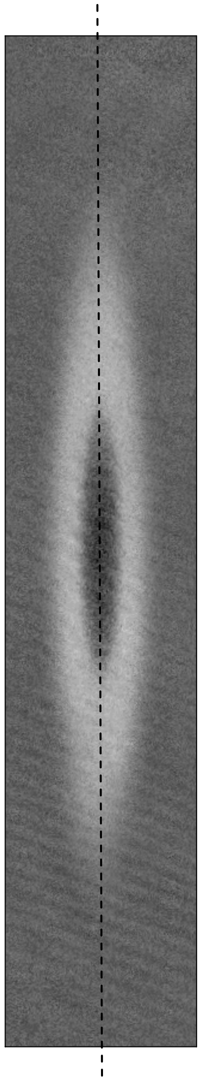
- Temperature-induced polarized superfluid.
- Thermal population of quasiparticles ($k_BT > \Delta$)

Phase separation: 1^{st} order Phase transition?

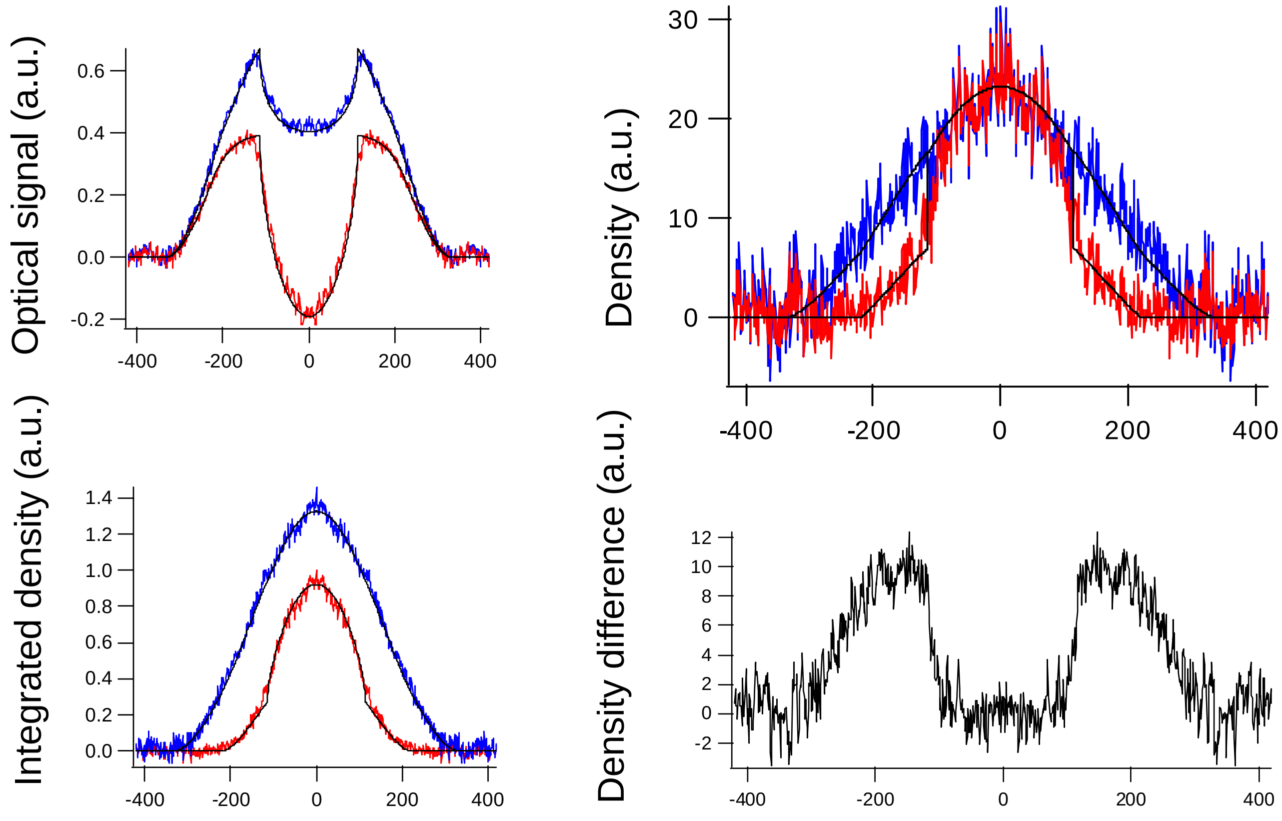
δ=55%



Signal = n_1-n_2

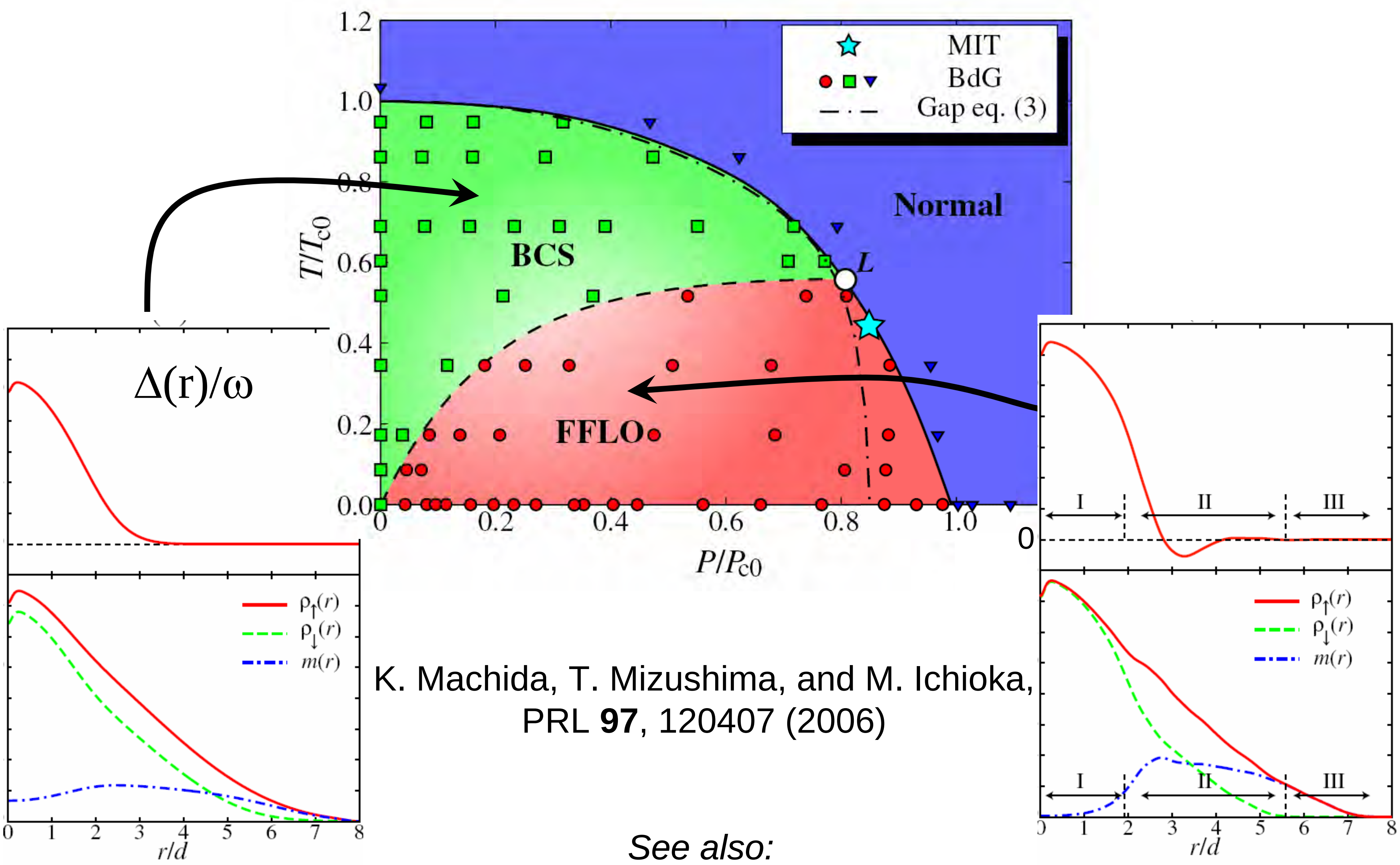


$0.8n_1$- $1.4n_2$



Sharp transition between SF at equal densities
and imbalanced, *partially* polarized state

Where is the LOFF-state?



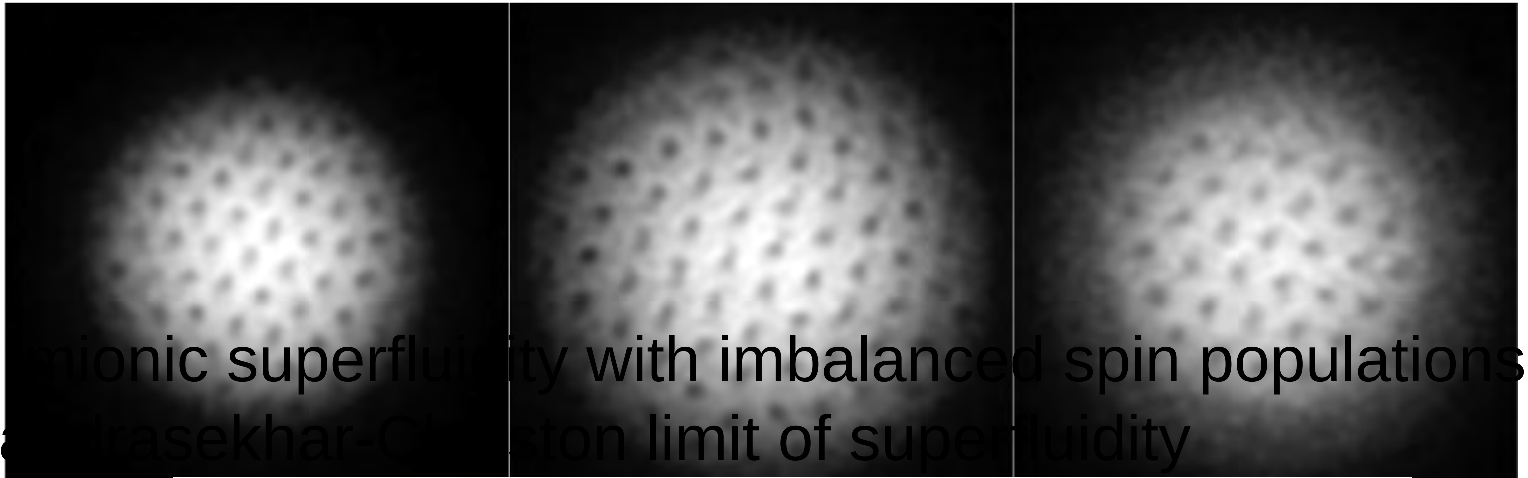
K. Machida, T. Mizushima, and M. Ichioka,
PRL **97**, 120407 (2006)

See also:

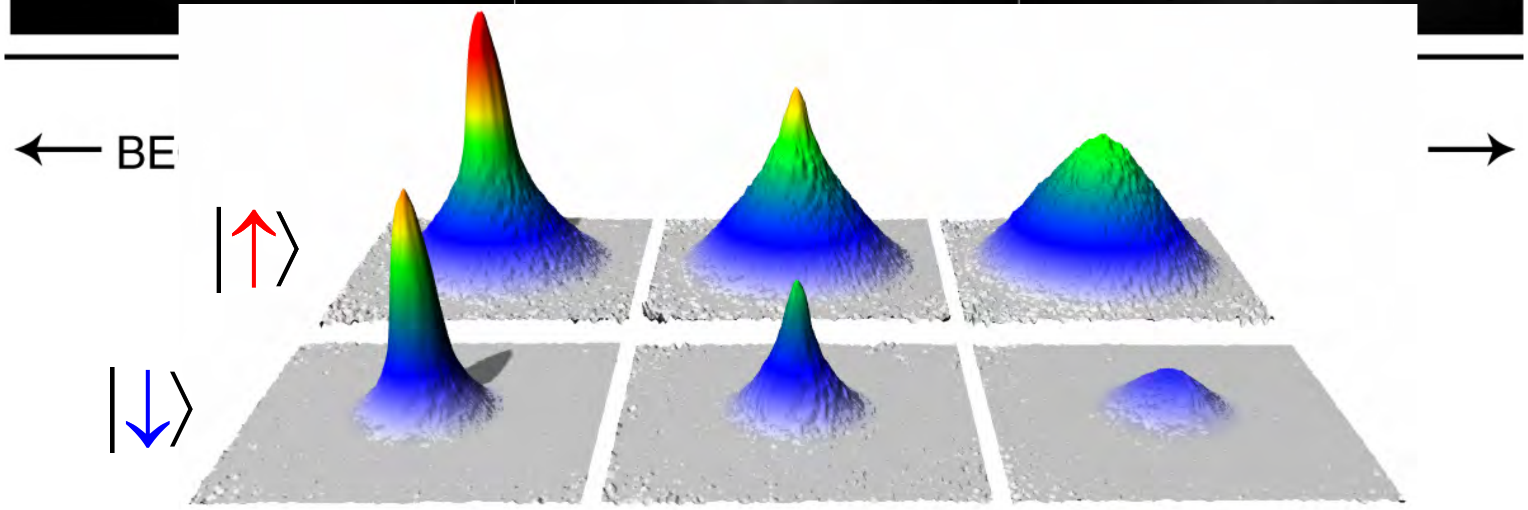
*J. Kinnunen et al., PRL **96**, 110403 (2006), Liu and Hu, Eur.Phys.Lett. **75**, 364 (2006), He et al., PRA **75**, 021602 (2007), Duan et al., cond-mat 0706.1253 (2007), Randeria et al.*

Conclusions

- Established superfluidity and phase coherence via observation of ordered vortex lattices

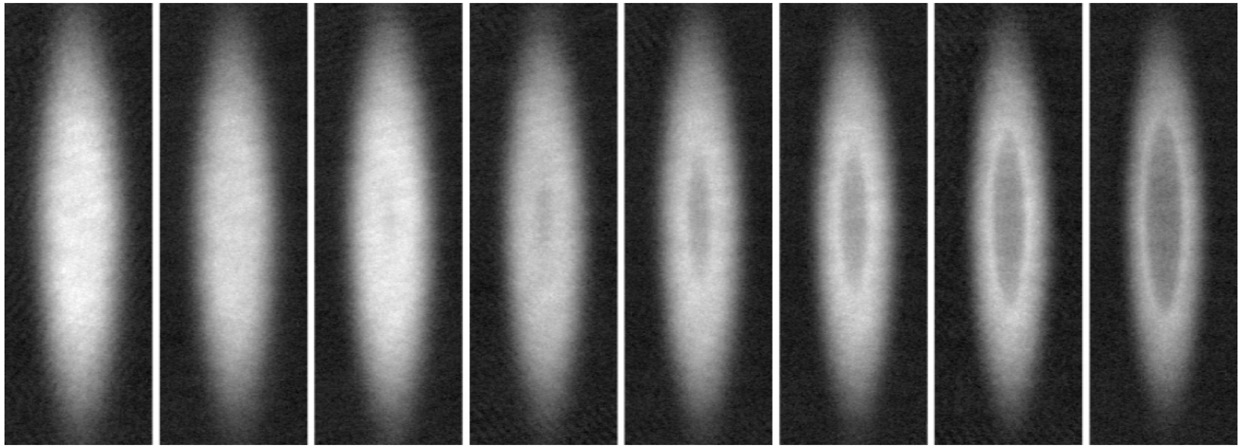


- Fermionic superfluidity with imbalanced spin populations Chandrasekhar-Clogston limit of superfluidity

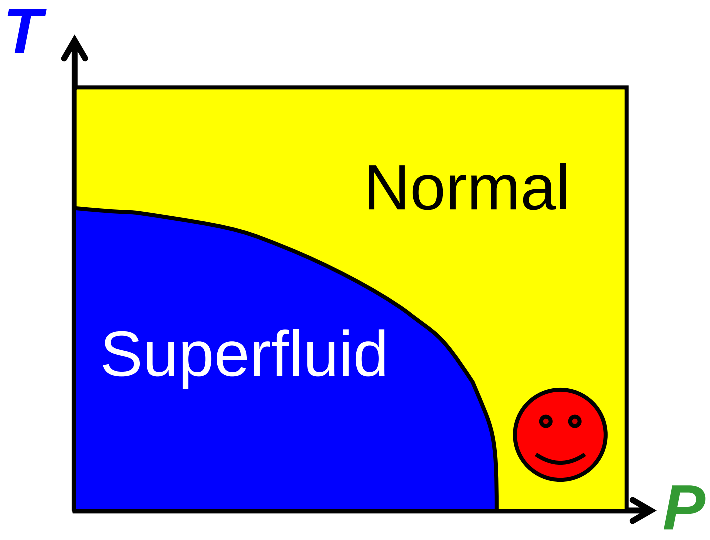


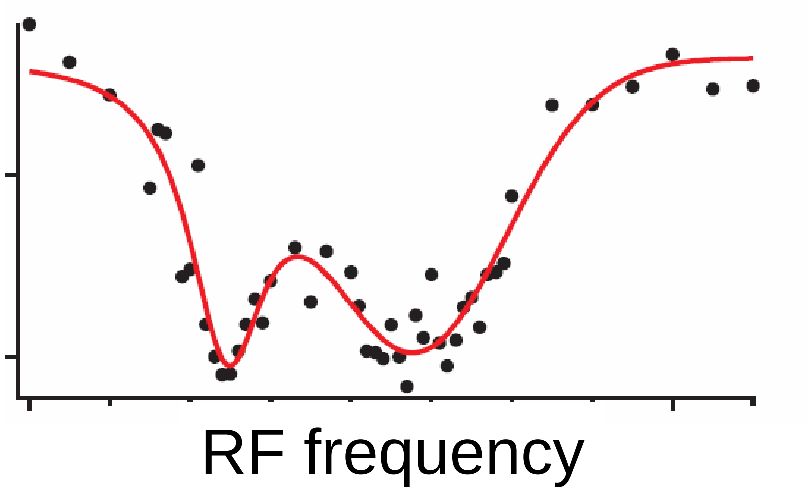
Conclusions

- Direct observation of the phase transition and phase separation



- Pairing without Superfluidity





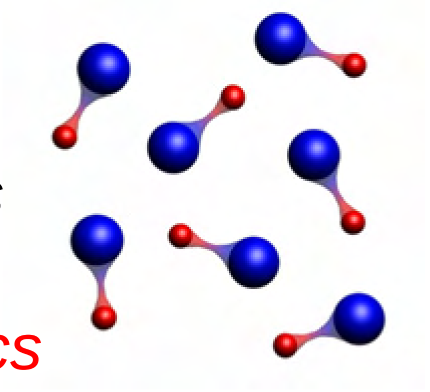
Outlook

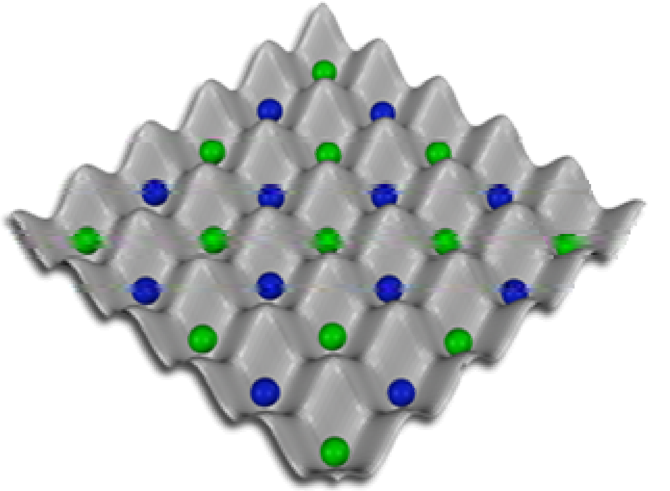
- Novel forms of superfluidity

  FFLO-State

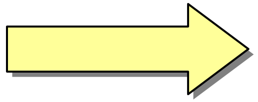
  Superfluid pairing between different species
- Fermionic mixtures in optical lattices

  Model systems for condensed matter physics

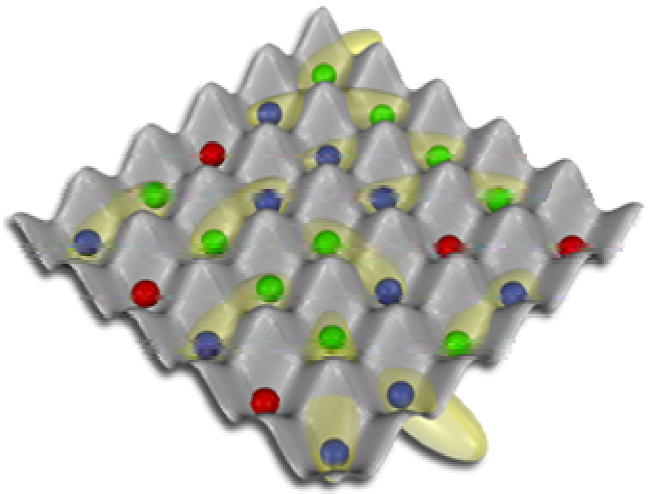




Antiferromagnetic Insulator



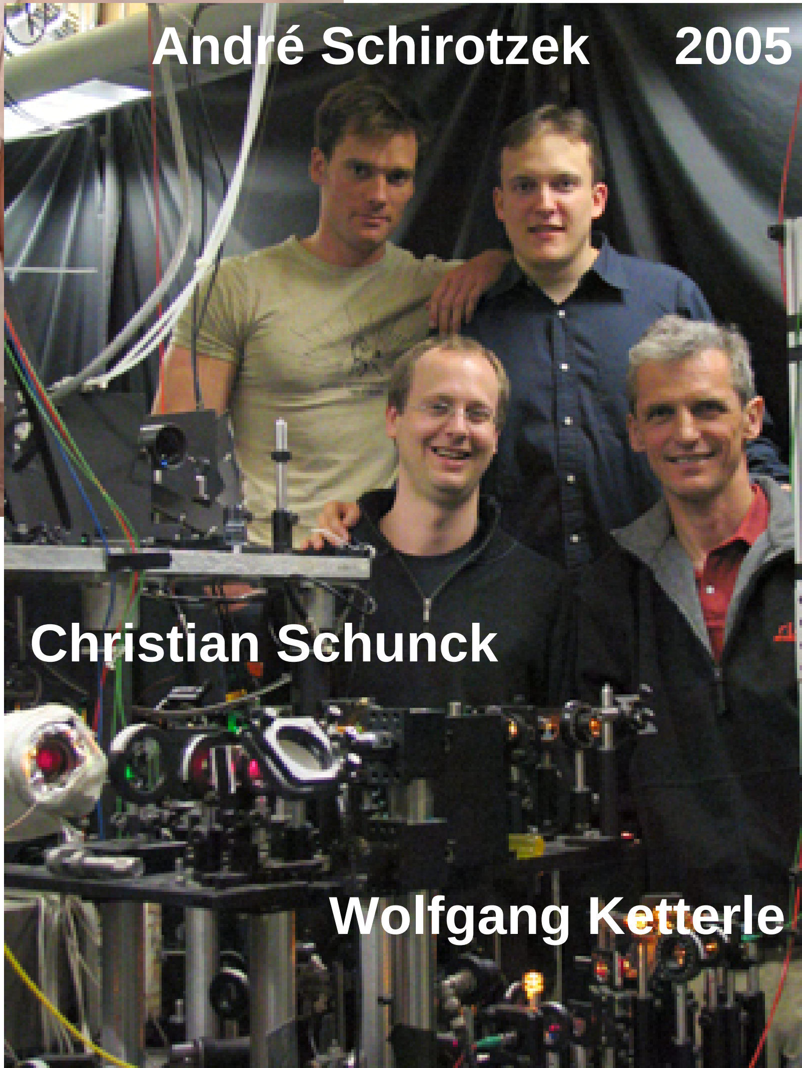
Doping



Spin liquid High-T_C Superconductor?

Use the tools and precision of Atomic Physics to study strongly correlated model systems

The team




Yong-Il Shin


Jamil Abo-Shaeer

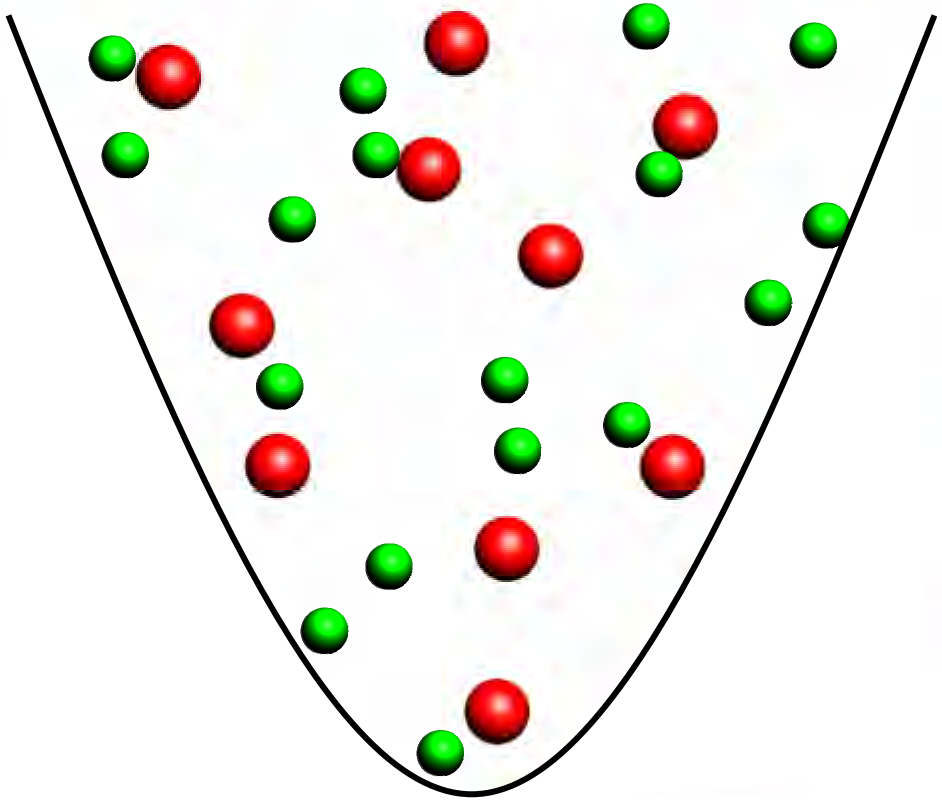
Source of ultracold fermions

- Our choice: Spin-polarized fermionic ^{6}Li
- The problem: Evaporative cooling does not work!

  At low temperatures: All but s-wave collisions frozen out

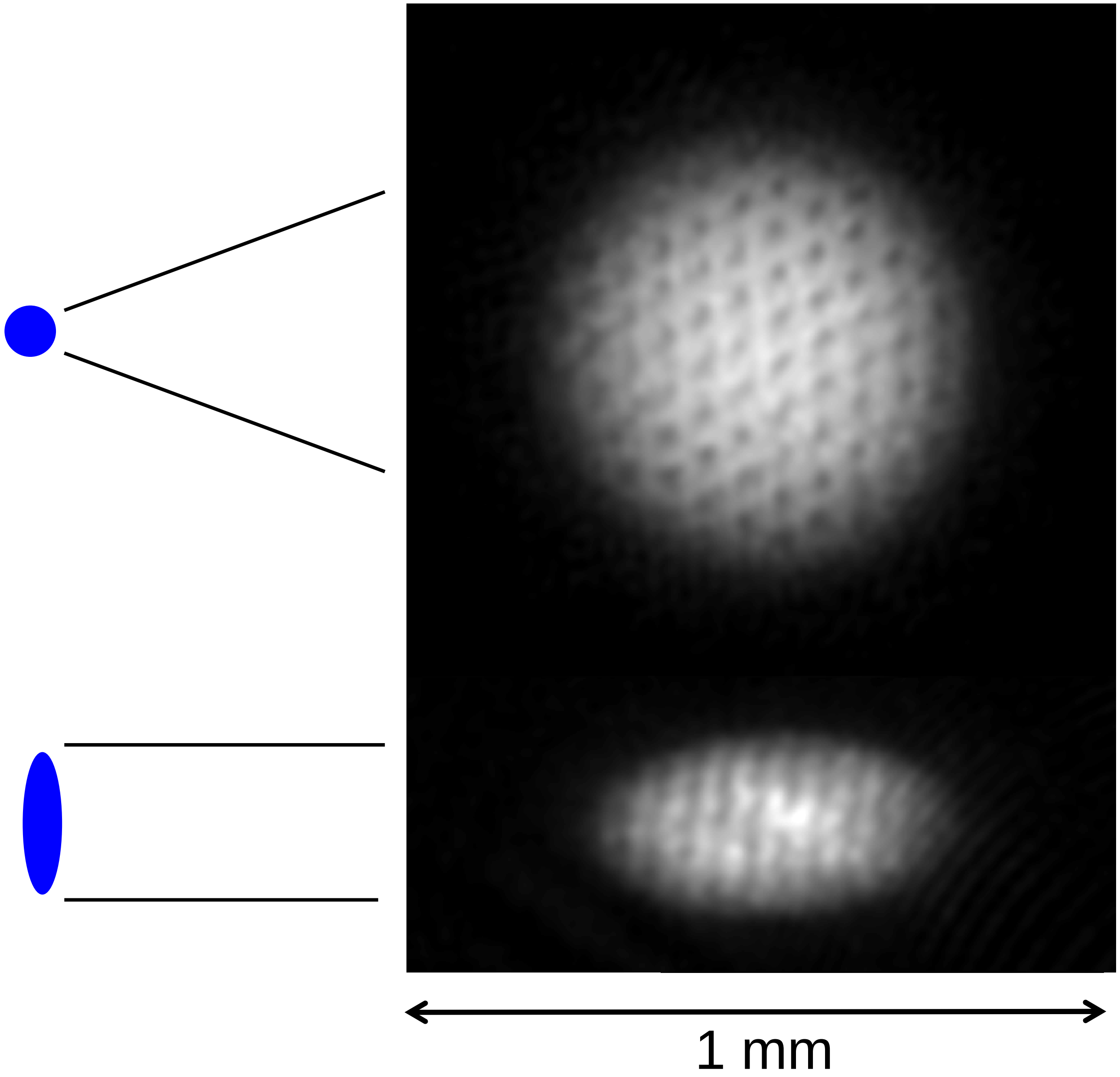
  s-wave collisions *forbidden* due to Pauli principle

  → No thermalization
- The solution: Use a coolant! *(Our case: Sodium atoms)*



In trap

After expansion



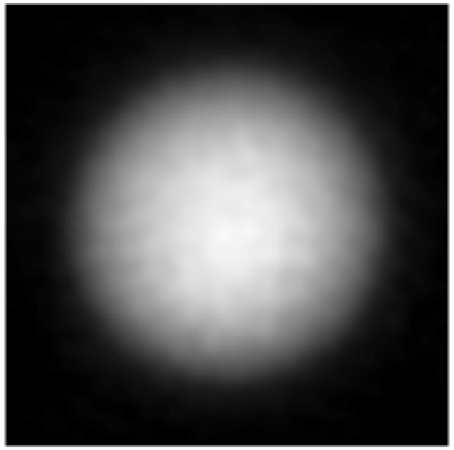
Side imaging

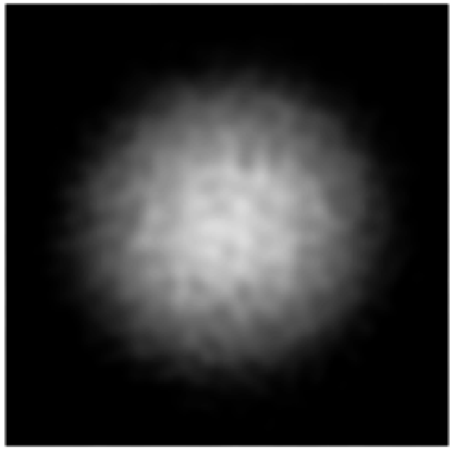
Top imaging

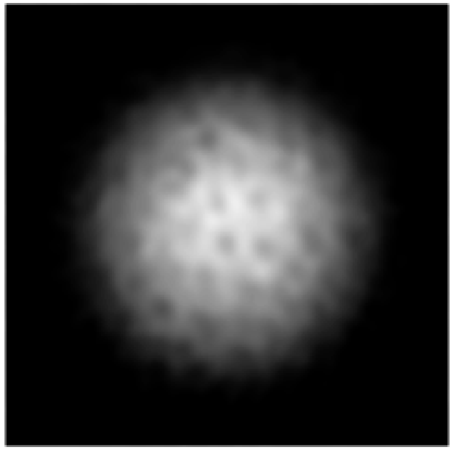
1 mm

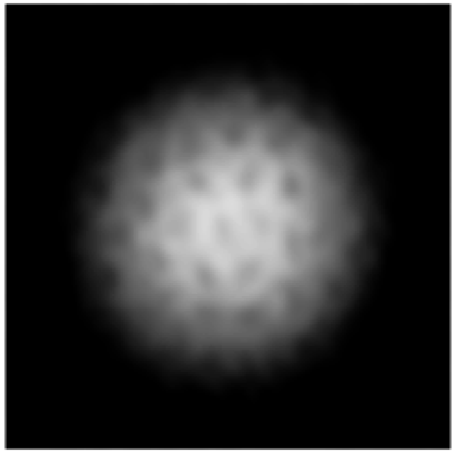
Formation of Vortex Lattice

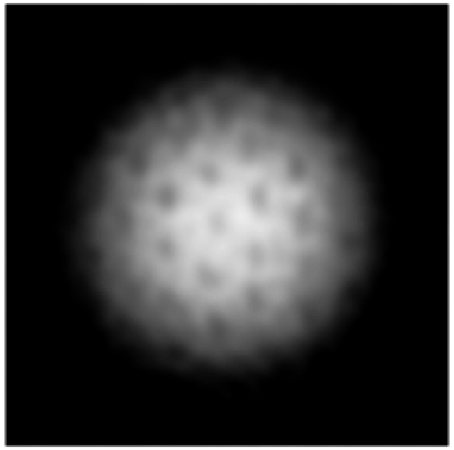
Equilibration close to resonance (812 G)

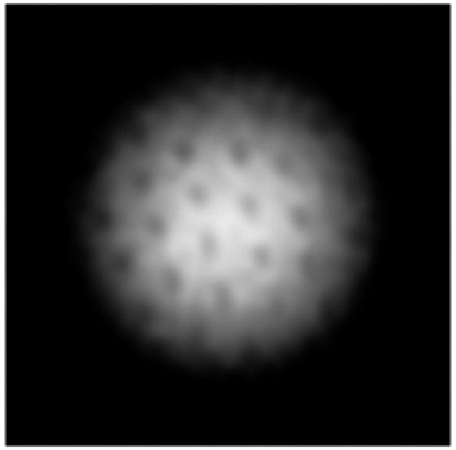

Initial state

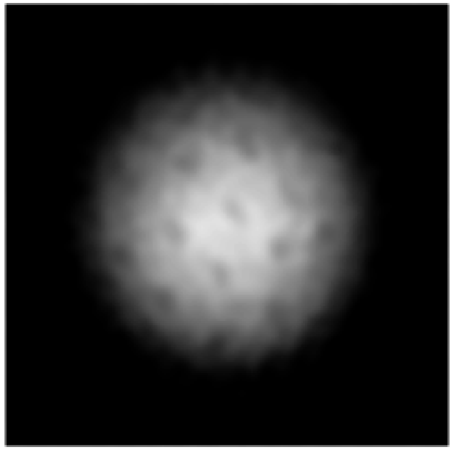

Stir + wait 40 ms

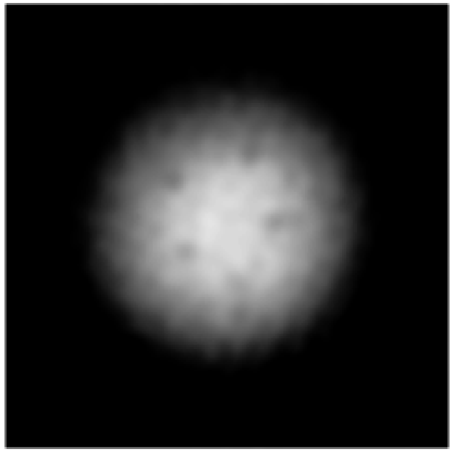

240 ms


390 ms


790 ms


1140 ms


1240 ms


2940 ms

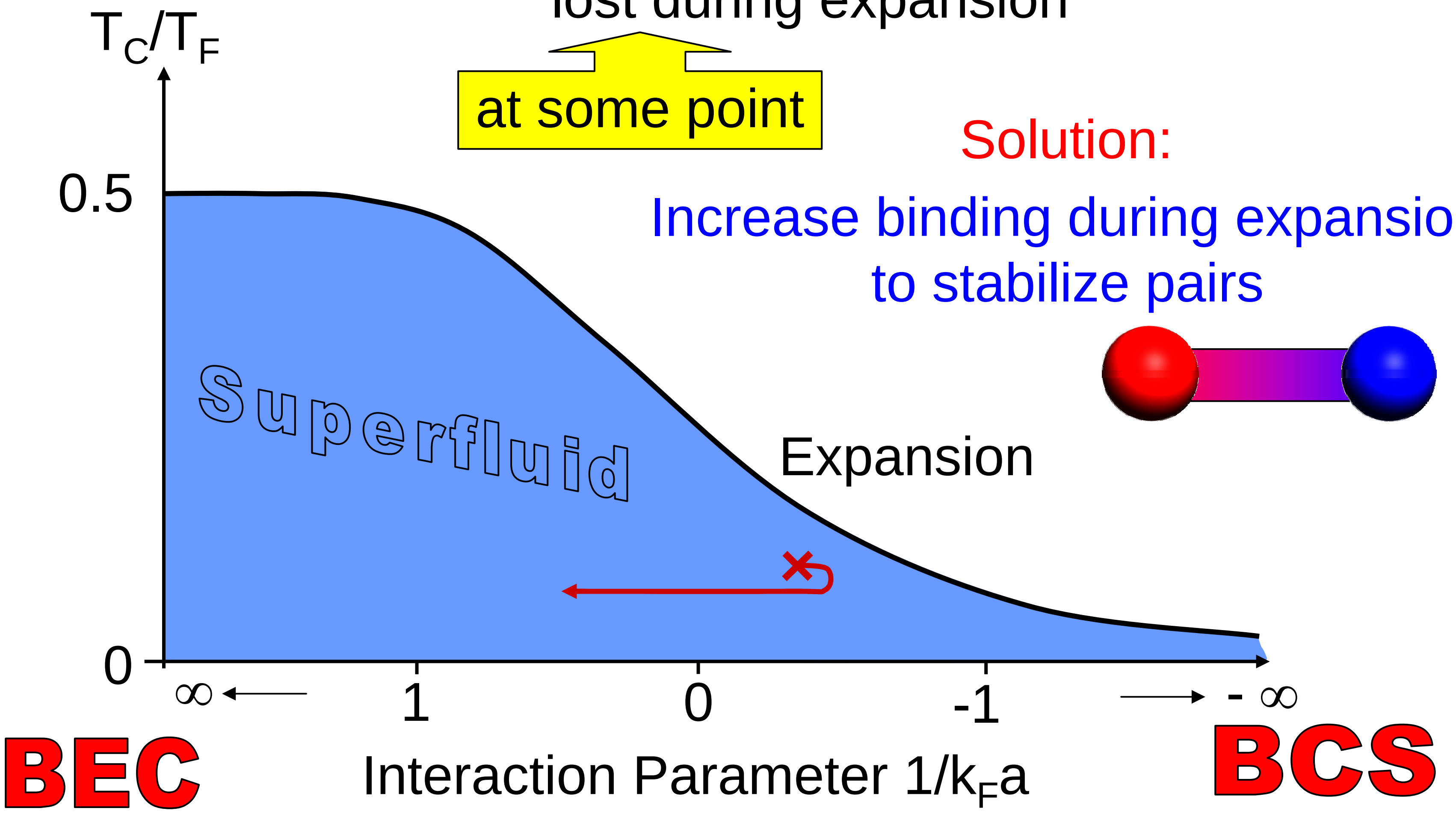
Superfluid expansion of fermion pairs

On the BCS-side, the superfluid state is fragile!

$\Rightarrow$ Pairs dissociate as cloud expands

$\Rightarrow$ Information on the COM wavefunction is lost during expansion

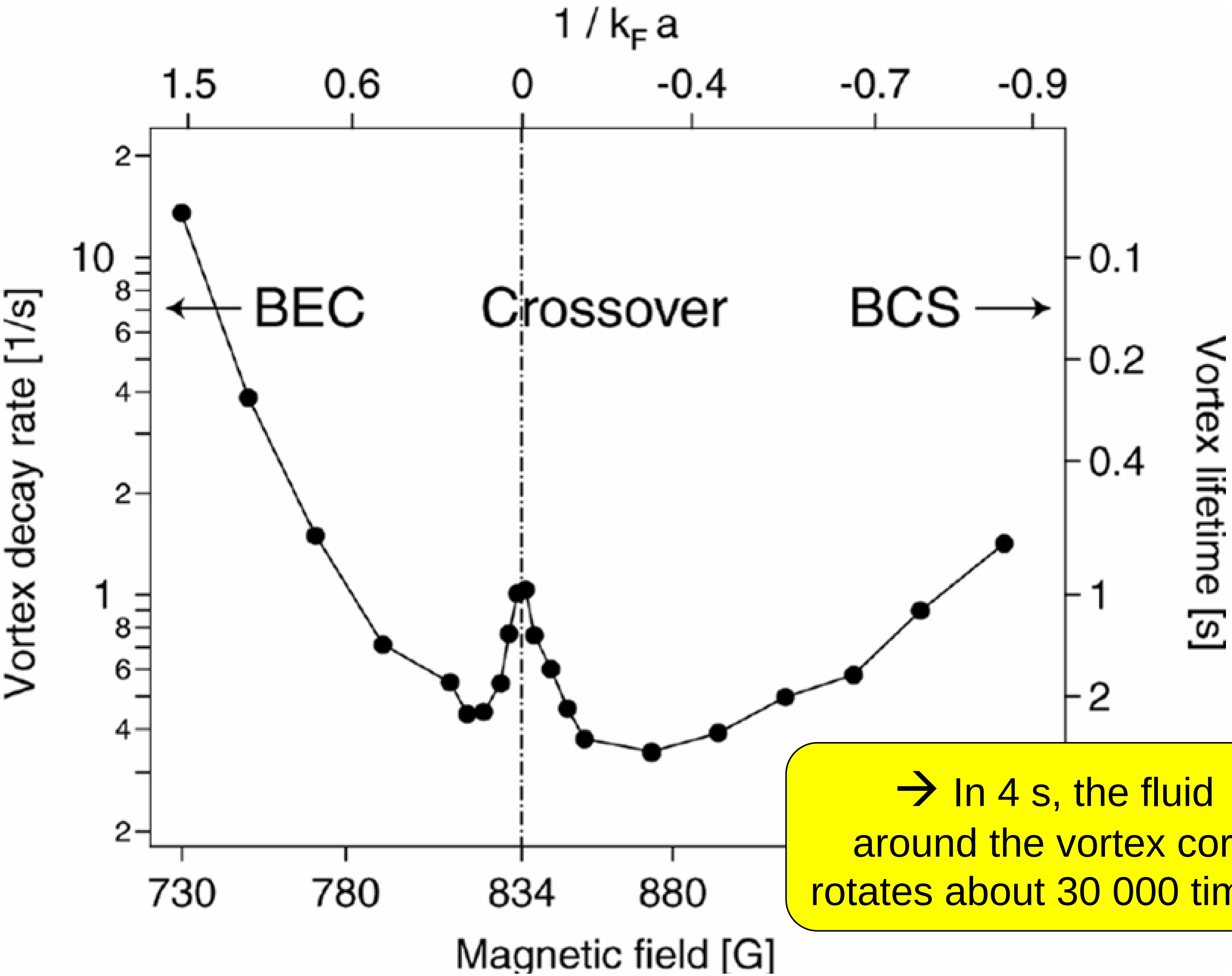
at some point



Solution:

Increase binding during expansion to stabilize pairs

Vortex lifetime in the Crossover



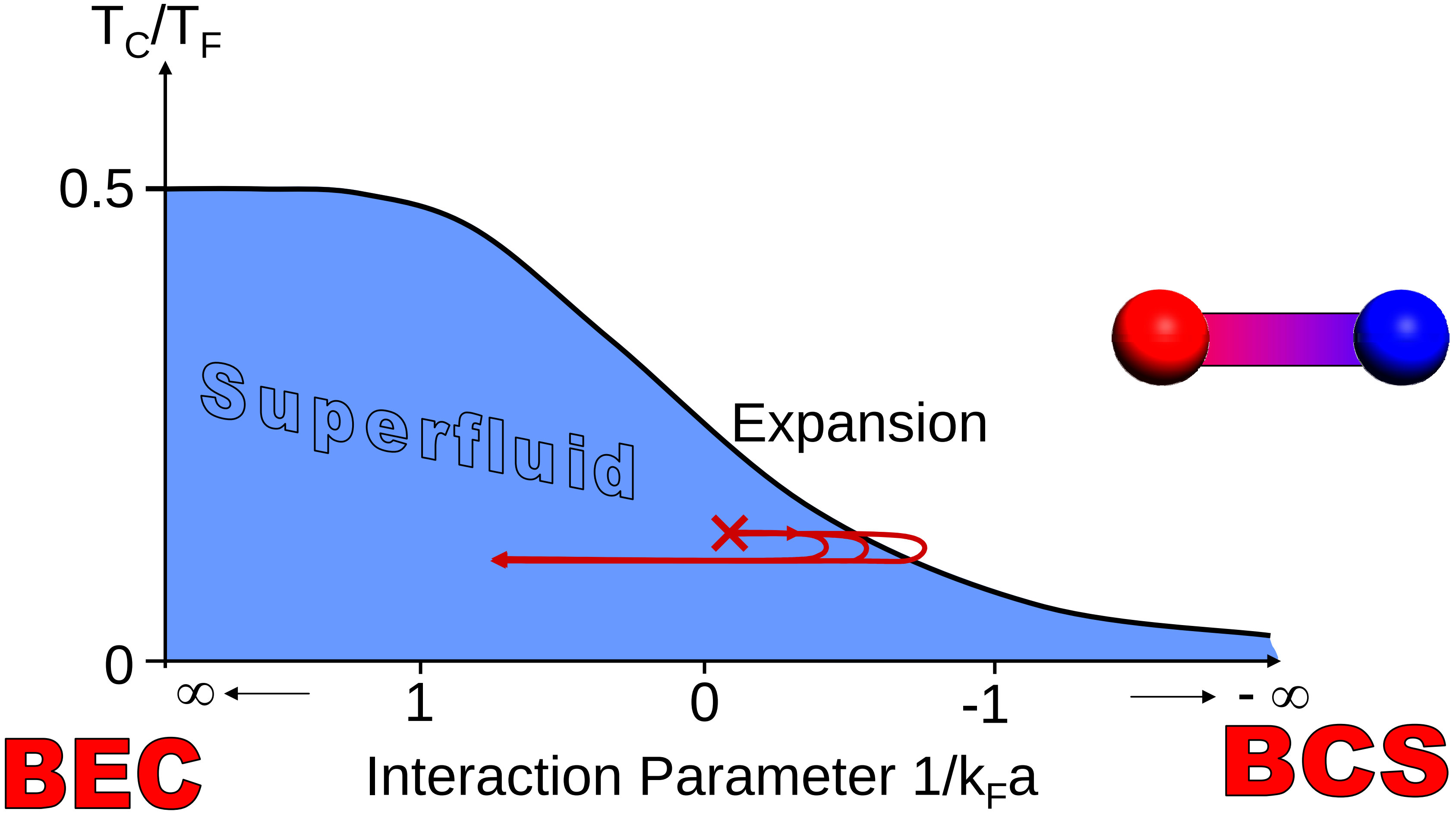
→ In 4 s, the fluid around the vortex core rotates about 30 000 times!

Superfluid expansion of fermion pairs

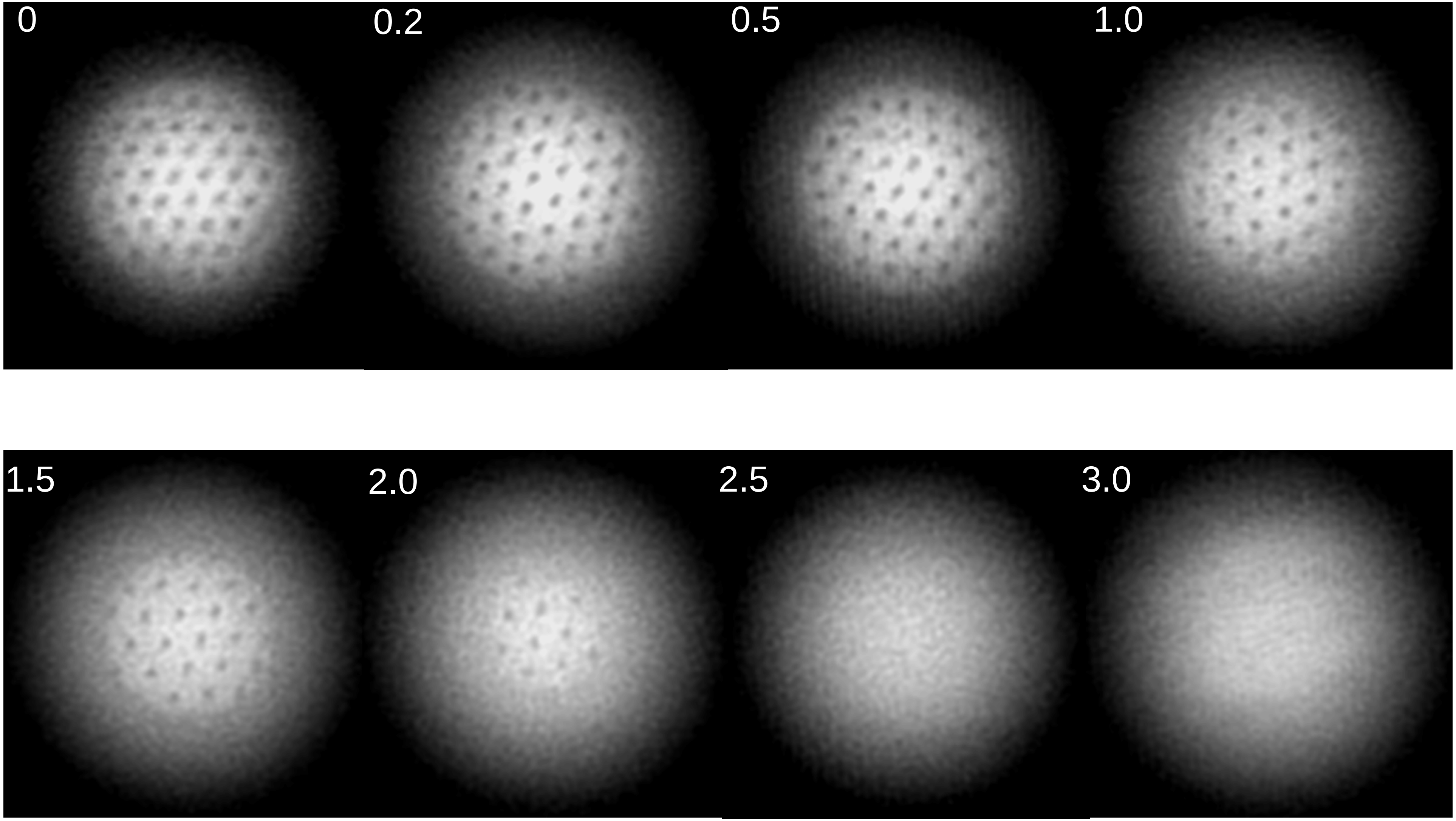
On the BCS-side, the superfluid state is fragile!

We can cross the phase boundary during expansion!

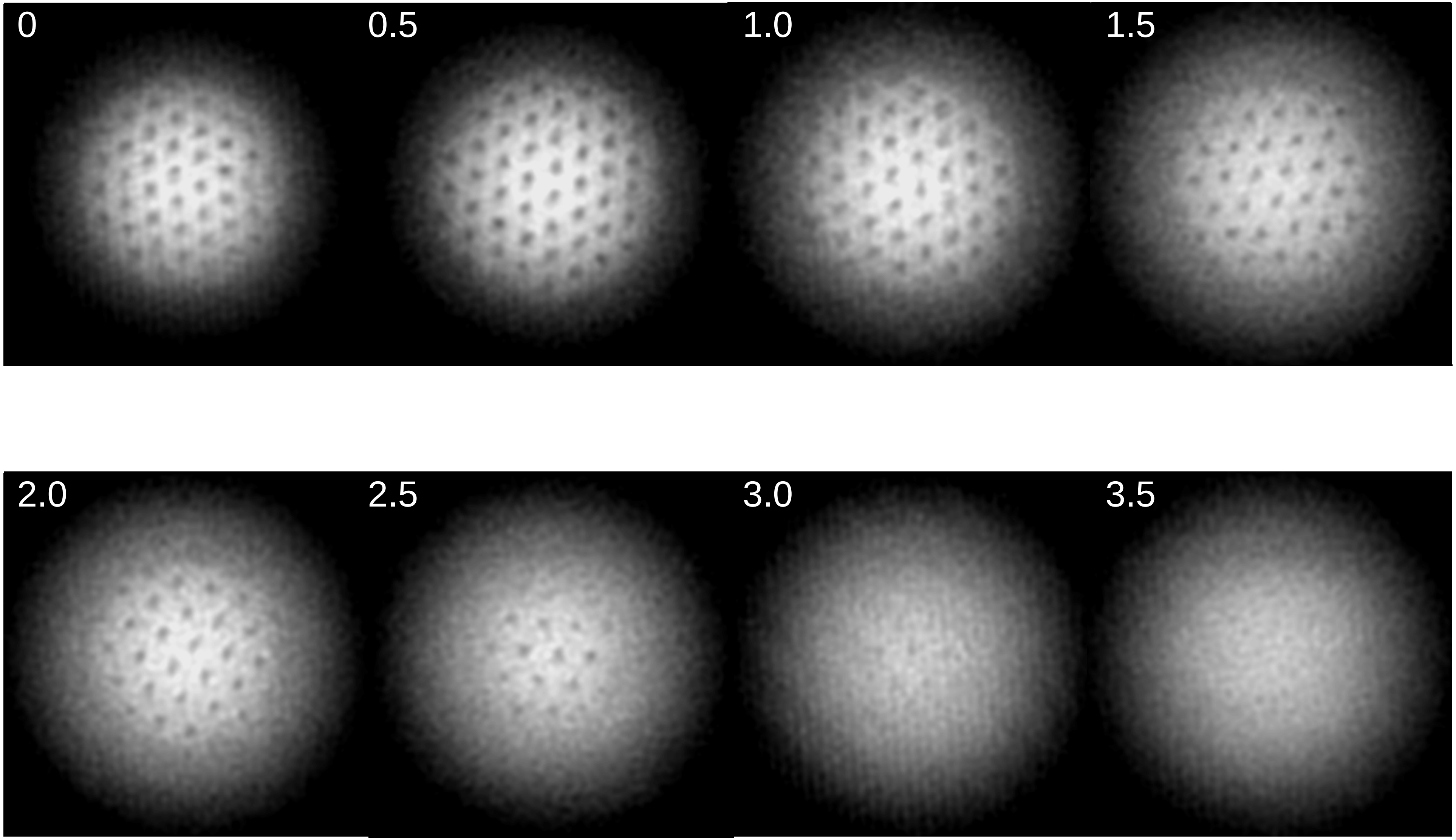
To observe this: Delay the “rescue” of fermion pairs



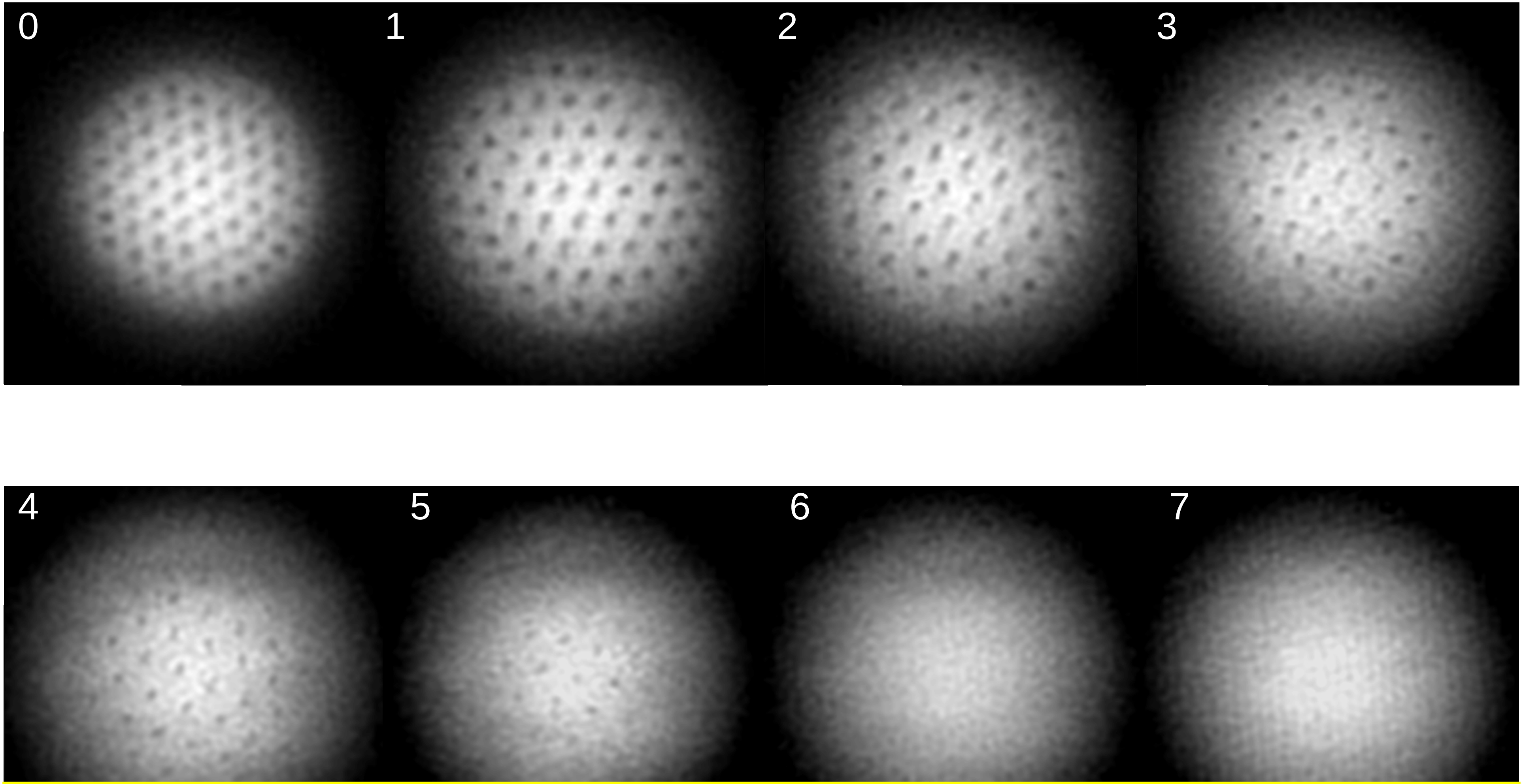
Pair breaking in TOF [ms] 930 G (small *a*)



Pair breaking in TOF [ms] 912 G (medium *a*)



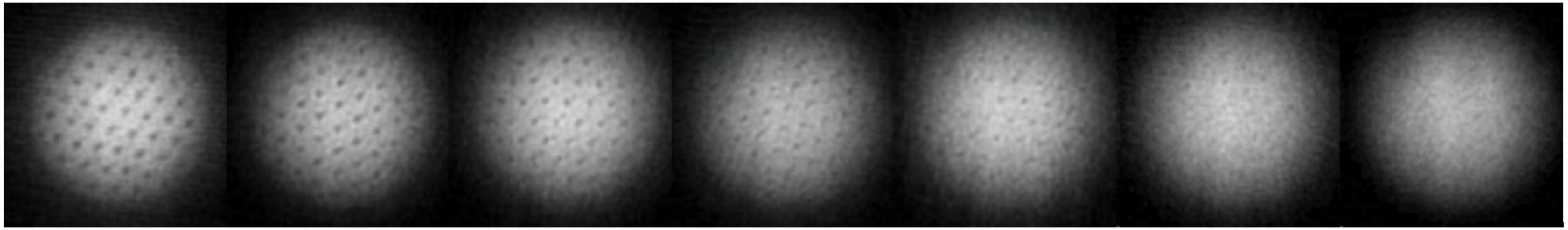
Pair breaking in TOF [ms] 875 G (large *a*)

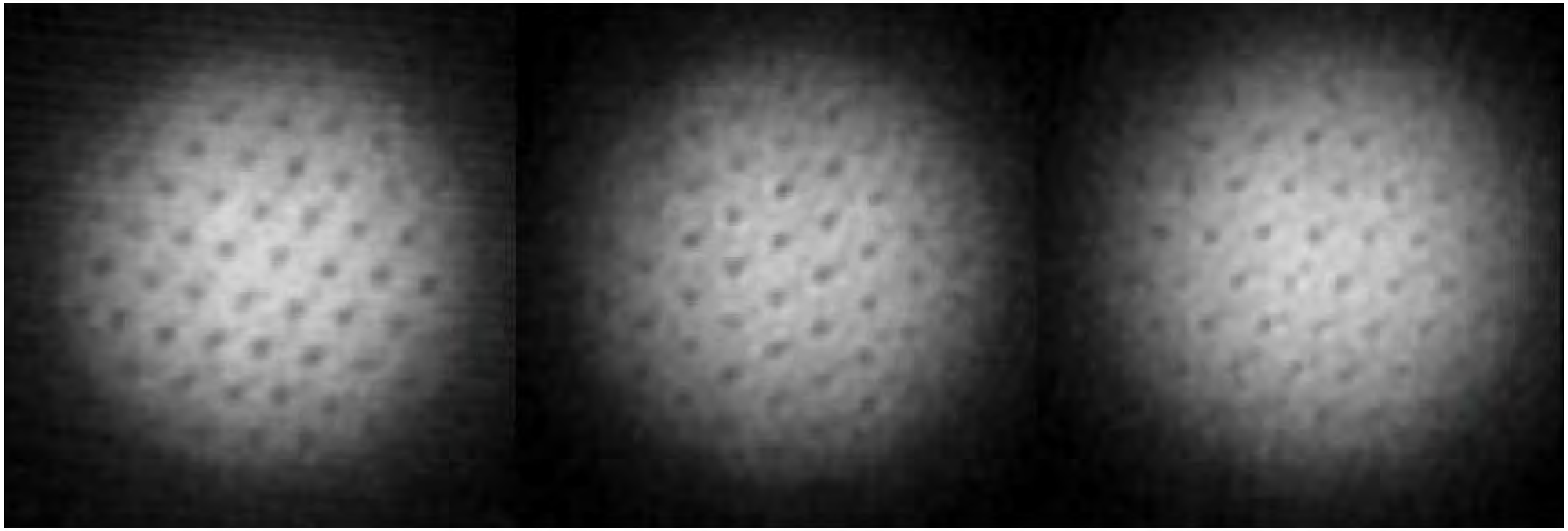


Fermionic superfluid survives expansion!
Eventual breakdown at $k_F\ |a| \approx 1$

Superfluid expansion of fermion pairs on resonance

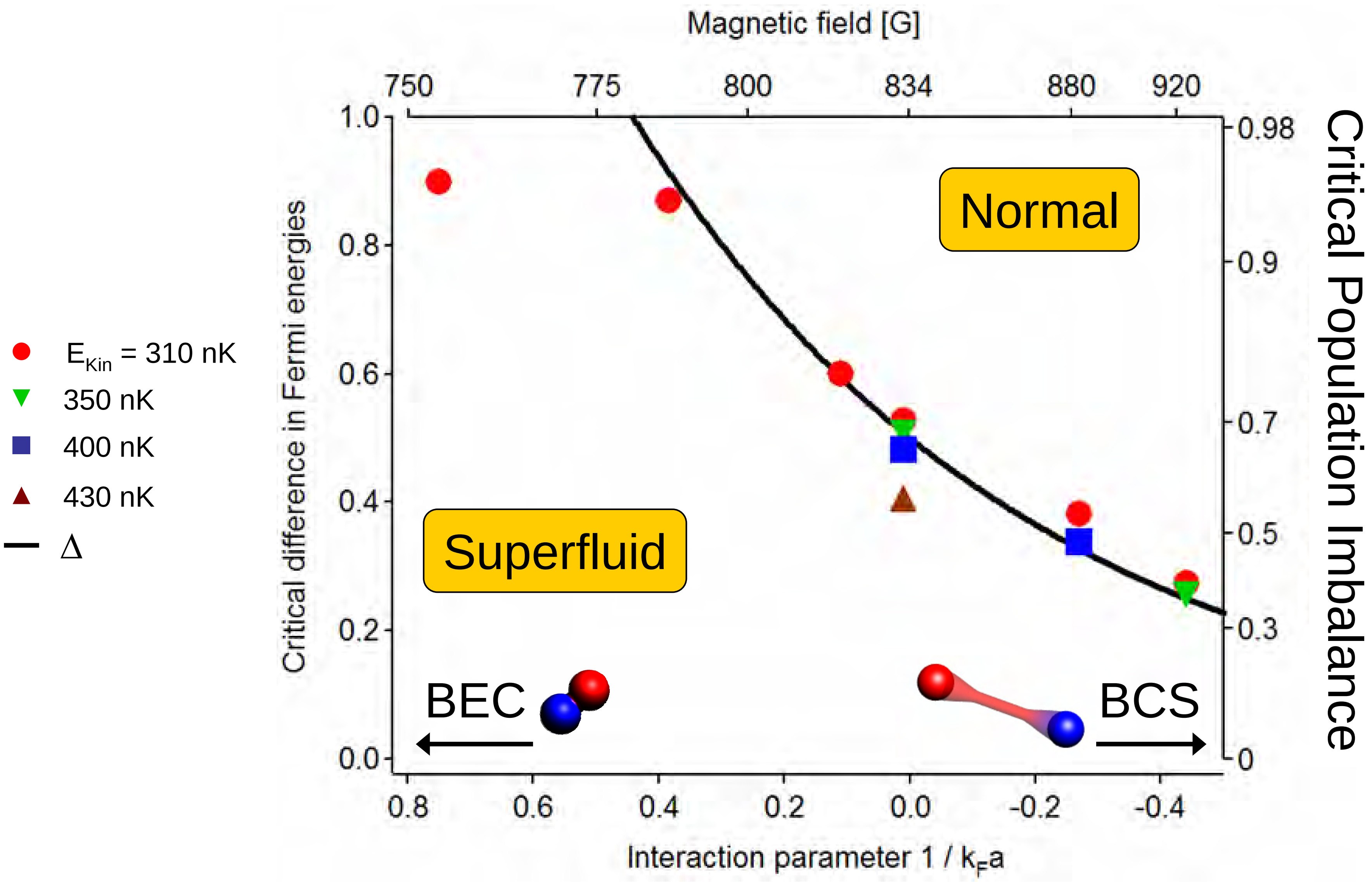
When $a \rightarrow \pm\infty$, T/T_C is *constant* during expansion





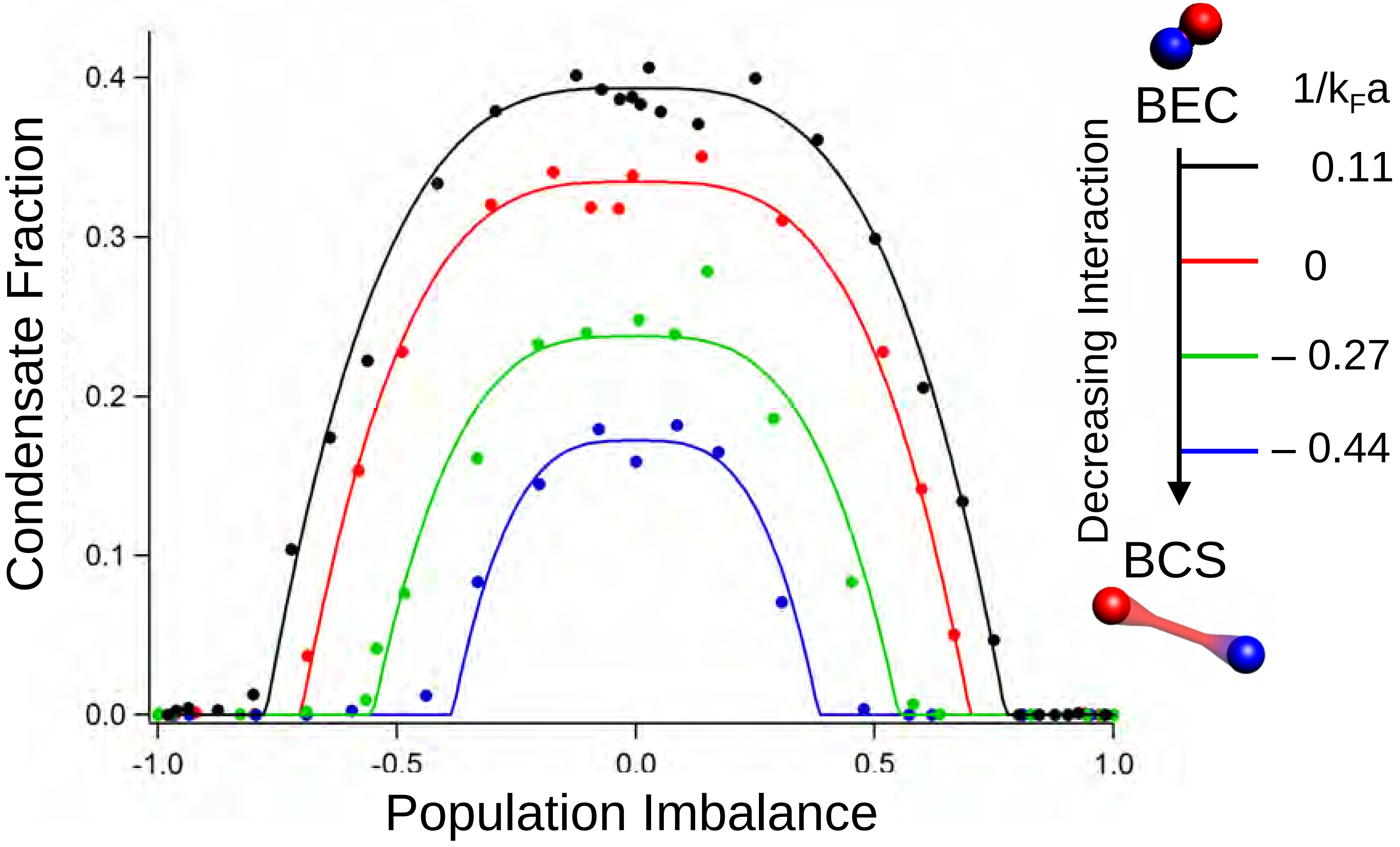
Vortices survive, but gradually fill in → Vortex cores support more and more bound states for normal particles

Phase Diagram for Unequal Mixtures



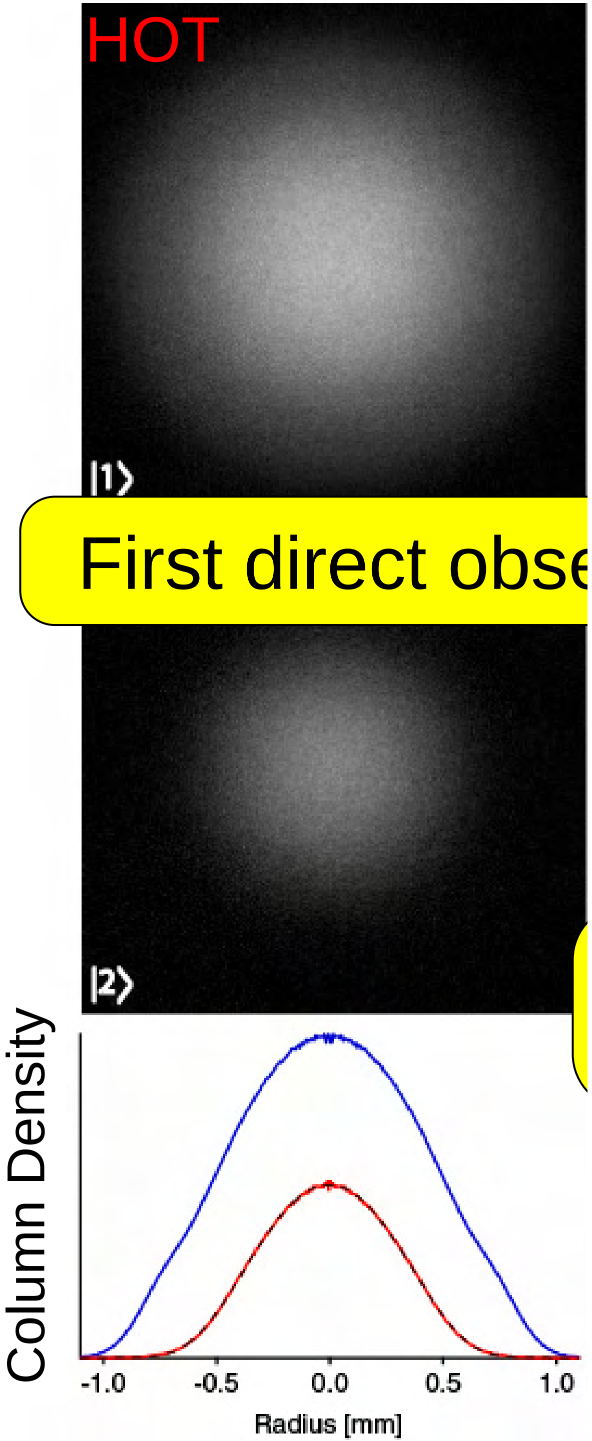
Breakdown: Critical mismatch in Fermi energies $\Delta E_F \approx$ Gap Δ

The Window of Superfluidity



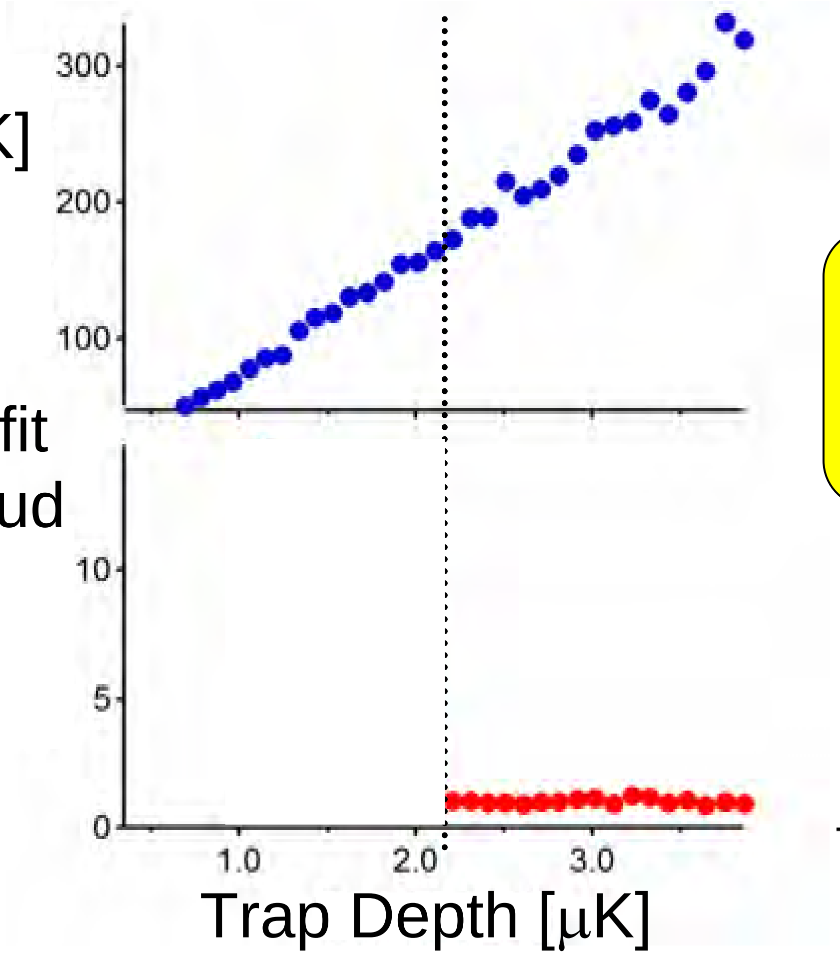
Superfluidity is <u>robust</u> in the strongly interacting regime!

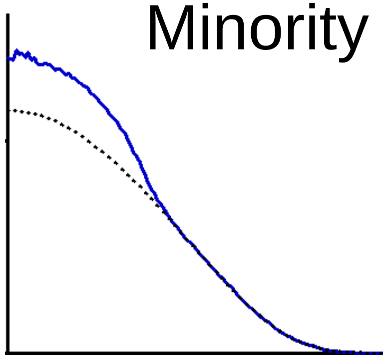
M.W. Zwierlein, A. Schirotzek, C.H. Schunck, W. Ketterle,
Science 311, 492 (2006)



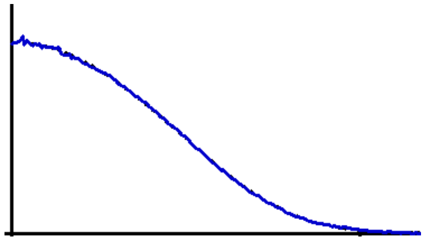
First direct obse

Direct Observation of the Phase Transition





Superfluid



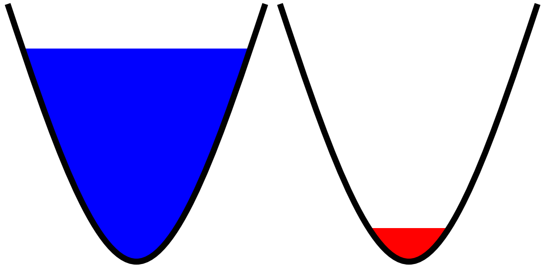
Normal

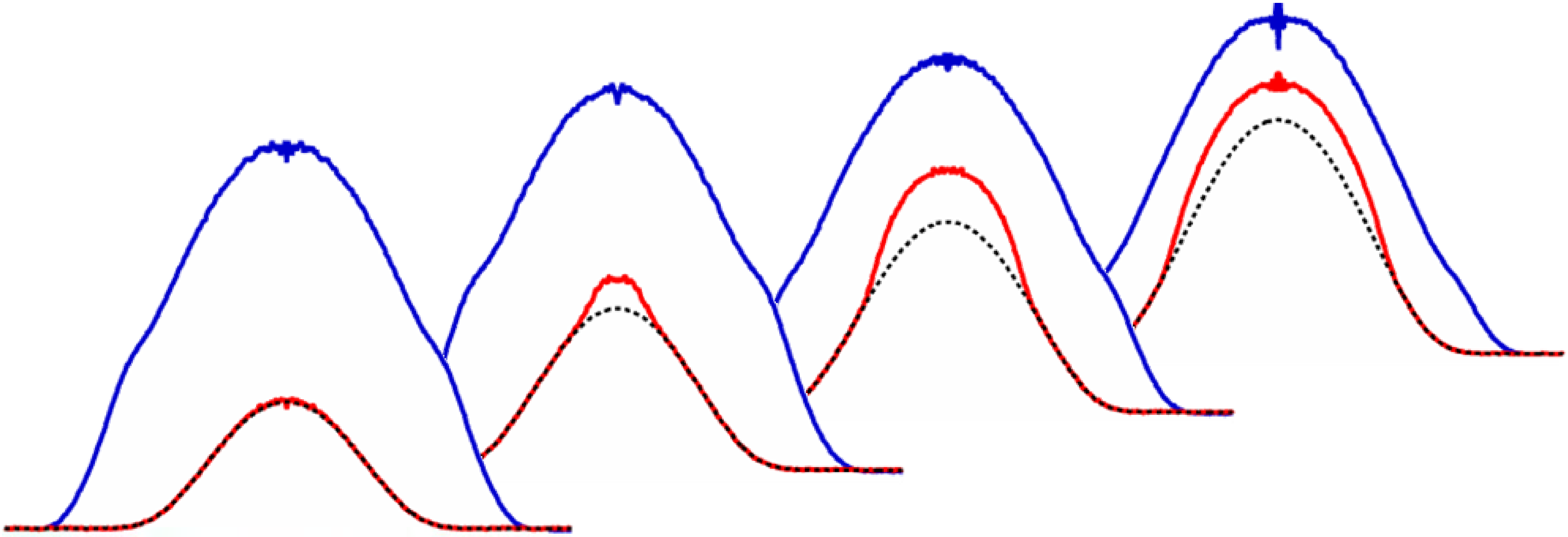
Transition at
$\delta = 59(3)\%$
$T/T_{F,0} = 0.12(2)$

M.W. Zwierlein, C.H. Schunck, A. Schirotzek, W. Ketterle,
Nature 442, 54 (2006)

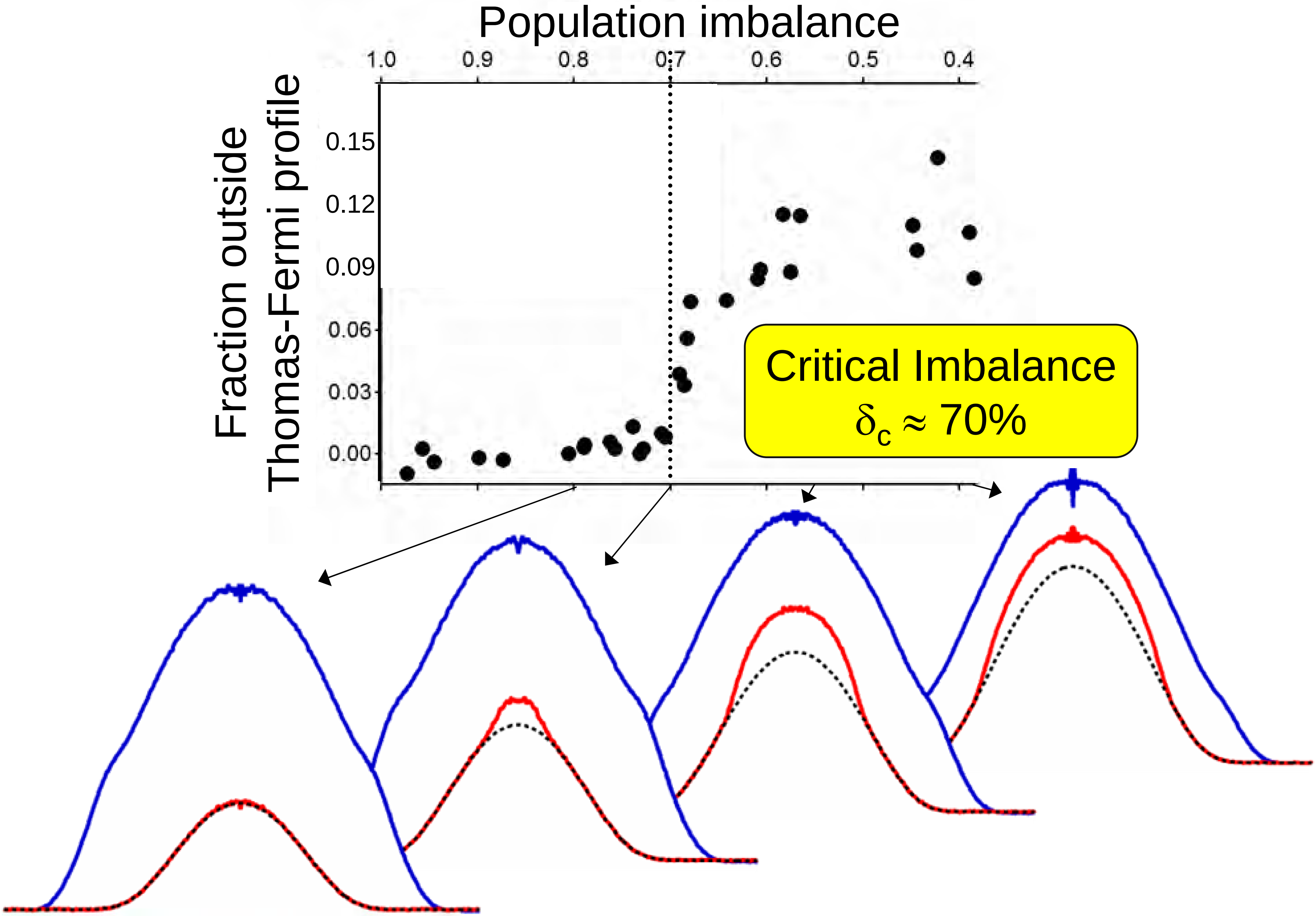
A condensate emerges from the Fermi sea

Increase atom number in smaller cloud





A condensate emerges from the Fermi sea

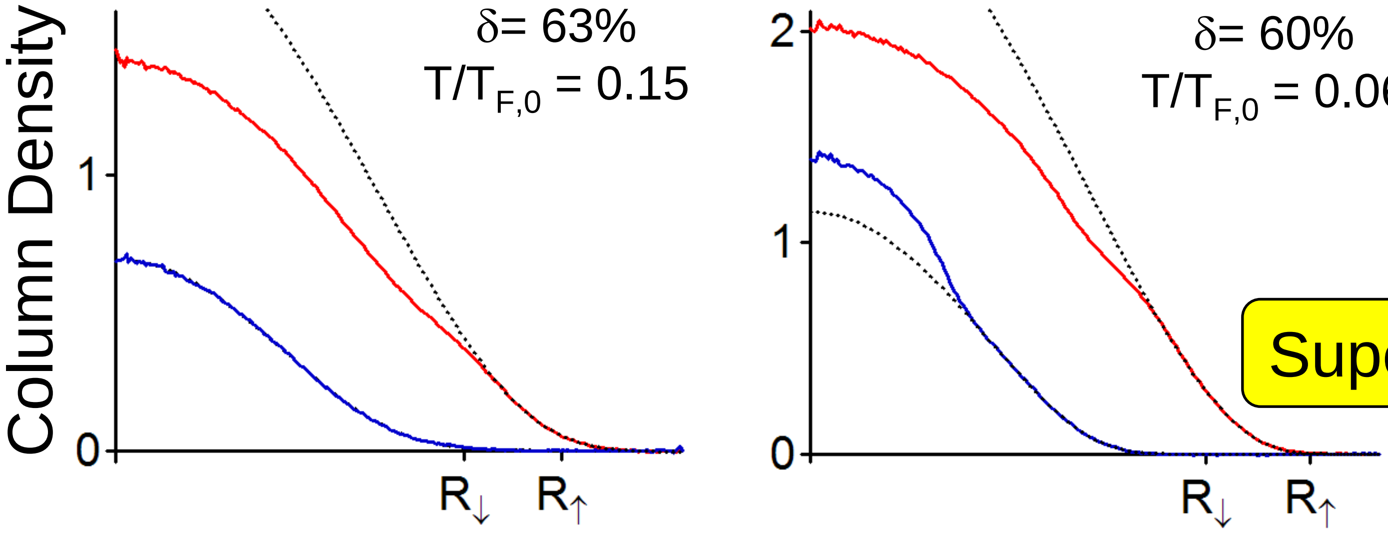


Critical Imbalance

$\delta_c \approx 70\%$

Density Profiles on Resonance: Unequal Mixtures

Normal

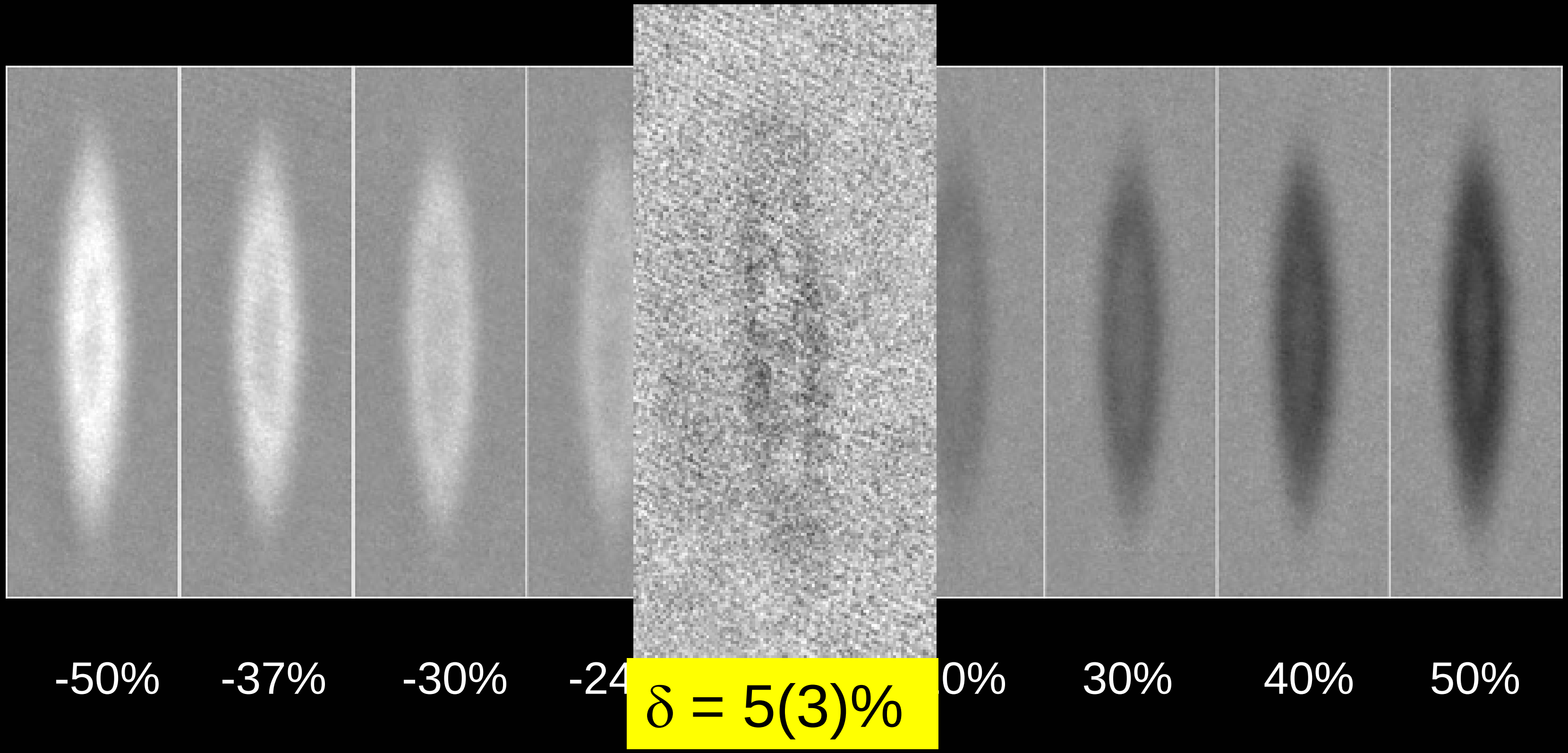


Superfluid

Depletion of excess fermions at the position of the condensate

→ Superfluid expells normal state; Phase separation?

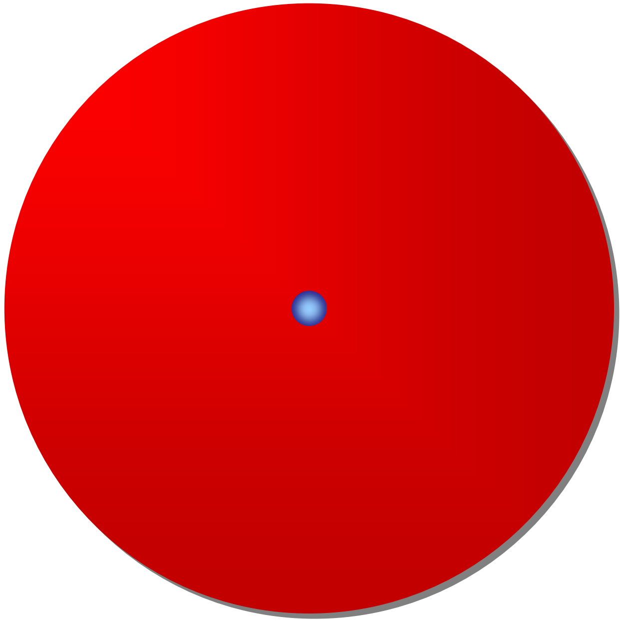
Shell Structure in an Imbalanced Fermi Gas

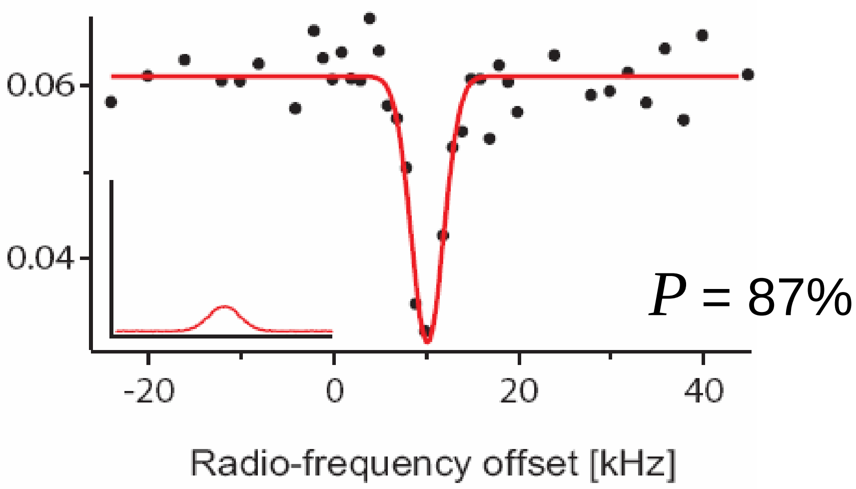


Y. Shin, M.W. Zwierlein, C.H. Schunck, A. Schirotzek, W. Ketterle,
PRL 97, 030401 (2006)

Limit of high imbalance

A single $|\downarrow\rangle$ atom immersed in a $|\uparrow\rangle$ cloud with unitarity limited interactions





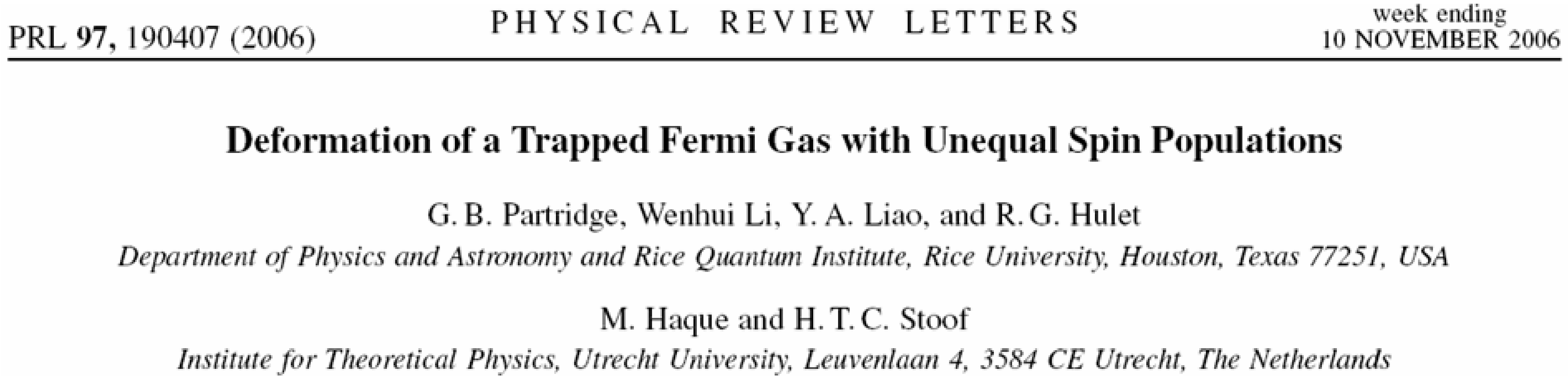
$$\boxed{\delta\nu_{\text{exp}} = -0.38}$$

Binding energy must be universal

$$\mu_\downarrow = \gamma\, E_{F\uparrow} \qquad \boxed{\gamma = -0.6}$$

F. Chevy PRA **74**, 063628 (2006), Variational Cooper pair Ansatz

C. Lobo, A. Recati, S. Giorgini, S. Stringari, PRL **97**, 200403 (2006), Monte-Carlo

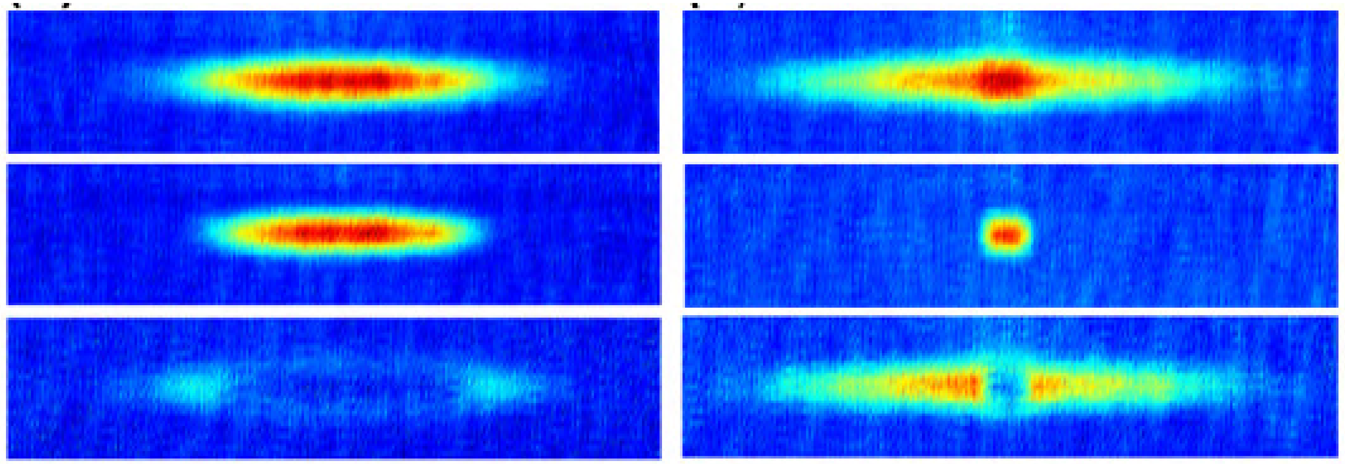


PRL **97,** 190407 (2006)
PHYSICAL REVIEW LETTERS
week ending
10 NOVEMBER 2006

Deformation of a Trapped Fermi Gas with Unequal Spin Populations

G. B. Partridge, Wenhui Li, Y. A. Liao, and R. G. Hulet
Department of Physics and Astronomy and Rice Quantum Institute, Rice University, Houston, Texas 77251, USA

M. Haque and H. T. C. Stoof
Institute for Theoretical Physics, Utrecht University, Leuvenlaan 4, 3584 CE Utrecht, The Netherlands



majority

minority

difference

Lower

higher

Imbalance

Different system:

Very elongated trap (aspect ratio of 45 vs. 6)
Very small samples (200,000 vs. 10 million atoms)

Very strong finite size and surface energy effect
Strong deformation of the cloud

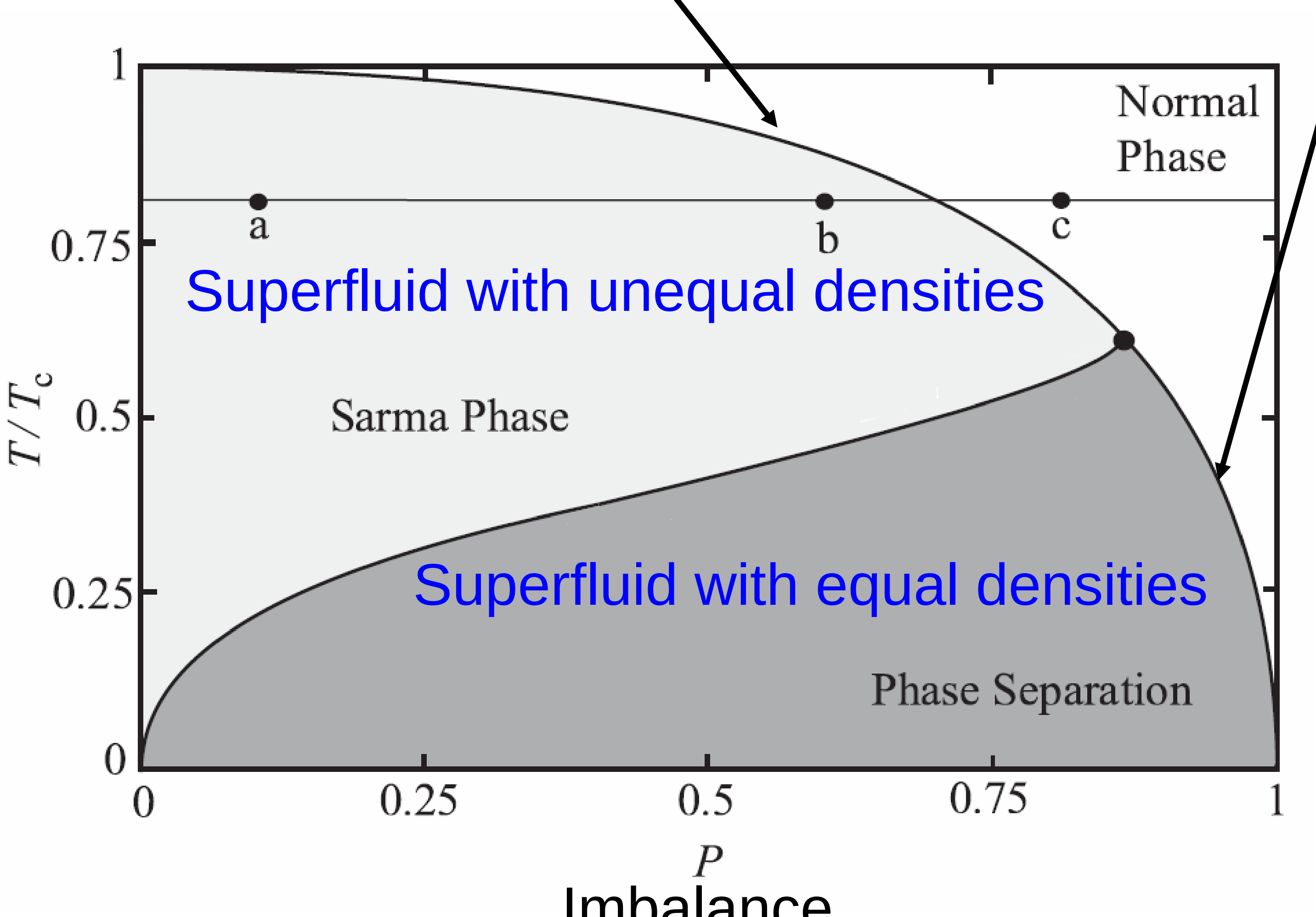
All conclusions are based on spatial deformations of the cloud

no observations of pair condensates
no observations of superfluidity (vortices)
no measurements in ballistic expansion
no observation of any phase transition vs. temperature
(data taken at only two different temperatures)

Phase separation

Second order phase transition

First order



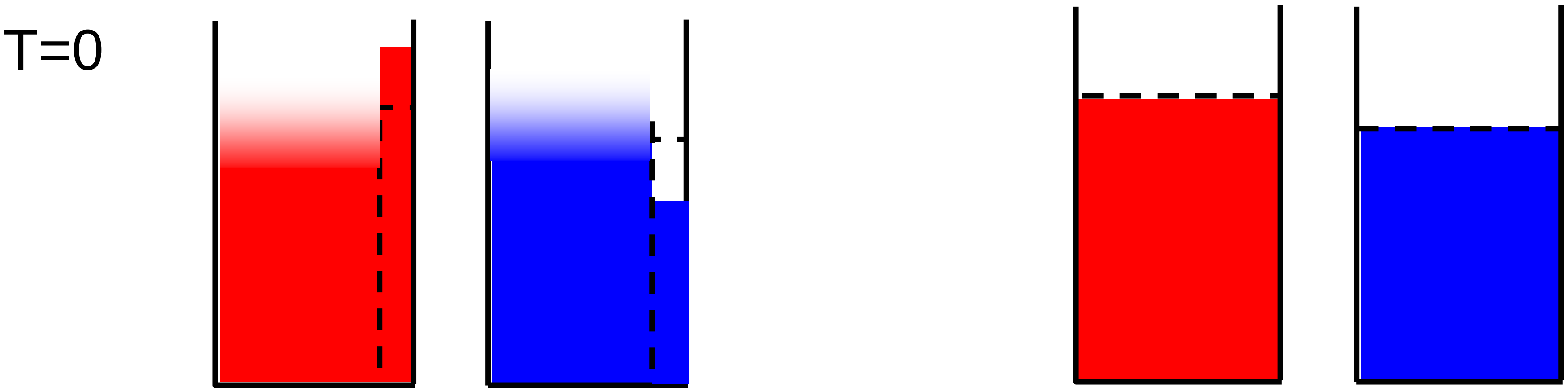
Superfluid with unequal densities

Superfluid with equal densities

Temperature

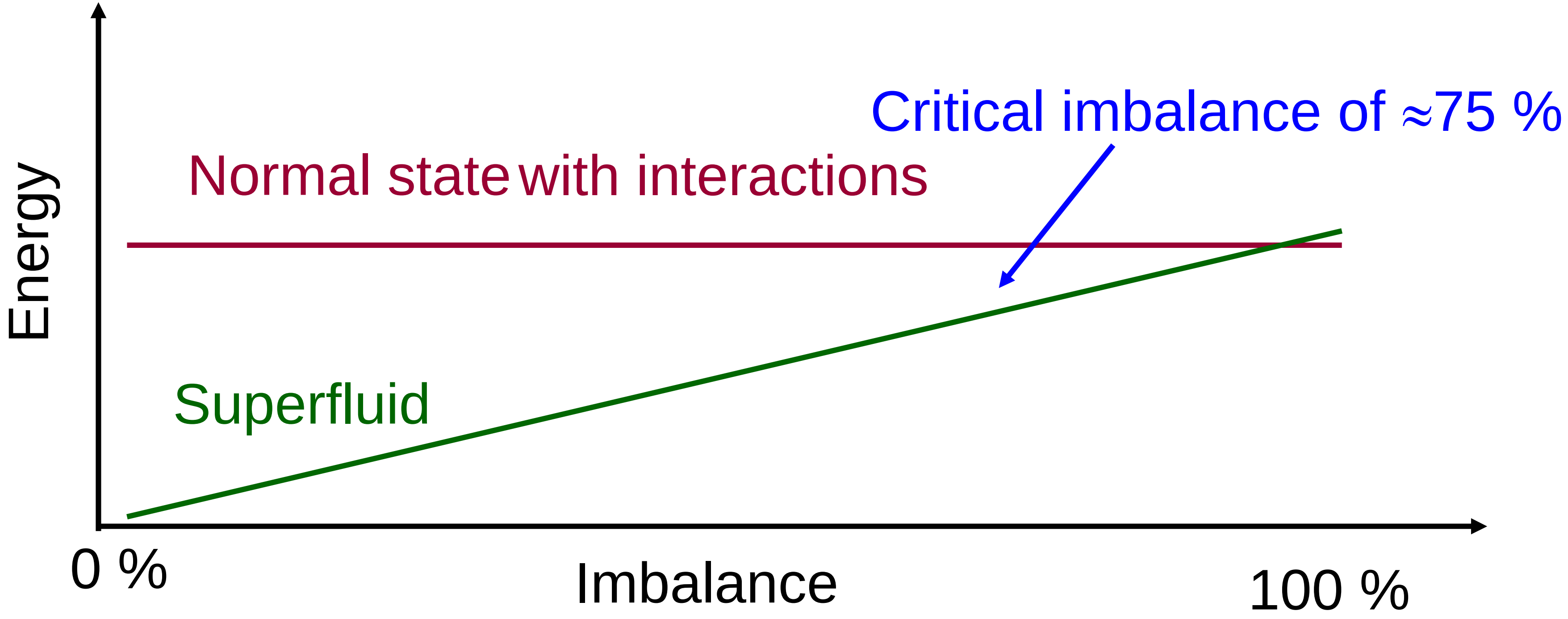
Imbalance

K.B. Gubbels, M.W.J. Romans, and H.T.C. Stoof, PRL 97, 210402 (2006)

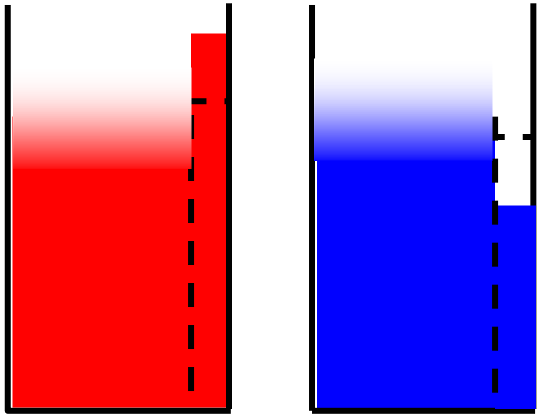


Superfluid state

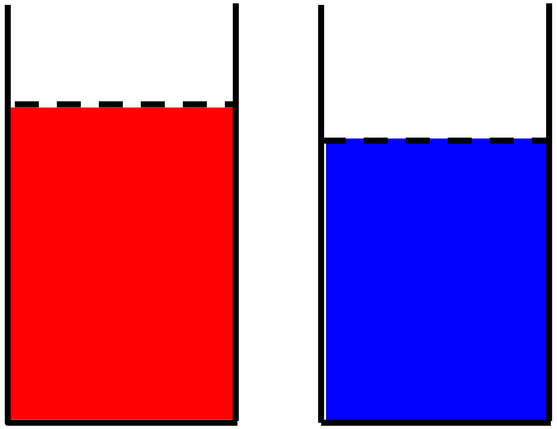
Normal state



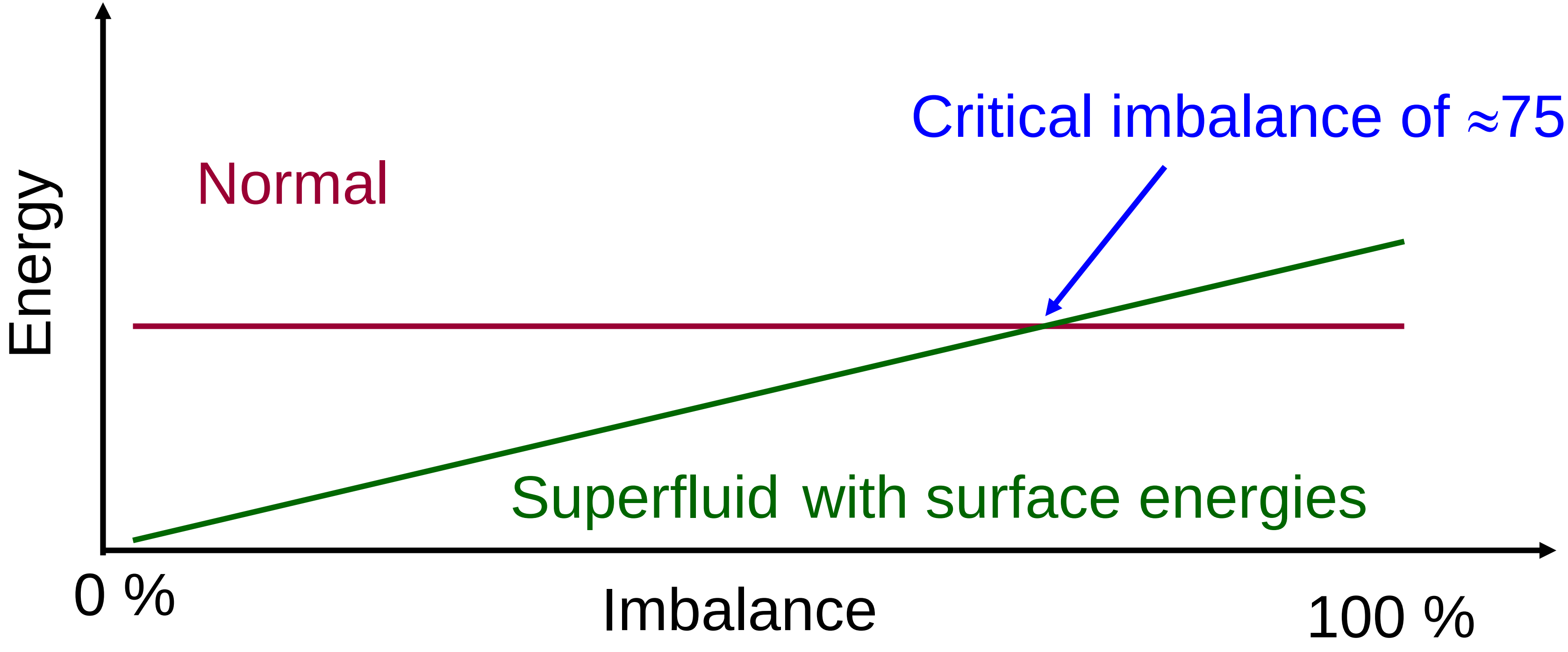
T=0

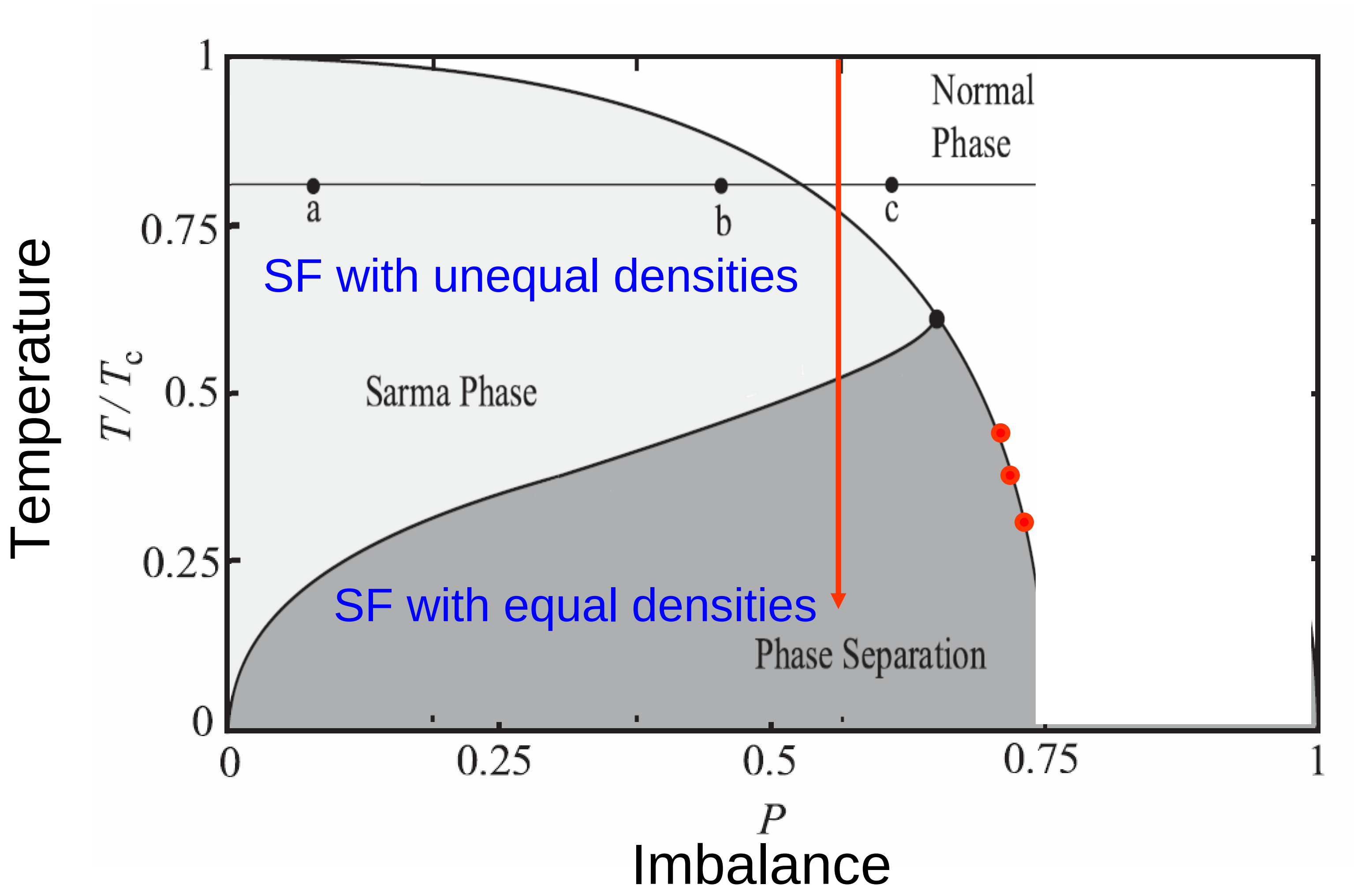


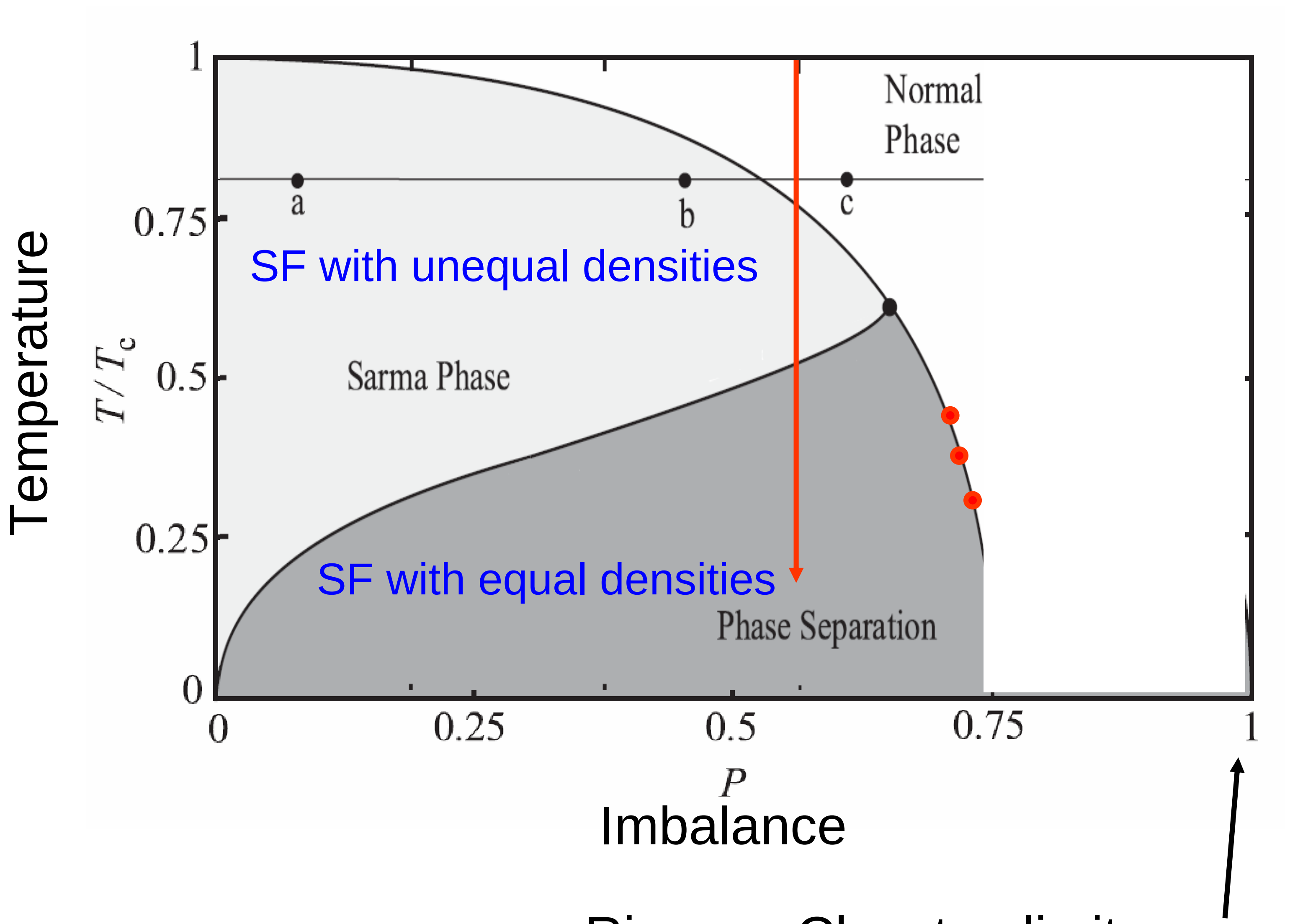
Superfluid state



Normal state




Temperature
T/T_c
1
0.75
0.5
0.25
0
0
0.25
0.5
0.75
1
P
Imbalance
Normal Phase
a
b
c
SF with unequal densities
Sarma Phase
SF with equal densities
Phase Separation

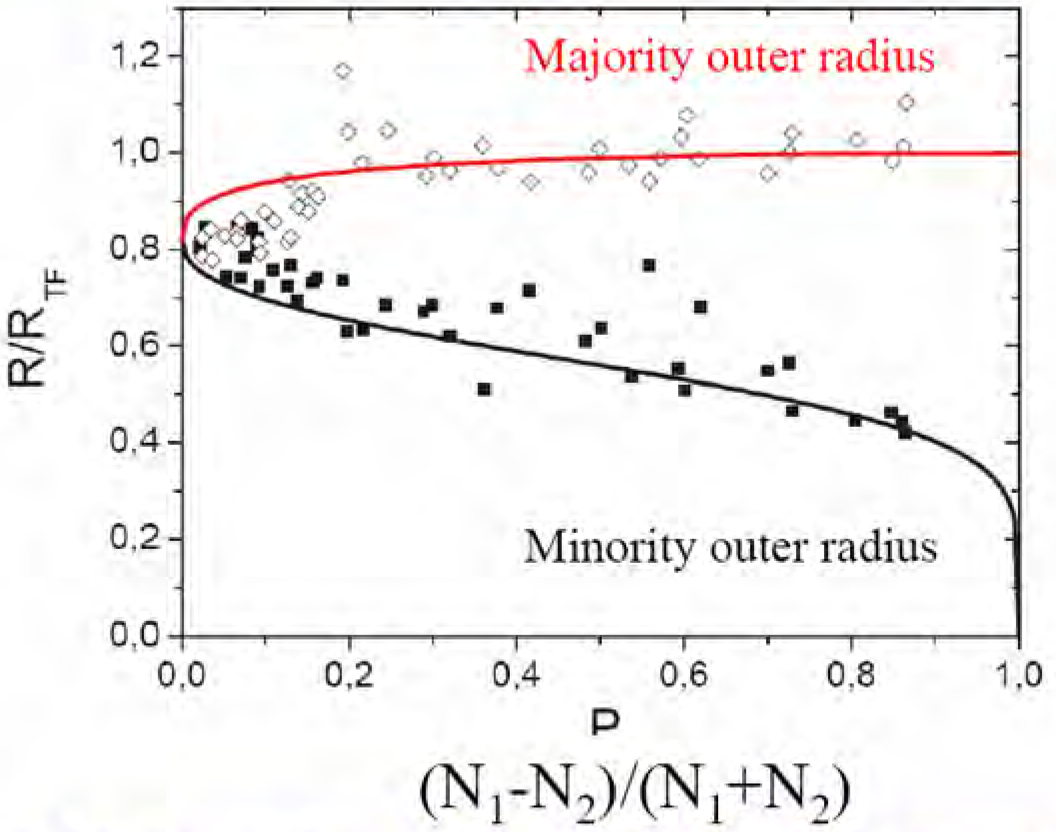


Rice: no Clogston limit
Superfluidity at > 90 % imbalance

Unresolved mystery: Rice expt

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

Experiment by Rice's group: fully compatible with 2 phase scenario (no intermediate phase+LDA). No adjustable parameters.



Slide of the Paris group (Chevy/Salomon)

For P=0.7, q~0.16 differs from MIT and contradicts theoretical bounds: q > 0.31 set by η_α> -0.1 and η_β< 0.60