“Ultracold Atoms – Dilute Gases with Strong Interactions”

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Massachusetts Institute of Technology
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CUA

4/23/07
KITP Workshop
Santa Barbara

BCS Theory 1957 -2007

John Bardeen

Leon Neil Cooper

John Robert Schrieffer

BCS state in lithium

BCS-1 Lithium Ion Battery Charger

Comp

This dedicated charger for the BLS-1 Lithium Ion Battery c
BLS-1 in about 210 minutes (at room temperature). Ratec
of 100 to 240 V allows use internationally*.

* Power outlet shapes vary by country/region, so be sure y
needed plug(s) before traveling.

BCS BROADCAST STORE

SEARCH Go

BCS ONLINE CATALOG
L.A.: 818-551-5858 • N.Y.: 212-268-8800

BROOKLYN COMPUTER SYSTEMS

BCS SilverGuard Wand - Reader SG5

Product:

Superconductivity in Dense Lithium

Viktor V. Struzhkin,[1*] Mikhail I. Eremets,[2] Wei Gan,[1,3]
Ho-kwang Mao,[1] Russell J. Hemley[1]

Superconductivity in compressed lithium is observed by magnetic susceptibility and electrical resistivity measurements. A superconducting critical temperature (T_c) is found ranging from 9 to 16 kelvin at 23 to 80 gigapascals. The pressure dependence

SCIENCE VOL 298 8 NOVEMBER 2002

Superconductivity in compressed lithium at 20 K

Katsuya Shimizu*†, Hiroto Ishikawa*, Daigoroh Takao*, Takehiko Yagi‡
& Kiichi Amaya*†

NATURE | VOL 419 | 10 OCTOBER 2002 | www.nature.com/nature

BCS-superconductivity of lithium at 50 GigaPascal

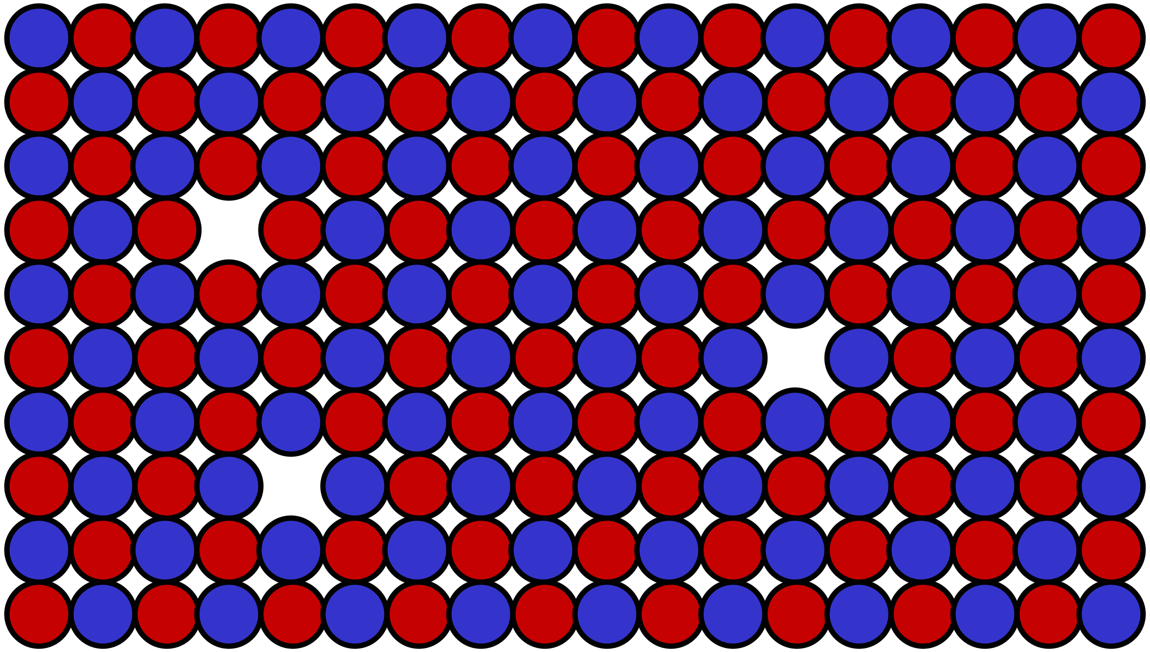
This talk:
BCS-superfluidity of lithium at 1 nanoPascal

Ultracold: nanokelvin
100 million times colder than outer space

Ultralow density: 10^{14} cm^{-3}
100,000 thinner than air

Ultracold atoms
A “toolbox” for designer matter

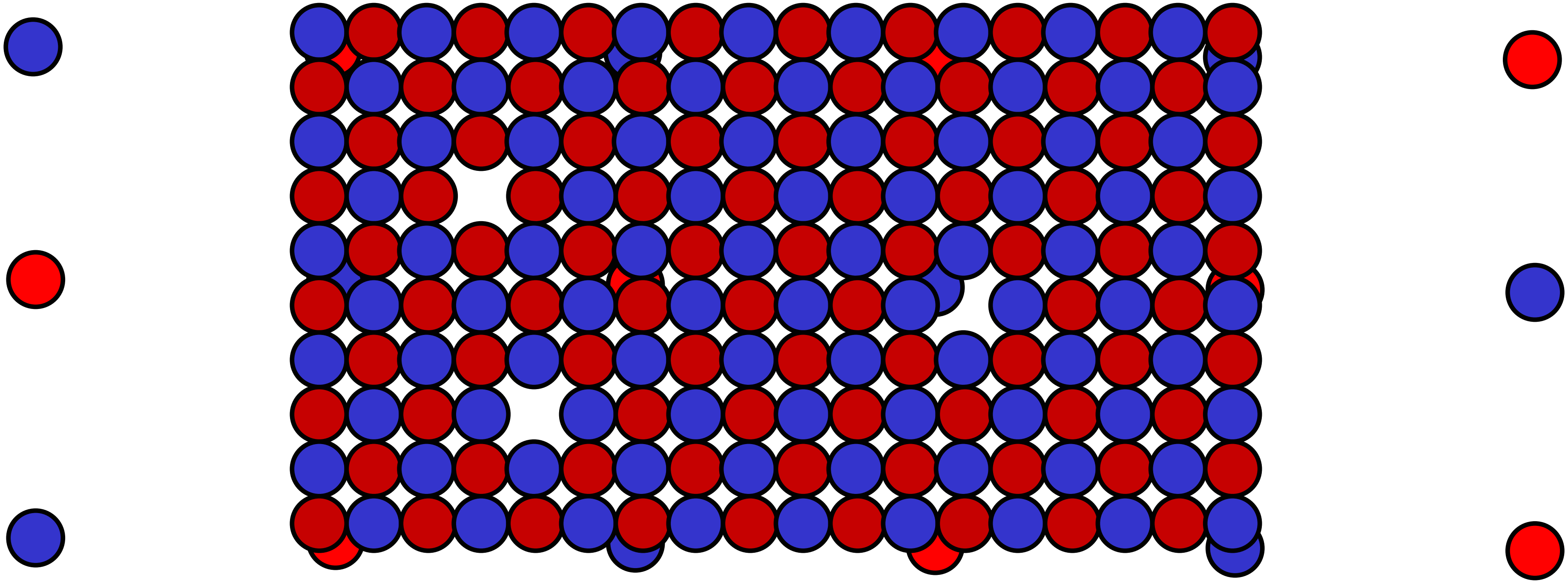
Normal matter
- Tightly packed atoms
- Complicated Interactions
- Impurities and defects



Ultracold atoms
A "toolbox" for designer matter

Matter of ultracold atoms
- 100 million times lower density

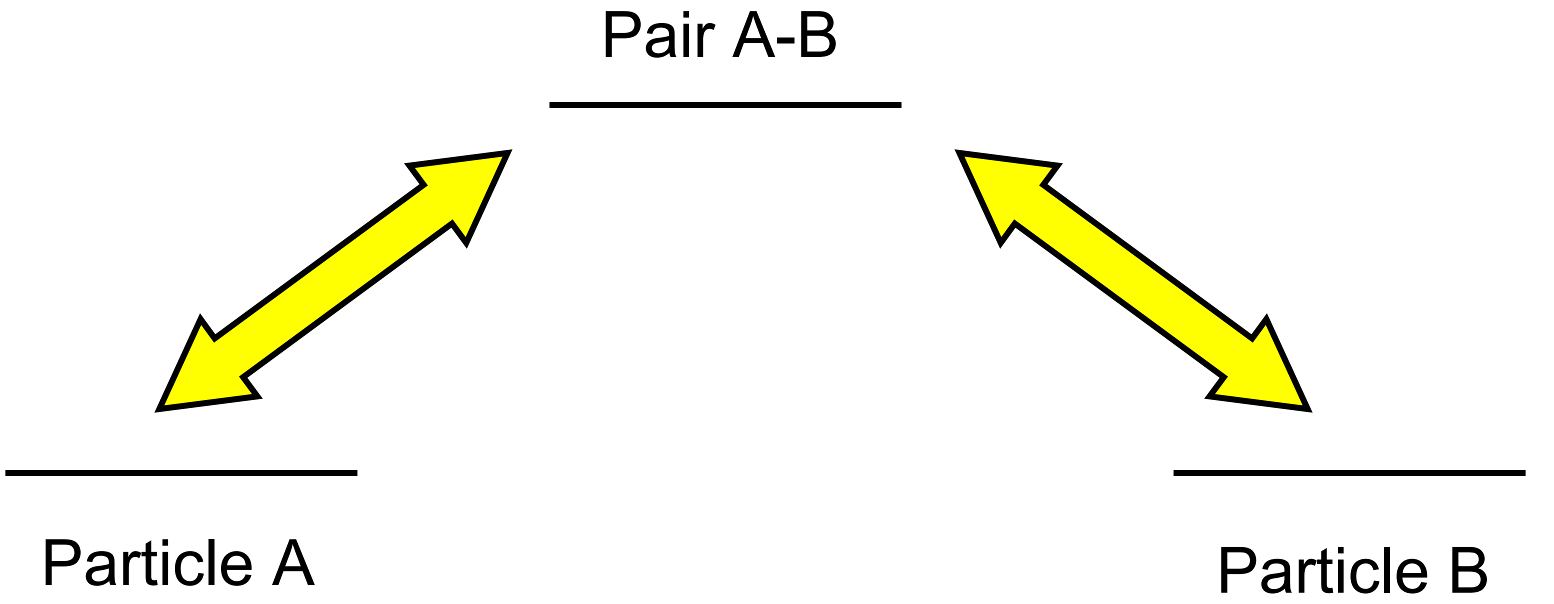
Need 100 million times colder temperatures



The combination of low density and low temperature provides a new approach to study strongly interacting systems in a controlled way

- Interactions understood and controlled
- no impurities
- exact calculations possible

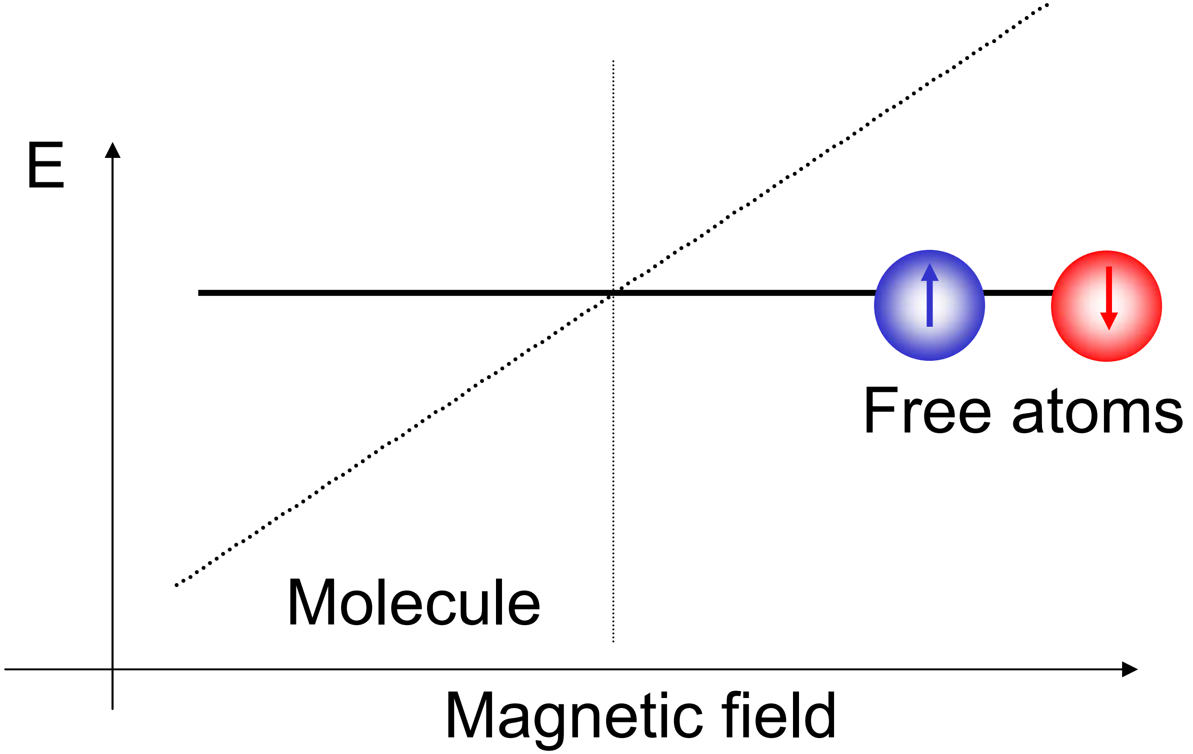
How to get strong interactions?



Resonant interactions have infinite strength

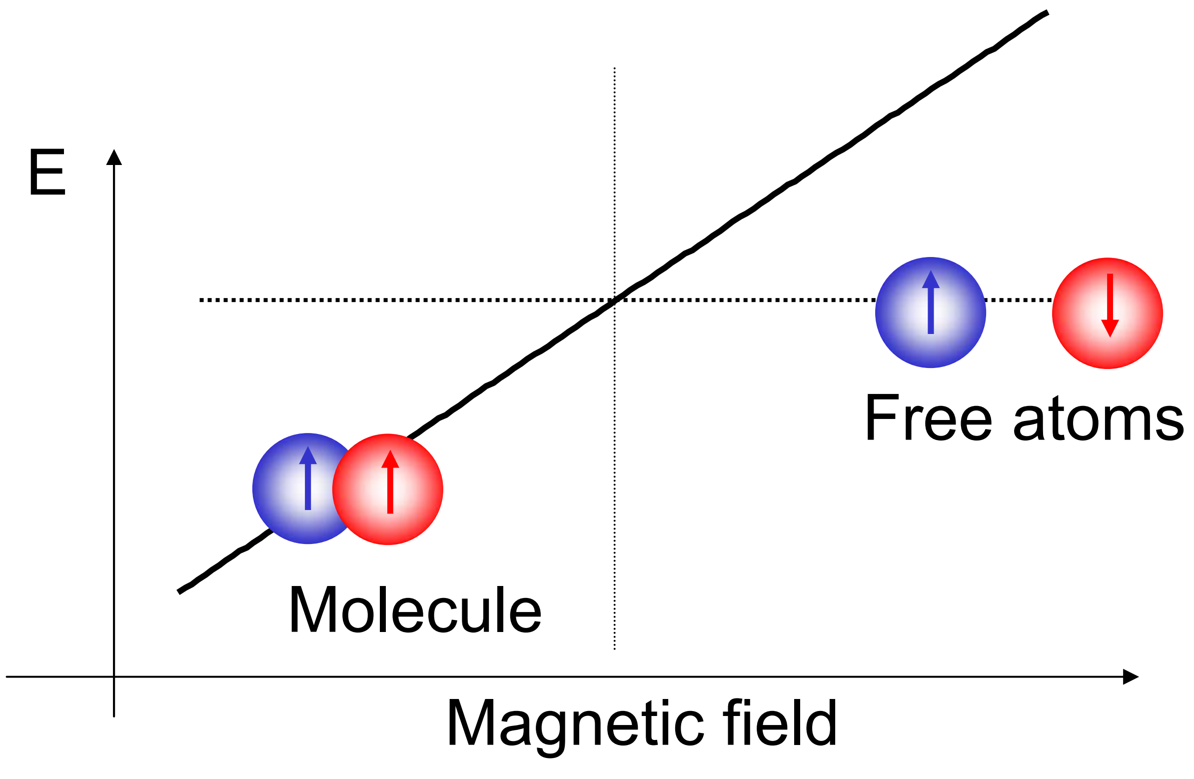
Unitarity limited interactions:

- Pairing in ultracold fermions
- Relevant to quark-gluon plasmas



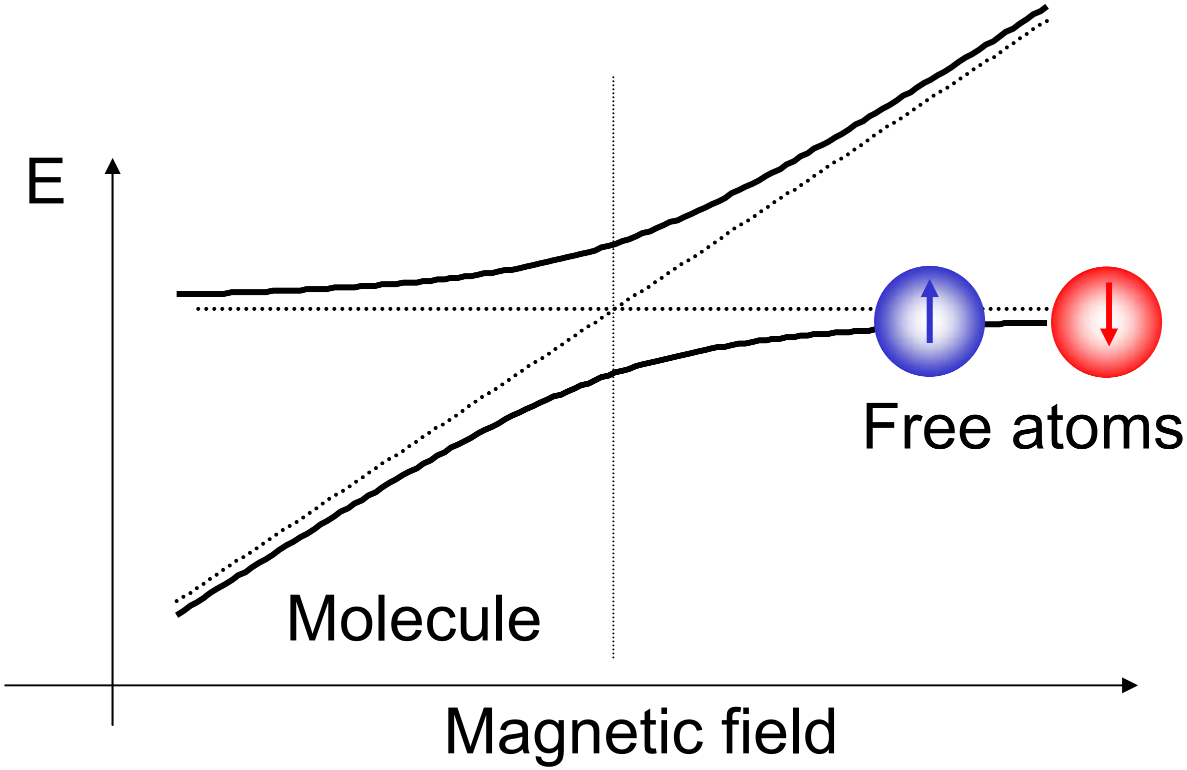
Feshbach resonance

Disclaimer: Drawing is schematic and does not distinguish nuclear and electron spin.



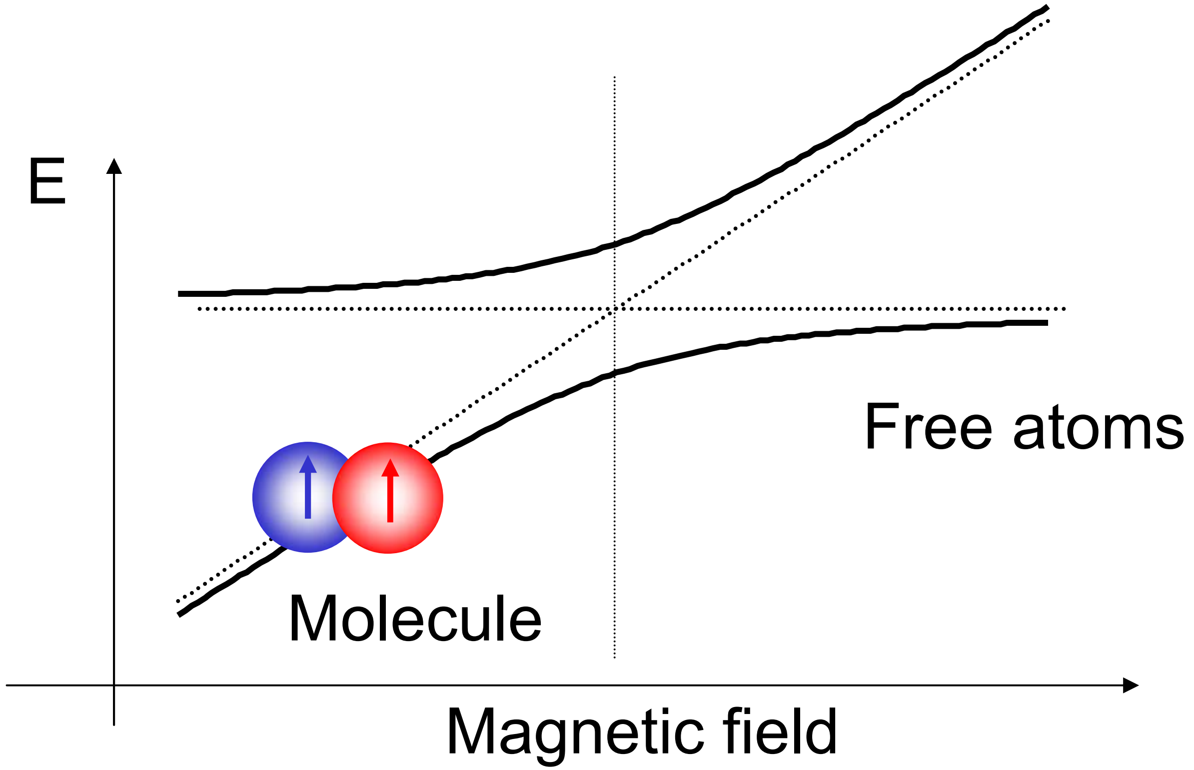
Feshbach resonance

Two atoms ….



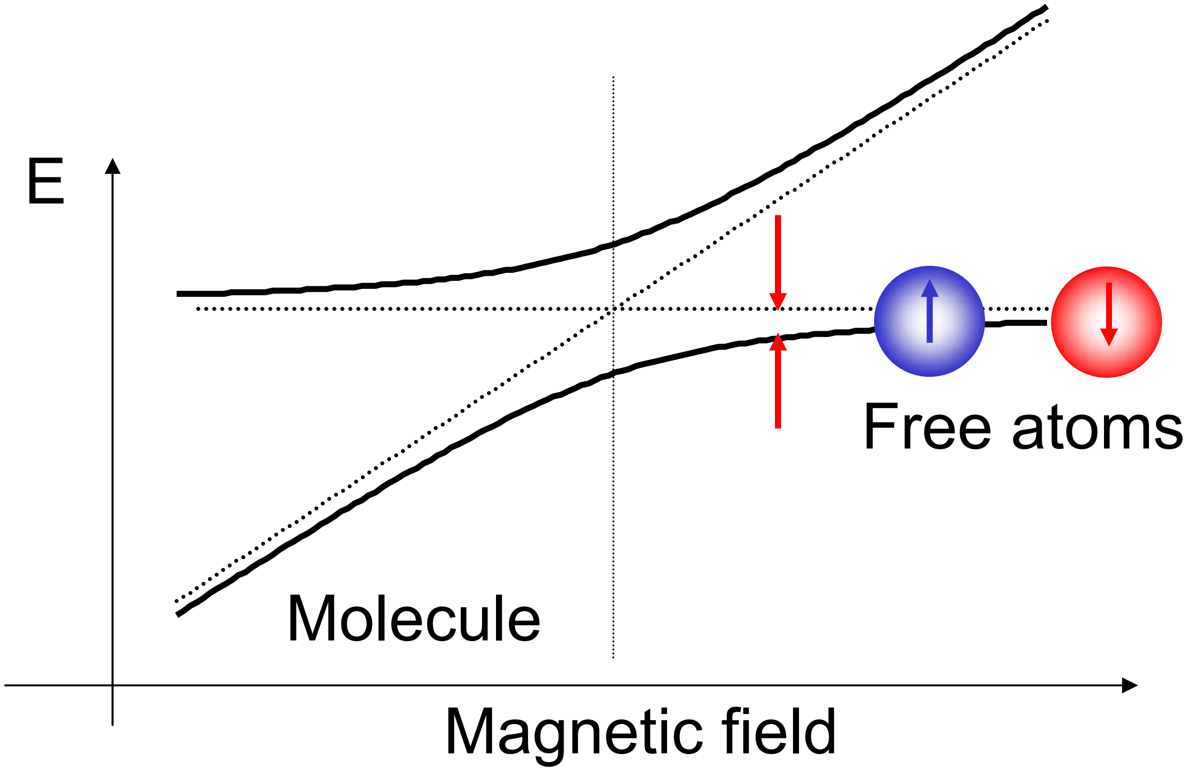
Feshbach resonance

… form a stable molecule



Feshbach resonance

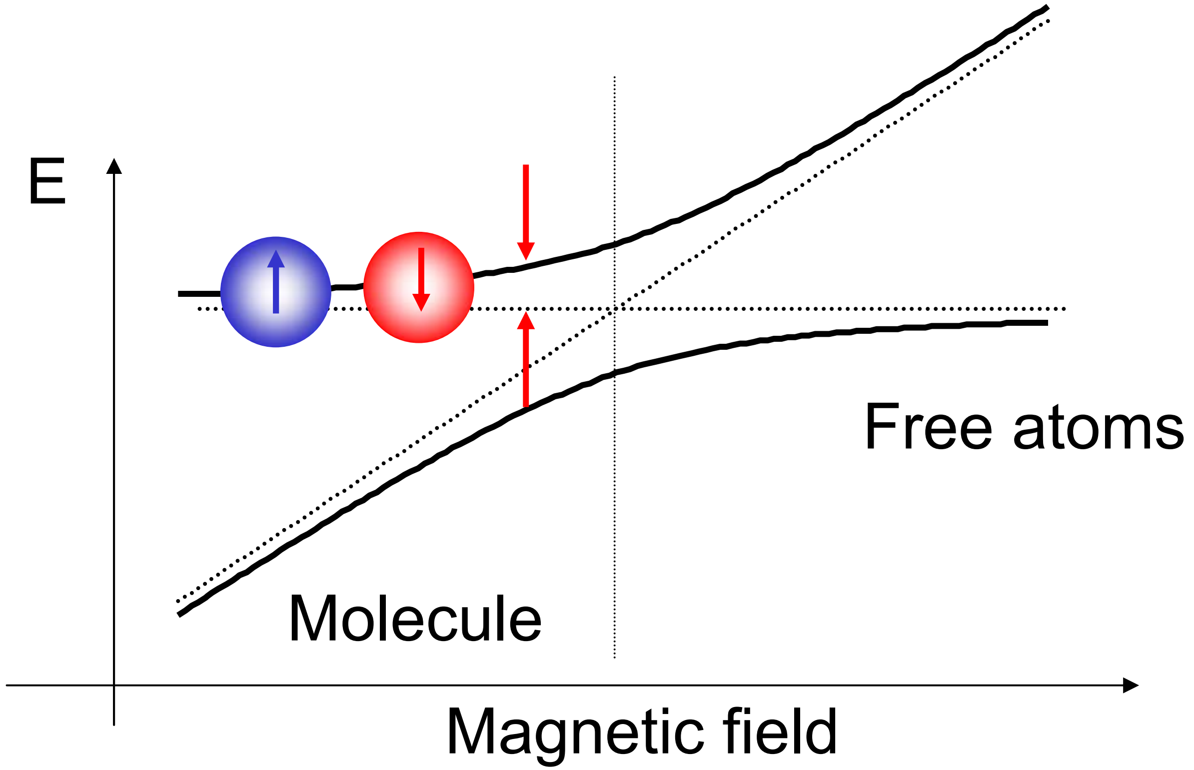
Atoms attract each other



Feshbach resonance

Atoms repel each other

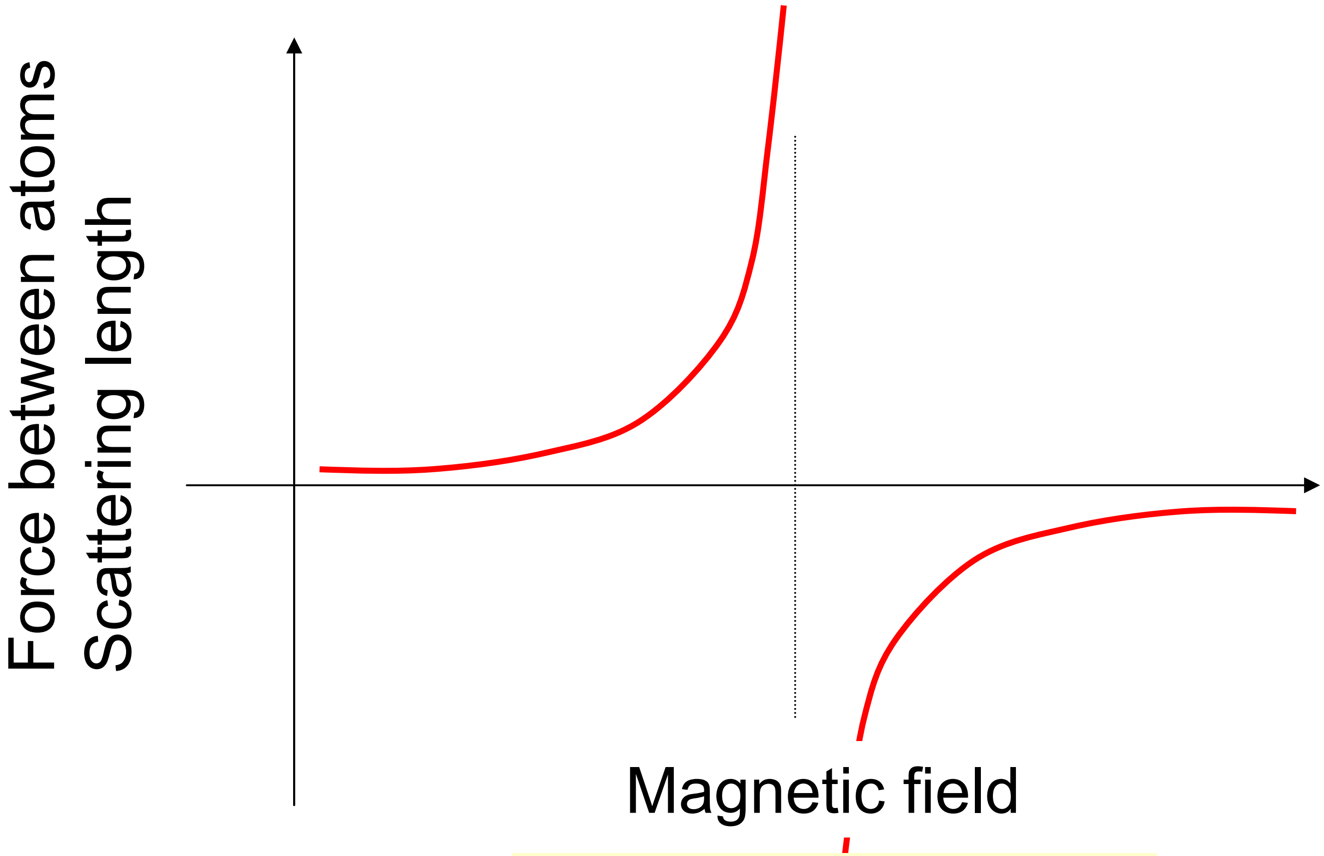
Atoms attract each other



Feshbach resonance

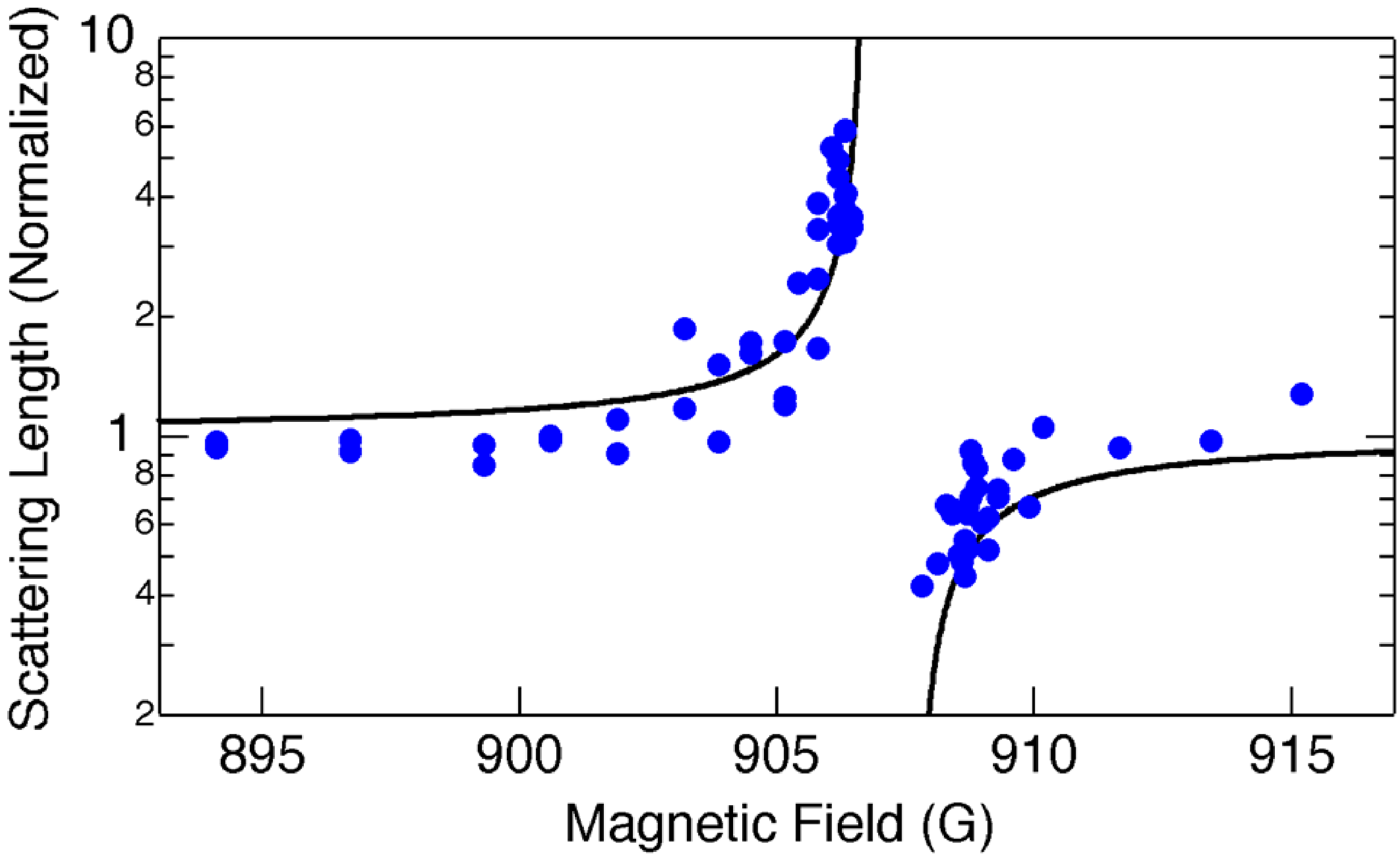
Atoms repel each other

Atoms attract each other



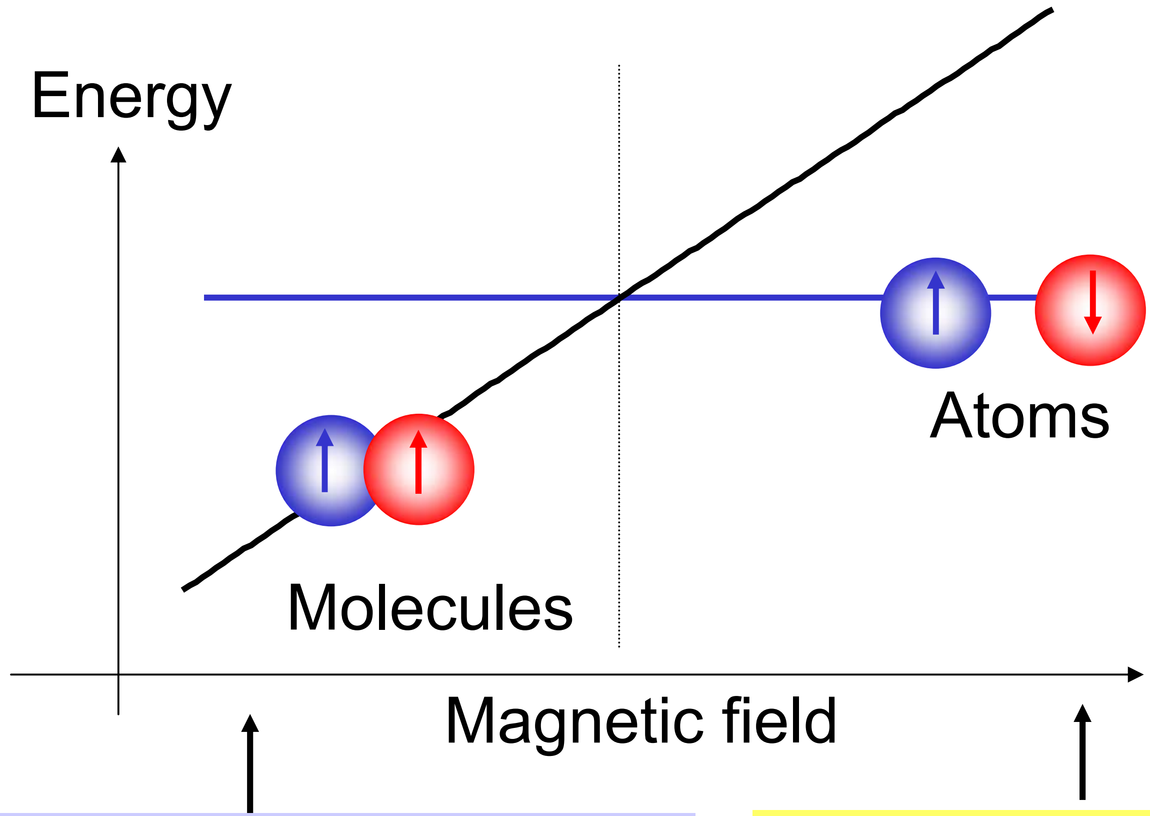
Feshbach resonance

Observation of a Feshbach resonance



S. Inouye, M.R. Andrews, J. Stenger, H.-J. Miesner, D.M. Stamper-Kurn, WK, Nature **392** (1998).

Feshbach resonances in ultracold Fermi gases



Atoms form stable molecules

Atoms repel each other
a>0

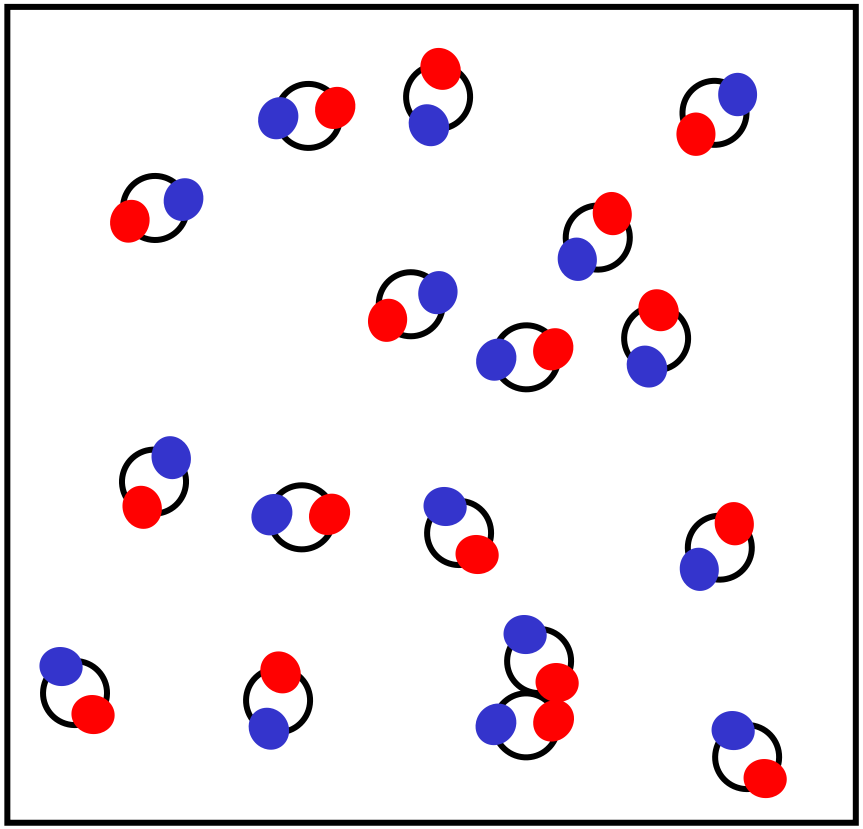
BEC of Molecules:
Condensation of
tightly bound fermion pairs

Molecules are unstable

Atoms attract each other
a<0

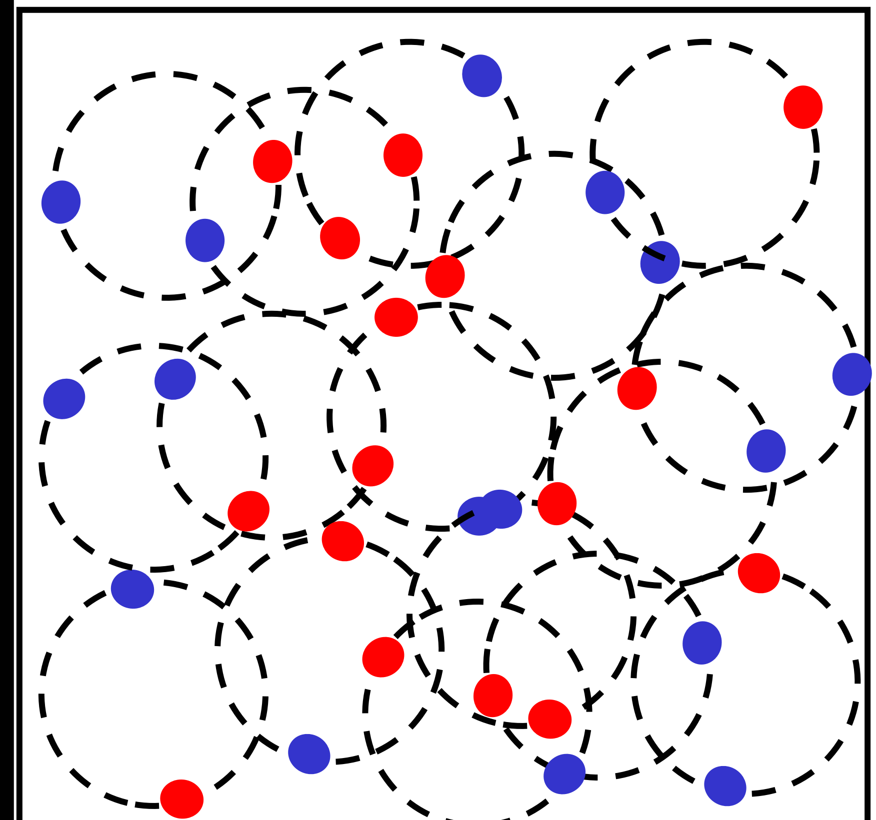
BCS-limit:
Condensation of
long-range Cooper pairs

Atom pairs

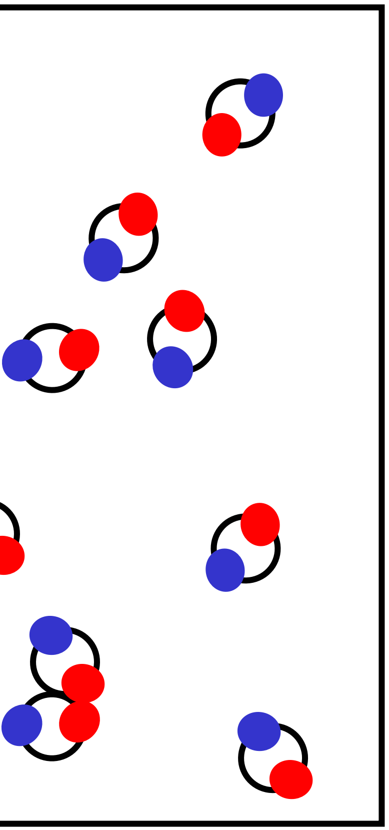


Bose Einstein condensate of molecules

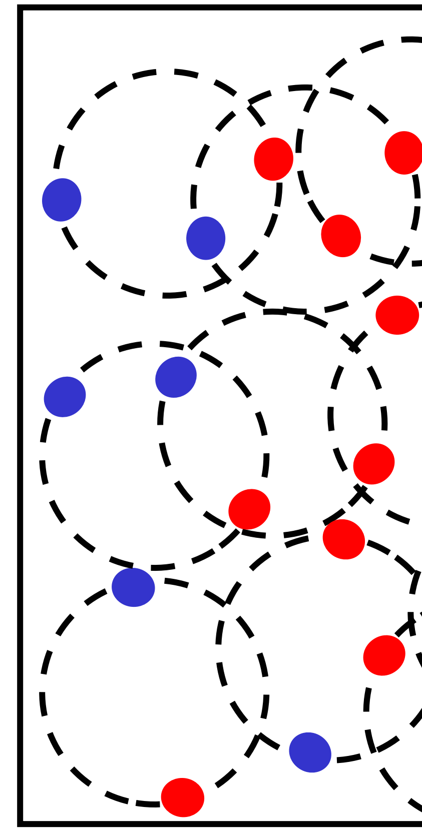
Electron pairs



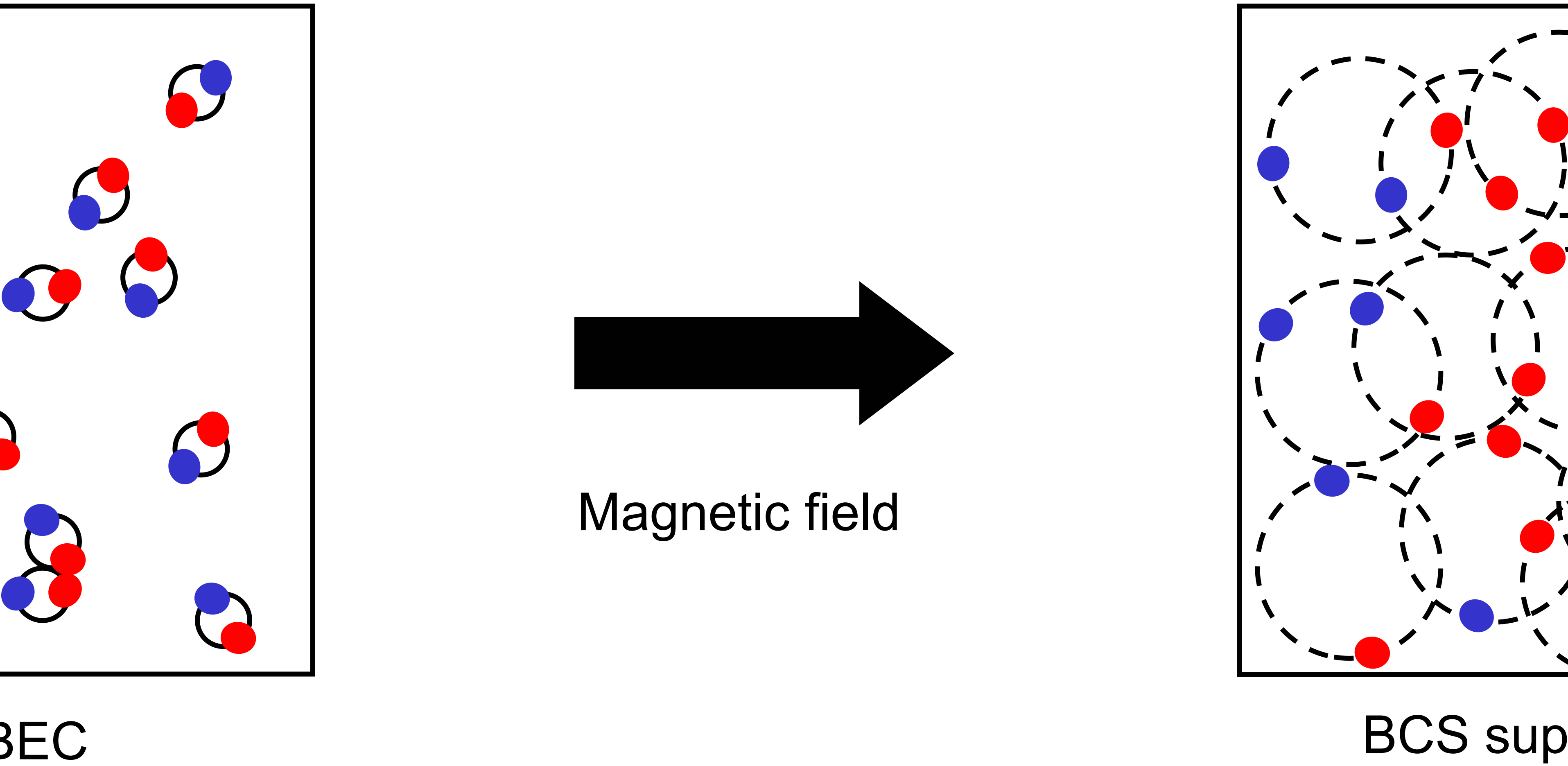
BCS Superconductor



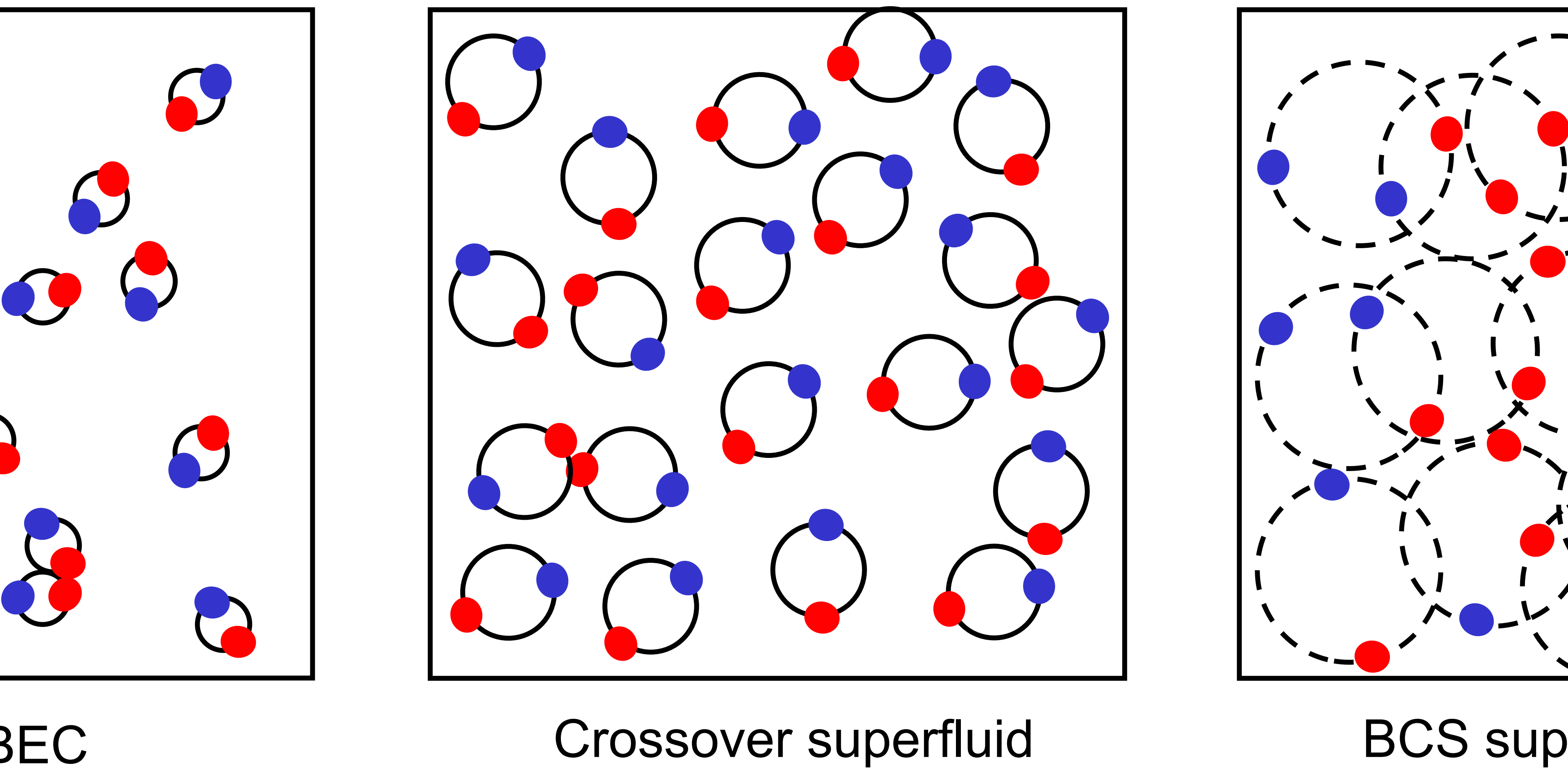
BEC



BCS sup



Magnetic field
BEC
BCS sup


Crossover superfluid

High-temperature superfluidity at 100 nK?

$$\frac{\text{Transition temperature}}{\text{Fermi temperature}} \approx \frac{\text{Binding energy of pairs}}{\text{Fermi energy}}$$

Fermi temperature, Fermi energy $\propto (\text{density})^{2/3}$

$10^{-5} \ldots 10^{-4}$	normal superconductors
10^{-3}	superfluid ^3He
10^{-2}	high T_c superconductors
0.2	**high T_c superfluid**

Scaled to the density of electrons in a solid:

Superconductivity far above room temperature!

BCS state

$$|\psi_{BCS}\rangle = \prod_k \left(u_k + v_k\, a^\dagger_{k,\uparrow}\, a^\dagger_{-k,\downarrow}\right)|0\rangle$$

BCS state

$$|\psi_{BCS}\rangle = \prod_k \left(u_k + v_k\, a^+_{k,\uparrow}\, a^+_{-k,\downarrow}\right)|0\rangle$$

Bound molecular pair

$$c^+_0 = \sum_k \Phi_k\, a^+_{k,\uparrow}\, a^+_{-k,\downarrow}$$

BCS state

$$|\Psi_{BCS}\rangle = \prod_k \left(u_k + v_k\, a^\dagger_{k,\uparrow}\, a^\dagger_{-k,\downarrow}\right)|0\rangle$$

Bound molecular pair

$$c^\dagger_0 = \sum_k \Phi_k\, a^\dagger_{k,\uparrow}\, a^\dagger_{-k,\downarrow}$$

BEC state of N pairs

$$|\Psi_{BEC}\rangle = \left(c^\dagger_0\right)^N |0\rangle$$

BCS state

$$|\psi_{BCS}\rangle = \prod_k \left(u_k + v_k\, a^\dagger_{k,\uparrow} a^\dagger_{-k,\downarrow}\right)|0\rangle$$

Bound molecular pair

$$c^\dagger_0 = \sum_k \Phi_k\, a^\dagger_{k,\uparrow} a^\dagger_{-k,\downarrow}$$

BEC state of N pairs

$$|\psi_{BEC}\rangle = \left(c^\dagger_0\right)^N |0\rangle$$

alternatively $\exp\left(N^{1/2} c^\dagger_0\right)|0\rangle$

BEC - BCS crossover

$$|\psi_{BEC}\rangle = \exp\left(\sum_k N^{1/2} \Phi_k \, a^+_{k,\uparrow} a^+_{-k,\downarrow}\right) |0\rangle$$

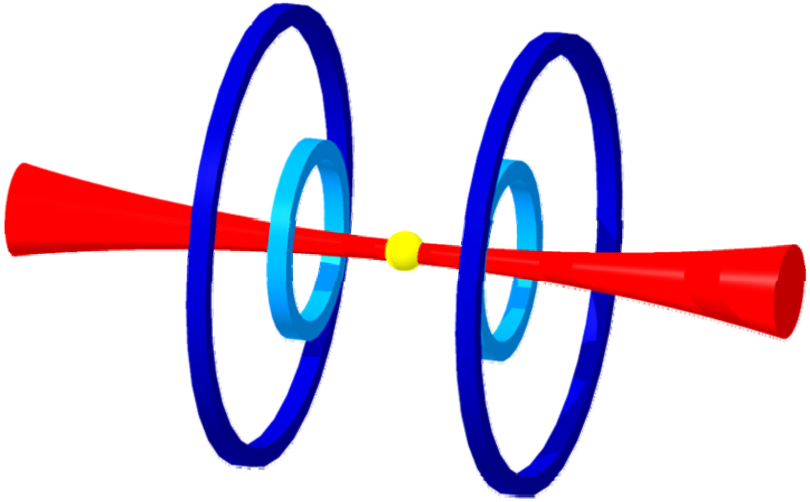
$$\approx \prod_k \left(1 + N^{1/2} \Phi_k \, a^+_{k,\uparrow} a^+_{-k,\downarrow}\right) |0\rangle$$

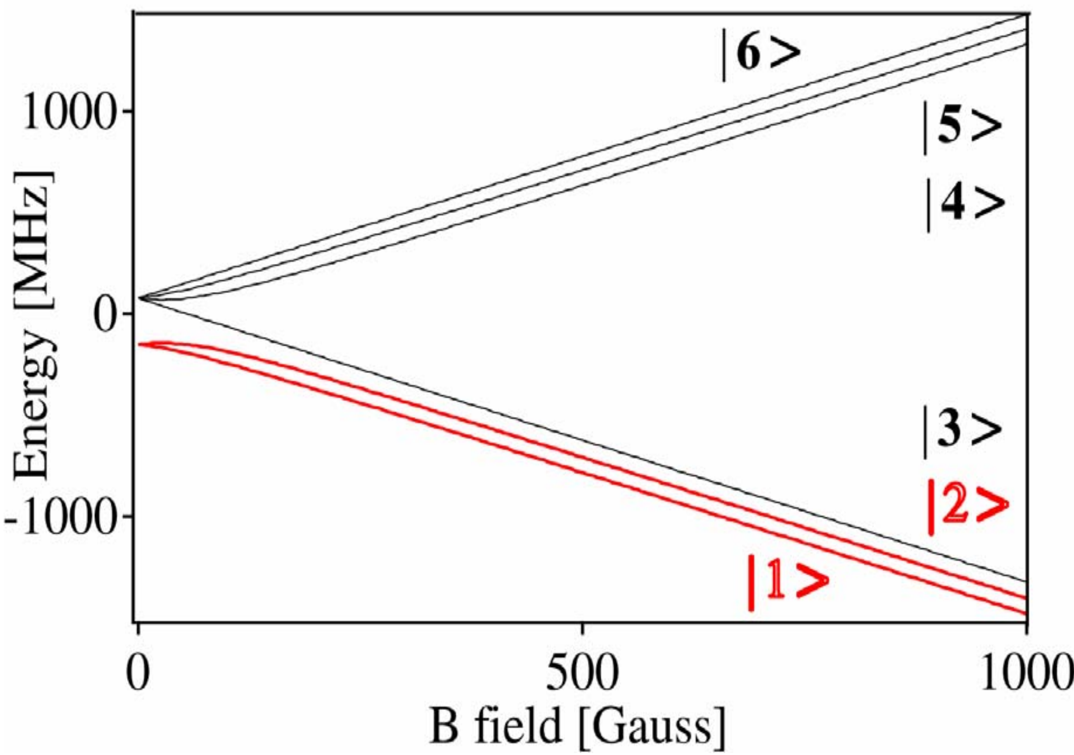
$$\simeq \prod_k \left(u_k + v_k \, a^+_{k,\uparrow} a^+_{-k,\downarrow}\right) |0\rangle =$$

with $v_k = \dfrac{N^{1/2} \Phi_k}{\underbrace{(1 + N|\Phi_k|^2)^{1/2}}_{\simeq 1}}$

$$= |\psi_{BCS}\rangle$$

Preparation of an interacting Fermi system in ^{6}Li





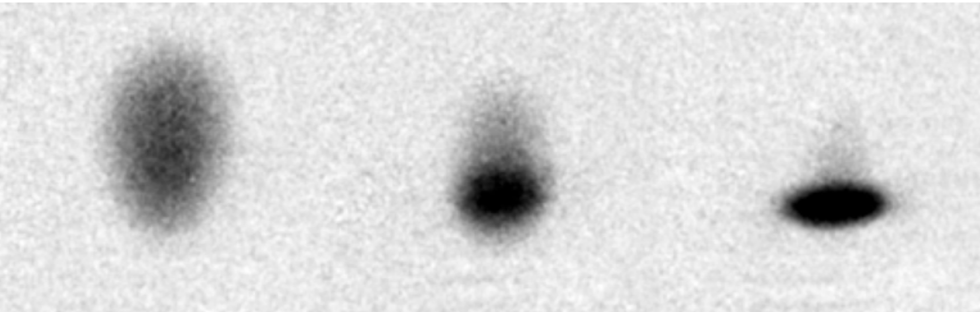
Setup:

Optical trapping:
9 W @ 1064 nm

$\omega = 2\pi \times (16, 16, 0.19)$ kHz
$E_{trap} = 800\ \mu K$

States |1> and |2> correspond to |↑> and |↓>

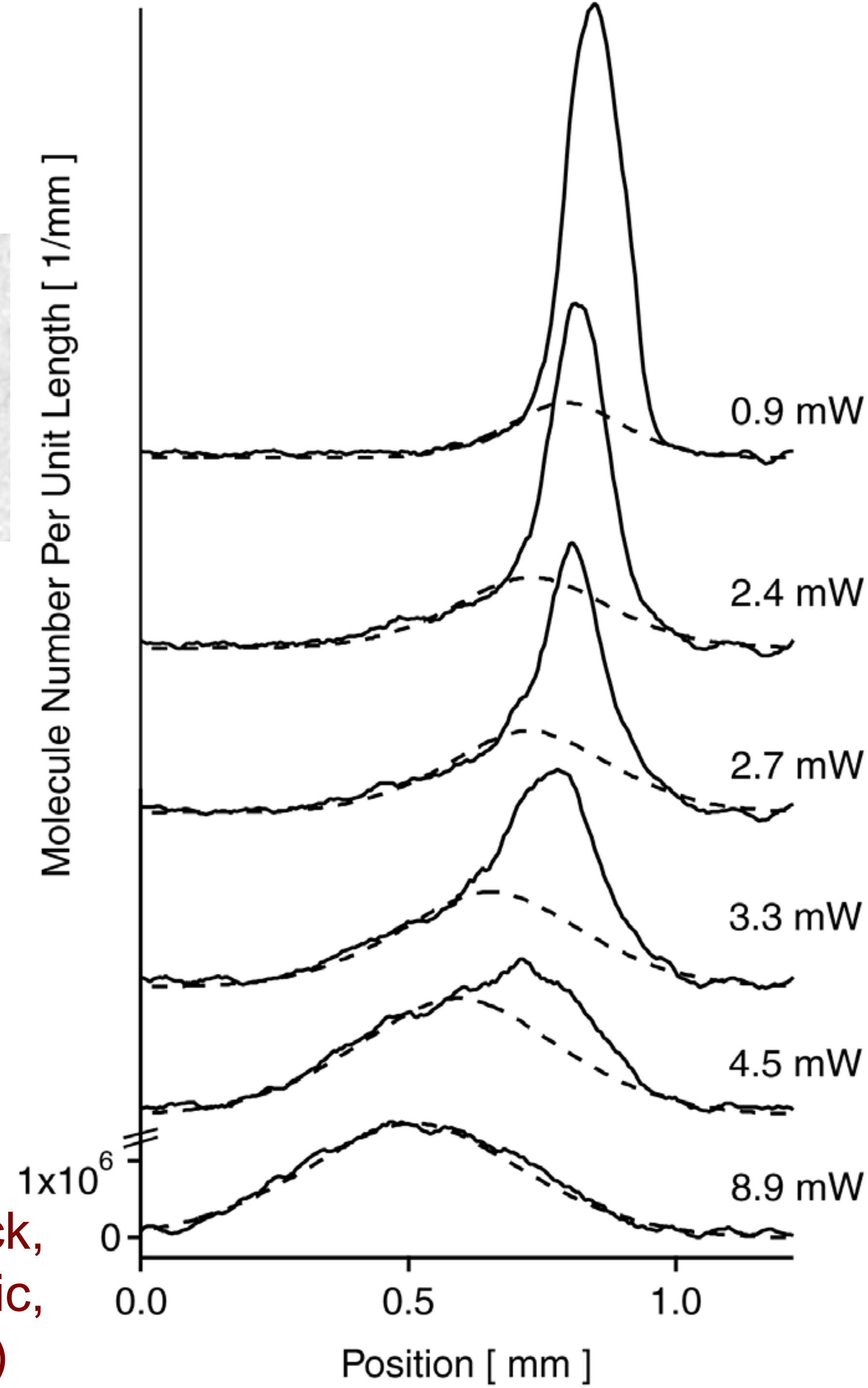
BEC of Fermion Pairs ("Molecules")



These days: Up to 10 million condensed molecules

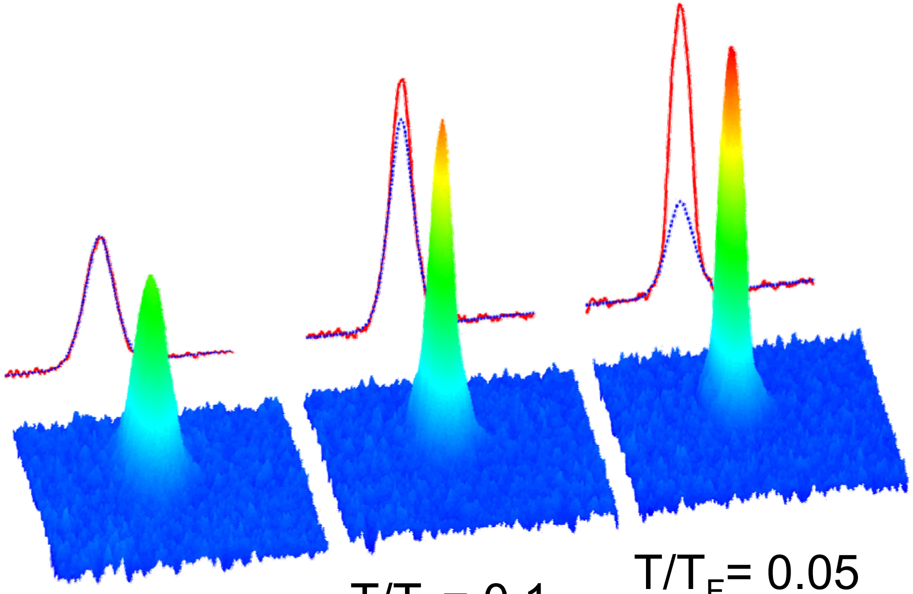
Boulder	Nov '03
Innsbruck	Nov '03, Jan '04
MIT	Nov '03
Paris	March '04
Rice, Duke	

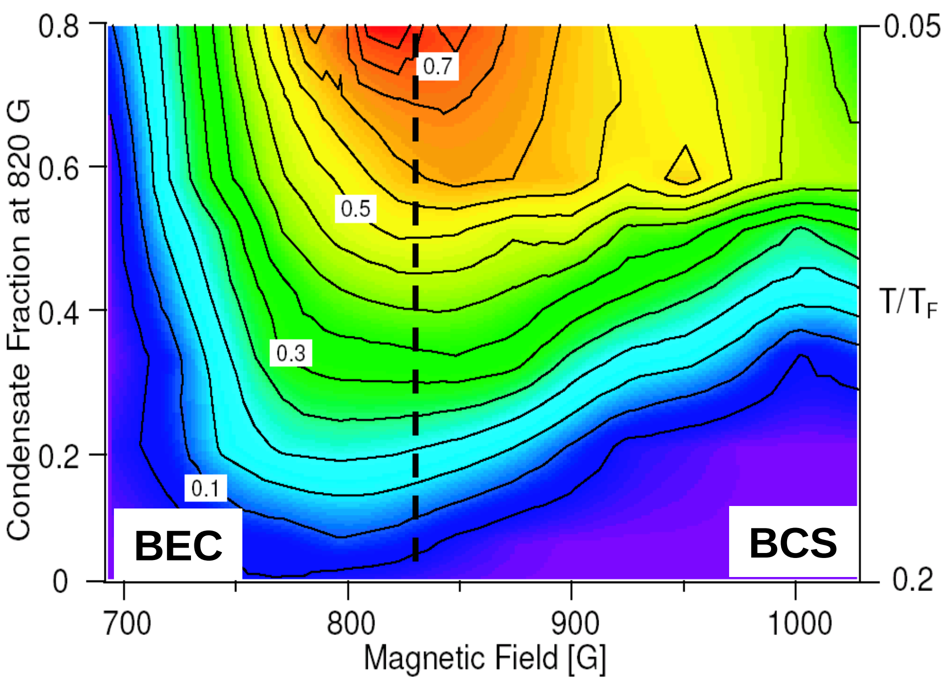
M.W. Zwierlein, C. A. Stan, C. H. Schunck, S.M. F. Raupach, S. Gupta, Z. Hadzibabic, W.K., Phys. Rev. Lett. 91, 250401 (2003)



Observation of Pair Condensates

At 900 G





C.A. Regal *et al.*, PRL **92**, 040403 (2004)
M.W. Zwierlein *et al.*, PRL **92**, 120403 (2004)

Quantum degenerate fermions

Potassium ^{40}K	Boulder	Toronto
	Florence	Mainz
	Zürich	
	Hamburg	
Lithium ^{6}Li	Rice	Tübingen
	Paris	
	Duke	
	MIT	
	Innsbruck	
Ytterbium ^{173}Yb	Kyoto	
Helium ^{3}He	Amsterdam	

Lots of work in progress:
more lithium, potassium (Munich, Melbourne, Amsterdam, Orsay,…), chromium (Stuttgart), strontium (Innsbruck)

Characterization of the strongly interacting regime

"Energy measurements"

Interaction energy
Duke, Innsbruck, Paris, Rice, JILA

Specific heat
Duke

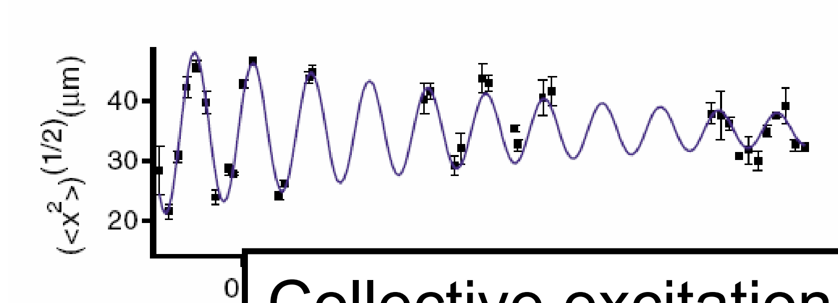
Momentum distribution
JILA, Paris

"Other"

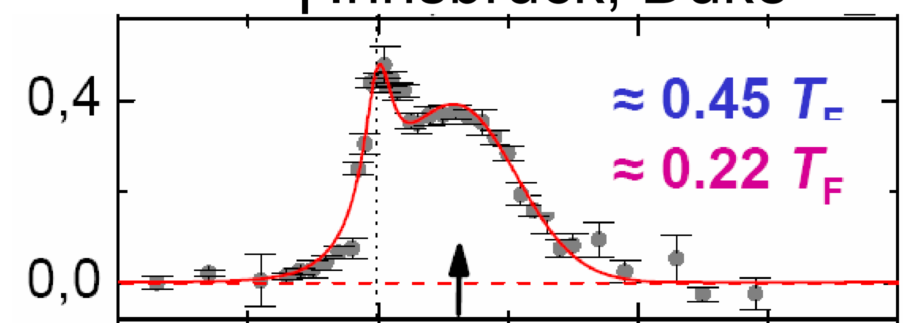
Condensate formation time
MIT

Characterization of pairs
Rice

"Excitation measurements"



Collective excitation
Innsbruck, Duke



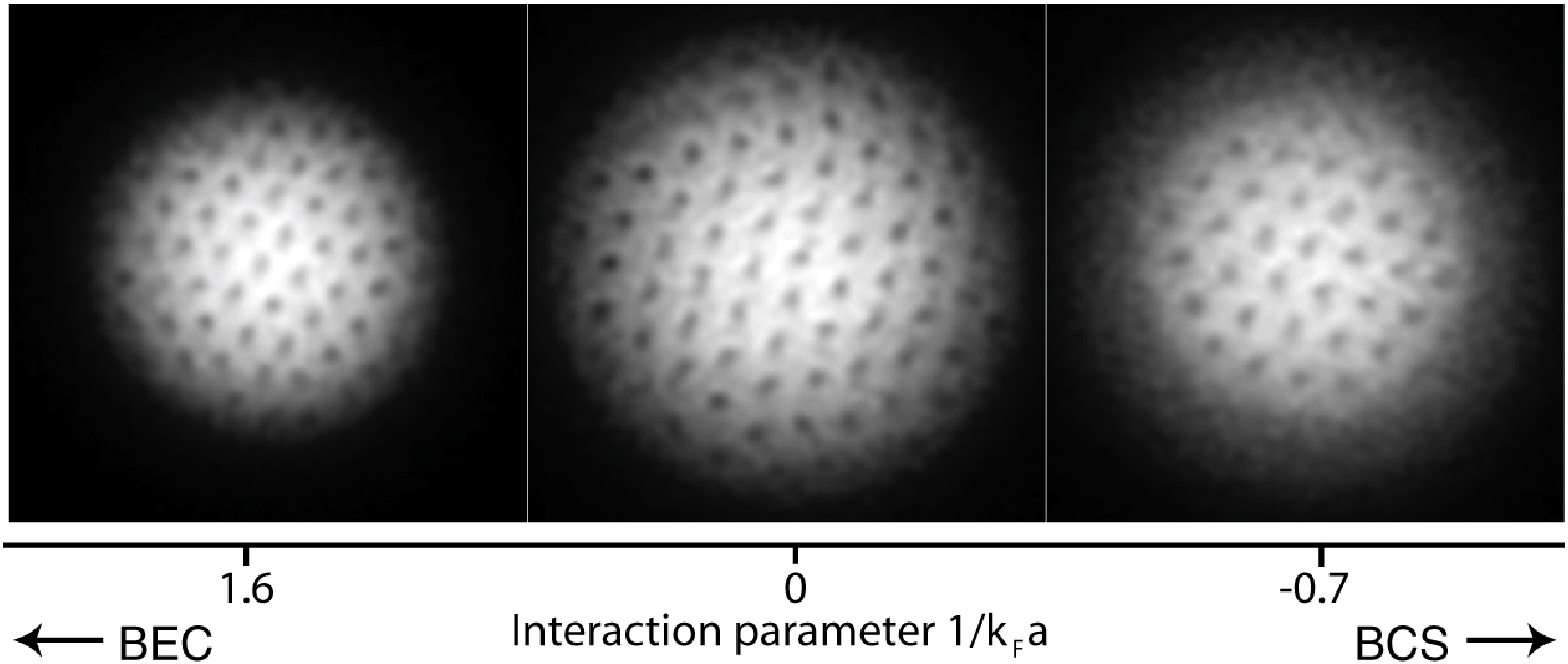
RF spectroscopy, pairing gap
Innsbruck

Magnetic modulation spectrum
JILA

Sound propagation, Duke 2006

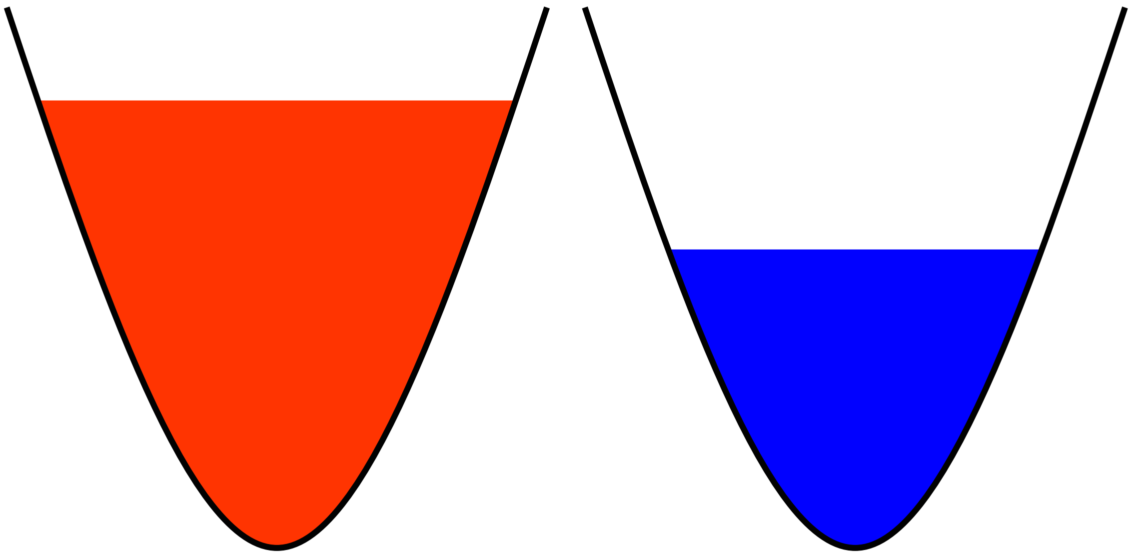
Vortex lattices in the BEC-BCS crossover

This establishes phase coherence and superfluidity in gases of molecules and of fermionic atoms



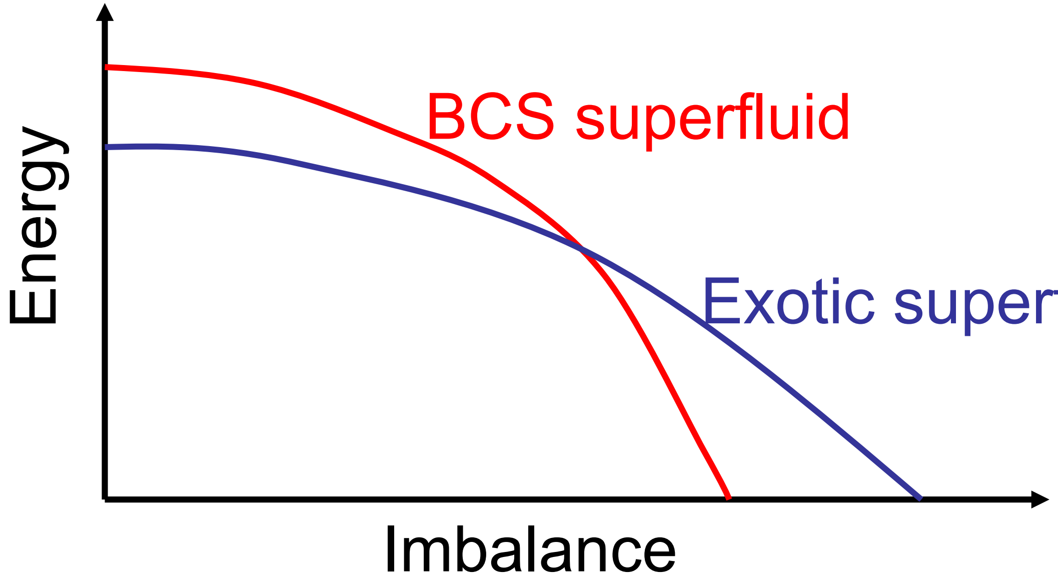
M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle, Nature 435, 1047-1051 (2005)

Fermionic Superfluidity with Imbalanced Spin Populations

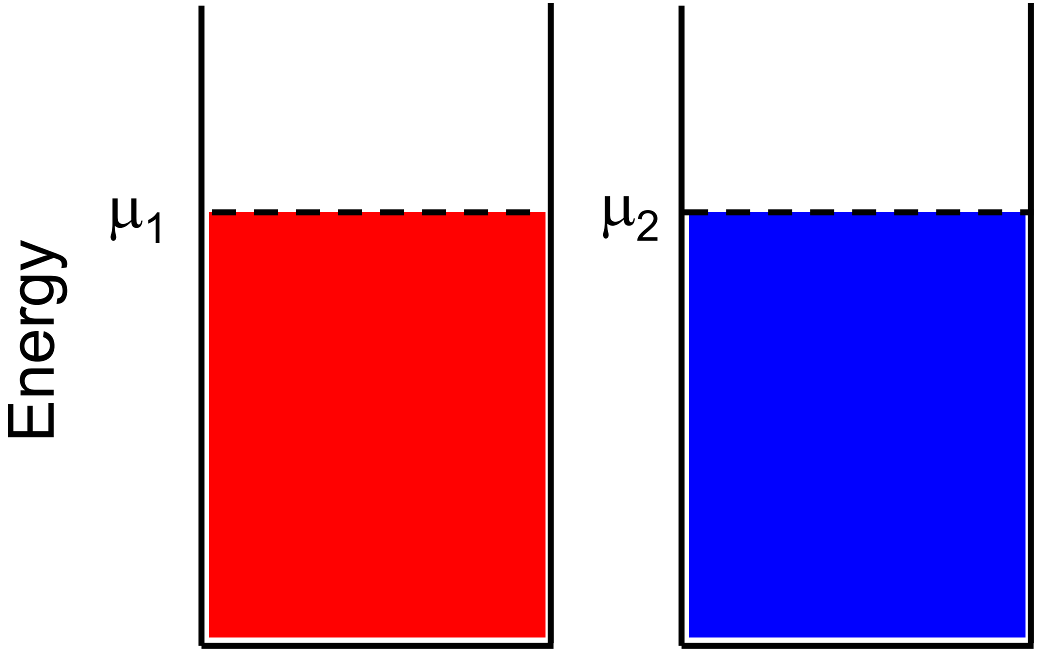


Why is superfluidity with unequal Fermi energies interesting?

- Superfluidity in quarks involves unequal Fermi surfaces (due to different quark masses)
- New superfluid states predicted:

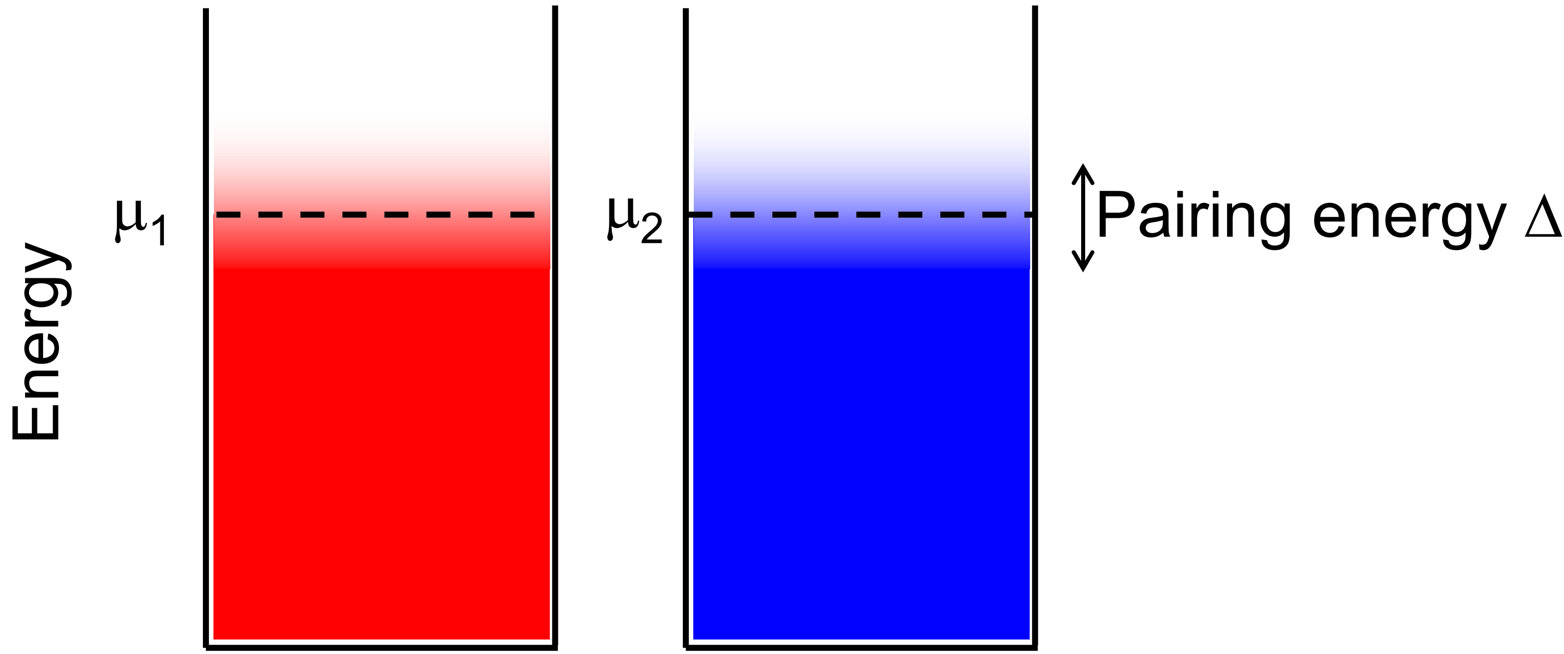


BCS Pairing of Fermions

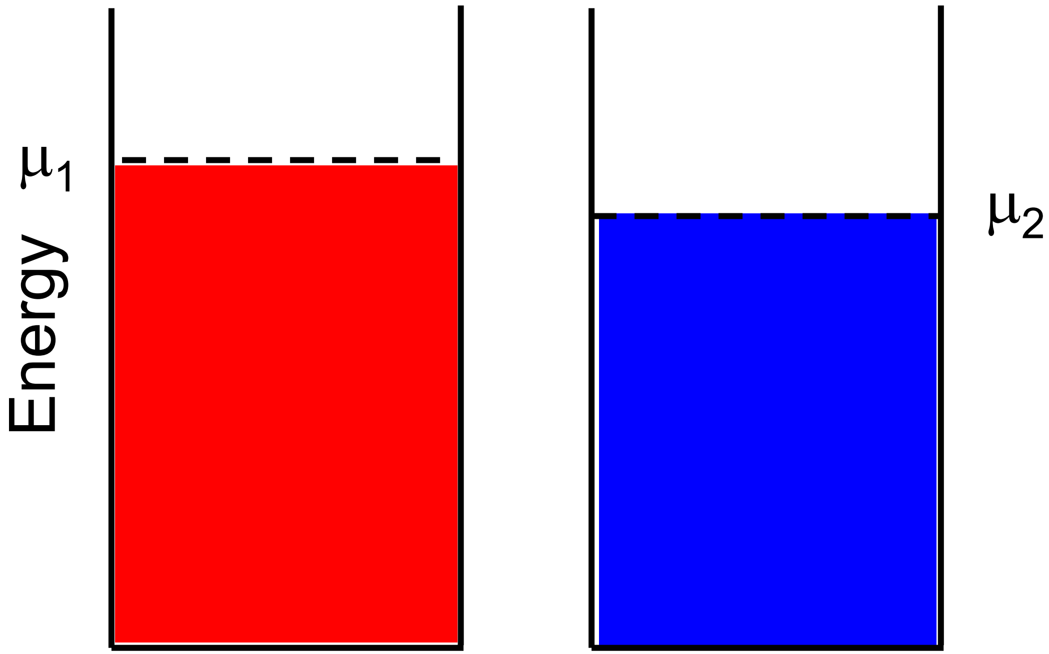


BCS Pairing of Fermions

Pairing costs kinetic energy, but there is gain in potential energy (attractive interaction between fermions)

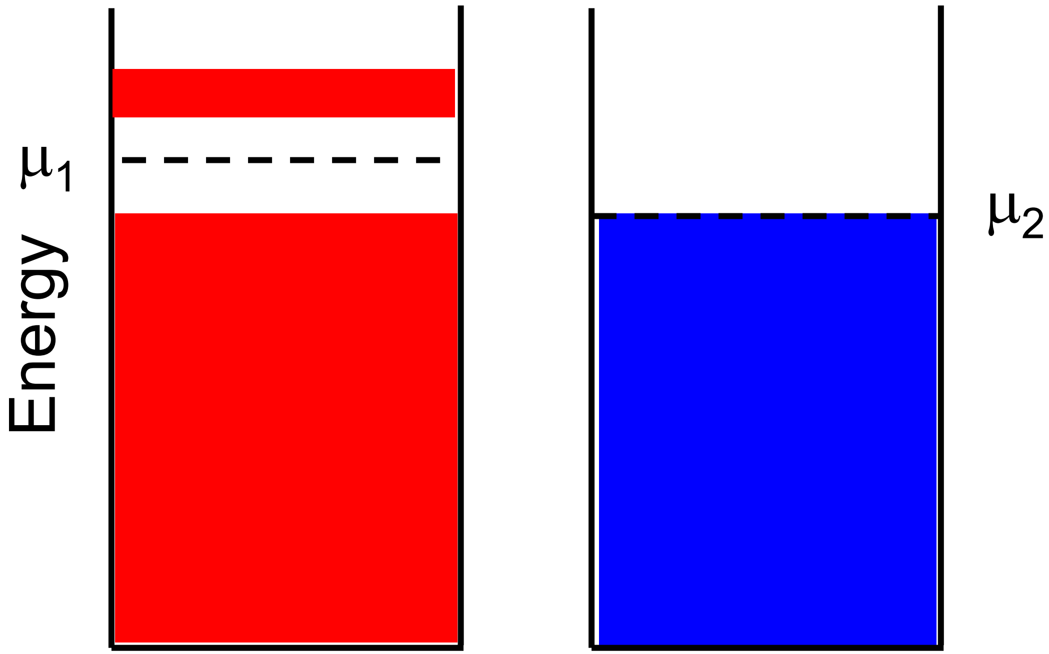


Sarma state



Sarma state

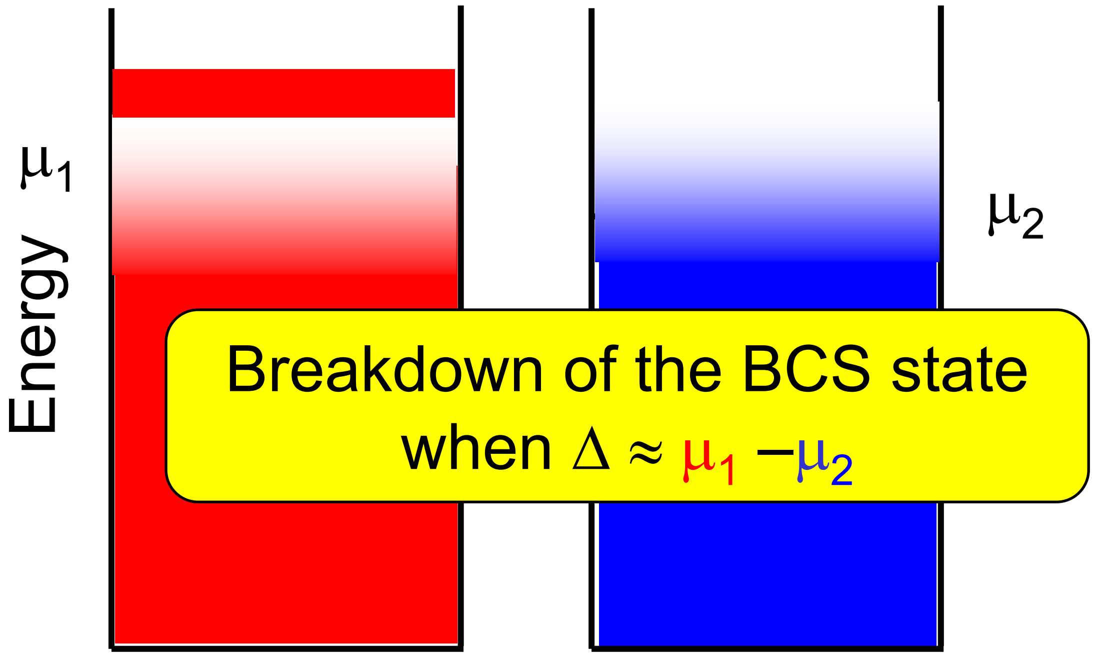
Fraction of atoms $(\mu_1-\mu_2)/E_F$ moved up by Δ



Sarma state

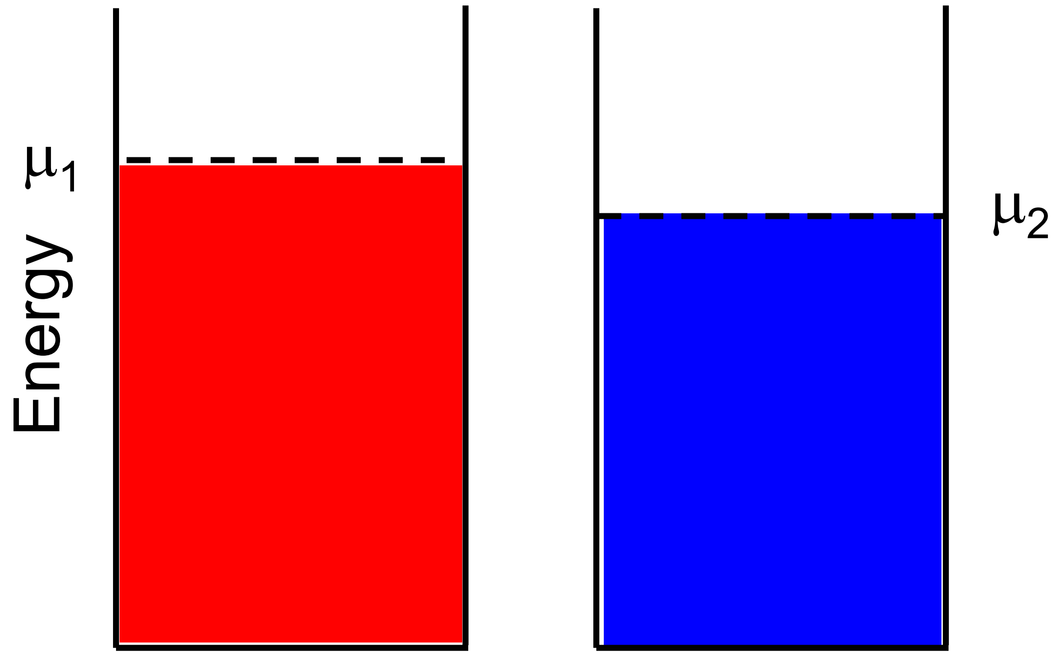
Fraction of atoms $(\mu_1-\mu_2)/E_F$ moved up by Δ

Fraction of atoms Δ/E_F gain energy Δ



BCS Pairing of Fermions

Phase separation (Bedaque, Caldas, Rupak 2003)



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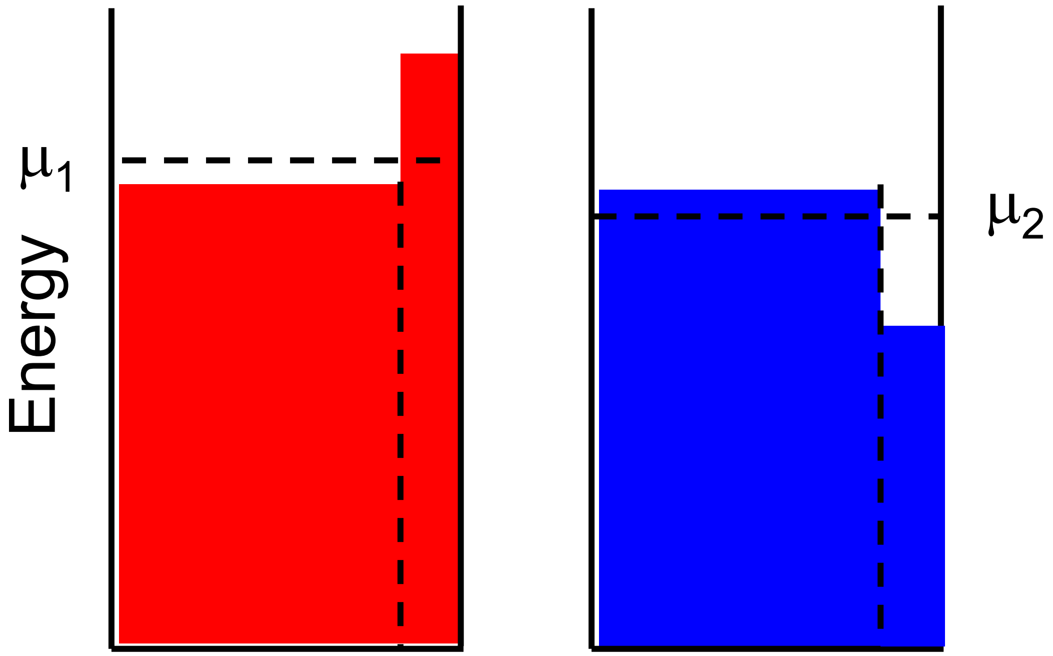

BCS Pairing of Fermions

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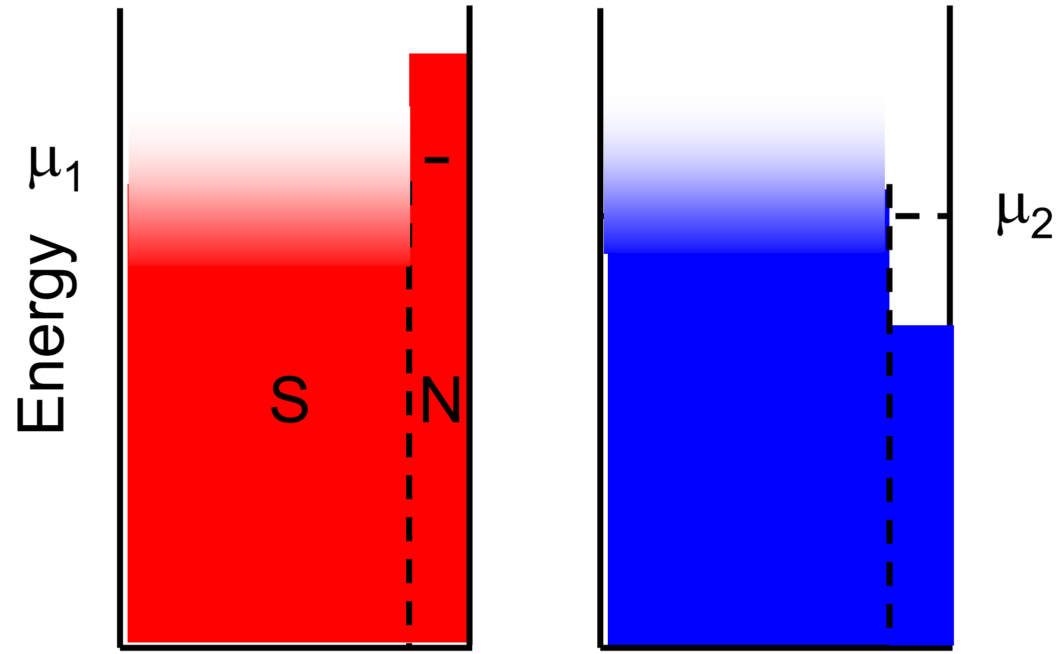


Superfluid dance with unequal populations

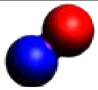
Does an excess population of men stop the dance?

Do the excess men stay off the dance floor?

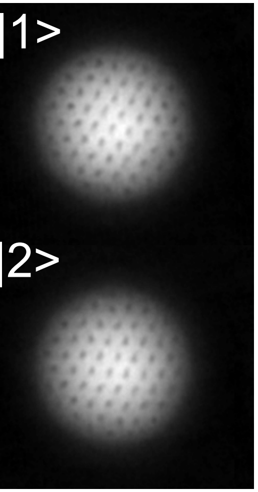
Do the excess men lead to a new dance where the partners are no longer matched?

Fermionic Superfluidity with Imbalanced Spin Populations

BEC-Side



$1/k_F a = 0.2$

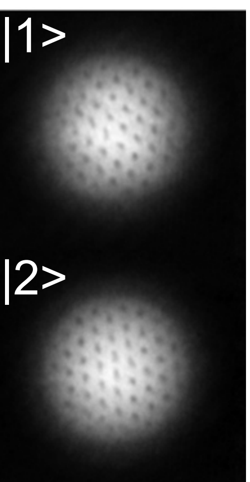


0%

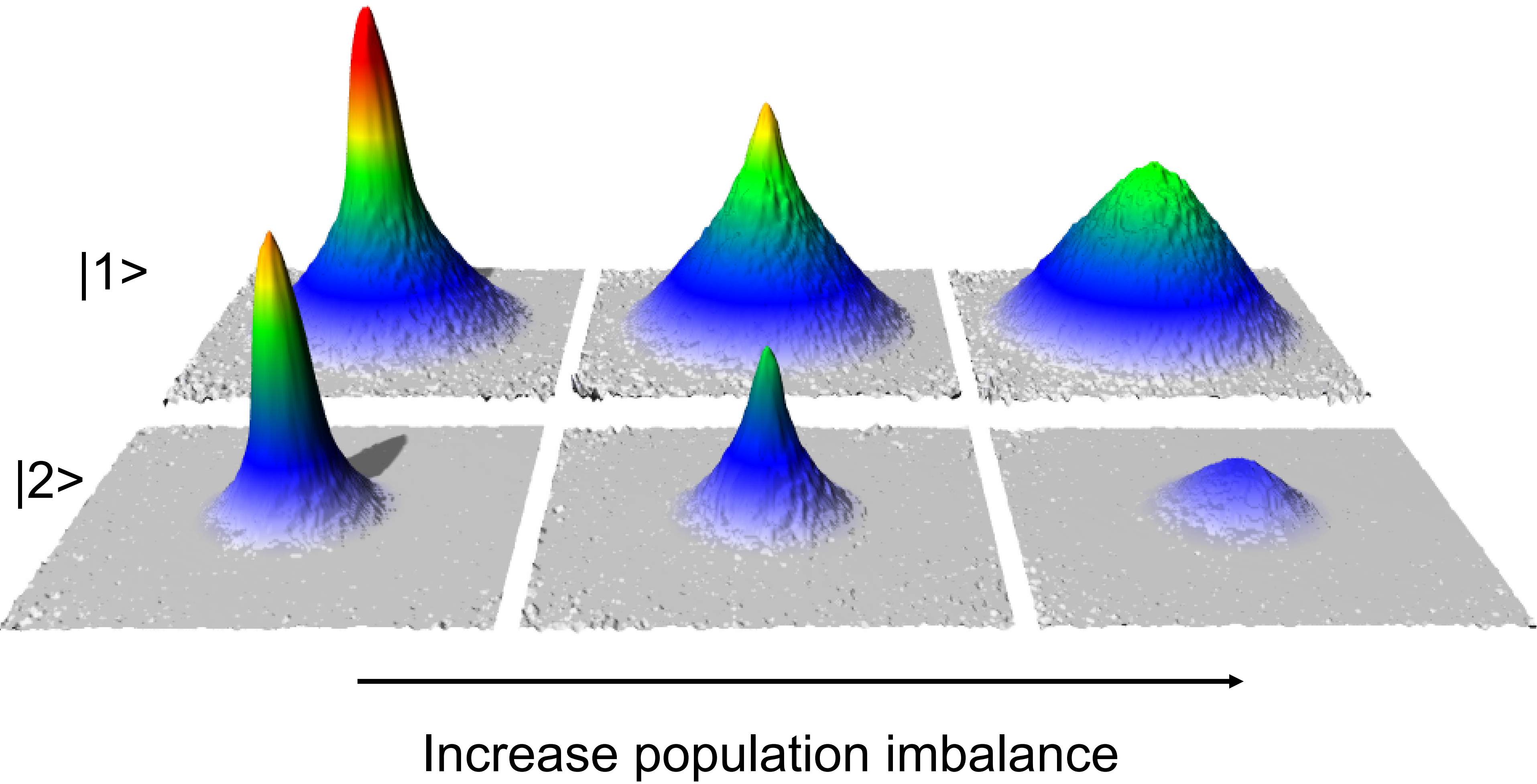
BCS-Side

Population Imbalance: $\delta = (N_2 - N_1)/(N_2 + N_1)$

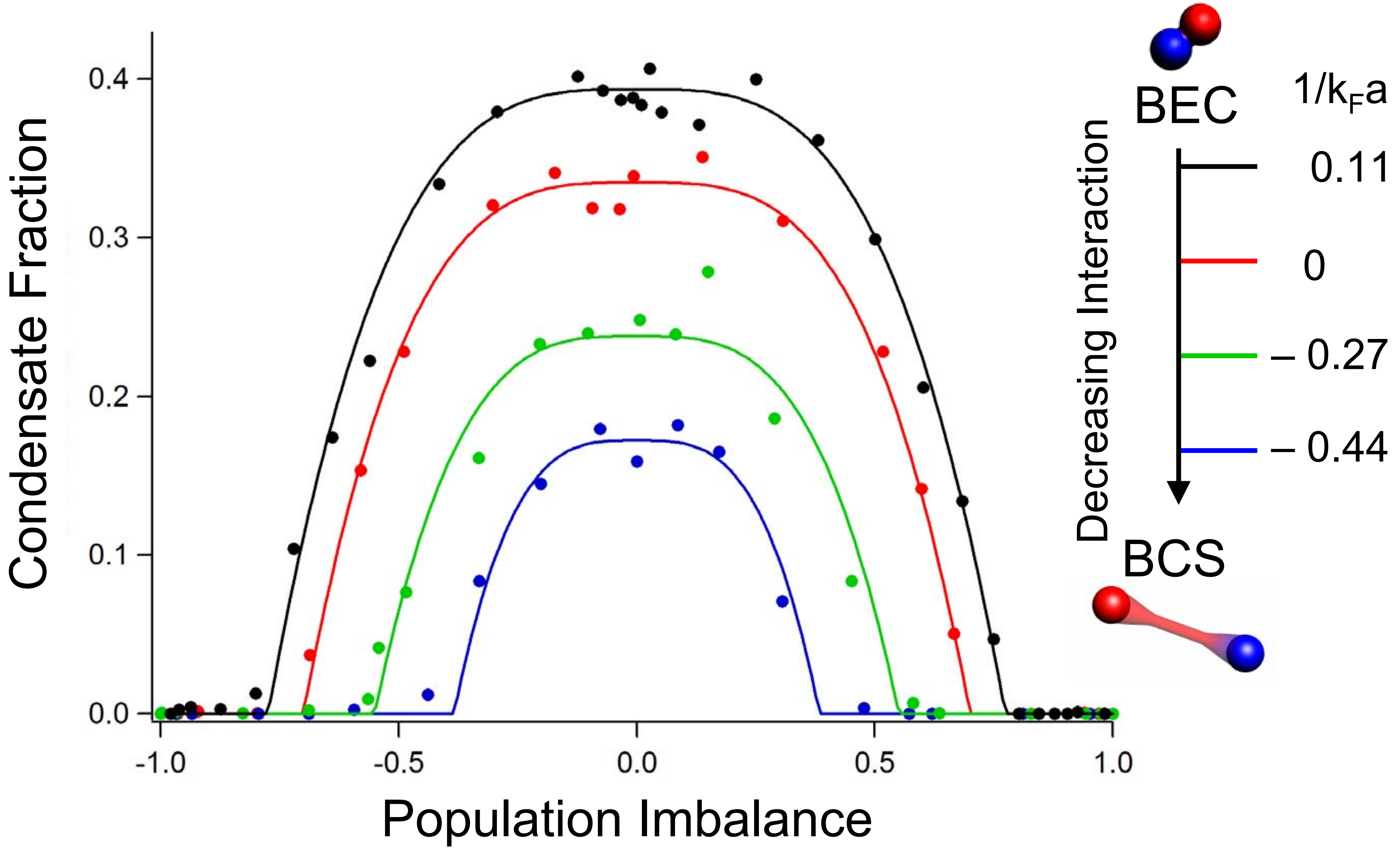
$1/k_F a = -0.15$



0%


|1>
|2>
Increase population imbalance

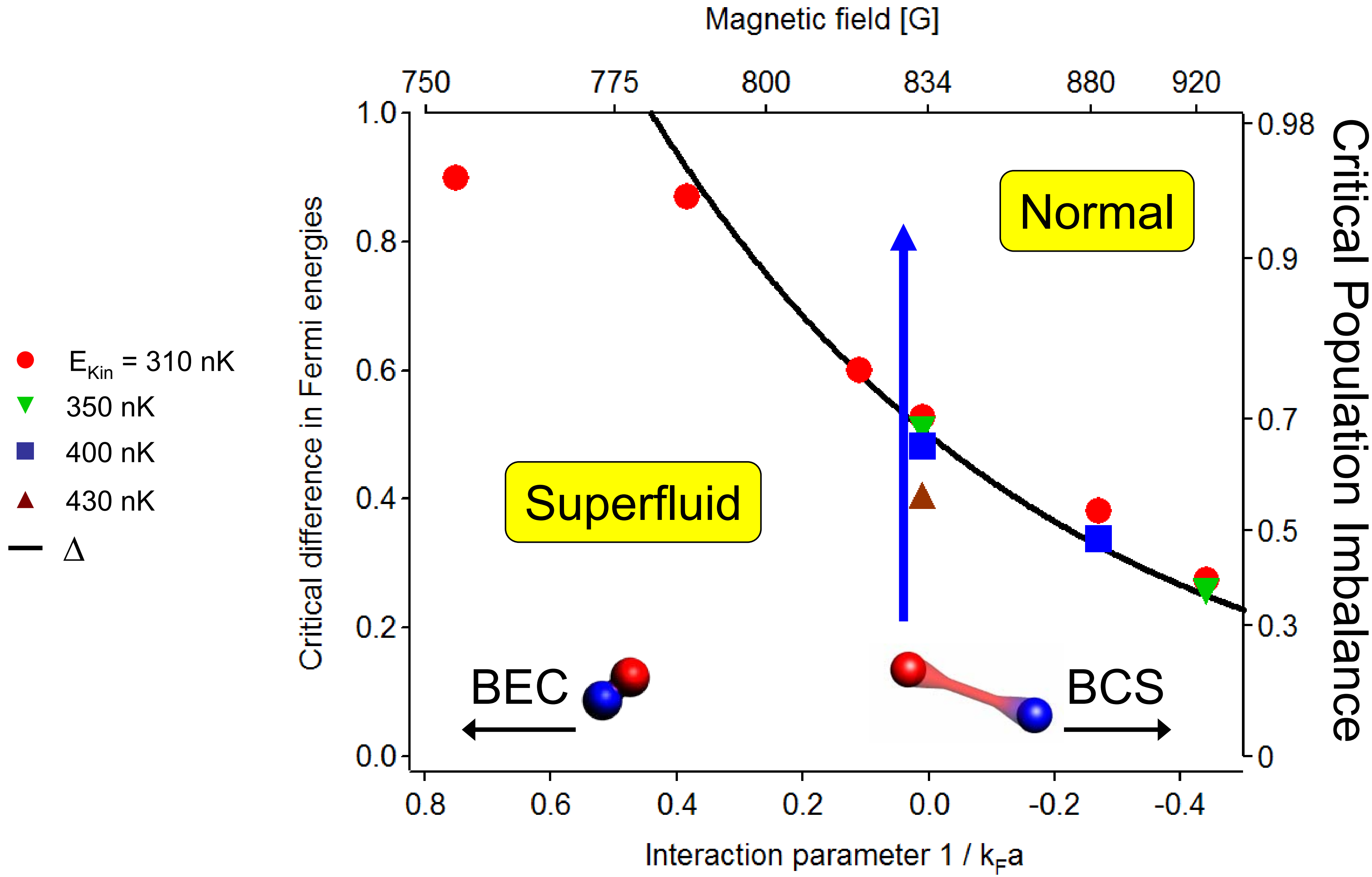
The Window of Superfluidity



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

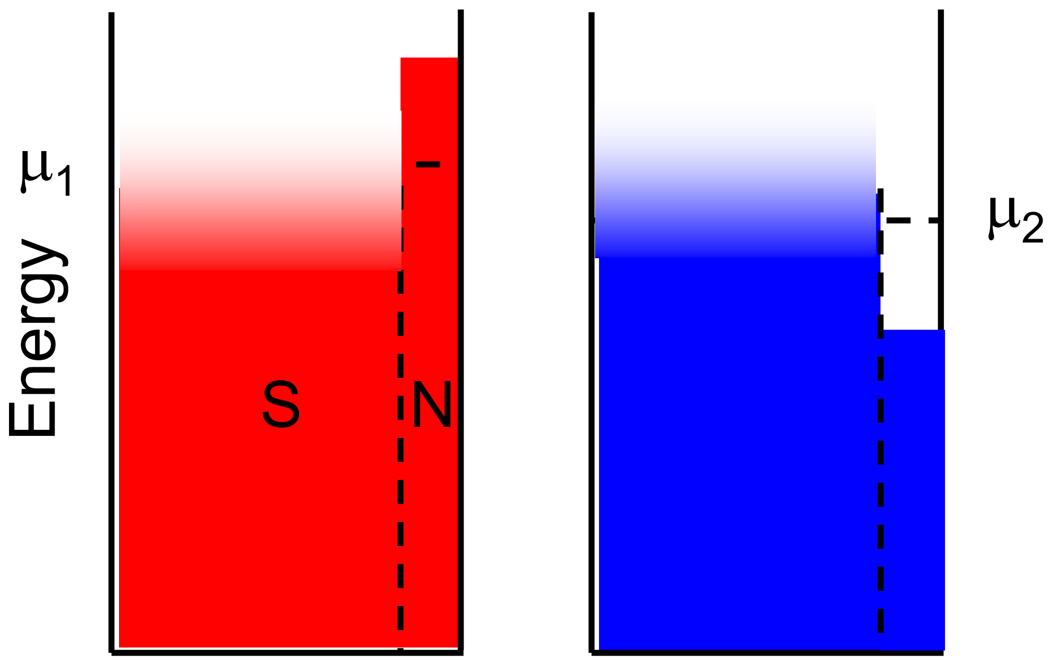
M.W. Zwierlein, A. Schirotzek, C.H. Schunck, W. Ketterle,
Science 311, 492 (2006), published online on Science Express 21 December 2005

Phase Diagram for Unequal Mixtures

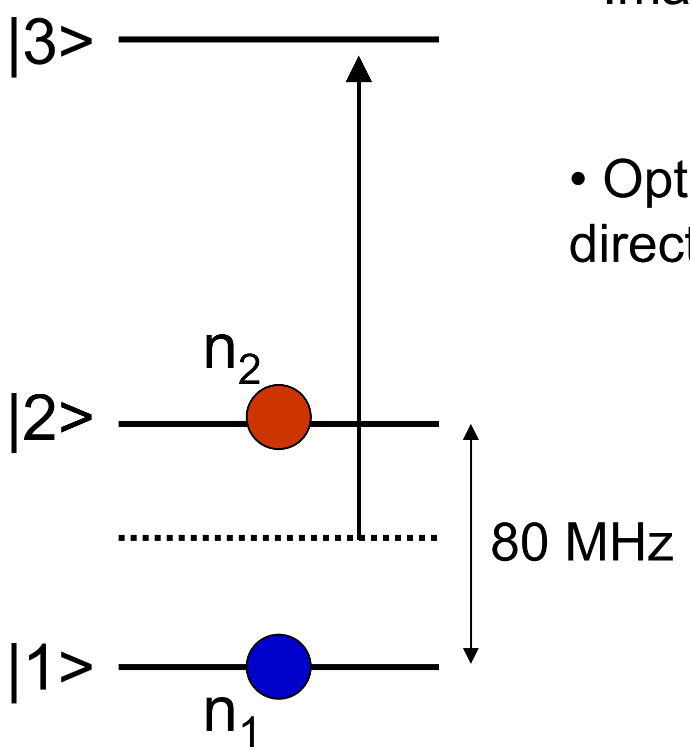


Breakdown: Critical mismatch in Fermi energies $\Delta E_F \approx$ Gap Δ

What is the nature of the superfluid state?



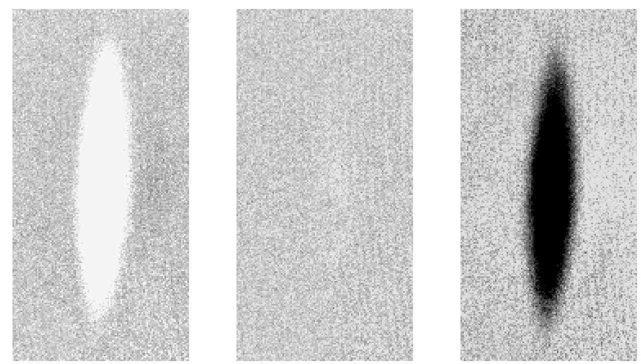
Phase Contrast Imaging



Li linewidth: Γ= 6 MHz

- Imaging beam red-detuned for |1>,
  blue-detuned for |2>

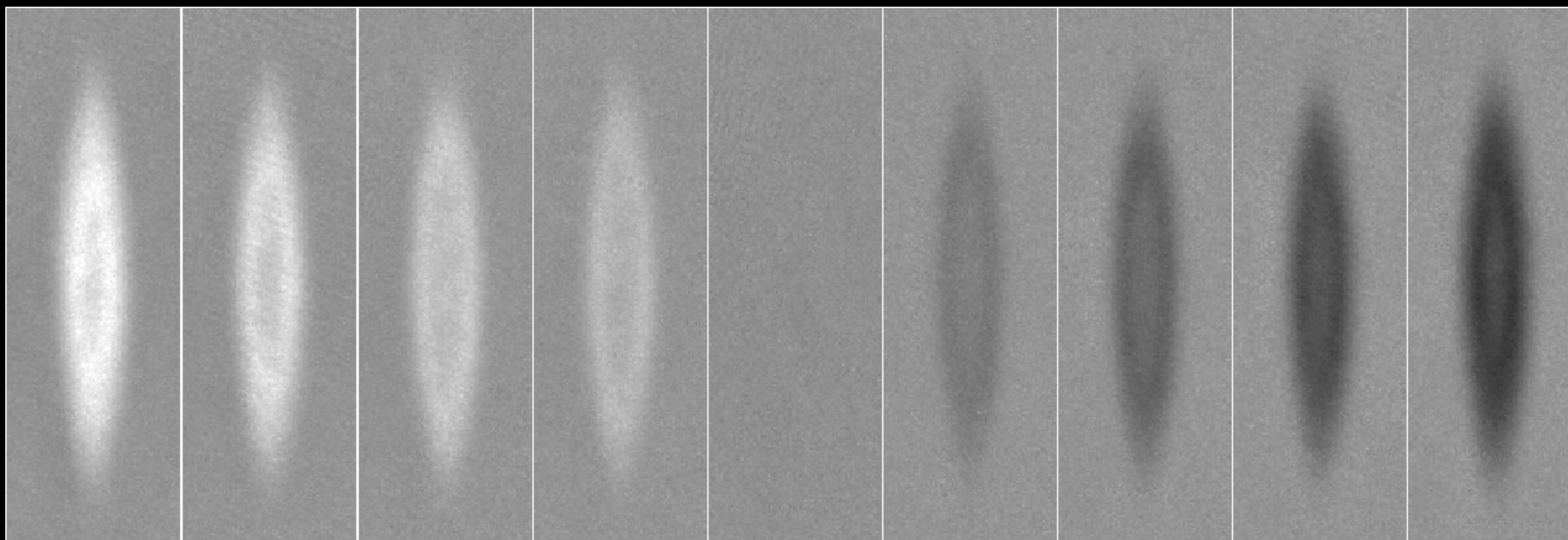
- Optical signal of phase-contrast imaging directly measures density difference $\Delta n=n_2-n_1$



|1>   Equal mixture |2>

In-trap images

Direct imaging of the density difference



-50% -37% -30% -24% 0% 20% 30% 40% 50%

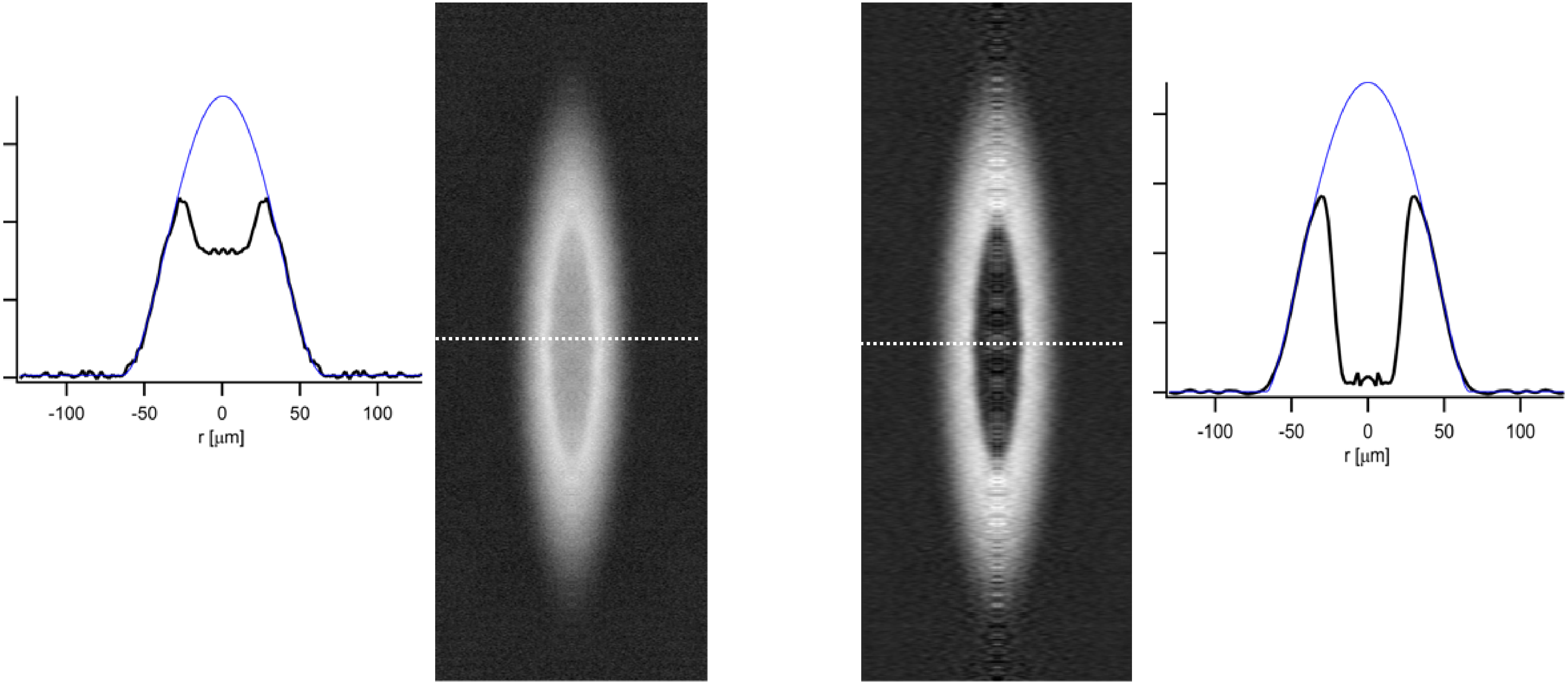
Population imbalance

The shell structure is a hint of the phase separation.

Reconstruction of 3D density profile

δ=0.6

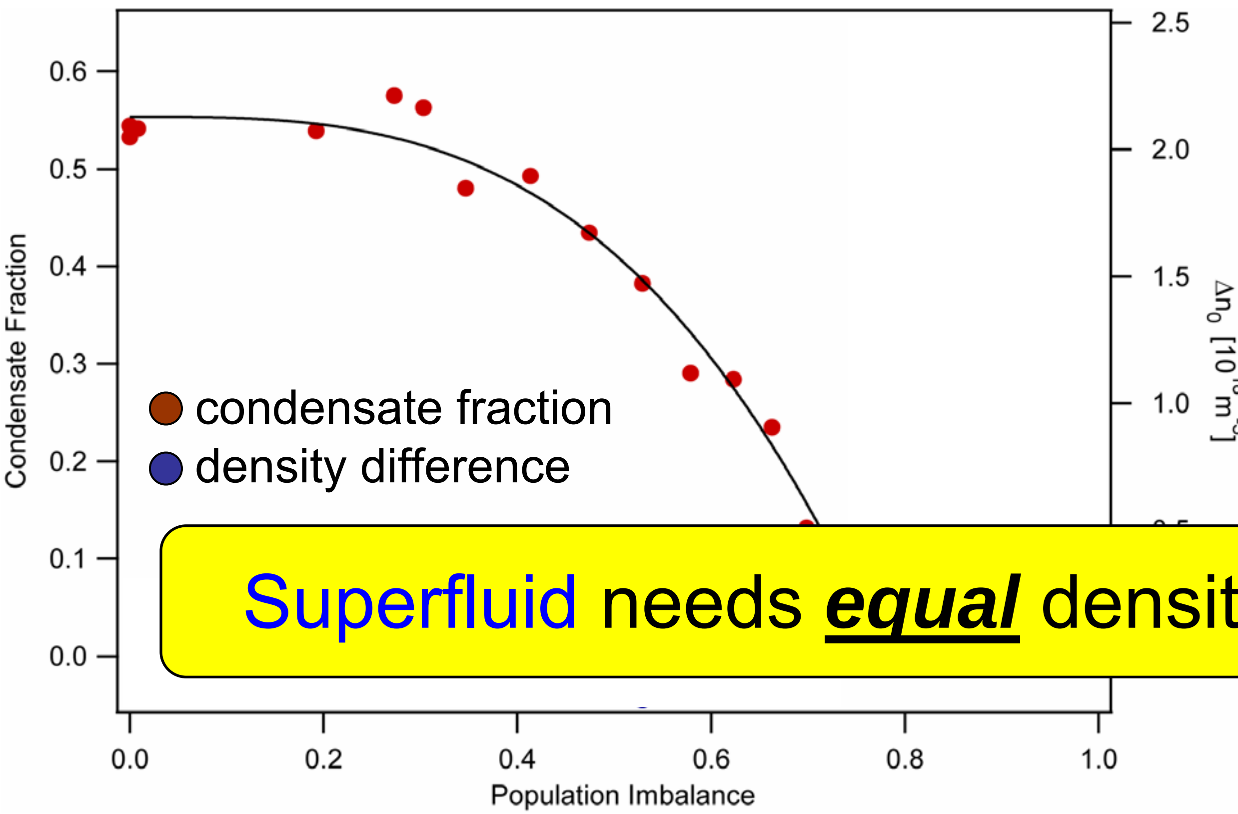
Only assumption: cylindrical symmetry

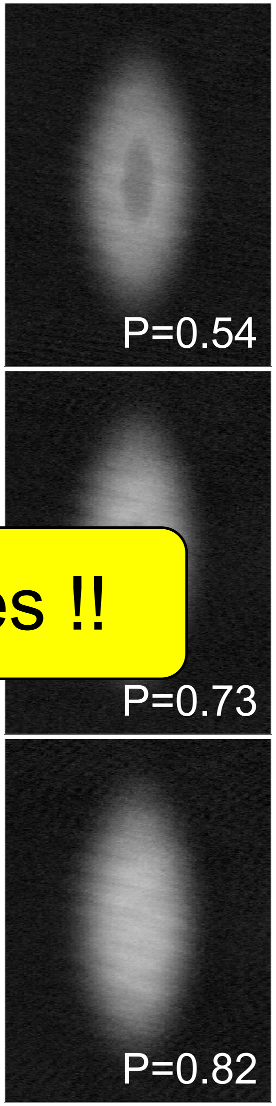


Phase Separation !!

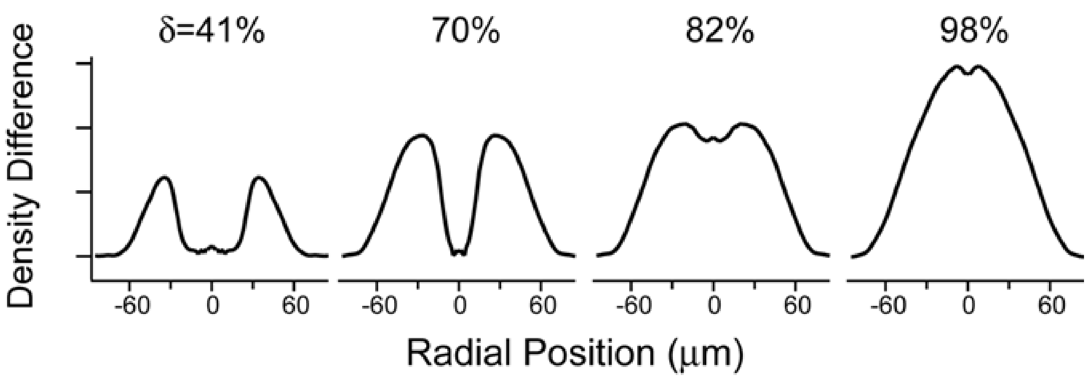
Superfluidity vs Polarization

Strategy: Correlation of Superfluidity and Central Polarization

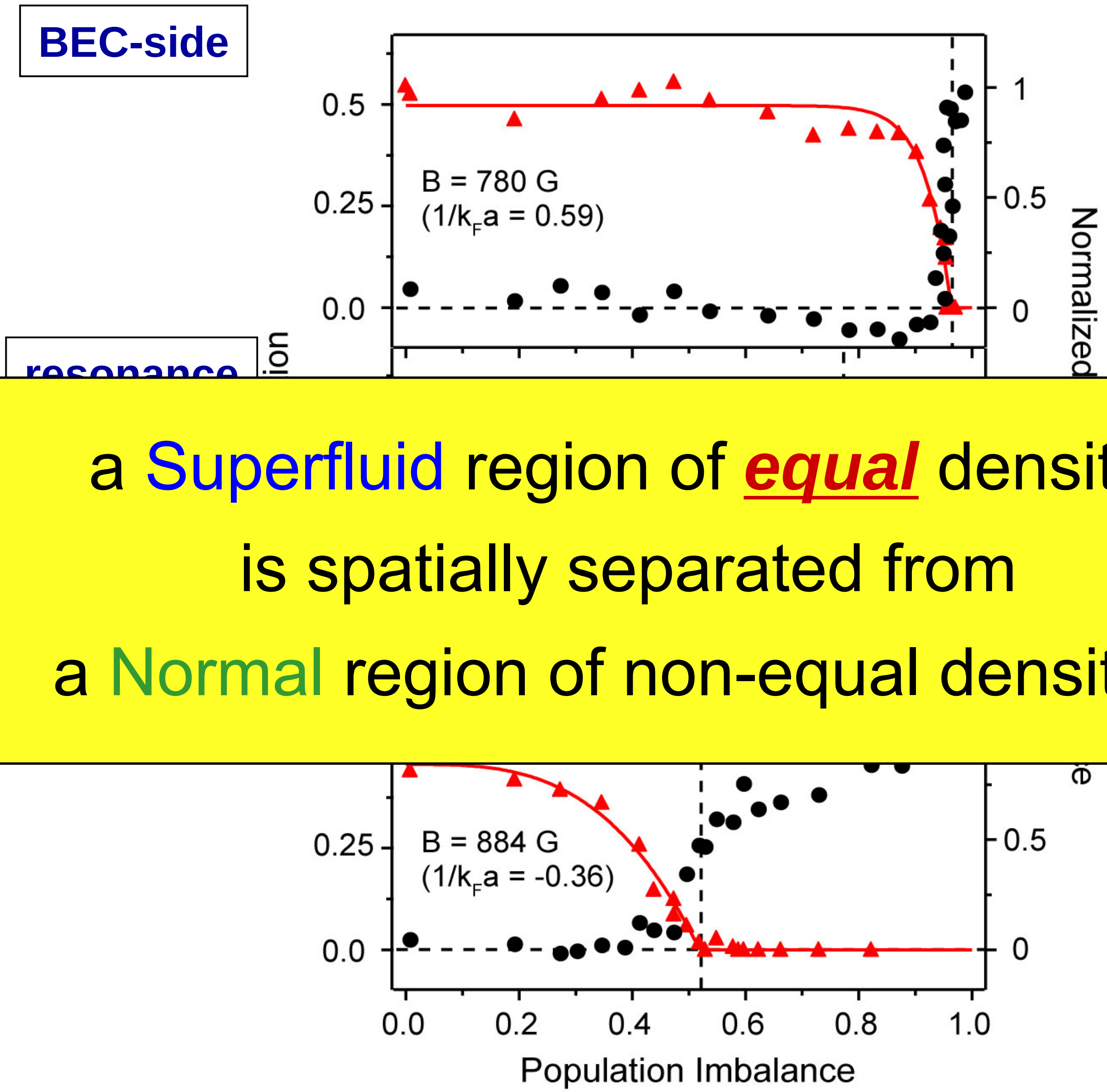




Superfluid needs *equal* densities !!



Phase Separation of a Polarized Fermi Gas



a Superfluid region of ***equal*** densities

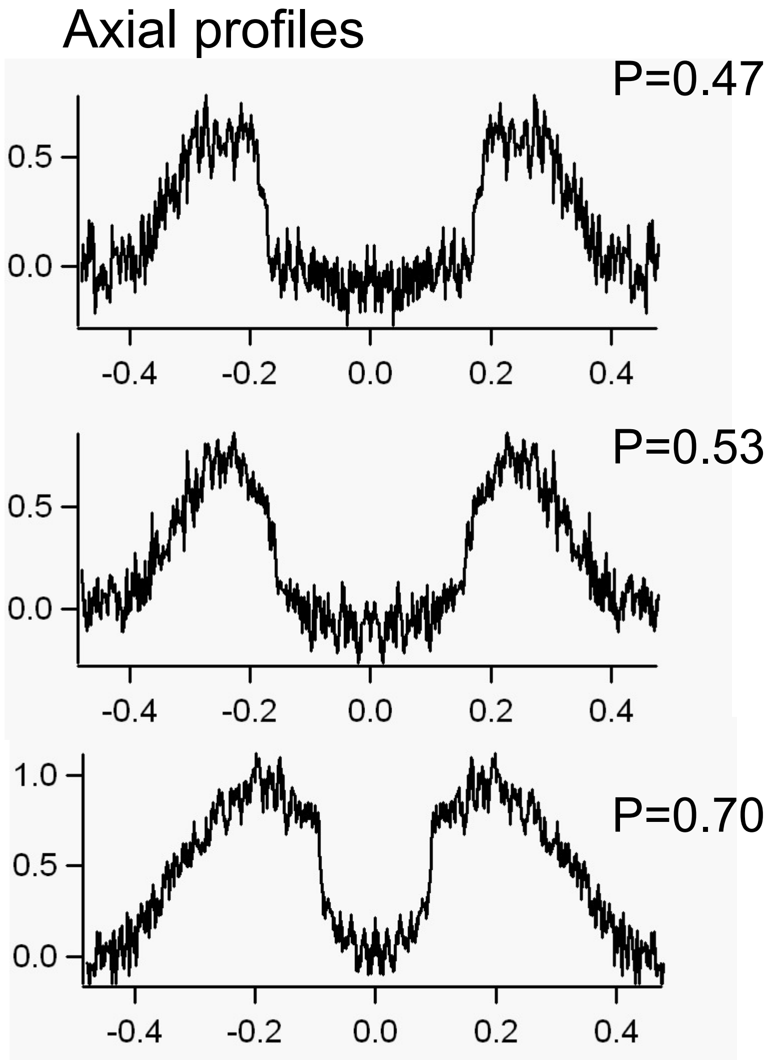
is spatially separated from

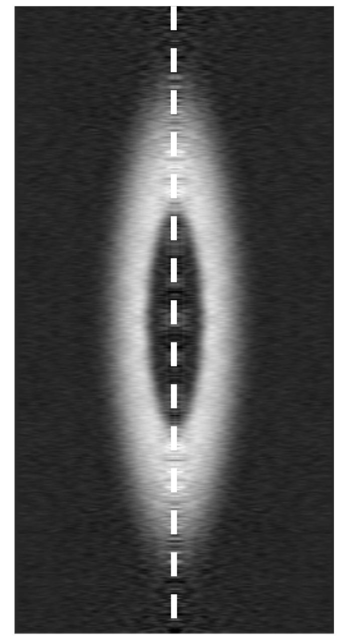
a Normal region of non-equal densities

Y. Shin et al., PRL **97**, 030401(2006)

Phase Separation: First-order Phase Transition ?

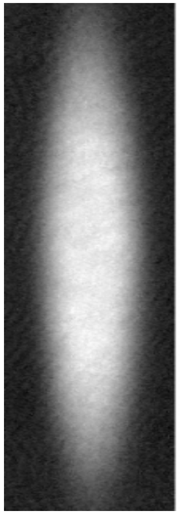
Sharpness of the boundary (the intermediate region)

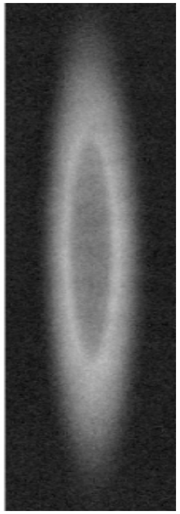




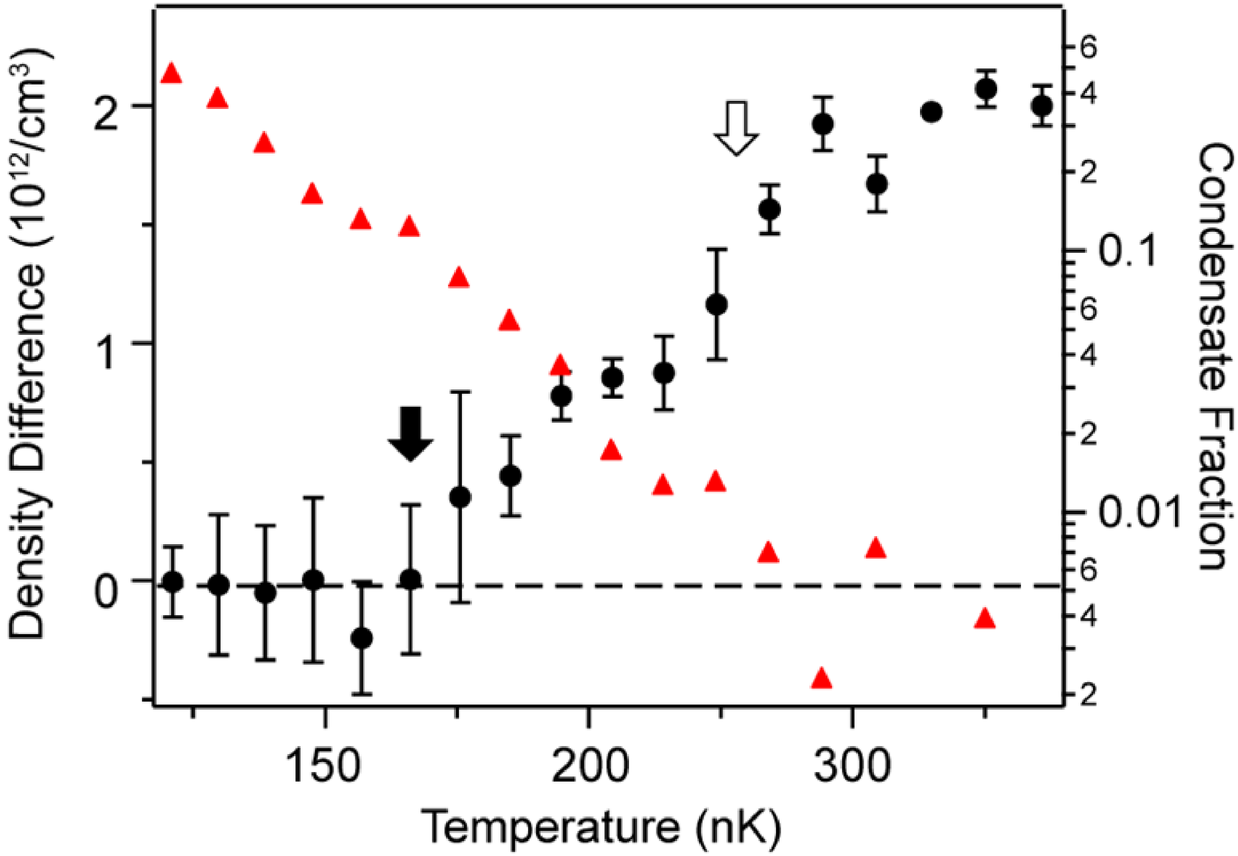
Direct Observation of Phase Transition

Normal — Cooling down → Superfluid





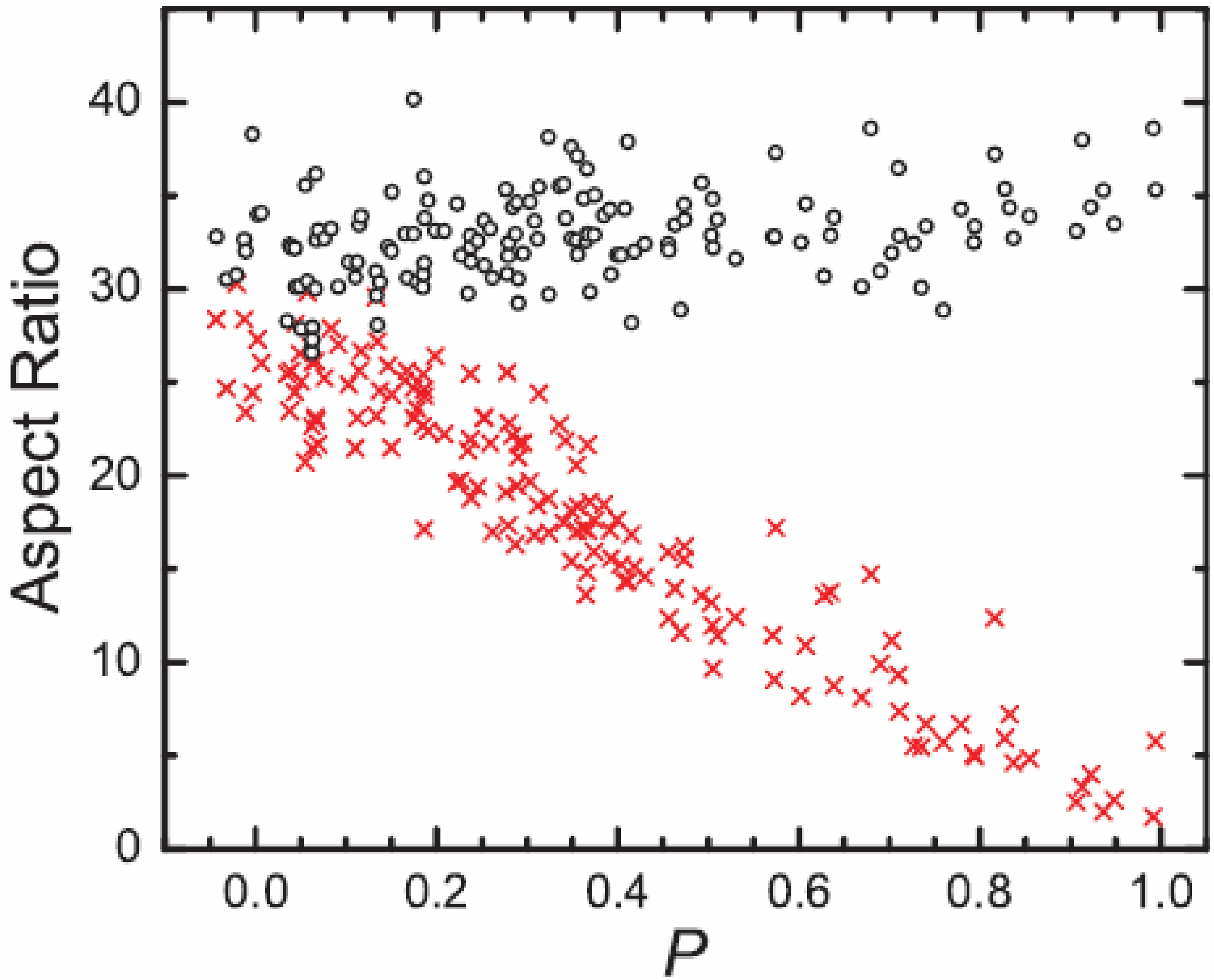
Finite Temperature Effects



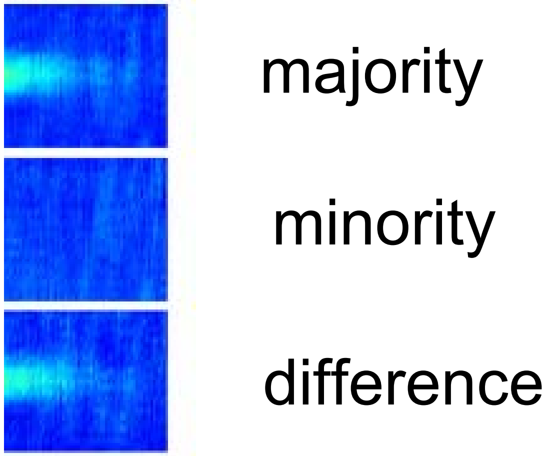
- Temperature-induced polarized superfluid.
- Thermal population of quasiparticles ($k_B T > \Delta$)

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

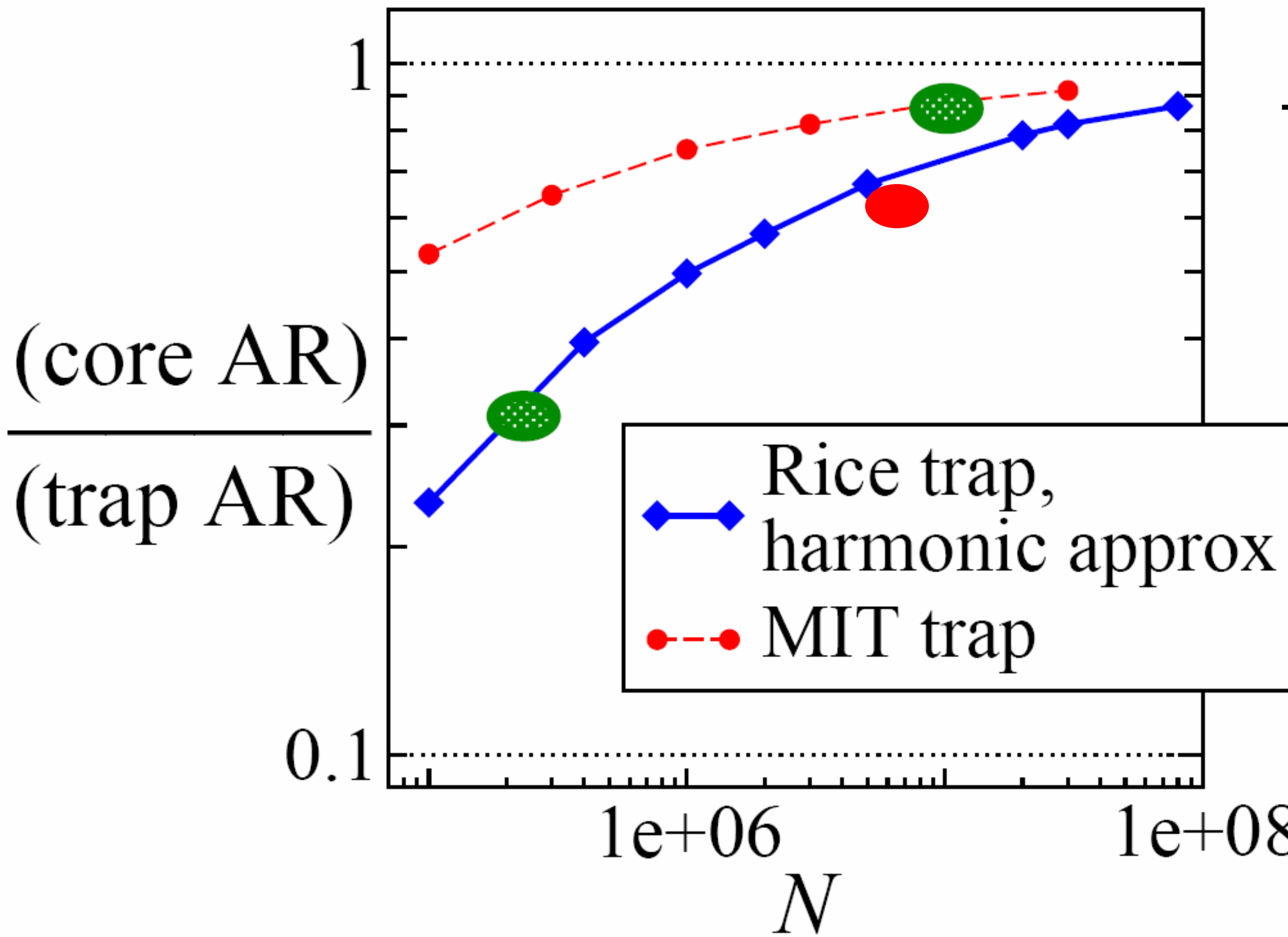


trecht, The Netherlands



Spatial distortion of trapped Fermi gases

Masudul Haque[1,2] and H. T. C. Stoof[2]



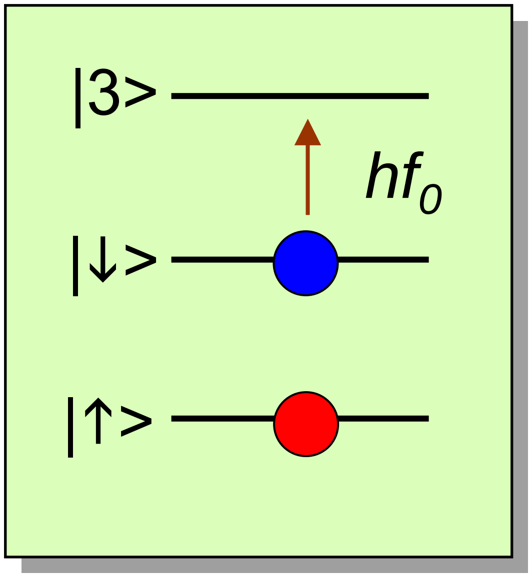
Trap AR 50

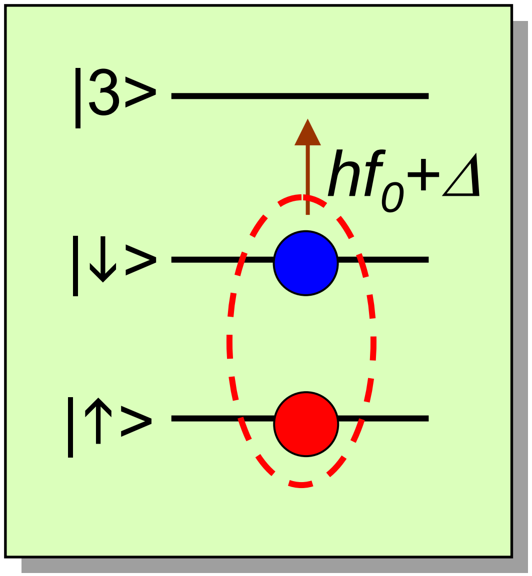
$T/T_F<0.1$

What happens at the Chandrasekhar-Clogston limit?

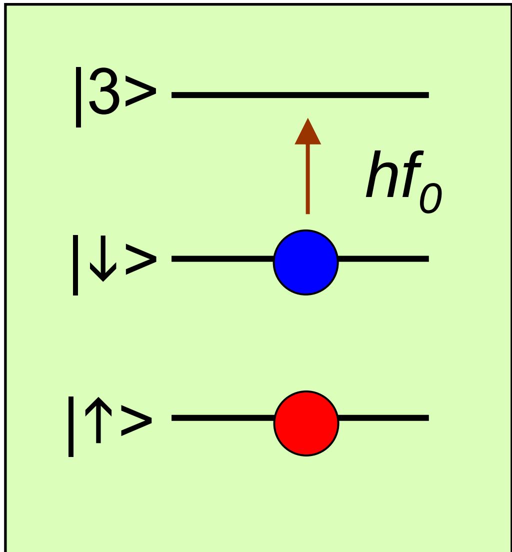
Also called the Pauli pair breaking limit …

RF spectroscopy

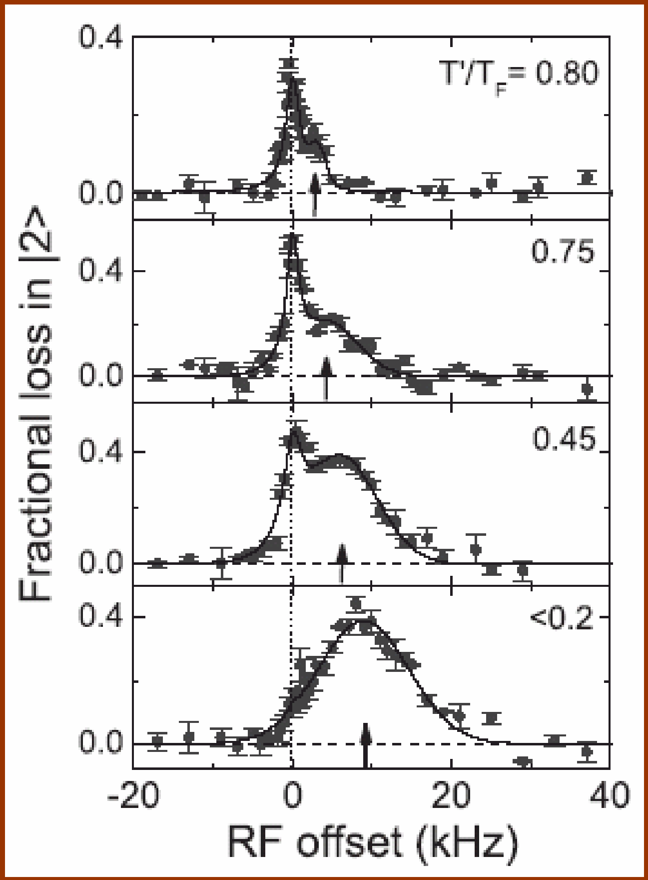




RF spectroscopy



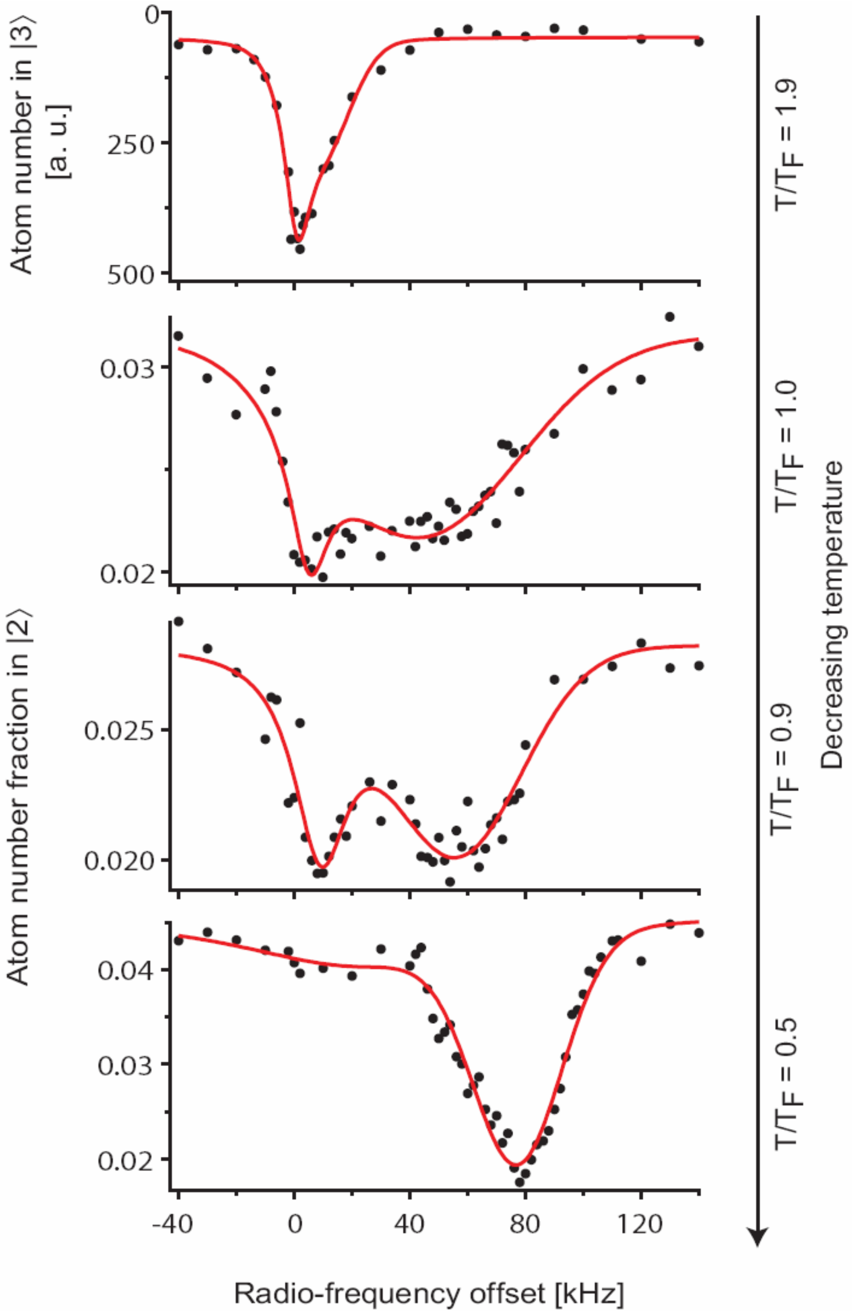
With Equal Mixtures



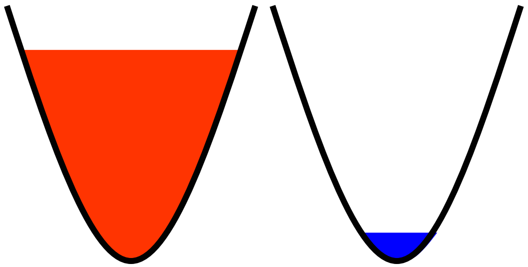
C. Chin et al., Science **305**, 1128 (2004)

The double peak structure indicates the presence of pairing.

RF Spectroscopy with Imbalanced Mixtures



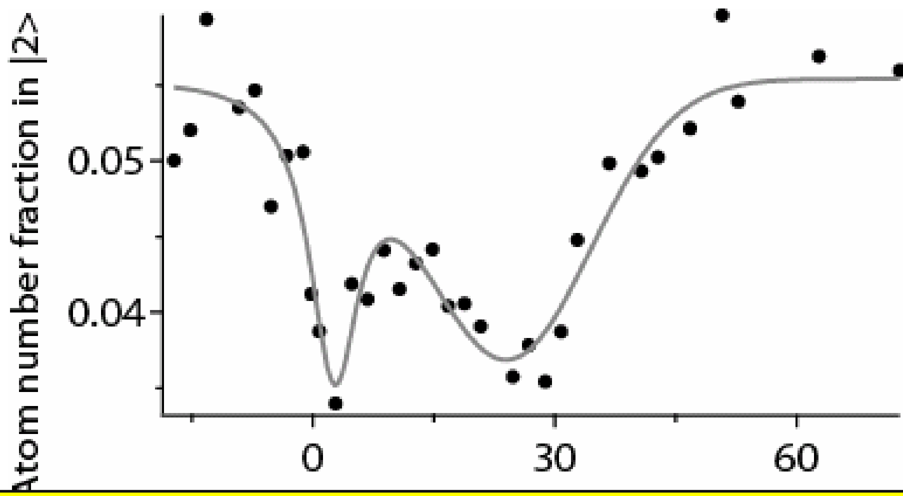
Imbalance $\delta > 90\%$



Atoms can be fully paired in the normal phase *even above* the critical imbalance.

C.H. Schunck, Y. Shin, A. Schirotzek, M.W. Zwierlein, WK: Science, in print; cond-mat 0702066

Pairing without Superfluidity



On the BCS side (936G)

Imbalance $\delta \sim 90\%$

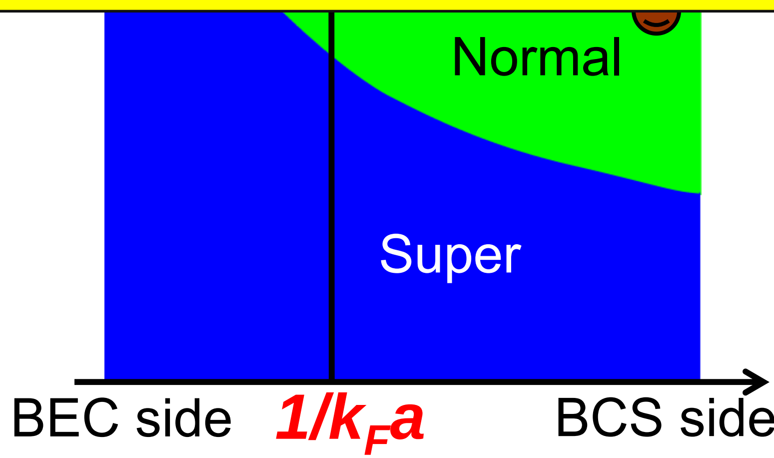
$T/T_F \sim 0.3$ ($E_F \sim h \times 280$kHz)

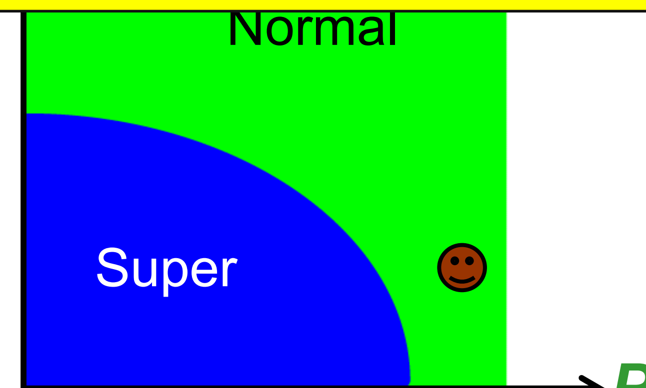
$1/k_F a = -0.18$

$\delta_{c,exp} \sim 60\%$

Fermion pairs(?) *cannot* Bose-condense even at T=0 !!

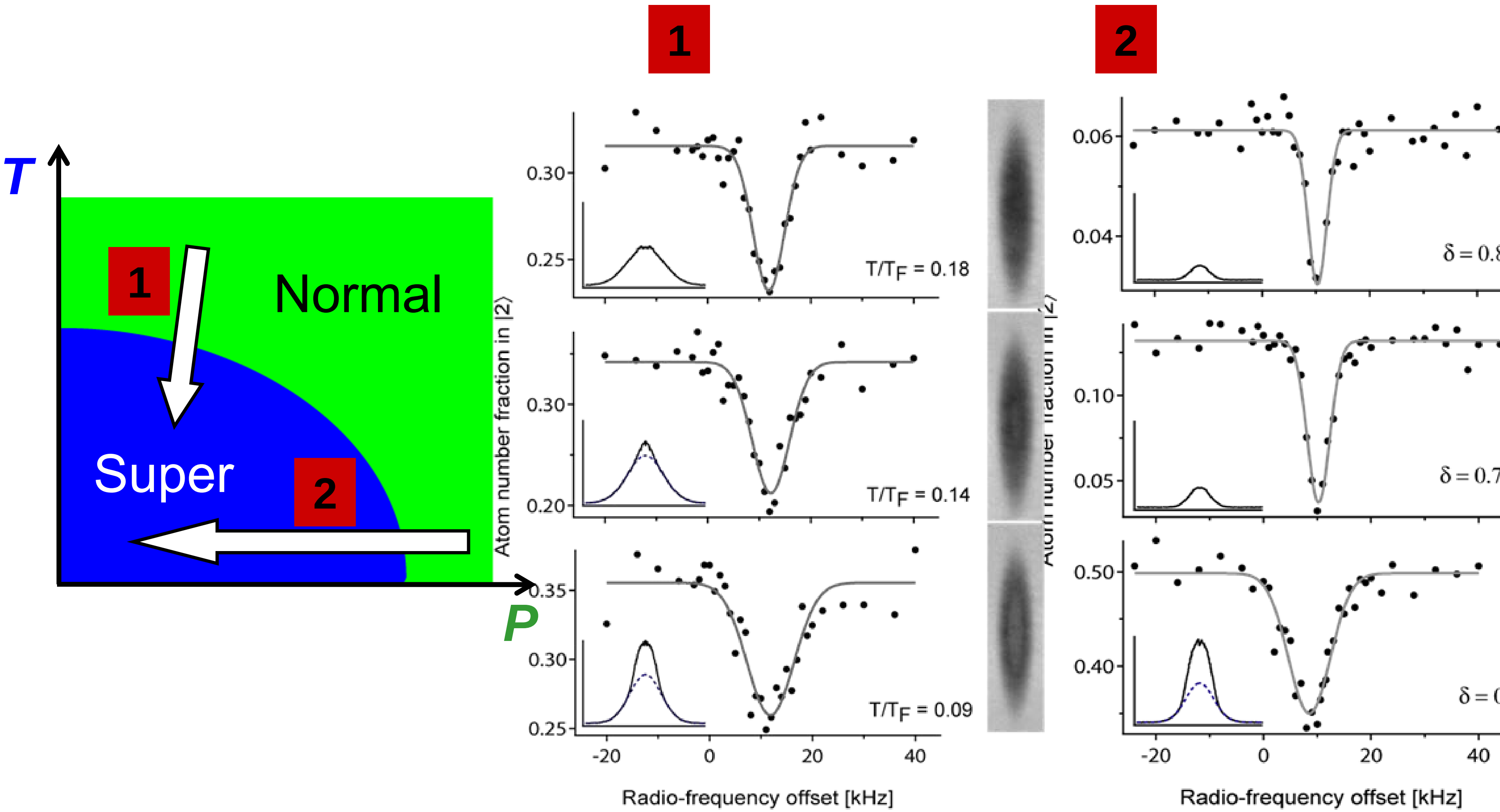
Pairing is *not* necessarily a precursor of **Superfluidity**.





C.H. Schunck et al., cond-mat/0702066

Rf spectroscopy across the phase transition



Rf-spectroscopy cannot reveal the onset of superfluidity.

Gap Tomography

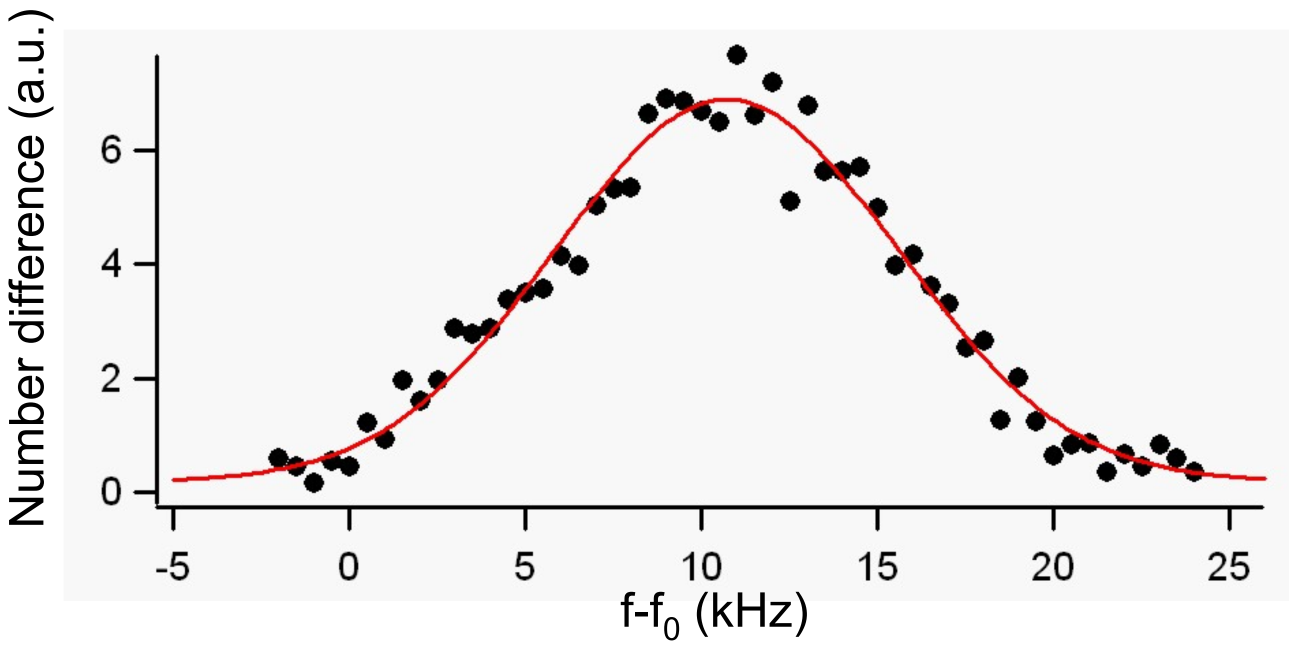
Inhomogeneous Sample

- Ultracold atom sample confined in a harmonic trap
- Inhomogeneous density profiles

→ Density broadening in the spectroscopic signal

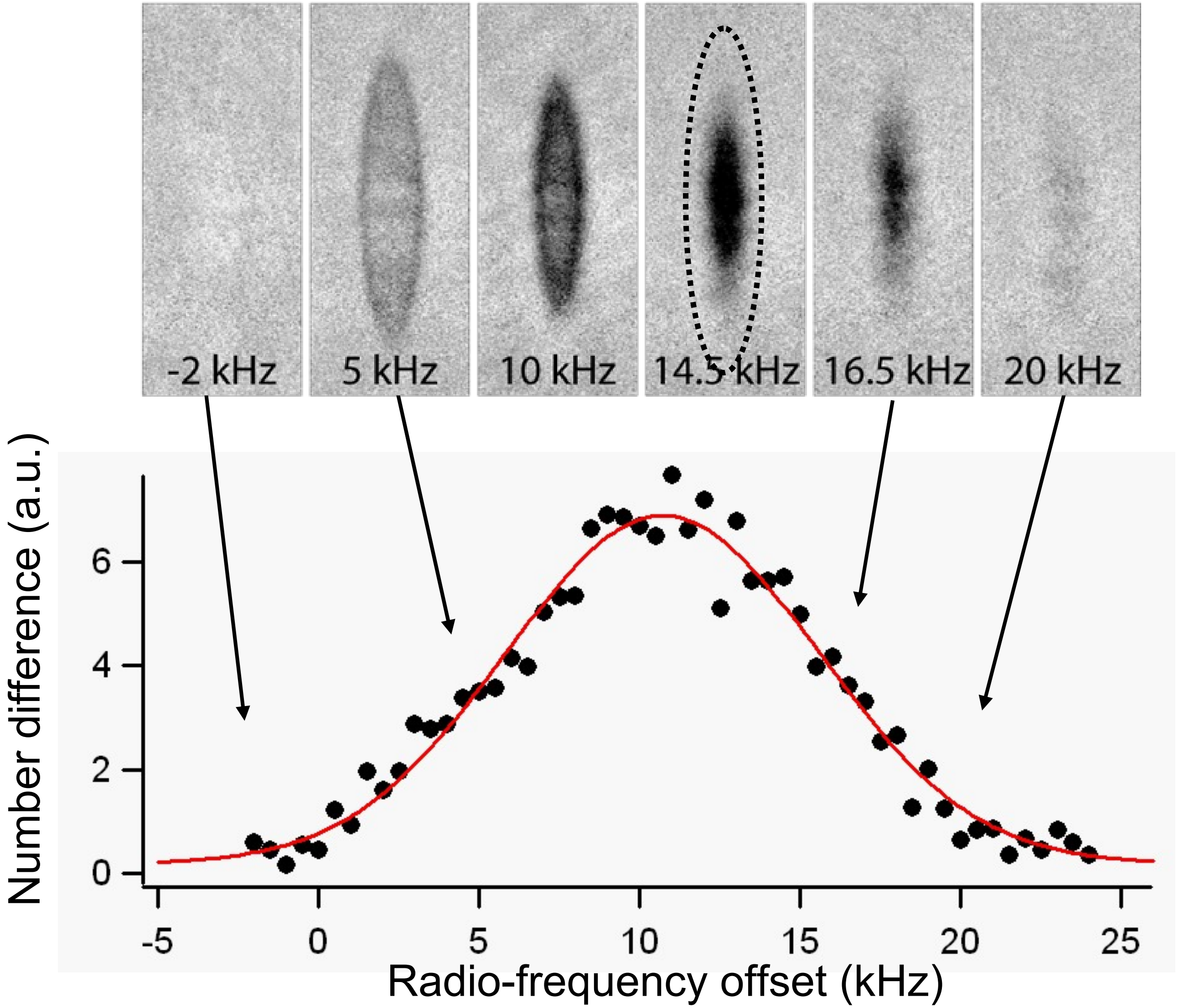
→ Difficult to compare with theoretical prediction

RF spectroscopy with equal mixtures



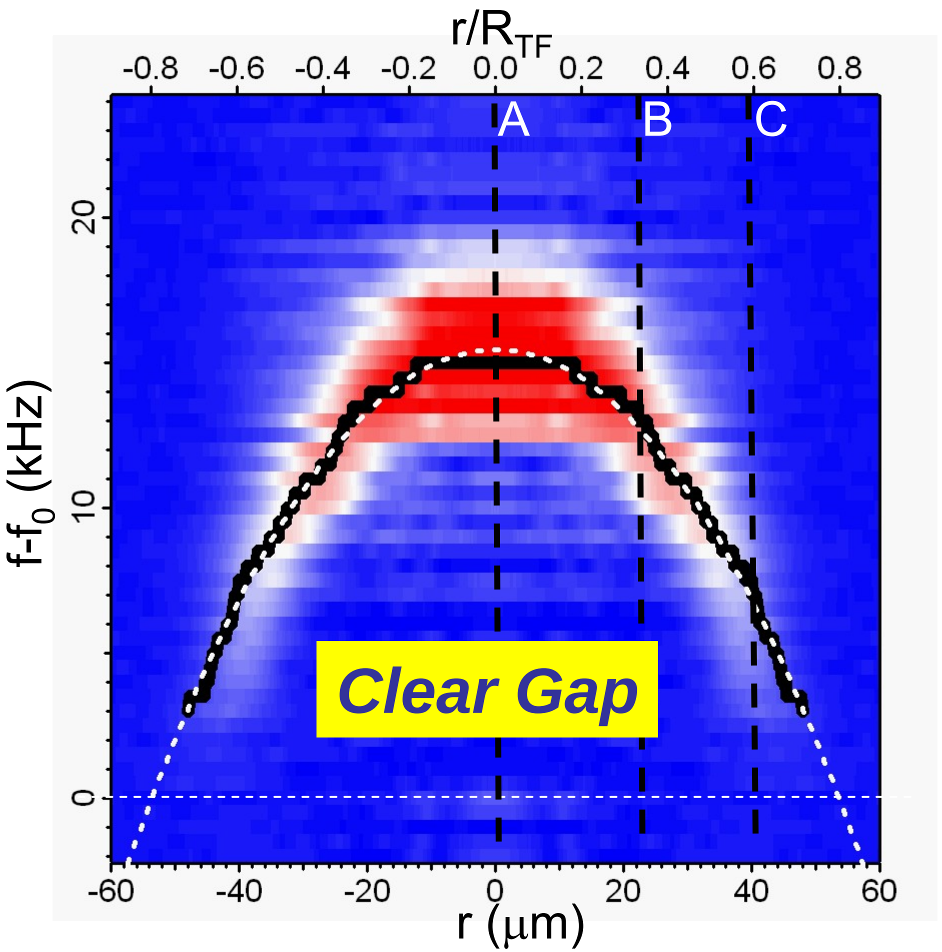
RF Spectroscopy with *in situ* Images

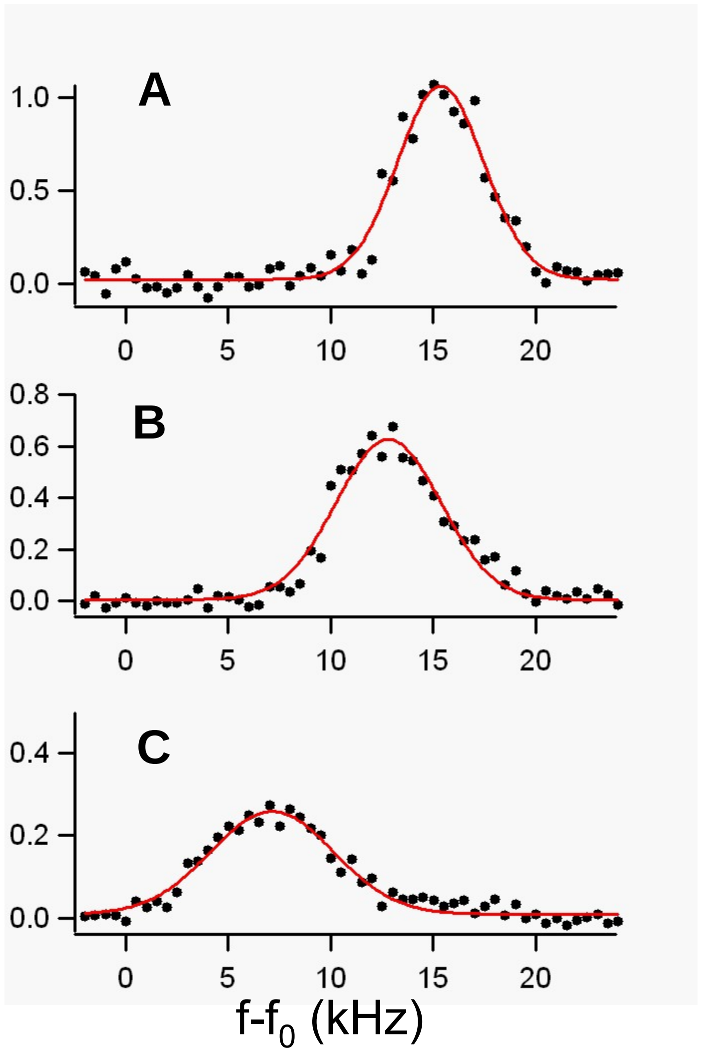
In situ phase contrast images measure the depletion region



Spatially resolved RF spectroscopy

On resonance, $T'/T_F < 0.05$



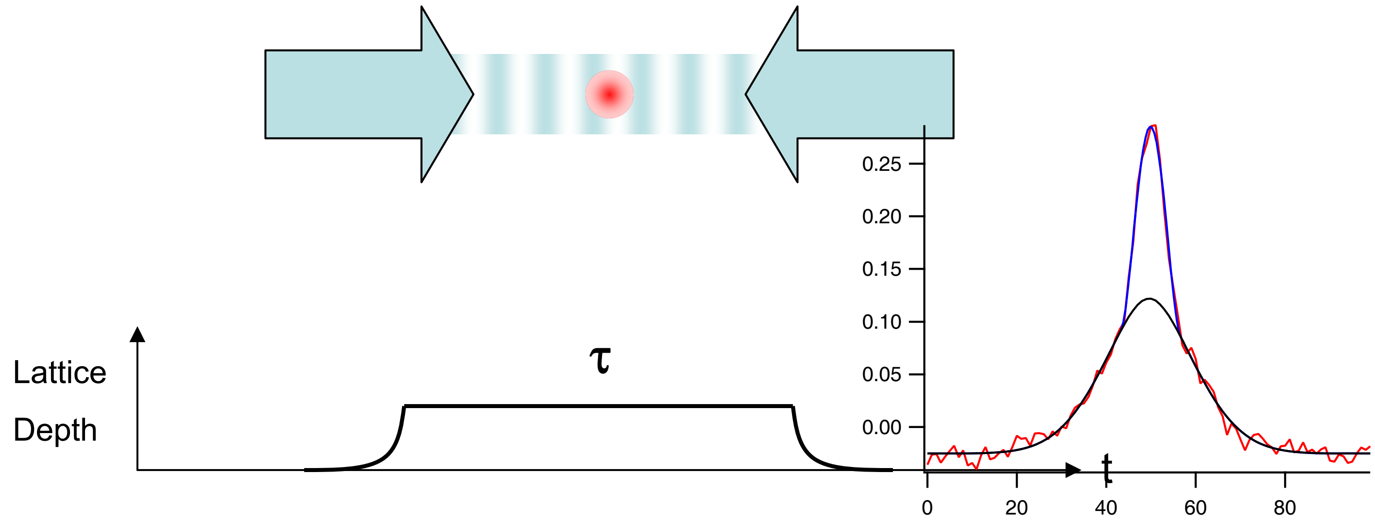


The parabolic profile is consistent with the harmonic confinement.

Critical Velocity

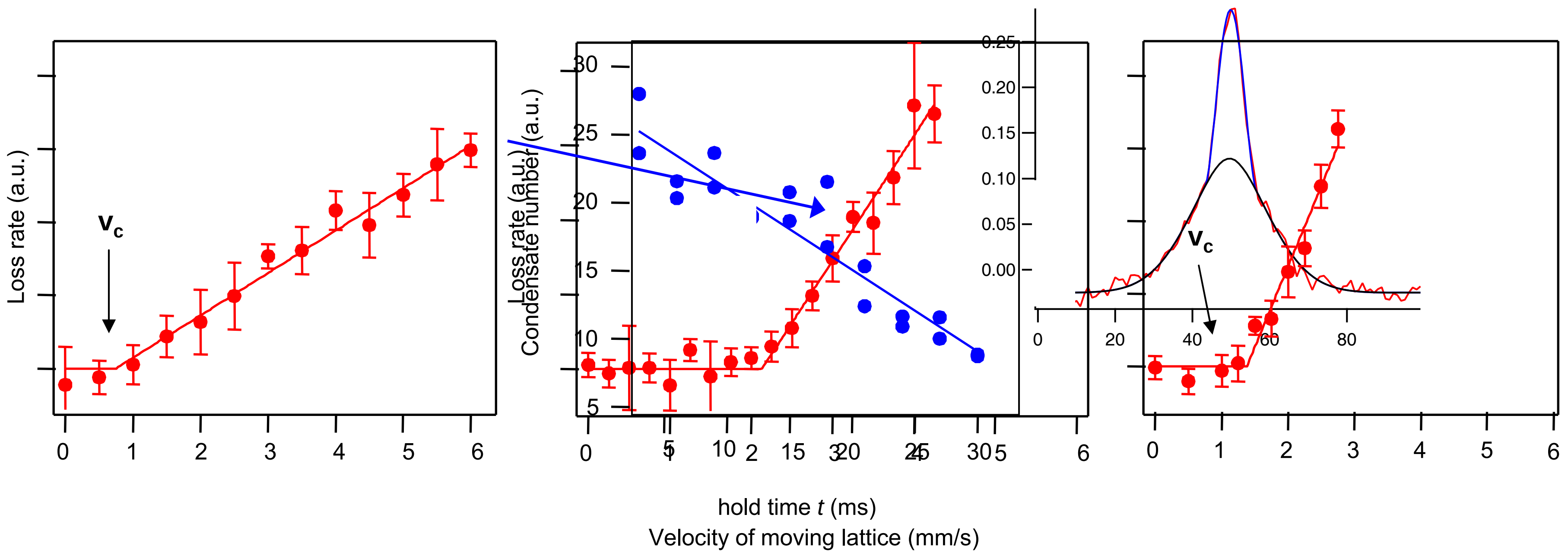
Dan Miller, Jitkee Chin et al., unpublished

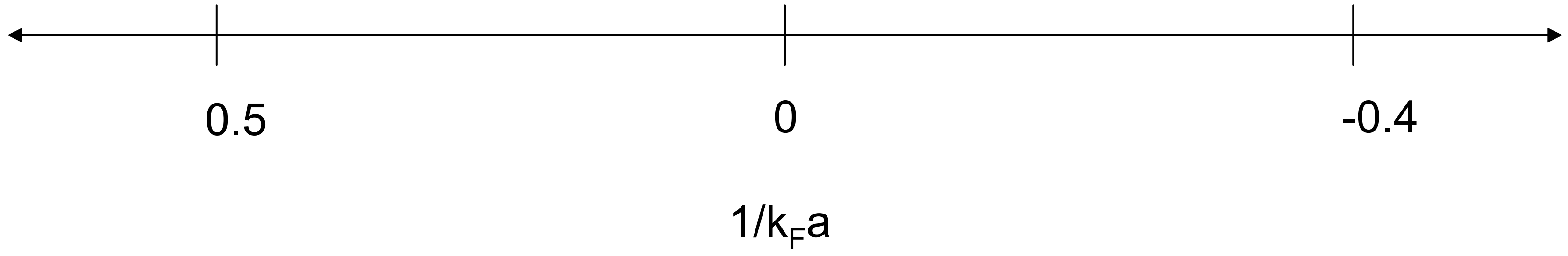
Experiment Overview



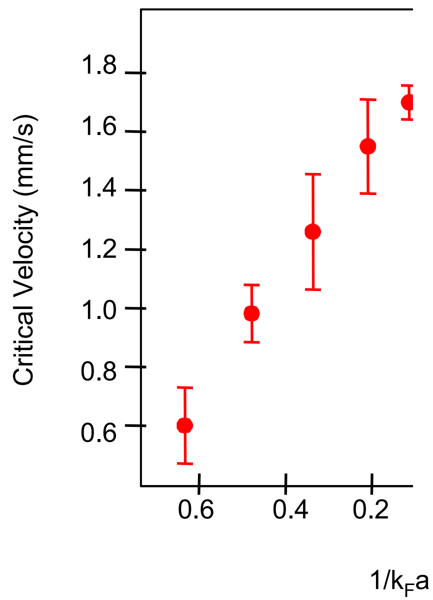
- A lattice with some fixed velocity is ramped up and held for a time τ.
- The cloud is released. Time of flight imaging reveals a bimodal distribution.

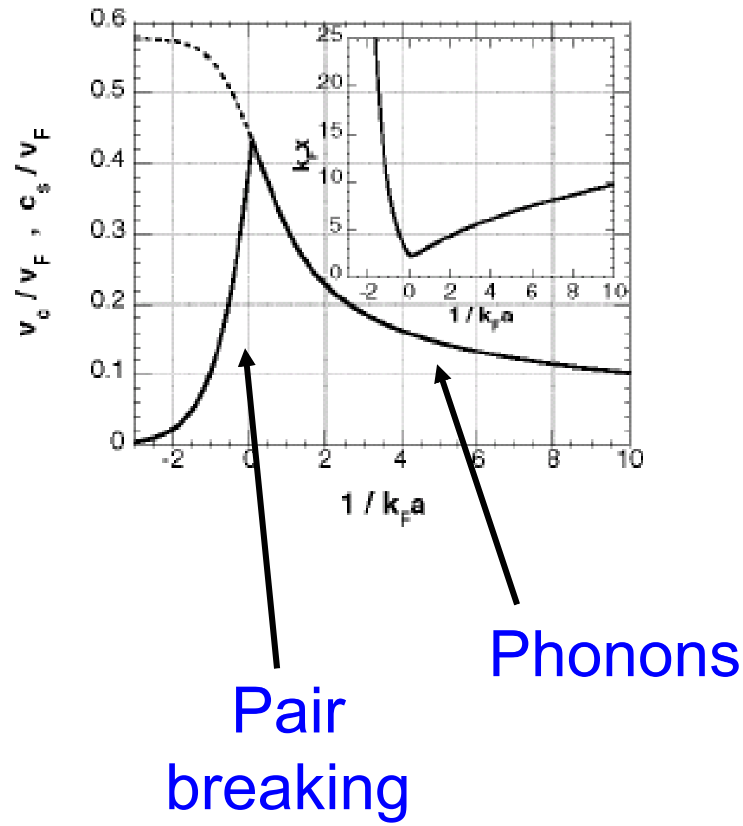
Experiment Overview





Conclusions





The superfluid is most robust on resonance

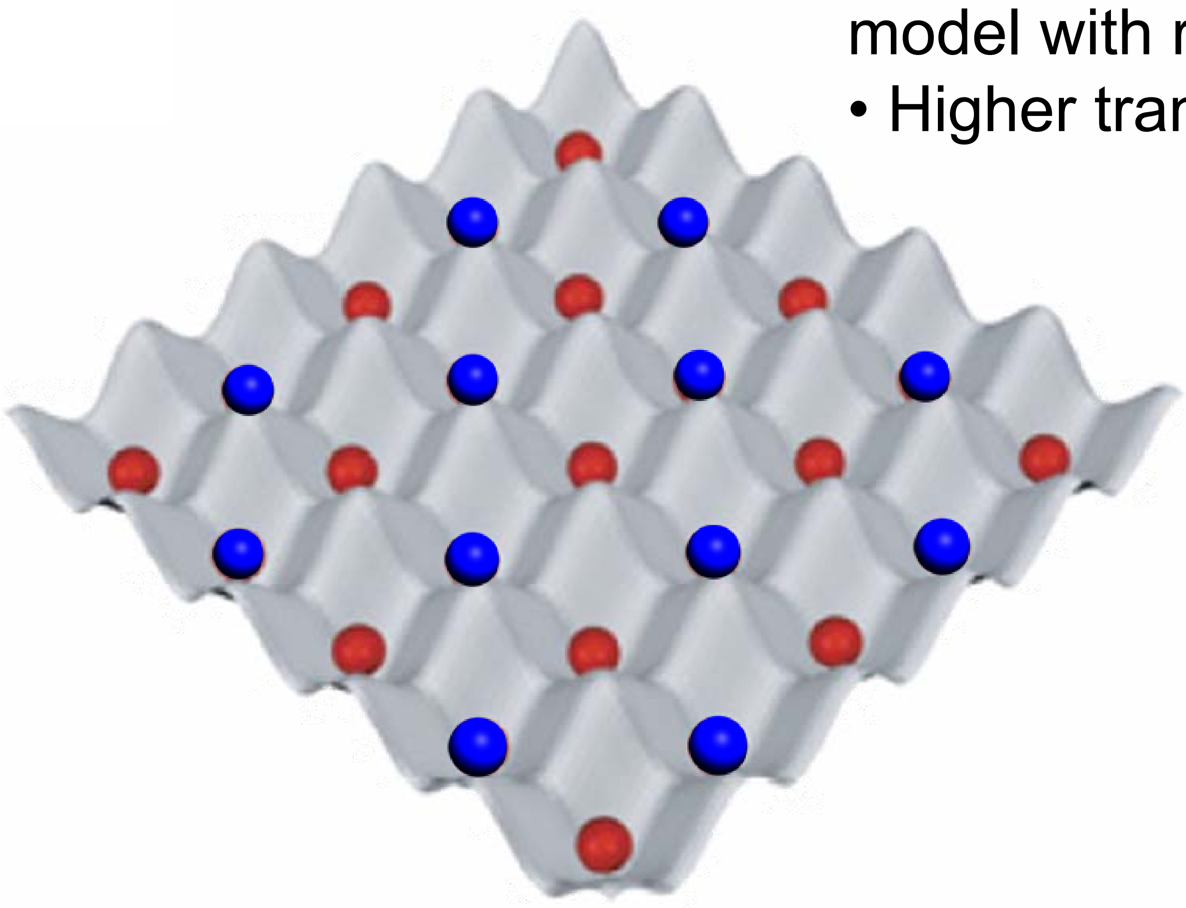
Observed *critical velocity* is an order of magnitude smaller than predicted.

Superfluidity of Ultracold Fermions in an Optical Lattice

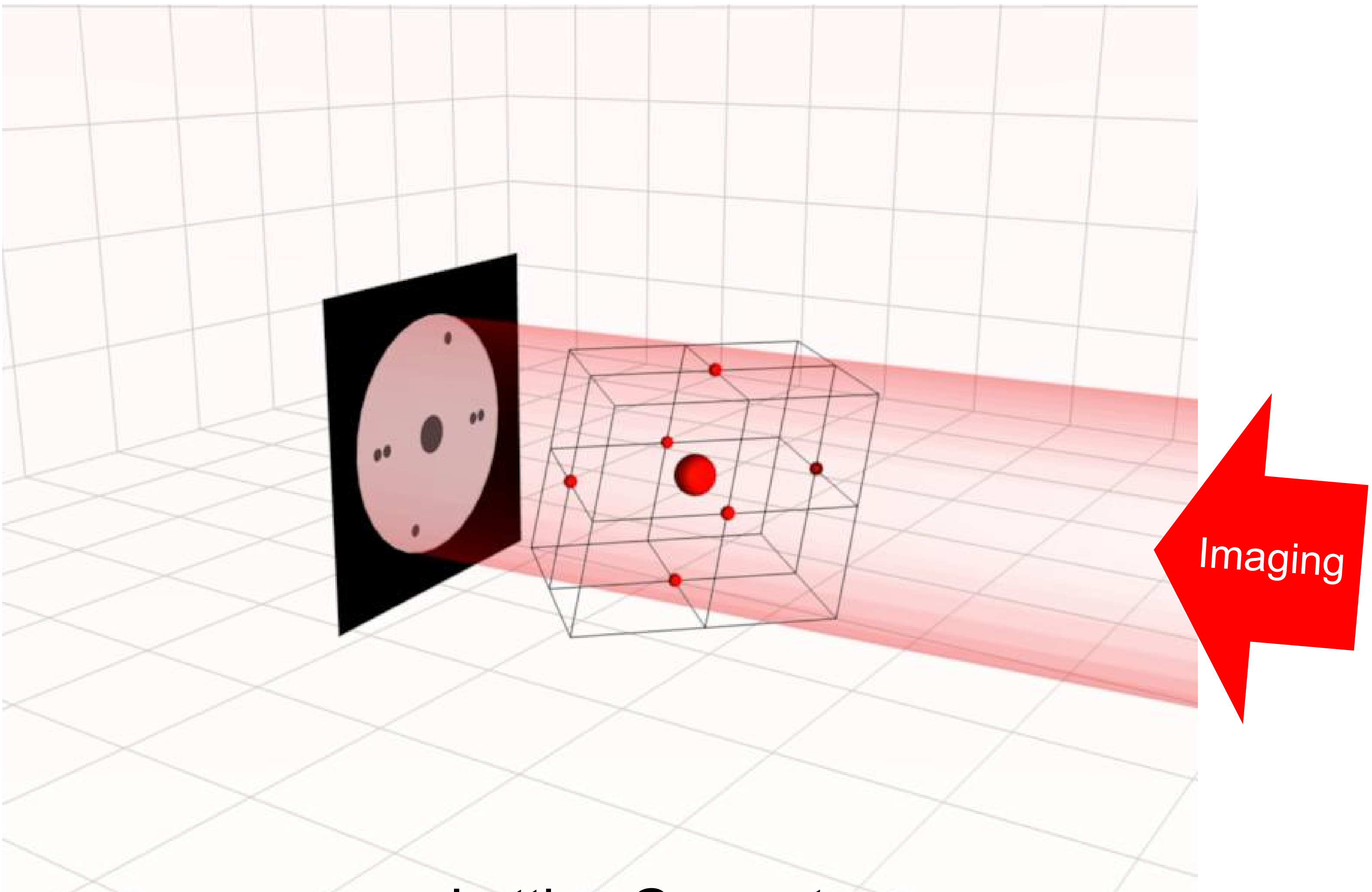
J.K. Chin, D.E. Miller, Y. Liu, C. Stan, W. Setiawan, C. Sanner, K. Xu, W.K., Nature **443**, 961-964 (2006).

Why lattice?

- Crystalline materials in nature
- Hubbard models; rich new phenomena
- Minimal model for high-T_c d-wave superfluidity is lattice Hubbard model with repulsive interactions
- Higher transition temperature

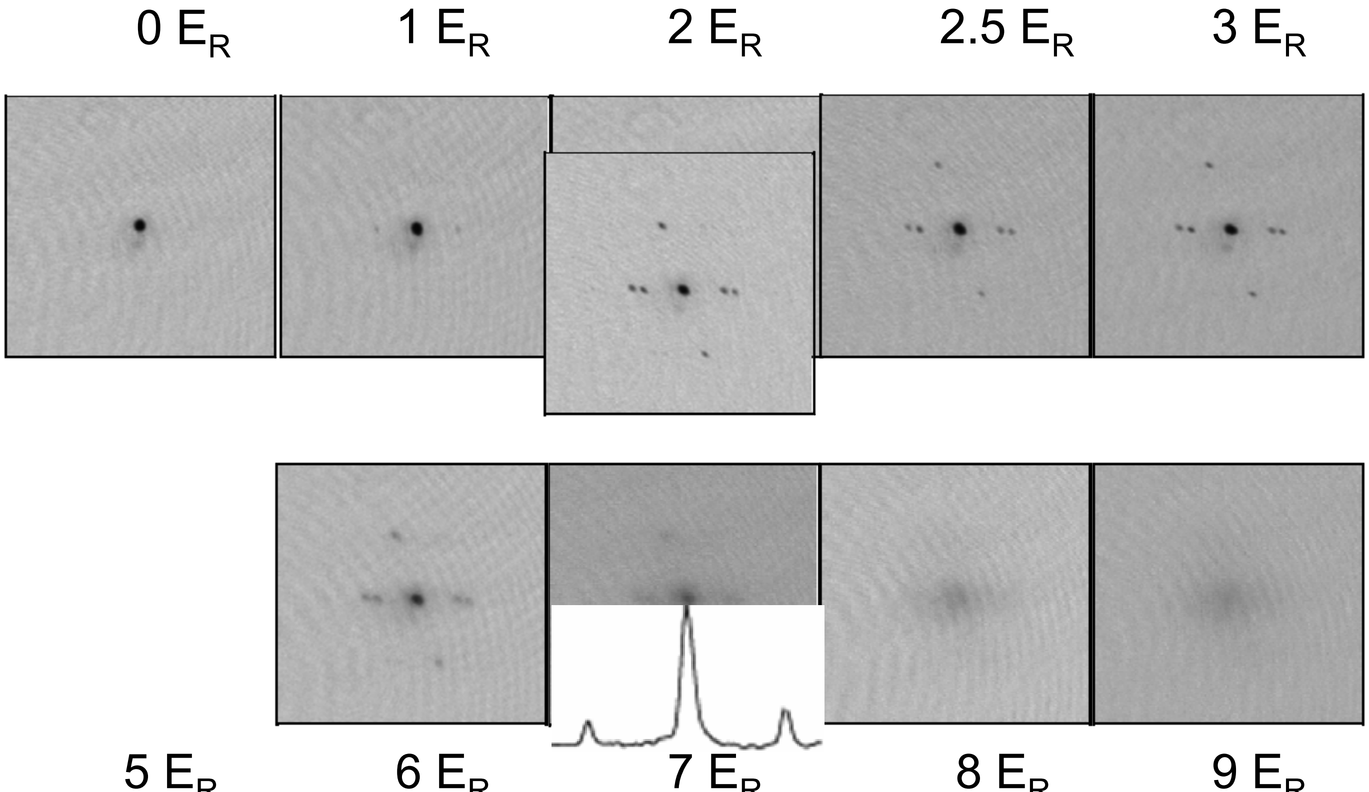


Retro-reflect far-detuned 1064nm light to form standing wave potentials in 3 dimensions.



Lattice Geometry
as seen in time-of-flight

Starting with a condensate of Li-6 pairs, then applying an optical lattice:

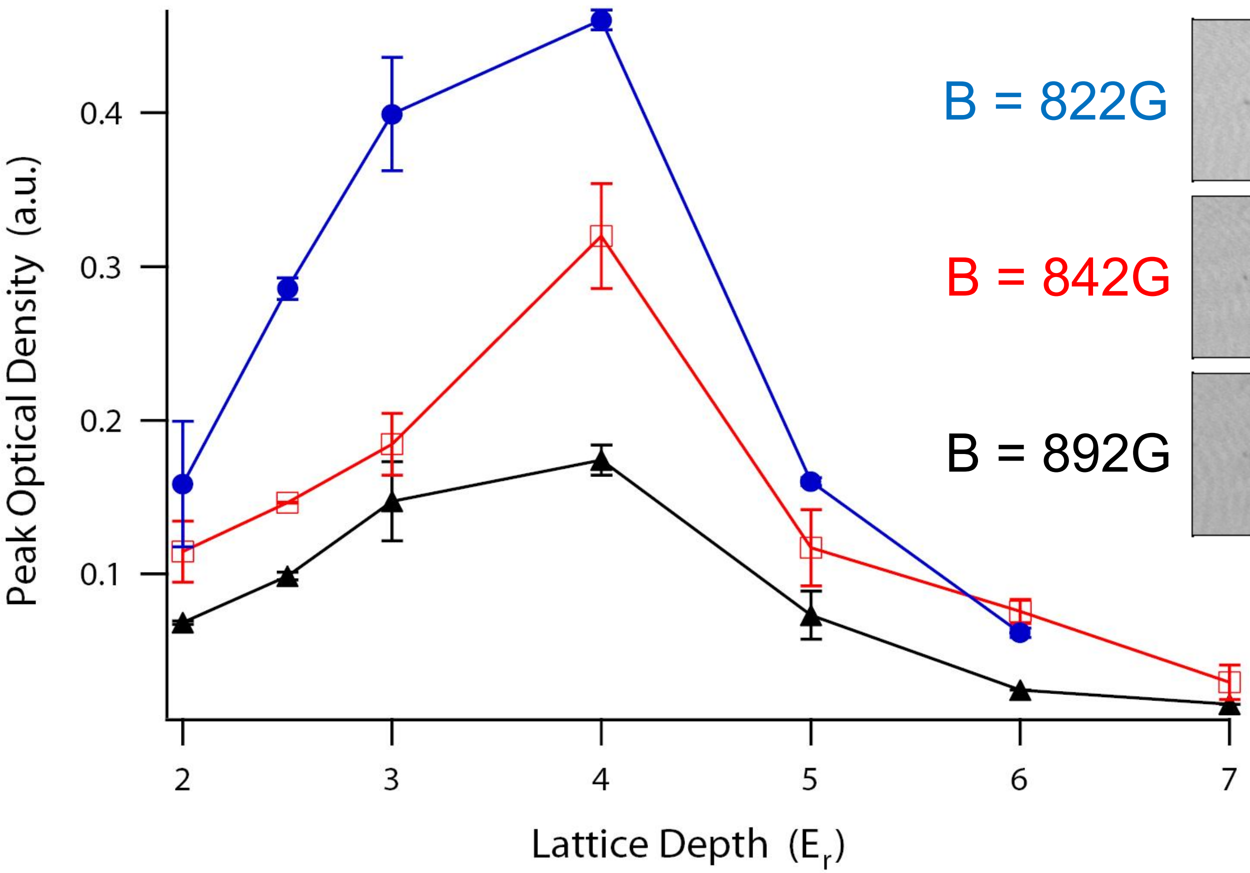


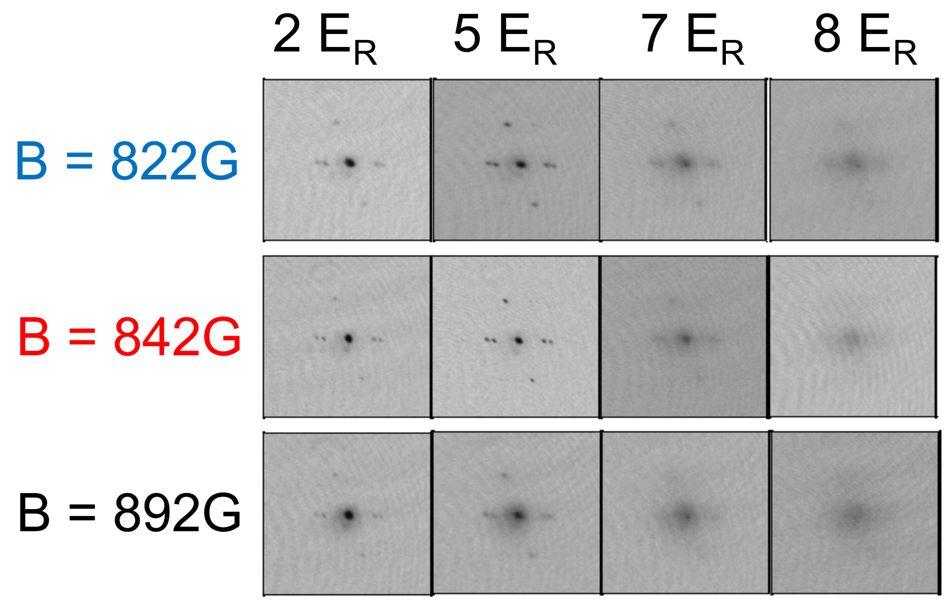
Width to separation ratio of interference peaks gives minimum coherence length of 10 lattice sites.

Long range phase coherence => Superfluidity!

B = 842 G (on BCS side of the resonance)

BEC-BCS Crossover in an Optical Lattice





Overall contrast decreases, but no change in the “transition point”

Nanokelvin atoms are a new toolbox to address fundamental questions of many-body physics

Quantum simulations of strongly correlated, strongly interacting systems

BEC I

Ultracold fermions

Christian Schunck
Andre Schirotzek
Yong-Il Shin

BEC II

Na, Li
Optical Lattices

Jit Kee Chin
Daniel Miller
Yingmei Liu
Widagdo Setiawan
Christian Sanner
Aviv Keshet

BEC III

Atom chips, surface atom optics

Tom Pasquini
Gyu-Boong Jo
Caleb Christensen
Ye-ryoung Lee
Jae Choi
Tony Kim
D.E. Pritchard

BEC IV

Atom optics and optical lattices

Jongchul Mun
Patrick Medley
David Hucul
David Weld
D.E. Pritchard

Opening for Postdoc

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