The Abdus Salam
International Centre for Theoretical Physics

United Nations
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1859-26

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 I

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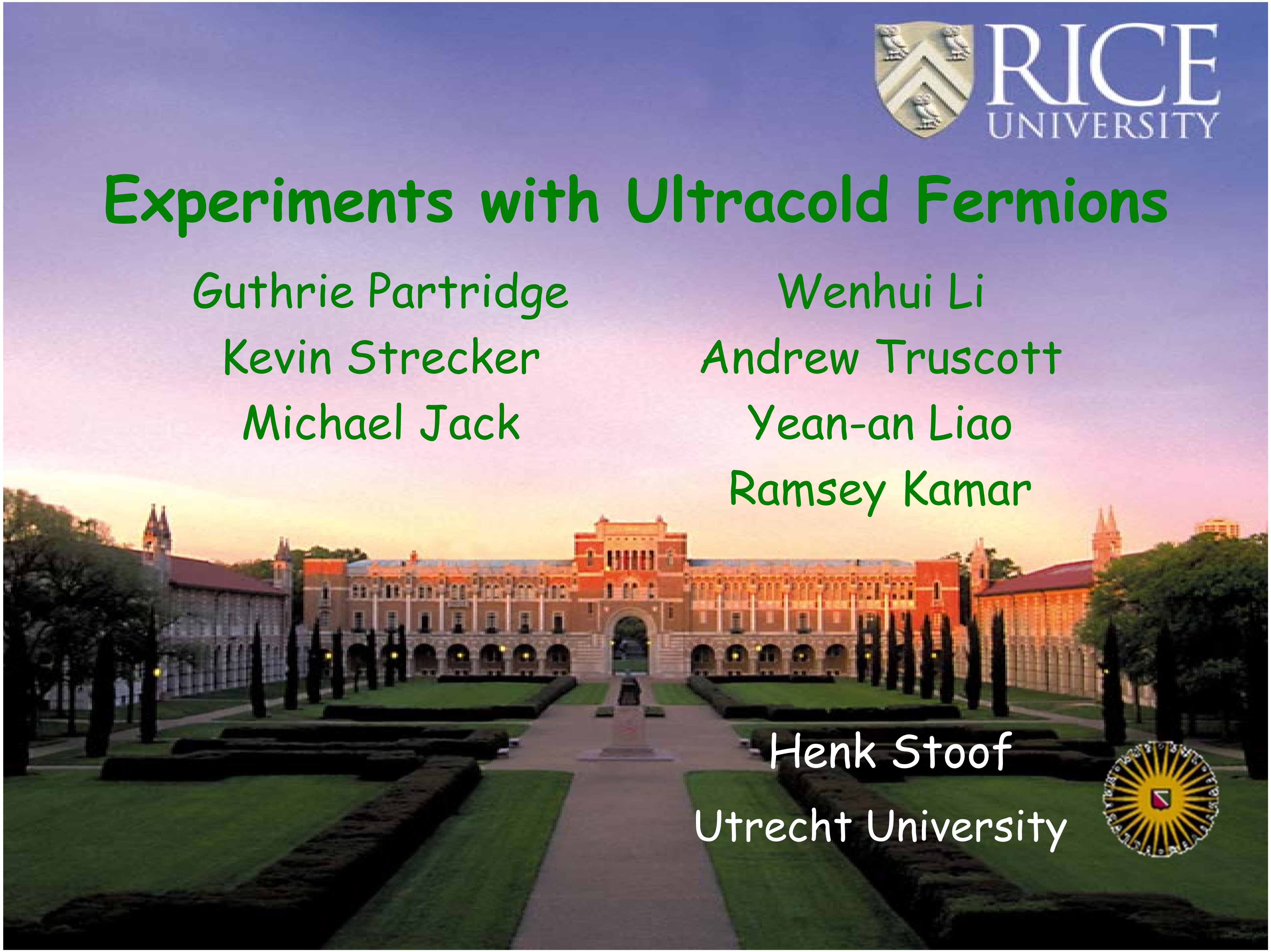

RICE UNIVERSITY

Experiments with Ultracold Fermions

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Kevin Strecker
Michael Jack

Wenhui Li
Andrew Truscott
Yean-an Liao
Ramsey Kamar

Henk Stoof
Utrecht University

Outline

Part 1

- Introduction to methods and concepts of cold atom physics

- BEC-BCS crossover with fermions
  - microscopic physics of pairing
  - universal energy of interaction for a unitary gas

Part 2

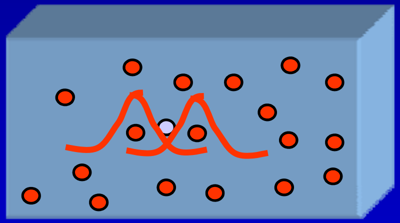
- Pairing with unequal spin populations

Quantum Gases

- Quantum regime $n\Lambda^3 \geq 1$

n = density
Λ = de Broglie wavelength

Identical particles!



- Gas phase $n \approx 10^{12}$ cm^{-3}
- Low temperature $T \approx 100$ nK

  $\Rightarrow \Lambda \approx 1$ µm

- Phase transitions
  - Bosons (^{7}Li): Bose-Einstein condensation
  - Fermions (^{6}Li): Fermion pairing

Lithium: Non-identical Twins

^{7}Li

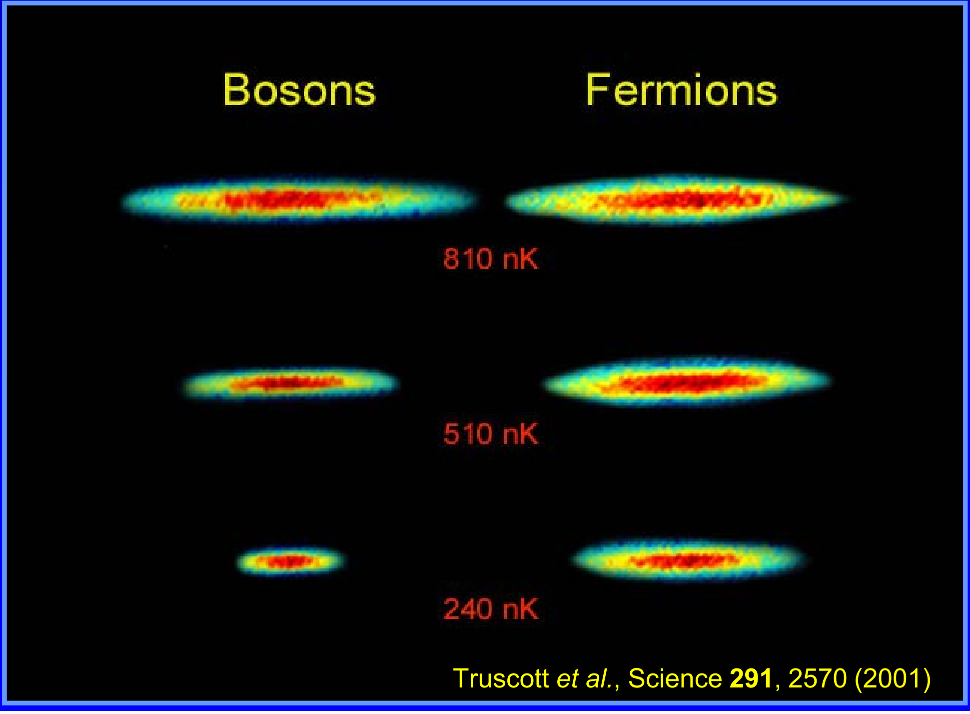
- 3 e's, 3 p's, 4 n's
  = 10 spin-½ particles
  ⇒ Boson

- 94% abundance

^{6}Li

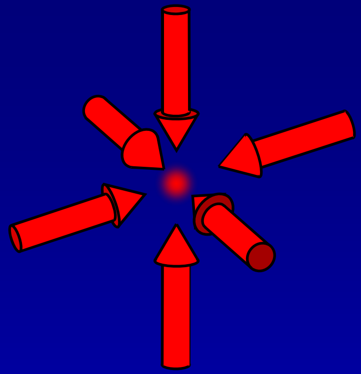
- 3 e's, 3 p's, 3 n's
  = 9 spin-½ particles
  ⇒ Fermion

- 6% abundance



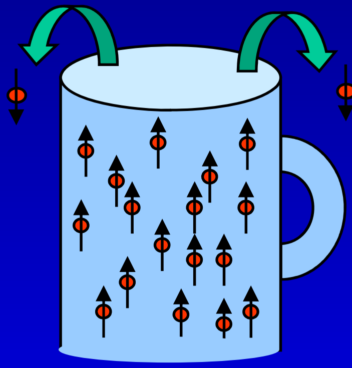
Truscott *et al.*, Science **291**, 2570 (2001)

Methods



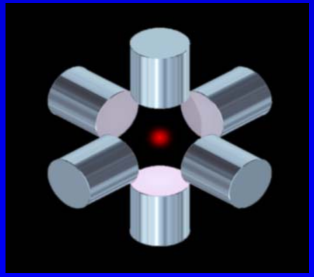
- Laser cooling

  $T \approx 100\ \mu K$



- Evaporative cooling

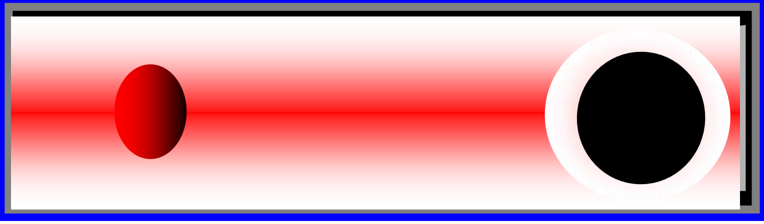
  $T \approx 100\ \mu K \rightarrow\ 10\ nK$



- Atom trapping

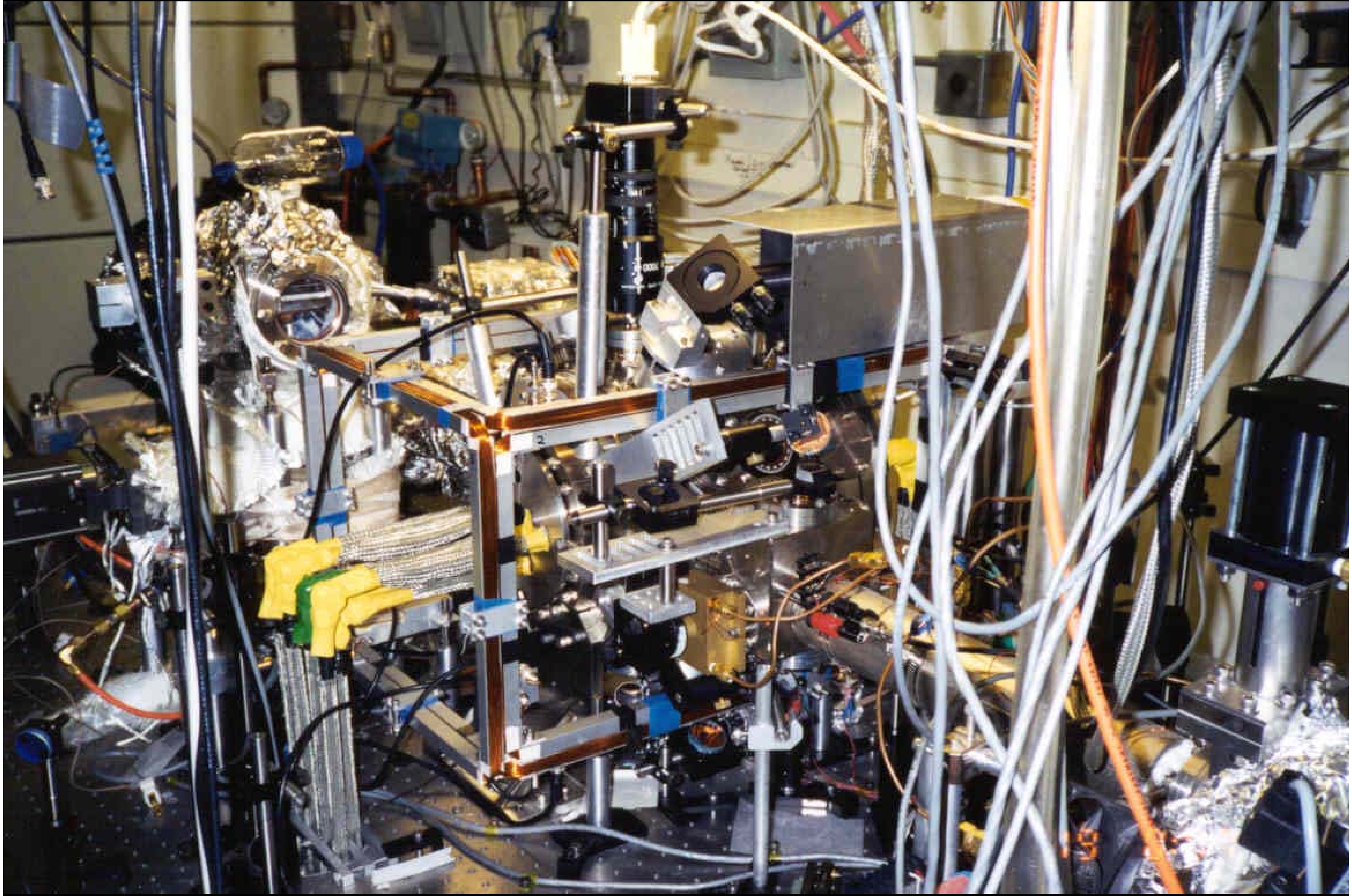
  $n \approx 10^{12} - 10^{14}\ cm^{-3}$, $N \approx 10^9 \rightarrow 10^6$

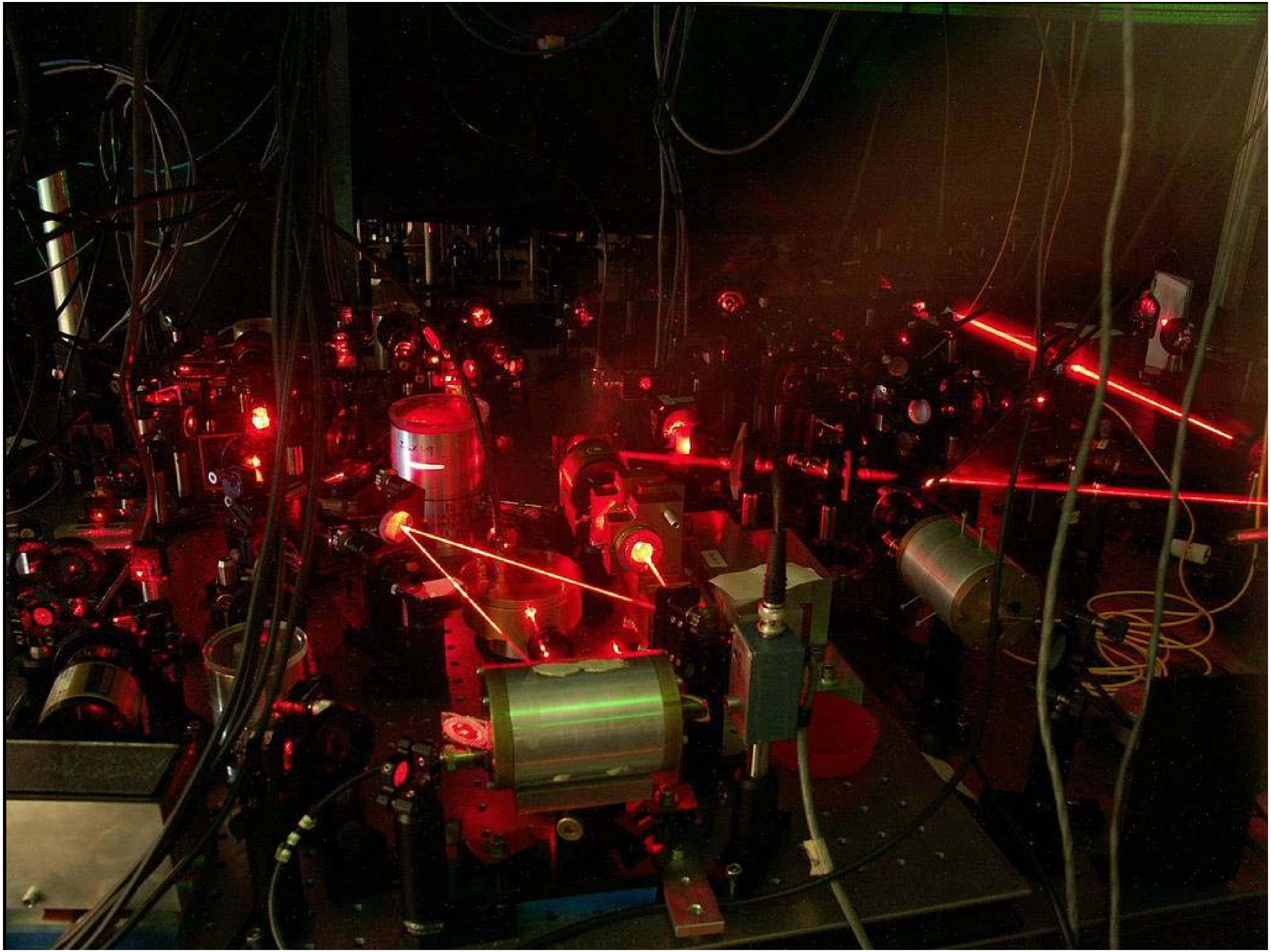
  trapping times ~ 1 minute



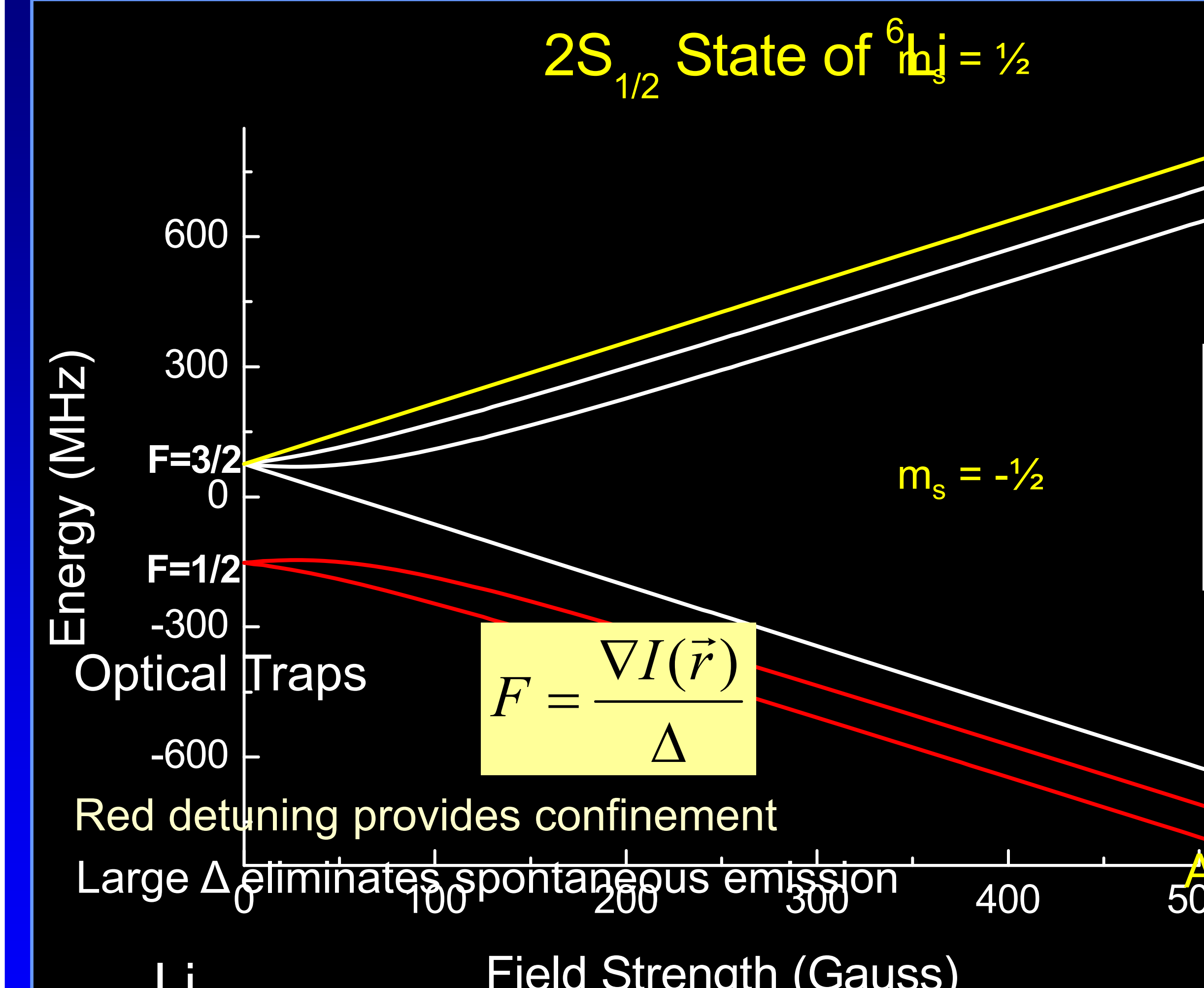
- Optical imaging

Imaging System



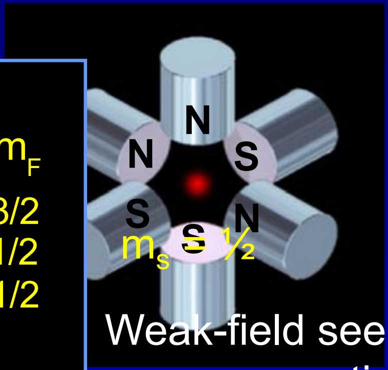


Trapping



m_s = ½

m_s = -½

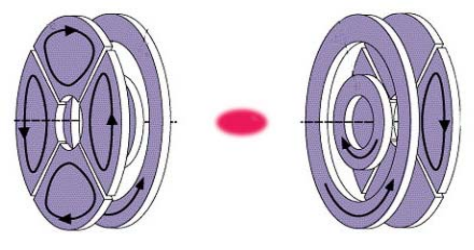


m_s = ½

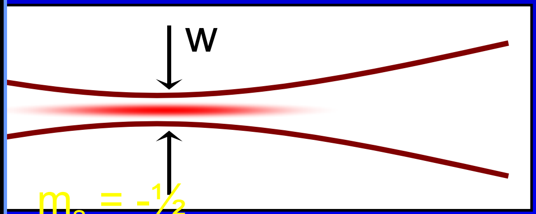
Weak-field seeking

→ magnetically trappable

Rice 1995



MIT 1998



m_s = -½

Strong-field seeking

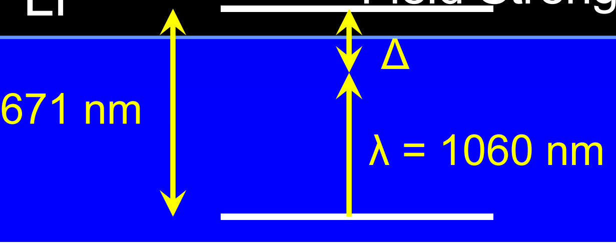
→ not magnetically trappable

Optical Traps

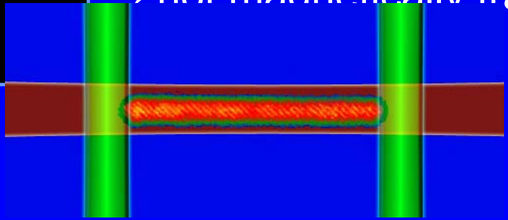
$$F = \frac{\nabla I(\vec{r})}{\Delta}$$

Red detuning provides confinement

Large Δ eliminates spontaneous emission



Aspect ratio ~ w/λ ~ 10-100



1060 nm

532 nm

532 nm

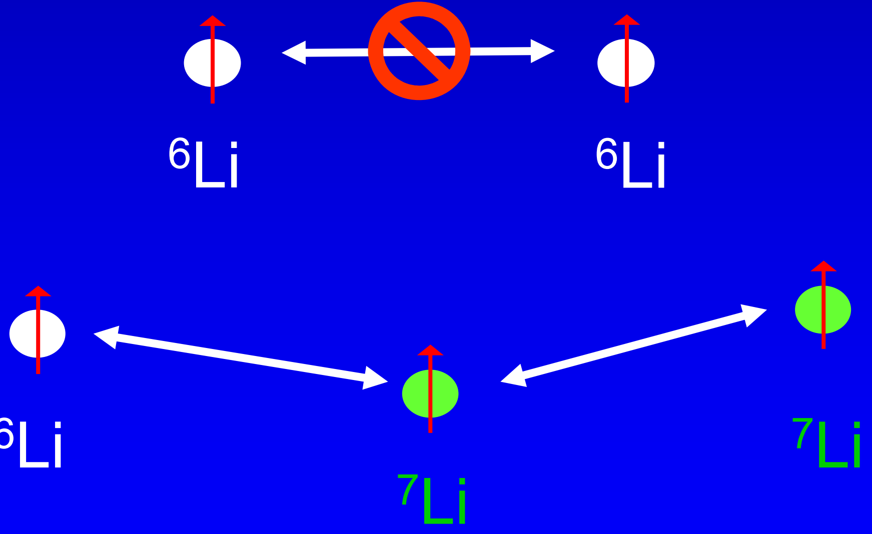
Evaporative Cooling of Fermions

- Evaporative cooling requires rethermalizing collisions
- Pauli principle forbids *s*-wave interactions between identical fermions

$\Psi(1,2) = \psi_{\text{spatial}}\,\chi_{\text{spin}}$ must be antisymmetric

but $\psi_{\text{spatial}} = (-1)^{\ell} = +1$ for *s*-wave collisions

Use both ^{6}Li and ^{7}Li

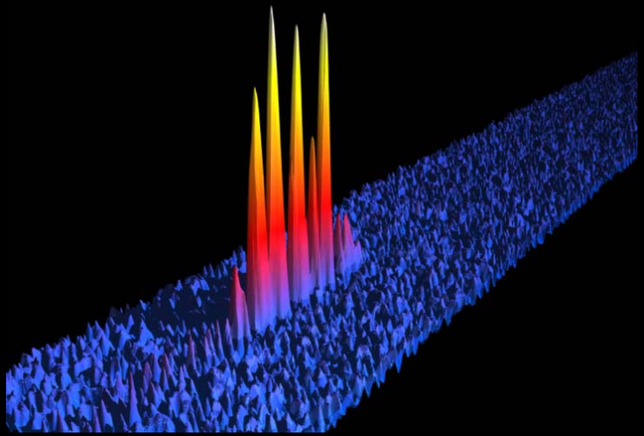


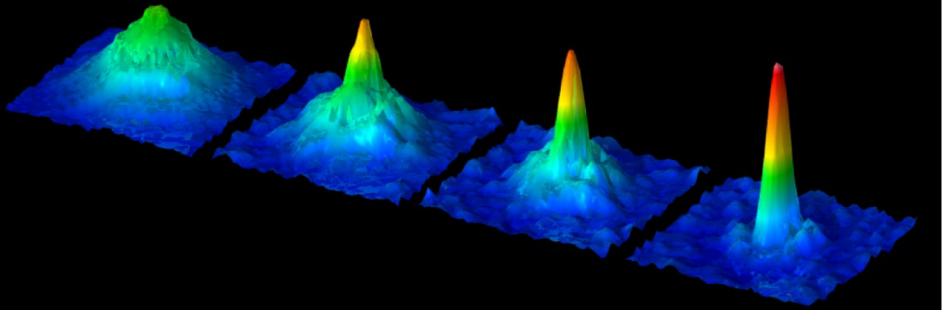
Fermions

Bosons

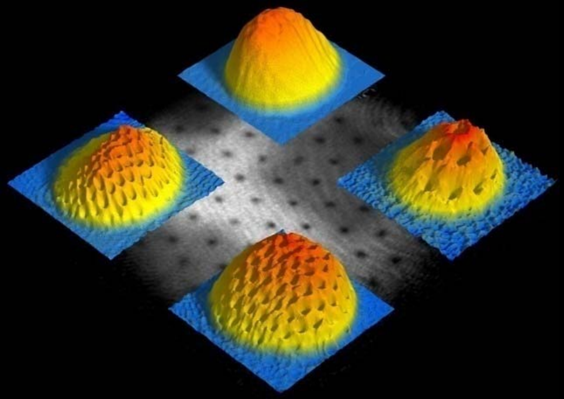
Other solutions: - Spin-state mixture in optical trap (JILA, Duke, Innsbruck)
- BEC of sodium (MIT); BEC of lithium (ENS)

Bose-Einstein Condensation


Rice (2002)



- Vortices
- Solitons
- Atom laser
- Atom wave guides
- Nonlinear atom optics
- Collective oscillations
- Josephson oscillations
- Mott-Insulator

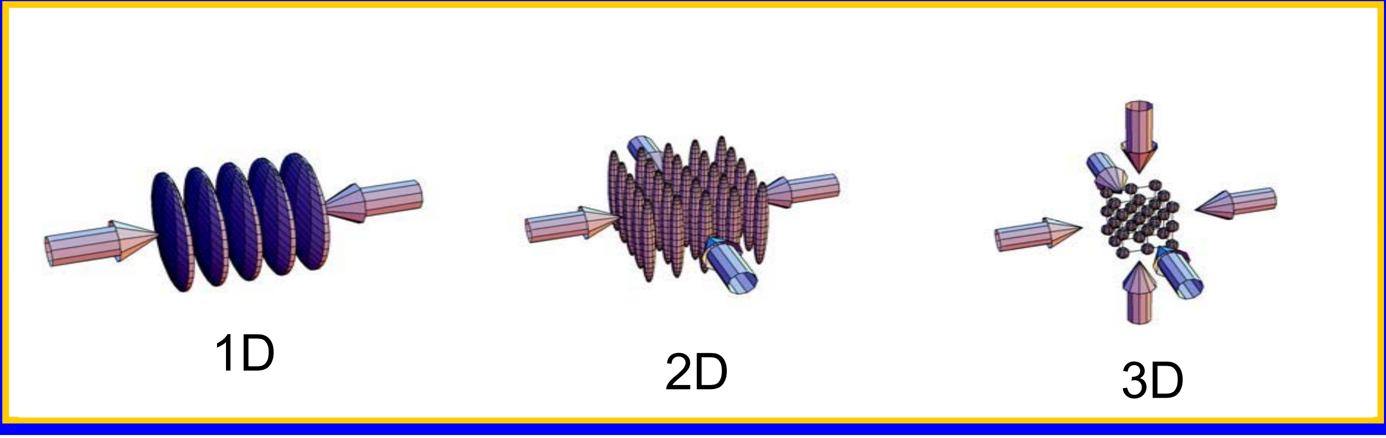

J.R. Abo-Shaeer, MIT (2001)

Interest in Ultracold Fermi Gases

- Strongly interacting fermions:
  - high-T_c superconductors
  - neutron stars
  - quark-gluon plasma
- Connections to condensed matter
  - Hubbard model of high-T_c
  - Pseudo-gap physics
  - Strong correlations in low dimensions:

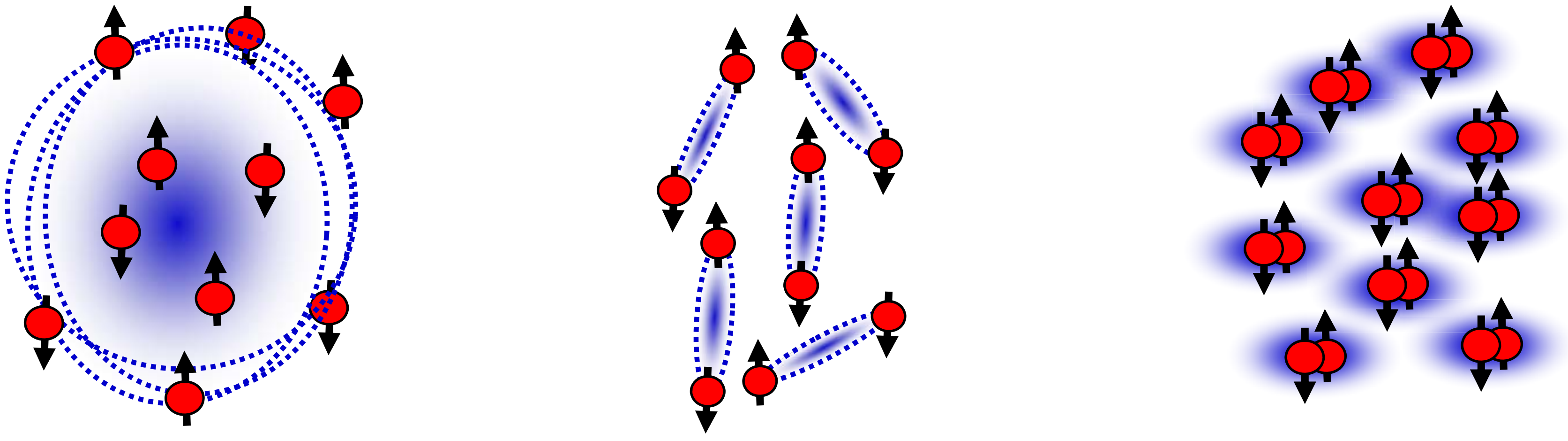
    Luttinger liquid, spin-charge separation, …

Optical lattice configurations

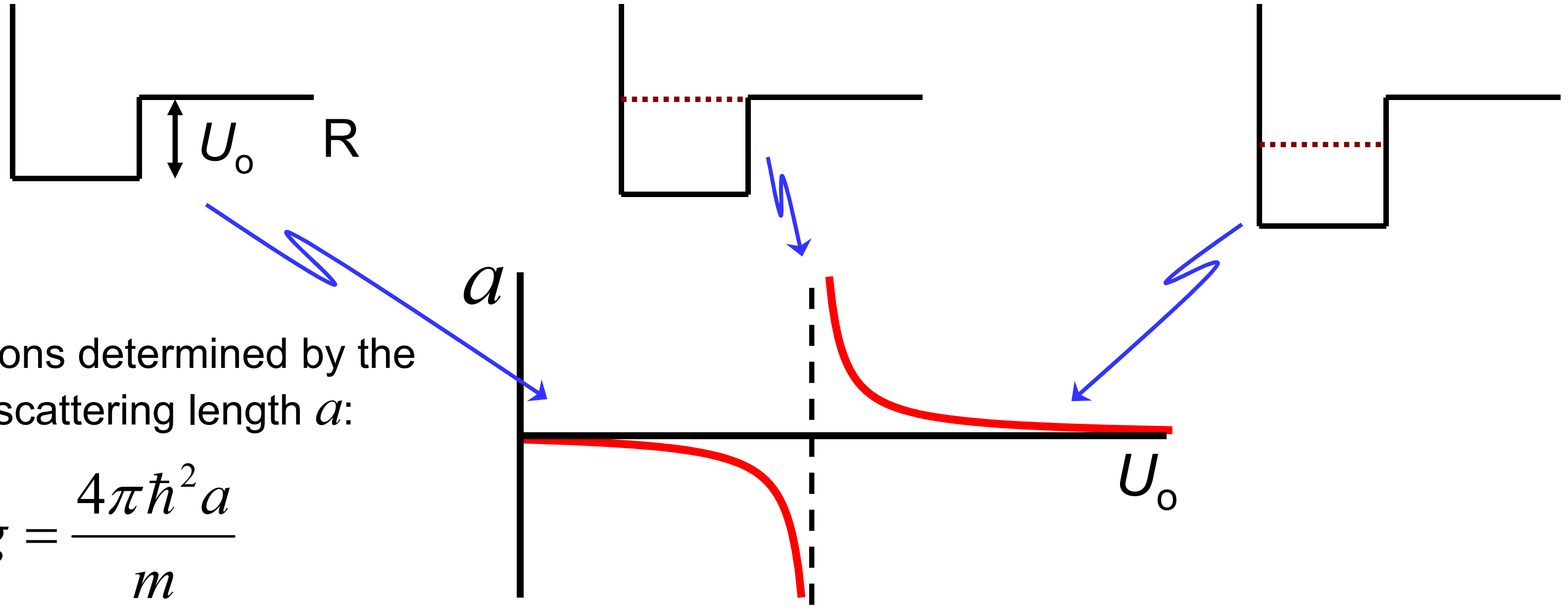


BEC-BCS Crossover

BCS pairing crosses over to Bose-Einstein condensation of molecules with increasing U_o:



BCS *Unitarity* $k_F|a| \to \infty$ *BEC*

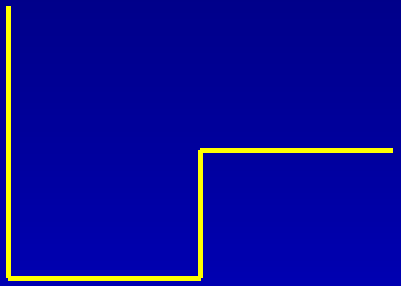


Interactions determined by the *s*-wave scattering length a:

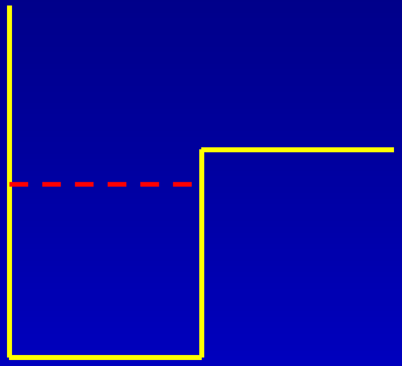
$$g = \frac{4\pi\hbar^2 a}{m}$$

BEC/BCS Crossover Models

One channel model - original crossover theory (Eagles, Leggett, ...):



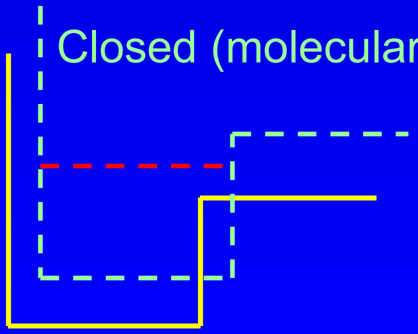
BCS – weakly attractive



BEC

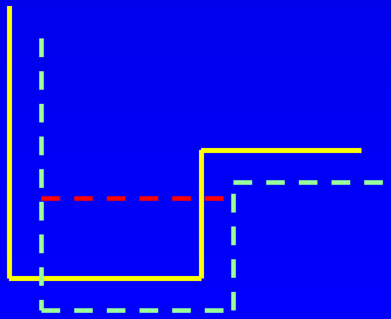
- physics is universal
  (length scale ~ $n^{-1/3}$)
- widely applicable
  e’s, nucleons, quarks

Two channel model - Feshbach resonance (Tiesenga, Stoof, Verhaar, 1993):



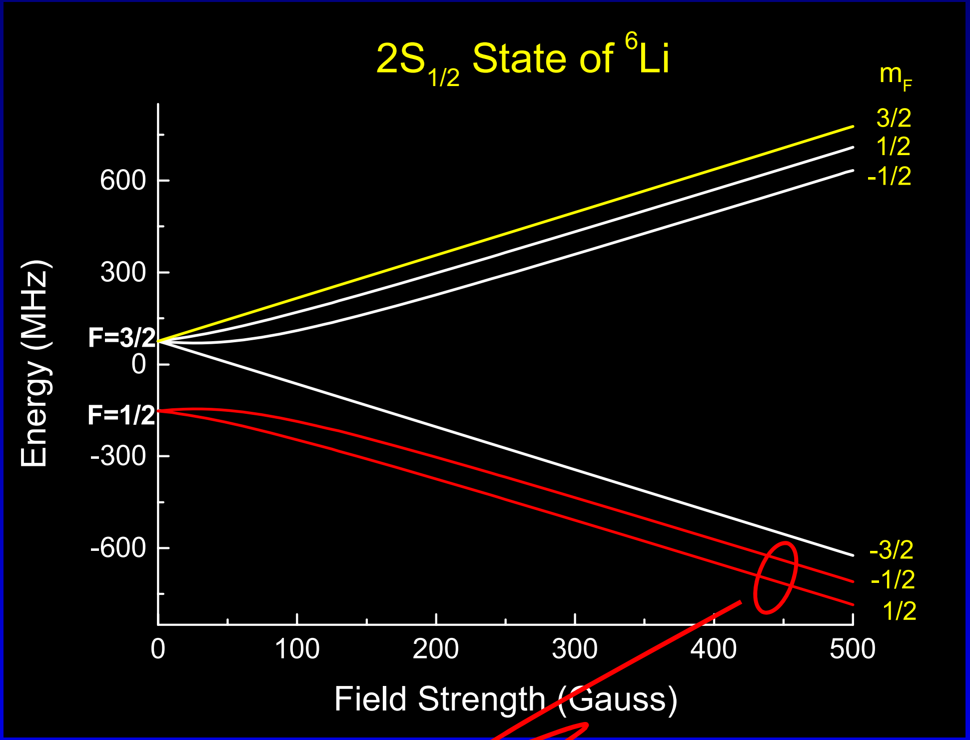
Closed (molecular) channel

Open (scattering) channel



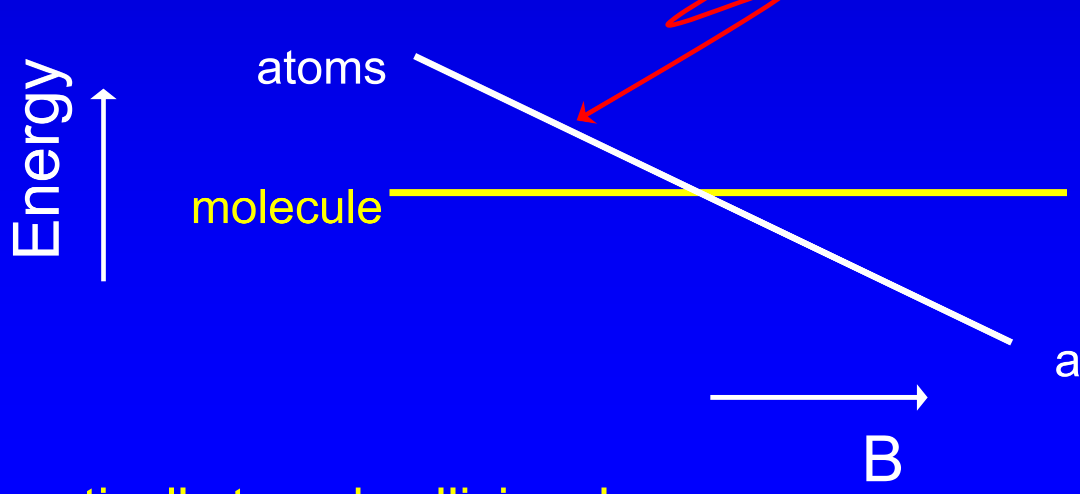
- universality?

Feshbach Resonance in ^{6}Li



s-wave pairing but
in an *electronic*
triplet state

Quasi-spin ½:
“spin-down” → |2〉
“spin-up” → |1〉

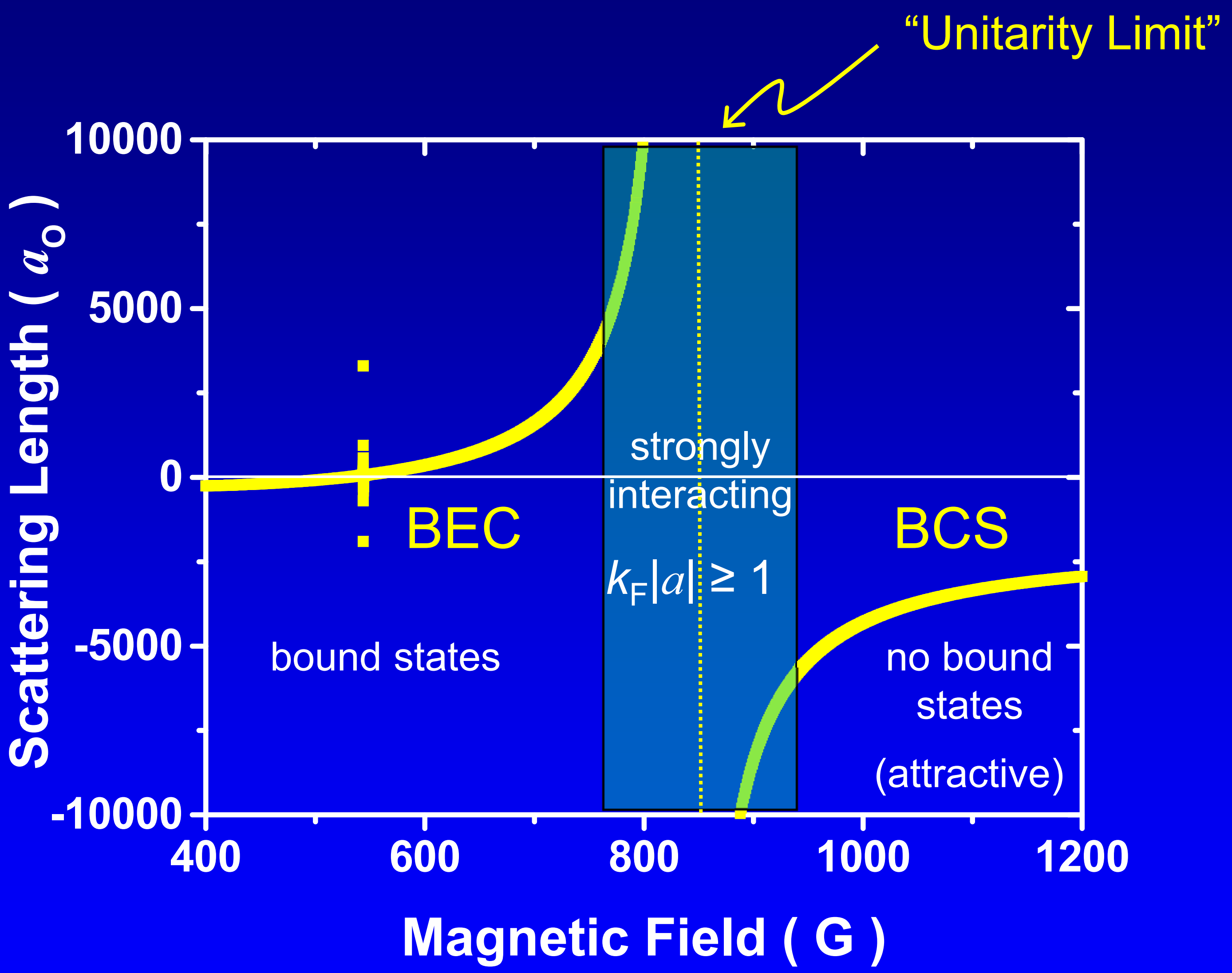


molecule $\mu = 0$ ($S = 0$)

atoms $\mu = -2\mu_B$ ($S = 1$)

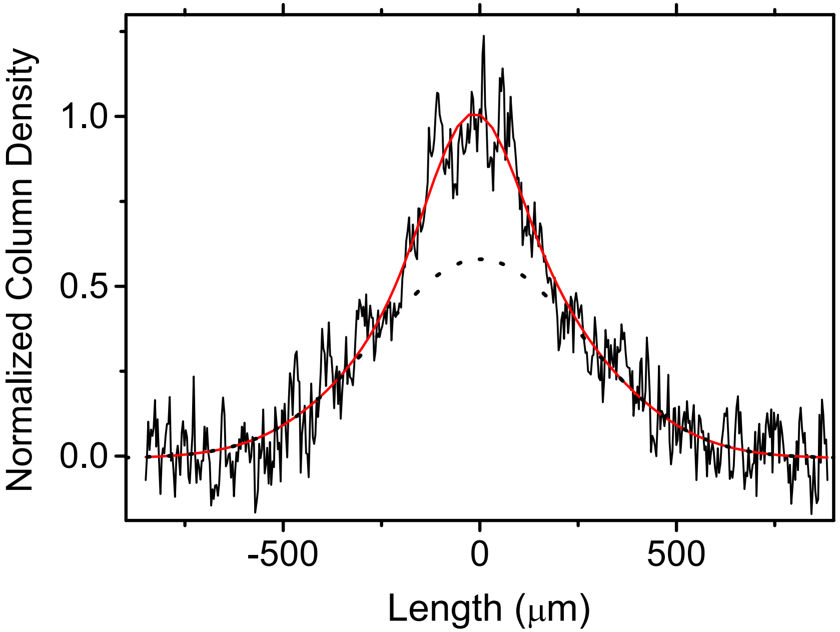
Magnetically tuned collisional resonance

Feshbach Resonances in ^{6}Li



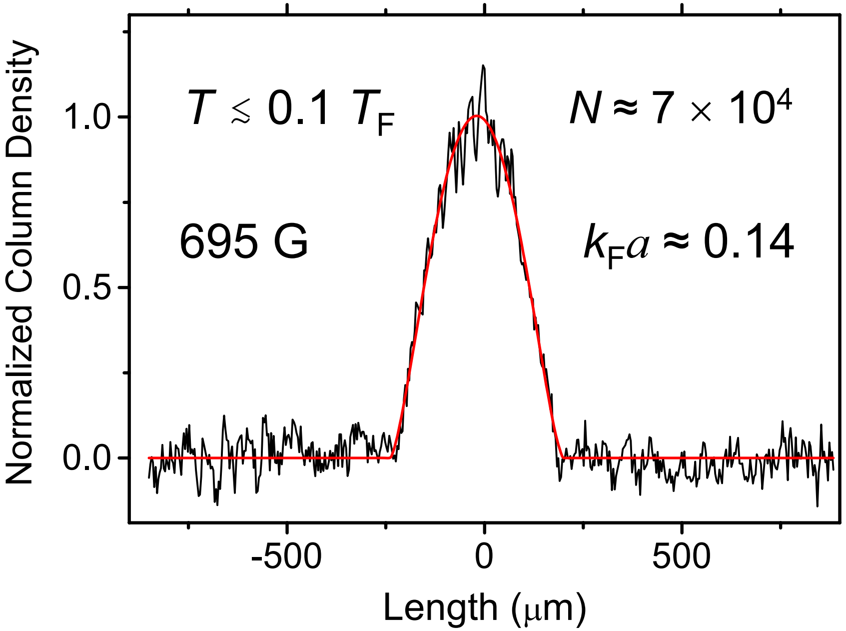
Houbiers, Stoof, McAlexander, Hulet, PRA **57**, R1497 (1998)
O'Hara *et al.*, PRA **66** 041401 (2002)

Molecular BEC



Thermal molecules plus BEC

(partial evaporation)



“Pure” BEC

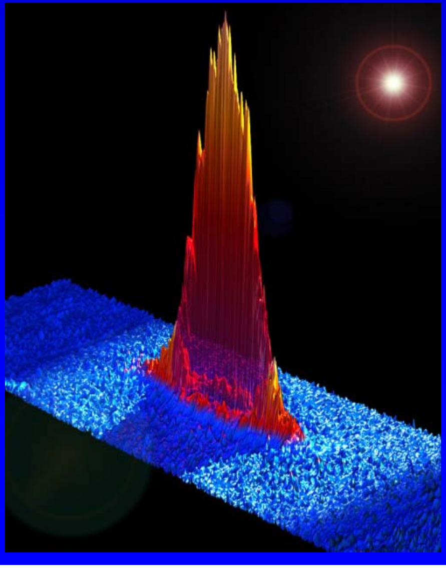
(full evaporation)

PRL **95**, 020404 (2005)

Molecular BECs: JILA, Innsbruck, MIT, ENS, Duke

BEC-BCS Crossover

- Many experiments over the past 3 years:
  - Collective mode frequencies and damping (Duke, Innsbruck)
  - Spectroscopy of gap (Innsbruck, JILA)
  - Universal thermodynamics (Duke, ENS, Innsbruck, JILA, Rice)
  - Vortices (MIT)
  - Pair correlation measurement (Rice)
  - Pairing with unequal spin populations (MIT, Rice)



Molecular Probe of BEC/BCS Crossover

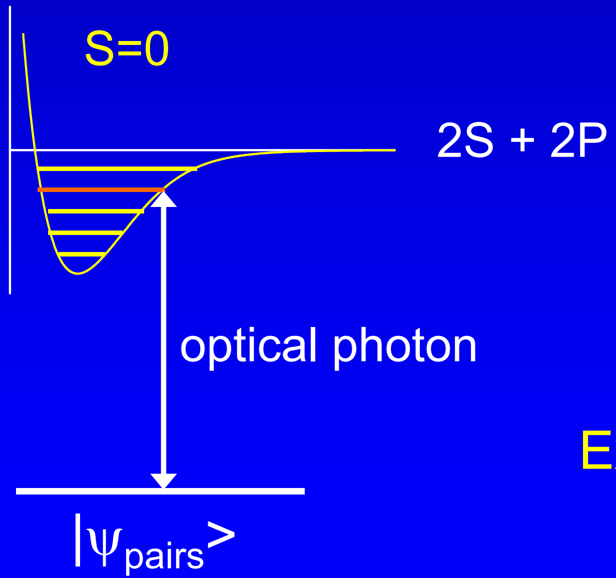
Two channel description: Romans and Stoof, PRL **95**, 260407 (2005)

$$|\psi_{pairs}> \;=\; Z^{1/2}\,|\psi_v\,(S=0)> \;+\; (1-Z)^{1/2}\,|\varphi_{aa}\,(S=1)>$$

~closed-channel molecules

~open channel atoms

Use molecular spectroscopy to project out closed-channel molecules:



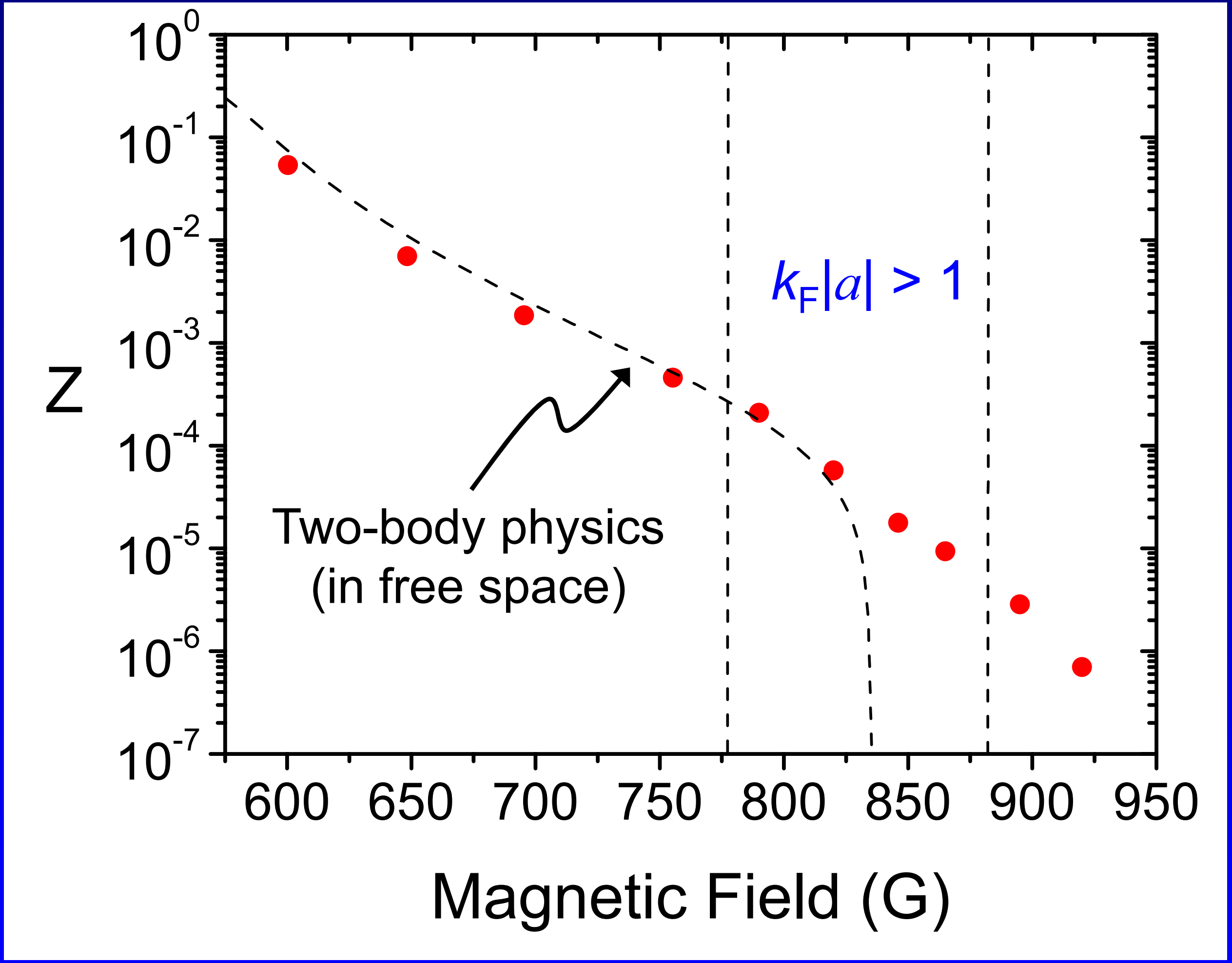
Excitation rate depends on singlet (closed) channel fraction *Z*:

$$\Gamma \propto Z$$

Excitation results in a detectable loss of atoms:

Pulse molecular probe on for time τ, then measure remaining number

Closed Channel Fraction - Z



$Z \propto \Gamma$

- *Z* continuous across resonance
  $\Rightarrow$ many-body effect
- Varies by 5 decades
- *Z* ≈ 10^{-5} on resonance

<1 closed channel molecule!

PRL **95**, 020404 (2005)

Reasonably good agreement with theory from:
Stoof *et al.*; Javanainen *et al.*; Levin *et al.*

Pair Correlations

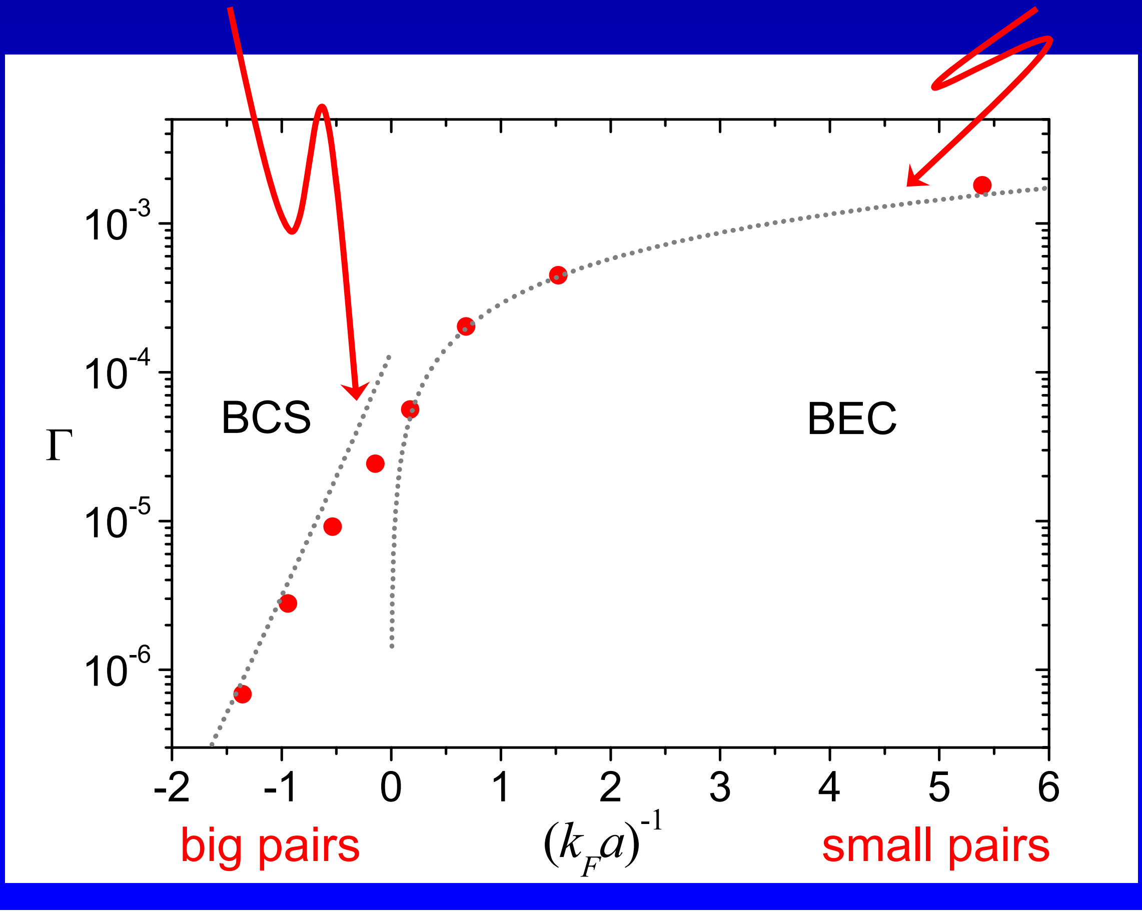
$$\partial n/\partial t \propto \langle\psi_\uparrow^\dagger\,\psi_\downarrow^\dagger\,\psi_\downarrow\,\psi_\uparrow\rangle = \langle\psi_\uparrow^\dagger\,\psi_\uparrow\rangle\langle\psi_\downarrow^\dagger\,\psi_\downarrow\rangle + \langle\psi_\uparrow^\dagger\,\psi_\downarrow^\dagger\rangle\langle\psi_\downarrow\,\psi_\uparrow\rangle$$

$\langle n_\uparrow\rangle\langle n_\downarrow\rangle$ — 2-body photoassoc.

$|\Delta(0)|^2 \propto g^{(2)}(0)$ — correlated pairs

$$|\Delta_{BCS}|^2 = E_F^2 \exp(-\pi/k_F|a|) \qquad |\Delta_{BEC}|^2 = (16/3\pi)\, E_F^2 / k_F a$$

Engelbrecht *et al*. (1997)



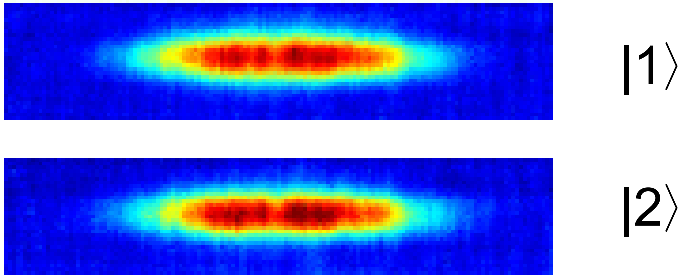
Single-channel theory

- universal behavior

PRL **95**, 020404 (2005)

Universal Interaction Energy at Unitarity

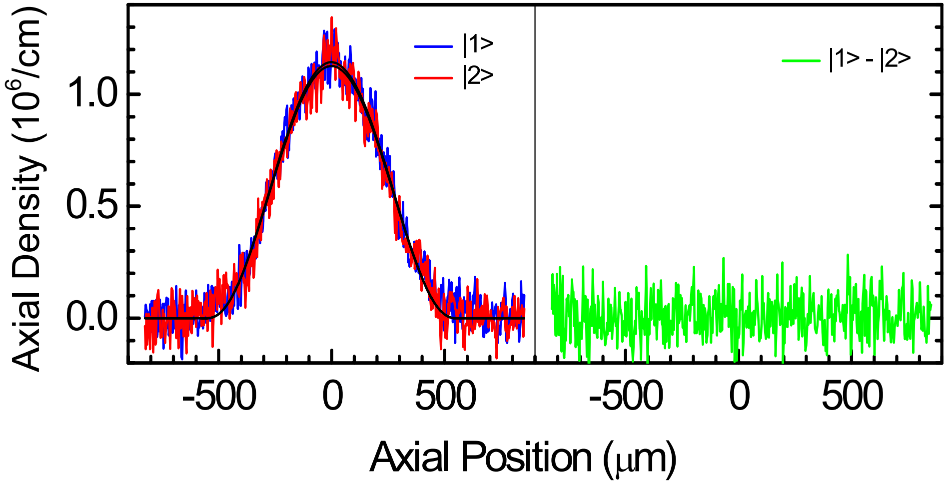
In-situ
absorption
images



Size of real space distribution reveals interaction and pairing energies

At unitarity, the chemical potential is reduced by pairing: $\mu = E_F(1+\beta)^{1/2}$

where β is a *universal* many-body parameter



Fit to non-interacting Fermi distribution:

$$n(z) = A\left(1-\frac{z^2}{R^2}\right)^{5/2}$$

Compare fitted *R* with the “Thomas-Fermi” radius of a *non-interacting* Fermi gas:

$$R_{TF} = \left(\frac{2E_F}{m\omega_z^2}\right)^{1/2}$$

Axial density is radially integrated column density

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

Universal Interaction Energy at Unitarity

At unitarity, real-space distributions shrink due to pairing energy:

$$\mu = E_F (1+\beta)^{1/2}$$

where β is a *universal* many-body parameter

$$\beta = (\frac{R}{R_{TF}})^4 - 1$$

Measurements give:

$$\frac{R}{R_{TF}} = 0.82 \pm 0.02$$

⇒ β = -0.54 ± 0.05

Agrees with:

- Recent Monte Carlo calculations: β = -0.58 ± 0.01 (Carlson *et al.*, Astrakharchik *et al.*)
- Theory: β = -0.545 (A. Perali *et al.*, PRL, 2004) and β = -0.599 (H. Hu *et al.*, EPL, 2006)
- Experiments at ENS, Innsbruck, Duke, and JILA

Summary

- BEC-BCS crossover
  - cold fermions + Feshbach resonance can be used to realize the crossover
- Universality
  - universal behavior of order parameter
  - universal energy of interaction at unitarity