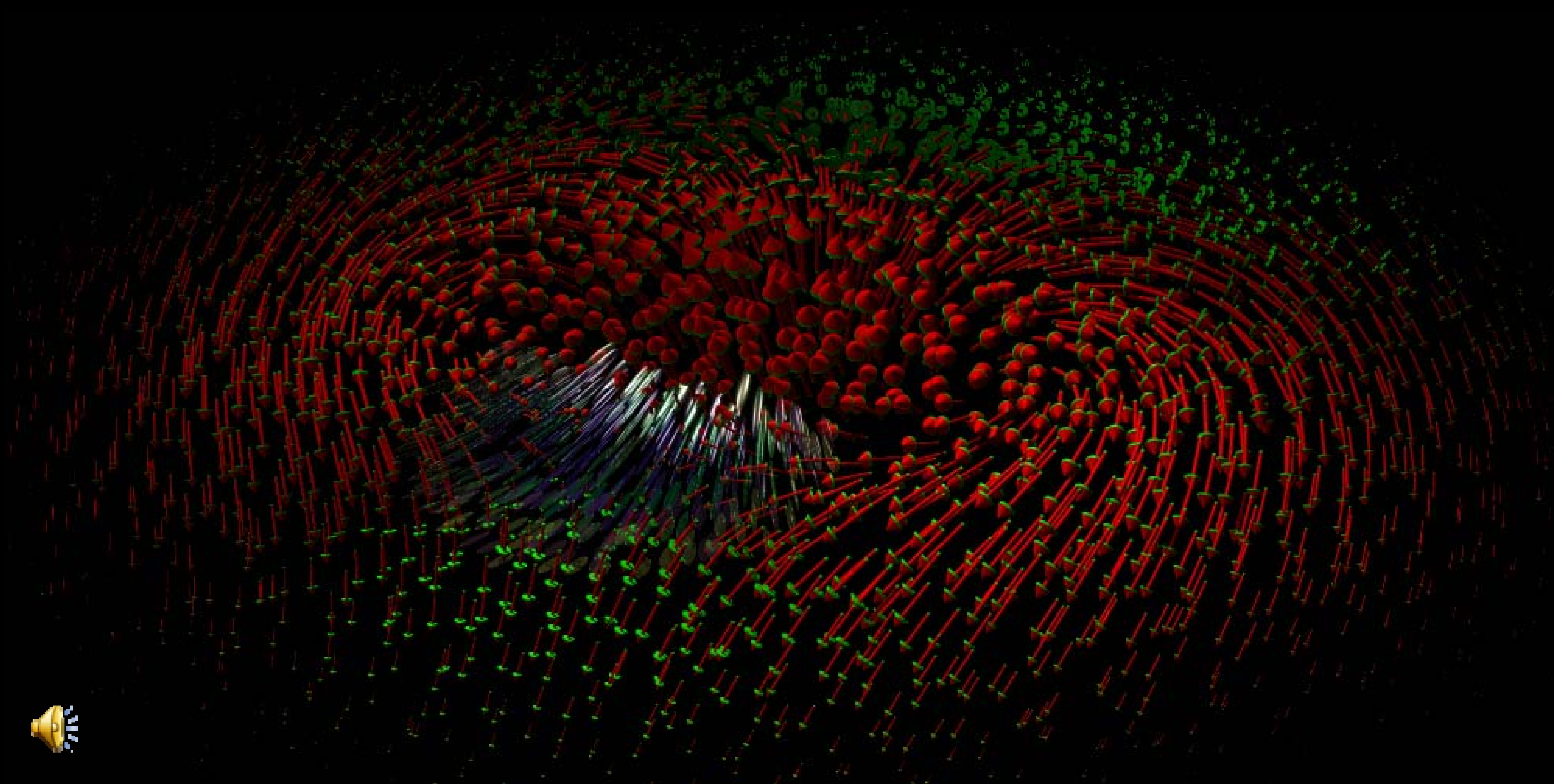
Recent Progress in Ultracold Atoms

Erich Mueller -- Cornell University



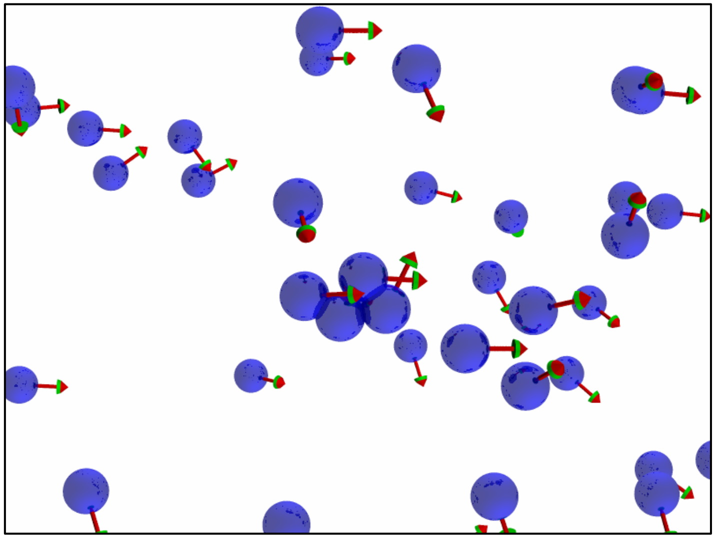
Outline

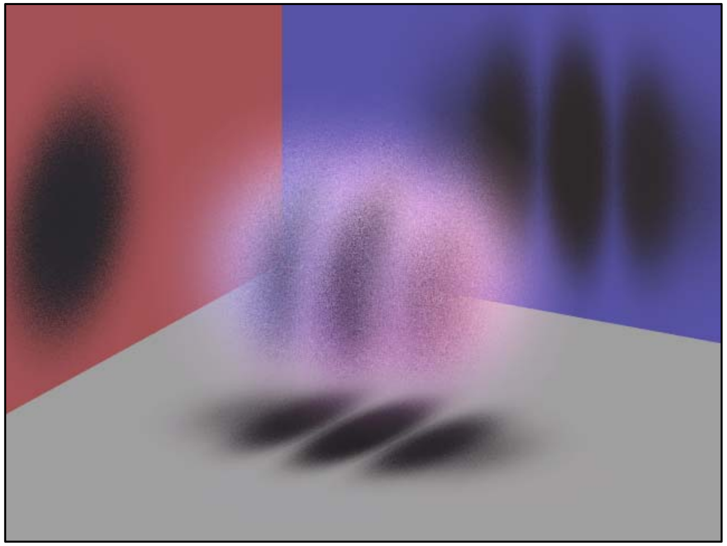
QuickTime?and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

- Background
  - cold gas experiments
  - quantum statistics
- Recent Progress
  - Controlling interactions [Feshbach Resonances]
  - BCS-BEC crossover

Why Study Ultra-Cold Gases?

Answer: Coherent Quantum Phenomena





High Temperature:
Random thermal motion dominates

Classical particle-like behavior

Low Temperature:
Underlying quantum behavior revealed

Quantum wave-like behavior

Quantum Coherence

Intellectually Exciting:
Counterintuitive,
Fundamental part of nature

Single particle "textbook" physics

↓

Correlated Many-body physics
-Connections to other fields
Condensed Matter, Nuclear

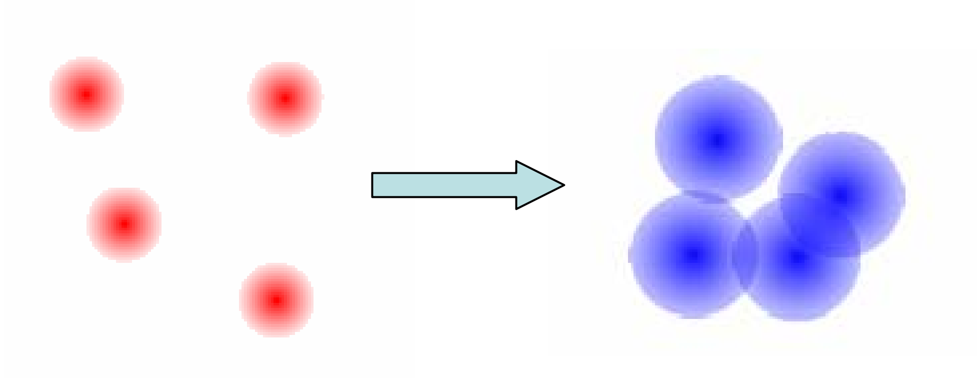
Technology:
Precision Measurement,
Navigation, Sensing

Direct Applications:
Quantum Computing,
Quantum Information Processing

Quantum Statistics

Heisenberg uncertainty principle: $\delta x \, \delta p \geq h$

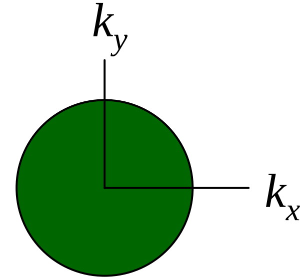
Cold $\Rightarrow$ δp small, δx big. Particles are fuzzy.

hot  cold

Bosons: Symmetric wavefunction. Lose identity when particles overlap. Particles are delocalized. Act collectively.

Fermions: Antisymmetric wavefunction. Cannot occupy same quantum state. Develop Fermi surface.

All momentum states with $|k|<k_f$ occupied

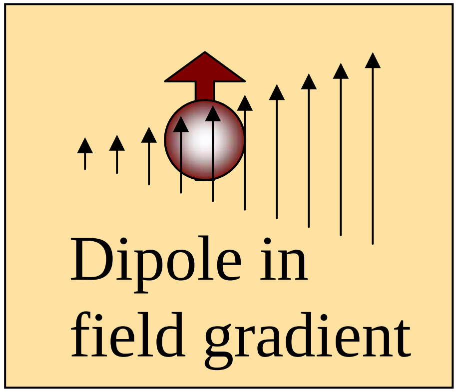


Statistics in Experiments

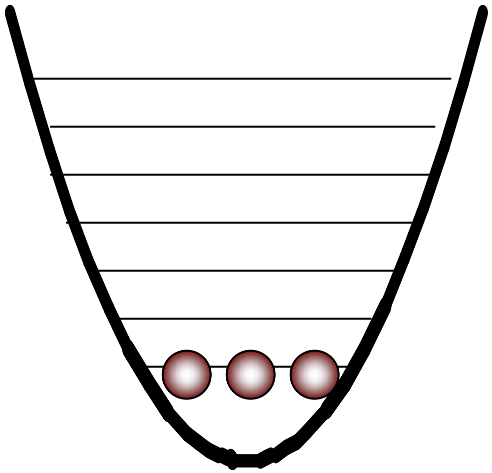
Confine atoms in magnetic or optical traps

Zeeman Effect

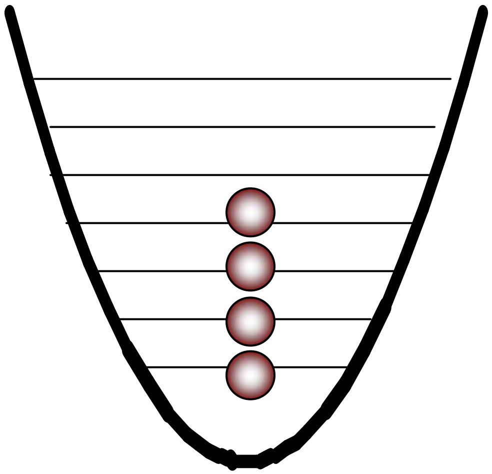
AC Stark Effect



Generally Harmonic:



Bosons



Fermions

High temperature: Boltzmann distribution

Imaging

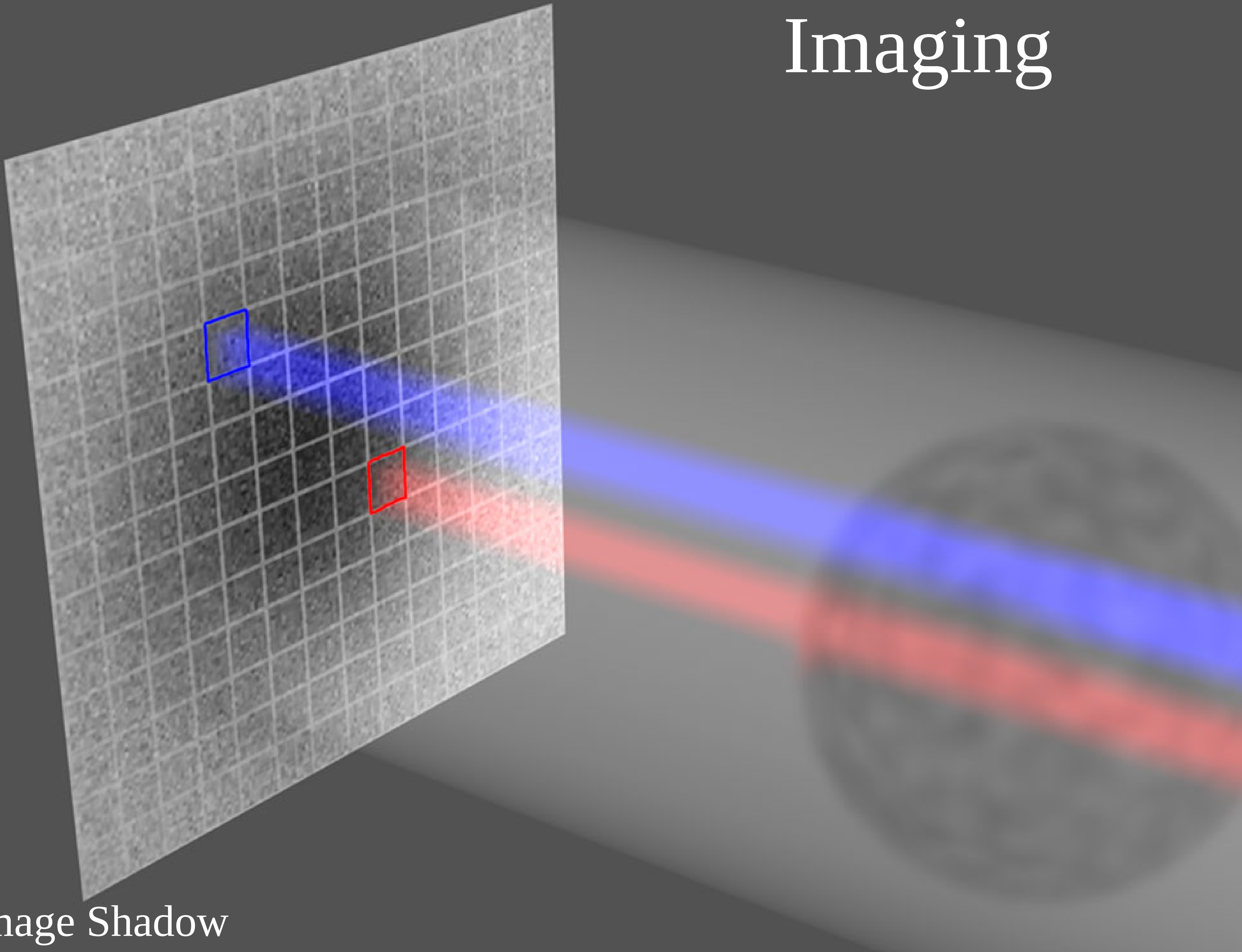
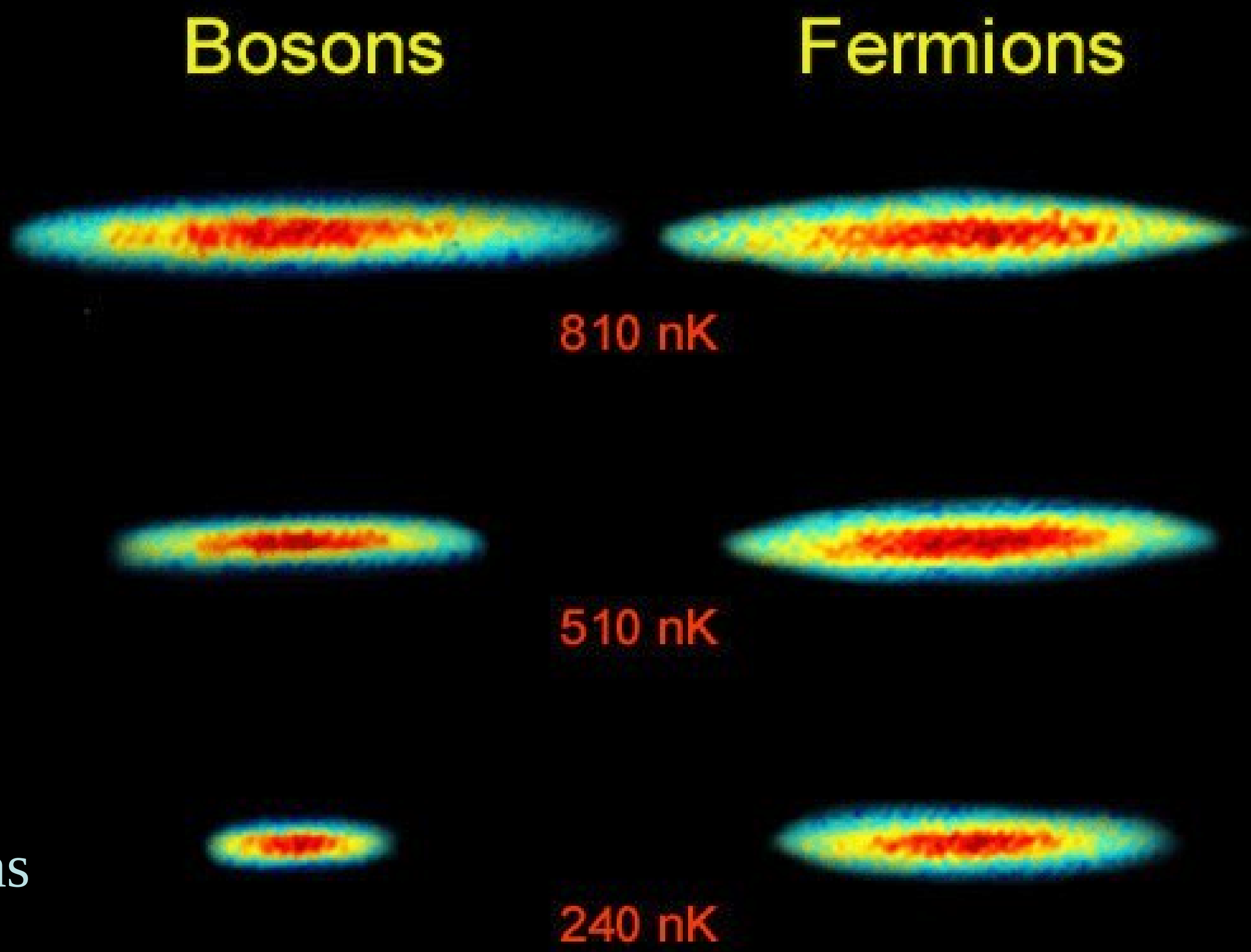


Image Shadow

Observing Statistics

High T:
Boltzmann
distribution



Low T:
Degenerate gas

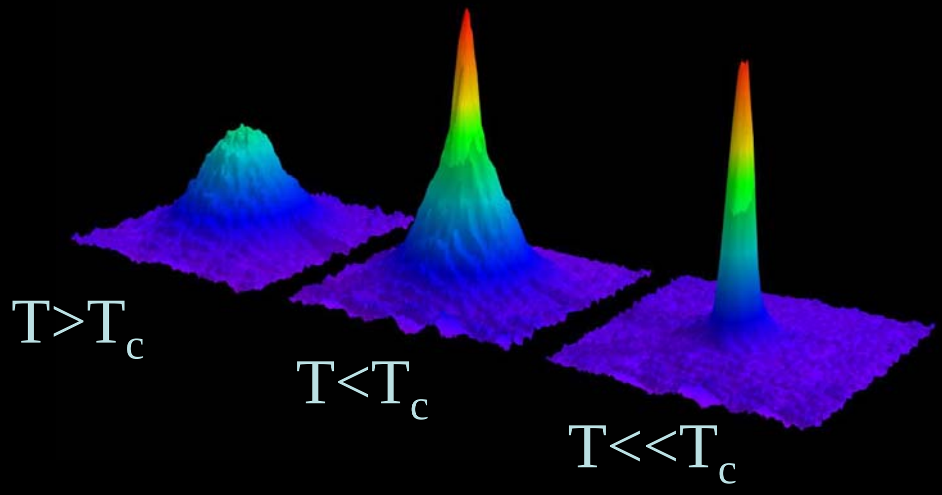
Hulet (2001)

Bose Condensation

Macroscopic occupation of lowest energy mode

(Frequency characterizes temperature)

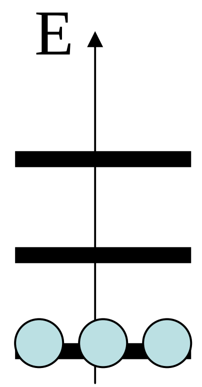
Bimodal Density is signature of condensation



Wolfgang Ketterle

Flow in Bose Condensates

Ground state of ideal Bose gas:



All particles occupy lowest single particle state

Many-body wavefunction: $\Psi(r_1 \dots r_N) = \prod_j \psi(r_j)$

Wavefunction of single particle state

Definition of Bose condensate

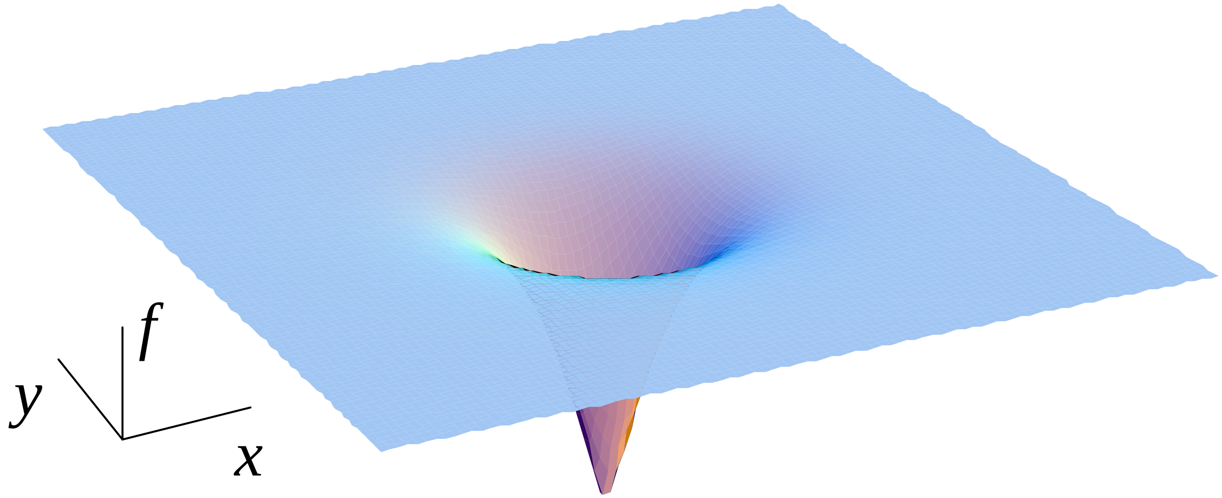
Local velocity is $\vec{v} = \frac{\hbar}{m}\vec{\nabla}\theta$ where $\psi = fe^{i\theta}$

So flow is irrotational $\vec{\nabla} \times \vec{v} = \frac{\hbar}{m}\vec{\nabla} \times \vec{\nabla}\theta = 0$

How to rotate an irrotational fluid?

Answer: Vortices

$$\psi = f e^{i\theta}$$

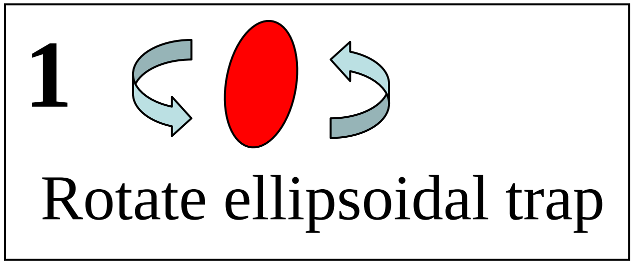


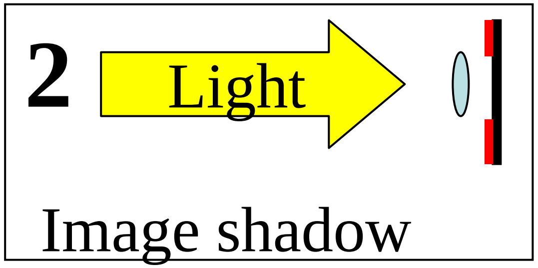
Wave function vanishes at a point. Phase winds by 2π.

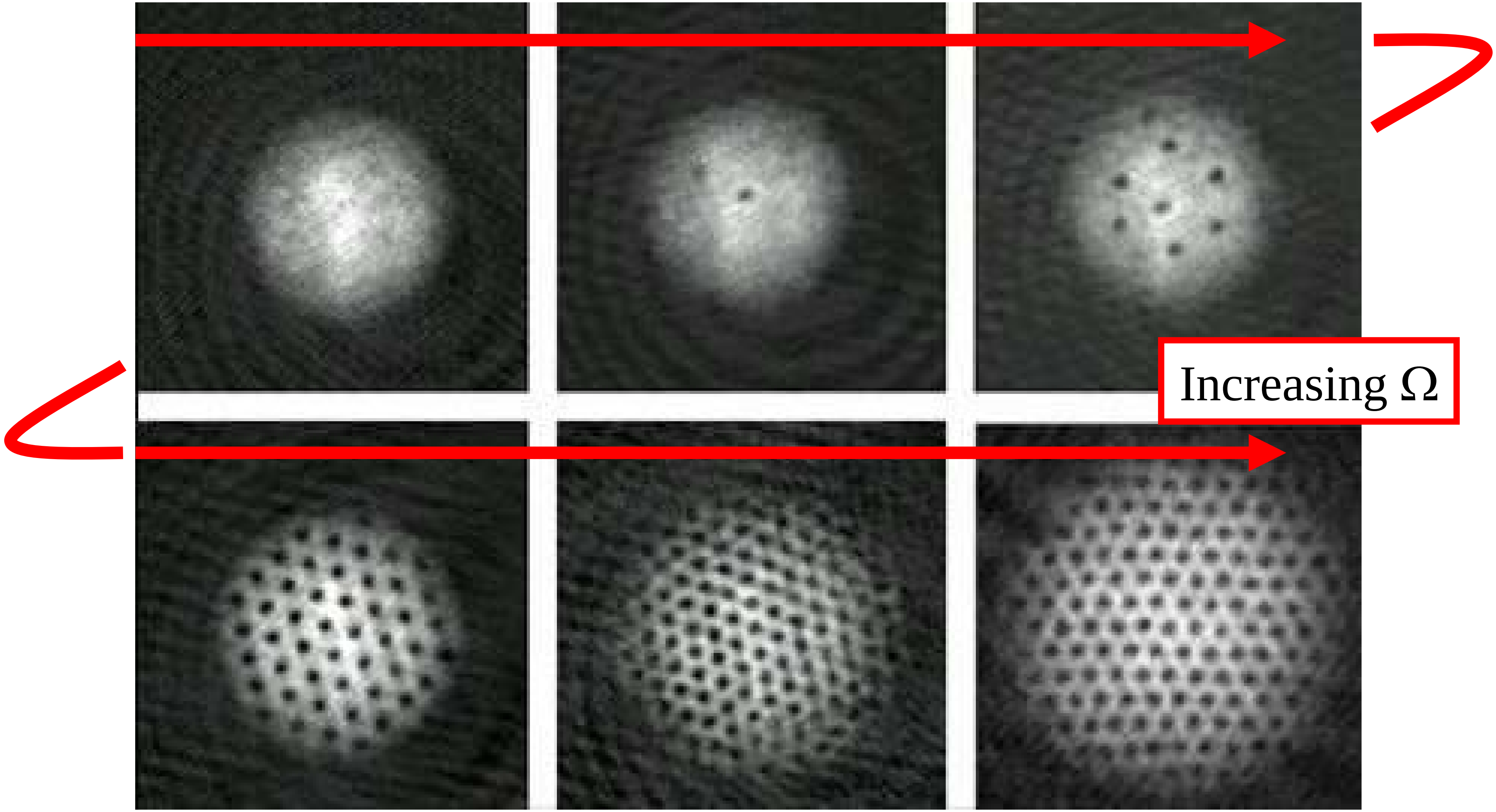
Ex:

$$\psi = \frac{x + iy}{1 + \sqrt{x^2 + y^2}}$$

Experiments:

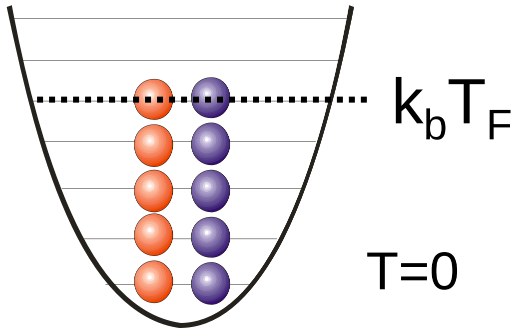


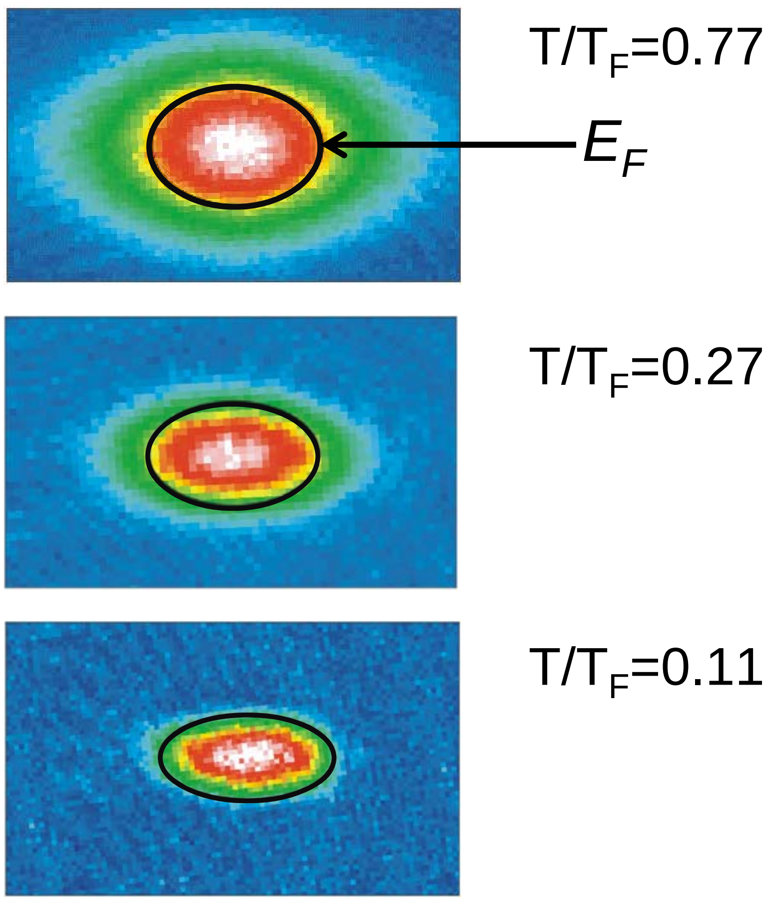




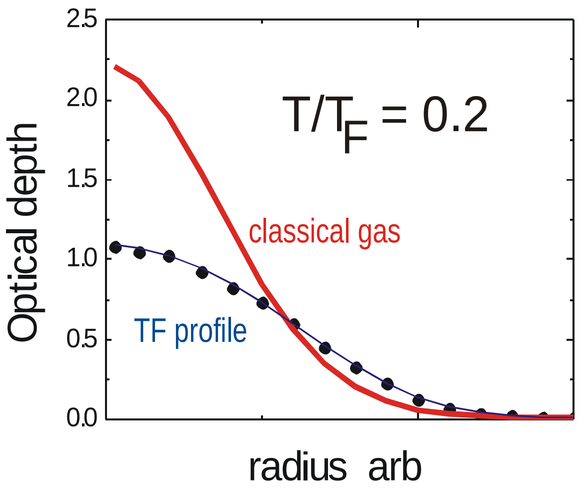
Smoking gun of condensate: Purely quantum phenomenon

Fermi degeneracy



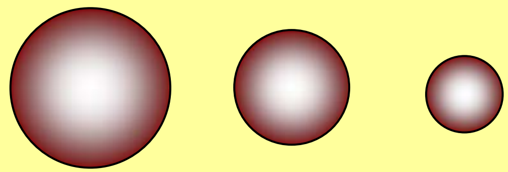


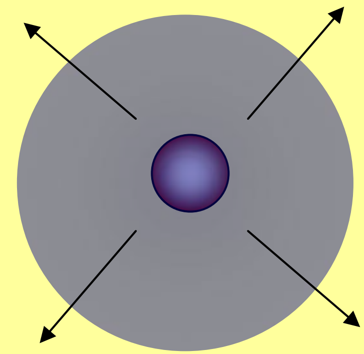
Cindy Regal -- JILA



More Dramatic Manifestation of Statistics

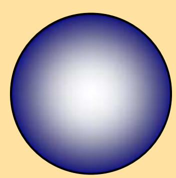
Bosons with attractive interactions





Cloud collapses, then "explodes"
(Bose-nova [Donley et al. Nature 412, 295 (2001)])

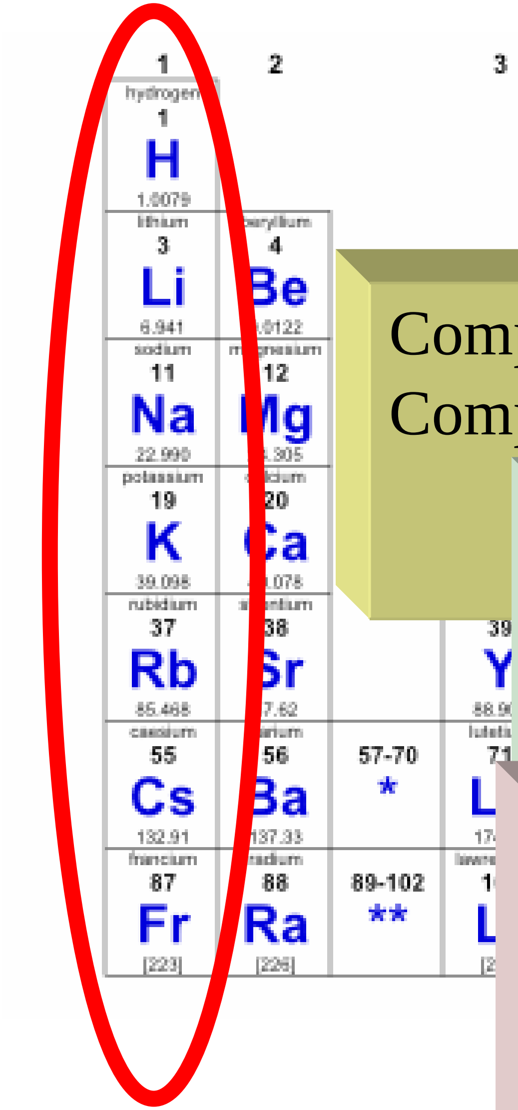
Fermions with attractive interactions



Fermi Pressure stabilizes cloud
(analogous to neutron star)

"Tabletop Astrophysics"

What are statistics of Alkali atoms?



Alkali Atoms

Why Alkali's?

Strong transitions in optical/near IR:

Easily manipulated with lasers

Composite Bosons: Made of even number of fermions

Composite Fermions: odd number of fermions

Nuclear physics:

Odd # neutrons + Odd # protons= Unstable

Alkali's tend to be Bosons: odd *p*,*e* even *n*

Only Fermionic Isotopes:

Atom	Isotope	Abundance	Half Life
H	2	0.01%	Stable
Li	6	8%	Stable
K	40	0.01%	10^9 years

Recent Progress

New Controls
- **Interactions**
- Photoassociation
- Controlled collisions (lattices)

New Settings
- Low Dimension
- Fast rotation
- Lattices
- Ring trap
- Chips

New States
- Massive Entanglement
- SF-Insulator Transition
- Tonks-Girardeau gas
- **BCS-BEC crossover**

New Probes
- RF Spectroscopy
- Noise Correlations
- Birefringence

Coupling Constants

Electromagnetism:

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \approx \frac{1}{137}$$

Dimensionless measure of strength of electromagnetism

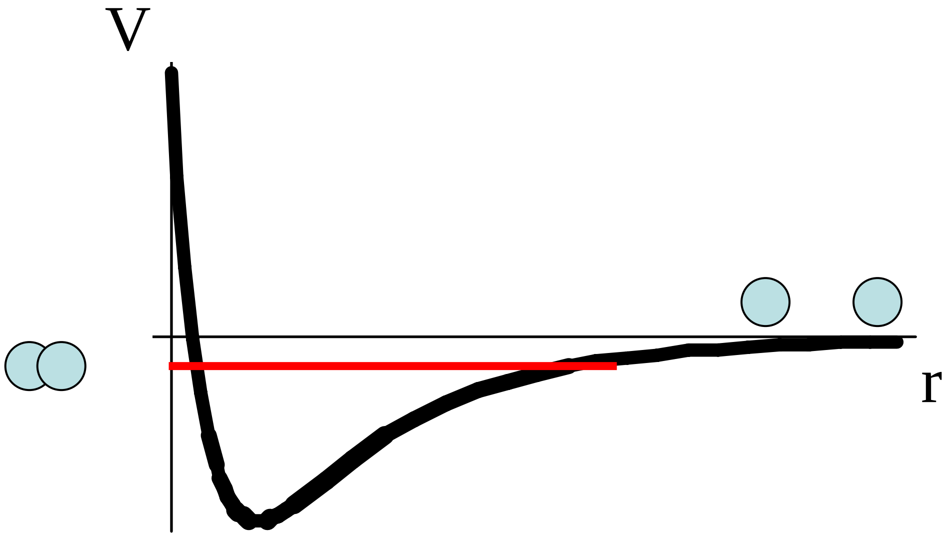
Small $\Rightarrow$ Perturbation theory works

What if you could tune the fine structure constant?

Controlling Interactions

Neutral atoms have short range interactions:

Scattering is dominated by bound state closest to threshold



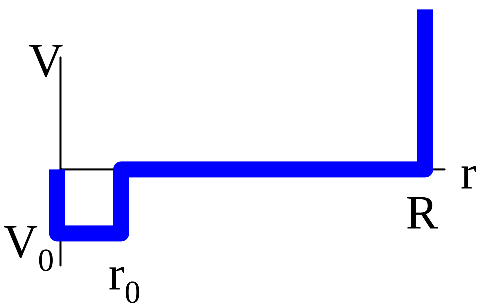
Bound state at threshold:

Interactions are very strong and universal (unitary limited)

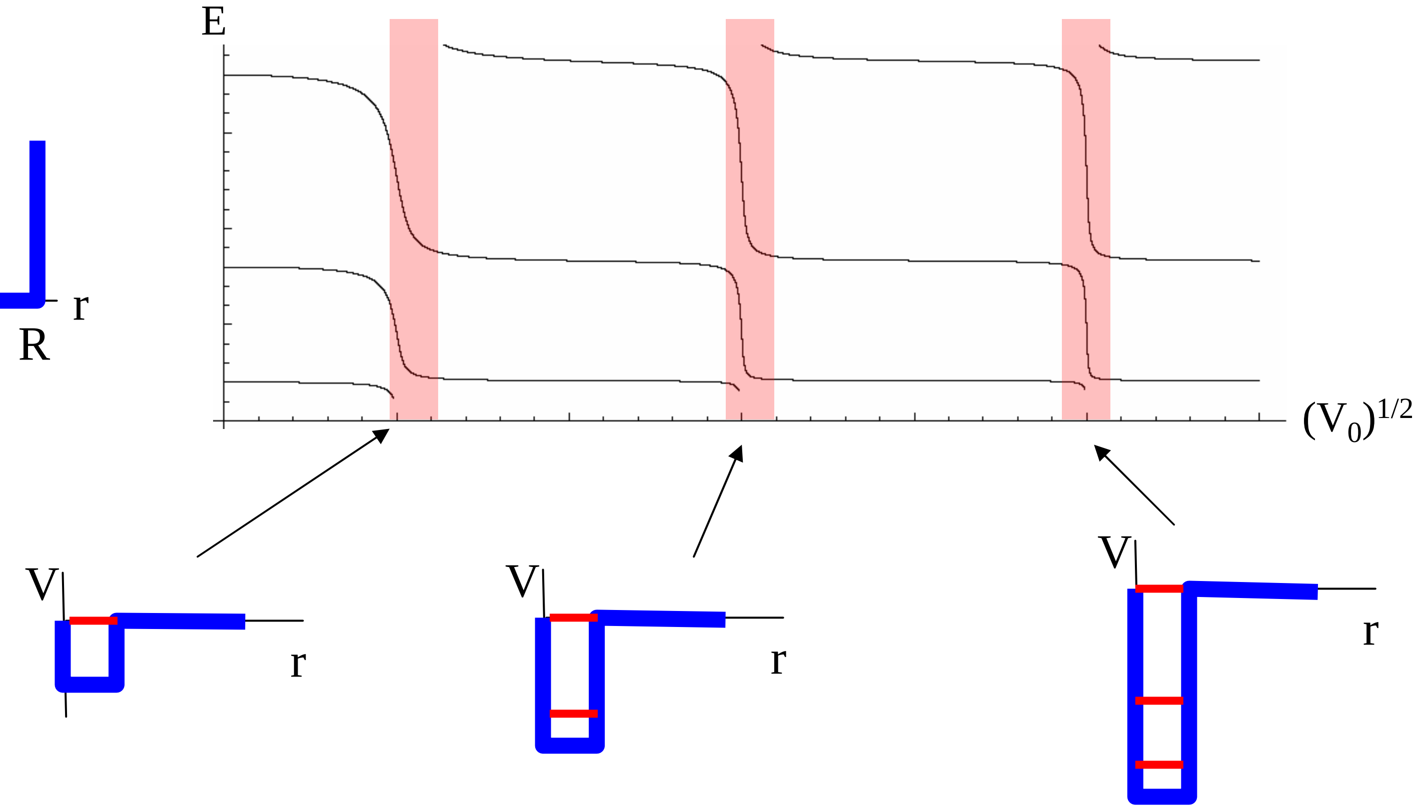
Typical Alkali atom: ~100 bound states

Toy model: attractive square well

Energy levels
in a box

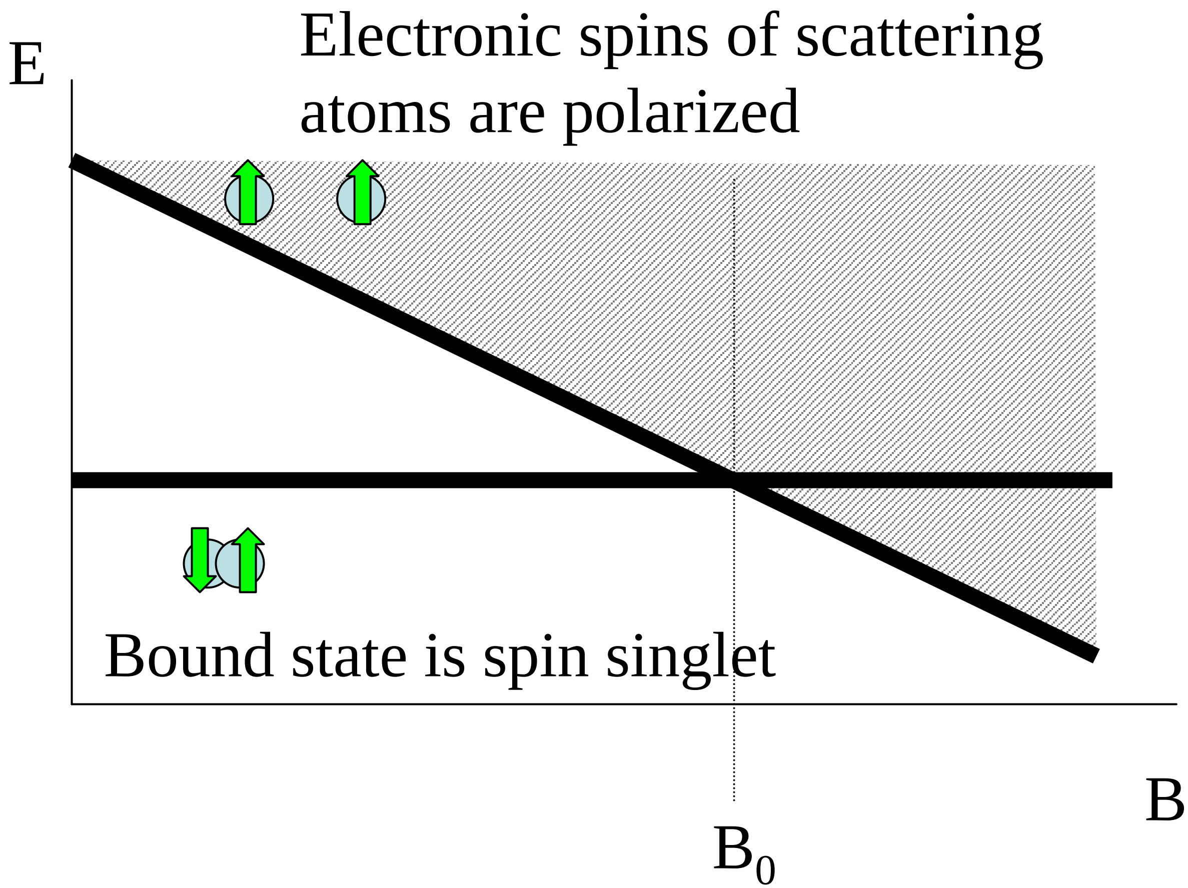


$R >> r_0$



Short range potential only provides strong interactions when a (quasi)bound state is at threshold

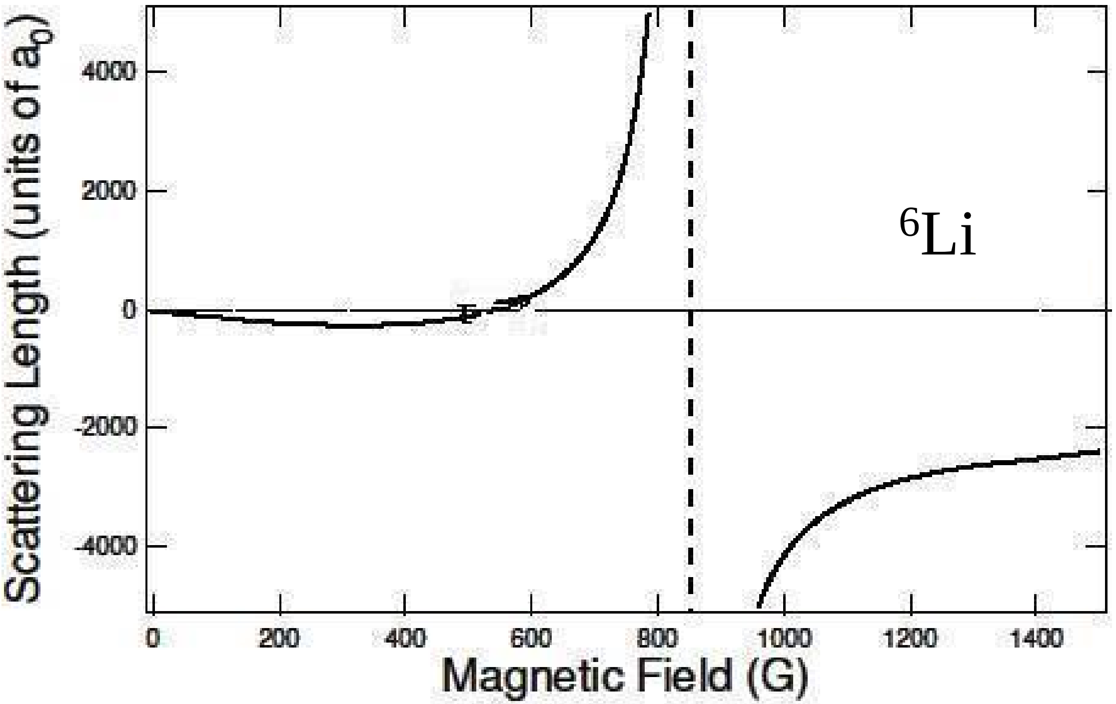
How to engineer a Resonance



Coupling provided by flipping nuclear spins (hyperfine interaction)

Magnetic field shifts bound state energy relative to continuum. Resonance occurs when this relative energy is zero.

How this works in practice



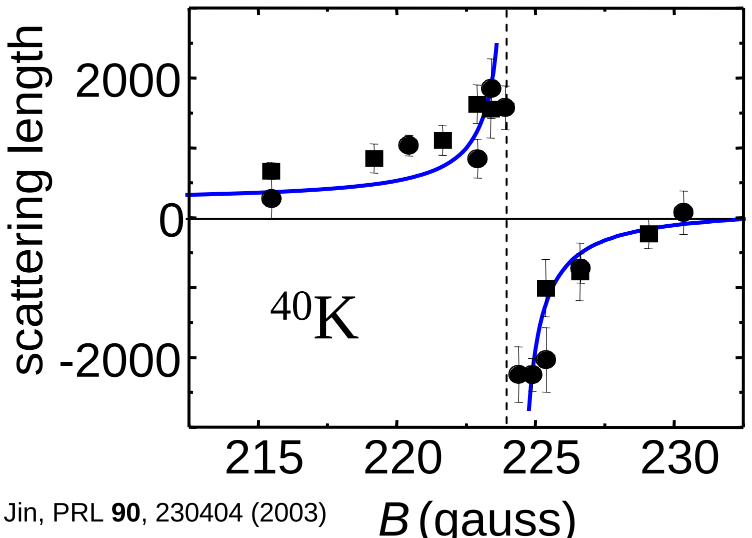
Scattering Length: Effective "size" of atoms in scattering

Cross-section

$$\sigma \approx \frac{4\pi a^2}{1 + a^2 k^2}$$

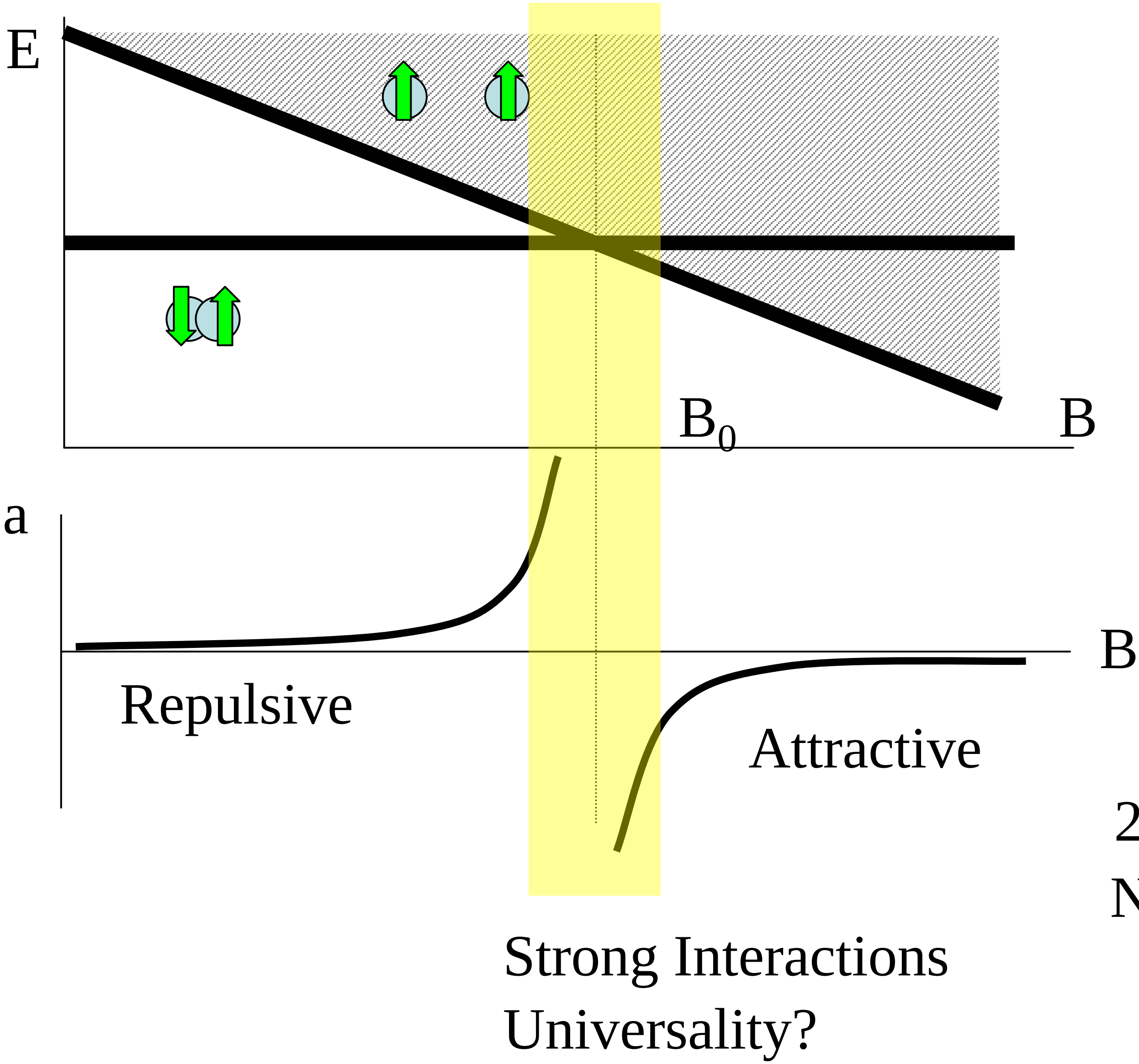
Houbiers et al. PRA **57**, R1497 (1998)
O'Hara *et al.*, PRA **66** 041401 (2002)

Experiment: extract scattering length from relaxation times or interaction induced energy shifts



C. A. Regal and D. S. Jin, PRL **90**, 230404 (2003)

Atoms at resonance



Experiment:
Bosons unstable
Fermions stable

2-body scattering:
No microscopic length

Universality

Only length-scale near resonance is density:

No microscopic parameters enter equation of state

$$\frac{E}{N} = \frac{3}{5} E_F (1 + \beta)$$

Hypothesis: β is Universal parameter -- independent of system

Nuclear matter is near resonance!!

$$p + n \longleftrightarrow d$$

Binding energy: 2 MeV << proton mass (GeV)
pion mass (140 MeV)

Implications: Heavy Ion collisions, Neutron stars

Tune quark masses: drive QCD to resonance

Braaten and Hammer, Phys. Rev. Lett. 91, 102002 (2003)

Implications: Lattice QCD calculations

Bertsch: Challenge problem in many-body physics (1998): ground state of resonant gas

Calculations

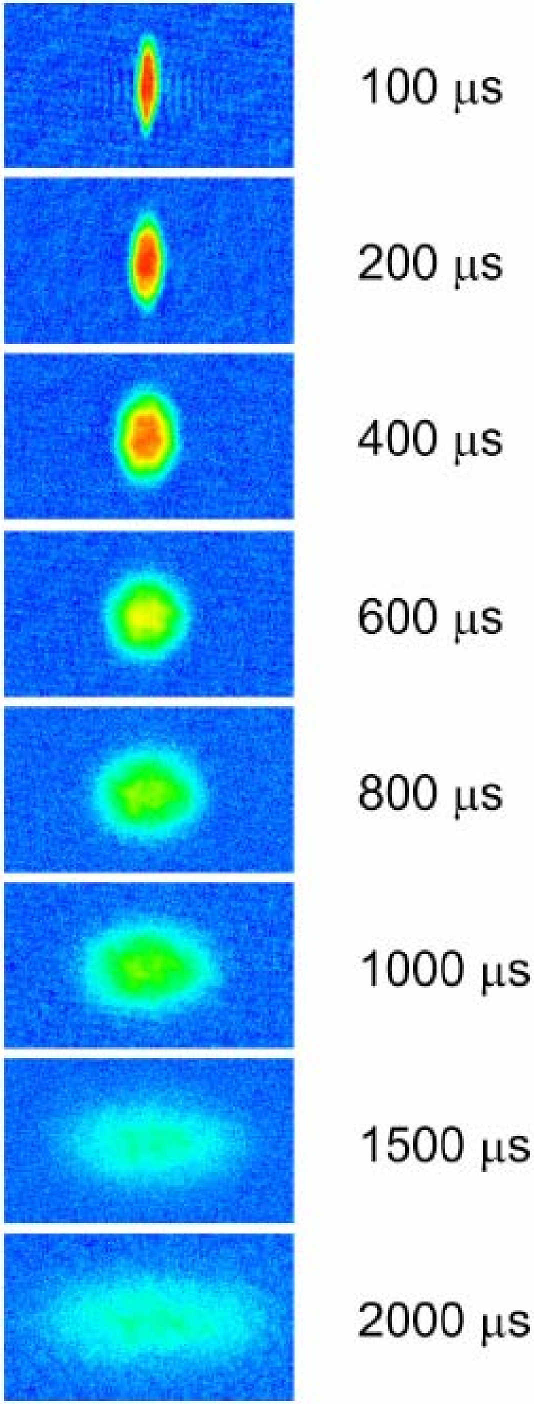
Fixed Node Diffusion Monte Carlo G. E. Astrakharchik, J. Boroonat, J. Casulleras, and S. Giorgini, Phys. Rev. Lett. 93, 200404 (2004)	$\beta = -0.58(1)$
Fixed Node Greens Function Monte Carlo J. Carlson, S.-Y Chang, V. R. Pandharipande, and K. E. Schmidt Phys. Rev, Lett. 91, 050401 (2003)	$\beta = -0.56(1)$
Lowest Order Constrained Variational Method H. Heiselberg, J. Phys. B: At. Mol. Opt. Phys. 37, 1 (2004)	$\beta = -0.33$
Linked Cluster Expansion G. A. Baker, Phys. Rev. C 60, 054311 (1999)	$\beta \in (-0.7, -0.4)$
Ladder (Galitskii) approximation H. Heiselberg, Phys. Rev. A 63, 043606 (2003)	$\beta = -0.67$
Resumation using an effective field theory Steele, nucl-th/0010066	$\beta = -0.67$
Mean field theory Engelbrecht, Randeria, and Sa de Melo, Phys. Rev. B 55, 15153 (1997)	$\beta < -0.41$

No systematic expansion

Experiments:

Duke: -0.26(7) ENS: -0.3 JILA: -0.4 Innsbruck: -0.68(1)

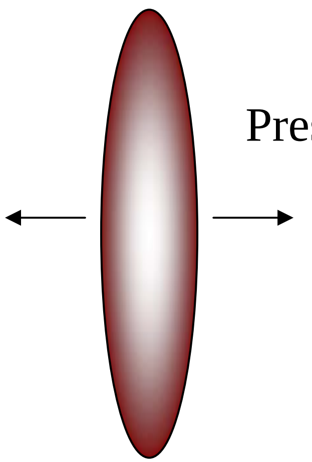
Measuring Equation of State



Free Expansion:

K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, and J. E. Thomas,
Science Dec 13 2002: 2179-2182

Turn off trap: cloud expands
Find equation of state: fit expansion



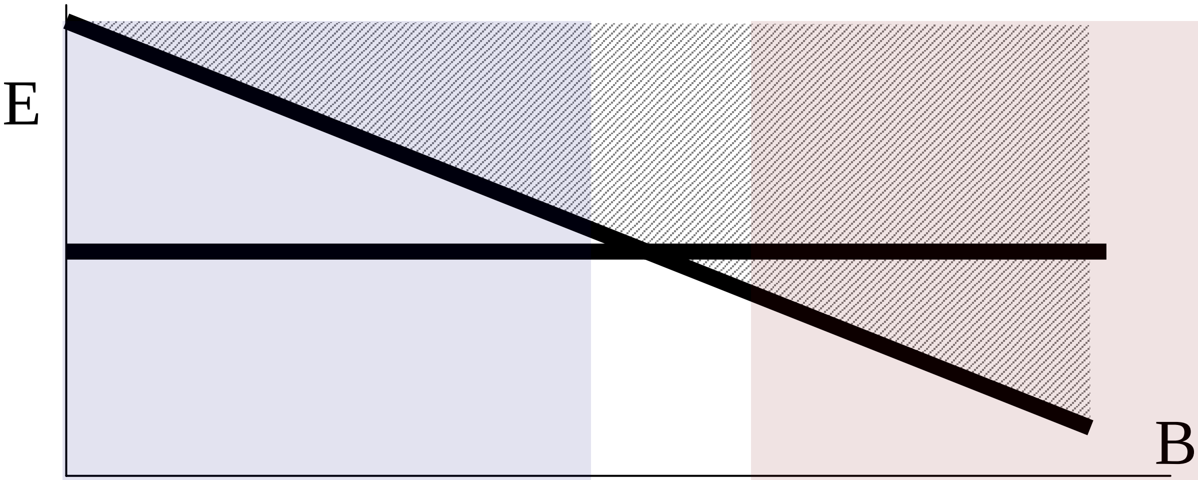
Pressure gradient largest in narrow direction
Expands asymmetrically

(Similar to "elliptic flow" in heavy ion collisions)

What to do with this tool!

Major paradigm of solid state physics: superfluidity/superconductivity

Superfluidity near resonance



Superfluidity: Needs bosons which condense

Molecules:

Bosons -- condense, form superfluid

Atoms:

Fermions with attractive interactions -- pair (cf BCS) form superfluid

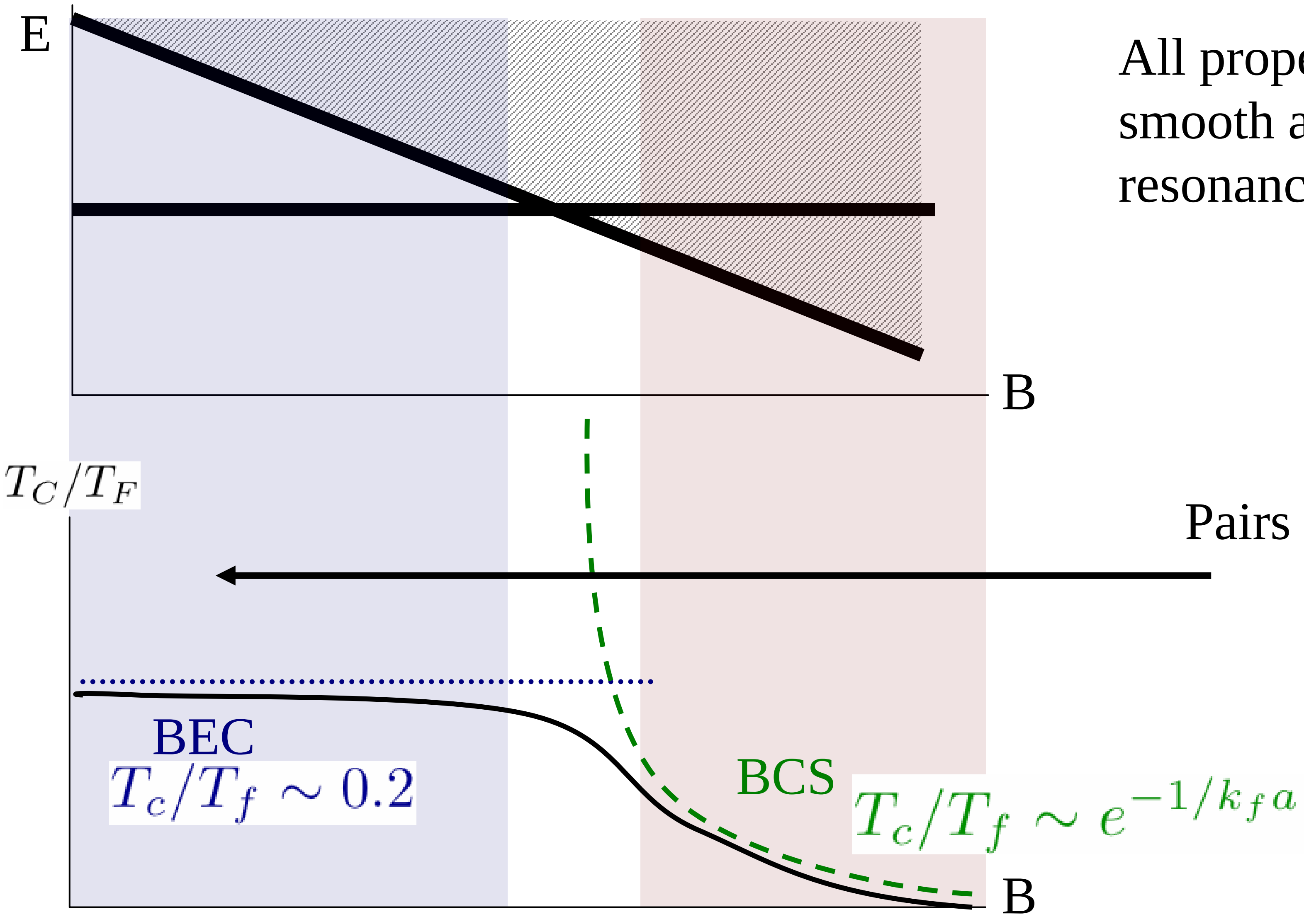
---

Theory: continuously deform one into other; BCS-BEC crossover

Leggett, J. Phys. (Paris) C7, 19 (1980)

P. Nozieres and S. Schmitt-Rink, J. Low Temp Phys. 59, 195 (1985)

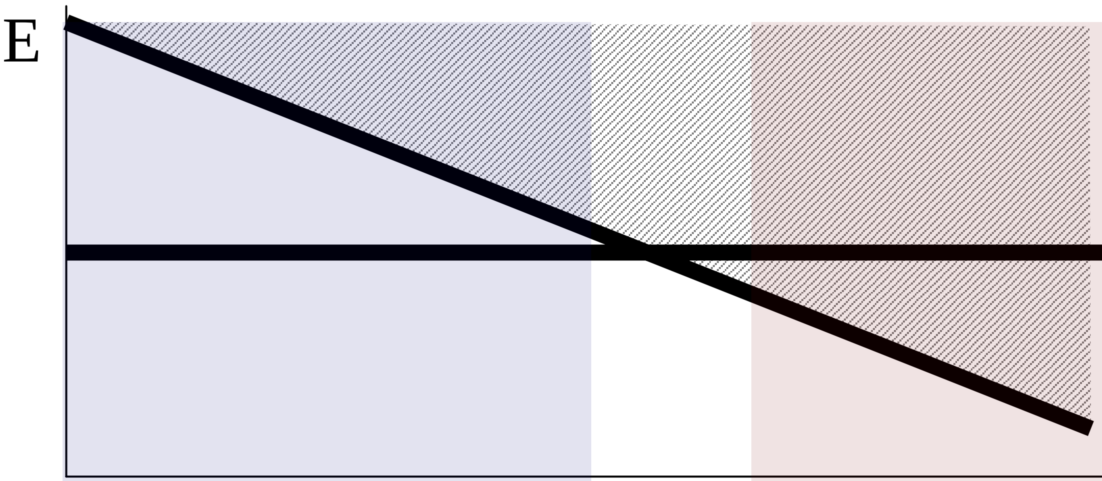
Superfluidity near resonance



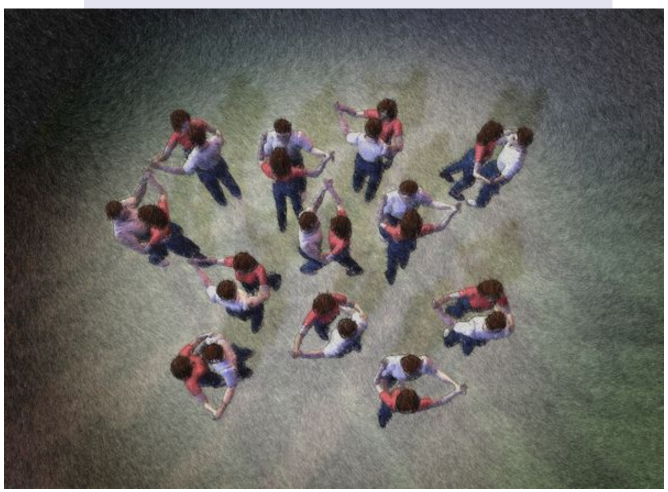
All properties smooth across resonance

Pairs shrink

Dance Analogy (Figures: Markus Greiner)



Slow Dance



Tightly bound pairs

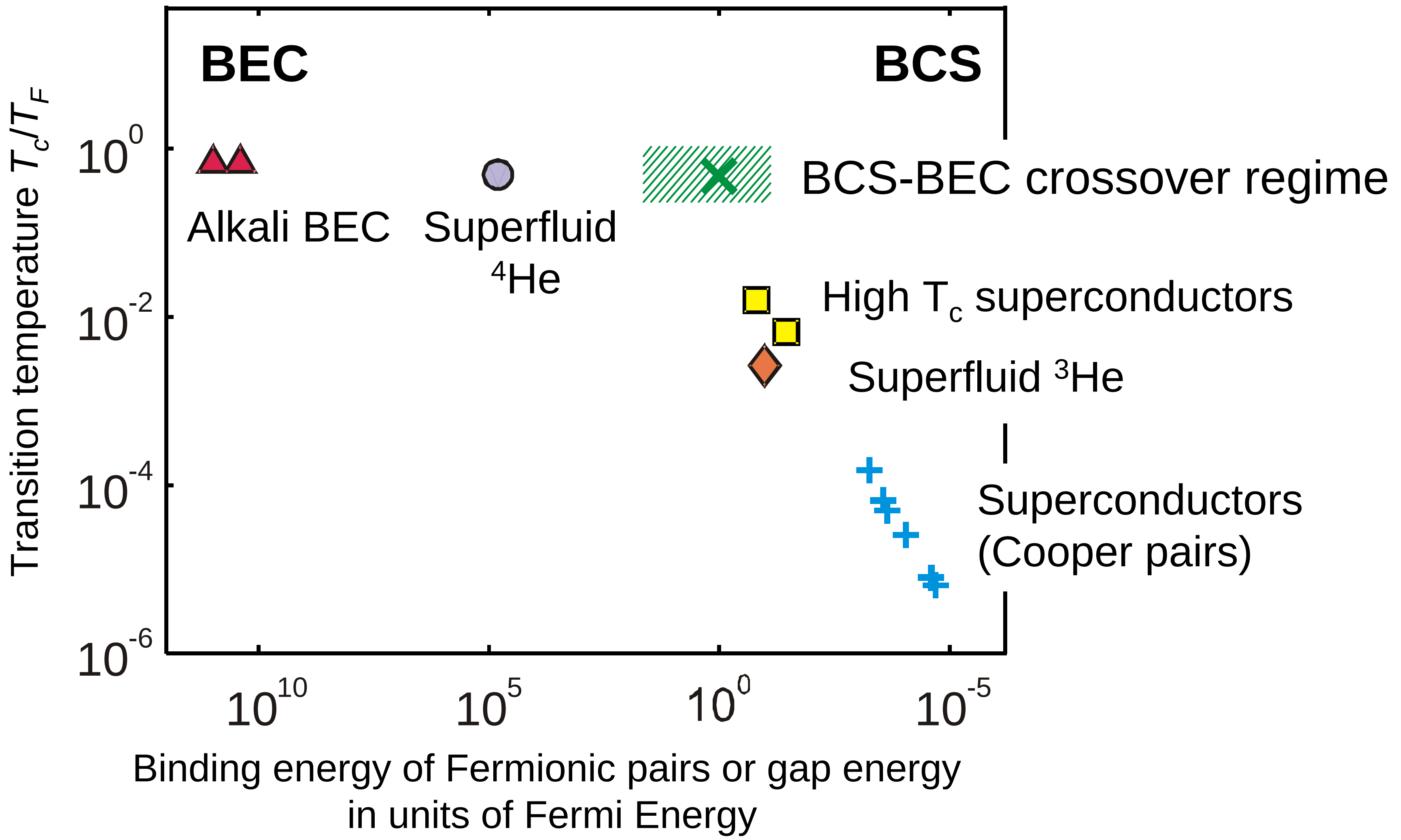
Fast Dance

Every boy is dancing with every girl: distance between pairs greater than distance between people

BCS-BEC landscape

Figure:
M. Holland *et al.*, PRL 87, 120406 (2001)

Cindy Regal



How to detect pairing/superfluidity

Direct approaches:

Imaging (Condensate Peak)

Spectroscopy (measure gap)

Vortices, persistent currents, Josephson effect

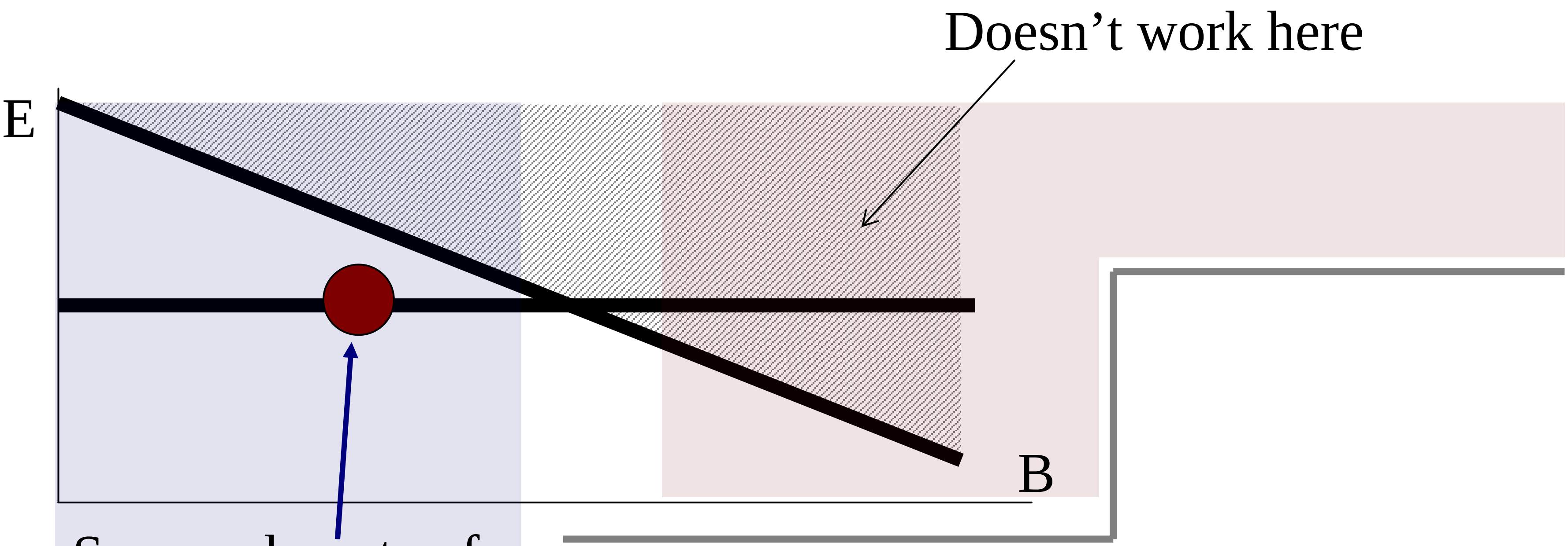
Indirect Approaches:

Discontinuities in thermodynamic functions (specific heat)

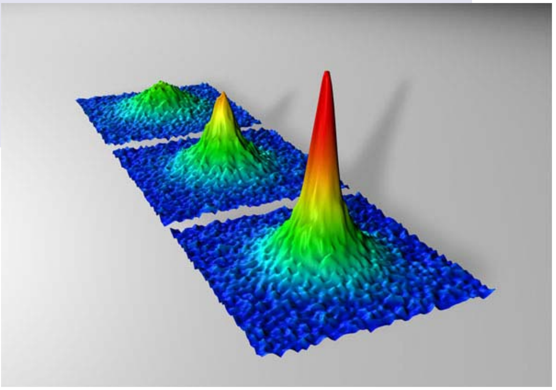
Collective Excitations

Punch line: Success -- the crossover has been observed

Condensate Peak



See condensate of molecules:



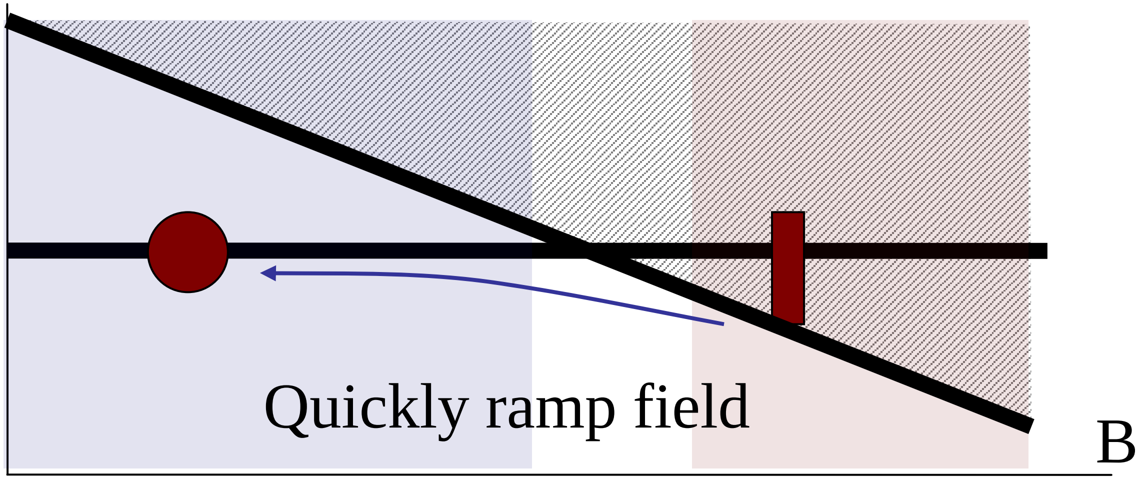
Emergence of a Molecular Bose-Einstein Condensate from a Fermi Sea
M. Greiner, C. A. Regal, and D. S. Jin, Nature **426**, 537 (2003).

S. Jochim, M. Bartenstein, A. Altmeyer, G. Hendl, S. Riedl, C. Chin, J. Hecker Denschlag, R. Grimm, Science 302, 3101 (2003)

QuickTime?and a
TIFF (LZW) decompressor
are needed to see this picture.

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

Projecting pairs onto molecules

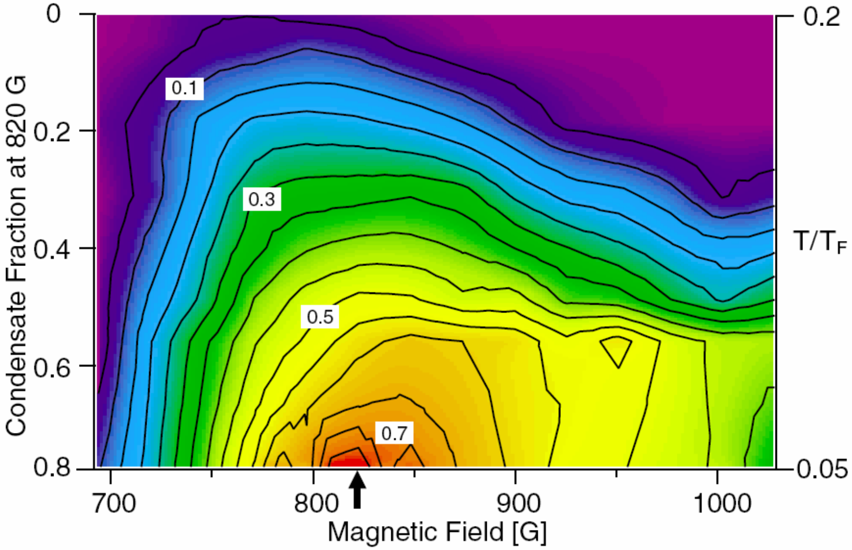


If overlap between Cooper pairs and Molecules nonzero:

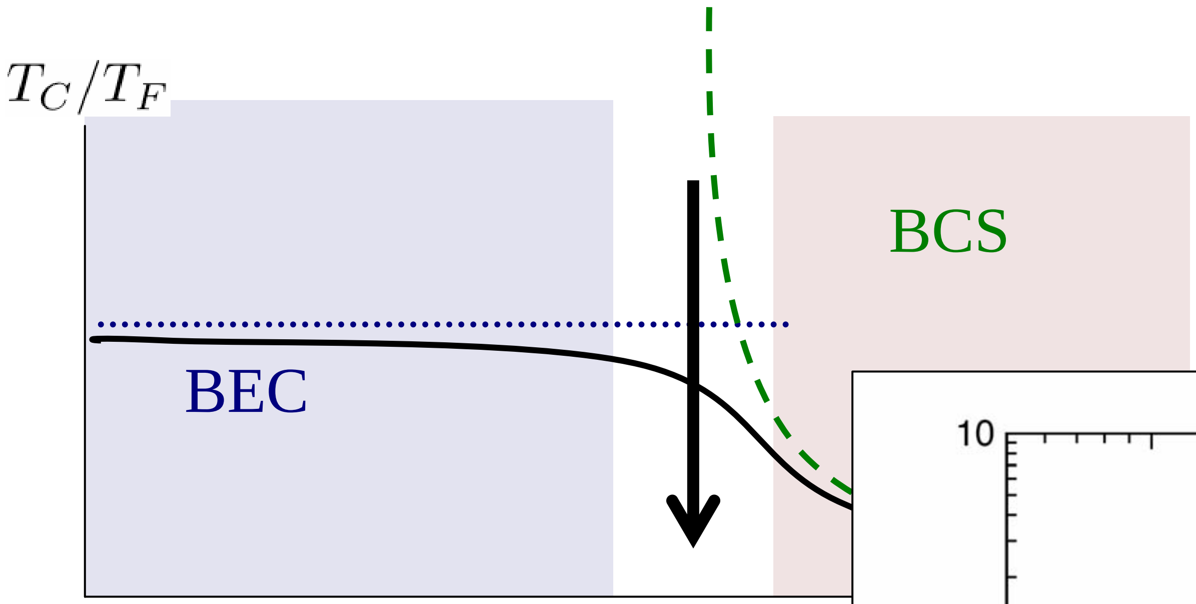
Produce molecular condensate
-image peak

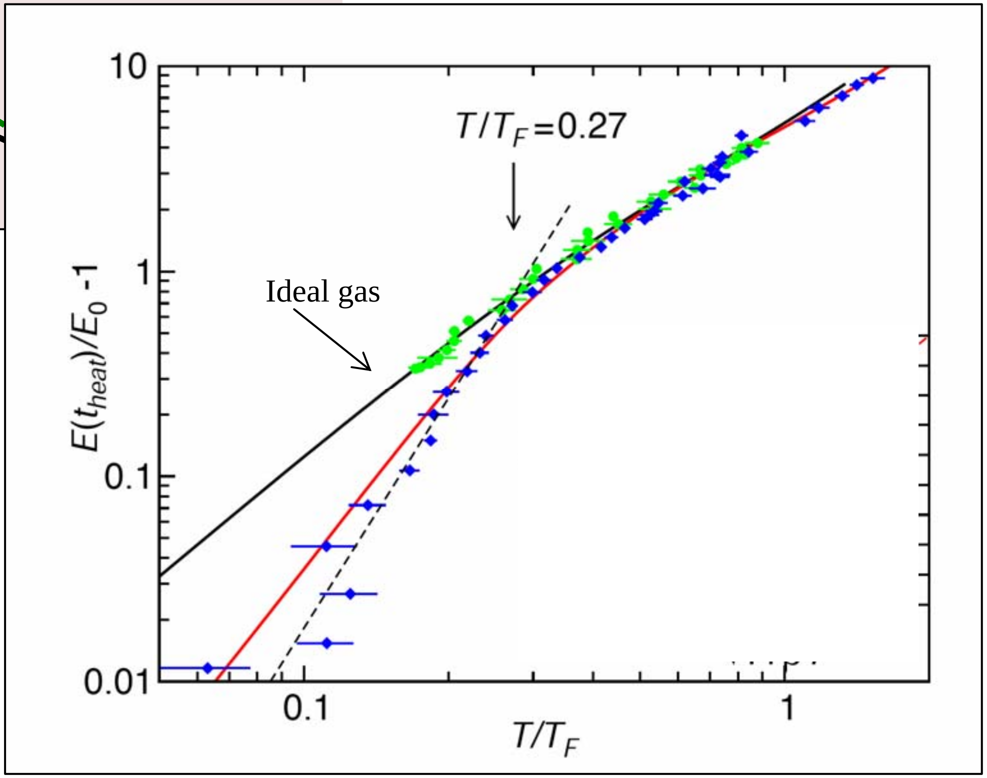
Observation of resonance condensation of fermionic atom pairs, C. A. Regal, M. Greiner, D. S. Jin, Phys. Rev. Lett. **92**, 040403, (2004)

M.W. Zwierlein, C.A. Stan, C.H. Schunck, S.M.F. Raupach, A.J. Kerman, and W. Ketterle. *Condensation of Pairs of Fermionic Atoms Near a Feshbach Resonance.* Phys. Rev. Lett. **92**, 120403 (2004).



Thermodynamics

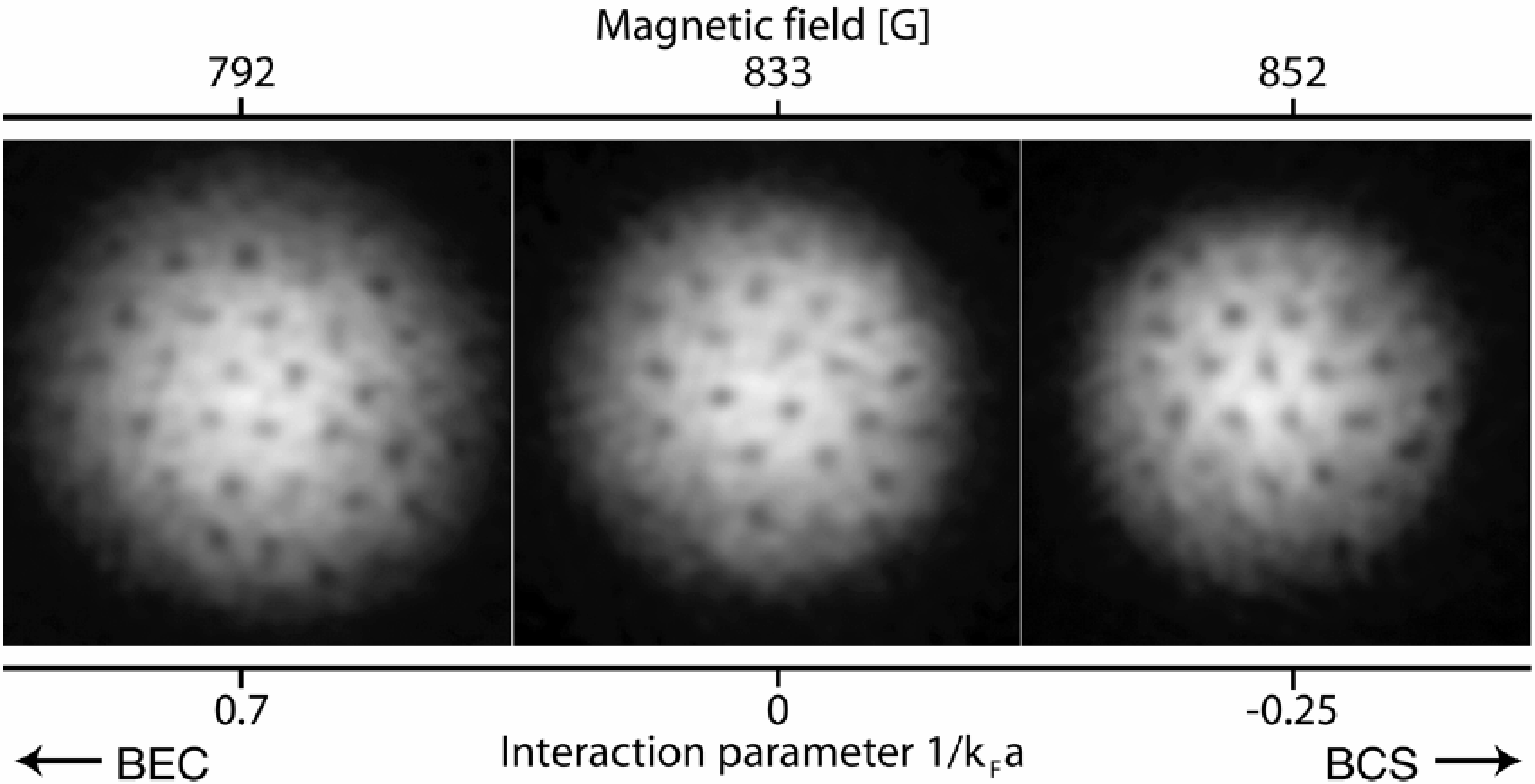




See specific heat anomaly

J Kinast, A Turlapov, JE Thomas, Chen, Stajic, & K Levin, Science, 27 January 2005

Vortices



M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle, cond-mat/0505635

See vortices

-- verify they survive sweeping across resonance

Recent Progress

New States
- Massive Entanglement
- SF-Insulator Transition
- Tonks-Girardeau gas
- **BCS-BEC crossover**

New Settings
- Low Dimension
- Fast rotation
- Lattices
- Ring trap
- Chips

New Probes
- RF Spectroscopy
- **Noise Correlations**
- Birefringence

New Controls
- Interactions

Future Directions

More new states of matter:

Normal state above Ω_{c2} in BEC-BCS crossover

Quantum Hall Effects

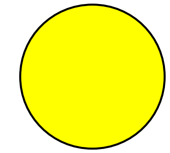
Quantum Simulations

Dipolar molecules/atoms

Quantum Computing

Precision spectroscopy

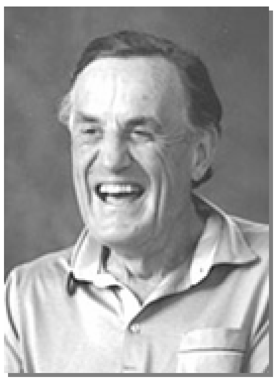
New Probes



Noise Correlations: “Noise is the signal”

star

Idea: Hanbury Brown-Twiss

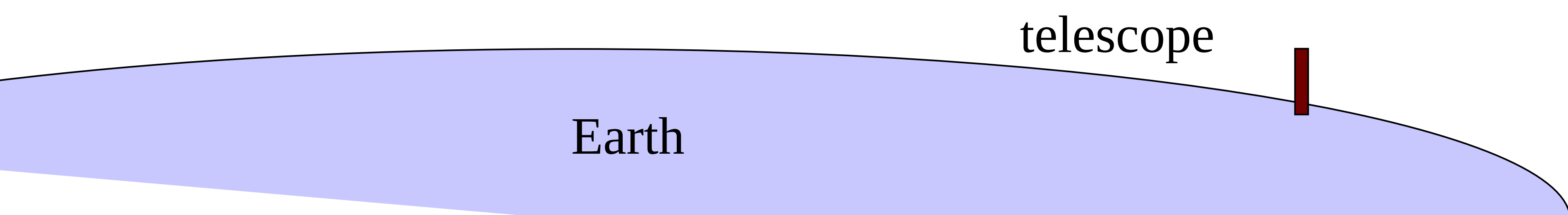


Hanbury Brown
1916-2002

How to determine size of stars?

Cannot resolve optically!!!!

Idea: use two telescopes -- correlate noise



Intensity Interferometry

Contribution to electric field at telescopes 1 and 2 from "A" and "B"

$$E_{1A} = E_A e^{i\phi_{1A} + \delta\phi_A} \qquad E_{2A} = E_A e^{i\phi_{2A} + \delta\phi_A}$$

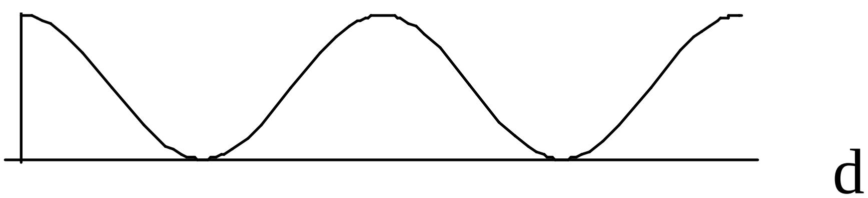
$$E_{1B} = E_B e^{i\phi_{1B} + \delta\phi_B} \qquad E_{2B} = E_B e^{i\phi_{2B} + \delta\phi_B}$$

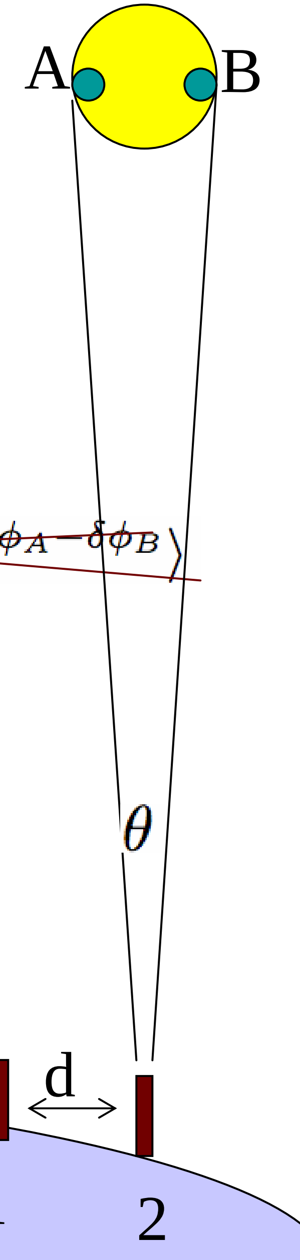
$$\langle I_1 \rangle = \langle |E_{1A} + E_{1B}|^2 \rangle = |E_A|^2 + |E_B|^2 + 2\mathrm{Re}\langle E_A E_B e^{i(\phi_{1A} - \phi_{1B} + \delta\phi_A - \delta\phi_B)} \rangle$$

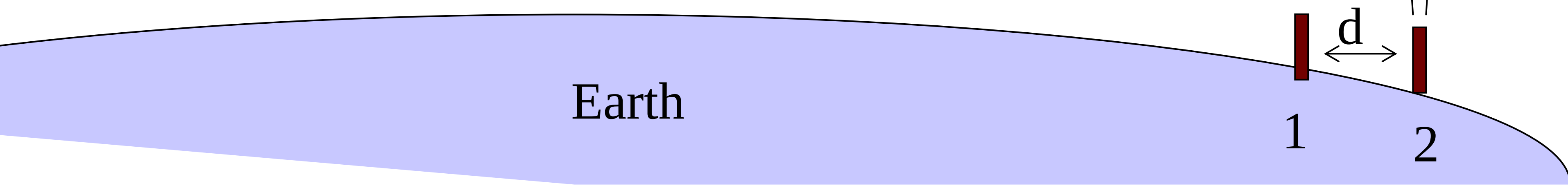
$$\langle I_1 I_2 \rangle = \langle I_1 \rangle \langle I_2 \rangle + 4E_A^2 E_B^2 \cos[(\phi_{1A} - \phi_{2A}) - (\phi_{1B} - \phi_{2B})]$$

$$kd\sin(\theta)$$

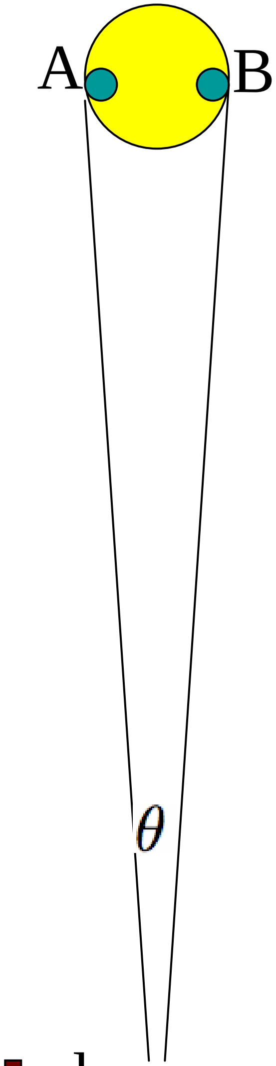
$\langle I_1 I_2 \rangle$





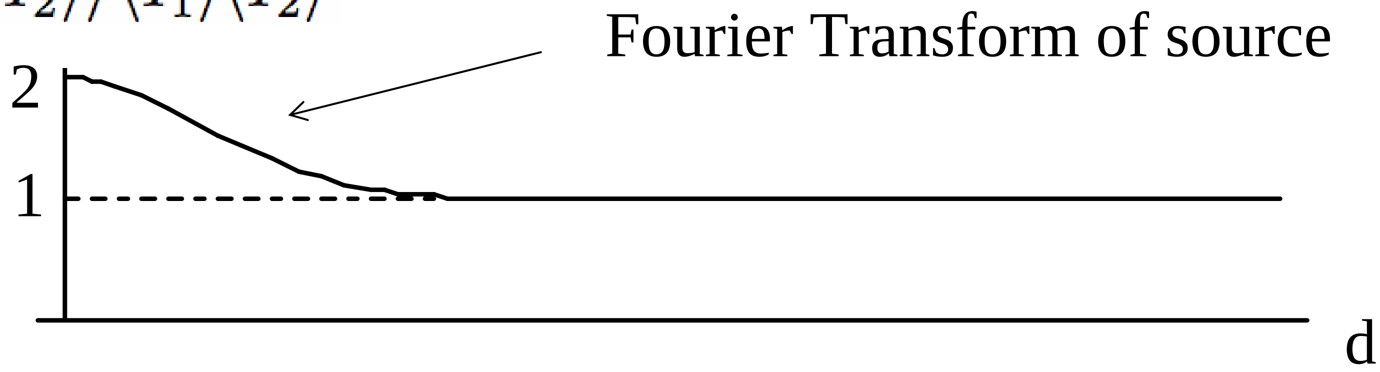


Intensity Interferometry

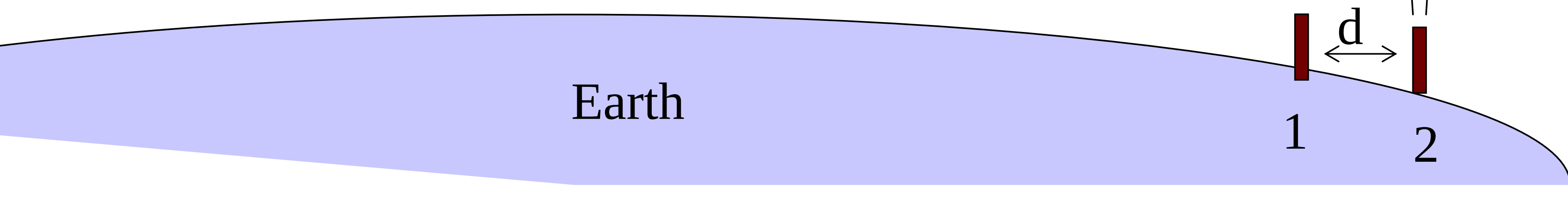


Same argument with continuous distribution

$\langle I_1 I_2 \rangle / \langle I_1 \rangle \langle I_2 \rangle$



Fermions: get dip instead of bump



Cold Atom Experiment

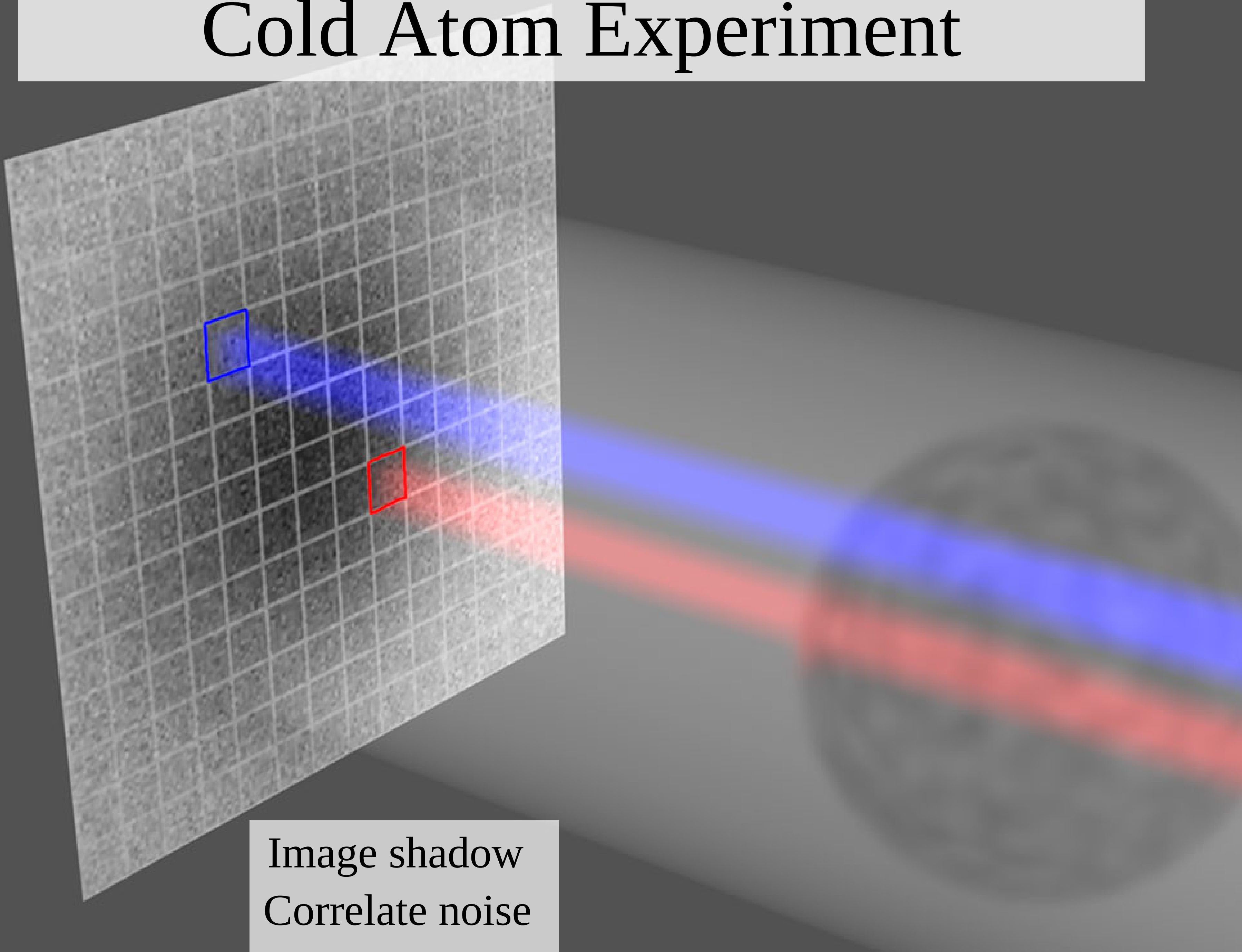
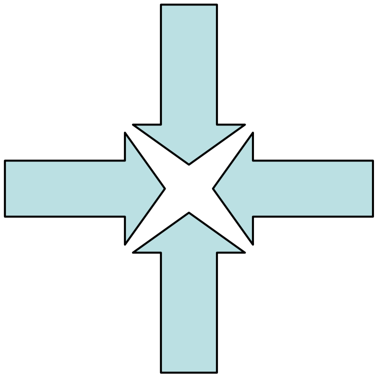


Image shadow
Correlate noise

Optical Lattice

Interfere laser beams



Create periodic potential

Insulator:
localized

QuickTime?and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Superfluid:
delocalized

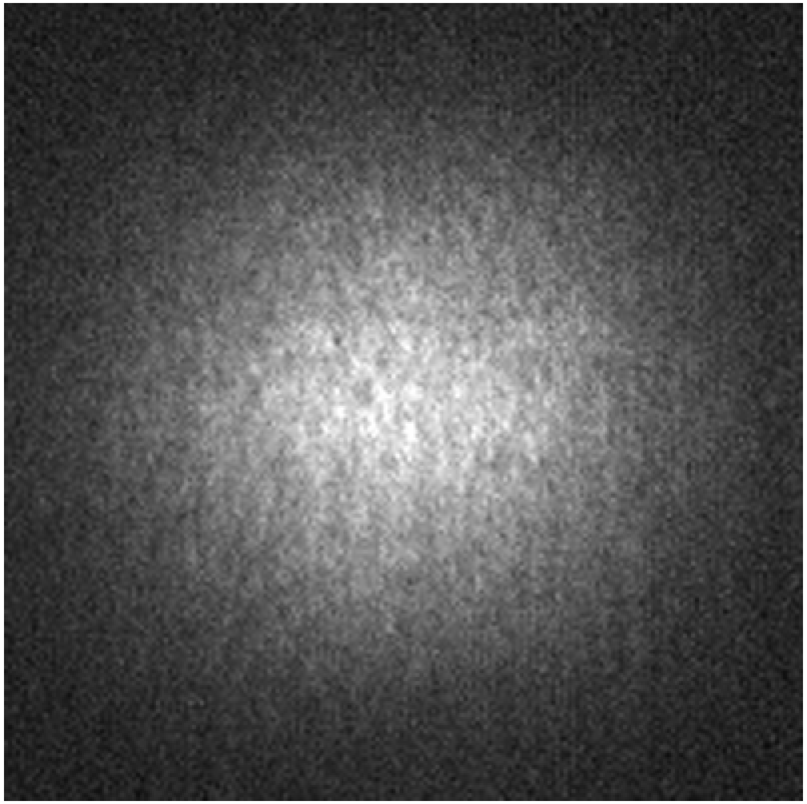
Turn off potential:
- let expand
- image

superfluid

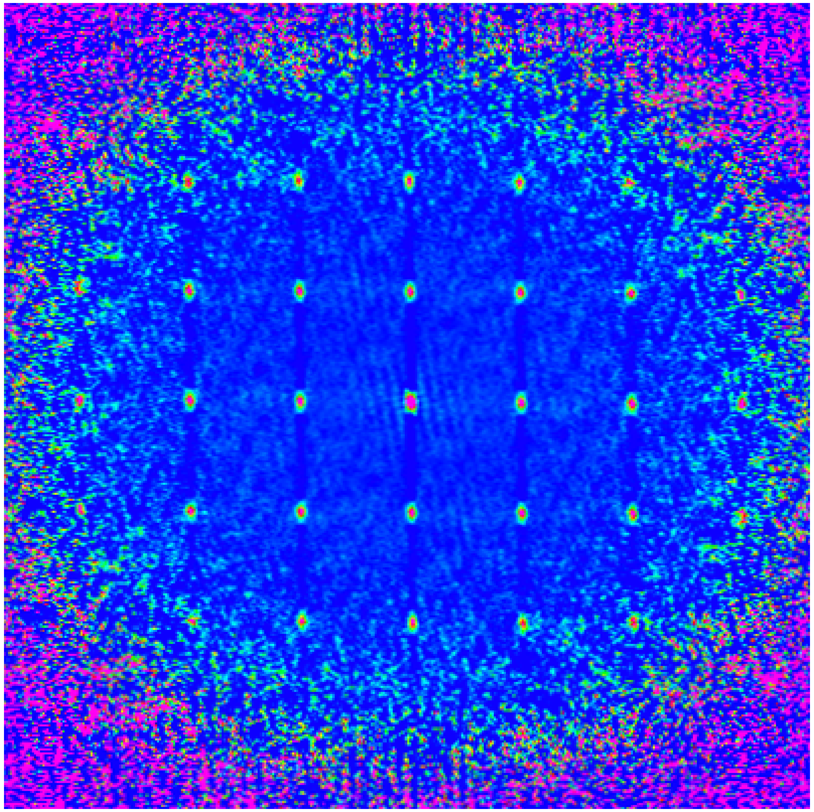
QuickTime?and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

insulator

Noise Correlations



Column density (Mott)



Folling et al. Nature **434**, 481-484 (24 March 2005)

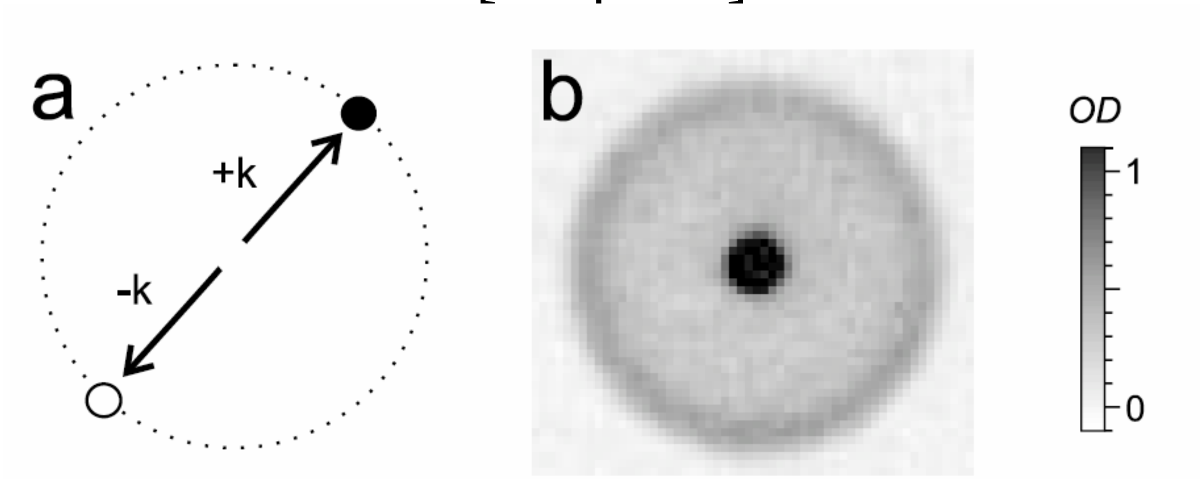
Autocorrelation:

Fourier transform of source

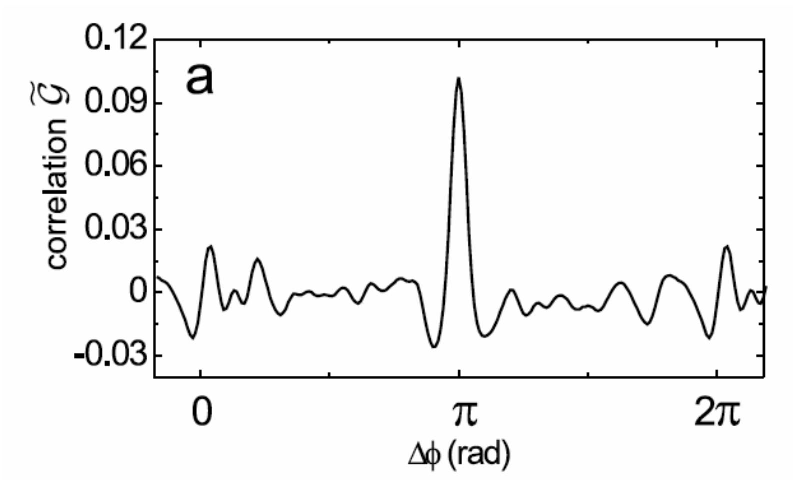
Great technical achievement [eliminate technical noise]

Pairing

Dissociate Molecules [RF pulse]



Angular correlation of noise



Atoms in molecule fly off in antipodal directions

Detection of Spatial Correlations in an Ultracold Gas of Fermions
M. Greiner, C.A. Regal, C. Ticknor, J.L. Bohn, and D. S. Jin, Phys. Rev. Lett. 92, 150405 (2004).

Recent Progress

New States
- Massive Entanglement
- SF-Insulator Transition
- Tonks-Girardeau gas
- **BCS-BEC crossover**

New Settings
- Low Dimension
- Fast rotation
- Lattices
- Ring trap
- Chips

New Probes
- RF Spectroscopy
- **Noise Correlations**
- Birefringence

New Controls
- Interactions

Future Directions

More new states of matter:

Normal state above Ω_{c2} in BEC-BCS crossover
Quantum Hall Effects

Quantum Simulations

Dipolar molecules/atoms

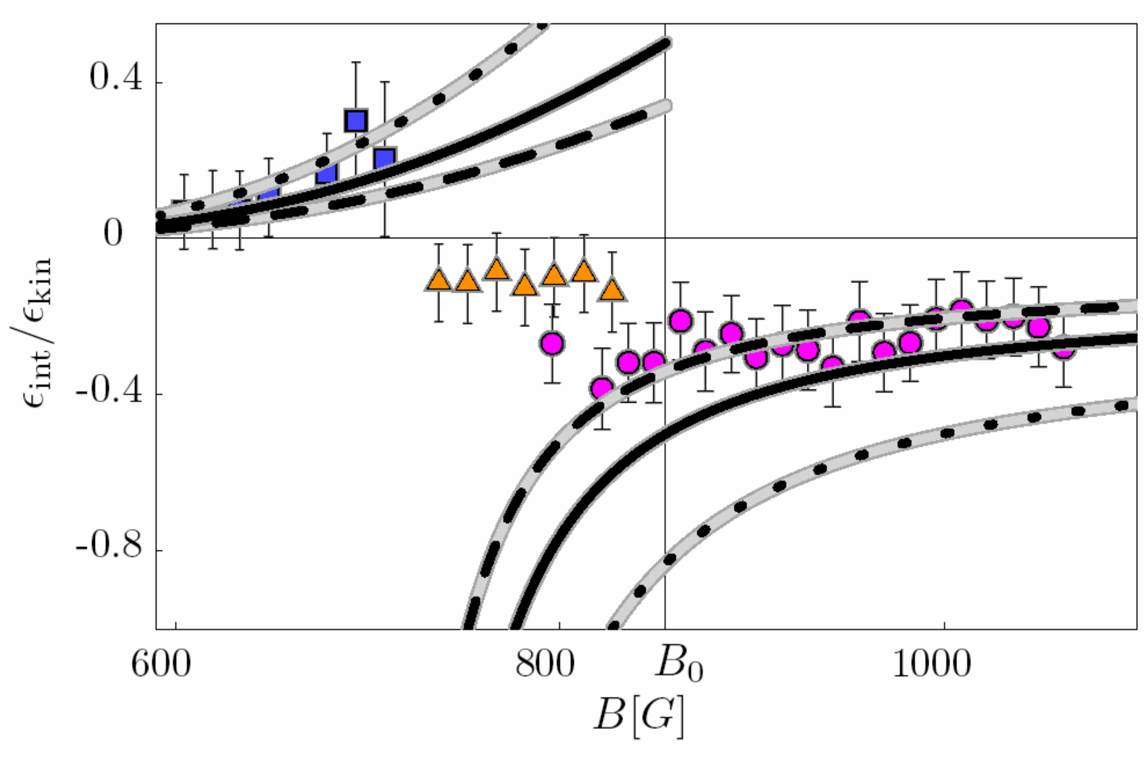
Quantum Computing

Precision spectroscopy

Direct Measurement of Energies

Measure total energy from expansion

Measure kinetic energy by “jumping” to field where a=0



Hysteresis:
Molecular formation

Data: T. Bourdel, J. Cubizolles, L. Khaykovich, K. M. F. Magalhães, S. J. J. M. F. Kokkelmans, G. V. Shlyapnikov, and C. Salomon Phys. Rev. Lett. 91, 020402 (2003)

Curves: High temperature expansion: T.-L. Ho and E. J. M.