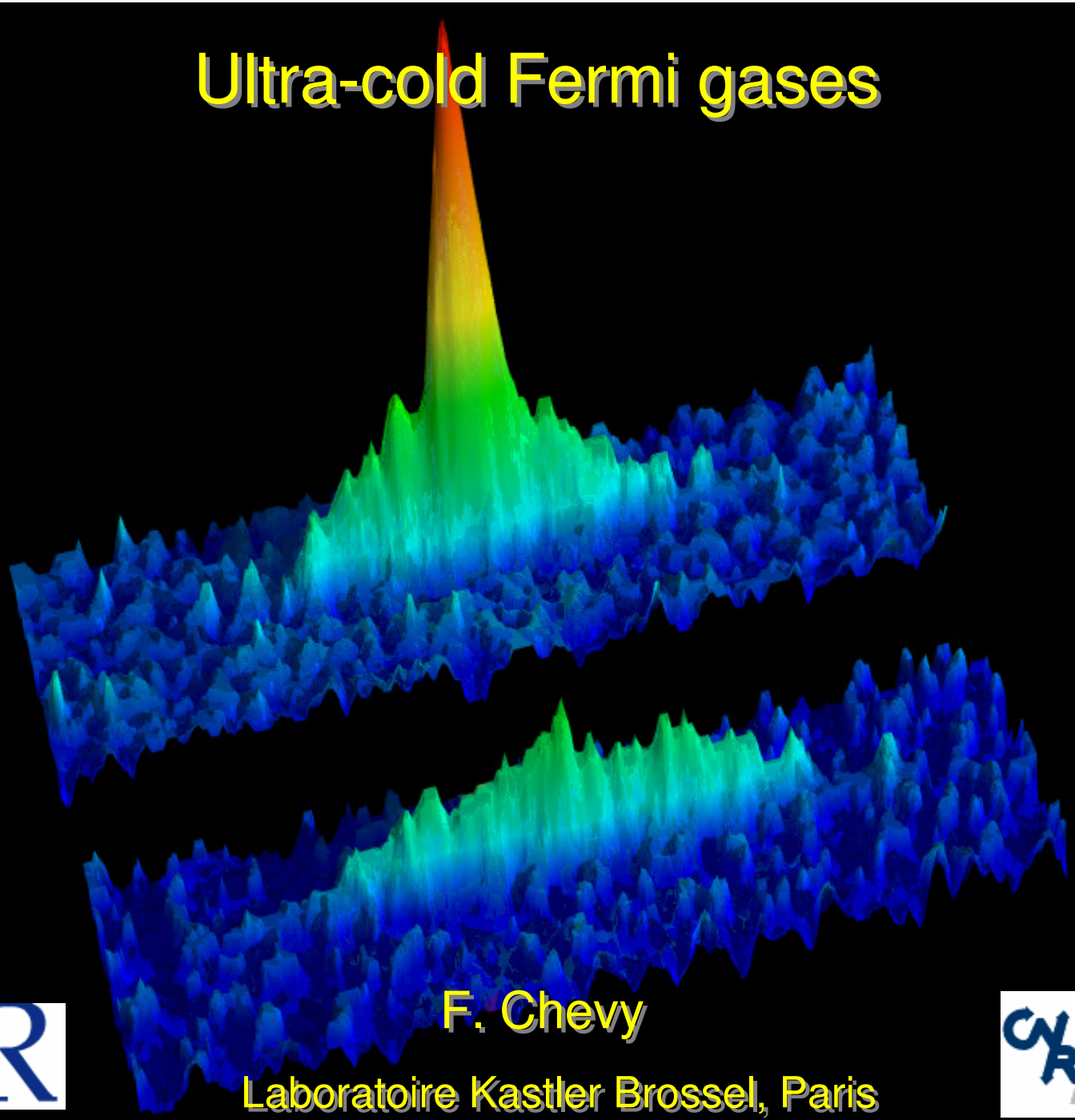
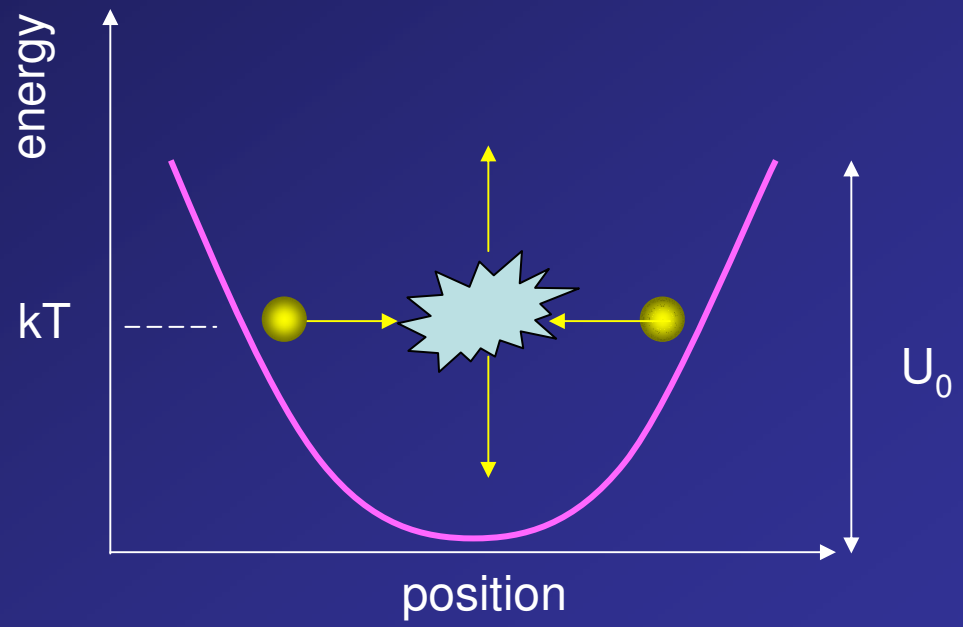
Ultra-cold Fermi gases



F. Chevy

Laboratoire Kastler Brossel, Paris

Evaporative Cooling of ultra-cold atoms



To maintain an efficient cooling, U_0 dereases with T

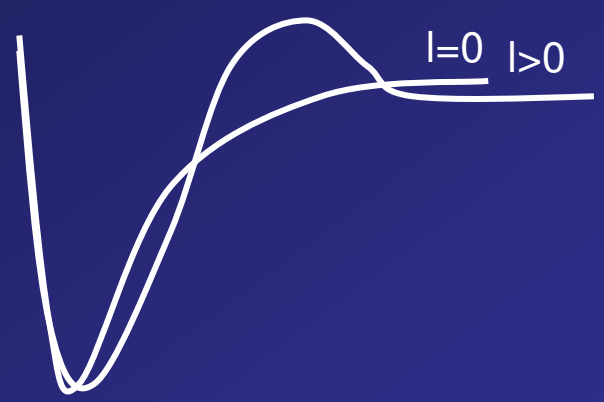
The Pauli Exclusion Principle and the evaporative cooling of ultra-cold Fermi gases

Collision between two atoms. Effective potential in the l-wave:

$$V_{\text{eff}}(r) = V(r) + \frac{\hbar^2 \ell(\ell+1)}{2mr^2}$$

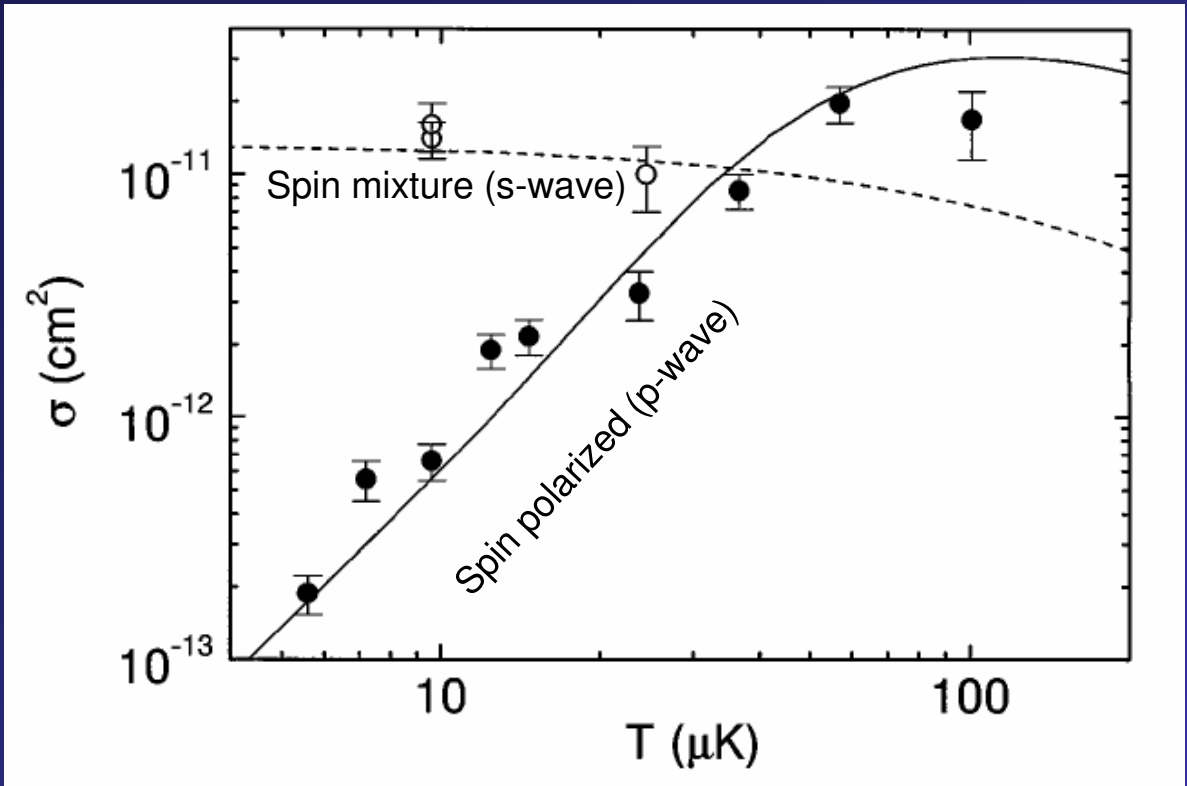
Interatomic potential

centrifugal potential



At low temperature, the atomes cannot cross the centrifugal Barrier: only s-wave collisions. Symmetrization for identical particles: even l-wave collisions forbidden for polarized fermions.

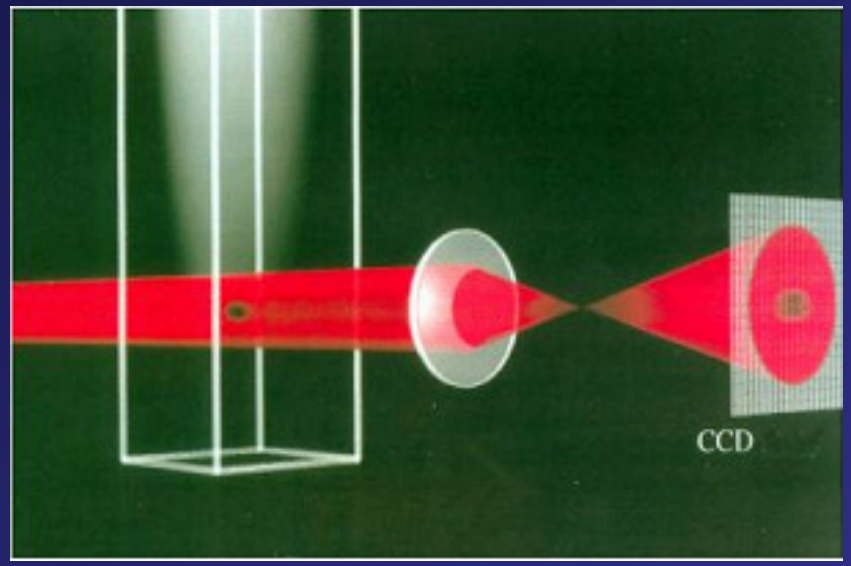
Suppression of elastic collisions in a spin polarized Fermi gas

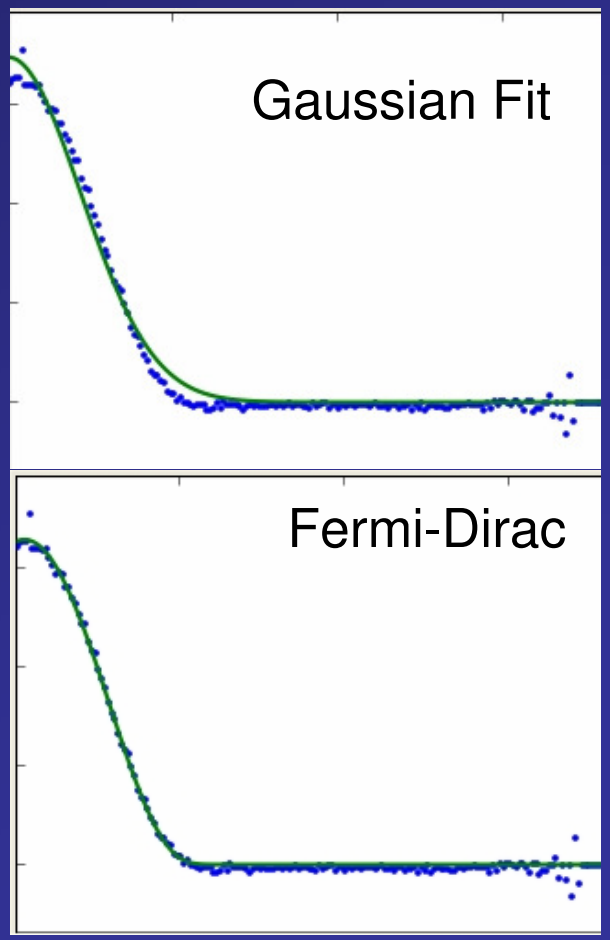


Use spin mixtures or several atomic species (eg ^{6}Li-^{7}Li, K-Rb…)

B. DeMarco, J. L. Bohn, J.P. Burke, Jr., M. Holland, and D.S. Jin, Phys. Rev. Lett. **82**, 4208 (1999).

How do we measure temperature: Time of flight absorption imaging



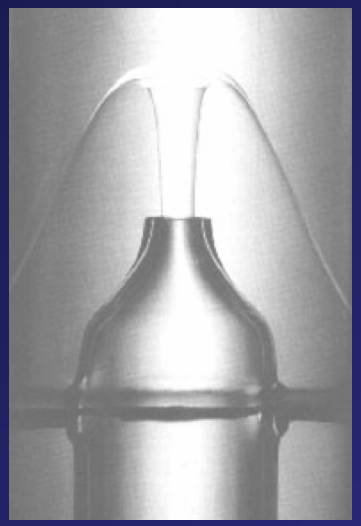


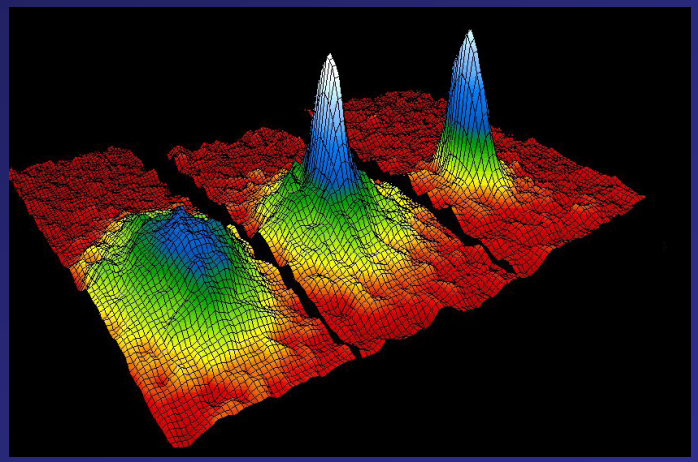
$T/T_F<0.05$
Atom number~10^5

Superconductivity and superfluidity

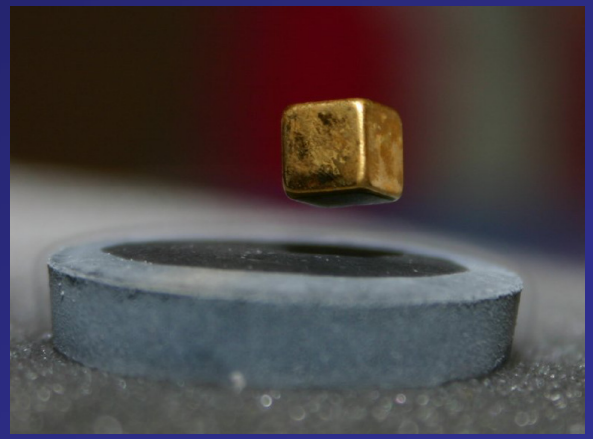
Quantum fluids

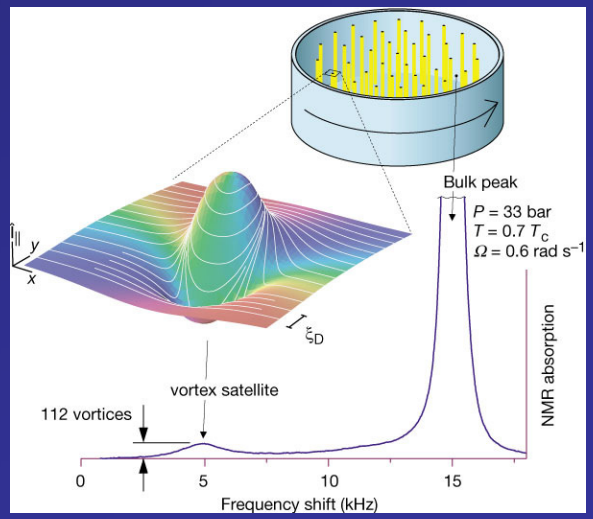
Bose Einstein condensates



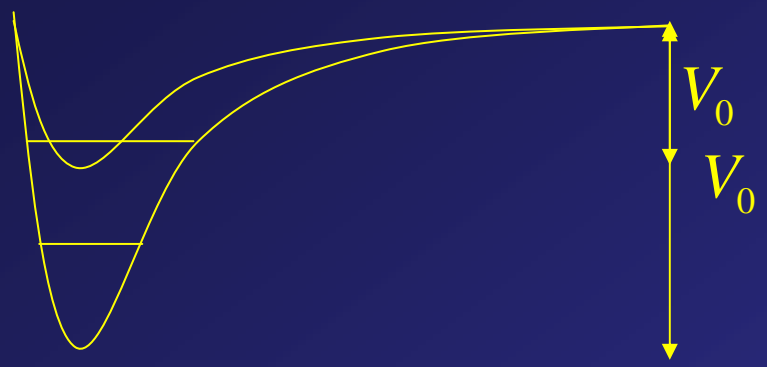


Superconductivity an helium 3



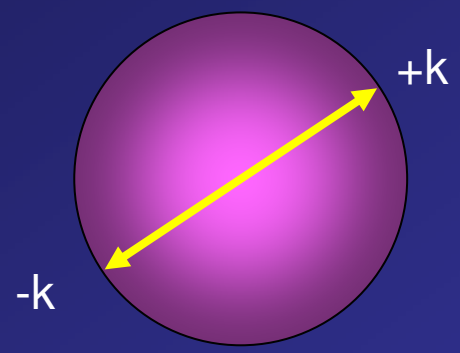


Attractive fermions at zero temperature



Deep potential : 2-body bound state.
Many body ground state : BEC of molecules

Shallow potential ($V_0 < V_0^*$):
no 2-body bound state.
No superfluid?



Many body effects:
BCS pairing at arbitrarily low V_0
(^{3}He, superconductors)

The BEC-BCS crossover

At low energy, real potential replaced by $V_{\text{pseudo}} = \frac{4\pi\hbar^2 a}{m}\delta(\mathbf{r})$

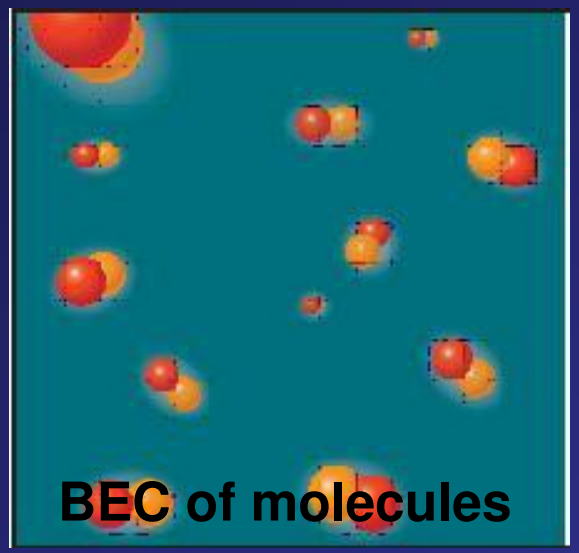
Scattering length $a \sim (V_0 - V_0^*)^{-1}$

$V_0 > V_0^* \Leftrightarrow a > 0$

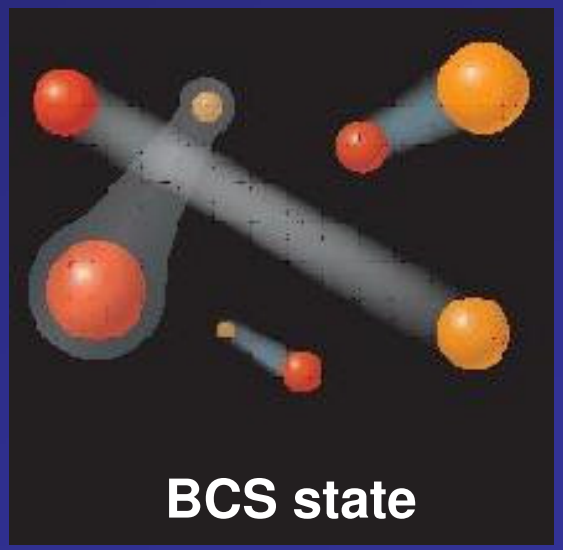
$V_0 \sim V_0^*$

$n|a|^3 \sim 1$

$V_0 < V_0^* \Leftrightarrow a < 0$



??????

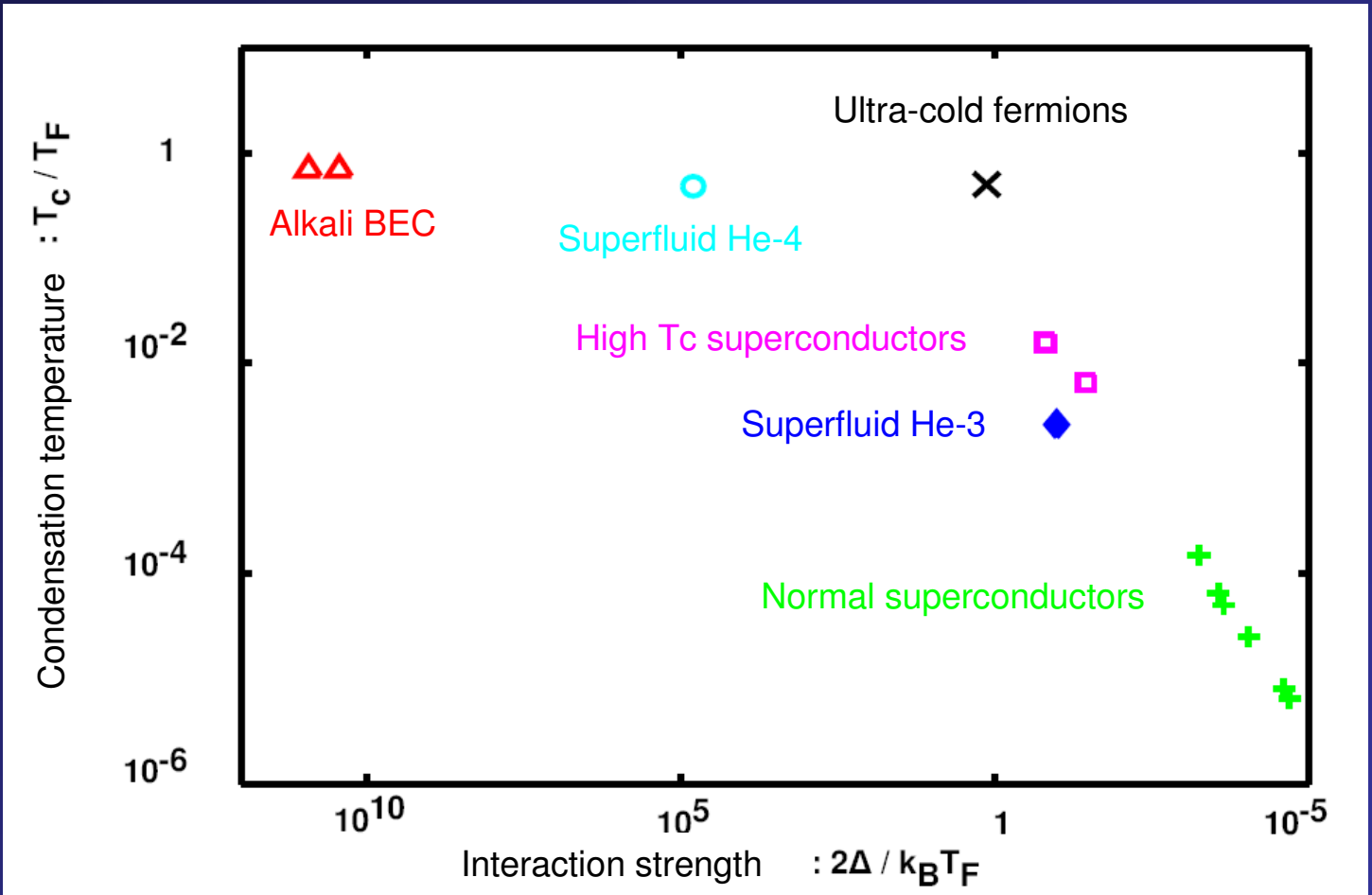


Size of the molecules ~ a

Binding energy $E_b = -\hbar^2 / ma^2$

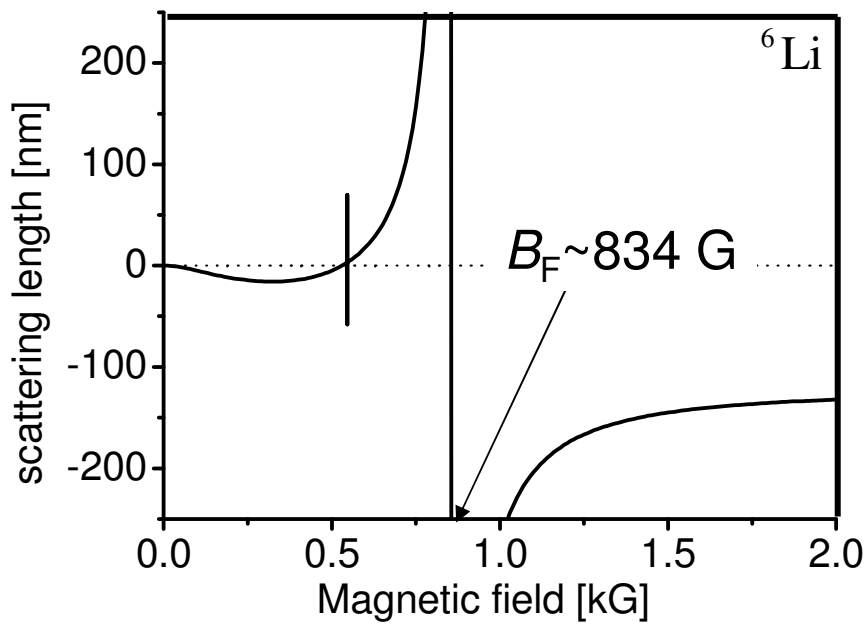
Binding energy $\sim E_F e^{-1/k_F|a|}$

The BEC-BCS « patchwork »



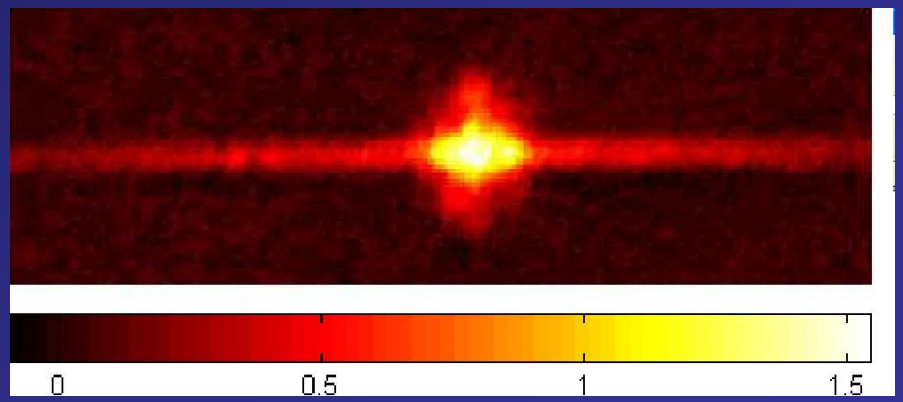
(Fano) - Feshbach resonances in cold atoms

^{6}Li



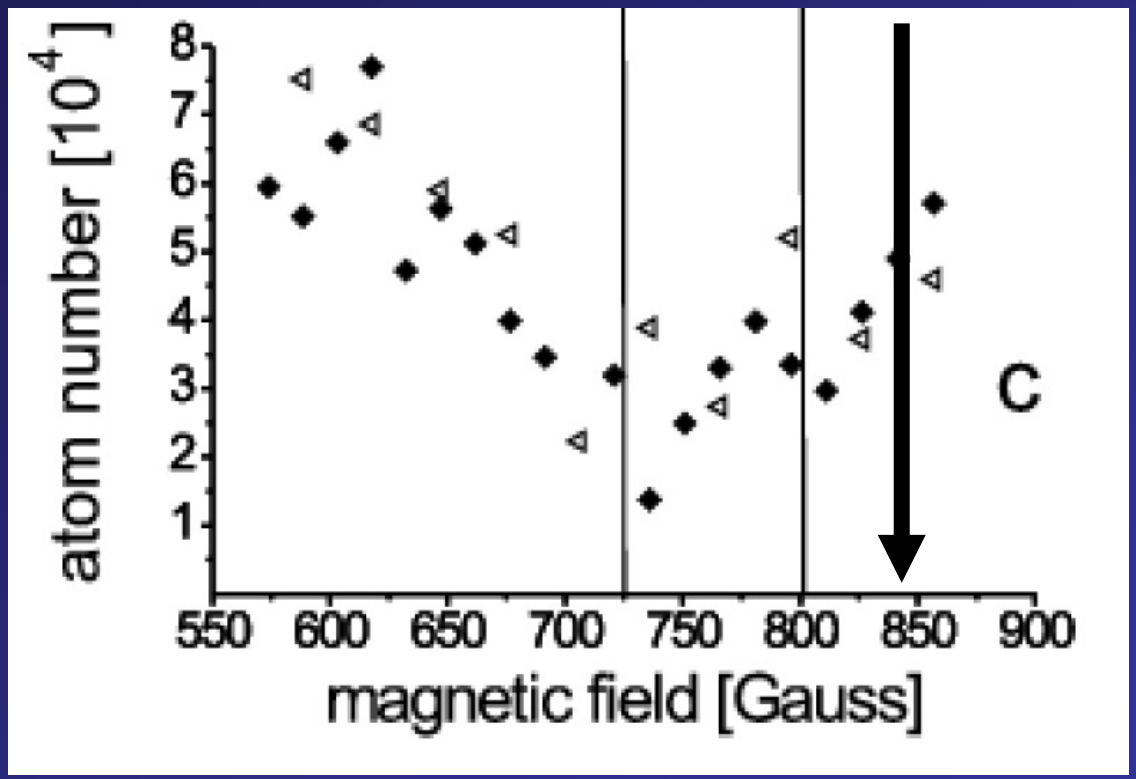
Bosons near a Feshbach resonance:

Bose-Nova (C. Weiman).



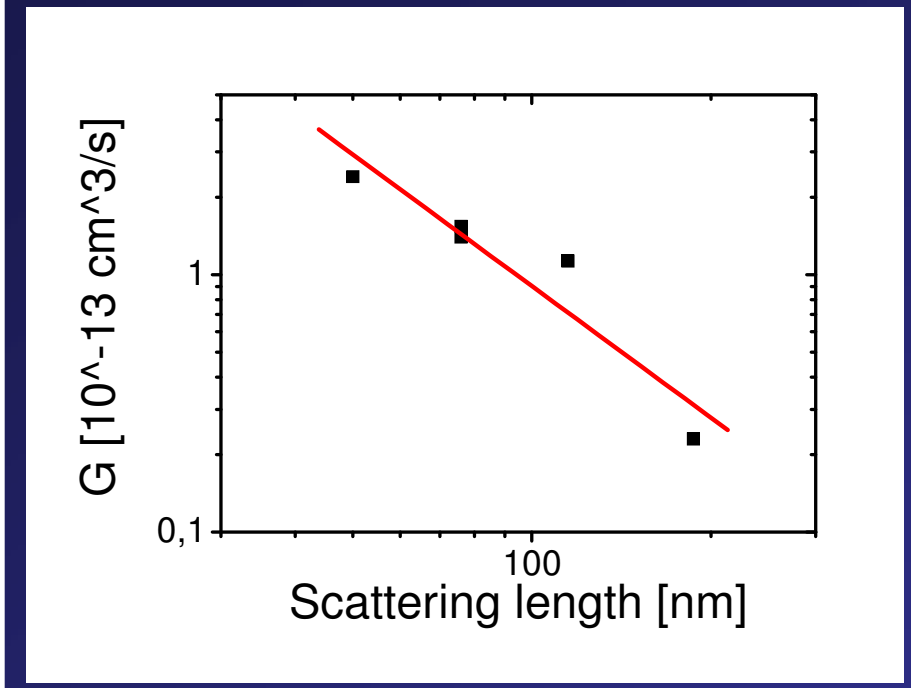
Looking for the Feshbach resonance of Lithium

Predicted position of the resonance



Losses in ^{6}Li (fermions)

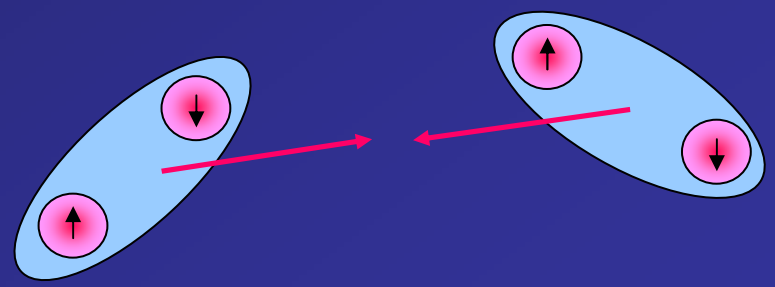
Inhibition of inelastic losses
In fermionic gases



Scaling law

$G \sim a^{-2.0 +/-0.8}$ (theory Petrov *et al.* $G \sim a^{-2.55}$)

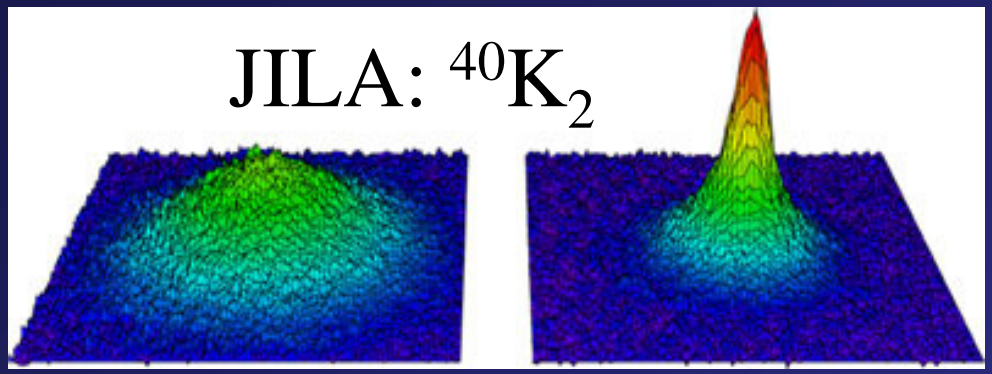
3/4 atom loss requires 2 atoms of same spin close to each other.

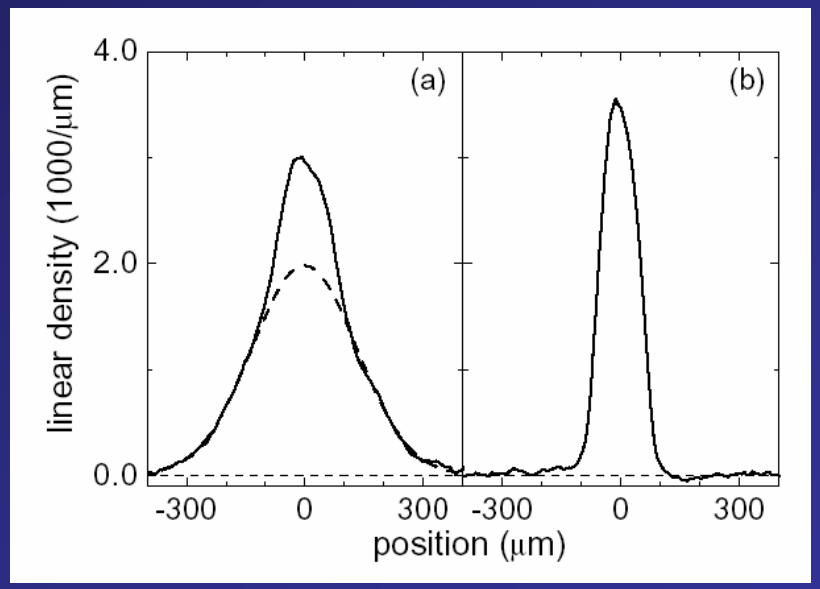


2 body (dimers) losses mainly :
decay towards deeply bound states)

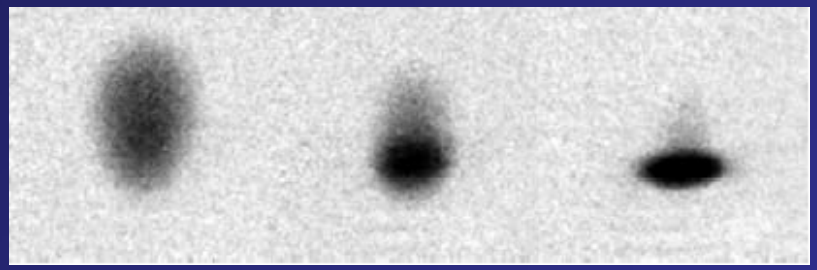
$$\dot{N} = -G\langle n \rangle N$$

Molecular BEC's around the world

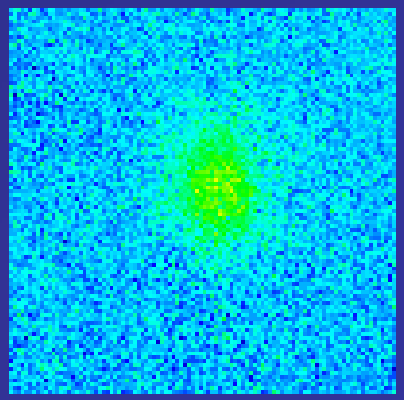




MIT
$^6Li_2$



$^6Li_2$:Innsbruck

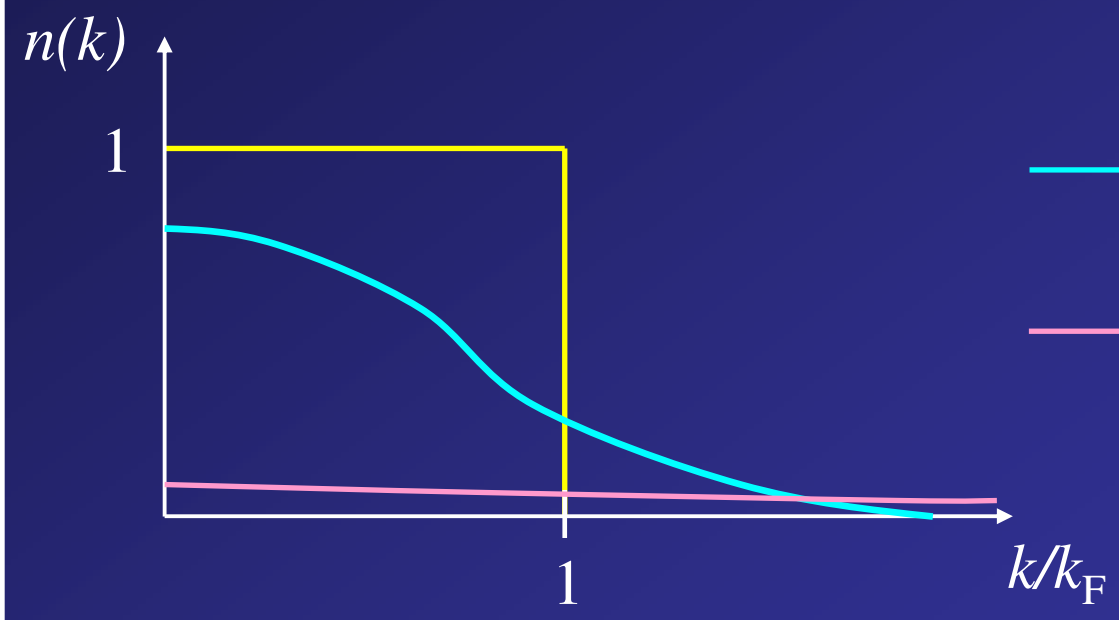


ENS
$^6Li_2$

Also Rice, Duke, Melbourne $^6Li_2$

Momentum distribution

Broadening of the Fermi-Dirac in the presence of interactions
(Viverit et al.PRA **69**, 013607 (2004))

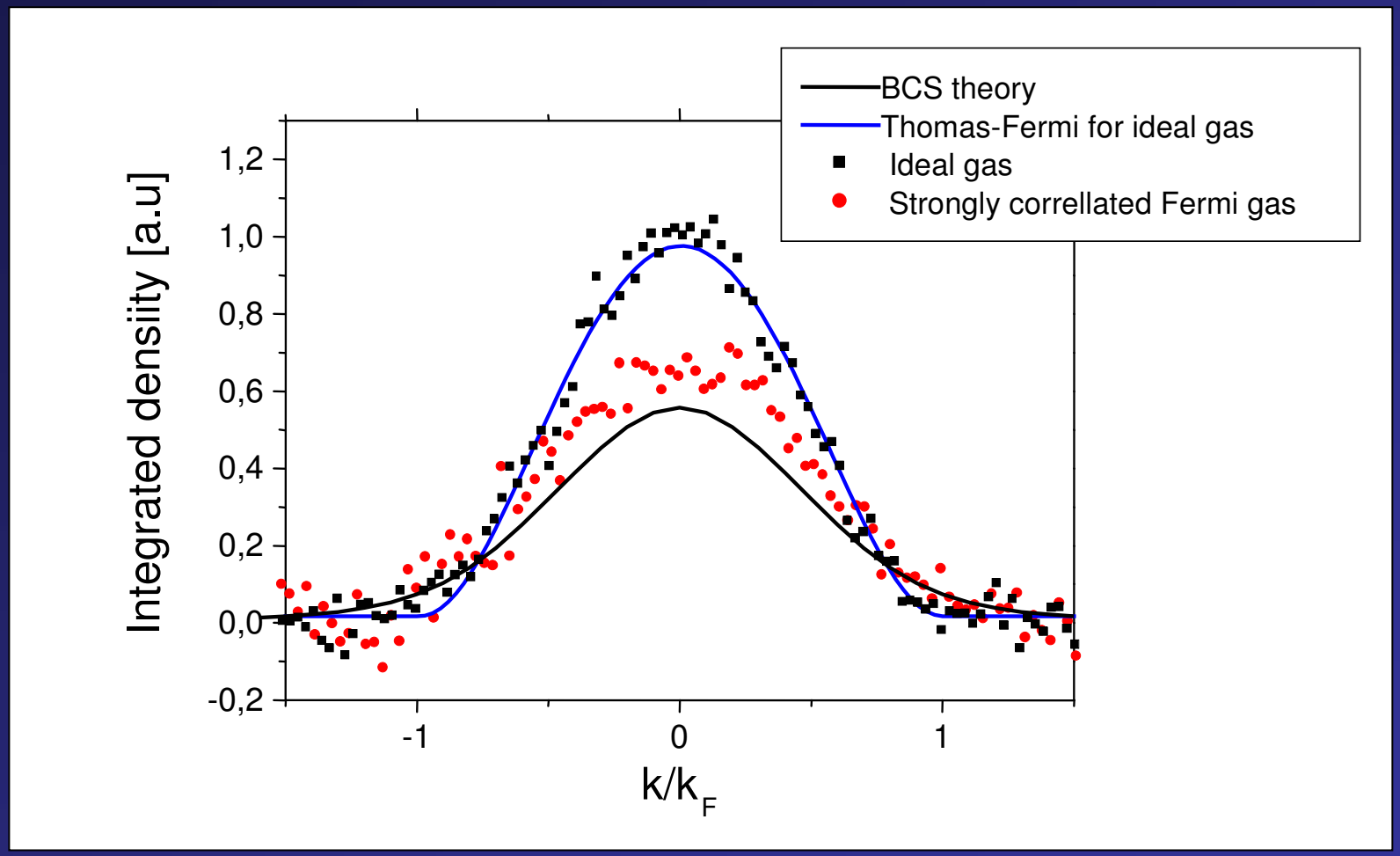


a<0, T=0 ideal gas, width k_F

a=◎, « unitary » gas

a>0, inner momentum distribution, width~ *1/a*

Experiment vs theory



Measurement of the zero temperature universal equation of state of the strongly interacting Fermi gas

Dimensional analysis:

$$\mu_\uparrow = \frac{\hbar^2}{2m}\left(6\pi^2 n\right)^{2/3} f(1/na^3)$$

For a=◎, f(1/na³)=f(0), independent on density

$$\mu_\uparrow = \xi \frac{\hbar^2}{2m}\left(6\pi^2 n\right)^{2/3}$$

Determination of ξ

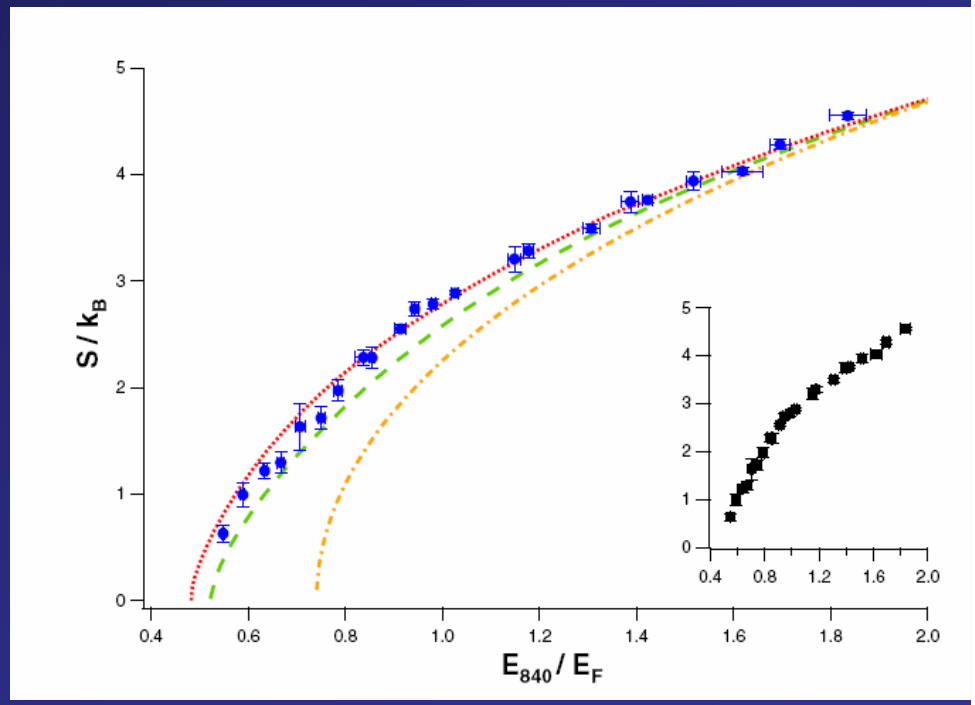
Experiment	*ENS*	0.41(15)
	Rice	0.46(5)
	JILA	0.46(10)
	Innsbruck	0.27(10)

Theory	*BCS*	0.59
	Astrakharchick	0.42(1)
	Perali	0.455
	Carlson	0.42(1)

Equation of state at finite temperature

Goal: measure the thermodynamical equation of state S(U,N)

- Prepare an ideal gas and measure $T/T_F \sim S$
- Ramp slowly the magnetic field to a=◎
- Measure the potential energy $E=m\blacklozenge^2\langle x^2\rangle/2=U/6$ (Virial theorem)

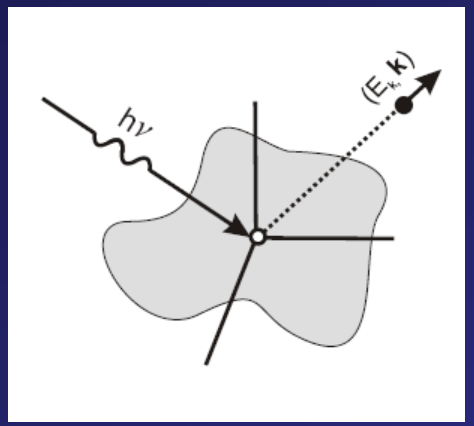


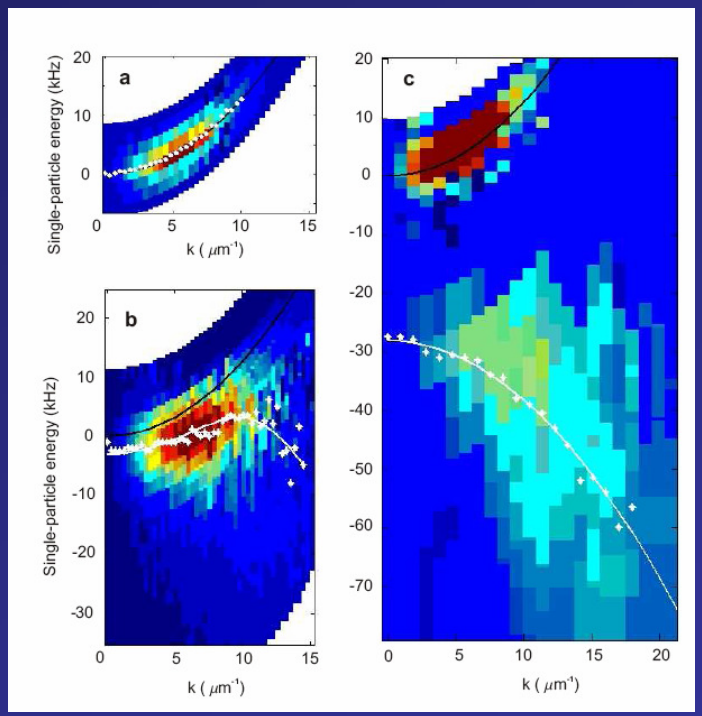
J. T. Stewart, J. P. Gaebler, C. A. Regal, and D. S. Jin, Phys. Rev. Lett. **97**, 220406 (2006).

L. Luo, B. Clancy, J. Joseph, J. Kinast, and J. E. Thomas, Phys. Rev. Lett. **98**, 080402 (2007)

Radio-frequency spectroscopy: Measurement of the excitation spectrum.

~ARPES (Angle Resolved Photo-Electrons Spectroscopy) in condensed matter physics

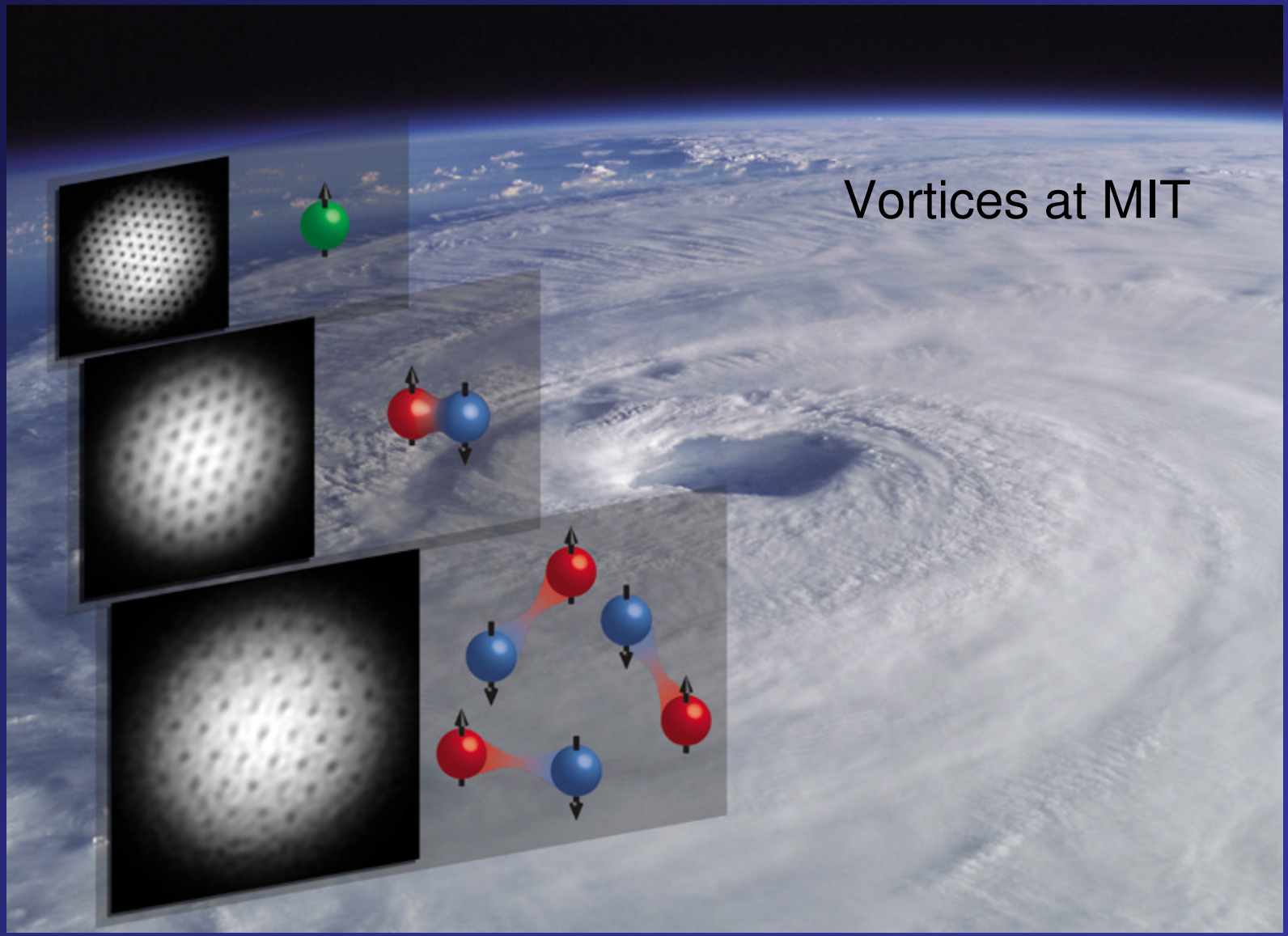




a) Non interagting Fermi gas
b) Unitary limit a=◎
c) Molecular BEC a>0

J. T. Stewart, J. P. Gaebler, and D. S. Jin, Nature **454**, 744 (2008).
T.-L. Dao, A. Georges, J. Dalibard, C. Salomon, and I. Carusotto. Phys. Rev. Lett. 98, 240402 (2007).

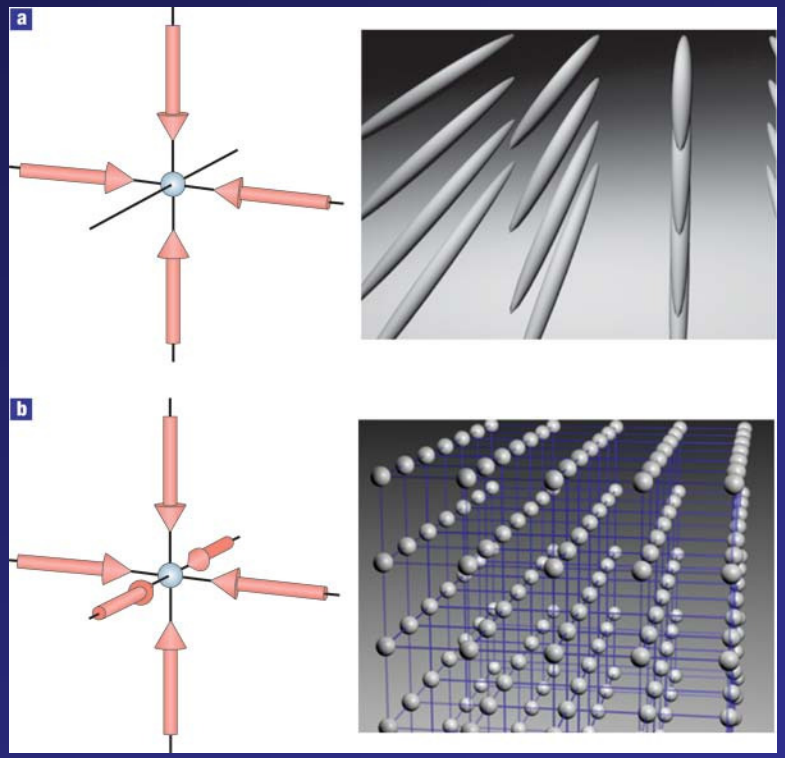
Superfluidity: vortex lattices (MIT)

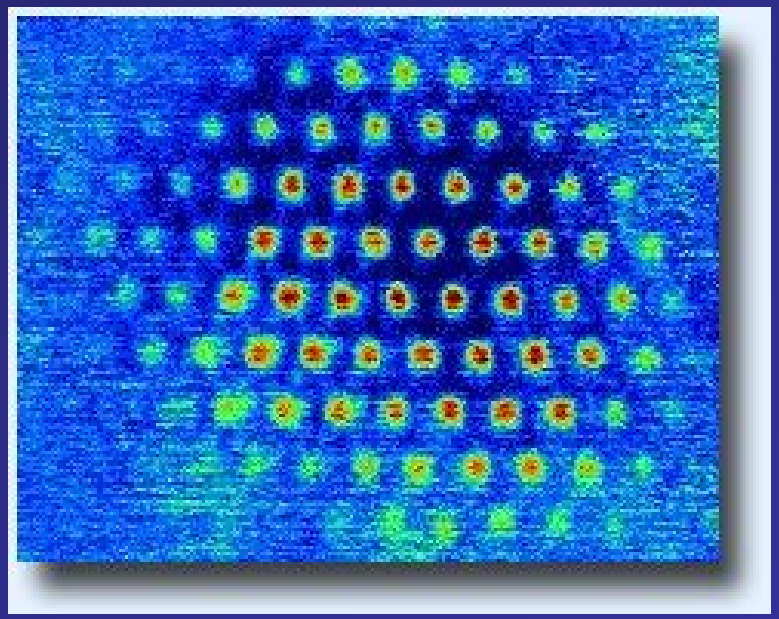


Fermions in optical lattices

Ultra cold atoms in Optical Lattices

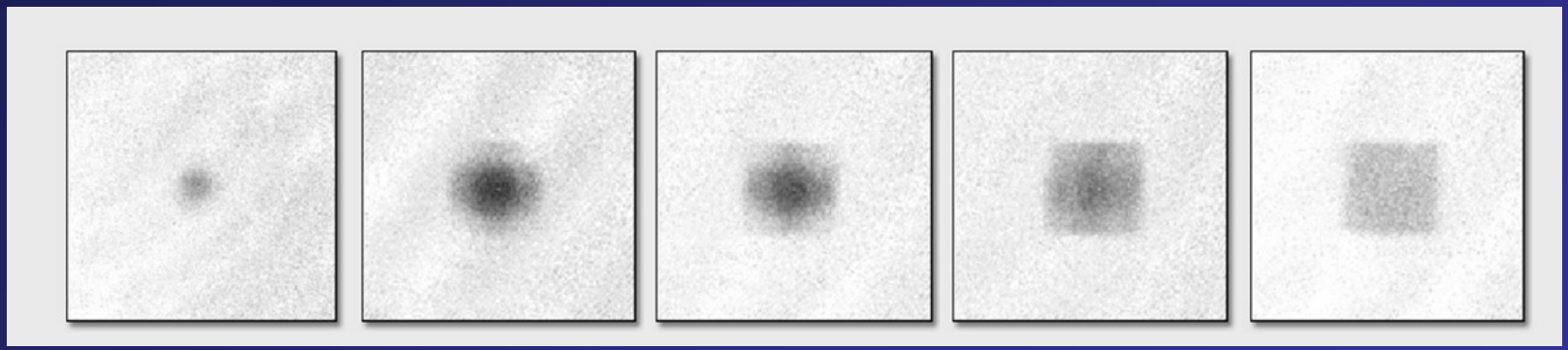
Optical lattices: periodic potential created by the interference of several laser beams





Imaging the first Brillouin Zone

Momentum distribution after time of flight for various filling factors.



M. Köhl, H. Moritz, T. Stöferle, K. Günter, T. Esslinger
Phys. Rev. Lett. **94**, 080403 (2005).

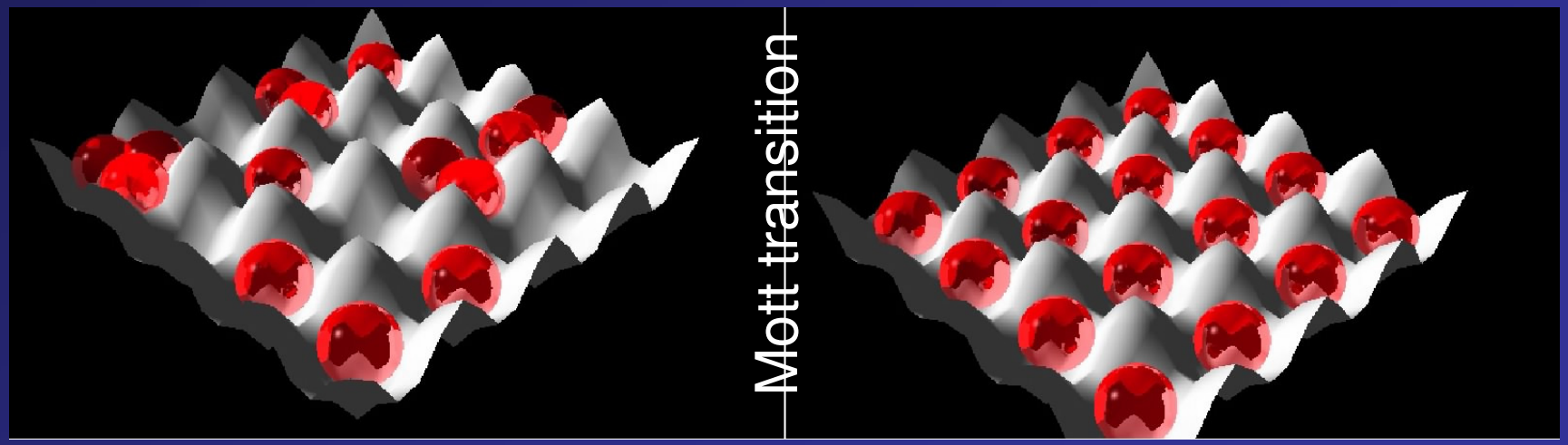
Repulsive fermions in an optical lattice

Fermi-Hubbard hamiltonian

$$H = J \sum_{\substack{\langle i,j \rangle \\ \sigma}} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_{i} c_{i\uparrow}^{\dagger} c_{i\uparrow} c_{i\downarrow}^{\dagger} c_{i\downarrow}$$

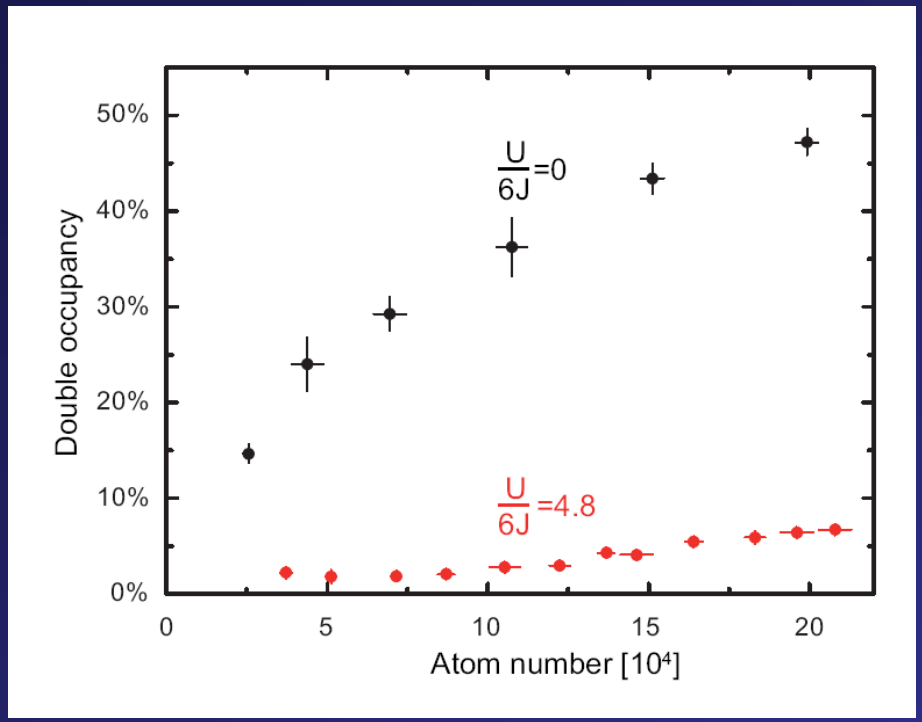
Small U/J: conductor

Large U/J: insulator

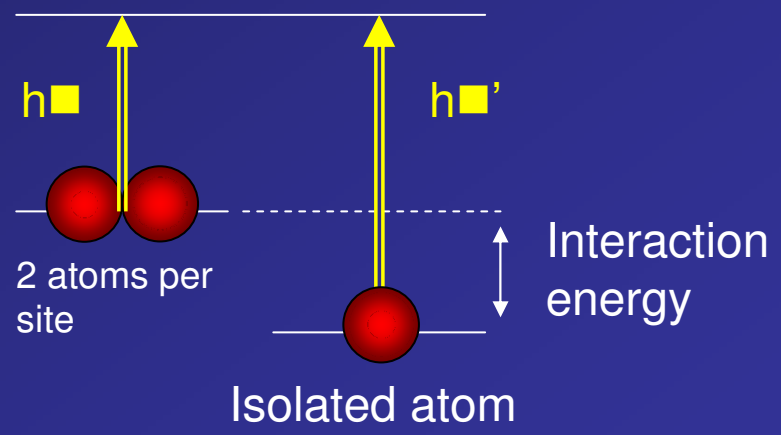


For bosons see M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch and I. Bloch Nature **415**, 39-44 (2002)

Mott transition in superfluid Fermi gases



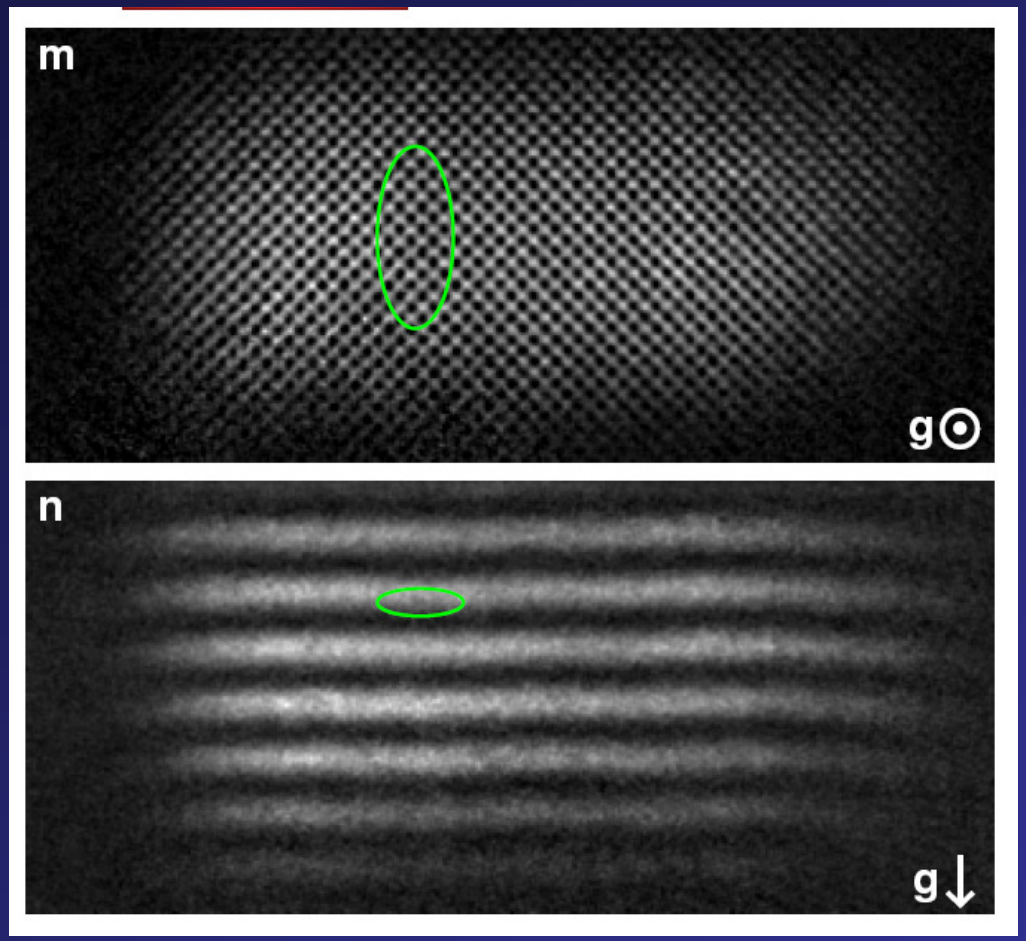
Double occupancy spectroscopic measurement

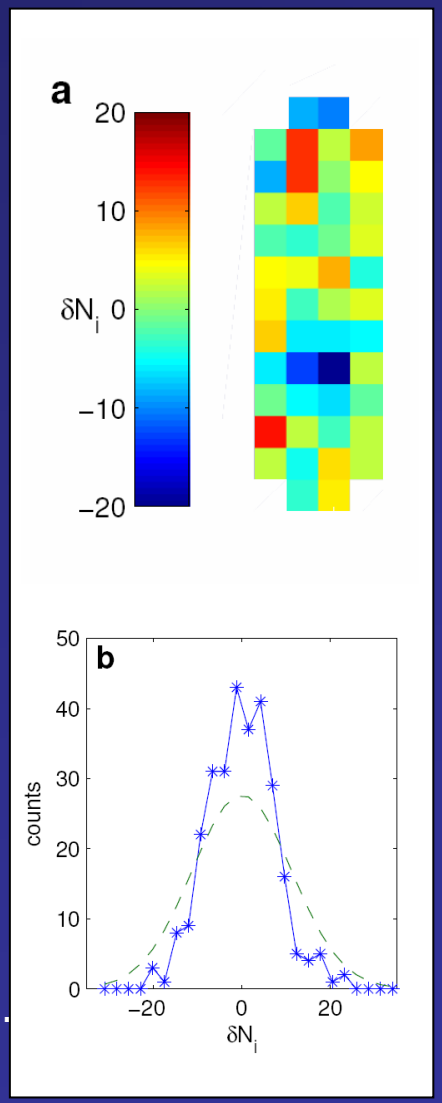


R. Jördens, N. Strohmaier, K. Günter, H. Moritz and Tilman Esslinger, Nature ***455****, 204-207 (11 September 2008)*

U. Schneider, L. Hackermuller, S. Will, Th. Best, I. Bloch, T. A. Costi, R. W. Helmes, D. Rasch, A. Rosch, Science **322**,1520 (2008)

High resolution imaging in optical lattices





A. Itah, H. Veksler, O. Lahav, A. Blumkin, C. Moreno, C. Gordon, J. Steinhauer, arXiv:0903.3282

P-wave Feshbach resonances

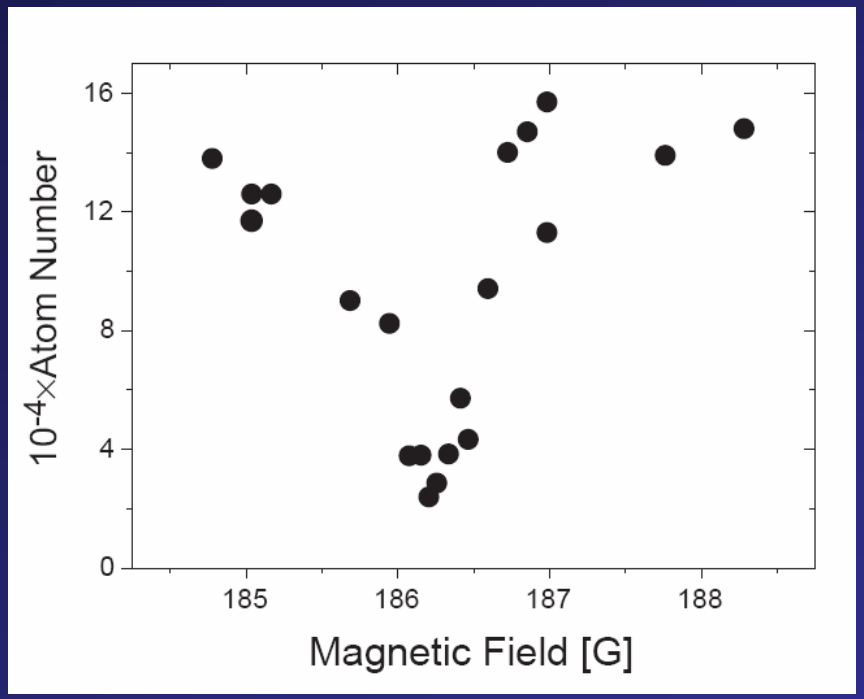
P-wave Feshbach resonances

Coupling to a l-wave Feshbach state: enhancement of l-wave interactions.

S-wave superfluid: coupling with spin degrees of freedom (see eg axial phase of ^{3}He)

P-wave Feshbach resonances in cold atoms

Localization of p-wave resonances in lithium and potassium

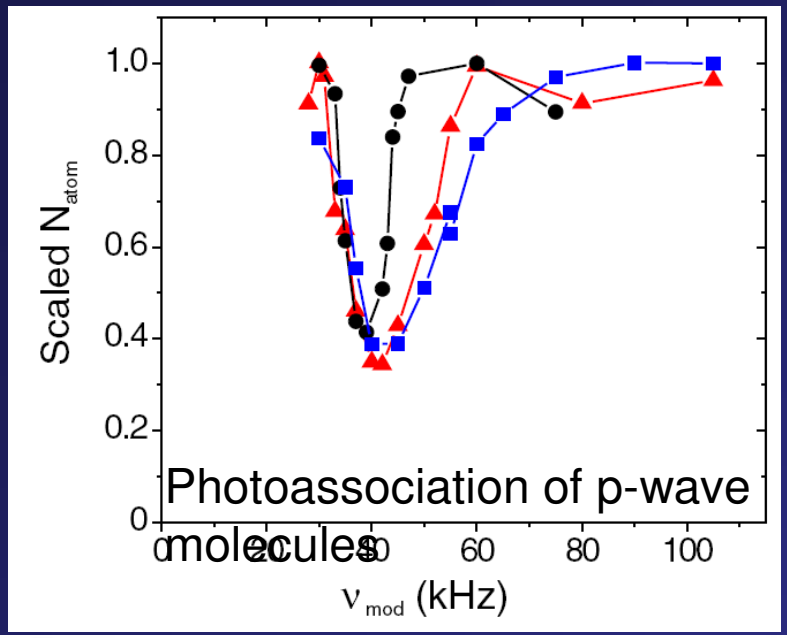


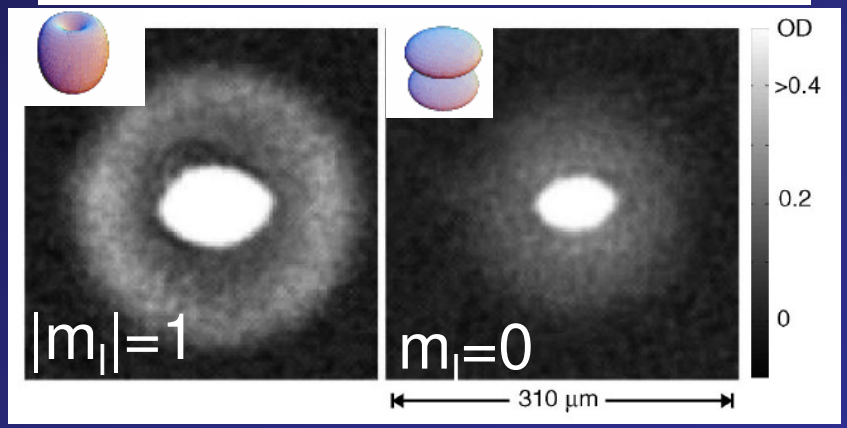
(m_{f_1}, m_{f_2})	Theory (G)	Experiment (G)
(1/2,1/2)	159	160.2(6)
(1/2,-1/2)	185	186.2(6)
(-1/2,-1/2)	215	215.2(6)

•J. Zhang, E.G.M. van Kempen, T. Bourdel, L. Khaykovich, J. Cubizolles, F. Chevy, M. Teichmann, L. Tarruell, S.J.J.M.F. Kokkelmans, and C. Salomon, Phys. Rev. A **70**, 030702 (2004);
•C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Phys. Rev. Lett. **90**, 053201 (2003).

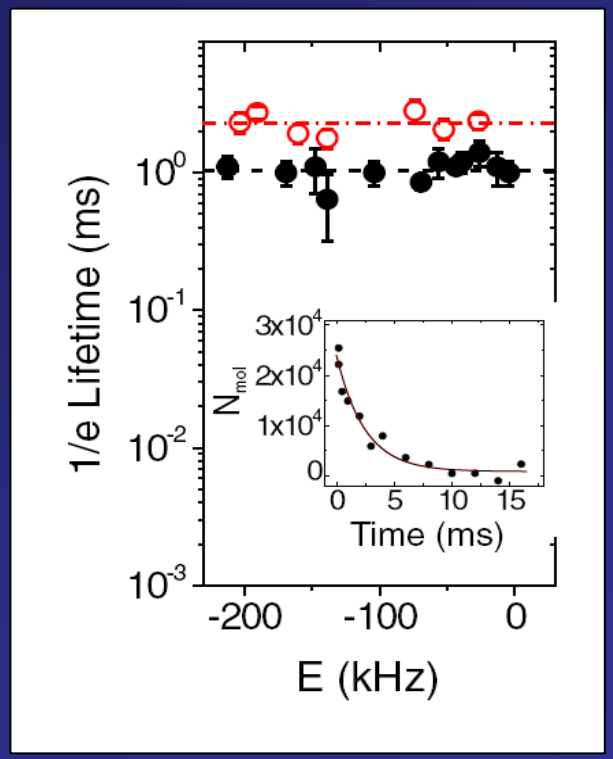
•Narrower structures than for s-wave resonances
•Higher loss rate

Observation of p-wave Feshbach molecules





Time of flight expansion of p-wave molecules



Lifetime of p-wave molecules

Prospects

- Spin imbalanced superfluids
- Stabilize p-wave molecules (eg in a Mott insulator state)
- Search for Néel antiferromagnetic state in lattice
- Frustration in triangular lattice
- Low dimensional systems (1D, 2D)
- Fast rotating systems, quantum Hall effect

The ENS ultra-cold Fermi group

The lithium group

The lithium-potassium group