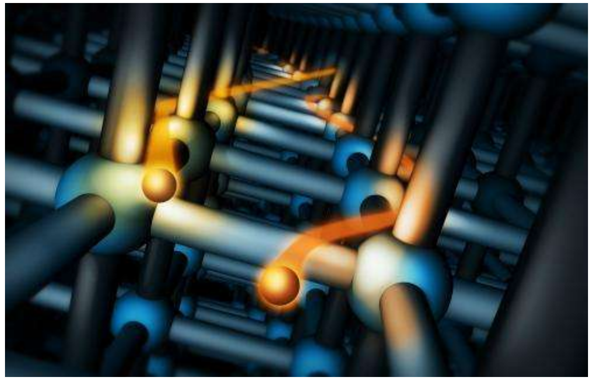
Attractive fermions: the BEC-BCS crossover and the unitary gas

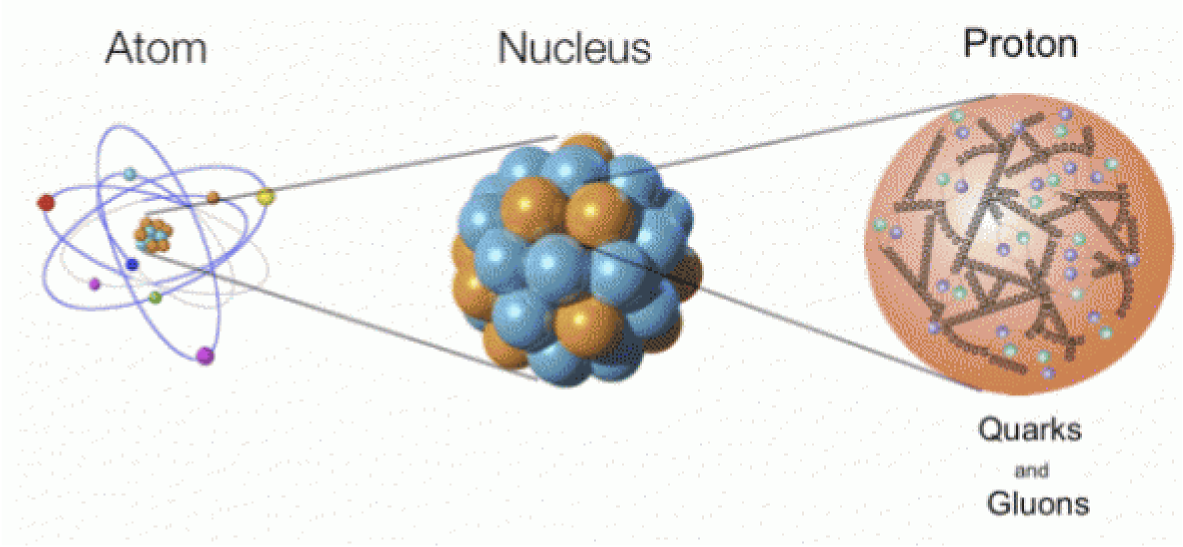
Frédéric Chevy

Les Houches 2018 School on Ultracold Fermions

Why should we care about fermions?

- Matter in made up of fermions





- Fermions are hard: the (infamous) **sign-problem**

Some orders of magnitude

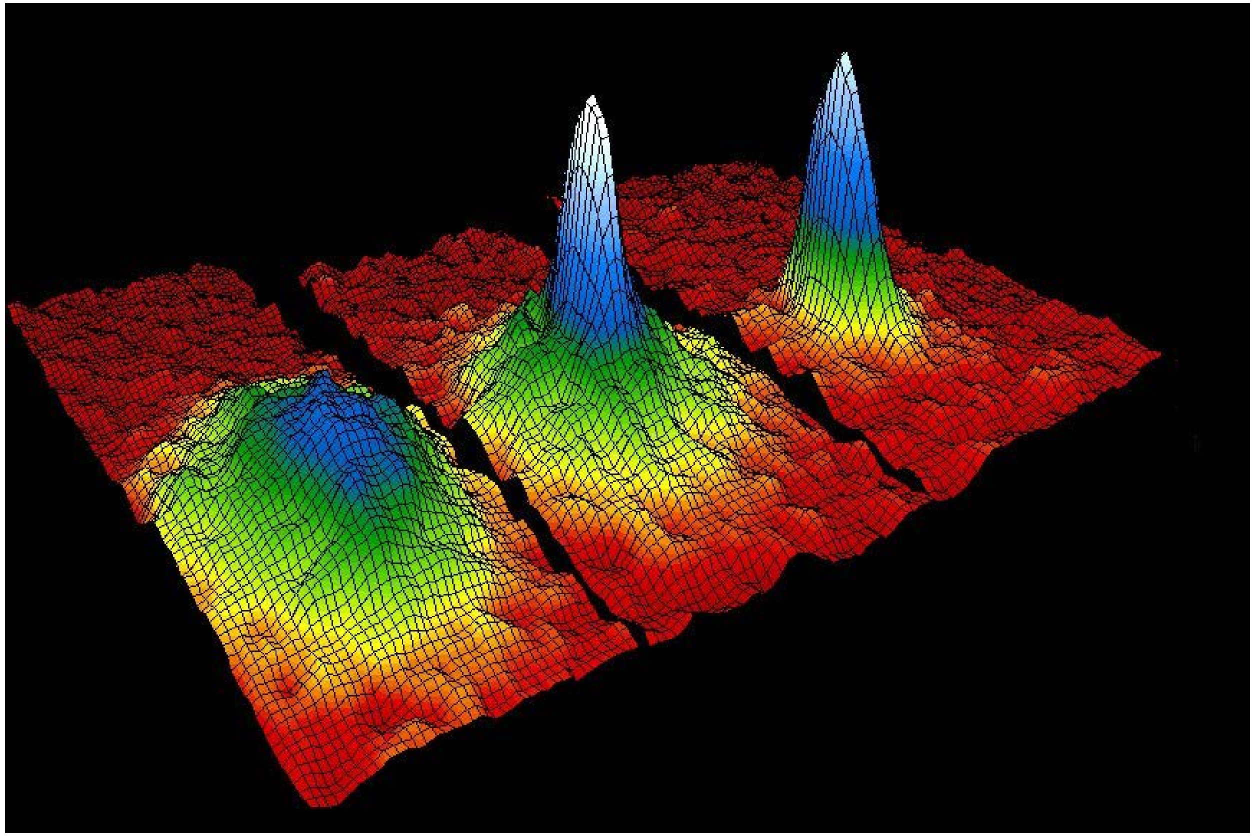
	Superconductors	**Neutron stars/Nucleus**	**Ultracold atoms**
Mass [kg]	10^{-30}	10^{-27}	10^{-26}
Density [m^{-3}]	10^{30}	10^{45}	10^{18}
Fermi temperature [K]	10^{5}	10^{12}	10^{-7}

$$E_F = k_B T_F = \frac{\hbar^2}{2m}(6\pi^2 n)^{2/3}$$

Cooling fermions

An historical perspective

1995: Bose-Einstein condensation of alkali vapors

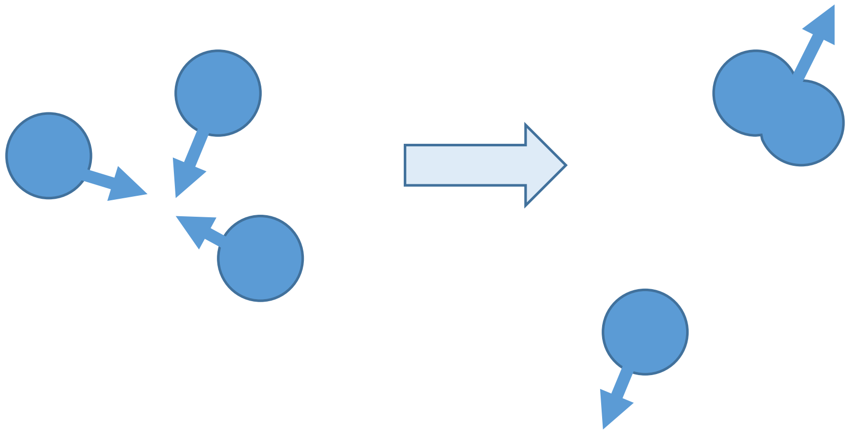


Recipe: evaporative cooling in a magnetic trap.

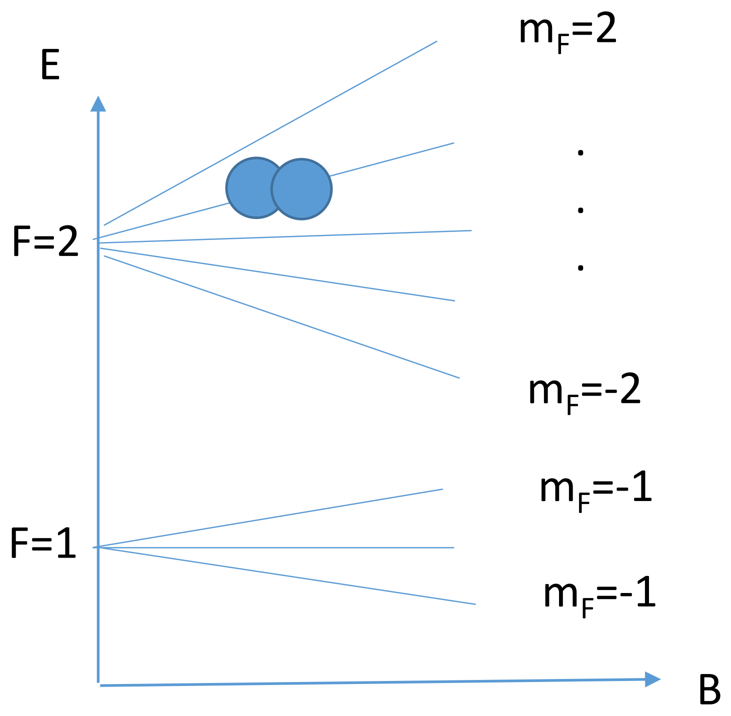
Good vs bad collisions

- Evaporation is driven by **elastic collisions**
- **Inelastic** collisions hinder evaporation

Three-body collisions (molecular recombination) : **work at low density.**



Two-body inelastic collisions
Spin-exchange collisions.
Hyperfine changing collisions



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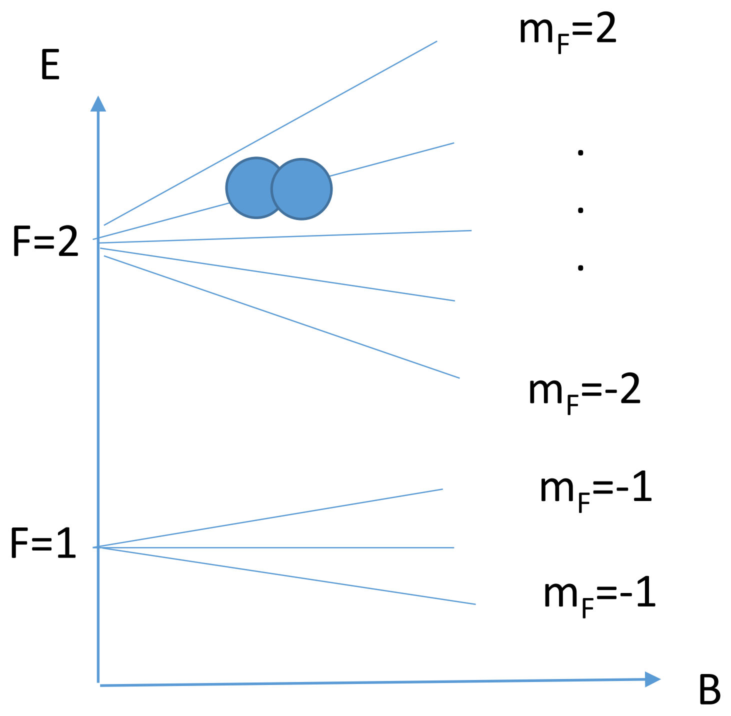

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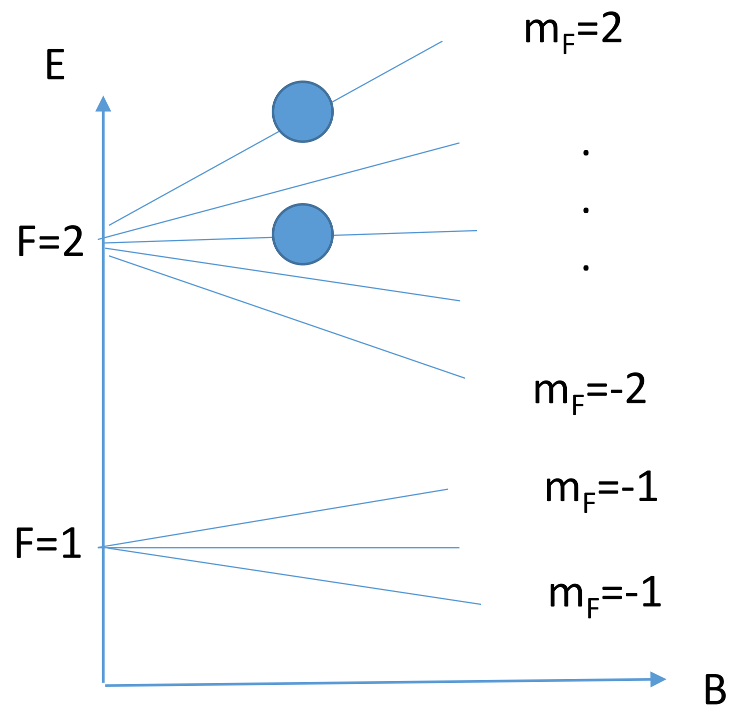

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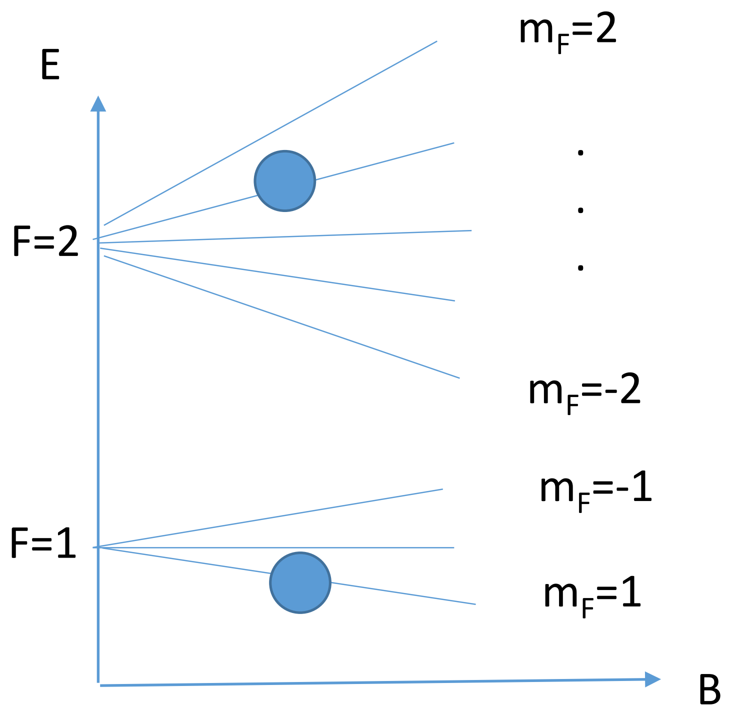

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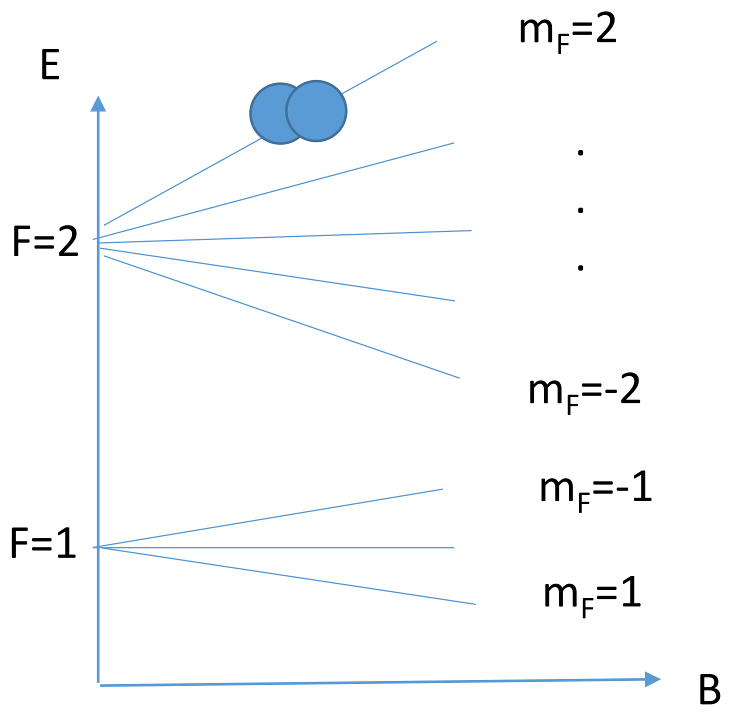
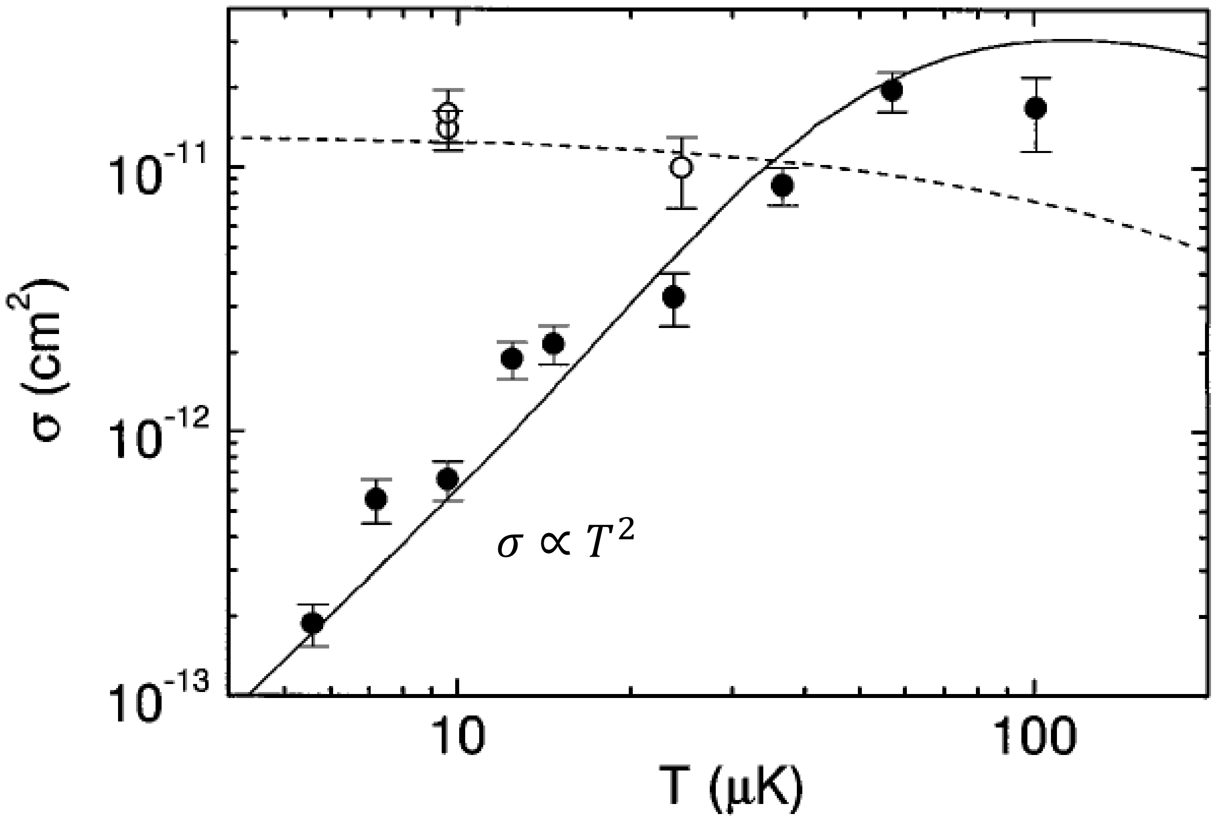
Two-body inelastic collisions
Spin-exchange collisions.
Hyperfine changing collisions
Solution: spin polarize the atoms in a stretched state of maximal angular momentum.



The road to fermionic quantum degeneracy

- ***Spin-polarized*** Fermions do not collide at low temperature!

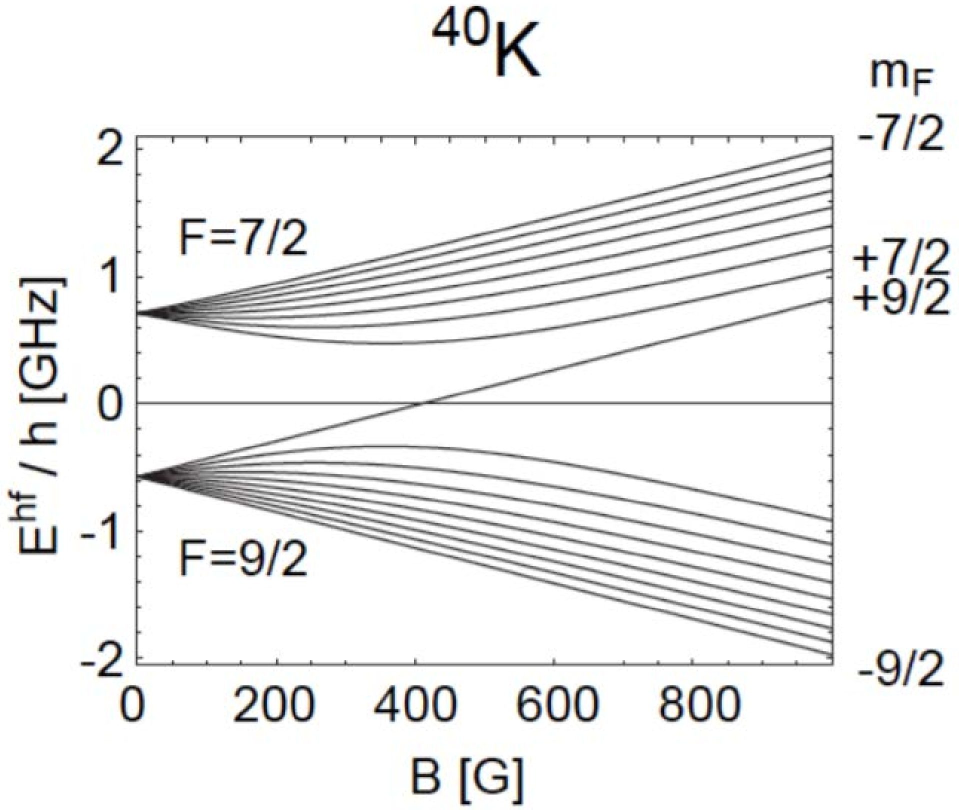


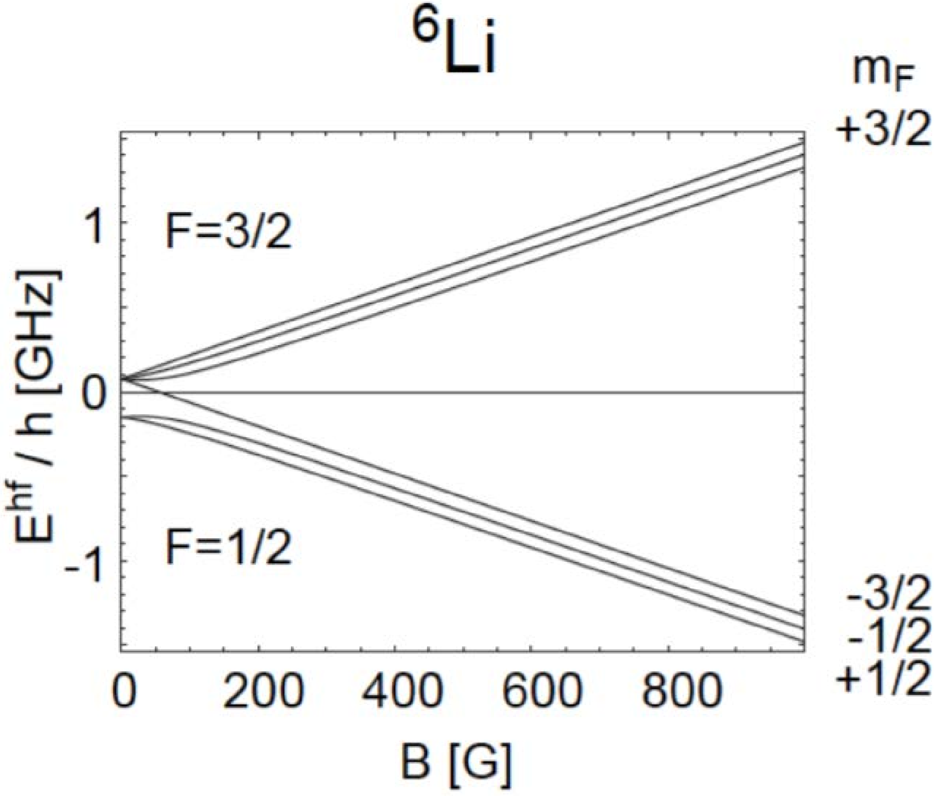
Spin polarized potassium

Potassium spin mixture

B. DeMarco *et al.* Phys. Rev. Lett. **82**, 4208 (1999).

- Potassium (^{40}K) and Lithium (^{6}Li) are the only alkali possessing stable fermionic isotopes





Mixture $\left|F = \frac{9}{2}, m_F = 9/2, 7/2\right\rangle$ is stable (at low temperature, <1mK)

- Mixture with **another atomic species** (e.g. ^{7}Li)
- **Optical trapping of the two lowest Zeeman states** in a far-detuned laser (+Feshbach resonance @ 832G).

N.B.: non-alkali fermionic atoms (Sr, Yb, Dy, Er…) have also been cooled to quantum degeneracy, but not to superfluidity

The ultracold Fermi Sea

The ideal Fermi gas

The Zero temperature Fermi gas

In a box of volume V density n=N/V: $D(E)=\frac{V}{2\pi^2}\sqrt{\frac{2m^3E}{\hbar^6}}$

$$N=\int f(E)D(E)dE \Rightarrow E_F=\frac{\hbar^2k_F^2}{2m} \quad \text{with} \quad k_F=(6\pi^2 n)^{1/3}$$

Rule of thumb: $\lambda_F = k_F^{-1}$~interparticle distance.

In a harmonic trap: $D(E)=\frac{E^2}{2(\hbar\bar{\omega})^3}$ with $\bar{\omega}^3=\omega_x\omega_y\omega_z$

$$N=\int f(E)D(E)dE \Rightarrow E_F=\hbar\bar{\omega}(6N)^{1/3}$$

Energy of a trapped Fermi gas

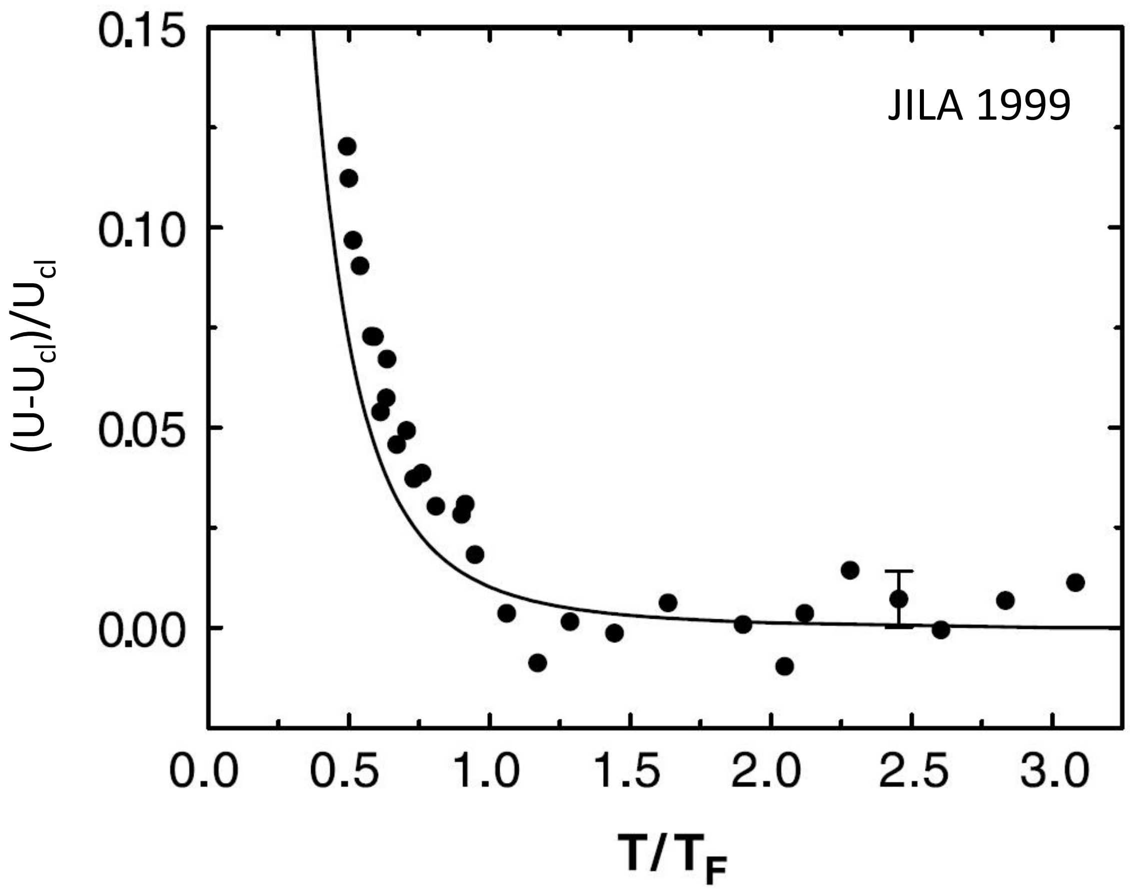
$$U = \int E f(E) D(E) dE$$

$T \gg T_F$: ideal Boltzmann gas (Equipartition Theorem)

$$U = U_{\text{clas}} = 3Nk_BT$$

$T \ll T_F$:

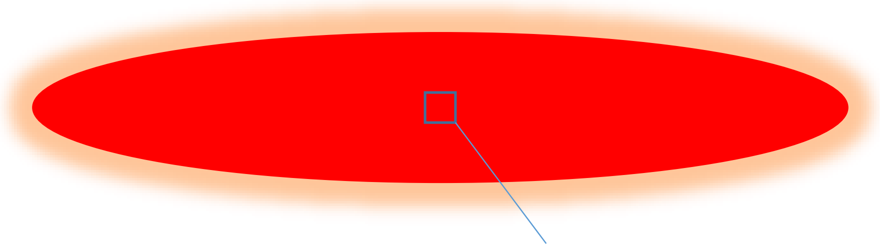
$$U = \frac{3}{4} N E_F$$



U measured by time of flight expansion and using virial theorem $U=2E_{kin}$. (F. Werner, PRA 2008)

Local Density Approximation

- What is the density profile of the cloud?

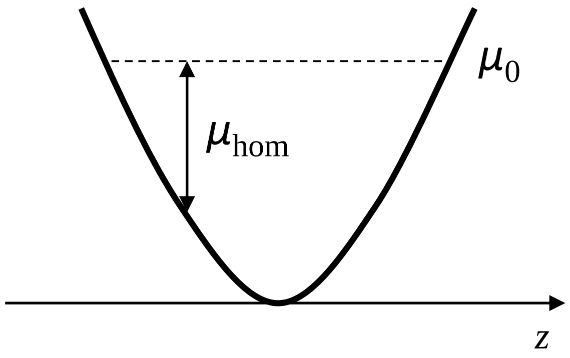


Mesoscopic volume where thermodynamical equilibrium is well defined (T(**r**),μ(**r**),P(**r**))

Equilibrium Condition: T,μ uniform.

Local Density Approximation:

$$\mu(\mathbf{r}) = \mu_{\mathrm{hom}}(n(\mathbf{r}),T) + V(\mathbf{r}) \equiv \mu_0$$



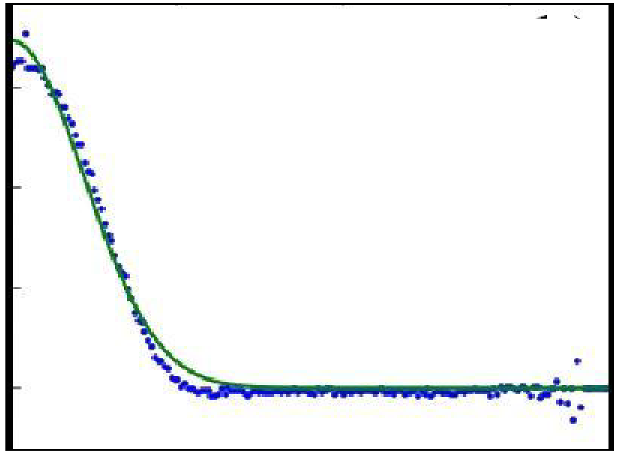
Note: this is the hydrostatic condition $\nabla P + n\nabla V = 0$ with the Gibbs-Duhem relation dP=ndμ at constant T.

Density profile of a trapped Fermi gas

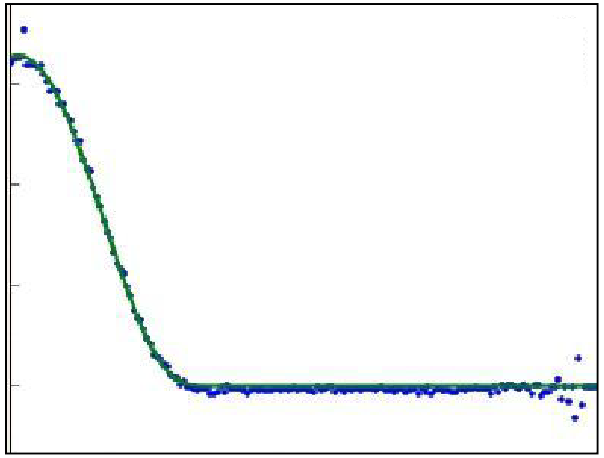
Zero temperature Fermi gas

$$\mu_{\text{hom}}(n,T=0)=\frac{\hbar^2}{2m}(6\pi^2 n)^{2/3}\Rightarrow n(r)=\frac{1}{6\pi^2}\left[\frac{2m}{\hbar^2}\left(\mu_0-V(r)\right)\right]^{3/2}$$

Thomas-Fermi profile



Gaussian Fit



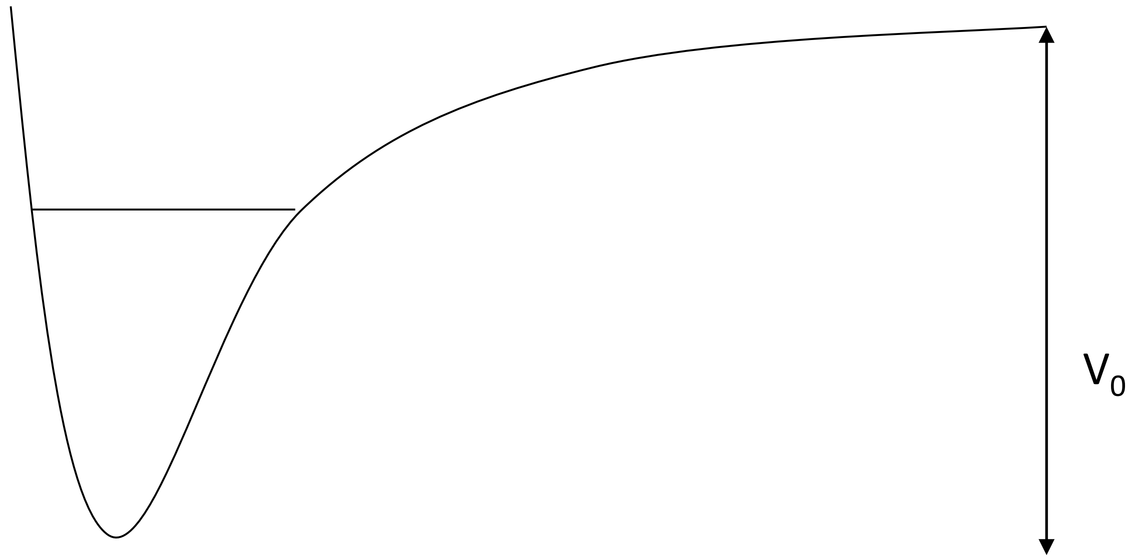
Thomas-Fermi Fit

N.B. $N=\int n(\mathbf{r})d^3\mathbf{r}\Rightarrow\mu_0=\hbar\overline{\omega}(6N)^{1/3}$, as before

The attractive Fermi gas

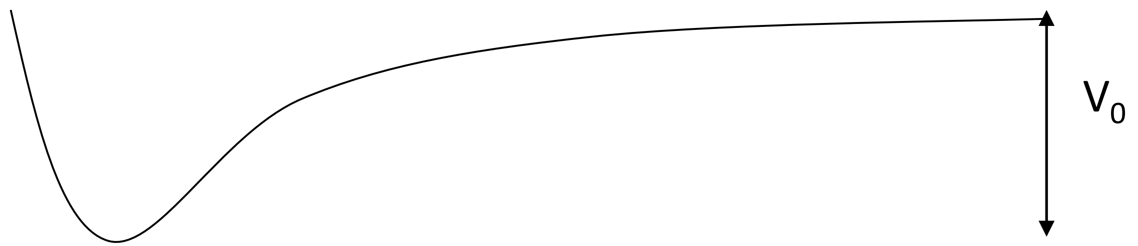
Fermionic superfluidity

Fermionic superfluidity



DEEP POTENTIAL : stable 2-body bound state with binding energy $E_b=-\hbar^2/ma^2$. Many-body ground state: BEC of molecules (a>0)

Fermionic superfluidity



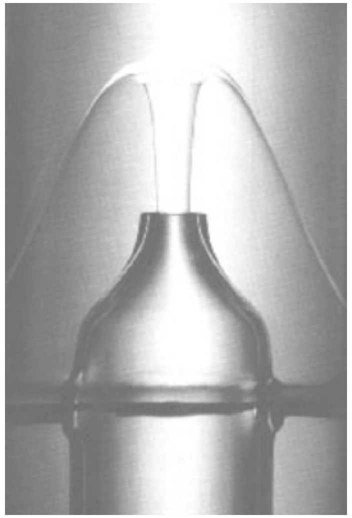
DEEP POTENTIAL : stable 2-body bound state with binding energy E_b=-$\hbar^2/ma^2$. Many-body ground state: BEC of molecules (a>0)

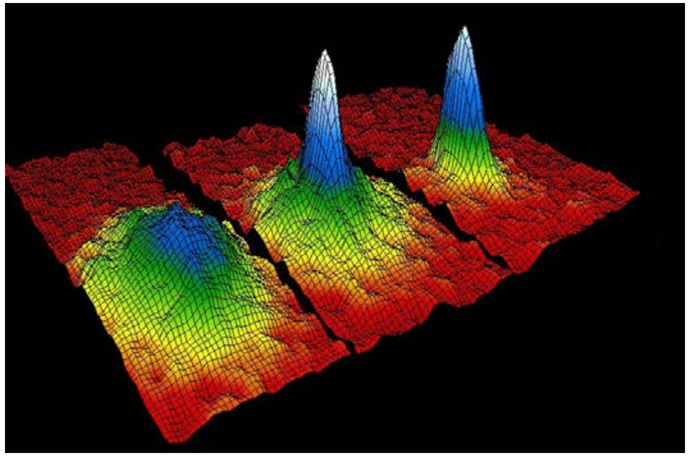
SHALLOW POTENTIAL (V_0<V_0^*, a<0):
No 2-body bound state, but Cooper pairing stabilized by Pauli blocking.

BOSE ENSTEIN CONDENSATION AND BCS THEORY APPEAR AS TWO LIMITING CASES OF A UNIFYING THEORY: THE BEC-BCS CROSSOVER

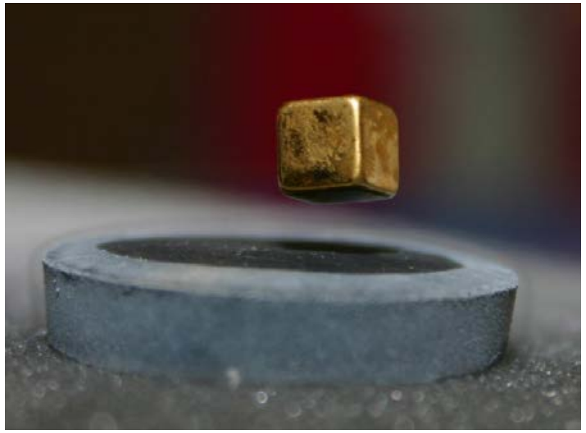
The experimental BEC-BCS Patchwork

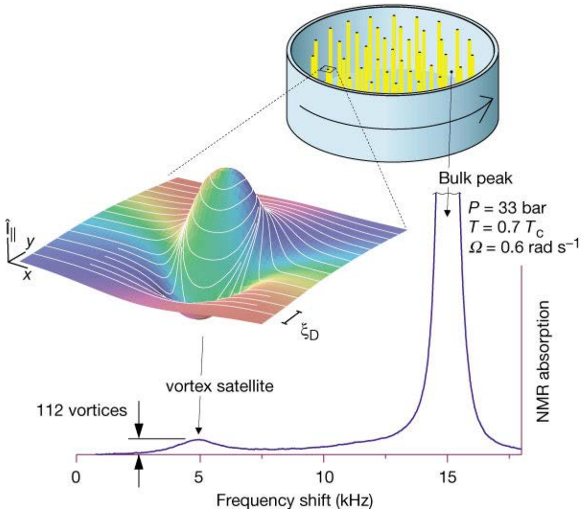
Bose Einstein condensates



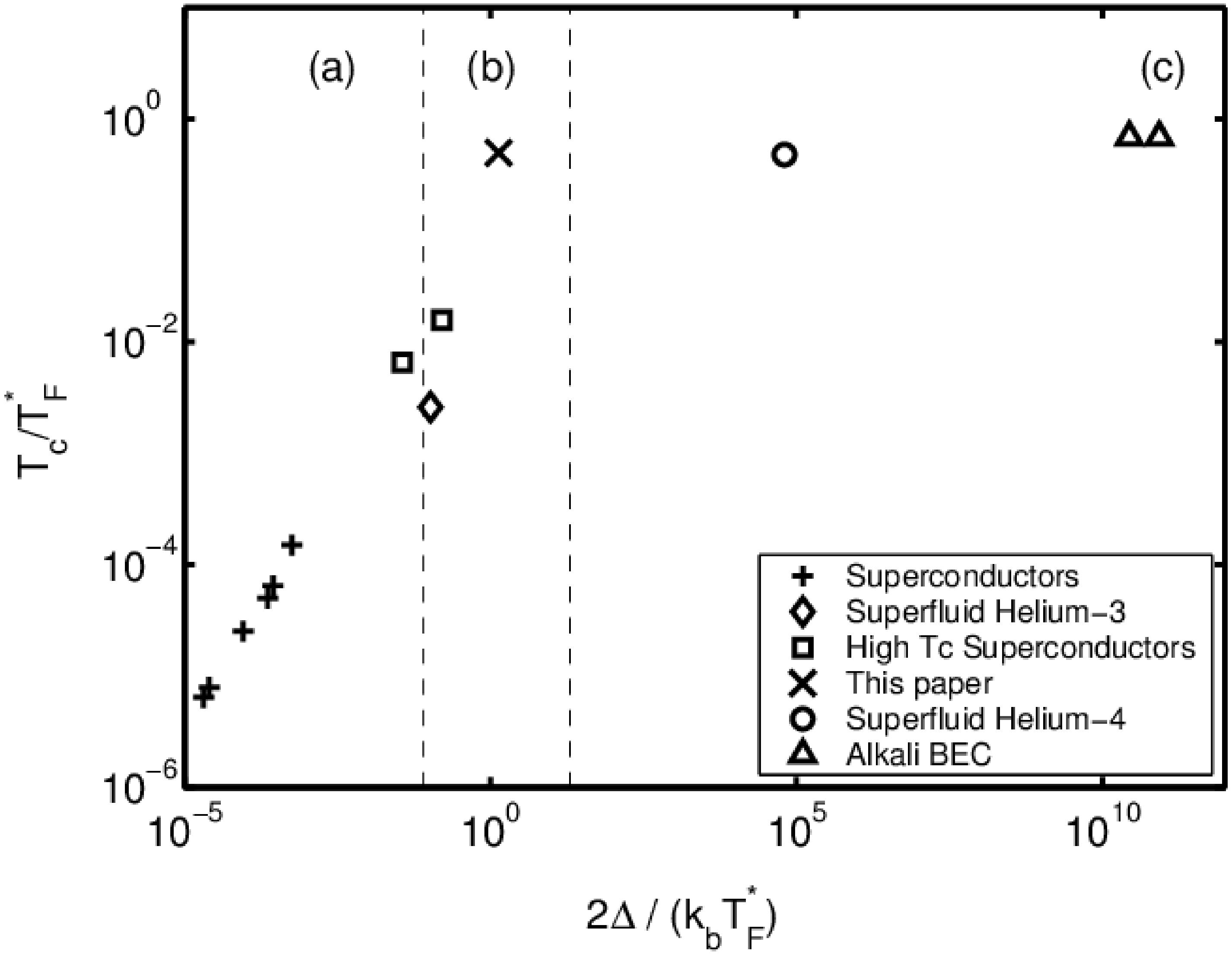


Superconductivity, helium 3, neutron stars





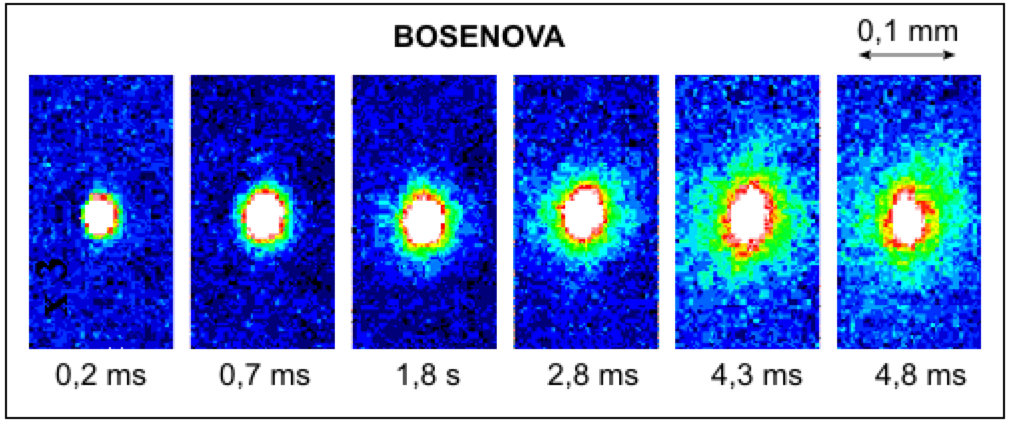
The experimental BEC-BCS Patchwork

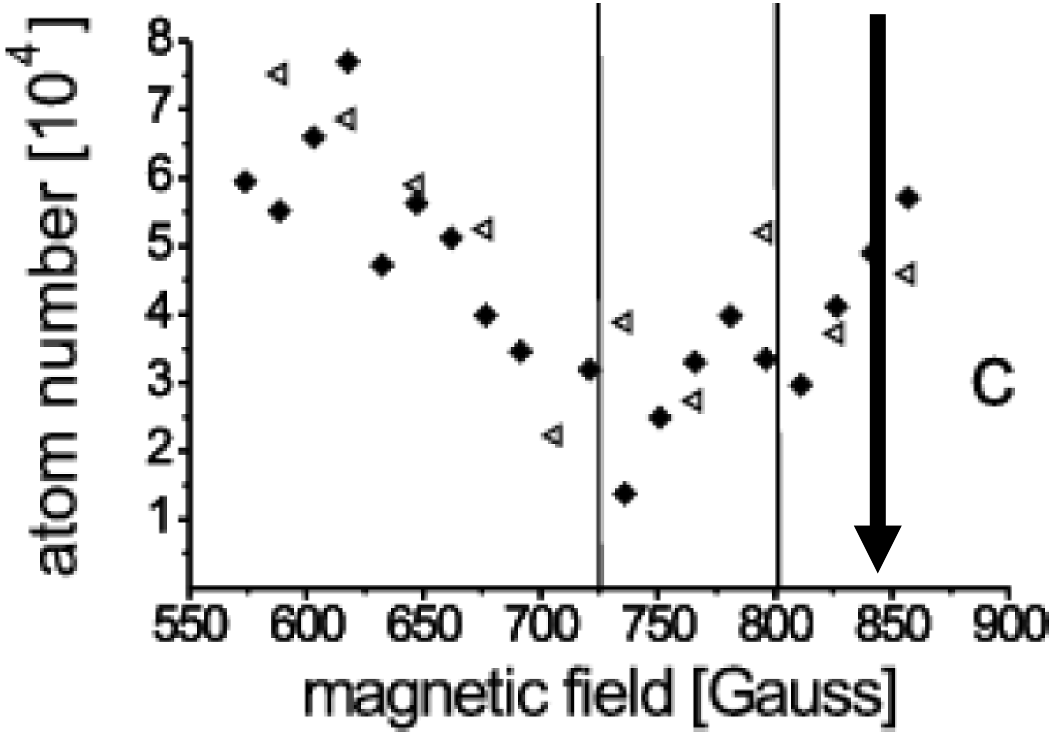


M. Holland *et al.* , PRL (2001)

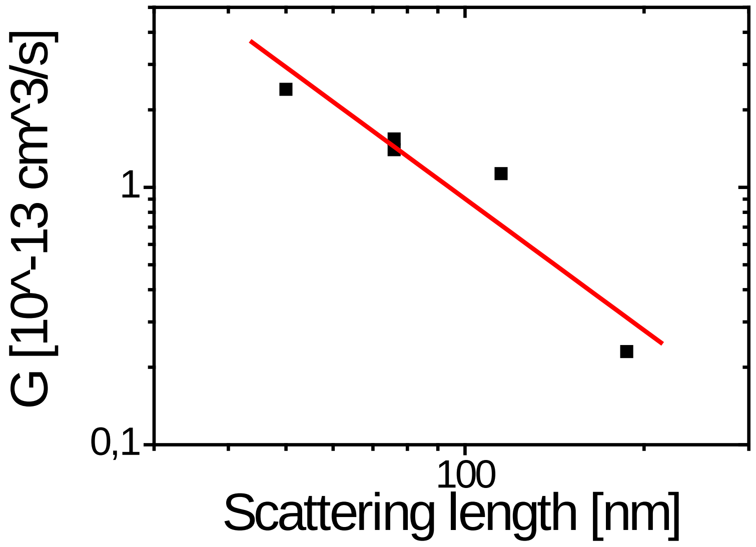
Looking for Feshbach Resonances in Lithium

Bosons close to a Feshbach resonance:
BoseNova instability (JILA)



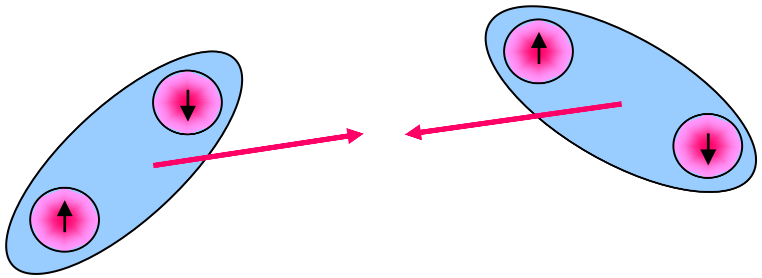


Inhibition of losses in Fermi gases



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.

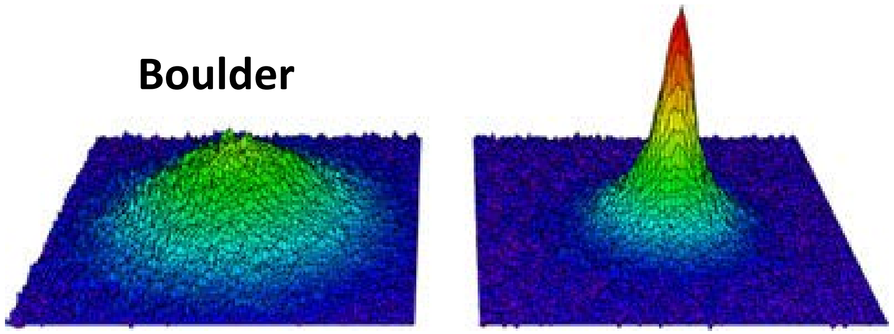


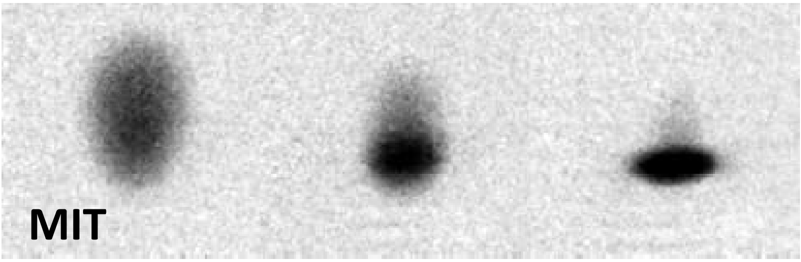
2 body (dimers) losses mainly : decay towards deeply bound states)

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

2003-2018: fifteen years of strongly correlated Fermi gases

Boulder





Innsbruck