Nearly perfect Fermi fluids

Selim Jochim
Physics Institute, Heidelberg University

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

Content

- Concepts of dilute ultracold fermions
- Interactions in ultracold gases
- How to make the fermions a fluid?
- Superfluid vs. hydrodynamic fluids
- Estimations for η/s

Ideal Fermi gas

Atoms are trapped in a conservative potential U(r), normally harmonic

$$V = \sum \frac{1}{2} m \omega_i^2 r_i^2$$

Fermi distribution:

$$f(\vec{r},\vec{p}) = \frac{1}{\exp[(\vec{p}^2/2m + V(\vec{r}) - \mu)/kT] + 1}$$

fixed particle number fixes μ:

$$N = \frac{1}{2(\hbar\omega)^3} \int_0^\infty \frac{E^2 dE}{\exp[(E-\mu)/kT]+1} \Rightarrow \mu(T=0) = (6N)^{1/3} \hbar\omega \equiv E_F$$

Density distribution

$$n(\vec{r}) = \frac{8}{\pi^2}\frac{N}{x_F y_F z_F}\left(1 - \frac{x^2}{x_F^2} - \frac{y^2}{y_F^2} - \frac{z^2}{z_F^2}\right)$$

$$n(\vec{p}) = \frac{8}{\pi}\frac{N}{p_F^3}\left(1 - \frac{p^2}{p_F^2}\right)^{3/2}$$

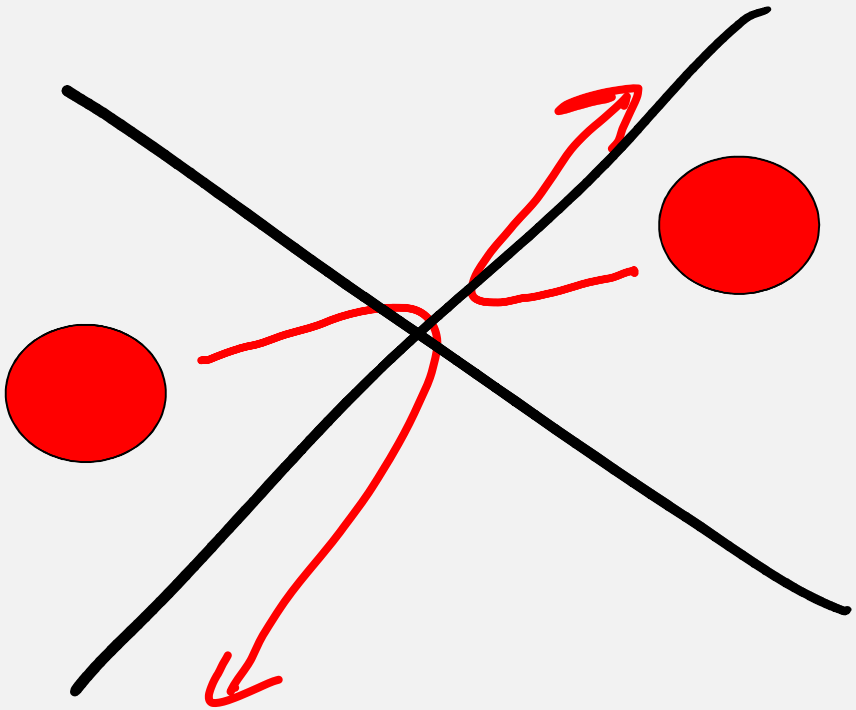
$$E_F \equiv \frac{1}{2} m \omega_i^2 r_i^2 \equiv \frac{p_F^2}{2m}$$

$\Rightarrow$ This leads to isotropic expansion of noninteracting cloud.

Identical Fermions do not interact …

only s-wave scattering occurs

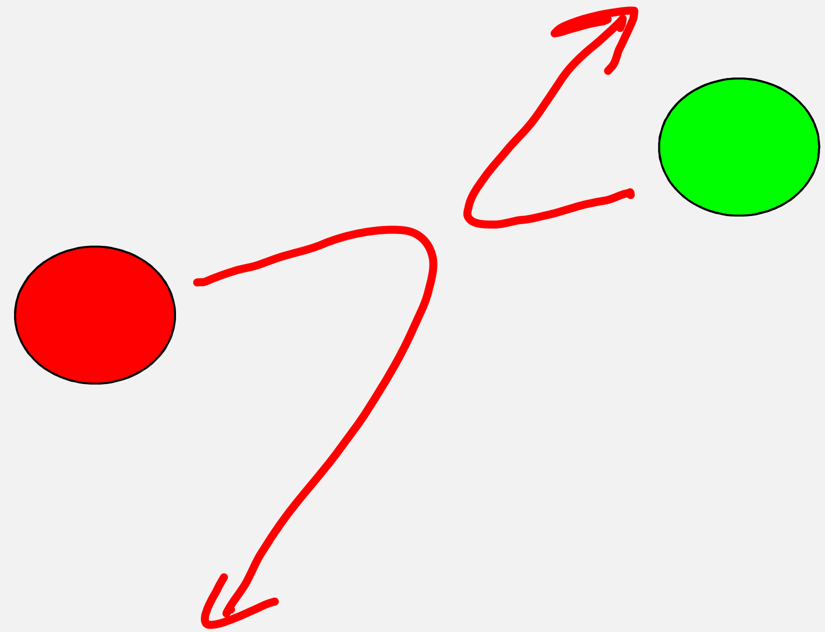
… at ultracold temperatures …



Max-Planck-Institut
für Kernphysik

Identical Fermions do not interact …

… need distinguishable particles …



Weakly interacting fermions

BCS Theory:

$$T_{BCS} \approx 0.28\, T_F \cdot \exp\left[-\frac{\pi}{2k_F a}\right] \qquad k_F = \frac{p_F}{\hbar}$$

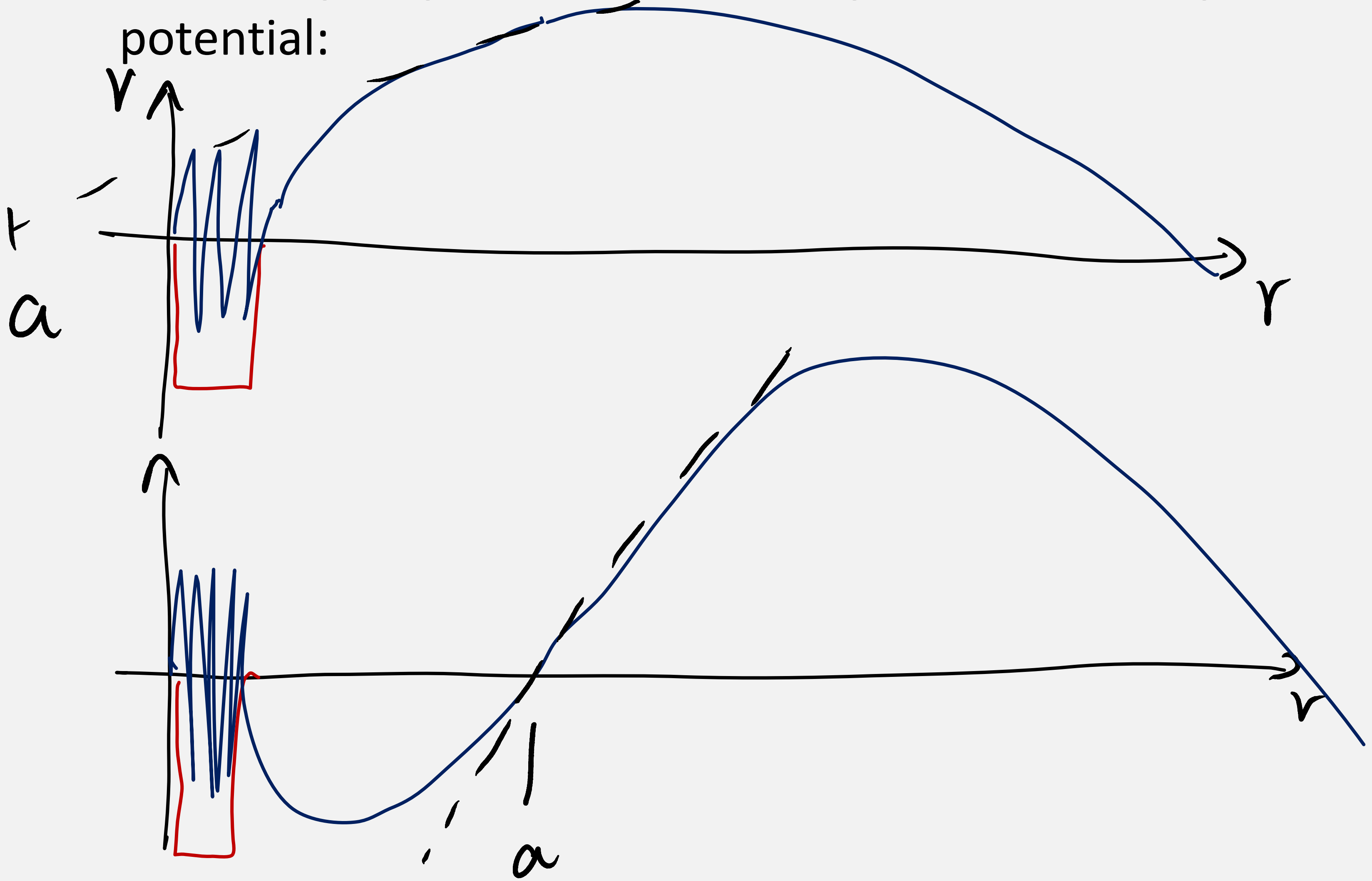
Small parameter $k_F a$ same as $n a^3$
($k_F \approx n^{1/3}$)

$$\Delta_{BCS} \approx 0.2\, E_F \exp\left[-\frac{\pi}{2k_F a}\right]$$

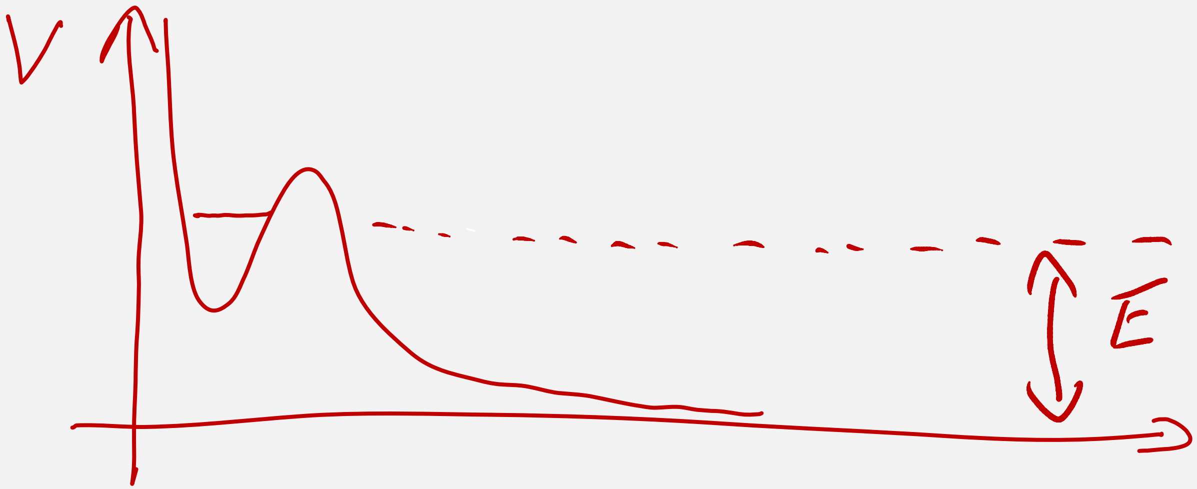
Max-Planck-Institut
für Kernphysik

How to tune a?

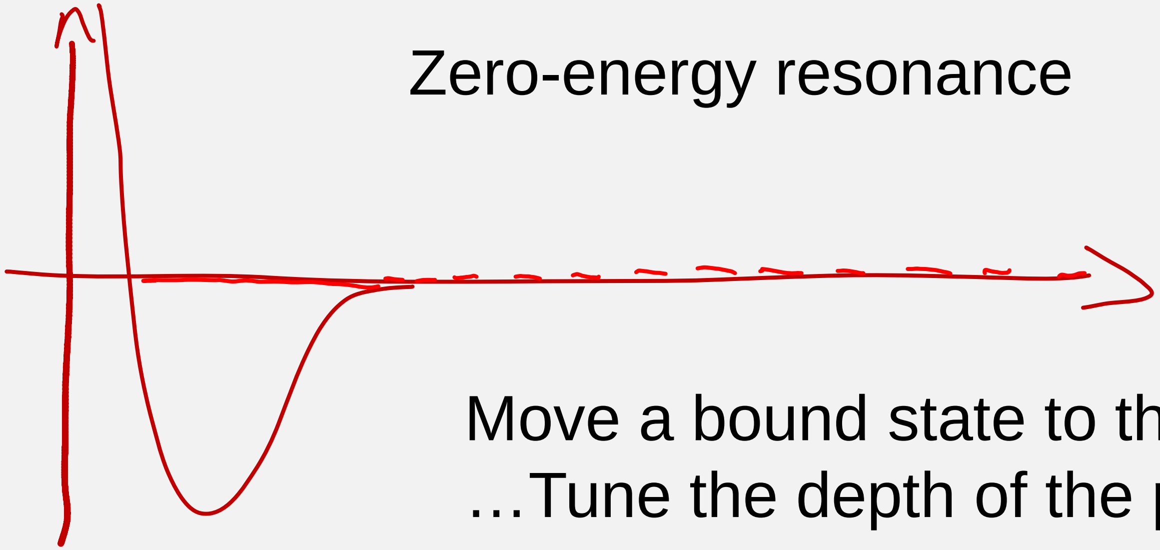
- Scattering length can be much larger than the range of the potential:



Scattering resonances

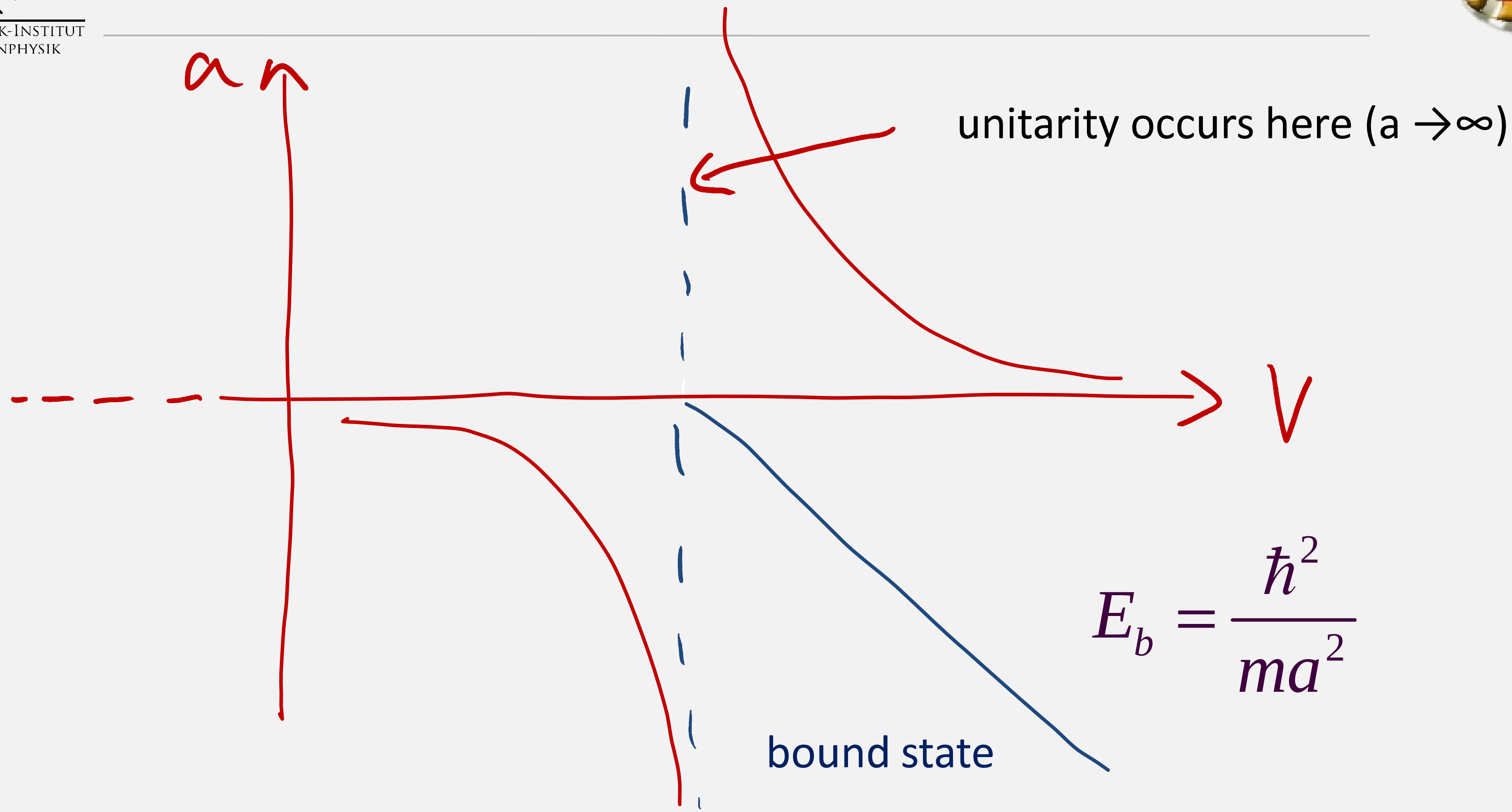


Zero-energy resonance



Move a bound state to the threshold!
…Tune the depth of the potential …

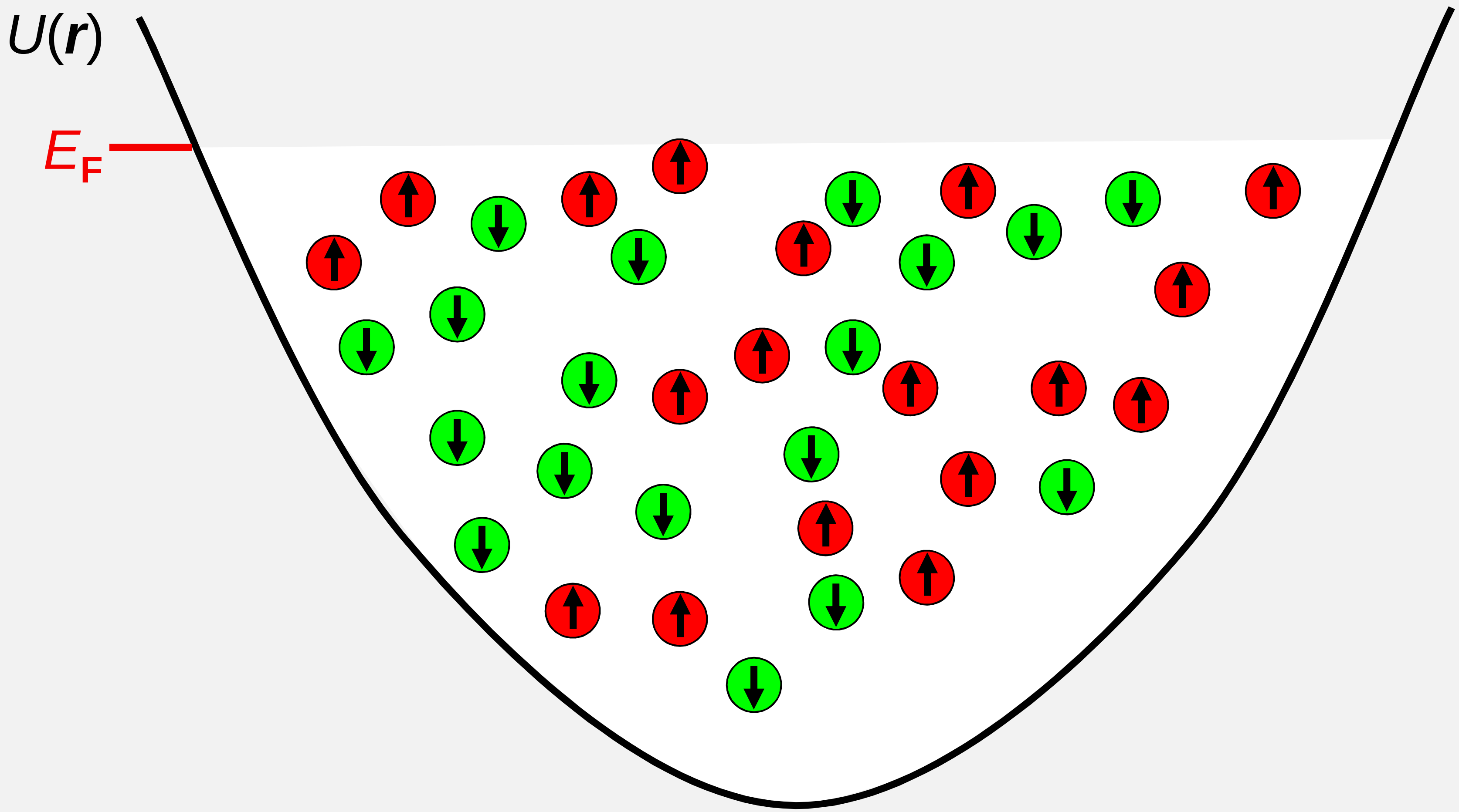
Controlling the scattering length



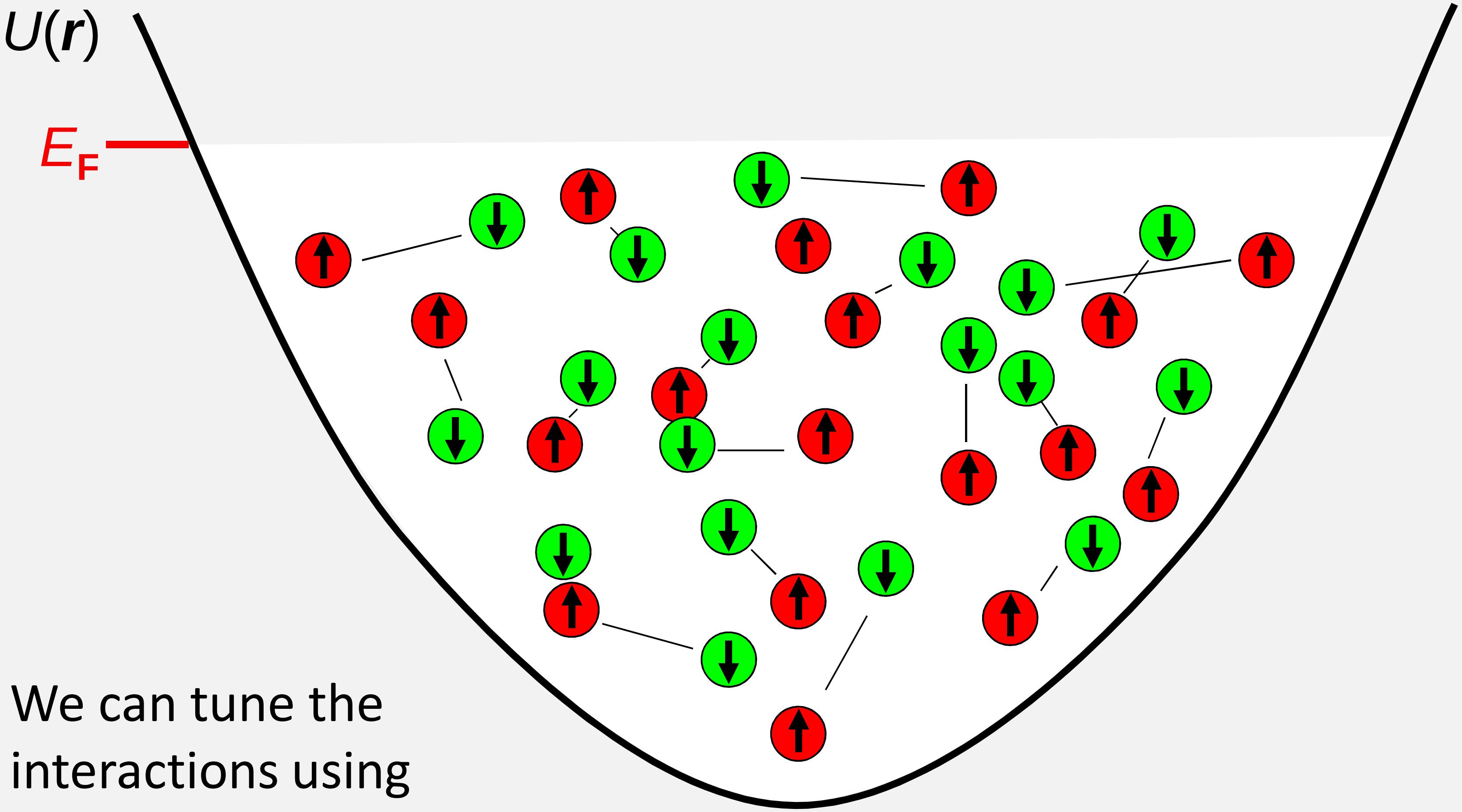
$$E_b = \frac{\hbar^2}{ma^2}$$

- One can make *a* much larger than the size of the potential!!!
- With cold atoms: Use Feshbach resonances to tune scattering length, by applying a magnetic field.
- for a review, see: C. Chin *et al.,* arXiv:0812.1496

Mixture of fermions

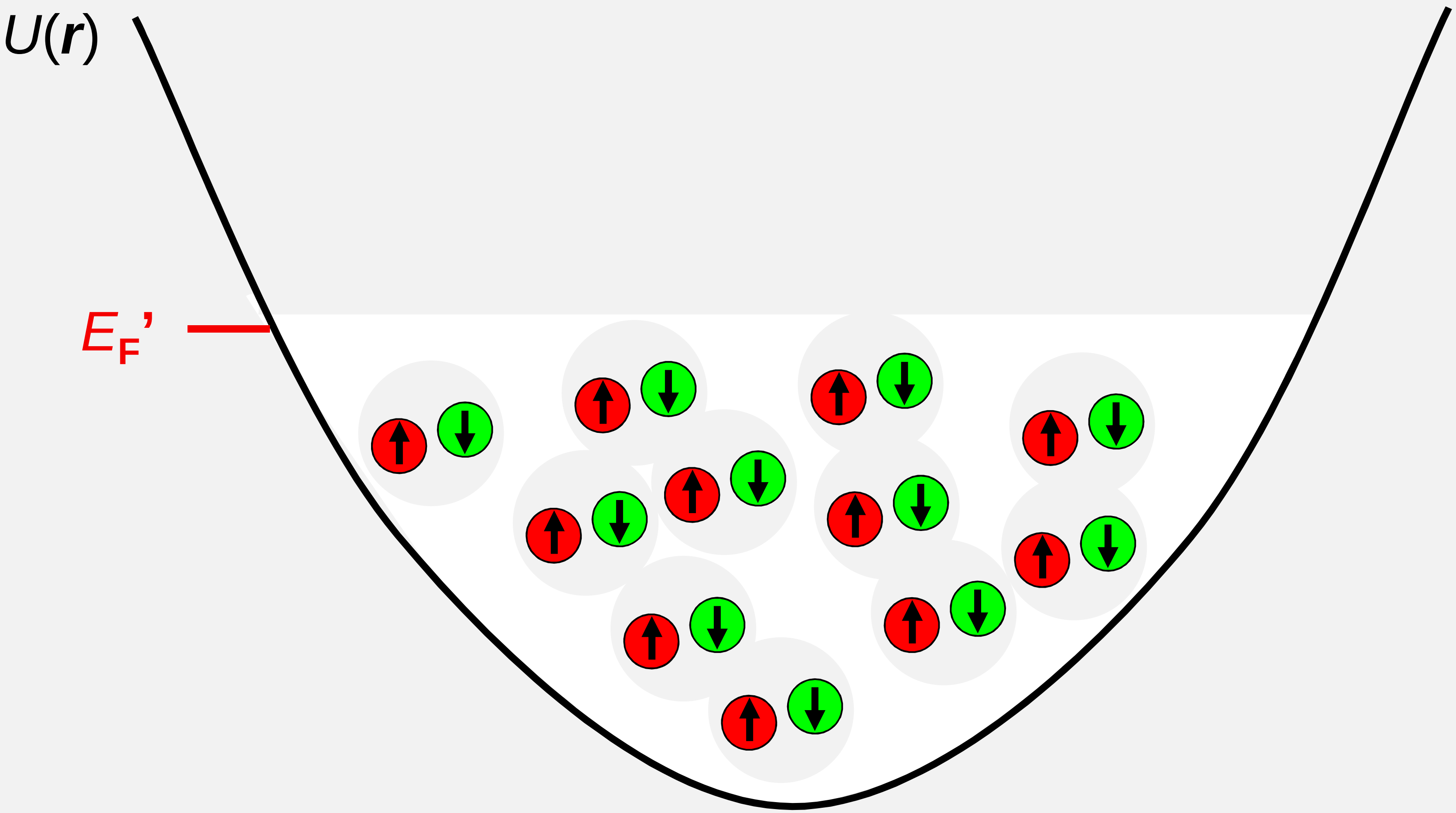


Interacting fermions



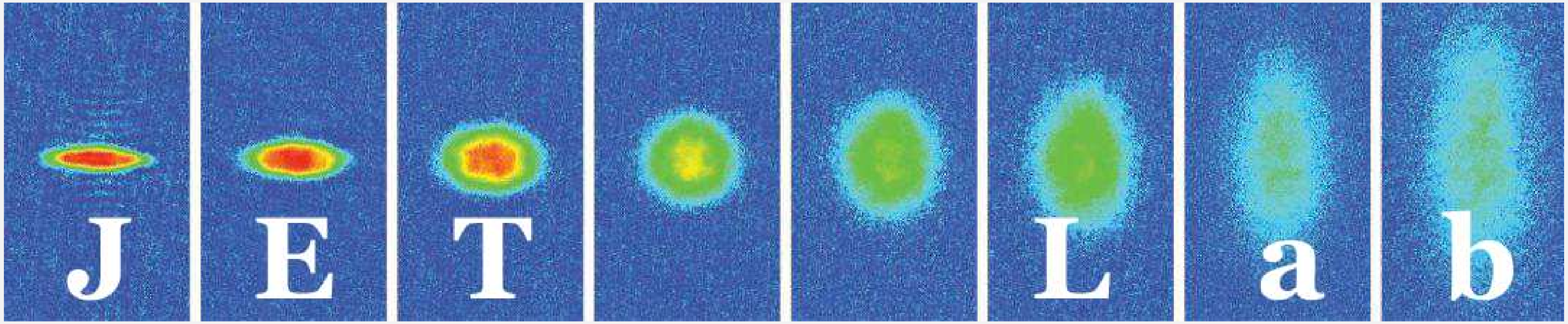
We can tune the interactions using Feshbach resonances

Strongly interacting fermions



Max-Planck-Institut
für Kernphysik

First experiments



Science 298, 2179 (2002)

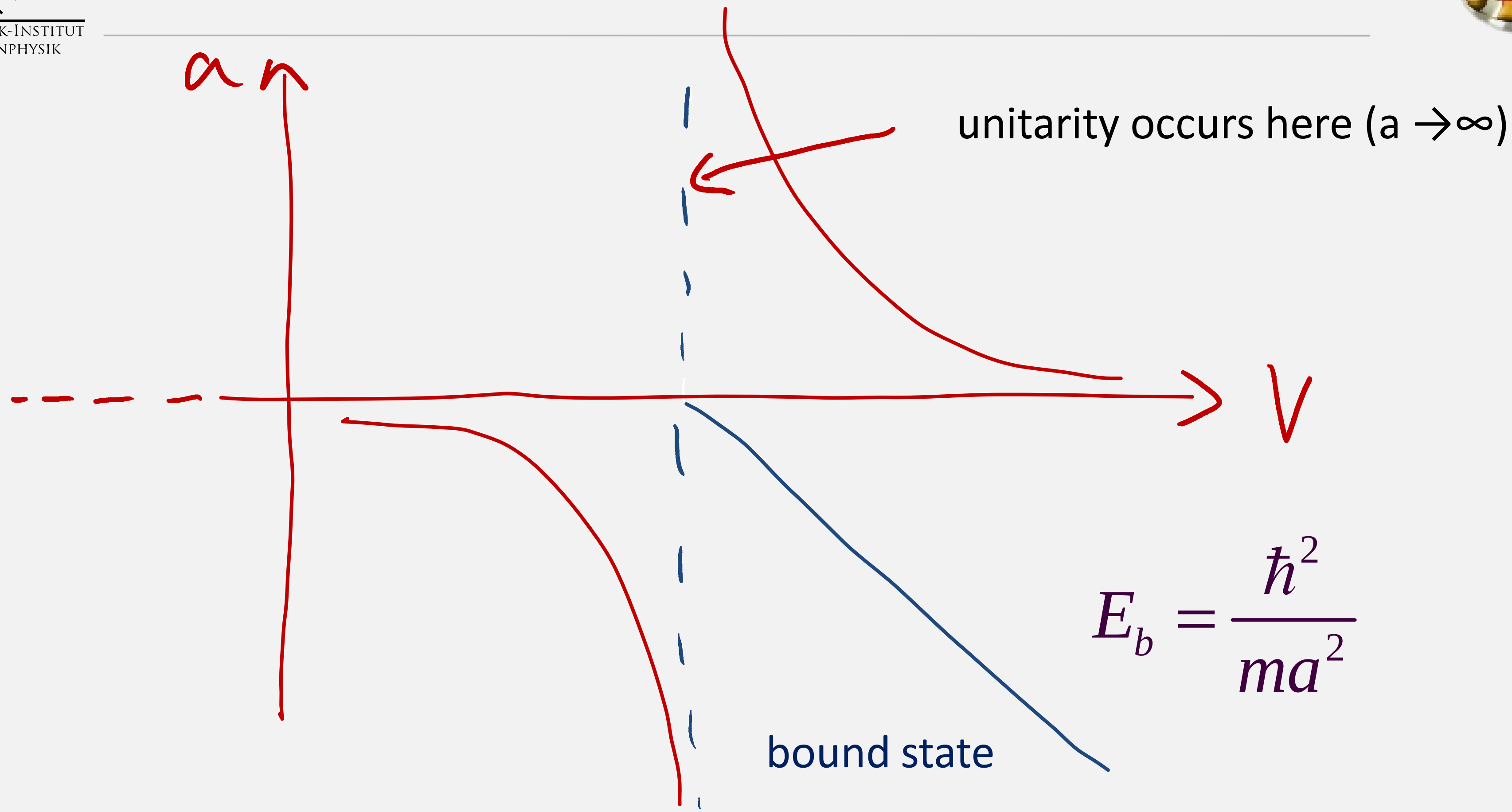
Euler equation:

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\,\vec{v} = -\frac{1}{mn}\vec{\nabla} p - \frac{1}{m}\vec{\nabla} U$$

exact behavior depends on Equation of State,

i.e. $p(n) \propto n^{\gamma+1}$

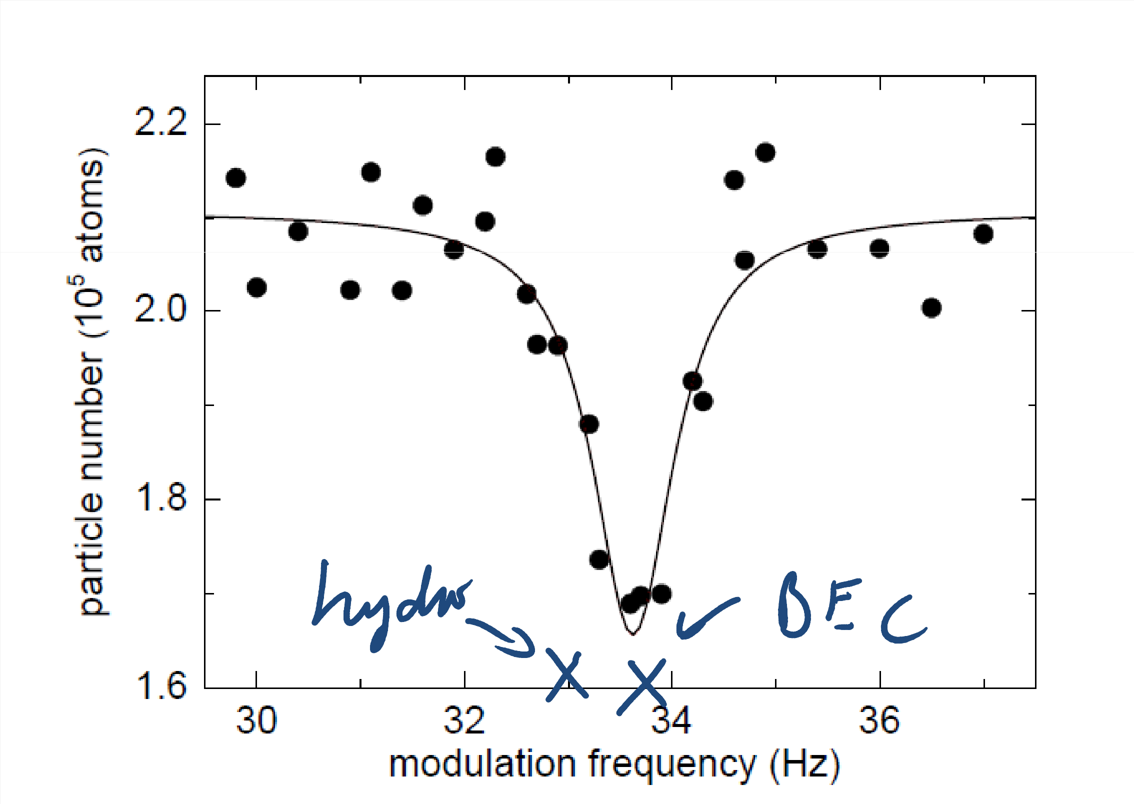
„Feshbach“ molecules



$$E_b = \frac{\hbar^2}{ma^2}$$

A BEC of molecules?

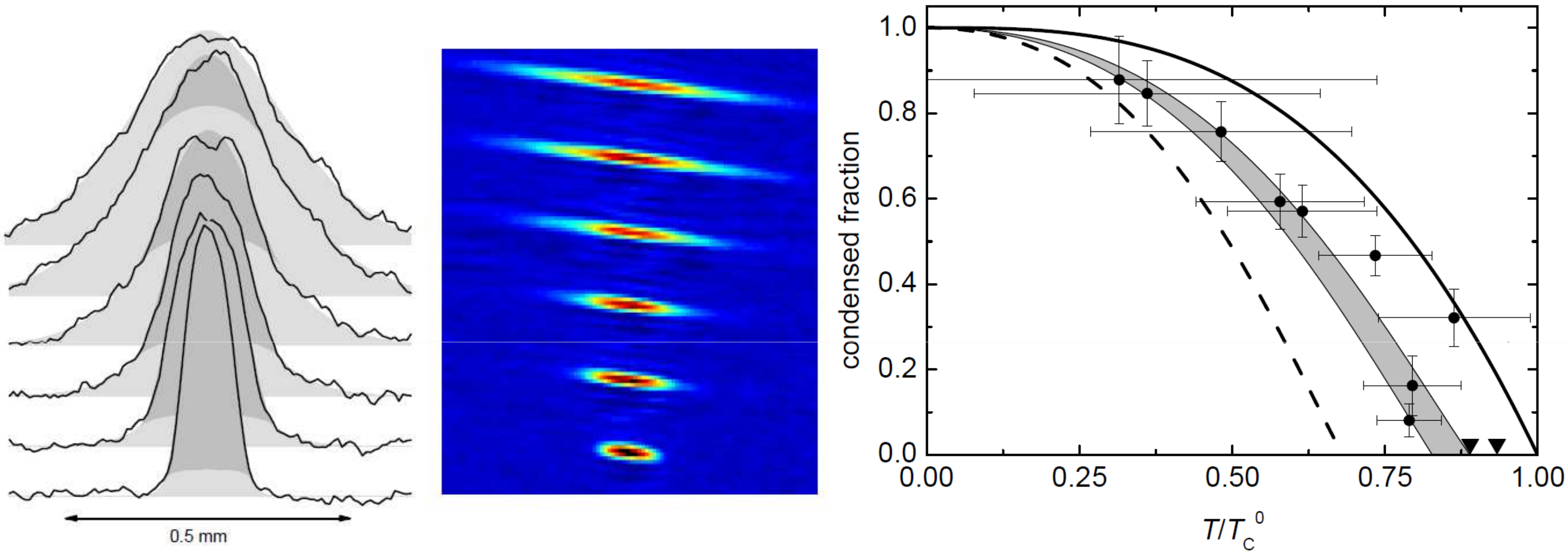
- Collective modes as a probe for the equation of state ….



$$\omega_{BEC} = \sqrt{\frac{5}{2}}\,\omega_z$$

$$\omega_{Hydro} = \sqrt{\frac{12}{5}}\,\omega_z$$

BEC of molecules

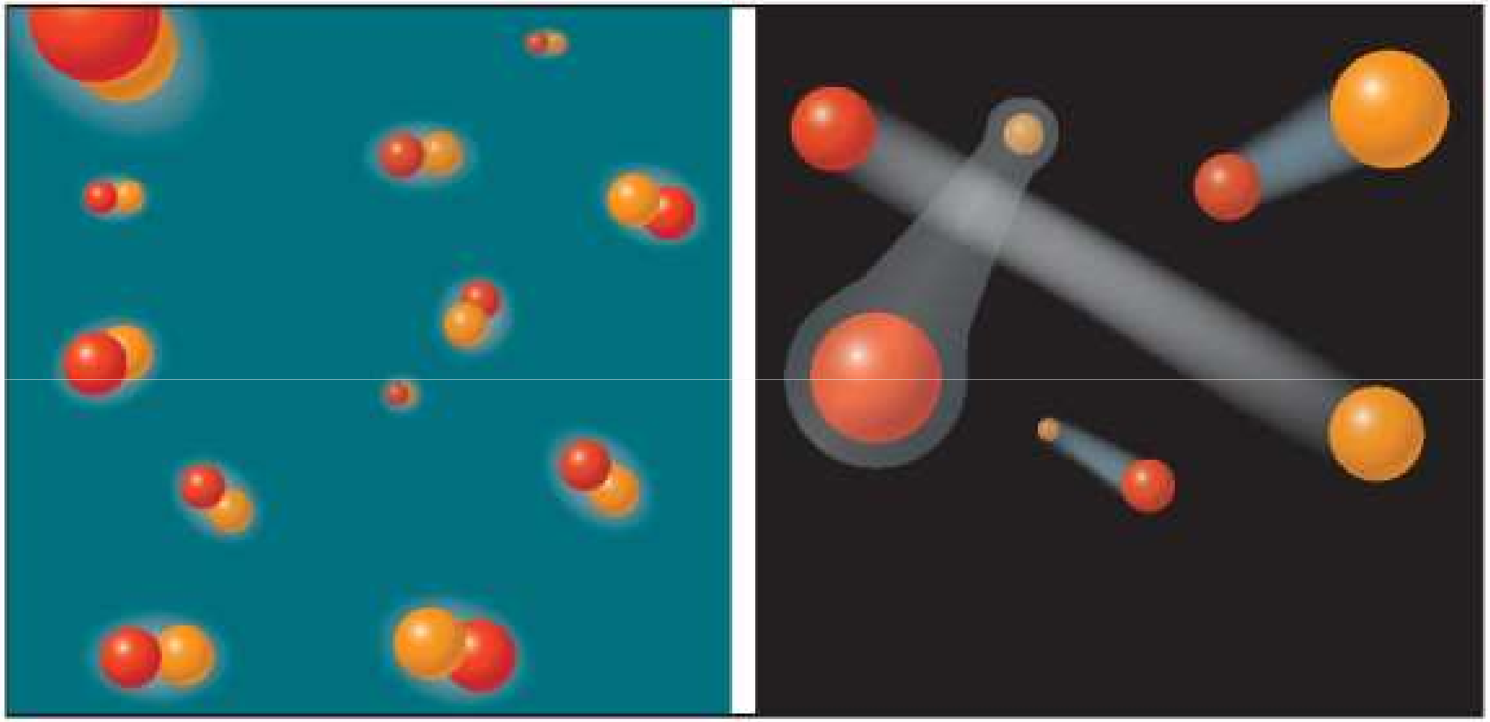


measure for shift in critical Temperature:

$$\frac{\mu(T=0)}{k_B T_c^0} = \left(N^{1/6}\frac{a}{a_{ho}}\right)^{2/5} \simeq 0.4 - 0.6$$

A very exciting playground ….

… for many-body physics

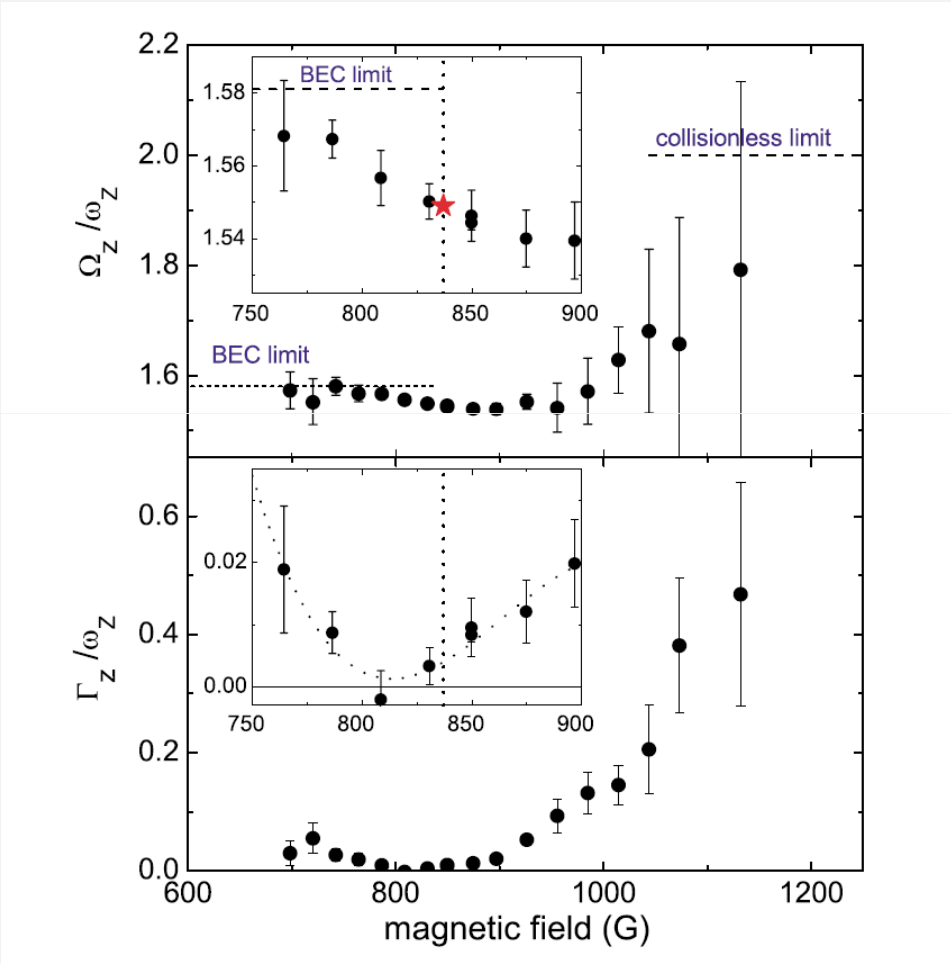


Tango or twist? In a magnetic field, atoms in different spin states can form molecules (*left*). Vary the field, and they might also form loose-knit Cooper pairs.

Cho, Science (2003)

Dynamics of a strongly interacting Fermi gas

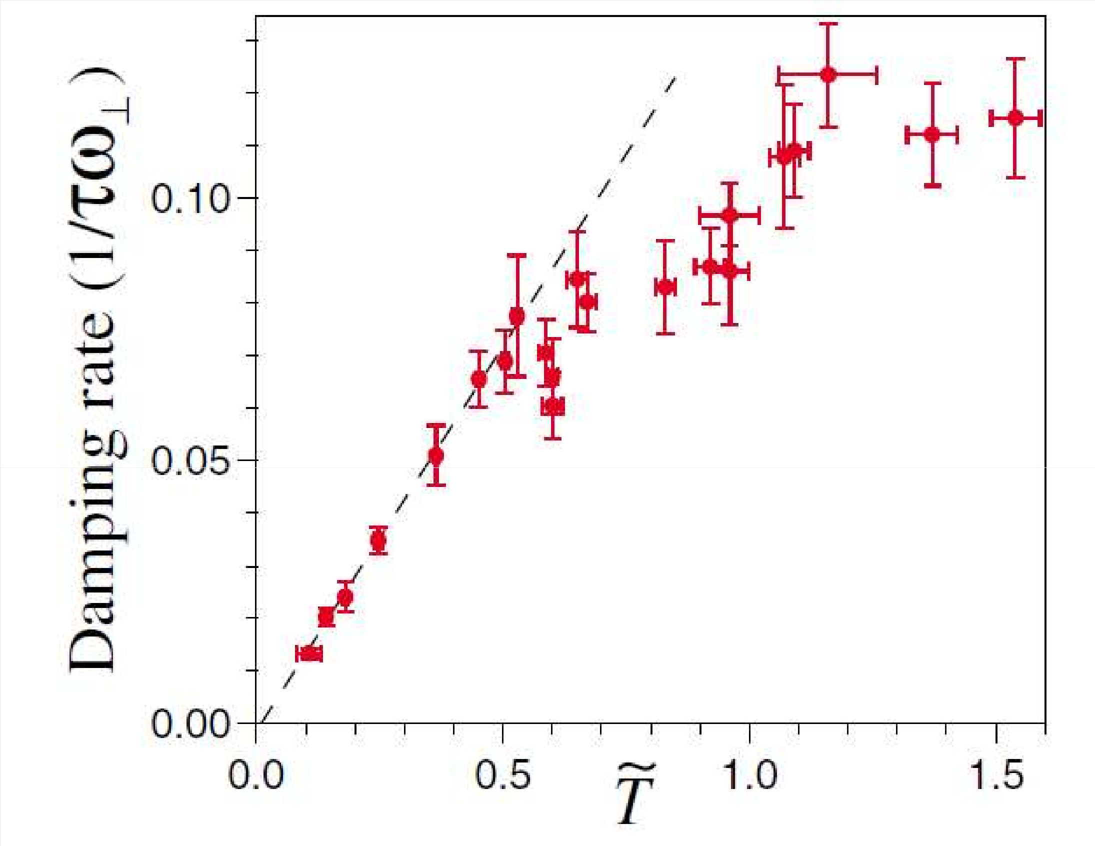
Max-Planck-Institut
für Kernphysik



Ω_z : Equation of state

Γ_z : Damping ~ Viscosity

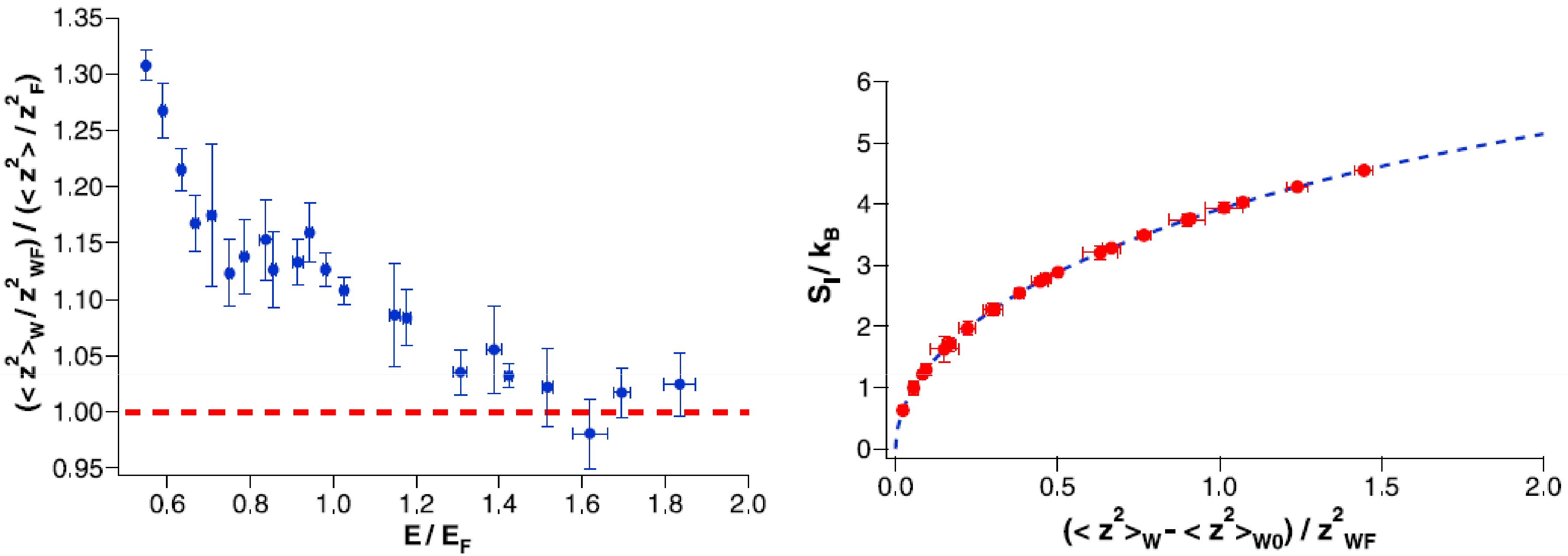
Estimating the viscosity …



- Radial breathing mode damping varies strongly with temperature!

PRL 94, 170404 (2005)

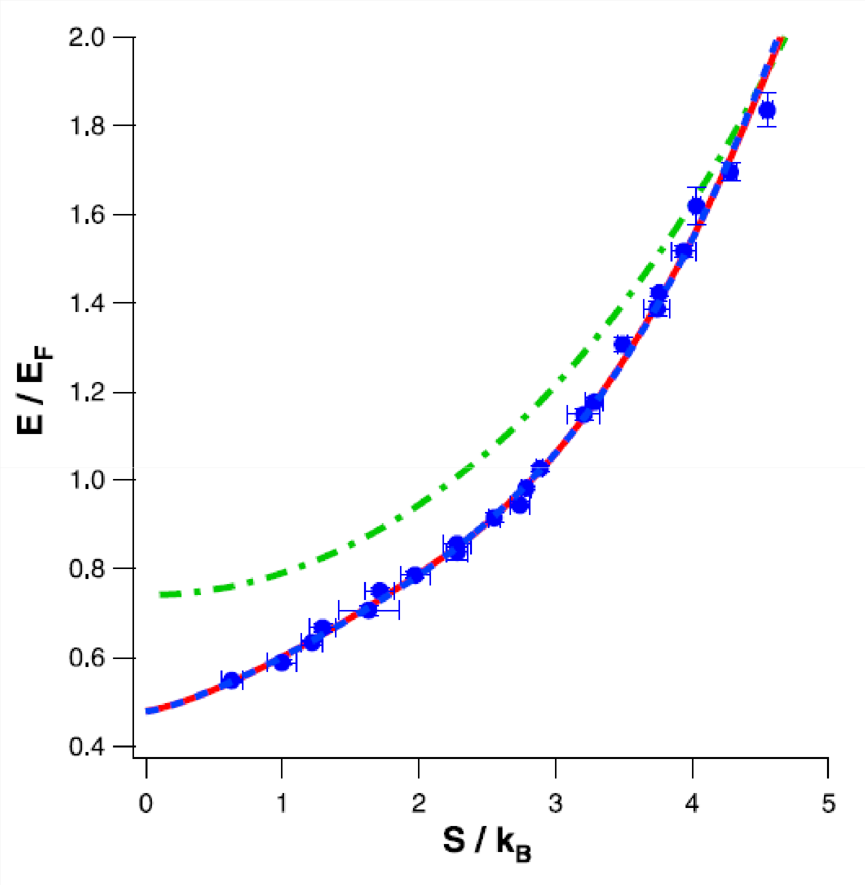
Temperature and entropy

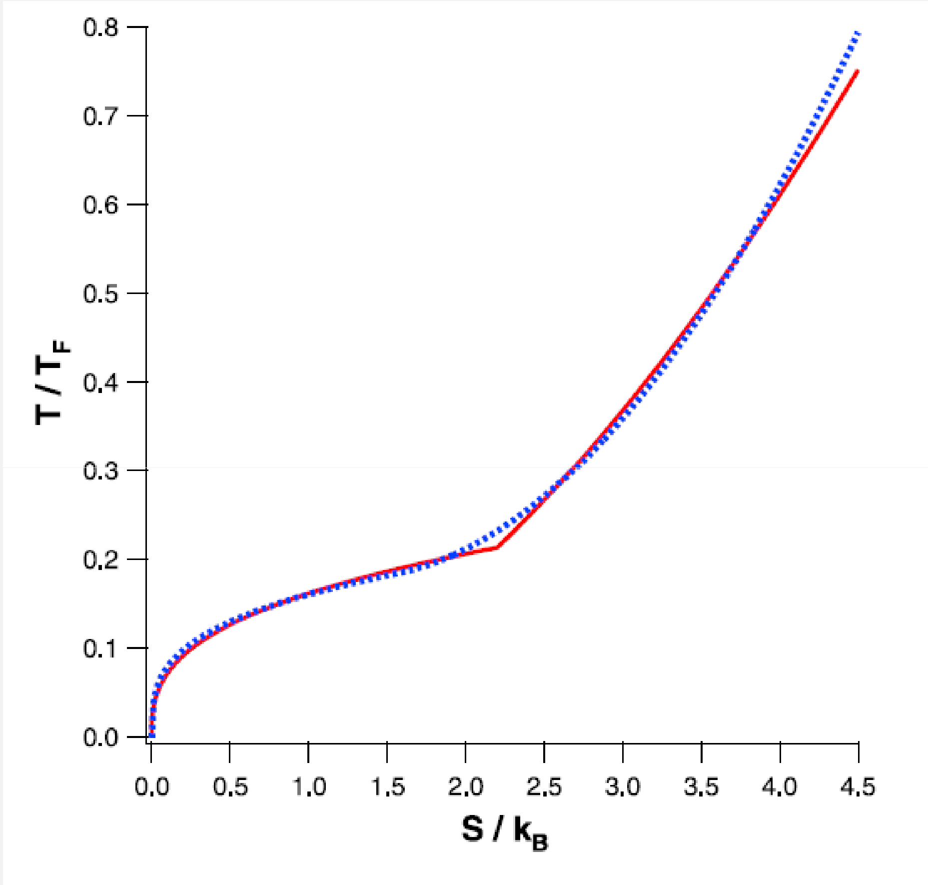


Make use of entropy conservation: Measure T, S in noninteracting sample

J Low Temp Phys 54,1 (2009)

Entropy and temperature calibration

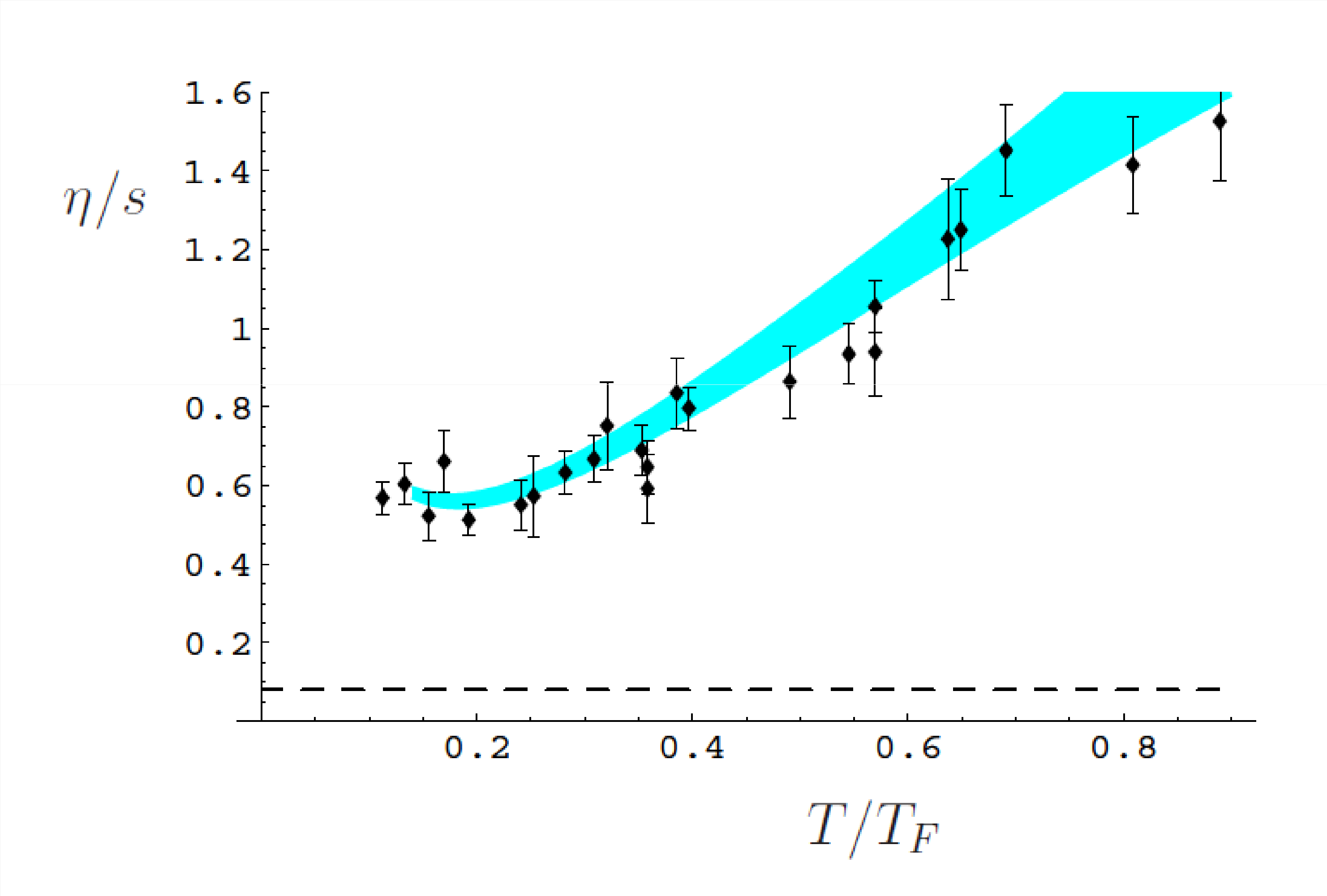




$$T = \frac{\partial E}{\partial S}$$

J Low Temp Phys 54,1 (2009)

Entropy vs. temperature



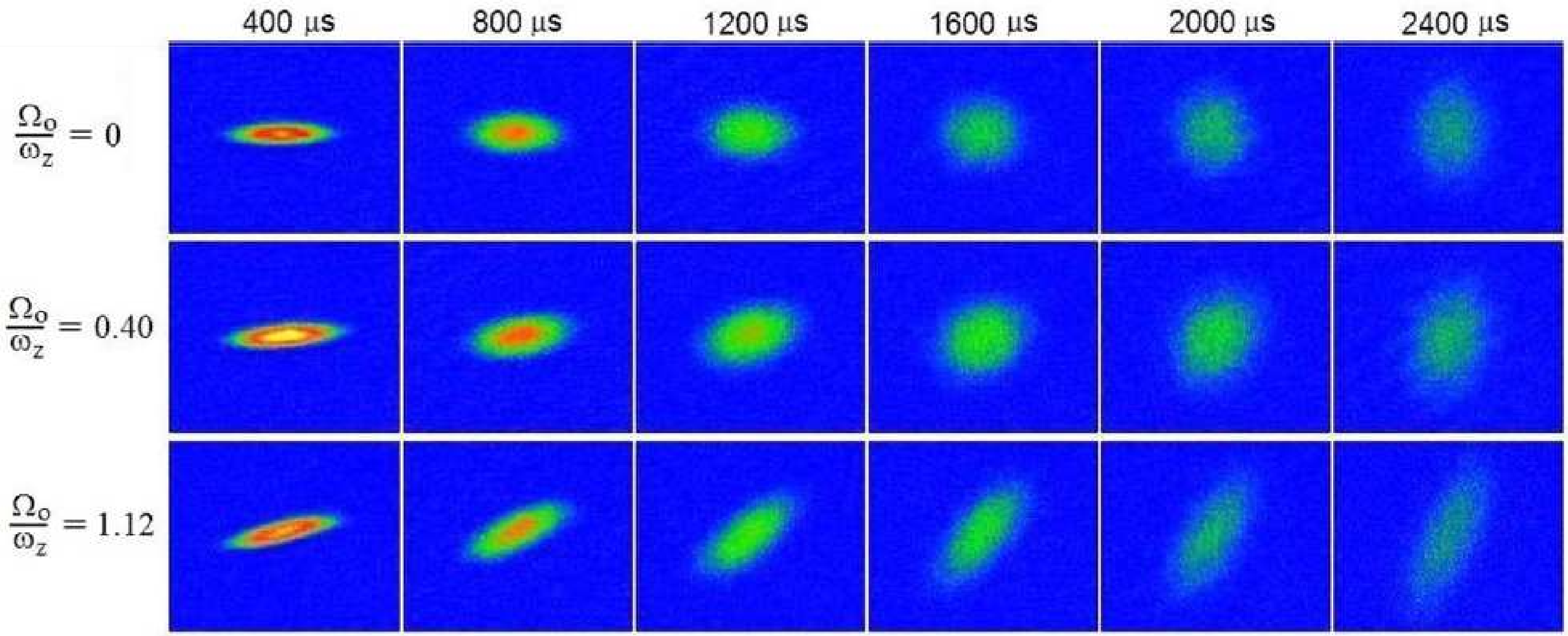
arXiv:cond-mat/0701251v4

Max-Planck-Institut für Kernphysik

Another approach

- A rotating Fermi cloud expands .....

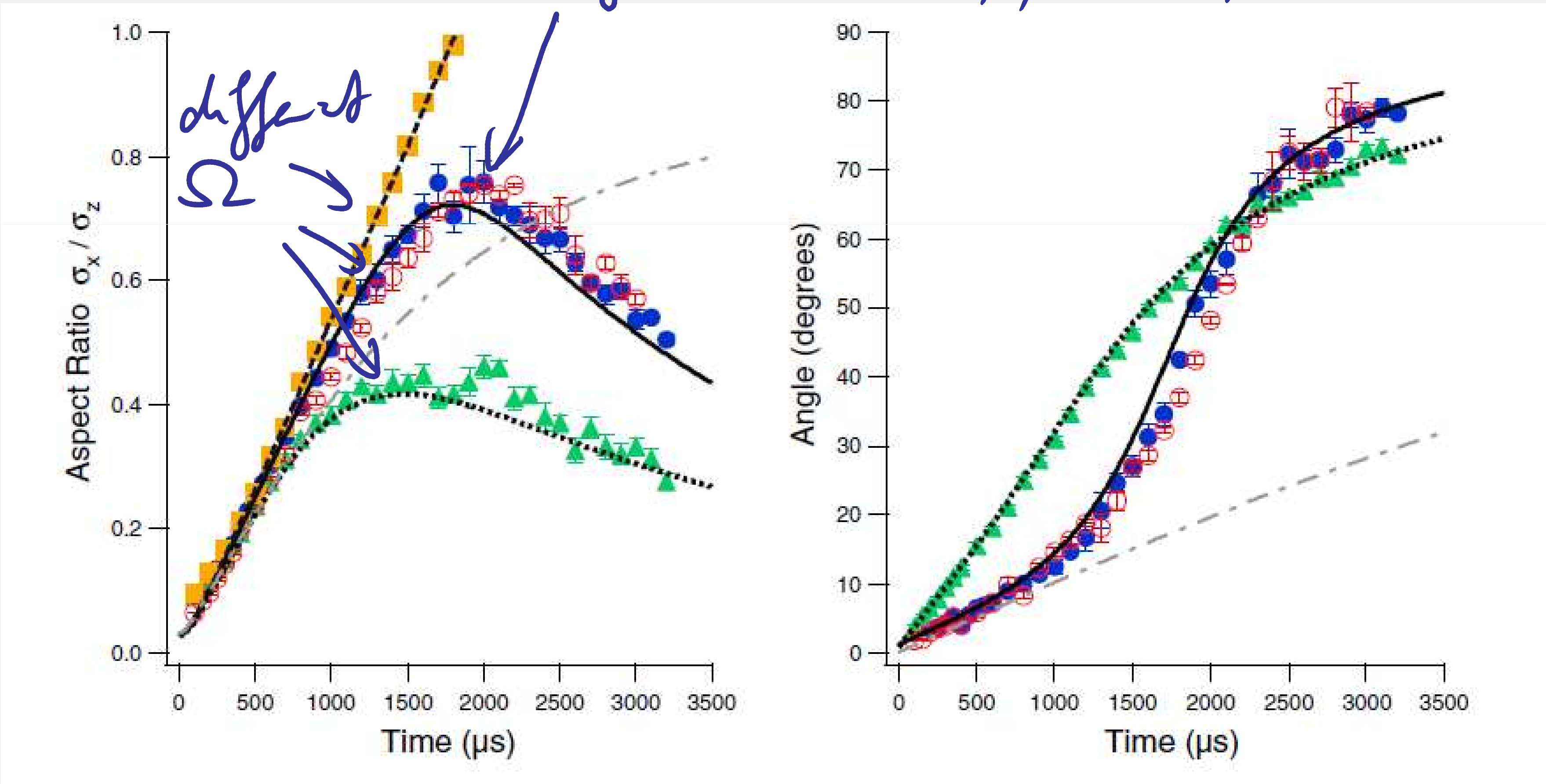
PRL 99, 140401 (2007)



MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

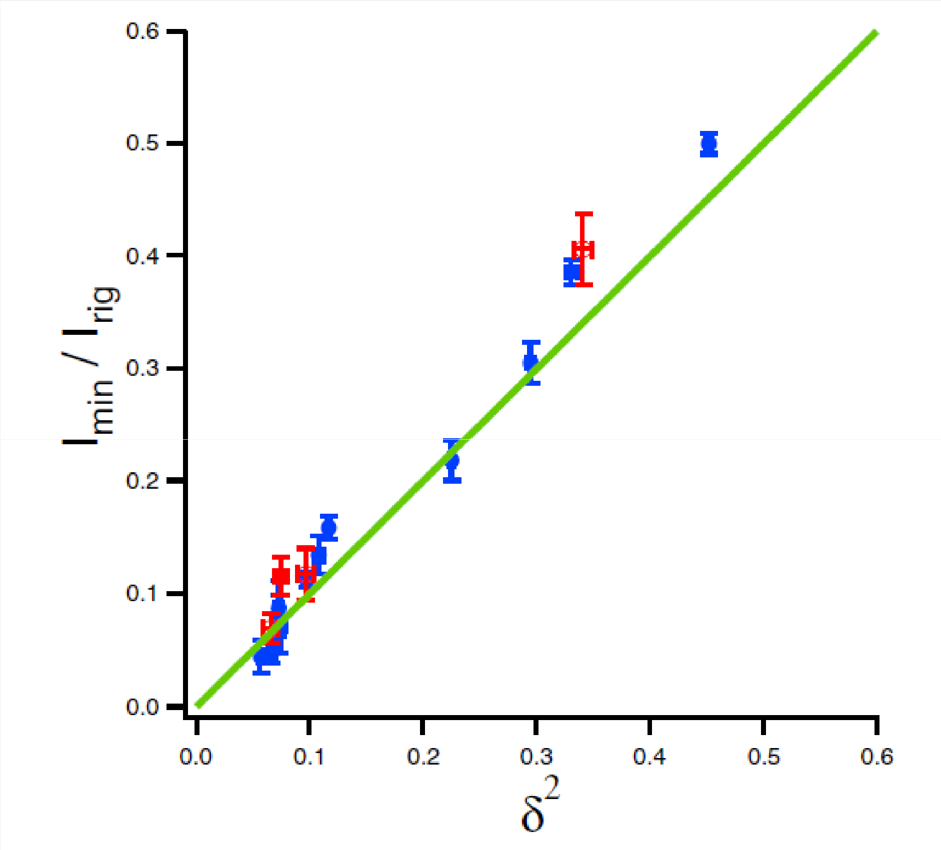
Expanding rotating cloud

- Irrotational flow: Expect quenching of moment of inertia …

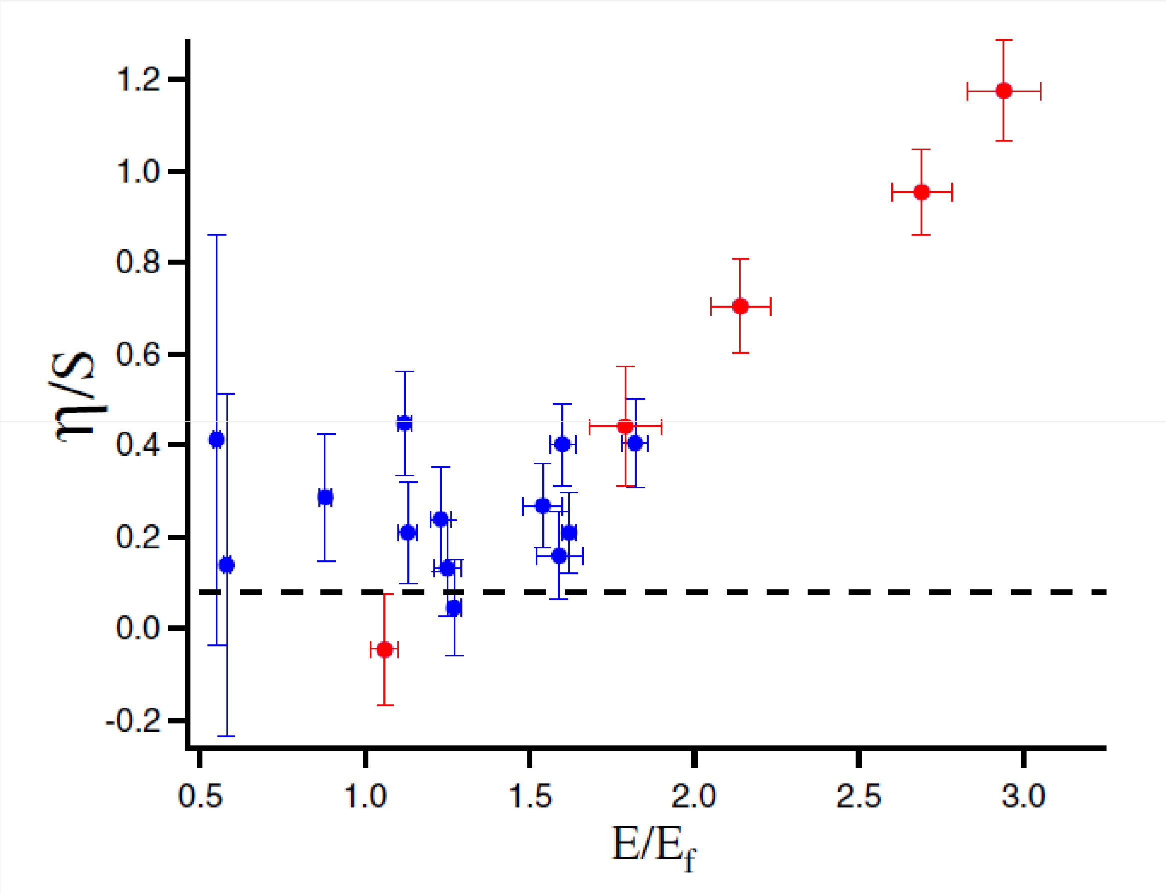


Max-Planck-Institut
für Kernphysik

Quenching of moment of inertia



Estimation of shear viscosity



Nuclear Physics A 830, 665c (2009)