Ultracold degenerate

Fermi gases

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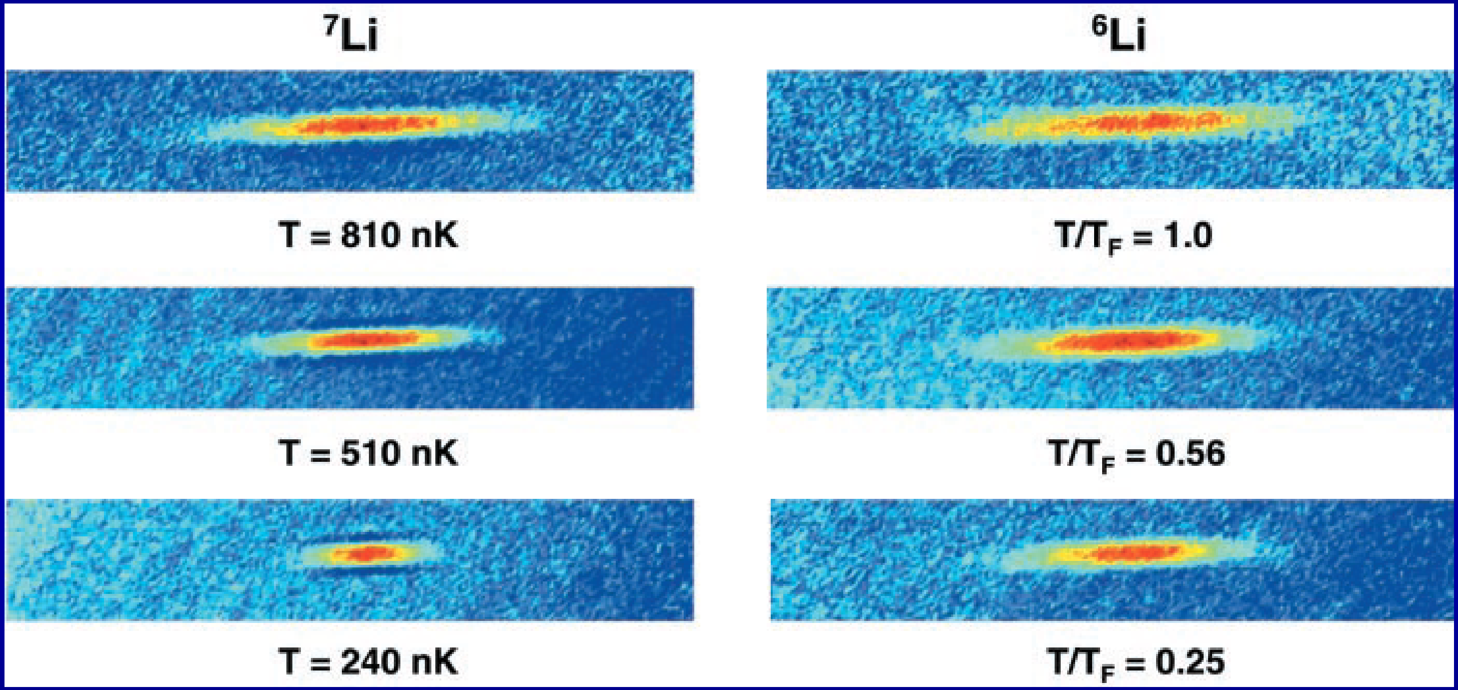

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Motivation

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- BEC: drastic effects when degeneracy is reached. Fermi gas: Every state is occupied with one single atom. Could this simply be boring???
- Non-ultracold systems: Superfluidity e.g. in BCS, but at very low temperature.
- Of course now: strongly interacting gases quite successful

Contents

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- Properties of degenerate Fermi gas in a harmonic trap
- Experimental realization:
  Challenges to prepare, and probe such a gas!
- Hint: How to obtain superfluidity in an ultracold Fermi gas?

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- …continue on black board …

Chemical potential of a Fermi Gas

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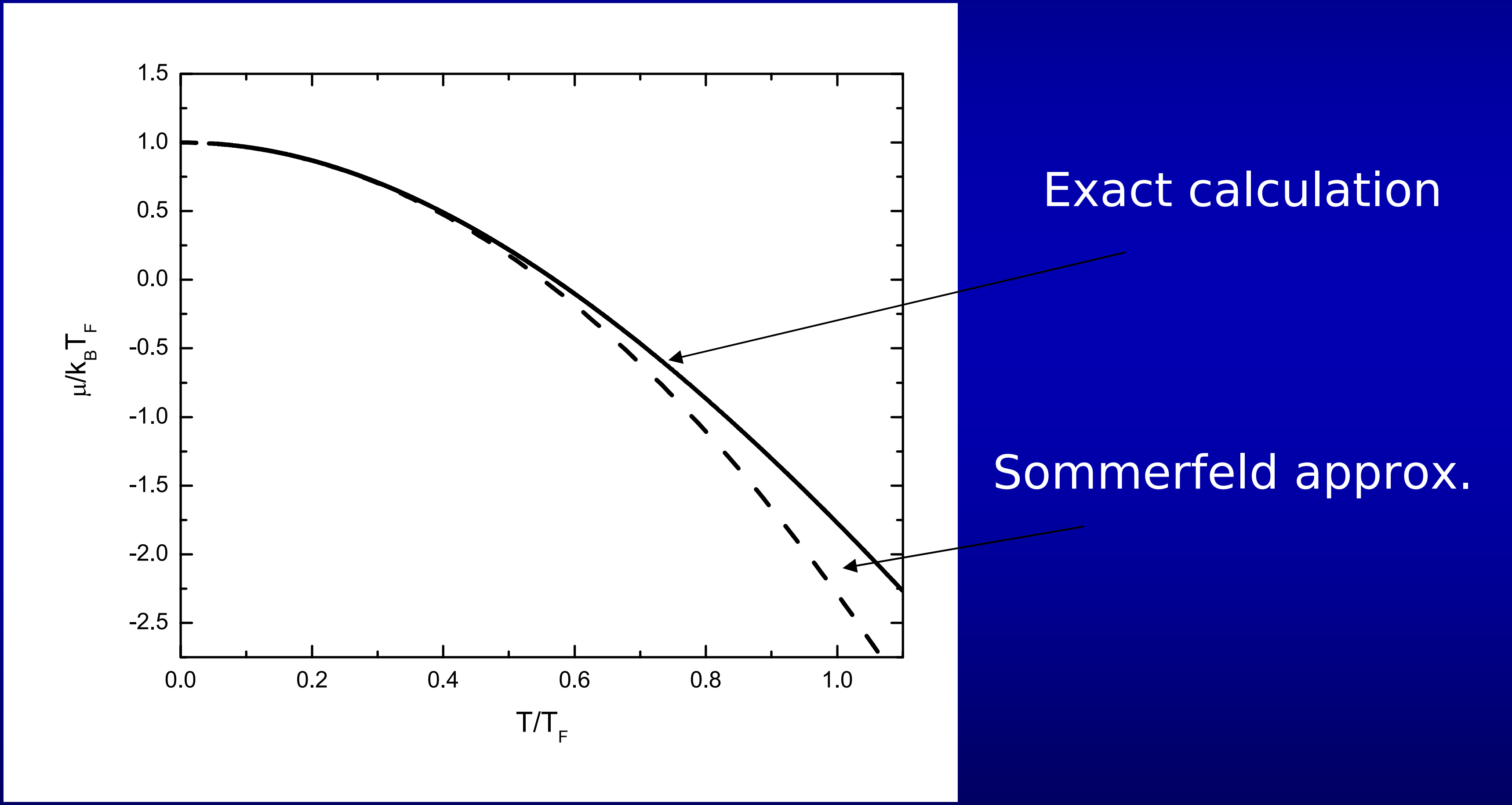
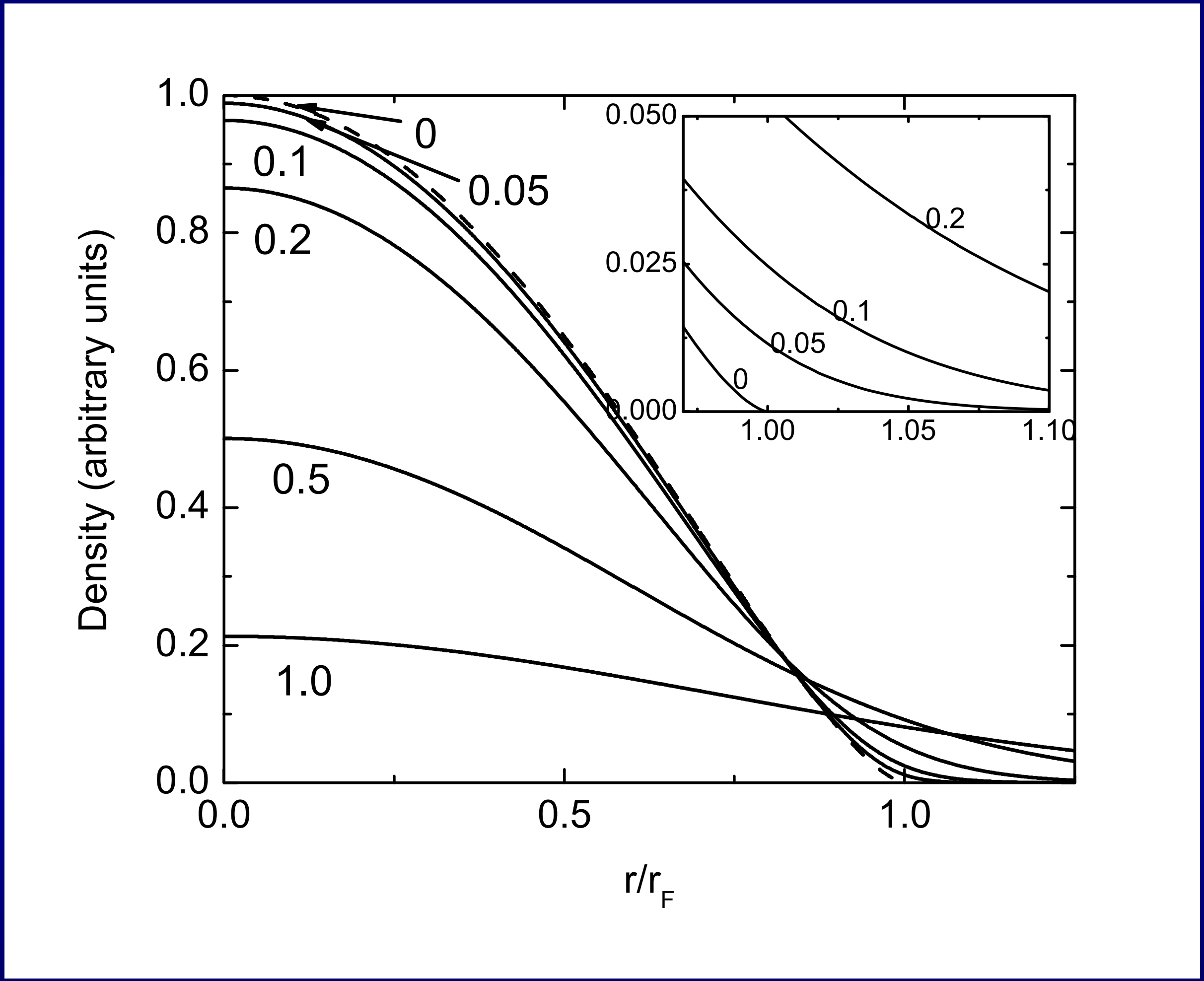


Density distribution



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Experiments

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- How to cool a Fermi gas?
- Evaporative cooling always require elastic collsions!

- In BEC: Worry about ratio of good to bad collisions
- Fermi gas: Collisions are suppressed in many ways!

Interactions of identical Fermions

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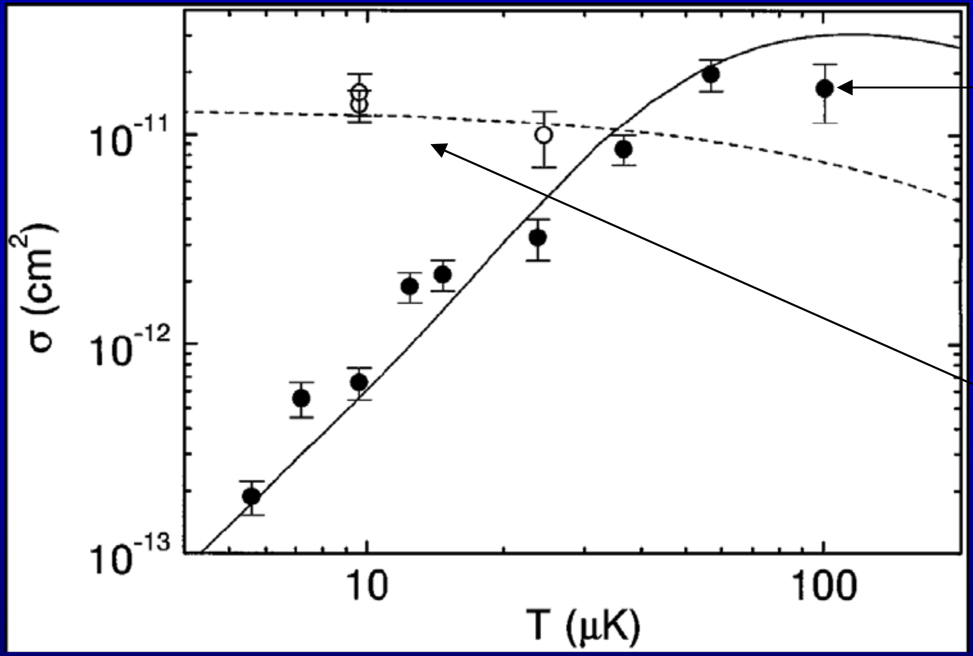
- Suppression of p-wave collisions:
- At ultracold temperatures: s-wave scattering cross section: s=0, p-wave scattering prop. to E^2.



Identical particles

Spin mixture

De Marco, ...Jin, PRL (1999)

No collisions mean no thermalization, no ev. cooling!
Non-identical particles are required!

Options for evap. Cooling of fermions

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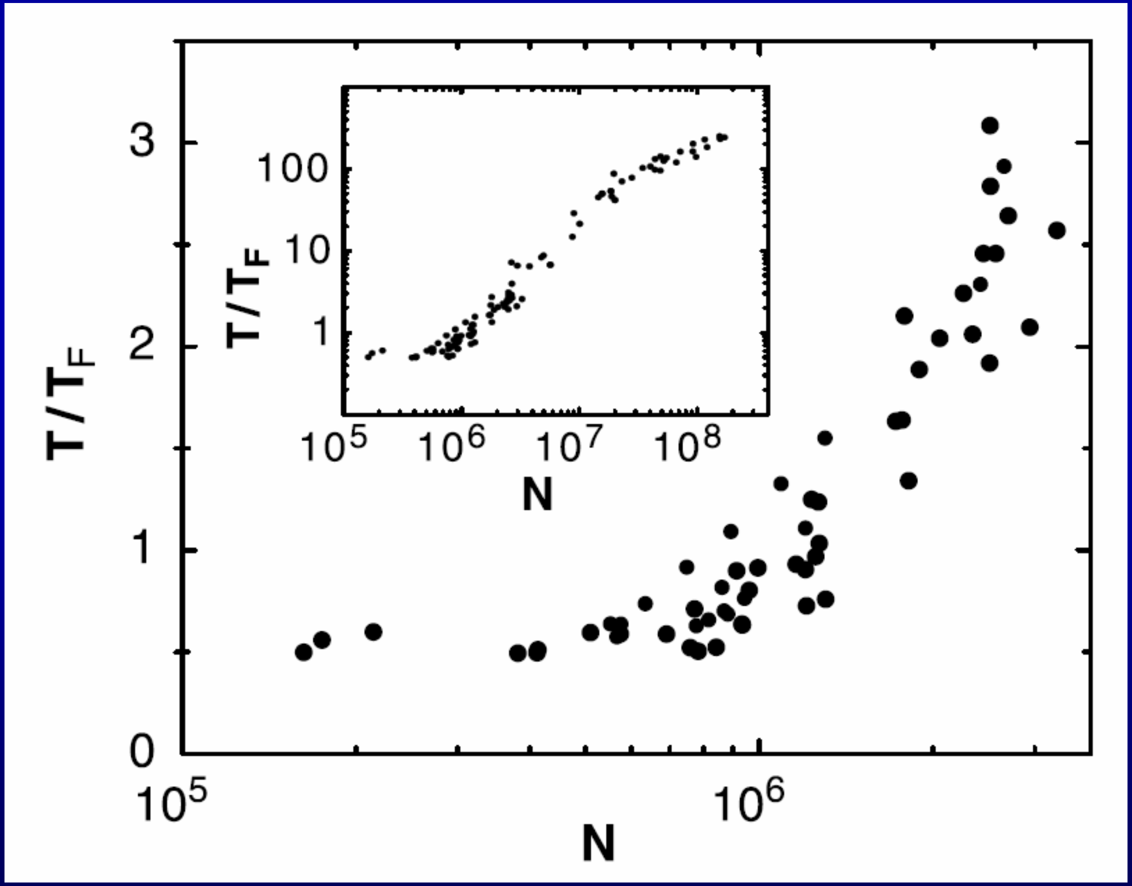
- Use different spin states of the same atoms:
  1. ^{40}K F=9/2, m_F=9/2,m_F=7/2 (magnetic trapping possible)
  2. ^{6}Li F=1/2, m_F=±1/2 (no magnetic trapping!)

- Use bosonic species of the same element as a coolant
  Mostly: ^{6}Li, ^{7}Li

- Use another (bosonic) atom for cooling
  Prime choice: ^{6}Li, ^{23}Na -> largest Fermi seas (up to 10^7)

First deg. Fermi gas: 40K

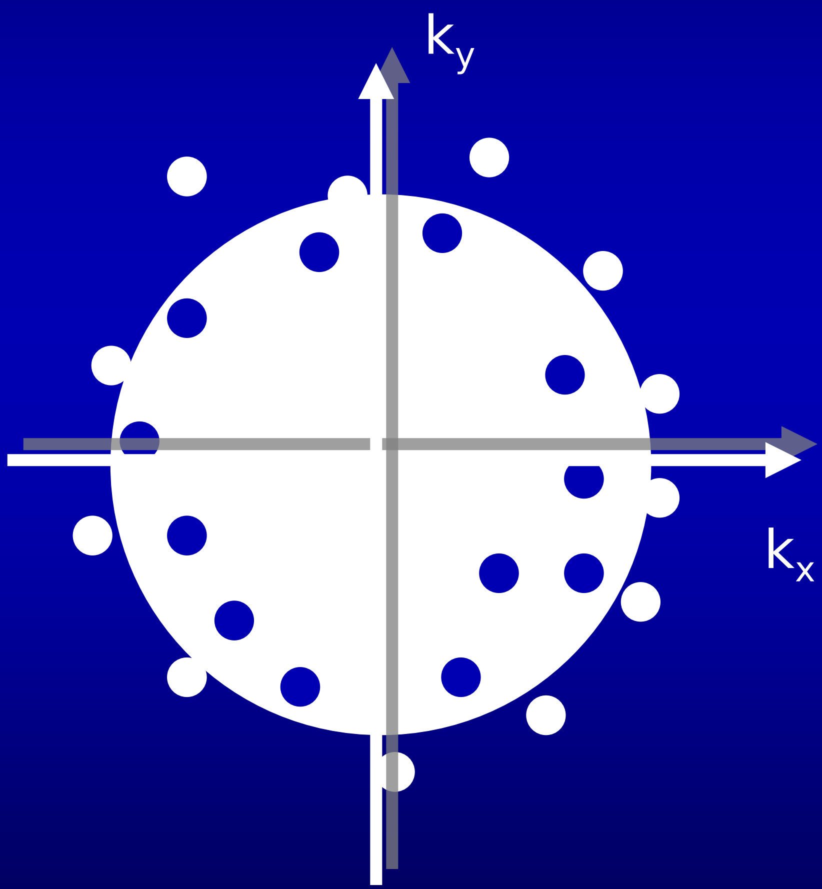
- Evaporative cooling trajectory:



Cooling does not proceed below $T \sim 0.5 T_F$ Why?

DeMarco and Jin, Science (1999)

Pauli Blocking



- in every collision that fills one hole, the final state of the collision partner must also be unoccupied.
- All the atoms inside the Fermi sphere cannot undergo collisions
- A Fermi gas at low temperature becomes collisionless!

How overcome Pauli-Blocking?

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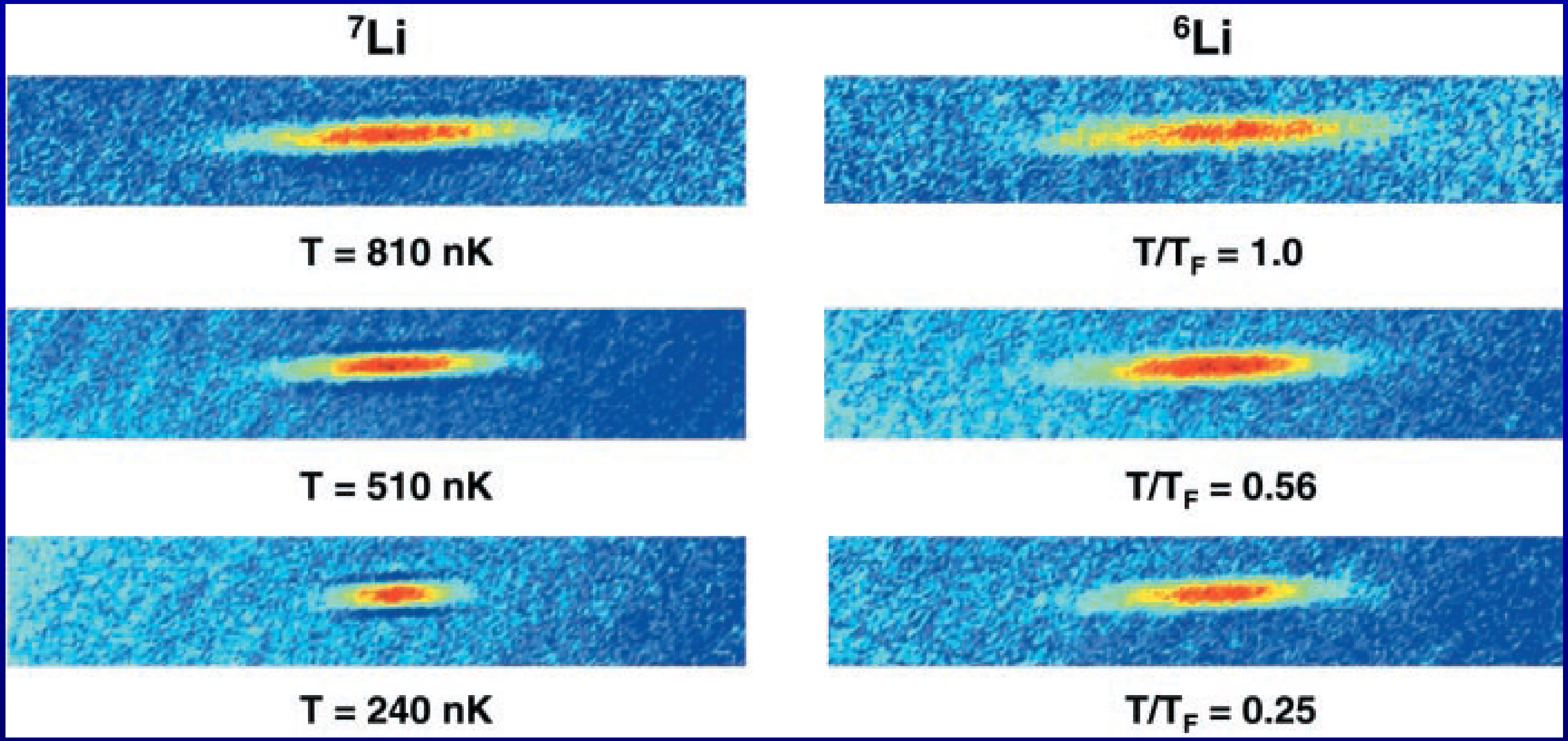
- Using a boson as a coolant can help quite a bit!



Truscott, ..., and Hulet, *Science* (2001)

Issues with a second species

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- Need more lasers for laser cooling, plus more complicated atom source
- Often times advisable: Use a different atom instead of isotope: Such as Na
- can produce large reservoirs! (BEC Ketterle …, NaLi here in HD)

Superfluidity?

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- Pairing of weakly attractive fermions leads to a gap:

$$\Delta_0 = \frac{1}{2}\left(\frac{2}{e}\right)^{7/3} E_F \exp\left(-\frac{\pi}{2k_F|a|}\right).$$

- And a critical temperature:

$$\mathrm{T}_{BCS} = \frac{e^{\gamma}}{\pi}\left(\frac{2}{e}\right)^{7/3} T_F \exp\left(-\frac{\pi}{2k_F|a|}\right) \approx 0.277 T_F \exp\left(-\frac{\pi}{2k_F|a|}\right)$$

- In a typical situation, T_{BCS} is extremely small!

Very low temperatures!

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- Suppose a Fermi gas paired into molecules:

It can be cooled into a BEC,

- Suppose you can convert the BEC of molecules into a Fermi gas of atoms, without changing the entropy, what temperature do you get?

- $2N_{atom}$->N_{mol}

- Ignore interactions

Very low temperatures!

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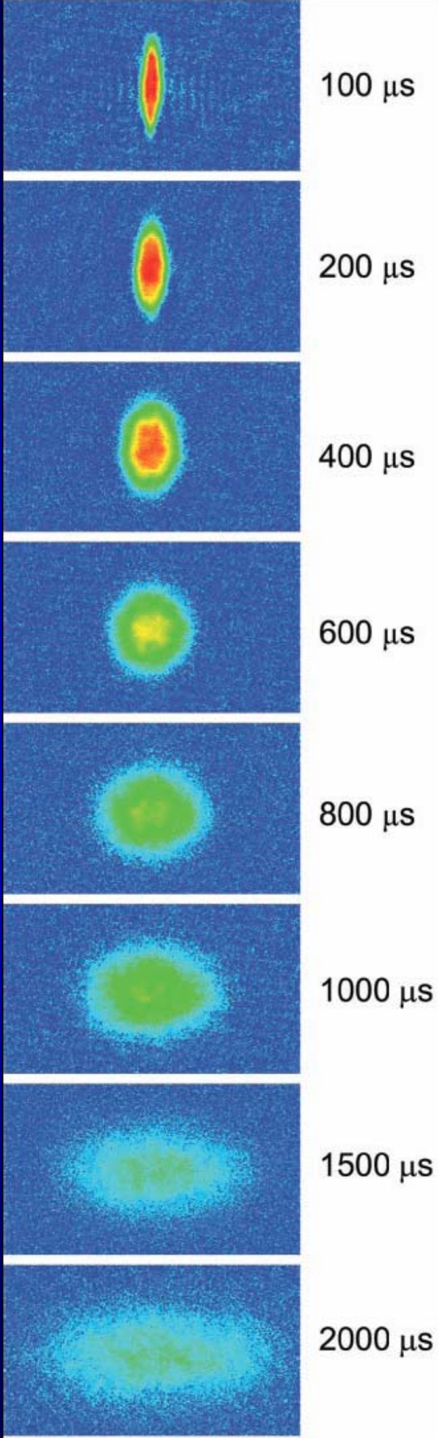
- Entropies for BEC and 2-comp. Fermi gas:

$$\mathrm{S}_{BEC} = k_B N_{mol} \frac{2\pi^4}{45\zeta(3)} \left(\frac{T}{T_{BEC}} \right)^3,$$

$$\mathrm{S}_{Fermi} = k_B N_{atom} \pi^2 \frac{T}{T_F}$$

$$\rightarrow \frac{T}{T_F} = \frac{\pi^2}{45\zeta(3)} \left(\frac{T}{T_{BEC}} \right)$$

For $T/T_{BEC}=1$ -> $T/T_F=0.18$; $T/T_{BEC}=0.25$ -> $T/T_F=3\times10^{-3}$!!!



Strongly interacting Fermi gases

Lets make a very large -> ∞ !

Expansion of a Fermi gas with infinite scattering length

Difficult to interpret: Is the expansion due to the gas being superfluid, or because it is hydrodynamic?

-> It is both!

O'Hara, … and Thomas, *Science* (2002)

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