Novel phases in strongly interacting Fermi gases

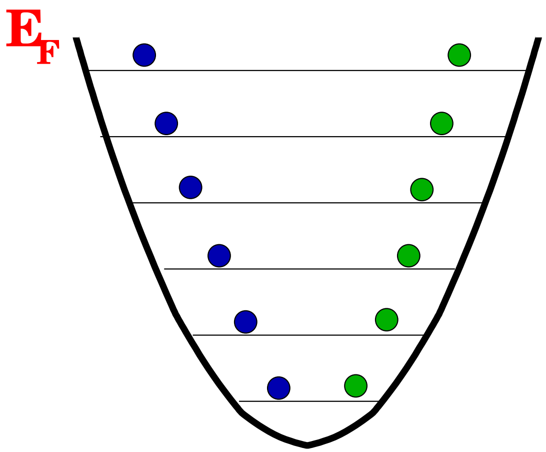
Gora Shlyapnikov
LPTMS, Orsay, France

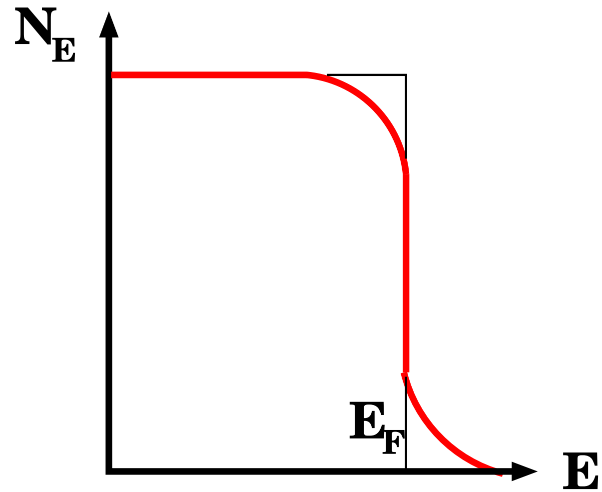
Outline

- Introduction. Molecules in Fermi gases
- Molecules in Ferm mixtures. Trimer states
- Crystalline phase and quantum transitions
- Stability and realization of the crystalline phase
- What is next?

Collaborations: D.S. Petrov, D.J. Papoular, C. Salomon (ENS), G.Astrakharchik (Barcelona)

Two-component trapped Fermi gas





$$E_F = \frac{\hbar^2 k_F^2}{2m}; \quad k_F = (3\pi^2 n)^{1/3}; \quad E_F \sim N^{1/3}\hbar\omega$$

Weakly interacting gas $n|a|^3 \ll 1;\ k_F|a| \ll 1$

$a < 0 \rightarrow$ Interspecies attraction $\rightarrow$ Cooper pairing at low T

Superfluid BCS transition $\rightarrow T_c \sim E_F \exp\{-\pi/2k_F|a|\}$

$T_c \ll 0.1 E_F$ for ordinary a Very hard to reach

Two-component Fermi gases. Experiments ^{40}K ^{6}Li

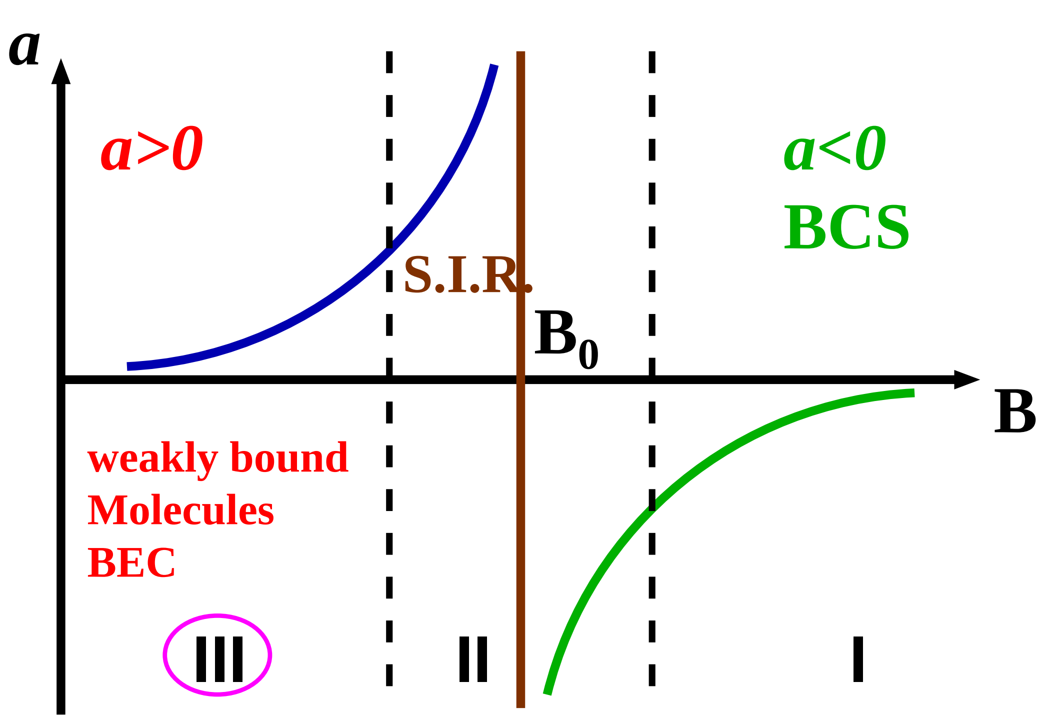
Dilute limit $nR_e^3 \ll 1$ Ultracold limit $\Lambda_T \gg R_e$

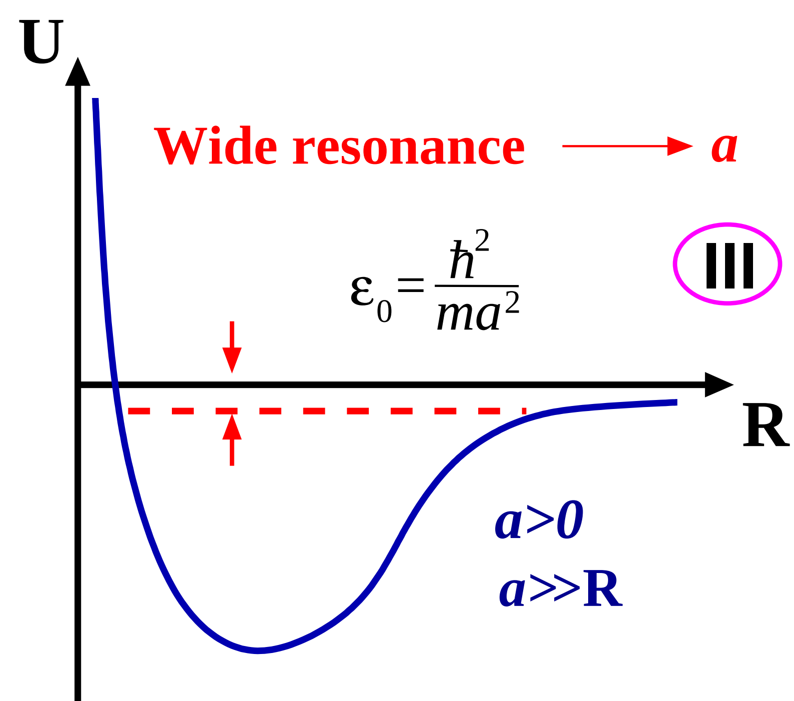
Quantum degeneracy $\rightarrow$ JILA 1998 ^{40}K

At present $n \sim 10^{13} - 10^{14}\mathrm{cm}^{-3}$; $T \sim 1\mu\mathrm{K}$

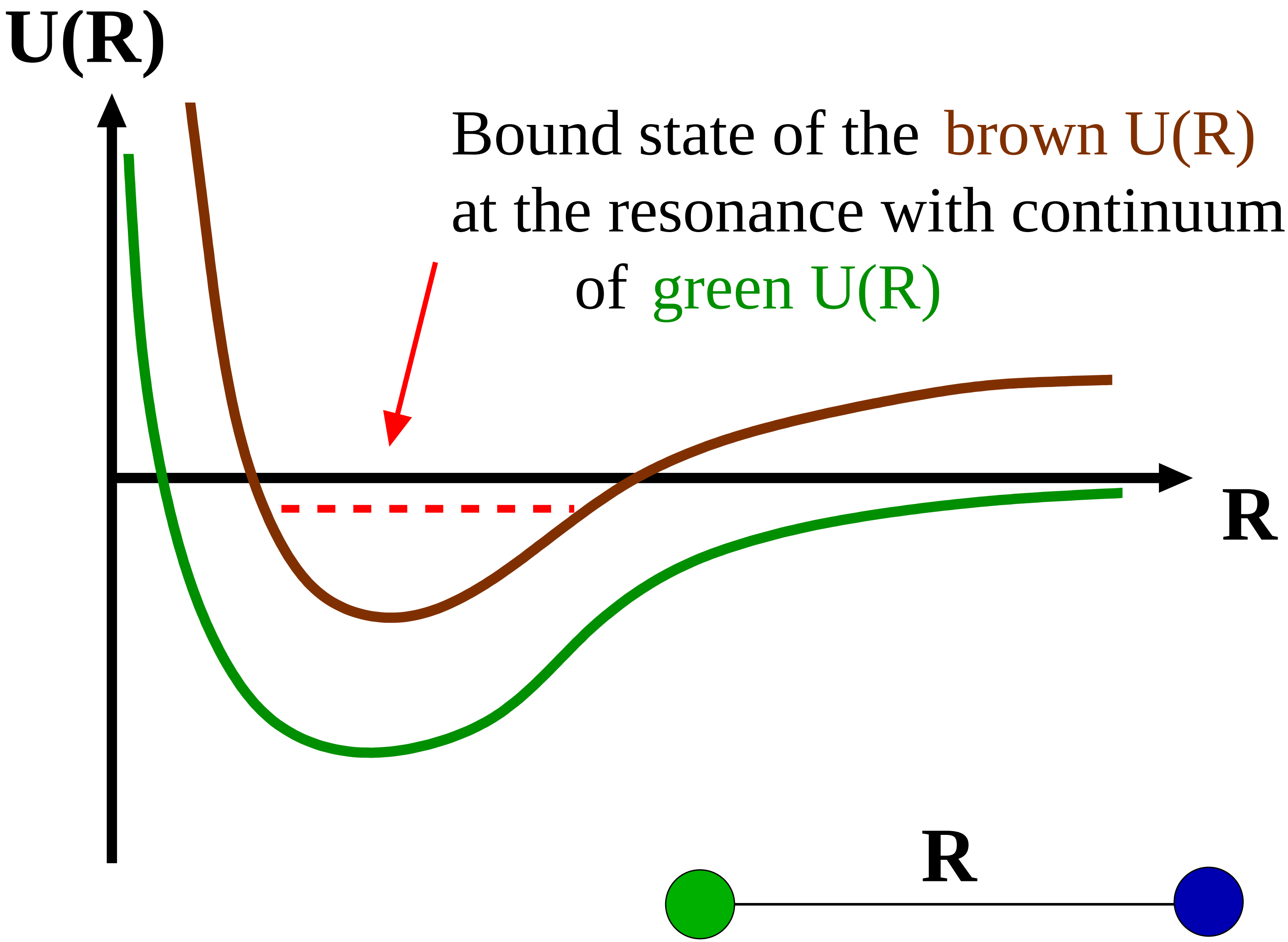
Superfluid behavior through vortex formation $\rightarrow$ MIT

BEC of bosonic molecules $\rightarrow$ JILA, Innsbruck, ENS, MIT, Rice





Feshbach resonance



Strongly interacting regime

$T = 0 \quad k_F|a| \gg 1 \quad \rightarrow$ Only one distance scale $n^{-1/3}$

Only one energy scale $E_F \sim \hbar^2 n^{2/3}/m$

Universal thermodynamis (J. Ho)

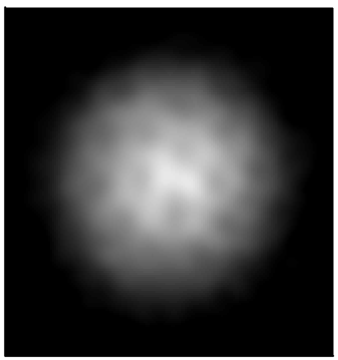
Monte Carlo studies $\rightarrow \mu \approx 0.4 E_F$
(Carlson et al, Giorgini/Astracharchik, etc.)
$T_c = 0.15 E_F$ UMASS-ETH

Theory $\rightarrow$ Nature of superfluid pairing, Transition temperature, Excitations

Experiments (JILA, MIT,Innsbruck, Duke,ENS)
Vortices (MIT)

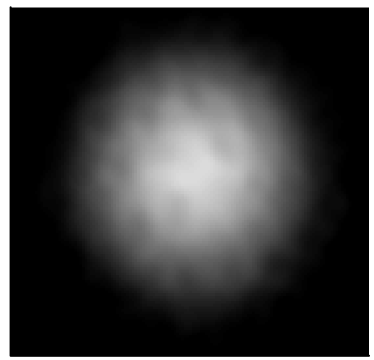
Vortex lattices

MIT, Zwierlein et al., Science 05

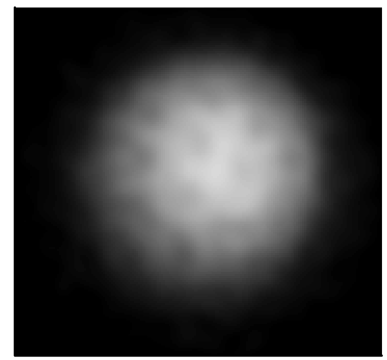


B_f = 835 G
$1 / k_F a = 0$

B_f = 843 G
$1 / k_F a = -0.13$



B_f = 854 G
$1 / k_F a = -0.27$

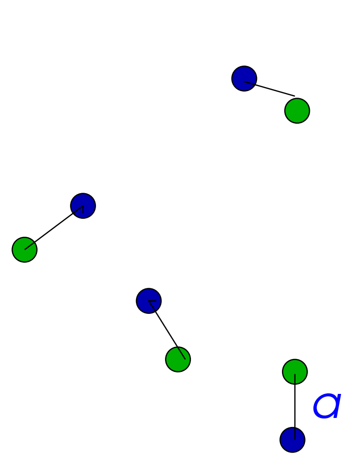


B_f = 864 G
$1 / k_F a = -0.39$

Direct proof of superfluidity !

Gas of bosonic molecules (dimers)

Region III $(a > 0) \Rightarrow$ gas of weakly bound bosonic molecules

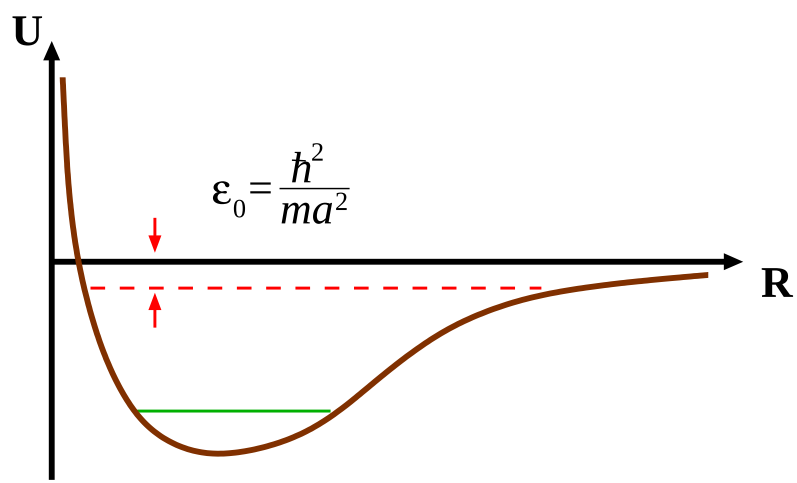


Size of a molecule

a

$na^3 \ll 1 \quad \Rightarrow$ weakly interacting Bose gas

Weakly bound dimers $\rightarrow$ The highest rovibrational state $\Rightarrow$ Collisional relaxation

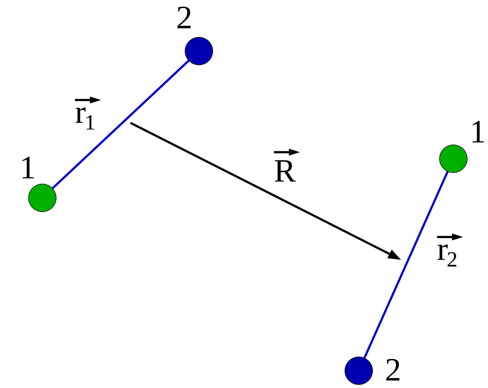


($\tau \sim 1$ms for Rb_2 at $n \sim 10^{13}$cm^{-3})

Weakly interacting gas of bosonic dimers

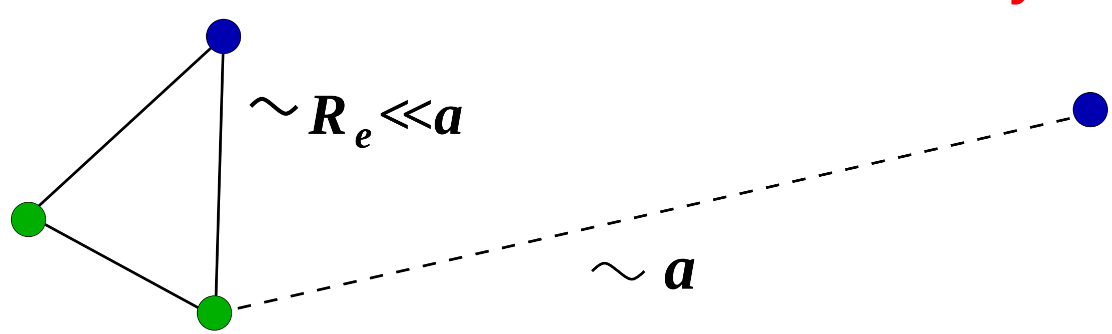
Elastic interaction   BEC stability

4-body problem   Exact solution for $a \gg R_e$ (Petrov et al 2003)



$$a_{dd} = 0.6a$$

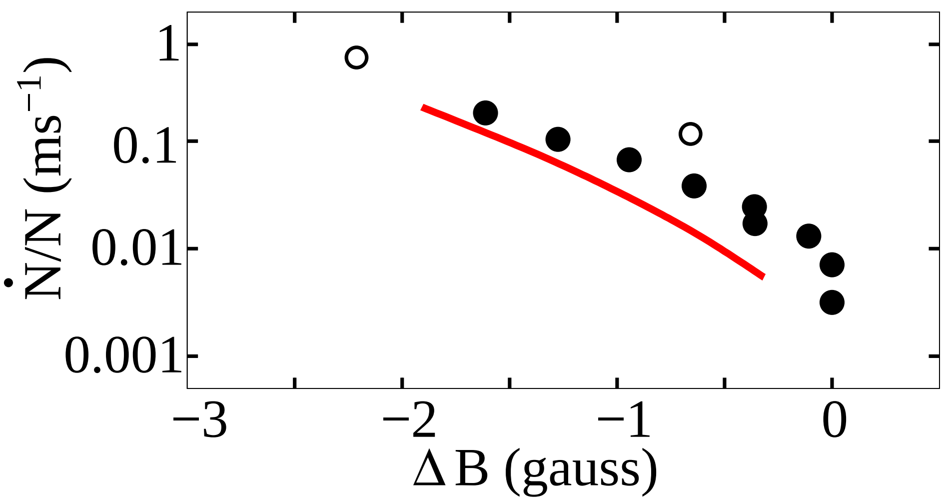
Remarkable collisional satability

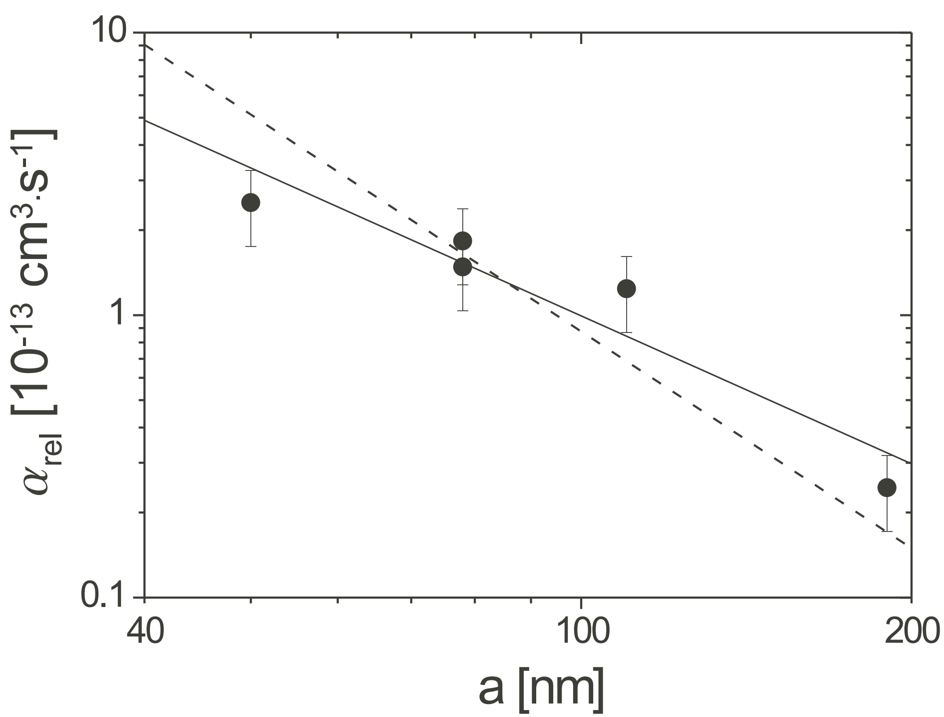


$$\alpha_{rel} \sim (k_{eff} R_e)^{2?} \sim (R_e/a)^{2?} \Rightarrow C(\hbar R_e/m)(R_e/a)^s; \quad s = 2.55$$

$\tau \sim (\alpha_{rel} n)^{-1} \sim$ seconds   (Petrov et al 2003)

Suppressed collisional relaxation





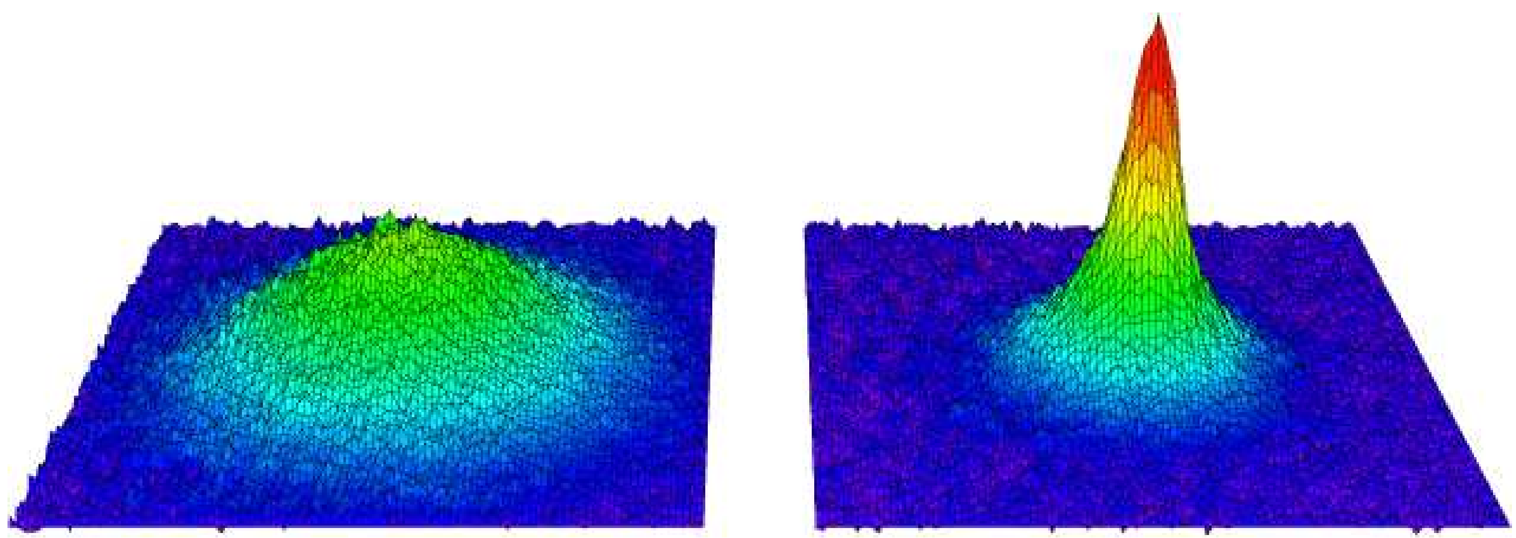
Bose-Einstein condensates of molecules

Suppressed relaxation **Fast elastic collisions** $a_{dd} = 0.6a$

$$^6\mathrm{Li}_2 \rightarrow \frac{\alpha_{rel}}{\alpha_{el}} \leq 10^{-4}$$

Efficient evaporative cooling $\rightarrow$ BEC

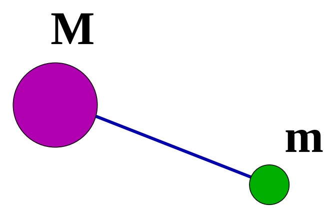
JILA, Innsbruck, MIT, ENS, Rice



Molecules in Fermi mixtures

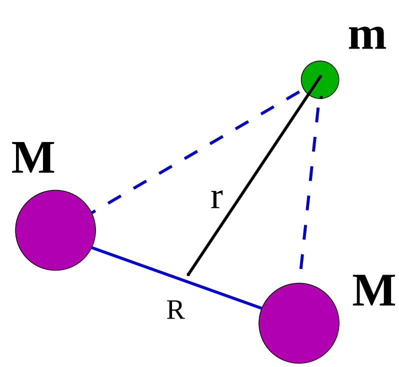
Heavy and light fermions $^6\mathrm{Li}^{40}\mathrm{K}$ $^6\mathrm{Li}^{87}\mathrm{Sr}$

$a > 0 \Rightarrow$ weakly bound molecules



Relaxation into deep bound states. What else ? $\longrightarrow$ Trimer states ?

$M \gg m \quad \rightarrow$ Born-Oppenheimer picture



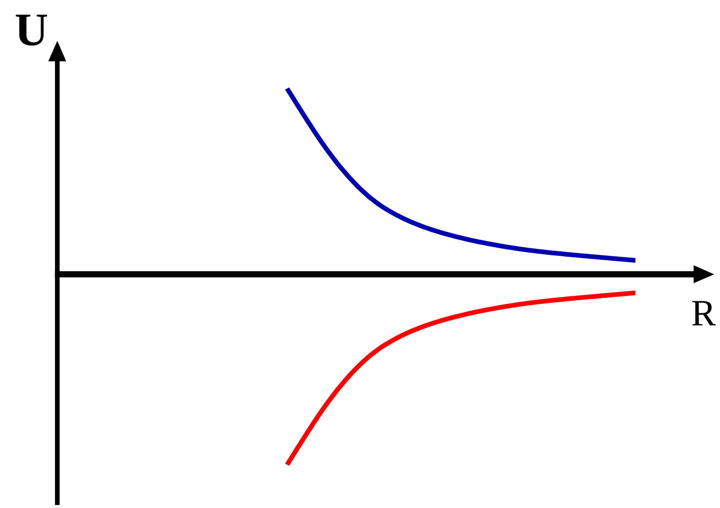
$r \ll a \rightarrow$ One bound state of a light atom with two fixed heavy ones

Mediated attractive potential $U(R) \approx -0.16\hbar^2/mR^2$

Trimer states

Pauli principle $\Rightarrow$ Centrifugal potential $U_c = 2\hbar^2/MR^2$

Mediated attraction competes
with Pauli principle



$$U_{eff}(R) = U(R) + U_c(R)$$
$$= -0.16\hbar^2/mR^2 + 2\hbar^2/MR^2$$

$M/m > 13.6 \quad \rightarrow$ fall into center short-range physics

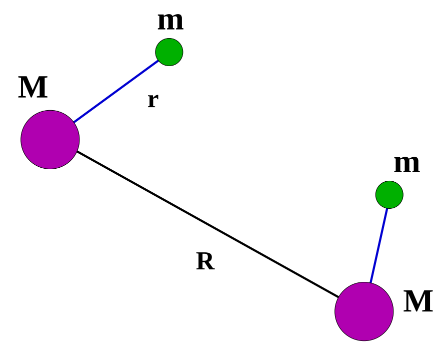
Many nodes of the wavefunction

Many (trimer) bound states

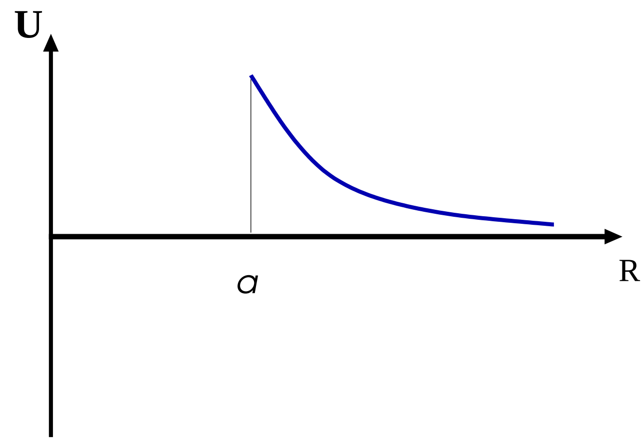
Long-range intermolecular repulsion

Molecules of heavy and light fermions Born-Oppenheimer picture

$R \gg a$



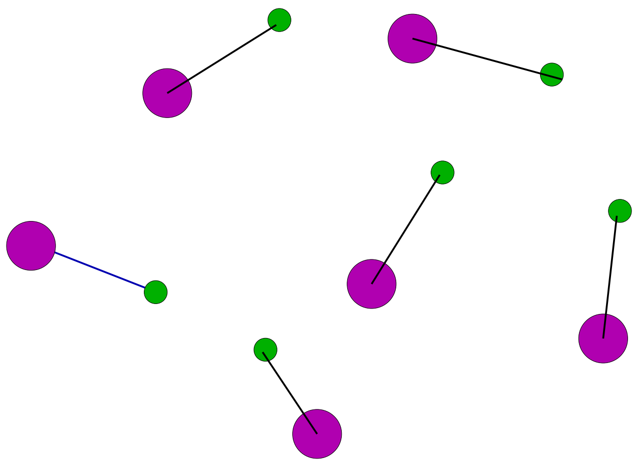
$$U(R) = 2\left(\frac{\hbar^2}{maR}\right)\exp(-2R/a)$$



$$P \sim \exp\left(-0.9\sqrt{\frac{M}{m}}\right)$$

$M >>> m \rightarrow$ Collisional stability independent of a

Many-body system of molecules



No interaction between light fermions

Born-Oppenheimer approach N lowest single-particle states for a light atom

Zero-range approximation for light-heavy interaction. Large inter-heavy distances $\Rightarrow$

Narrow band of N light-atom states, by $\sim \epsilon_0$ below the continuum

Total energy $E = -N\epsilon_0 + (1/2)\sum_{i,j} U(R_{ij})$

$\epsilon_0 = \hbar^2\kappa_0^2/2m \Rightarrow$ molecular binding energy, $\kappa_0^{-1} \rightarrow$ molecular size

$$U_{3D}(R) = 4\epsilon_0[1 - 2(\kappa_0 R)^{-1})]\exp(-2\kappa_0 R); \quad (1/\kappa_0 R)\exp(-\kappa_0 R) \ll 1$$

$$U_{2D}(R) = 4\epsilon_0[\kappa_0 R K_0(\kappa_0 R)K_1(\kappa_0 R) - K_0^2(\kappa_0 R)]; \quad K_0(\kappa_0 R) \ll 1$$

$R \approx 2/\kappa_0$ or larger

Phase diagram

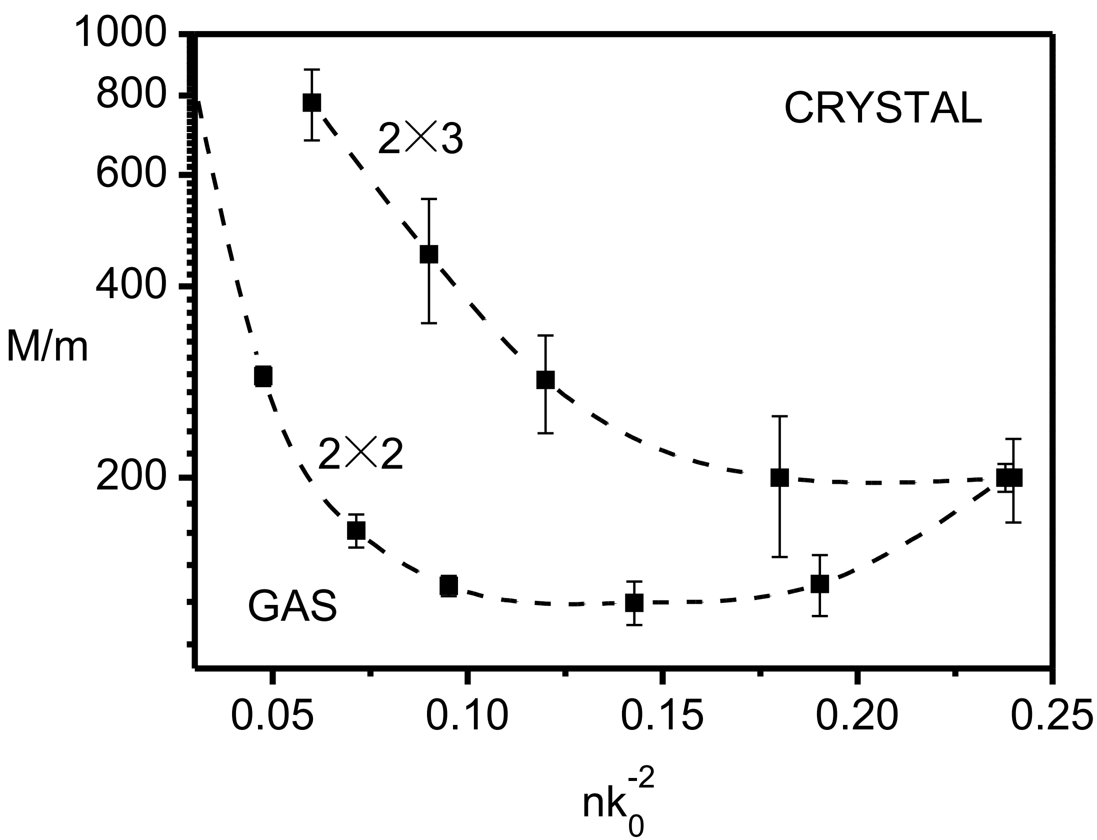
2D motion of heavy atoms

$$H = -(\hbar^2/2M)\sum_i \Delta_{R_i} + (1/2)\sum_{i,j} U(R_{i,j})$$

$(M/m) > (M/m)_c \rightarrow$ crystalline phase

2D motion of light atoms $\Rightarrow$ $(M/m)_c = 120$ triangular lattice

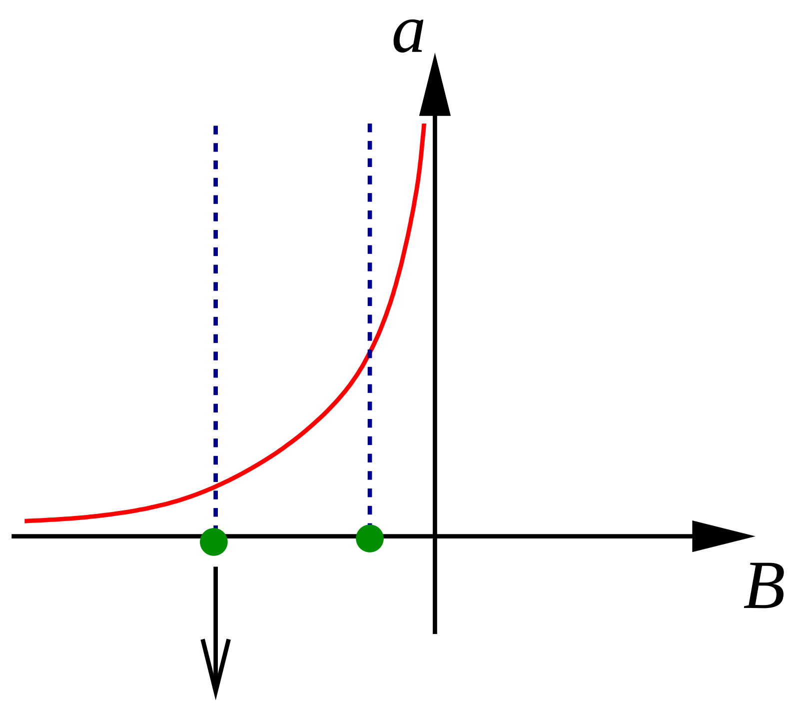
3D motion of light atoms $\Rightarrow$ $(M/m)_c = 200$ triangular lattice



Quantum transitions

$$\frac{M}{m} > \left(\frac{M}{m}\right)_c \quad \text{and } n \text{ fixed}$$

Increase a



depends on $\frac{M}{m}$ but always $na^3 \ll 1$

first-order transition

Realization of the crystalline phase

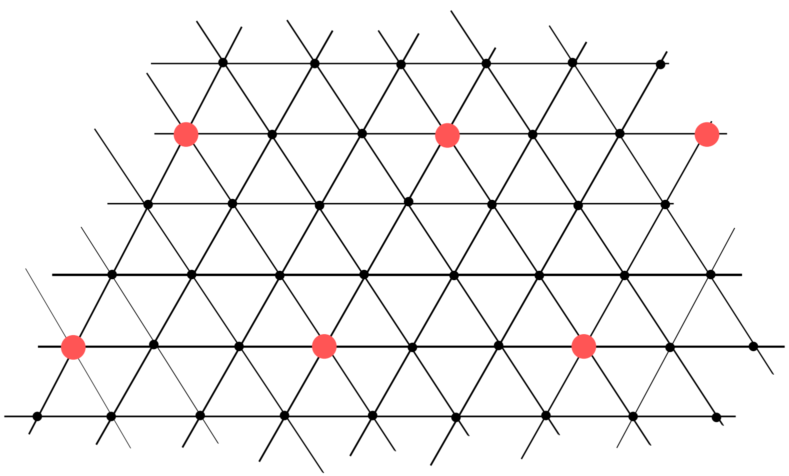
$$\frac{M}{m} \approx 200 \quad \text{or} \quad \frac{M}{m} \approx 200 \quad \rightarrow \text{no gas phase possible}$$

How to obtain the crystalline phase?

Optical lattice for heavy fermions

Small filling factor $\Rightarrow$ Increase of M/m

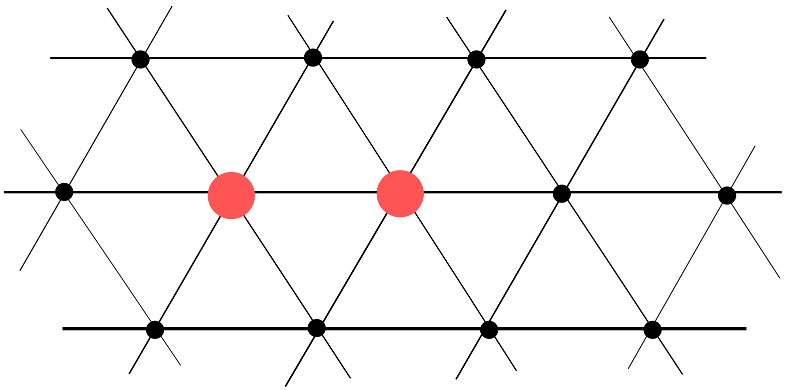
Increase of M by a factor of 20 or more is possible



Formation of a superlattice

Stability of the crystalline phase

Relaxation into deep bound states



heavy atoms $\Rightarrow$ neighboring sites $\Rightarrow$

jump to one and the same site $\Rightarrow$ undergo relaxation process

τ exceeds 10s even for $n \sim 10^9$cm^{-2}

Formation of trimer states (2 heavy and 1 light atom)

Heavy atoms are localized in different lattice sites

4-body problem in a lattice $\Rightarrow$ τ can be $\lesssim 1$ s for $n \sim 10^9$ cm^{-2}

The rate can be suppressed by increasing M_*/m

Realistic?

- ^{6}Li-^{40}K mixture with a lattice for K
- Lattice period 250 nm and K effective mass $M_* = 20M$ $\Rightarrow$ tunneling rate $\sim 10^3$ s
- $a = 500$ nm $\Rightarrow \epsilon_0 = 300$ nK $\Rightarrow T \ll \epsilon_0$
- 2D densities in the range $10^7 - 10^8$ cm^{-2}

Conclusions

- Remarkable physics of weakly bound molecules in cold Fermi gases
- Novel physics of molecular collisional stability in mixtures of Fermi gases
- Possibilities to create new macroscopic quantum systems