Dipolar Fermi gases

Gora Shlyapnikov
LPTMS, Orsay, France
University of Amsterdam

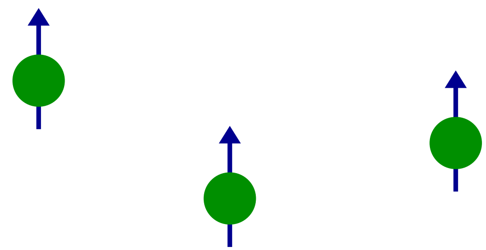
Outline

- Introduction,
- Experiments with magnetic atoms and polar molecules
- Topologcal $p_x + ip_y$ phase in 2D
- Bilayer systems of dipolar fermions. BCS-BEC crossover
- Concluding slide

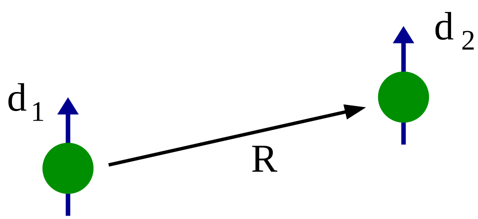
Reisenburg, July 29, 2016

Dipolar gas

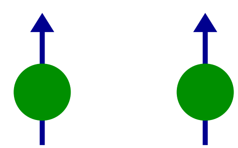
Polar molecules or atoms with a large magnetic moment



Dipole-dipole interaction $V_d = \frac{\vec{d}_1\vec{d}_2R^2 - 3(\vec{d}_1\vec{R})(\vec{d}_2\vec{R})}{R^5} \sim \frac{1}{R^3}$



long-range, anisotropic



repulsion

attraction

Different physics compared to ordinary atomic ultracold gases

Alkali-atom molecules d from $0.6\,D$ for KRb to $5.5\,D$ for LiCs

Atoms with large μ

Remarkable experiments with Cr atoms ($\mu = 6\mu_B \Rightarrow d \approx 0.05$ D)

T. Pfau group (Stuttgart)

Effects of the dipole-dipole interaction in the dynamics

Stability diagram of trapped dipolar BEC

Spinor physics in chromium experiments at Villetaneuse, B. Laburthe-Tolra

Bubble structure of bosonic Dy in Stuttgart

Now dysprosium ($\mu = 10\mu_B$, (B. Lev))

and erbium ($\mu = 7\mu_B$, (F. Ferlaino)) are in the game

Fermionic atoms with large μ

Fermionic Er (Innsbruck) $\Rightarrow$ quantum degeneracy, deformation of the Fermi surface

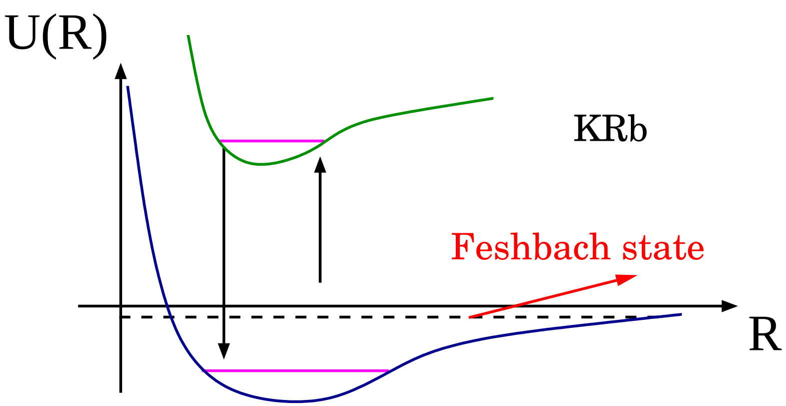
Fermionic Dy (Stanford) and Cr (Villetaneuse) $\Rightarrow$ quantum degeneracy

Polar molecules. Creation of ultracold clouds

Photoassociation

Transfer of weakly bound KRb fermionic molecules to the ground rovibrational state

JILA, D. Jin, J. Ye groups



$$n \sim 10^{12} - 10^{13}\ \text{cm}^{-3}$$
$$T \approx 200nK \ \sim E_F$$

Ground-state LiCs molecules at Heidelberg

Ground-state RbCs molecules in Innsbruck

Ground-state KRb bosonic molecules in Tokyo

Experiments with NaK (MIT, Munich),KCs (Innsbruck), NaRb (HongKong), LiRb (Vancouver)

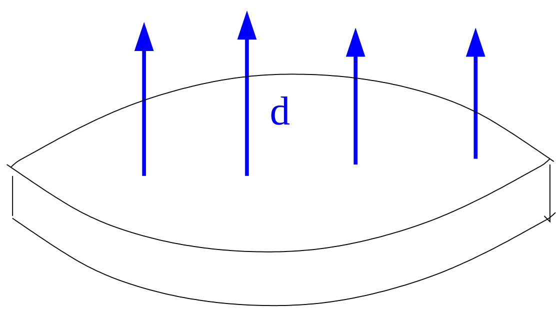
Ultracold chemistry

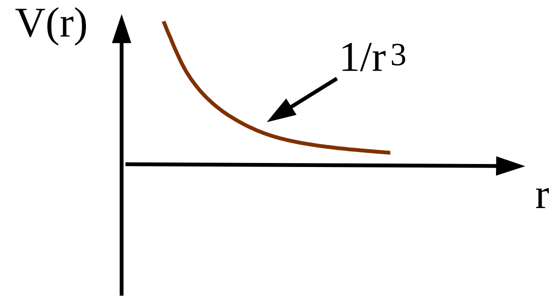
Ultracold chemical reactions $\mathrm{KRb} + \mathrm{KRb} \Rightarrow \mathrm{K_2} + \mathrm{Rb_2}$

New trends in ultracold chemistry

Suppress instability $\rightarrow$ induce intermolecular repulsion

For example, 2D geometry with dipoles perpendicular to the plane





Reduction of the decay rate by 2 orders of magnitude at JILA

Select non-reactive molecules, like NaK, KCs, RbCs

Creation of ground-state NaK fermionic molecules (MIT, now also Munich)

What are prospects for novel physics ?

Theoretical studies

Collisional physics

Julienne (Gaithersburg), Krems (Vancouver), Greene (Purdue)

Bohn (Boulder), Dulieu (Orsay), Hutson (Durham)

Many-body physics

Santos (Hannover), Pupillo (Strassbourg), Demler (Harvard)

Zoller/Baranov (Innsbruck), Gorshkov (Maryland)

Lewenstein (Barcelona), Carr (Colorado), G.S.

Many other works

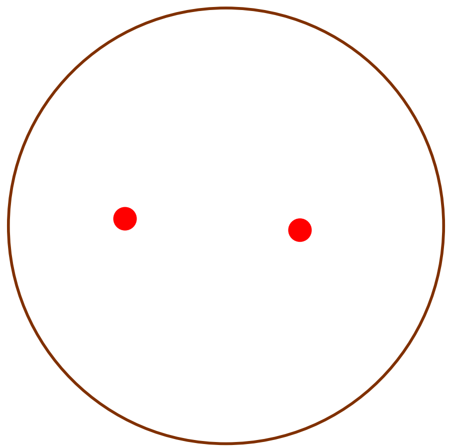
Are there novel many-body states?

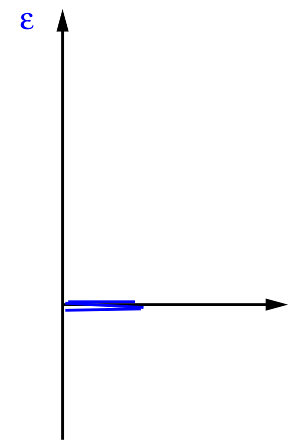
Does the dipole-dipole interaction lead to the emergence of novel phases for identical fermions?

Why single-component fermions are interesting?

Topological aspects of $p_x + ip_y$ state in 2D

Vortices. Zero-energy mode related to two vortices. (Read/Green, 2000)





The number of zero-energy states exponentially grows with the number of vortices $2^{(N_v/2-1)}$

Non-abelian statistics $\Rightarrow$ Exchanging vortices creates a different state!

Non-local character of the state. Local perturbation does not cause decoherence

Topologically protected state for quantum information processing

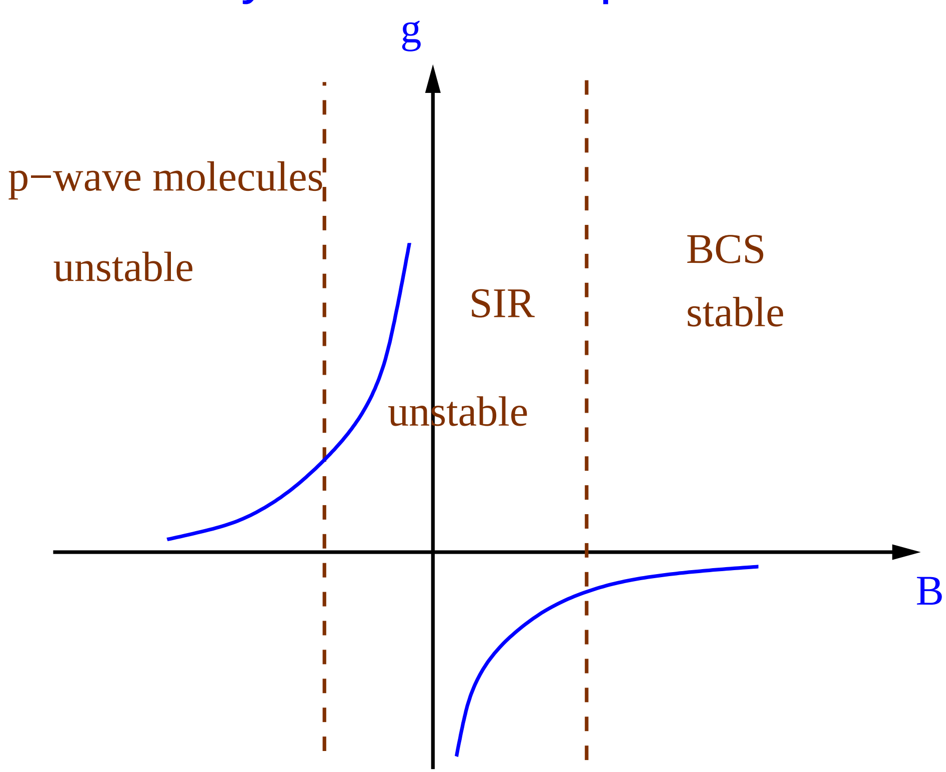
p-wave resonance for fermionic atoms

p-wave resonance Experiments at JILA, ENS, Melbourne, Tokyo, elsewhere

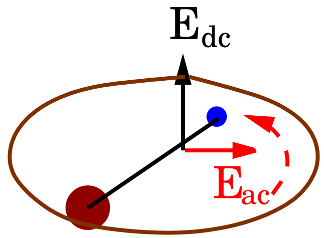
BCS $\Rightarrow$ $T_c \sim \exp\left(-\frac{1}{(k_F b)^2}\right)$ practically zero

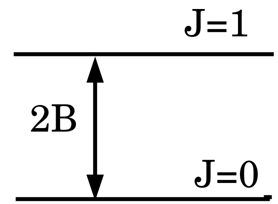
Molecular and strongly interacting regimes $\Rightarrow$ rather high T_c, but collisional instability

Gurarie/Radzihovsky; Gurarie/Cooper; Castin/Jona-Lazinio



RF-dressed polar molecules in 2D (Gorshkov et al, 2007)





σ^+ polarized RF E_{ac}

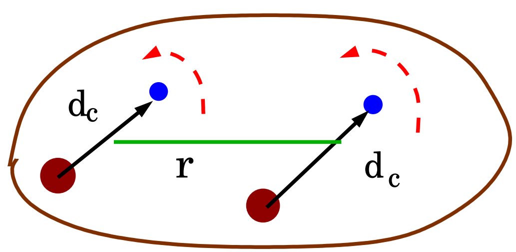
$+$ constant $E_{dc} \longrightarrow 0$

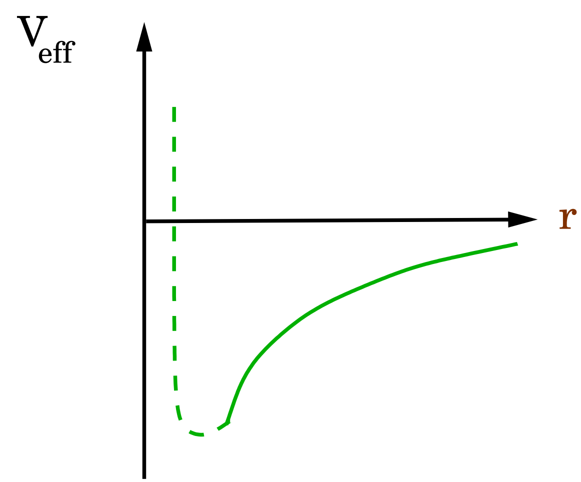
Dressed states $\quad |+\rangle = \alpha|0,0\rangle + \beta|1,1\rangle; \quad ,|-\rangle = \beta|0,0\rangle - \alpha|1,1\rangle$

$$\alpha = -\frac{A}{\sqrt{A^2+\Omega^2}}; \quad \beta = \frac{\Omega}{\sqrt{A^2+\Omega^2}}; \quad A = \frac{1}{2}(\delta + \sqrt{\delta^2 + 4\Omega^2})$$

Two RFD molecules in 2D. The dipole moment is rotating with RF frequency

$d_c = 2^{1/2} \alpha \beta d$





Large $r \rightarrow \quad V_{eff} = \langle (1 - 3\cos^2\phi) \rangle \frac{d_c^2}{r^3} = -\frac{d_c^2}{2r^3}; \quad r_* = m d_c^2 / 2\hbar^2$

Fermionic RFD molecules. Superfluid transition

Fermionic RFD molecules in a single quantum state in 2D

J. Levinsen, N.R. Cooper, G.S. (2009-2011)

Attractive interaction for the p-wave scattering ($l = \pm 1$)

$$\hat{H} = \int d^2r\, \hat{\Psi}^{\dagger}(\mathbf{r})\{-(\hbar^2/2m)\Delta + \int d^2r' \hat{\Psi}^{\dagger}(\mathbf{r}')V_{eff}(\mathbf{r}-\mathbf{r}')\hat{\Psi}(\mathbf{r}') - \mu\}\hat{\Psi}(\mathbf{r})$$

$$\Delta(\mathbf{r}-\mathbf{r}') = \langle V_{eff}(\mathbf{r}-\mathbf{r}')\hat{\Psi}(\mathbf{r})\hat{\Psi}(\mathbf{r}')\rangle$$

Gap equation $\Delta(\mathbf{k}) = -\int \frac{d^2k}{(2\pi)^2} V_{eff}(\mathbf{k}-\mathbf{k}')\Delta(\mathbf{k}')\frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')}$

$$\epsilon(k) = \sqrt{(\hbar^2k^2/2m-\mu)^2 + |\Delta(k)|^2}; \quad \mu \approx E_F$$

$$T_c \approx E_F \exp(-3\pi/4k_F r_*)$$

$\Delta(\mathbf{k}) = \Delta \exp(i\phi_k) \quad p_x + ip_y$ state ($l = \pm 1$)

Superfluid transition. Role of anomalous scattering

For short-range potentials should be $V_{eff} \propto k^2$ and $T_c \propto \exp(-1/(k_F b)^2)$
This is the case for the atoms

Anomalous scattering in $1/r^3$ potential $\rightarrow$ Contribution from $r \sim 1/k$

$$V_{eff}(k) = -\frac{8\hbar^2}{3m}(kr_*); \qquad |k| = |k'|$$

$$T_c \propto \exp\left(-\frac{1}{\nu(k_F)|V_{eff}(k_F)|}\right); \qquad \nu = \frac{m}{2\pi\hbar^2}$$

$$T_C \propto \exp\left(-\frac{3\pi}{4k_F r_*}\right)$$

Transition temperature

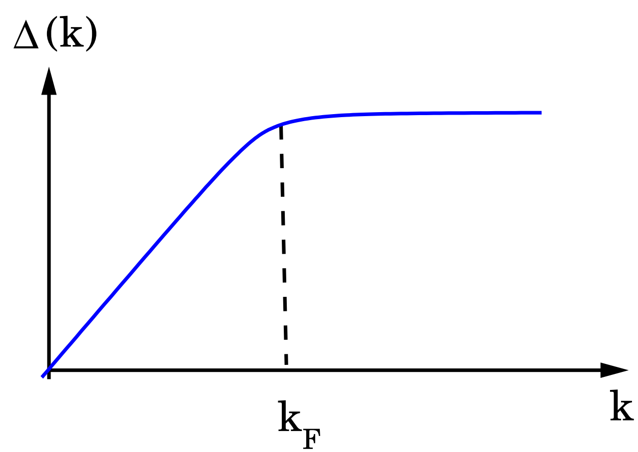
Do better than simple BCS. Reveal the role of short-range physics

Renormalized gap equation

$$\Delta(\mathbf{k}') = -\int f(\mathbf{k}',\mathbf{k})\Delta(\mathbf{k})\left\{\frac{\tanh[\epsilon(k)/2T]}{2\epsilon(k)} - \frac{1}{(E_k - E_{k'} - i0)}\right\}\frac{d^2k}{(2\pi)^2}$$

$\Delta(\mathbf{k}) = \Delta(k)\exp(i\phi_k)$; $f(\mathbf{k}',\mathbf{k}) = f(k',k)\exp[i(\phi_k - \phi_{k'})]$ scattering amplitude

$$\Delta(k) = \Delta(k_F)f(k,k_F)/f(k_F,k_F)$$



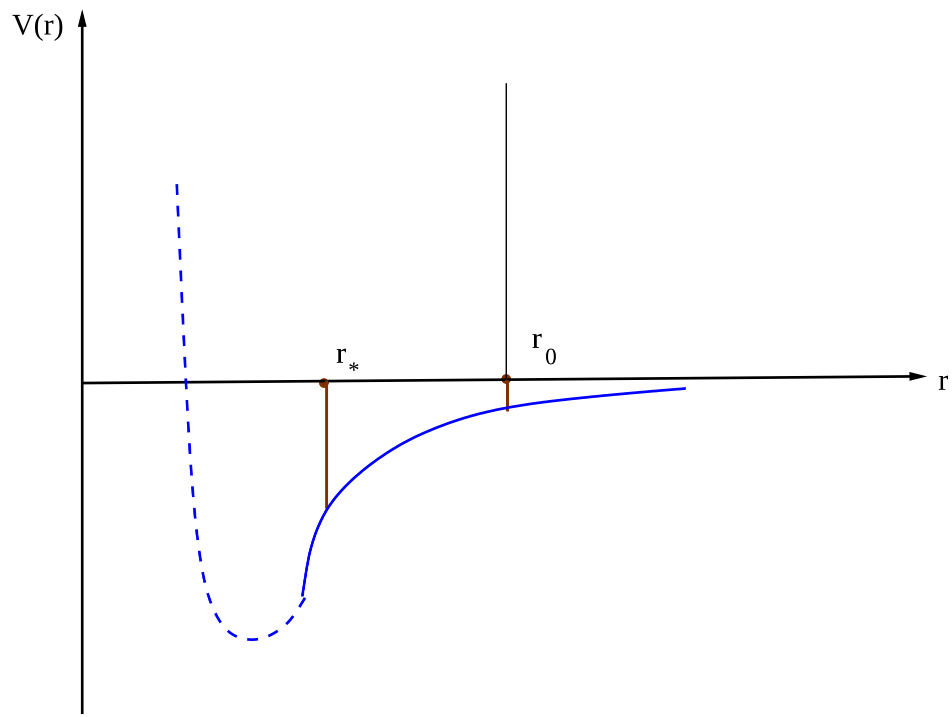
2D scattering in the potential with a $1/r^3$ tail

Scattering amplitude. No transparent exact solution for a finite k

Asymptotic method for slow scattering ($kr_* \ll 1$)

Divide the range of distances into two parts, $r < r_0$ and $r > r_0$

The distance r_0 is such that $r_0 \gg r_*$, but $kr_0 \ll 1$



$r < r_0$ Match exact zero-energy with free finite-k solution at $r = r_0$: $f \Rightarrow (\pi/2)d^2 r_* k^2 \ln k$

$r > r_0$ interaction as perturbation: $f = -(8\pi/3)d^2 k + (\pi/2)d^2 r_* k^2 \ln k$

Related results for the off-shell scattering amplitude

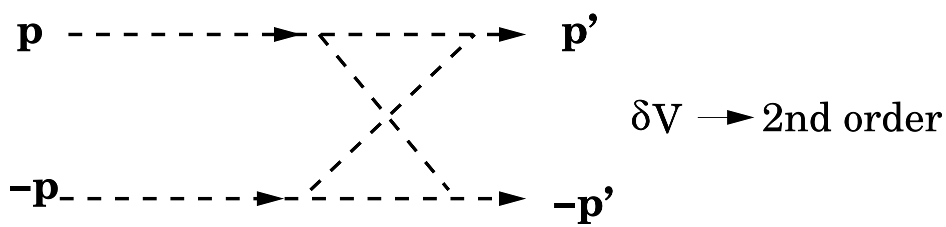
Manipulate T_c?

$$f(k',k) = -\pi d^2 k F\left(\frac{1}{2}, -\frac{1}{2}, 2, \frac{k^2}{k'^2}\right); \;\; k \le k'; \;\; kr_* \ll 1$$

Include k^2-term $f = \dfrac{1}{2}\pi d^2 r_* k^2 \ln[kr_* u]$

$$T_c = \frac{2e^C}{\pi} E_F \exp\left\{-\frac{3\pi}{4k_F r_*} - \frac{9\pi^2}{64}\ln[k_F r_* u]\right\}$$

Take into account second-order Gor'kov-Melik-Barkhudarov processes



$$\Delta(\mathbf{k}) = -\int \frac{d^2k'}{(2\pi)^2} f(\mathbf{k},\mathbf{k}')\left\{\frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')} - \frac{1}{2(E_{k'} - E_k)}\right\}\Delta(\mathbf{k}')$$
$$-\int \frac{d^2k'}{(2\pi)^2} \delta V(\mathbf{k},\mathbf{k}') \frac{\tanh(\epsilon(k')/T)}{2\epsilon(k')}\Delta(\mathbf{k}')$$

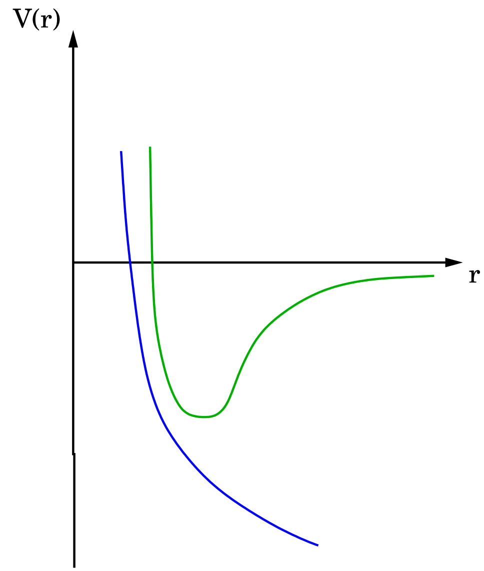
$$T_c = \kappa E_F^{0.3} E_*^{0.7} \exp\left\{-\frac{3\pi}{4k_F r_*}\right\}; \quad E_* = \frac{\hbar^2}{2mr_*^2} \gg E_F$$

κ depends on short-range physics and can be varied within 2 orders of magnitude

Collisional stability and T_c

p-wave atomic superfluids: $\mathrm{BCS} \Rightarrow T_c \to 0$ Resonance $\Rightarrow$ collisional instability

Polar molecules $\Rightarrow$ sufficiently large T_c and collisional stability

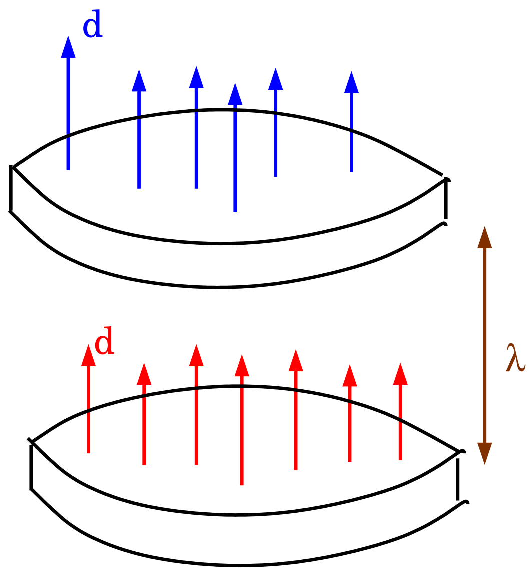


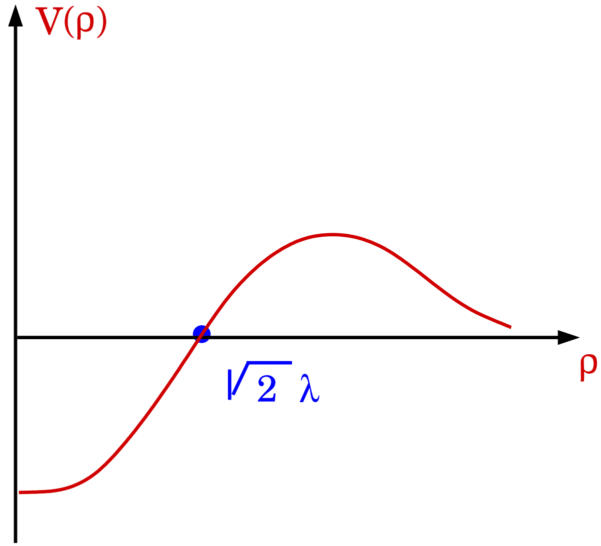
$\alpha_{in} = A\frac{\hbar}{m}(kr_*)^2;\quad A \Rightarrow\ 10^{-3} - 10^{-4}\quad \alpha_{in} \to\ (10^{-8} - 10^{-9})$ cm^2/s

NaK molecules $\to$ $d \simeq 2.7$ D $\quad r_* \approx 3200a_0$

$n = 2 \times 10^8$ cm^{-2} $\Rightarrow$ $E_F = 2\pi\hbar^2 n/m \approx 100$ nK $\quad T_c \approx 10$ nK; $\quad \tau \sim 2$s

Bilayered dipolar fermionic systems





$$V(\rho) = d^2 \left\{ \frac{1}{(\rho^2+\lambda^2)^{3/2}} - \frac{3\lambda^2}{(\rho^2+\lambda^2)^{5/2}} \right\}$$

Dipole-dipole length $r_* = md^2/\hbar^2$ Dipole-dipole strength $\beta = r_*/\lambda$.

$$V_{min} = -\frac{2d^2}{\lambda^3}; \quad \int_0^\infty V(r) r dr = 0$$

Always a bound state of $\uparrow$ and $\uparrow$ dipoles $\rightarrow$ B. Simon, 1974

$$\beta \lesssim 1 \Rightarrow \quad \epsilon_b \simeq \frac{\hbar^2}{m\lambda^2} \exp[-8/\beta^2 + 8/\beta - (5 + 2C - 2\ln 2)]$$

BCS-BEC crossover

$\epsilon_b \ll E_F (r_b \gg n^{-1/2}) \Rightarrow f < 0 \rightarrow$ s-wave BCS pairing

$\epsilon_b \gg E_F \Rightarrow$ Molecules of $\uparrow$ and $\uparrow$ dipoles (interlayer dimers). Molecular BEC

New BCS-BEC crossover (Pikovski, Klawunn, Santos, GS), 2010

Baranov et al, 2011, Zinner et al, 2011

Transition temperature

Kosterlitz-Thouless transition $\epsilon_b \ll E_F \to T_{KT}$ is close to T_{BCS}

$k_F r_* \ll r_*^2/\lambda^2 \to$ Short-range contribution $f = -4\pi\hbar^2/m \ln(E_F/\epsilon_b)$

$$T_{KT} \simeq \frac{e^\gamma}{\pi}\sqrt{2E_F\epsilon_b}$$

$k_F r_* \gg r_*^2/\lambda^2 (\lambda \gg r_*) \to$ Anomalous scattering wins

$$f(k) = \frac{\hbar^2}{m}\left\{-8kr_* - \frac{\pi r_*^2}{2\lambda^2} + 4\pi k^2 r_*\lambda + 3\pi(kr_*)^2 \ln \xi k\lambda\right\}; \quad k\lambda \ll 1 \;\; \xi \approx 6$$

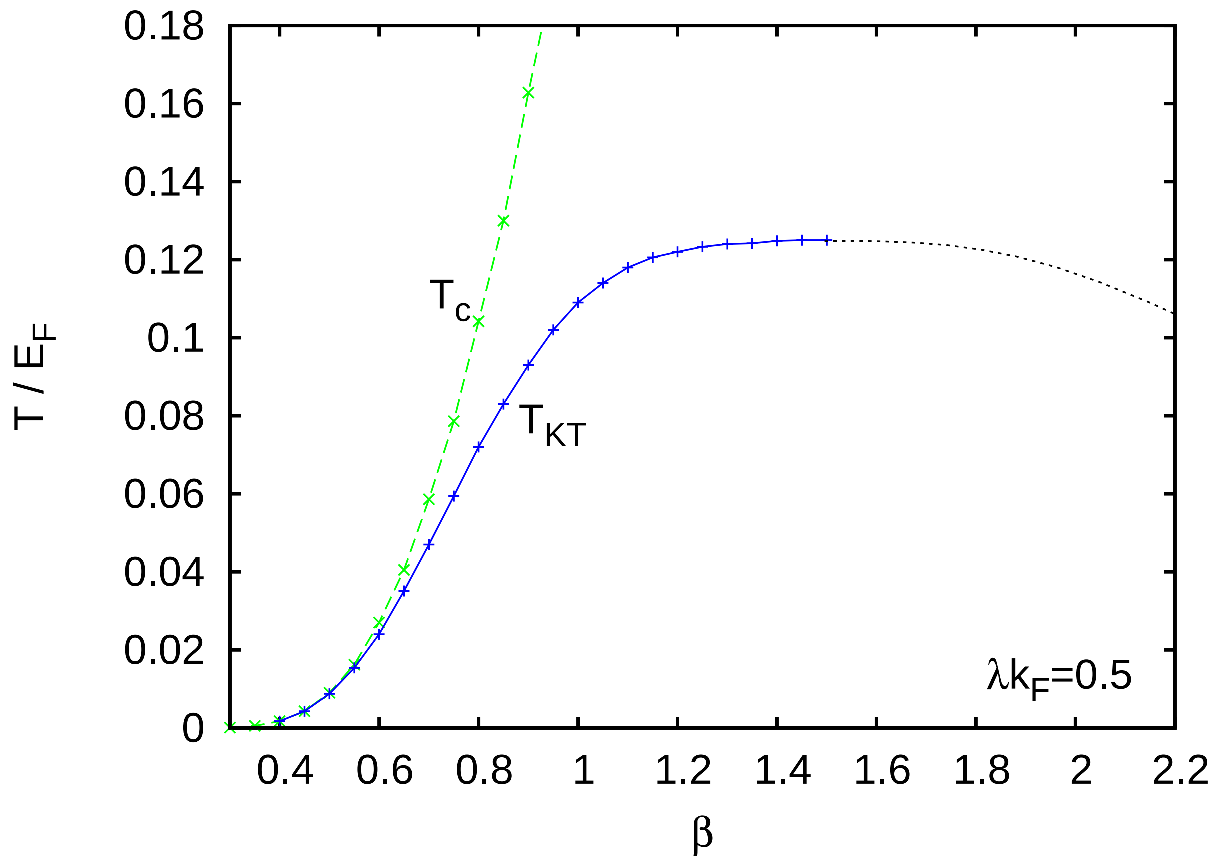
$$T_{KT} \simeq 0.1\left(\frac{E_0}{E_F}\right)^{0.46} \exp\left\{-\frac{\pi}{4k_F r_*}G(k_F\lambda, r_*/\lambda)\right\}$$

$$E_0 = \hbar^2/m\lambda^2; \;\; G(x,y) = (1 - \pi x/2 + \pi y/16x)^{-1}$$

$E_F \ll \epsilon_b \to$ Formation of bound pairs by fermions of different layers

T_{KT} of a weakly interacting Bose gas

Transition temperature



NaK molecules $\lambda \simeq 250$ nm, $n \simeq 5 \times 10^8$ cm^{-2}, $k_F\lambda \simeq 2$, $E_F \simeq 230$ nk

$\Rightarrow T_{KT}$ up to ~ 10 nK

Concluding slide

Many possibilities to generate novel many-body states in dipolar Fermi gases

Thank you for attention