Stability of quantum degenerate fermionic polar molecules with and without microwave shielding

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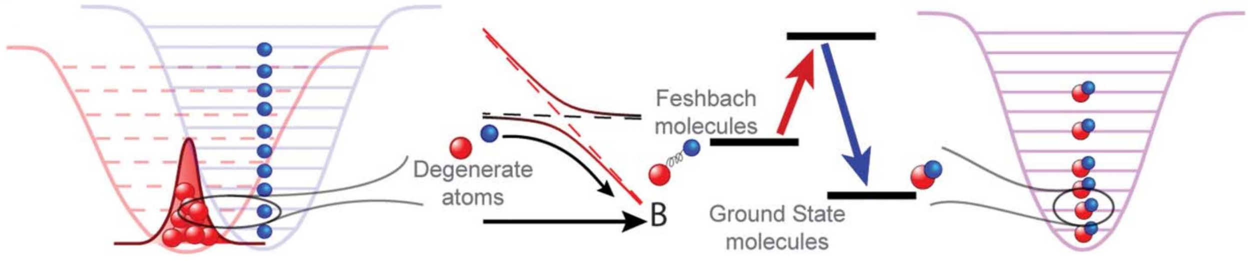
Abstract

A stabilization of a fermionic molecular gas towards collapse in attractive head-to-tail collisions and its evaporative cooling below the Fermi temperature has so far been achieved in two ways. Either a strong dc electric field is applied to confine the molecular motion to 2D [1] or inelastic collisions in 3D are strongly suppressed by applying a circularly polarized microwave field [2]. Here we use a Hartree-Fock mean-field theory [3,4] in order to determine the 3D properties of quantum degenerate fermionic molecules. In particular, we compare the stability diagrams occurring with and without microwave shielding, where a dipole-dipole interaction with negative and positive sign is present. In case when the orientation of the electric dipoles with respect to the trap axes is unknown, we outline how to reconstruct it from time-of-flight absorption measurements.

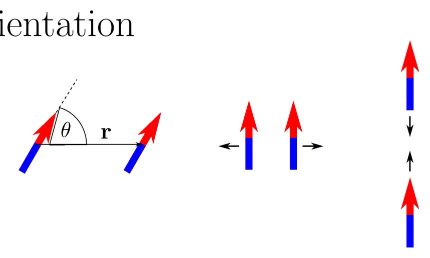
Quantum degeneracy for dipolar fermionic molecules in 2D and 3D

- ⋆ Dipole-dipole interaction (DDI) leads to novel quantum phenomena in ultracold atoms and molecules
- ⋆ JILA: 2D setup, due to stability [1]

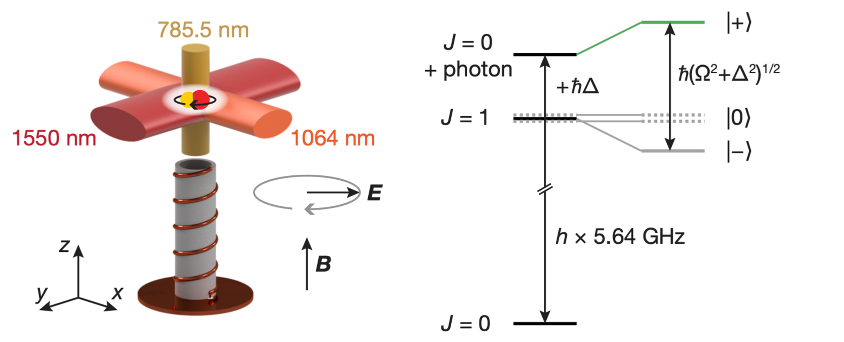


DDI leads to elongation of the Fermi surface (FS) **along** the dipoles' orientation

Potential for the dipole-dipole interaction: $V_{\mathrm{int}}(\mathbf{r}) = \dfrac{d^2}{4\pi\varepsilon_0}\dfrac{1-3\cos^2\theta}{r^3}$



- ⋆ MPQ Munich: microwave shielding (MS) in full 3D [2]



MS-induced interaction potential:

$$V_{\mathrm{int}}(\mathbf{r}) = -\frac{d_{\mathrm{eff}}^2}{4\pi\varepsilon_0}\frac{1-3\cos^2\theta}{r^3}$$

$$d_{\mathrm{eff}} = \frac{d}{\sqrt{12(1+\Delta^2/\Omega^2)}}$$

MS leads to elongation of the FS **orthogonal** to the dipoles' orientation

Wigner function approach

- ⋆ First experimental observation of the FS deformation by the Ferlaino group [5]
- ⋆ Hartree-Fock mean-field theory [3,4] based on the Wigner function approach

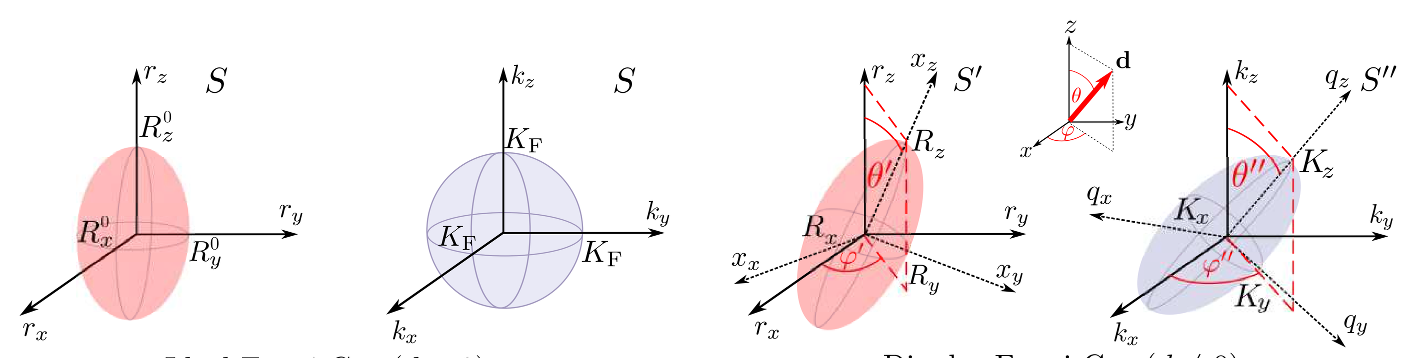
$$\nu(\mathbf{r},\mathbf{k}) = \int d\mathbf{r}'\, e^{-i\mathbf{k}\cdot\mathbf{r}'}\rho\left(\mathbf{r}+\mathbf{r}'/2,\, \mathbf{r}-\mathbf{r}'/2\right)$$

where $\rho(\mathbf{r},\mathbf{r}') = \langle\hat{\Psi}^\dagger(\mathbf{r})\hat{\Psi}(\mathbf{r}')\rangle$ is one-body density matrix

- ⋆ Ansatz for the Wigner function at zero temperature:

$$\nu^0(\mathbf{r},\mathbf{k}) = \Theta\left(1-\sum_{i,j}x_i\mathbb{A}_{ij}x_j-\sum_{i,j}q_i\mathbb{B}_{ij}q_j\right)$$

$$\mathbb{A}' = \begin{pmatrix}1/R_x'^2 & 0 & 0\\ 0 & 1/R_y'^2 & 0\\ 0 & 0 & 1/R_z'^2\end{pmatrix} \quad\text{and}\quad \mathbb{B}'' = \begin{pmatrix}1/K_x''^2 & 0 & 0\\ 0 & 1/K_y''^2 & 0\\ 0 & 0 & 1/K_z''^2\end{pmatrix}$$



Ideal Fermi Gas ($d = 0$) Dipolar Fermi Gas ($d \neq 0$)

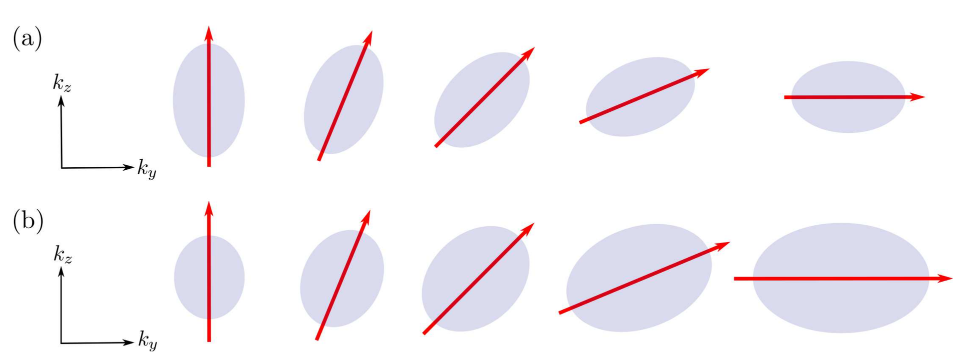
- ⋆ Total energy of the system:

$$E_{\mathrm{tot}} = \frac{N}{8}\left(\sum_i\frac{\hbar^2K_i^2}{2M}+\sum_{i,j}\frac{M\omega_i^2\mathbb{R}_{ij}'^2R_j^2}{2}\right)-\frac{6N^2c_0}{R_xR_yR_z}\left[F_A\left(\frac{R_x}{R_z},\frac{R_y}{R_z},\theta,\varphi,\theta',\varphi'\right)-F_A\left(\frac{K_x}{K_z},\frac{K_y}{K_z},\theta,\varphi,\theta'',\varphi''\right)\right]$$

where generalized anisotropy function [4] is defined as:

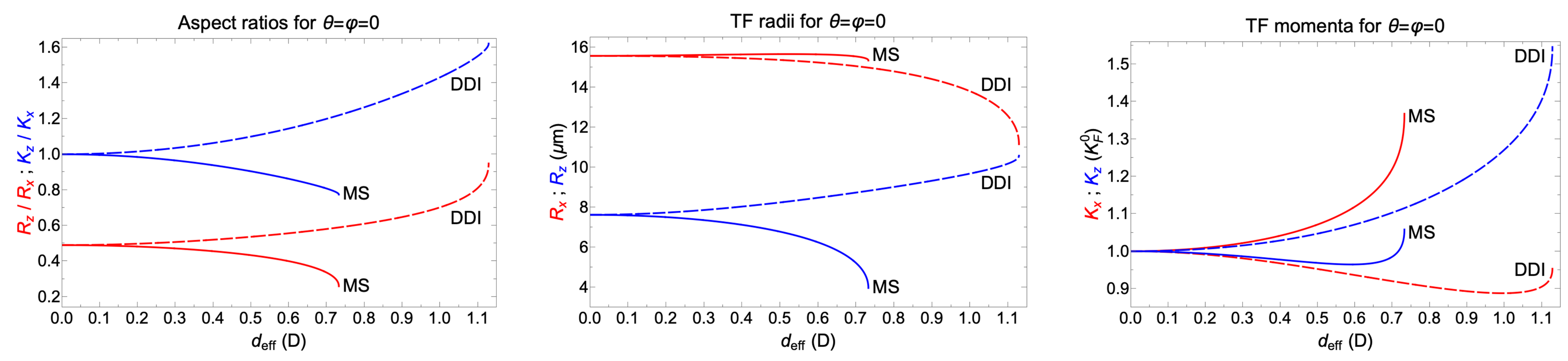
$$F_A(x,y,\theta,\varphi,\tilde{\theta},\tilde{\phi}) = \left(\sum_i\mathbb{R}_{iz}\tilde{\mathbb{R}}_{ix}\right)^2 f\left(\frac{y}{x},\frac{1}{x}\right)+\left(\sum_i\mathbb{R}_{iz}\tilde{\mathbb{R}}_{iy}\right)^2 f\left(\frac{x}{y},\frac{1}{y}\right)+\left(\sum_i\mathbb{R}_{iz}\tilde{\mathbb{R}}_{iz}\right)^2 f(x,y)$$

- ⋆ Dipolar atoms → rigid FS
- ⋆ Polar molecules → soft FS



Ground state properties

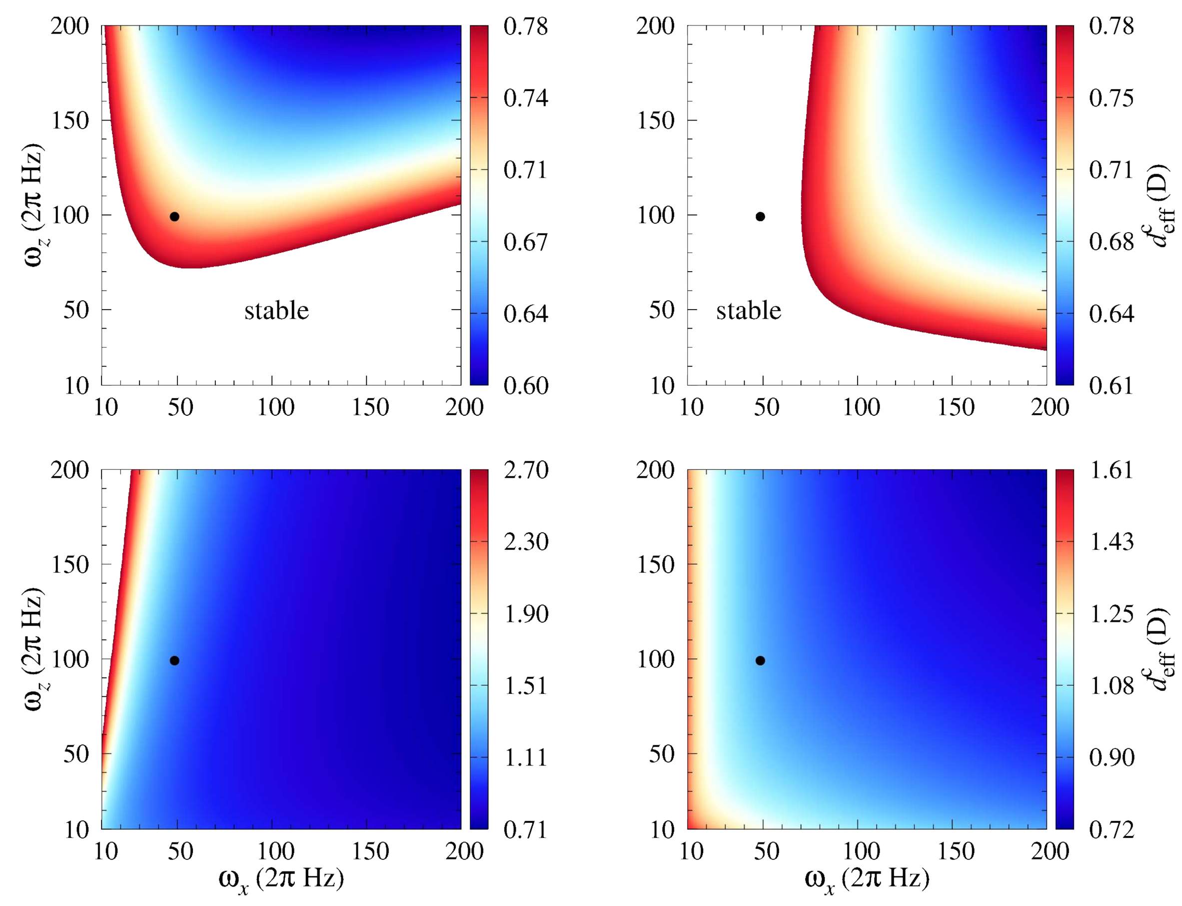
- ⋆ Aspect ratios and Thomas-Fermi radii and momenta for systems with DDI and MS-induced DDI



$(\omega_x,\omega_y,\omega_z) = (48.5, 48.5, 99)\times 2\pi$ Hz

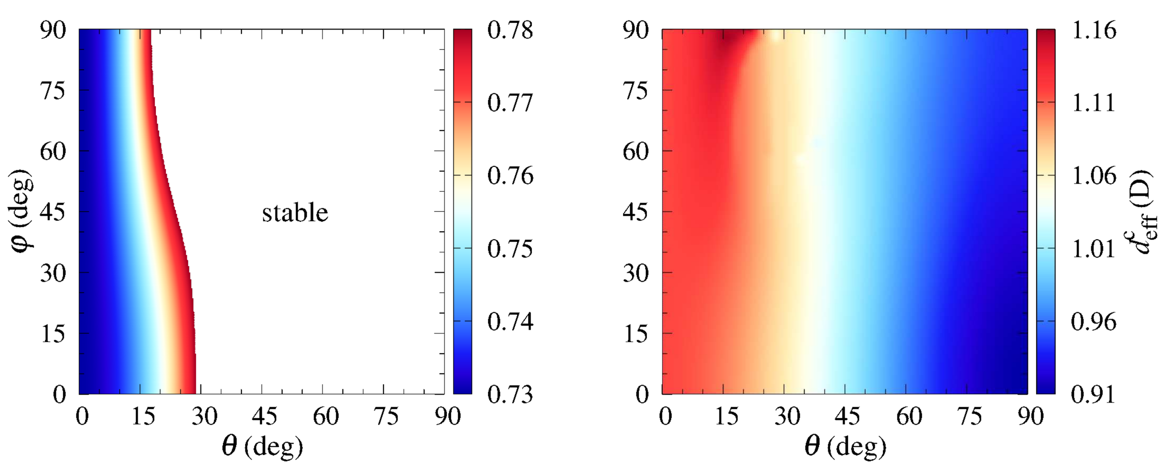
Stability of the system: critical dipolar strength

- ⋆ MS-induced DDI (top) and regular DDI (bottom) for $\theta = 0$ (left) and $\theta = 60°$ (right)



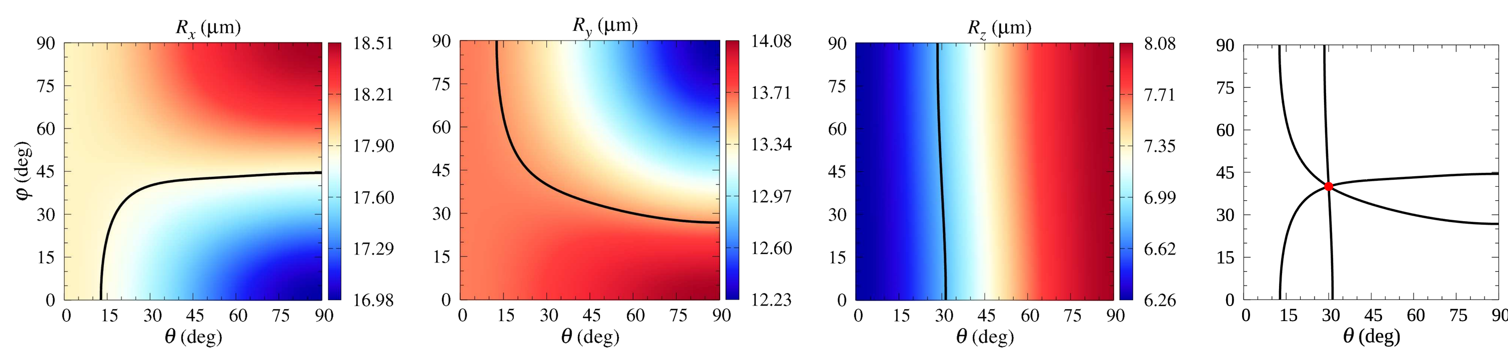
Black dot corresponds to the trap frequencies of experiment from Ref. [2].

- ⋆ Fixed trap frequencies: MS-induced DDI (left) and regular DDI (right)



Reconstruction of dipoles' orientation

- ⋆ Combined theoretical and experimental analysis



Conclusions

- ⋆ Microwave shielding offers more stable dipolar fermionic systems
- ⋆ Interplay of the DDI strength, orientation of dipoles, and geometry
- ⋆ When the DDI is not switched off at the beginning of TOF, it strongly influences the evolution
- ⋆ Ballistic evolution during the TOF cannot be assumed anymore; theory is needed
- ⋆ Fermi surface is rigid for weak interactions, but becomes soft as d_{eff} increases

[1] L. De Marco et al., Science **363**, 853 (2019); G. Valtolina et al., Nature **588**, 239 (2020).
[2] A. Schindewolf, et al., Nature **607**, 677 (2022).
[3] V. Veljić, et al., New J. Phys. **20**, 093016 (2018).
[4] V. Veljić, A. Pelster, and A. Balaž, Phys. Rev. Research **1**, 012009(R) (2019).
[5] K. Aikawa et al., Science **345**, 1484 (2014).

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