# Stability diagrams and dynamics of quantum degenerate Fermi gases of polar molecules

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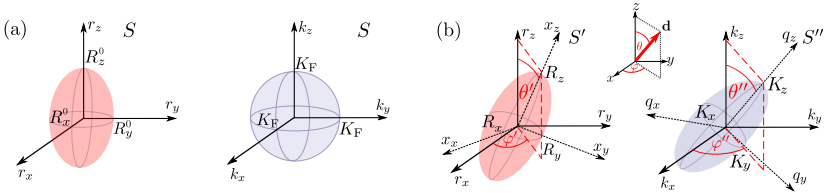
# Motivation

- Observation of the Fermi surface (FS) deformation

  F. Ferlaino group, Science **345**, 1484 (2014)

- Realization of the degenerate Fermi gas of polar molecules

  J. Ye group, Science **363**, 853 (2019)




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

Veljić, Balaž, Pelster, Phys. Rev. A **95**, 053635 (2017)

Veljić et al., New J. Phys. **20**, 093016 (2018)

# Wigner function approach

- Variational phase-space approach for the Wigner function

$$\nu(\mathbf{r},\,\mathbf{k}) = \int d^3r'\, e^{-i\mathbf{k}\cdot\mathbf{r}'}\, \rho\left(\mathbf{r}+\frac{1}{2}\mathbf{r}',\,\mathbf{r}-\frac{1}{2}\mathbf{r}'\right)$$

using the Hartree-Fock approximation

- Ansatz for the Wigner function at zero temperature:

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

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

# Energy and Thomas-Fermi radii and momenta

- Total energy of the system:

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

- Generalized anisotropy function:

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

- Particle number conservation: $N = \frac{1}{48} R_x R_y R_z K_x K_y K_z$
- Fermi surface remains cylindrically symmetric ellipsoid: $K_x = K_y$

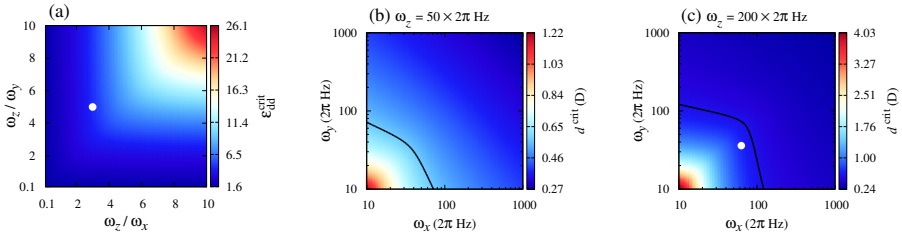
Veljić, Pelster, Balaž, `arXiv:1902.09518`

# Stability diagrams

- Non-dimensional form of equations: species-independent!
- Relative DDI strength:

$$\varepsilon_{\rm dd} = \frac{d^2}{4\pi\varepsilon_0}\sqrt{\frac{M^3}{\hbar^5}}(\omega_x\omega_y\omega_z N)^{1/6}$$

- Stability only depends on the trap aspect ratios and the dipoles' orientation



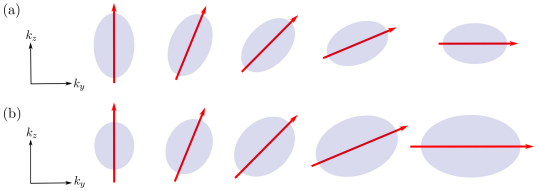

Veljić, Pelster, Balaž, arXiv:1902.09518

# Fermi surface deformation

- Fermi surface deformation:

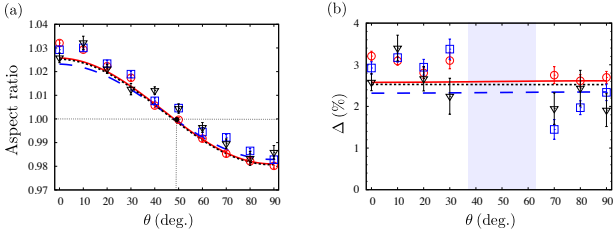
$$\Delta = \frac{K_z}{K_x} - 1$$

- Fermi surface orientation along the dipoles' direction: $\theta'' = \theta$, $\varphi'' = \varphi$
- For polar molecules effect of FS deformation is more dominant and complex
- Dipolar atoms $\rightarrow$ rigid FS; Polar molecules $\rightarrow$ soft FS



# Fermi surface deformation - Er

- Comparison of theoretical results for $A_{\mathrm{K}}$ and $\Delta$ with the experimental results for $A_{\mathrm{R}}(t = 12\,\mathrm{ms})$ for $^{167}$Er
- Ballistic expansion: $A_{\mathrm{K}}(0) = \lim_{t\to\infty} A_{\mathrm{R}}(t)$

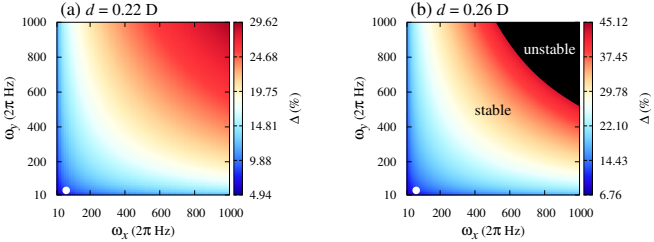



- $\varphi = 14^\circ$, $\gamma = 28^\circ$
- $N = 6.6 \cdot 10^4$, (579, 91, 611) Hz
- $N = 6.3 \cdot 10^4$, (428, 91, 459) Hz
- $N = 6.1 \cdot 10^4$, (408, 212, 349) Hz

Veljić et al., New J. Phys. **20**, 093016 (2018)

# Fermi surface deformation - KRb

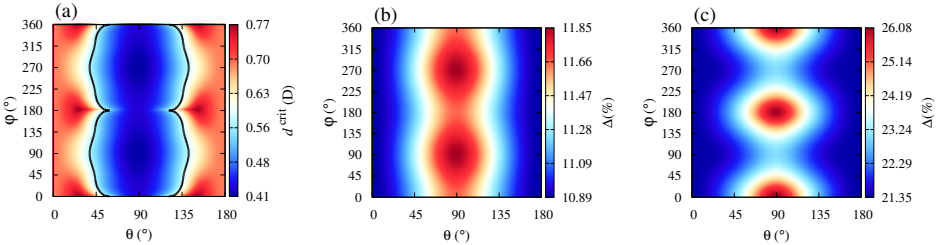
- FS deformation is much larger in gases of polar molecules
- $N = 3 \cdot 10^4$, $\omega_z = 2\pi \times 200$ Hz, $\theta = \varphi = 0$
- Even small changes in the dipolar moment strength can significantly affect the systems' stability




Veljić, Pelster, Balaž, arXiv:1902.09518

# Fermi surface deformation - KRb

- FS deformation and its angular distribution can be tuned by changing the trap frequencies
- $N = 3 \cdot 10^4$, $2\pi \times (63, 36, 200)$ Hz; $2\pi \times (50, 500, 900)$ Hz




Veljić, Pelster, Balaž, arXiv:1902.09518

# Conclusions

- General Hartree-Fock theory for the ground state of polarized trapped fermions with arbitrary $\mathbf{d}$ at $T = 0$
- Species-independent, universal stability diagrams
- Molecular cloud shape and FS deformation strongly depend on the dipoles' orientation
- FS not only rigidly follows the dipoles' orientation, but changes its shape
- DDI has a significant role during the TOF
- Our new theory enables the study of the interplay between the FS deformation and superfluid pairing
- Outlook: 2D and 1D geometry