Tunable Wigner states with dipolar atoms and molecules

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Wigner localization

- Particle localization induced by long-range repulsive interactions

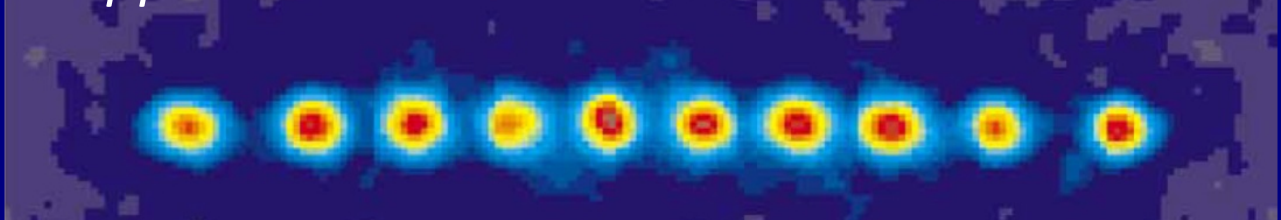
Electrostatic Coulomb interaction between ions:

$$V(\mathbf{r}_1, \mathbf{r}_2) = \frac{e^2}{4\pi\epsilon_0\epsilon_r}\frac{1}{|\mathbf{r}_1 - \mathbf{r}_2|}$$

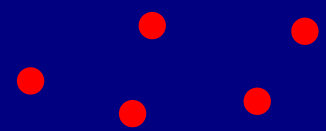
Quantum mechanical particles prefer to spread out as much as possible to minimize kinetic energy.

But sufficiently strong long-range repulsive interactions may cause particles to localize at individual positions.

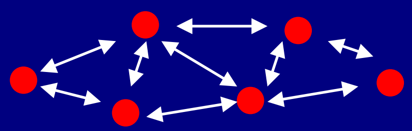
Trapped ultra-cold ions



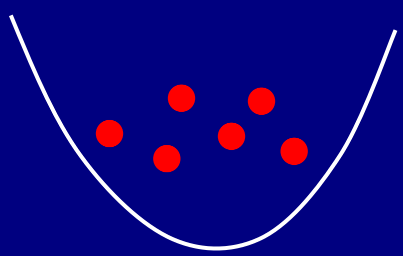
from Nägerl *et al.*, Appl. Phys. B 66, 603 (1998) ultra-cold atomic (or molecular) gas



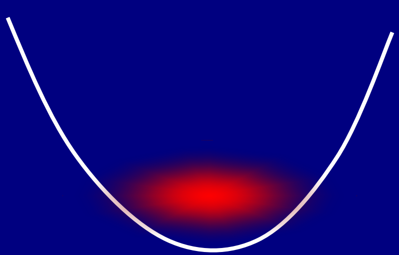
interactions:
- short-range van der Waals
- long-range dipole-dipole
  for some particles



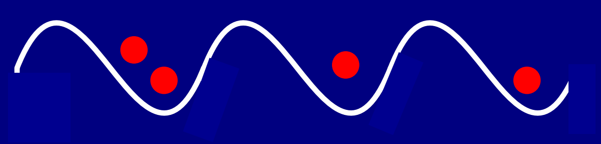
trap using lasers



Bose-Einstein condensate

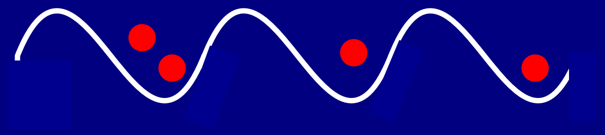


periodic potentials (lattices),
few particles in each well



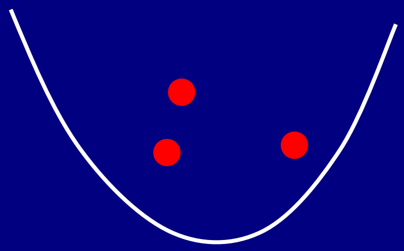
Ultra-cold few-body systems

periodic potentials (lattices),
few particles in each well

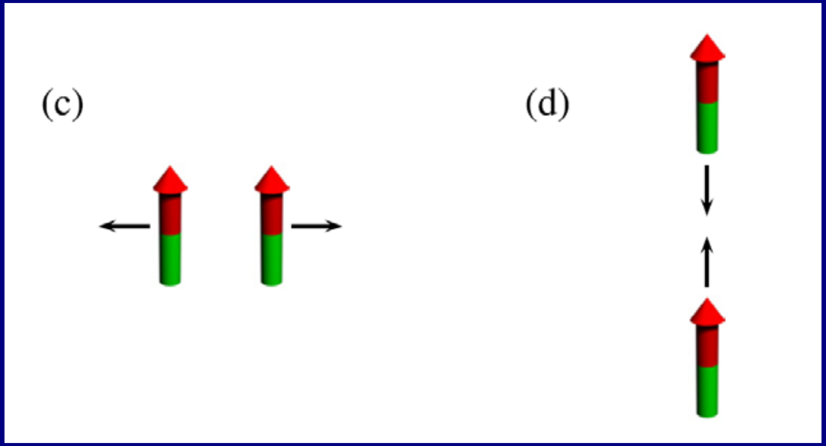


recently developed
"micro-trap",

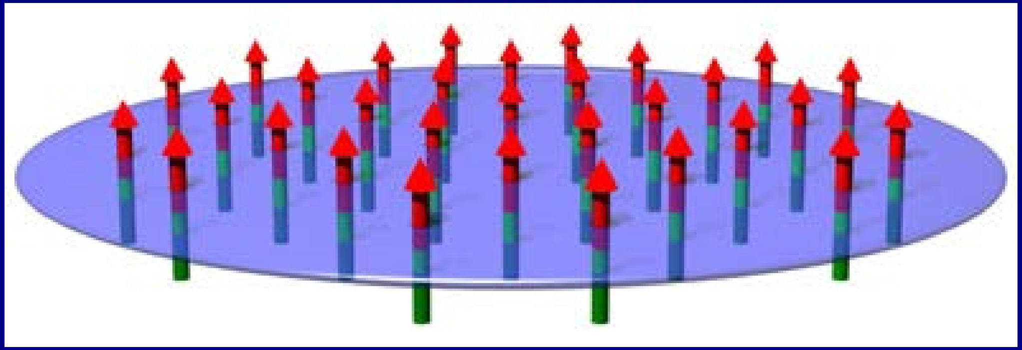
handles few particles



The dipole-dipole interaction depends both on the distance between the particles, but also their relative orientation:



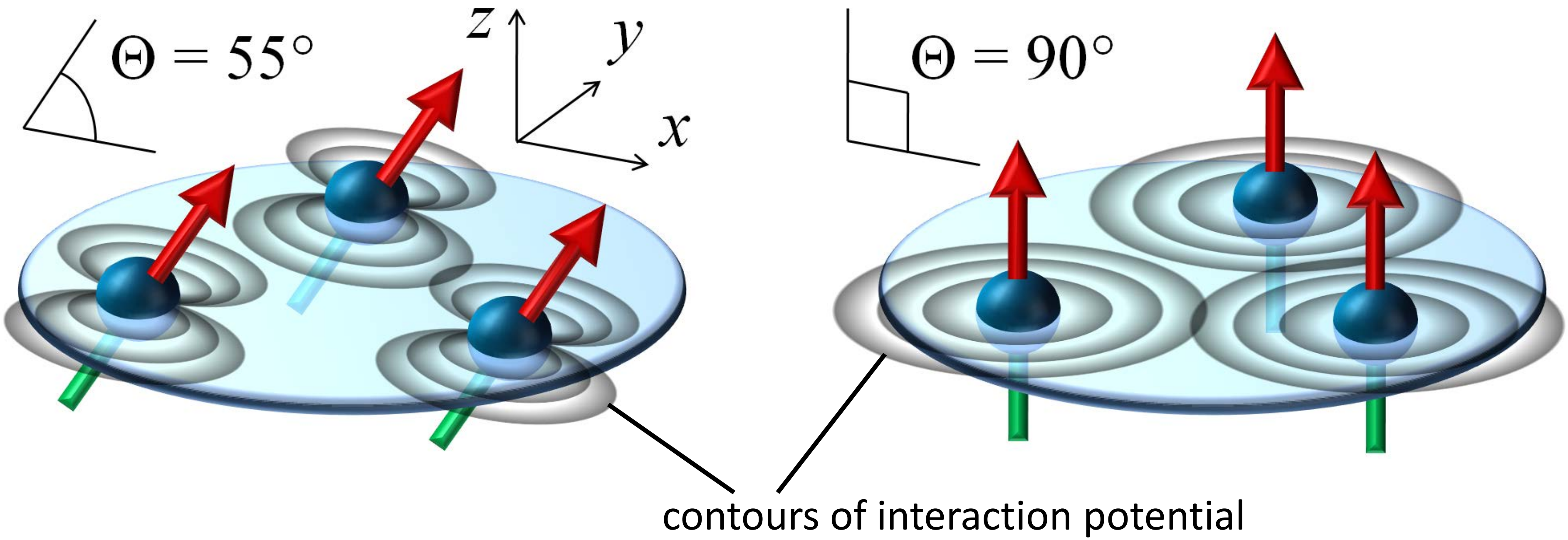
Attraction may give collapse, but quasi-2D confinement + external aligning field could stabilize system



Realized with dysprosium atoms, see
Lu *et al.*, arXiv:1108.5993v2

Figures from Lahaye, Menotti, Santos, Lewenstein, Pfau, Rep. Prog. Phys. 72, 126401 (2009)

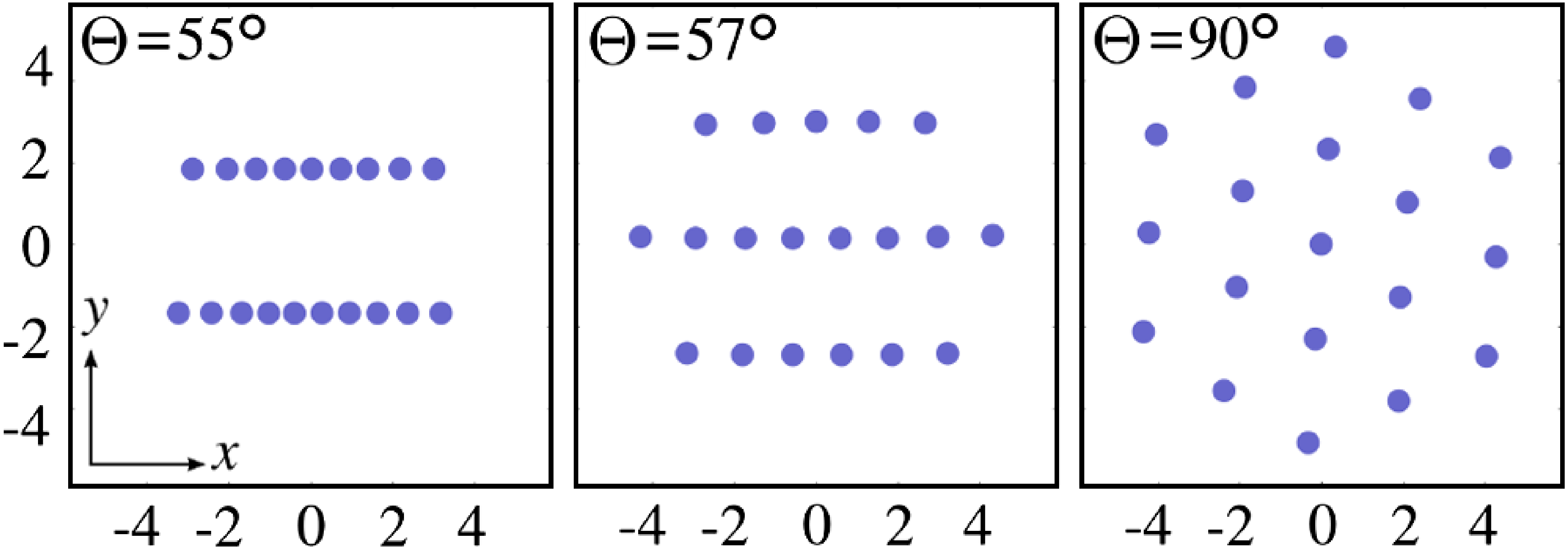
Ultra-cold dipolar atoms or molecules

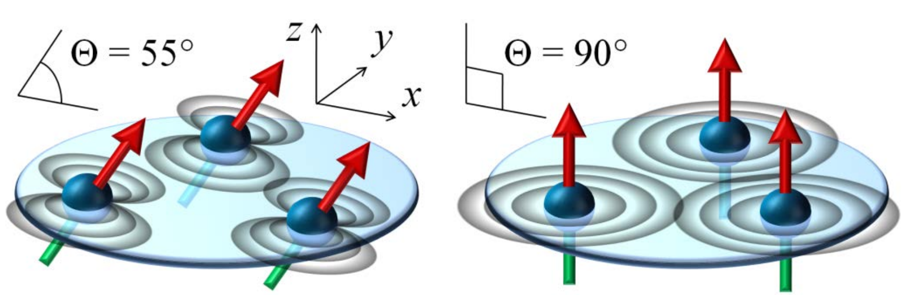


- particles in quasi-2D confinement
- dipole-dipole interaction
- dipoles aligned to external field (forms angle Θ with plane)

-> tunable anisotropic interaction

19 classical point-particle dipoles

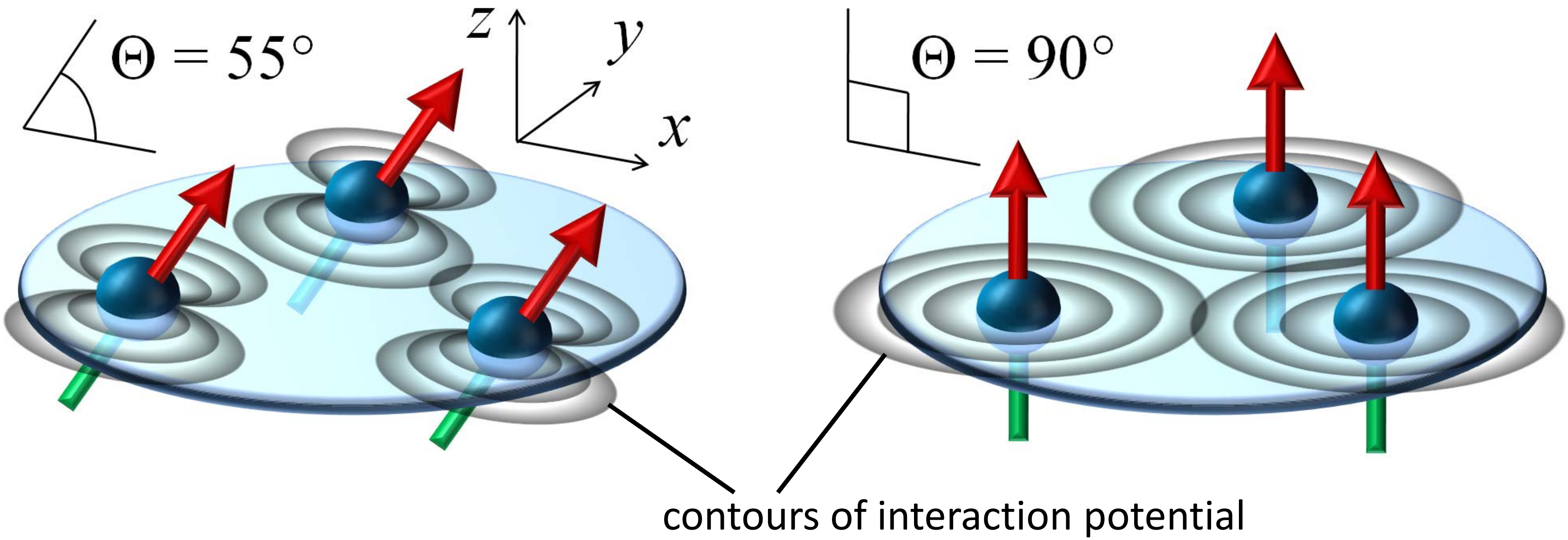




D = interaction strength

19 classical point particles, with dipole-dipole interaction, in 2D harmonic trap

Interaction for quantum particles

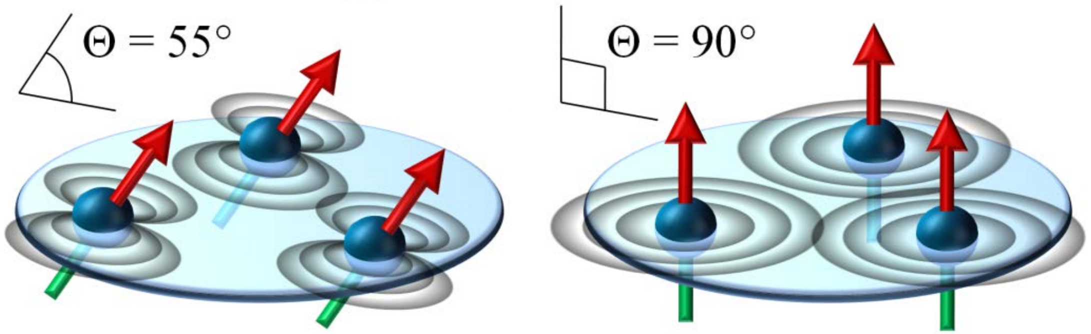


- assume tight trap in *z*-direction,
  with no *z*-nodes in wavefunction
- integration along *z* gives effective in-plane interaction
- we ignore any short-range interactions

Results with 3 quantum mechanical particles

- trapped atoms or molecules with dipolar interactions
- dipole moments aligned to external field
- quasi-2D trap gives anisotropic interaction

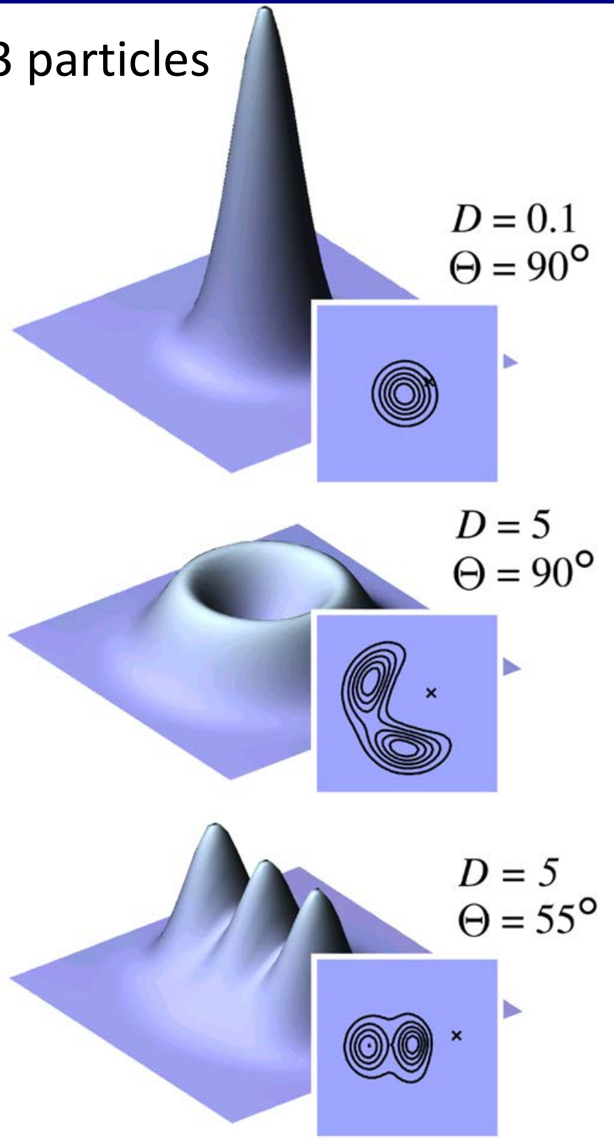
Schematic setup:



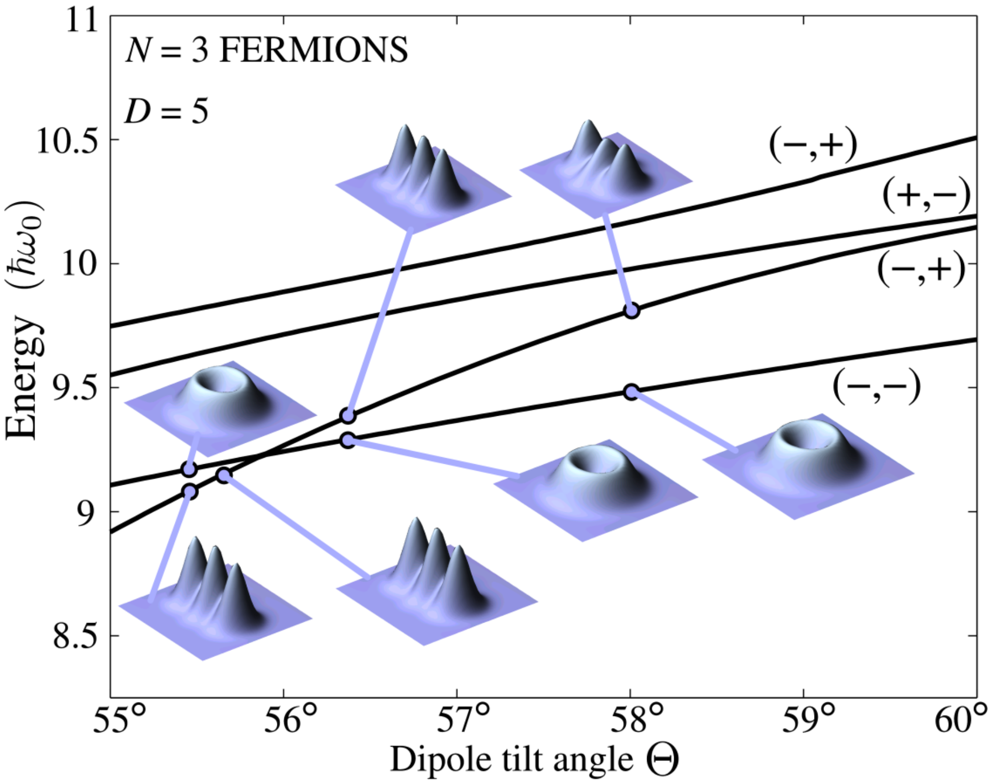
D = interaction strength (dipole moment)

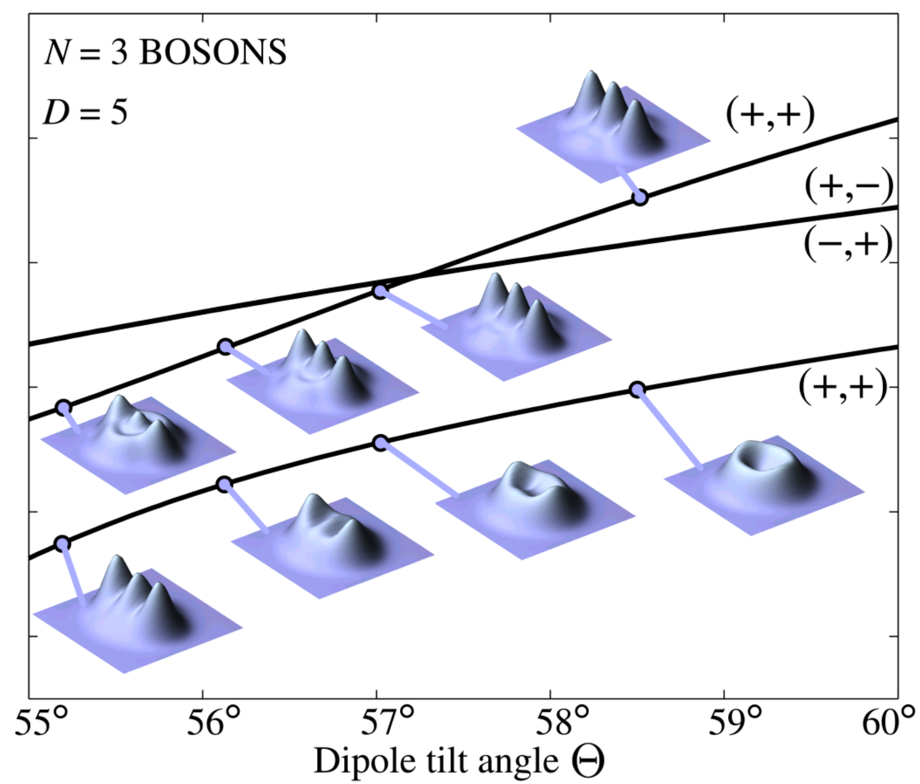
Tunable Wigner states, due to tunable anisotropic interaction.

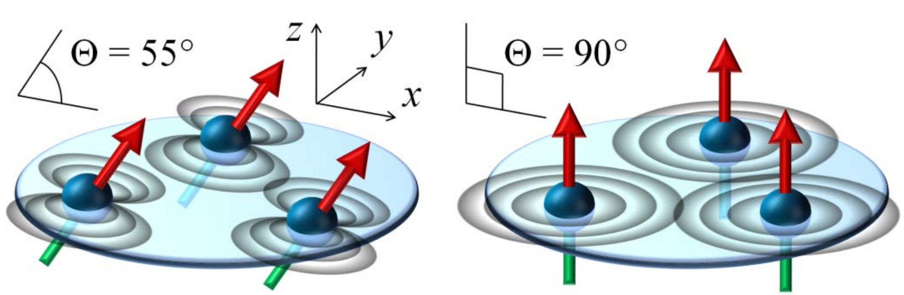
3 particles



Results with 3 quantum mechanical particles



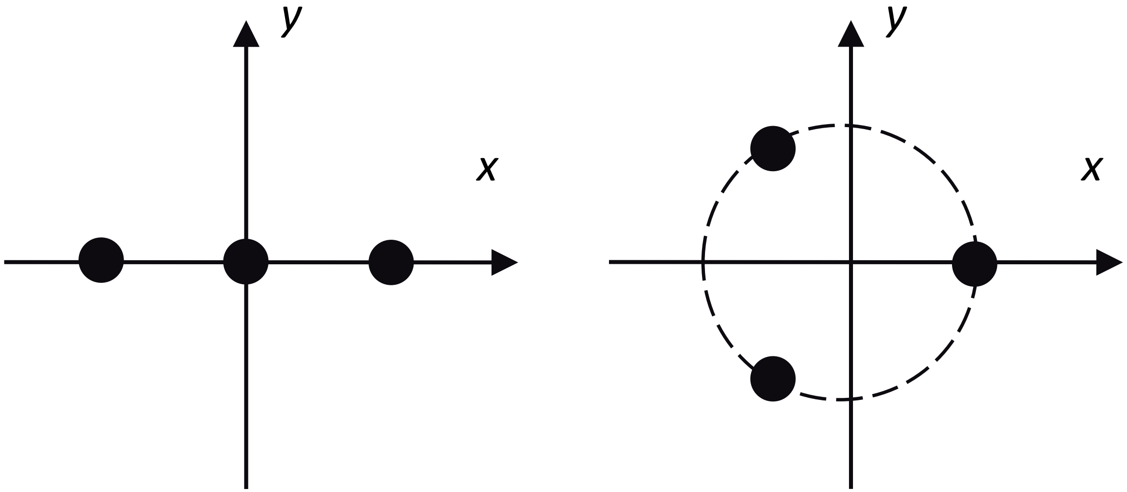




D = interaction strength

Crossing for fermions, anti-crossing for bosons.

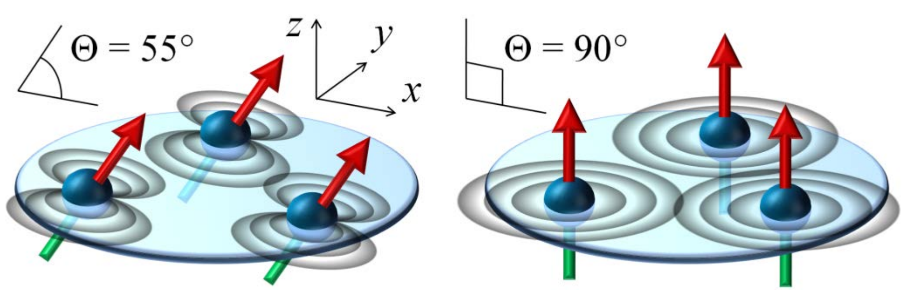
Wigner localized dipoles: Parities



$P_x : \ (x,y) \rightarrow (-x,y)$

$P_y : \ (x,y) \rightarrow (x,-y)$

The Hamiltonian, and its eigenstates, have conserved mirror-parities.
Here, a parity flip may correspond to exchanging two particles,
so parity gets connected to the many-body (anti-)symmetry.



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