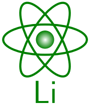
Spins, superfluids, and ultracold atomic gases

Pascal Bugnion and Gareth Conduit

QMC in the Apuan Alps 2013

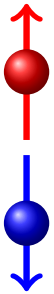
Why cold atoms?

Simulate complex many body systems that are often difficult to observe in the solid state.



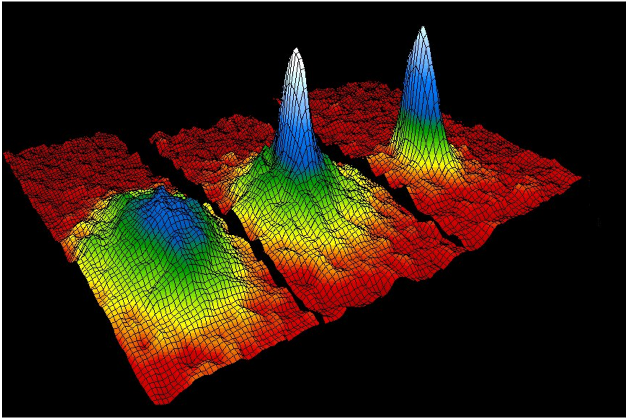
$$|F = 1/2, m_F = 1/2\rangle \longrightarrow$$

$$|F = 1/2, m_F = -1/2\rangle \longrightarrow$$

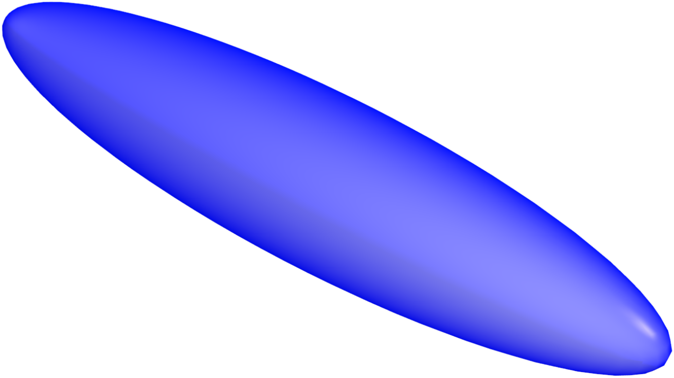


The inter-atom interactions can be tuned by changing an external magnetic field.

Attractive interactions



Experimental setup



F. Serwane et al., Science **332**, 336 (2011)

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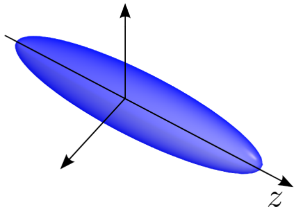
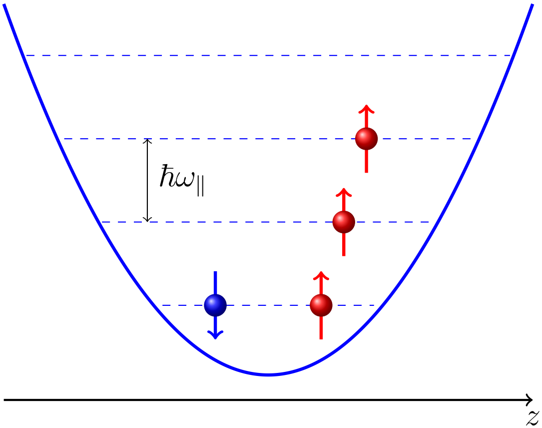


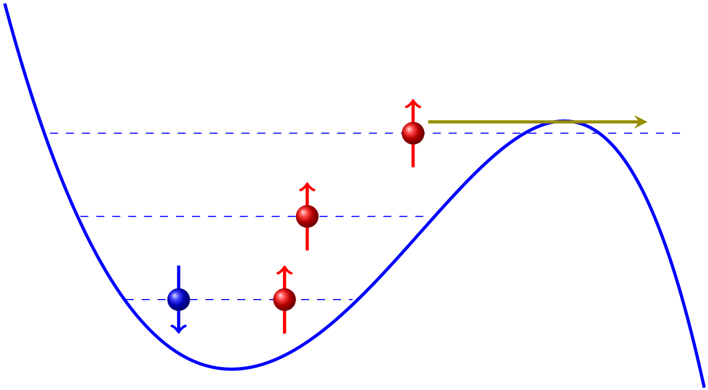
$\omega_\parallel \approx 10\omega_\perp$



F. Serwane et al., Science **332**, 336 (2011)

Experimental setup

Measure energy by tilting the trap until an atom tunnels out.



Hamiltonian

$$V(\mathbf{r}_i - \mathbf{r}_j) = \begin{cases} g\delta(\mathbf{r}_i - \mathbf{r}_j) & \text{anti-parallel spins} \\ 0 & \text{parallel spins} \end{cases}$$

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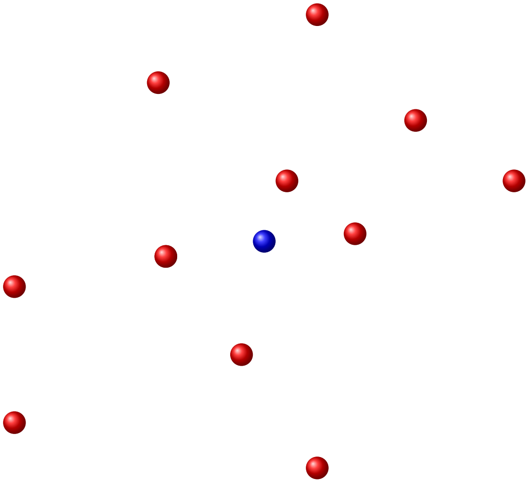
$$\hat{\mathcal{H}} = \sum_{i \in \{\uparrow, \downarrow\}} \hat{h}(\mathbf{r}_i) + g \sum_{i \in \uparrow, j \in \downarrow} \delta(\mathbf{r}_i - \mathbf{r}_j)$$

POB and GJC, PRA **87** 060502(R) (2013)

Polarons



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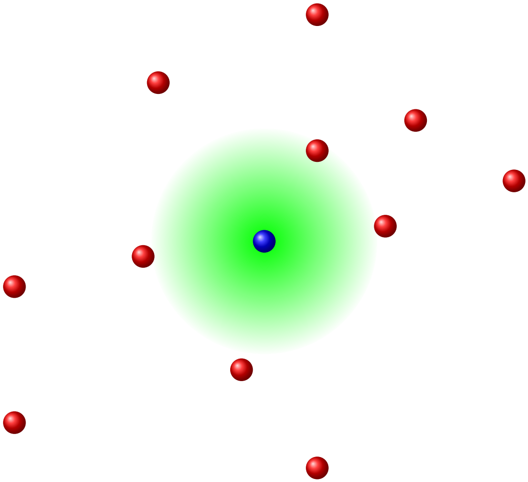
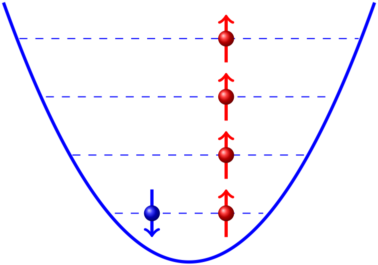


Polarons in a trap



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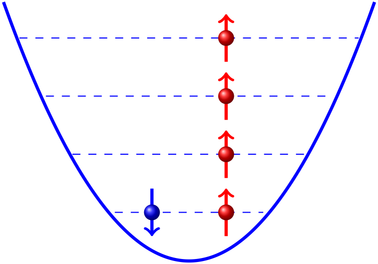
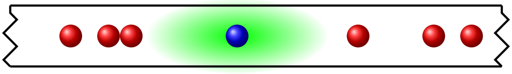
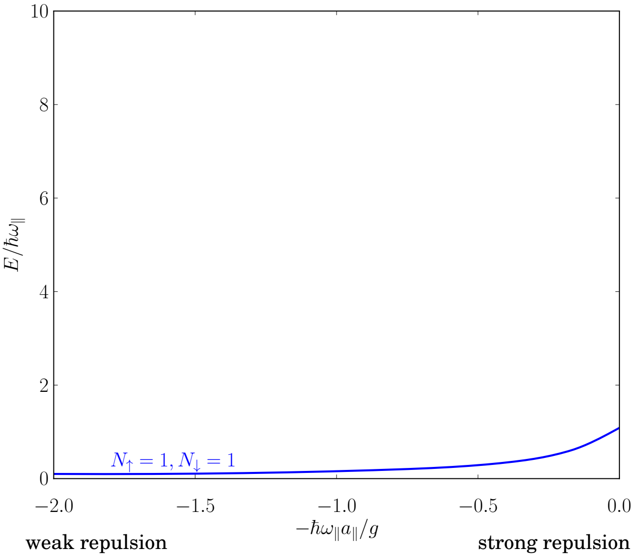
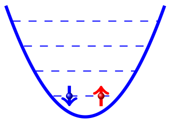




Polaron results





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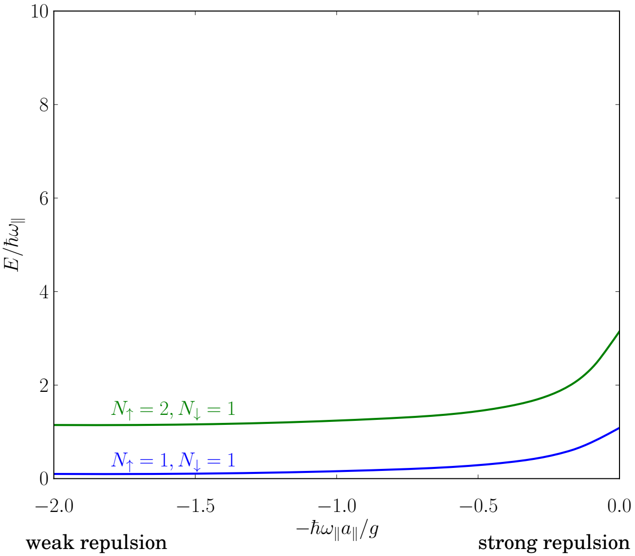

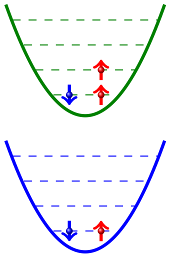

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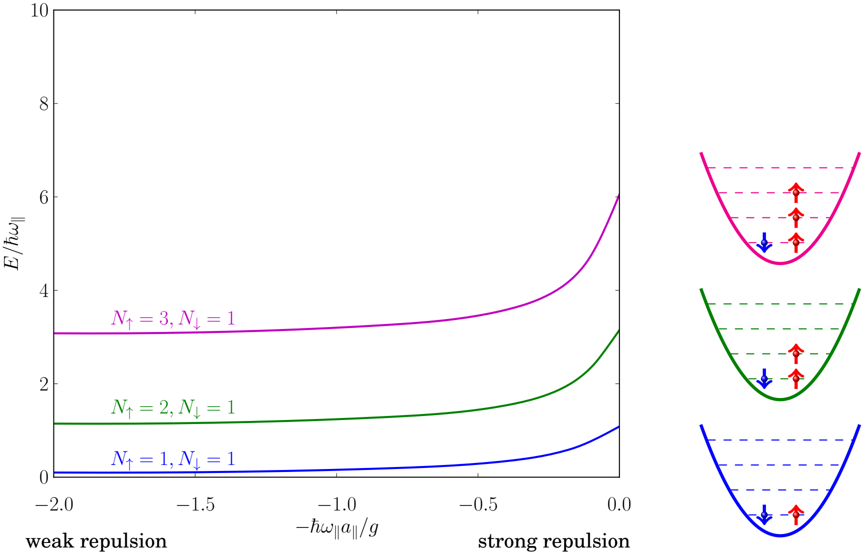

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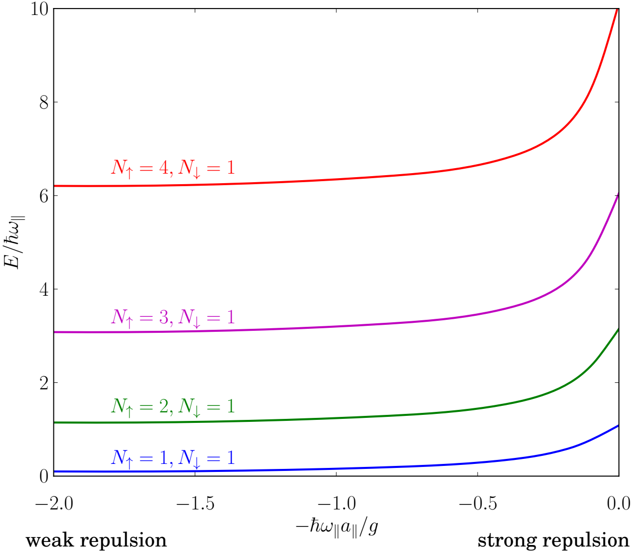

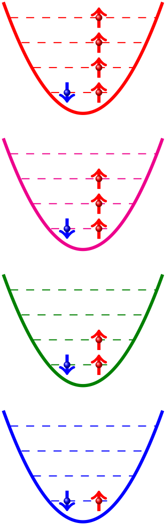

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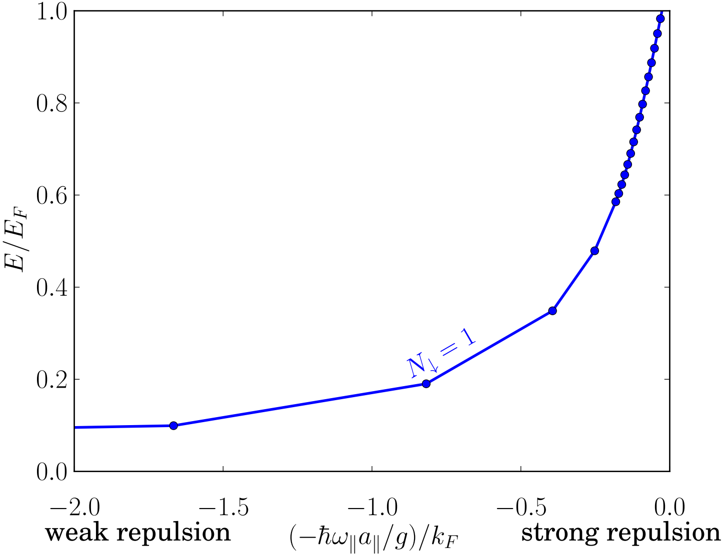

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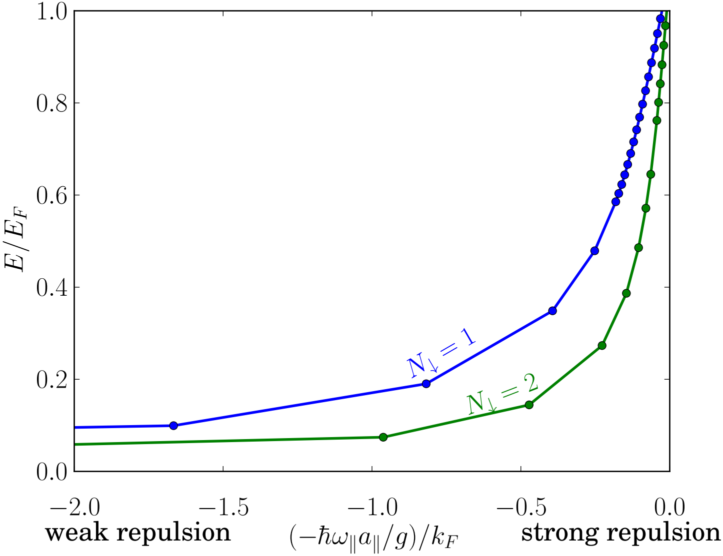

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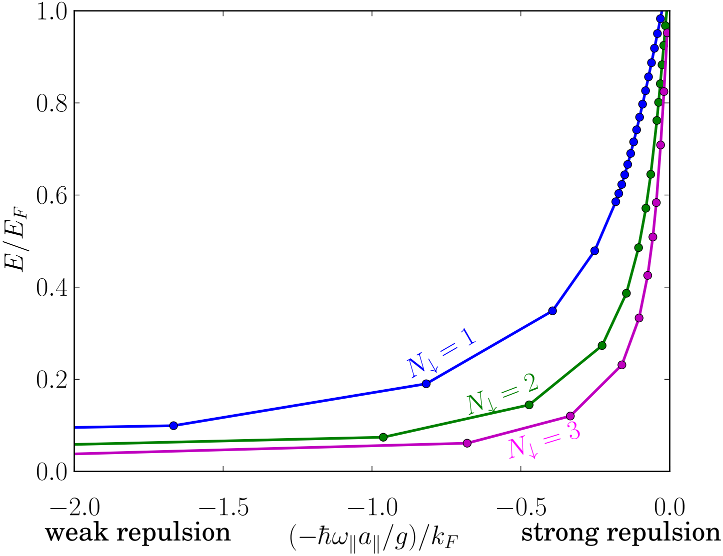

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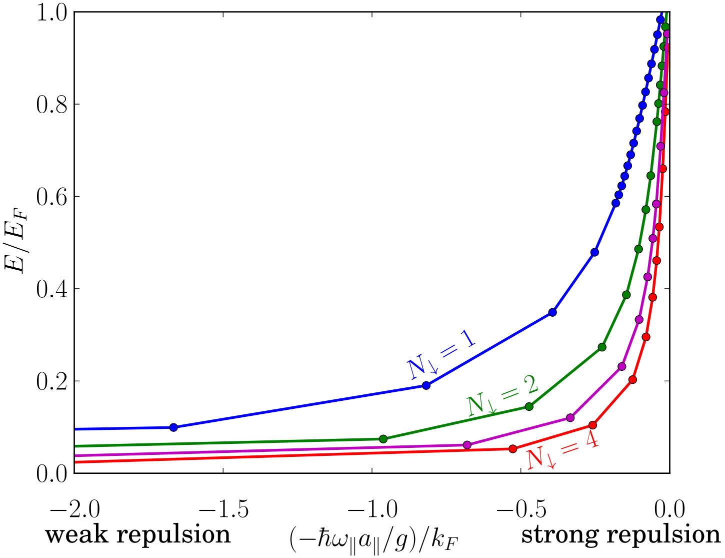

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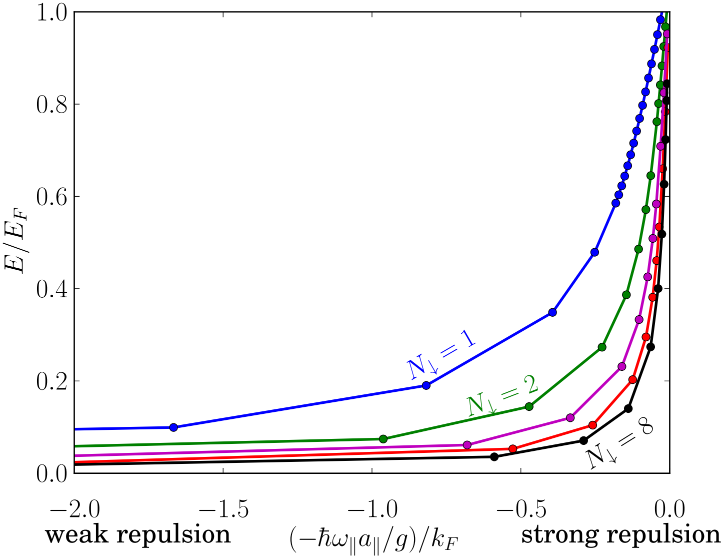
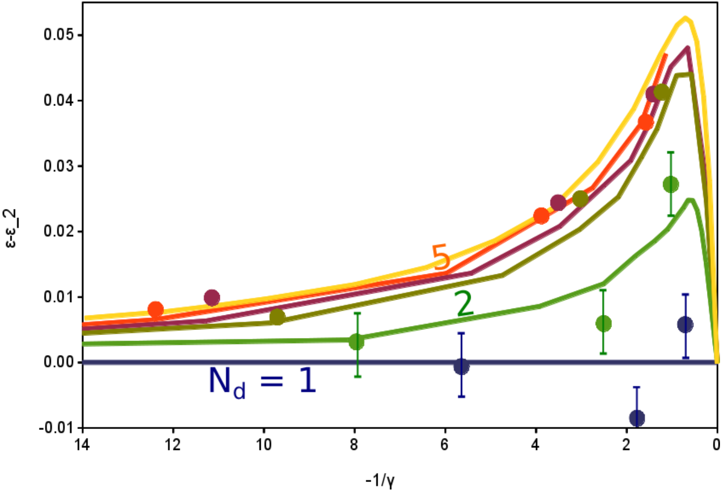
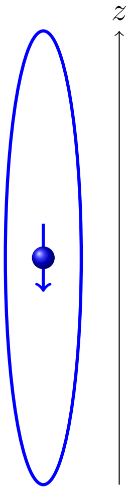


Polaron results: experiment



A.N. Wenz et al., arXiv 1307.3343

Polaron: density matrices



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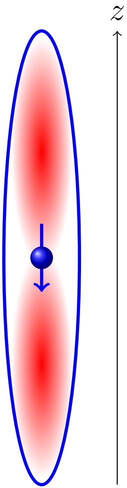

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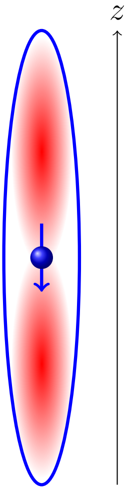

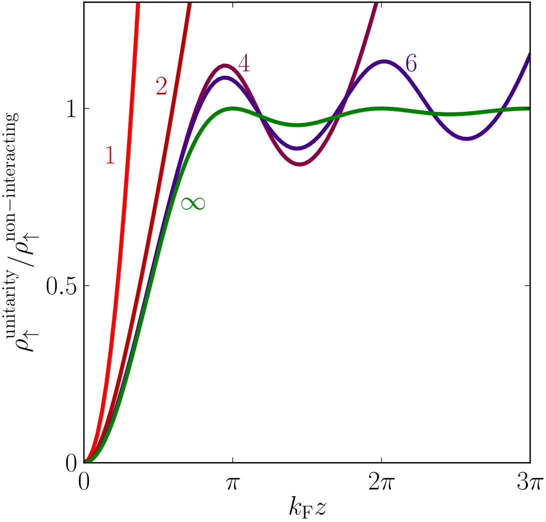

Methods

Configuration Interaction

- Full CI or truncated CI for larger systems.
- Need excited states.
- Use the quantum Harmonic oscillator eigenfunctions as basis state.

Quantum Monte-Carlo

Use DMC for larger systems.

POB and GJC, PRA **87** 060502(R) (2013)

Itinerant ferromagnetism?

$$\hat{\mathcal{H}} = \sum_{i \in \{\uparrow,\downarrow\}} \hat{h}(\mathbf{r}_i) + g \sum_{i \in \uparrow, j \in \downarrow} \delta(\mathbf{r}_i - \mathbf{r}_j)$$

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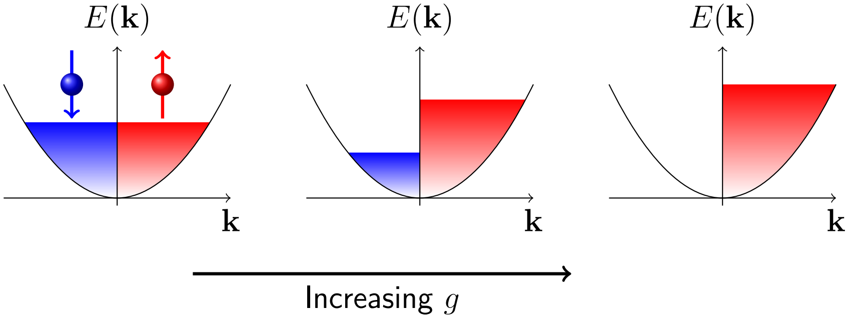
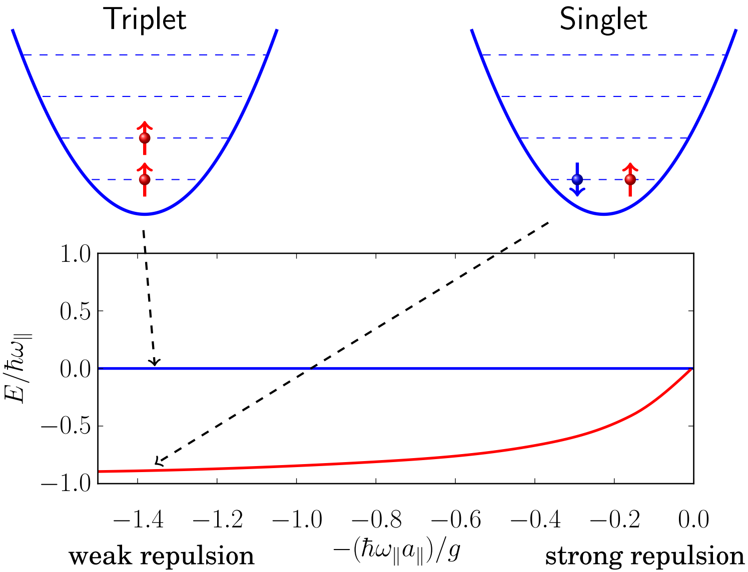


Two atom results



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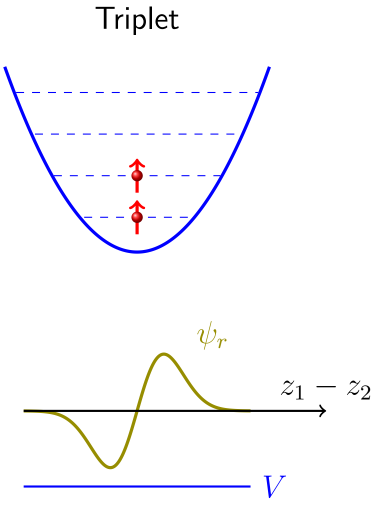

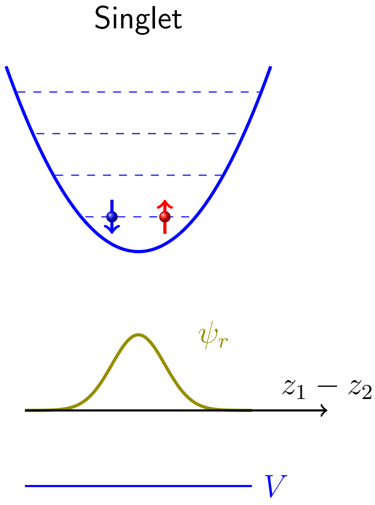

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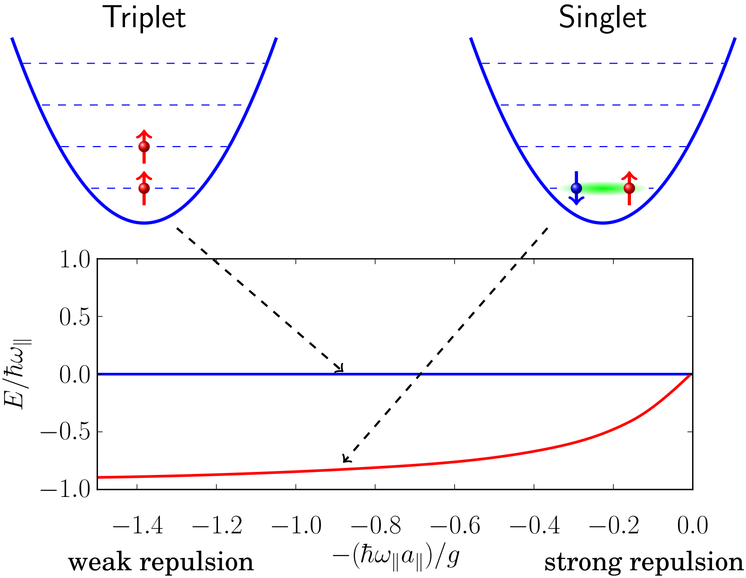

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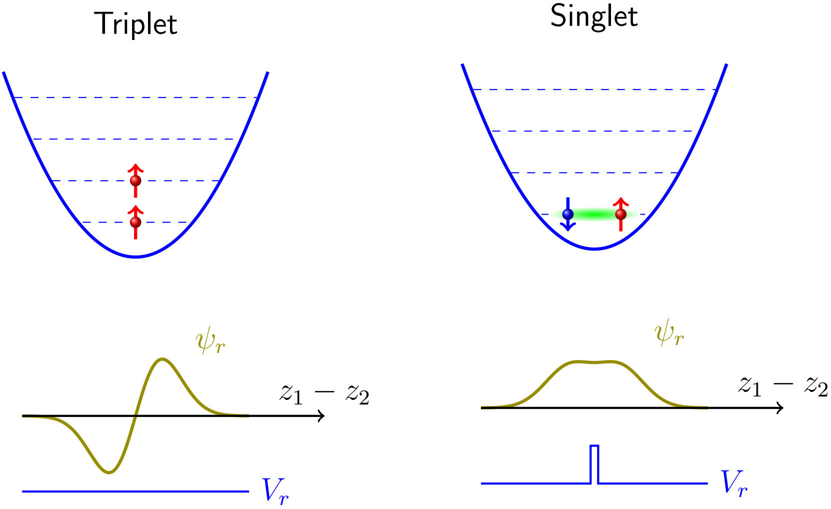
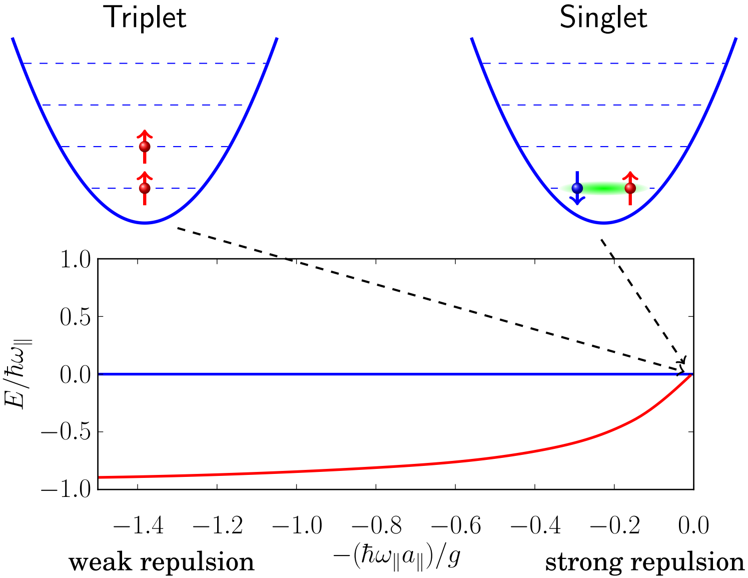
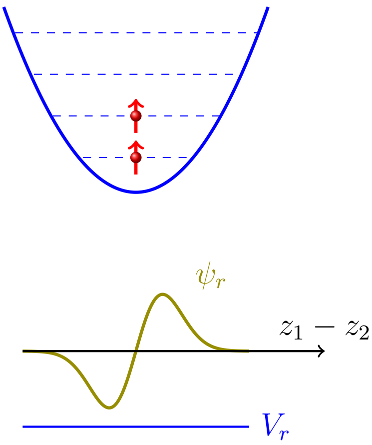


Fermionization: $g \to \infty$

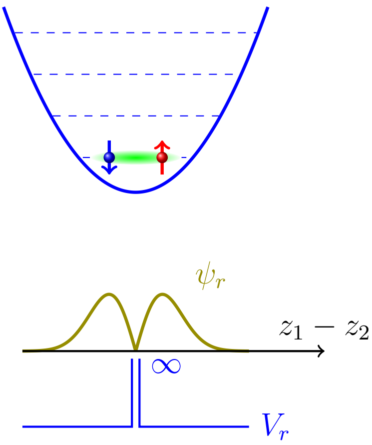


Fermionization: wavefunctions

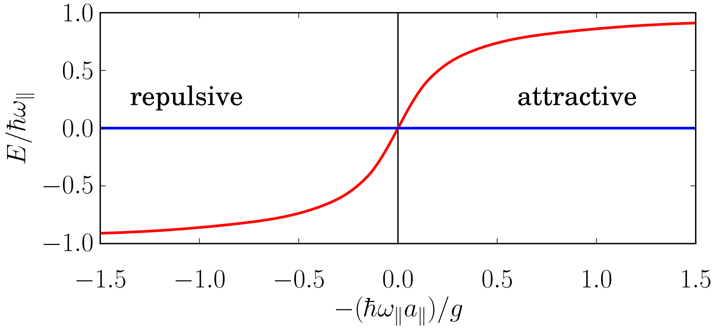
Triplet



Singlet



Beyond unitarity: Super-Tonks regime



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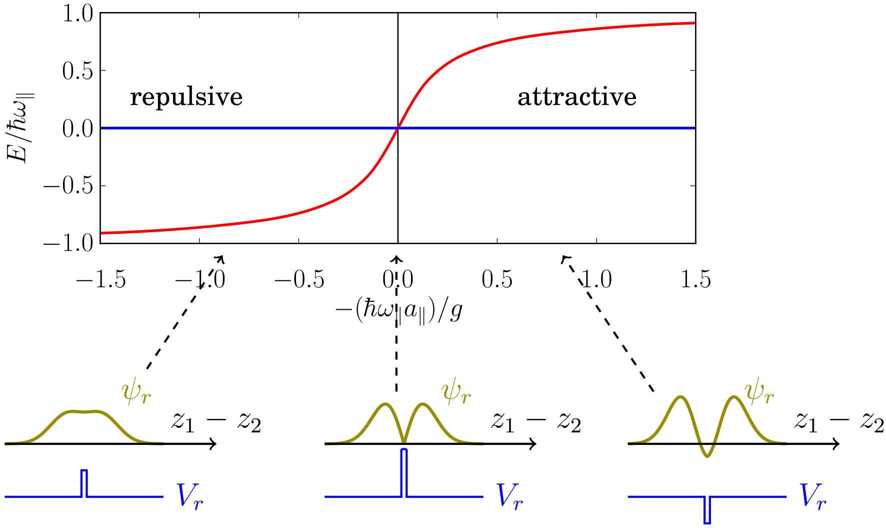
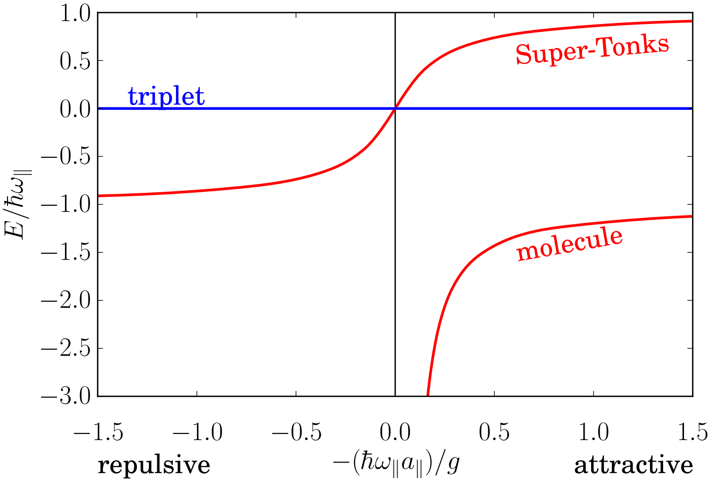
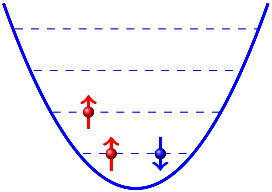


Molecular bands



Observable: tunnelling experiment



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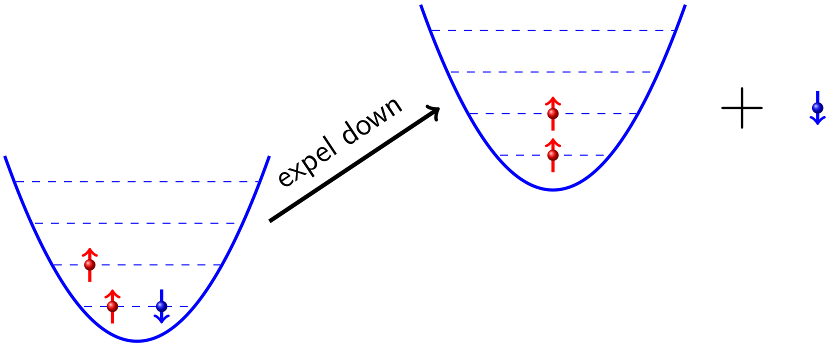

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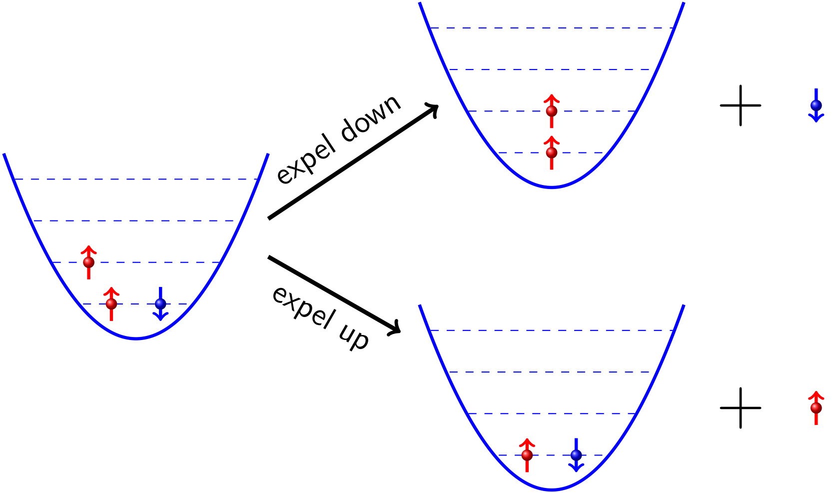
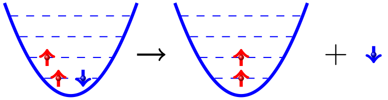
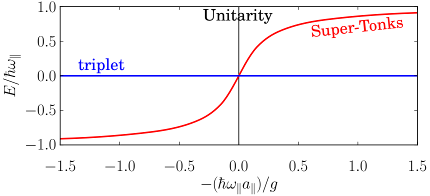
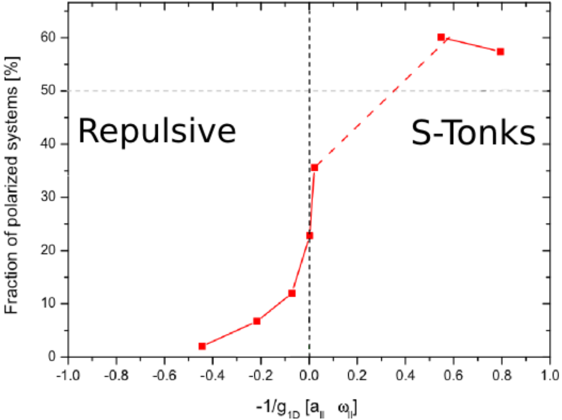


Tunnelling results







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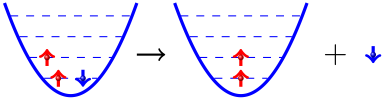
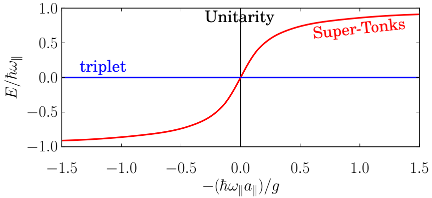
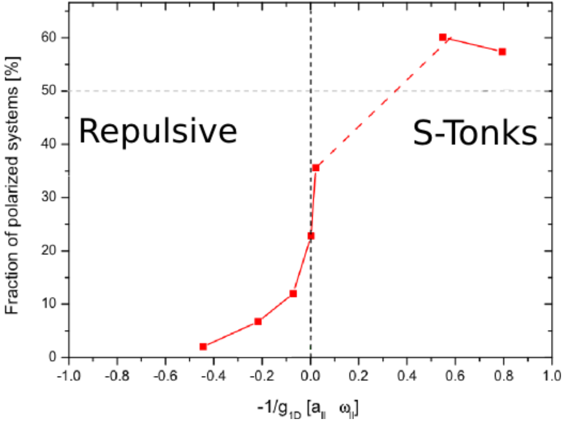


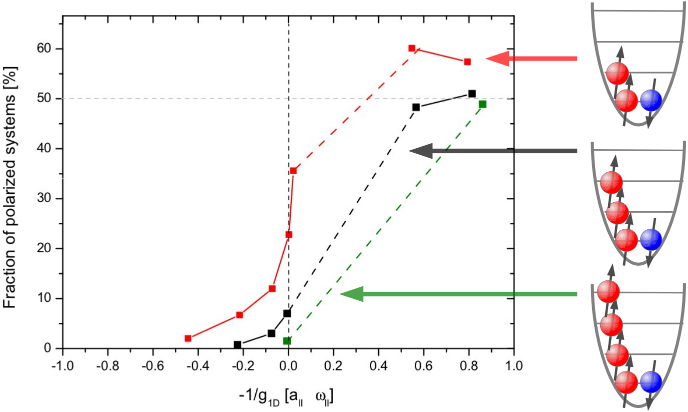




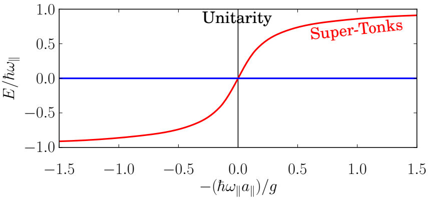
$$|\uparrow\uparrow\downarrow\rangle \rightarrow |\uparrow\uparrow\rangle\, |\downarrow\rangle$$

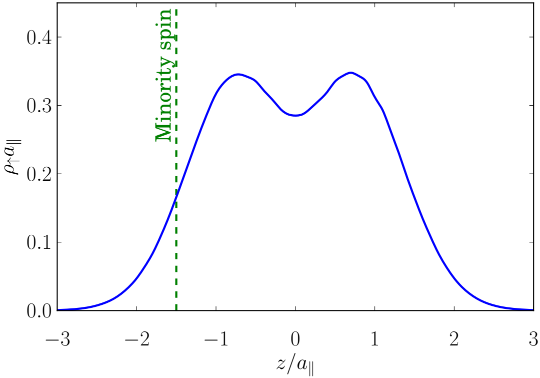
$$|\uparrow\uparrow\downarrow\rangle \rightarrow \left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right) |\uparrow\rangle$$

Tunnelling results



Magnetic correlations? $N_\uparrow = 2, N_\downarrow = 1$





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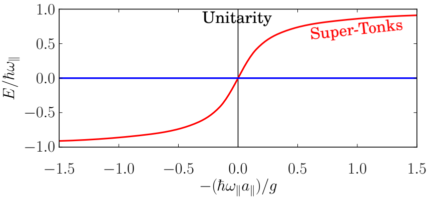

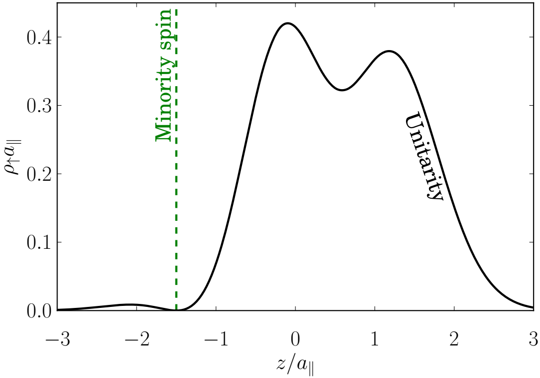

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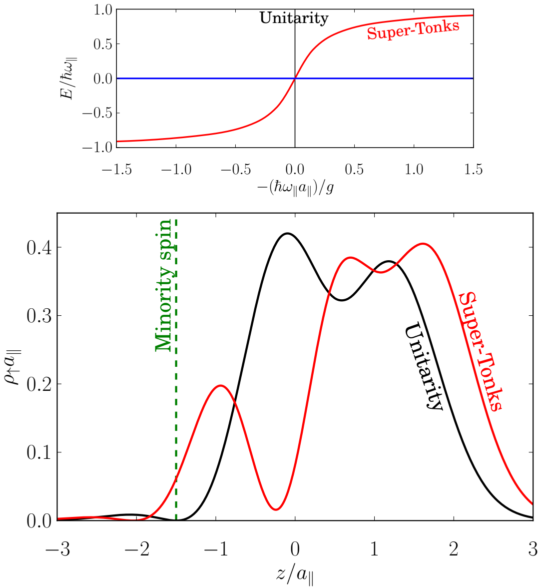
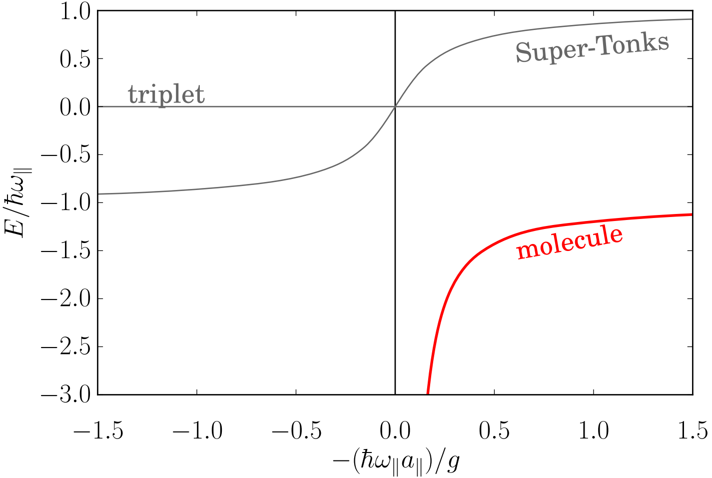
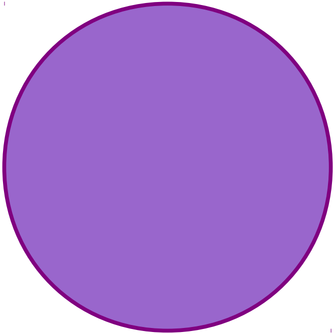


POB, J. Lofthouse and GJC, PRL **111** 045301 (2013)

Attractive interactions



Homogeneous superconductivity



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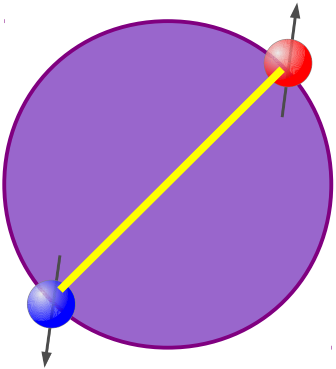
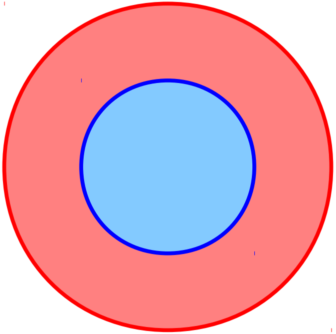


Spin imbalanced superconductors



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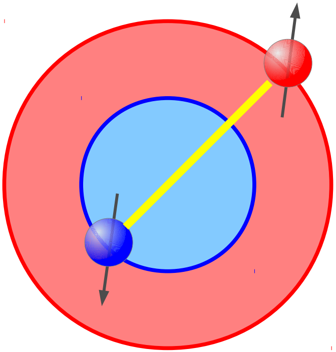

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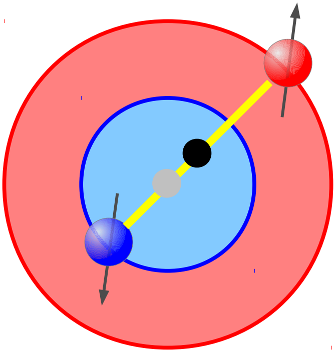
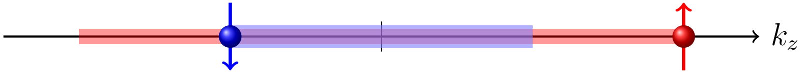


One-dimensional case



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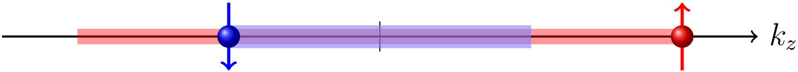
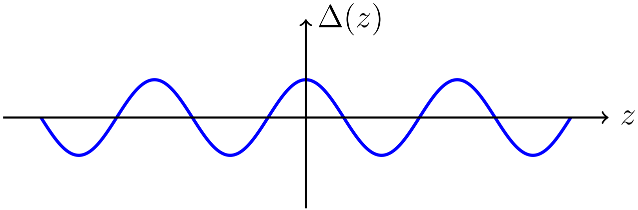


$$\Delta(z) = \Delta_0 \cos(q_z z)$$



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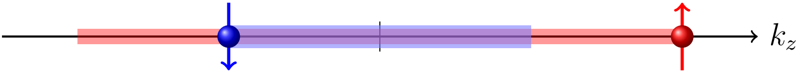

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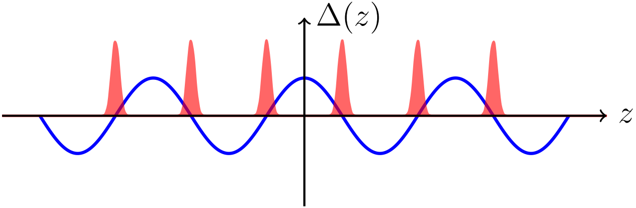
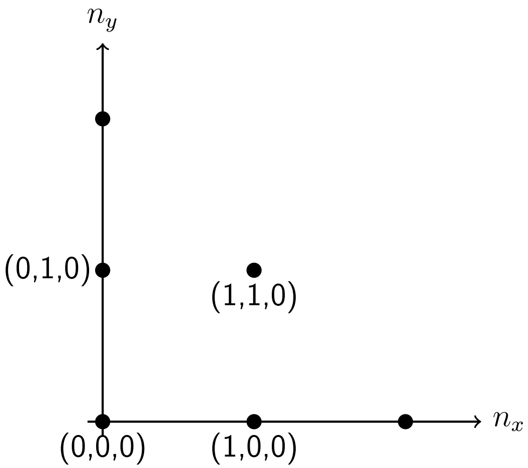
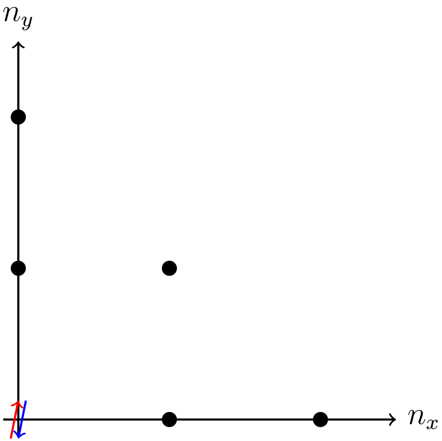


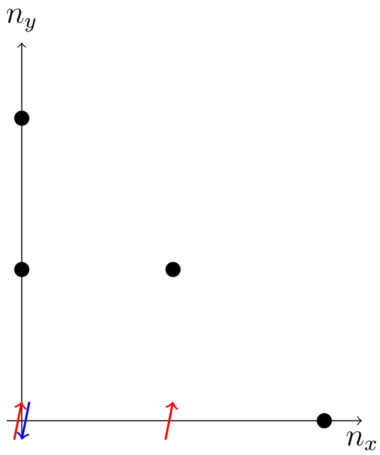
Spherical trap



Spherical trap: two atoms

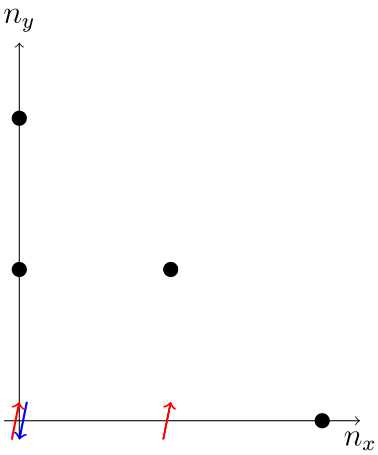


Spherical trap: three atoms

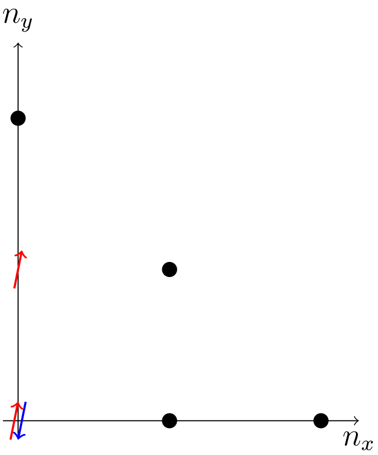


Excess up-spin in (1,0,0).

Spherical trap: three atoms

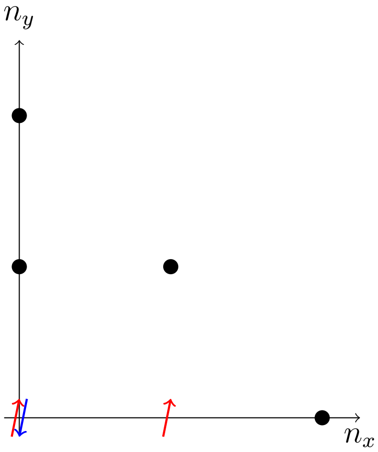


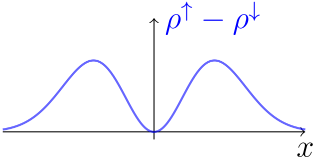
Excess up-spin in (1,0,0).



Excess up-spin in (0,1,0).

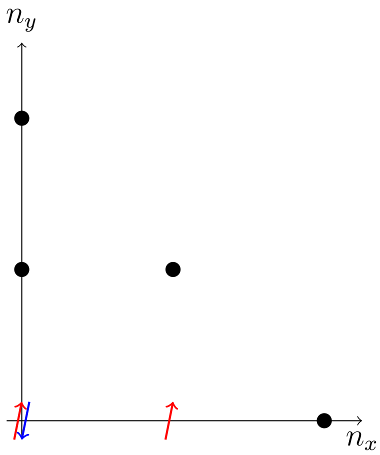
Three atoms: magnetisation

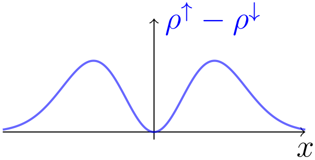


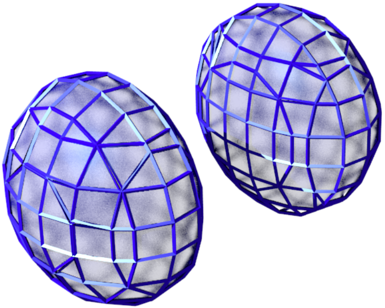


Excess up-spin in (1,0,0).

Three atoms: magnetisation

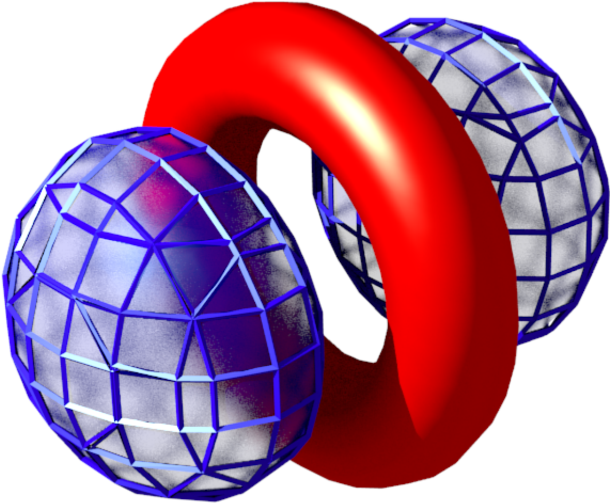




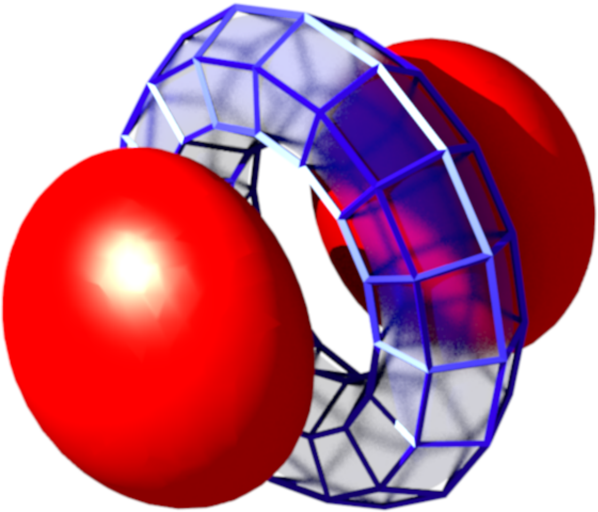


Excess up-spin in (1,0,0).

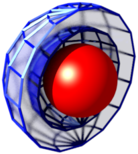
$N_\uparrow = 2, N_\downarrow = 1$



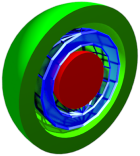
$N_{\uparrow} = 3, N_{\downarrow} = 1$



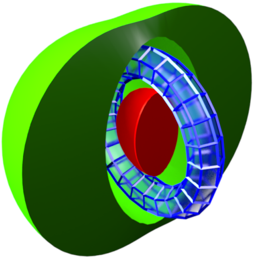
More atoms



$N_\uparrow = 4, N_\downarrow = 1$



$N_\uparrow = 5, N_\downarrow = 1$



$N_\uparrow = 5, N_\downarrow = 2$

Conclusions

Few fermion systems allow the study of the emergence of complex many-body phenomena in a theoretically and experimentally tractable setting.

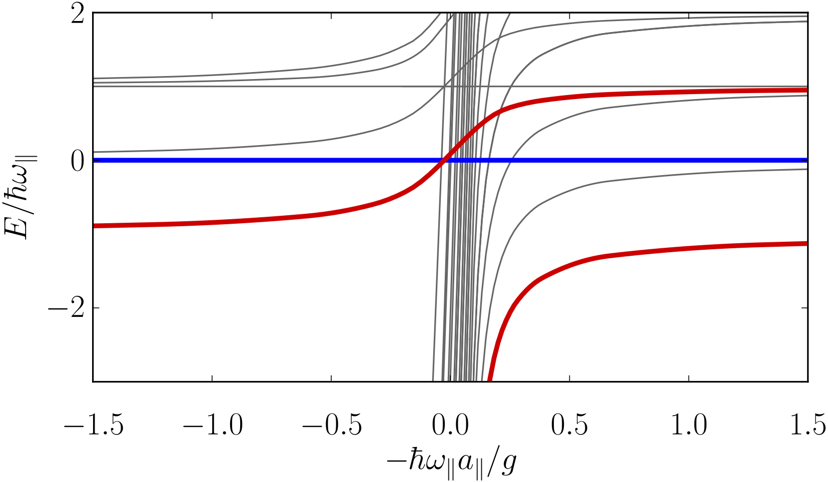
Repulsive interactions

- Repulsive polaron
- Emergence of itinerant magnetic correlations in the Super-Tonks regime

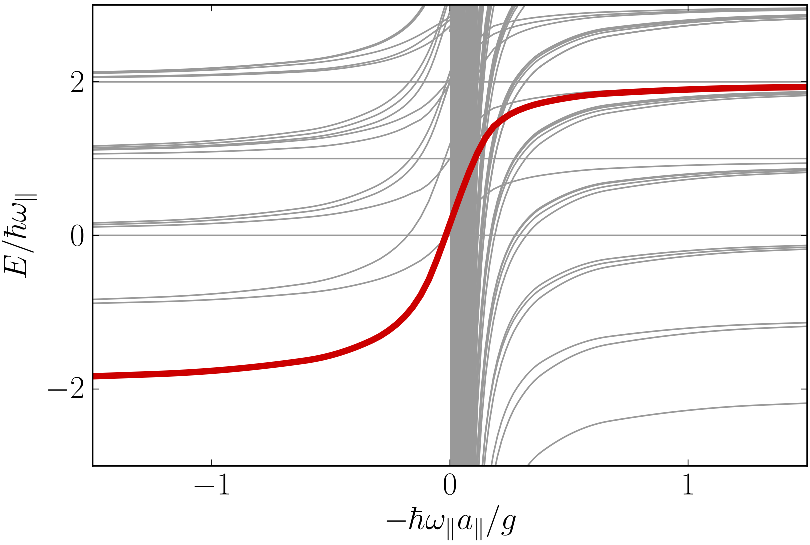
Attractive interactions

- Inhomogeneous pairing

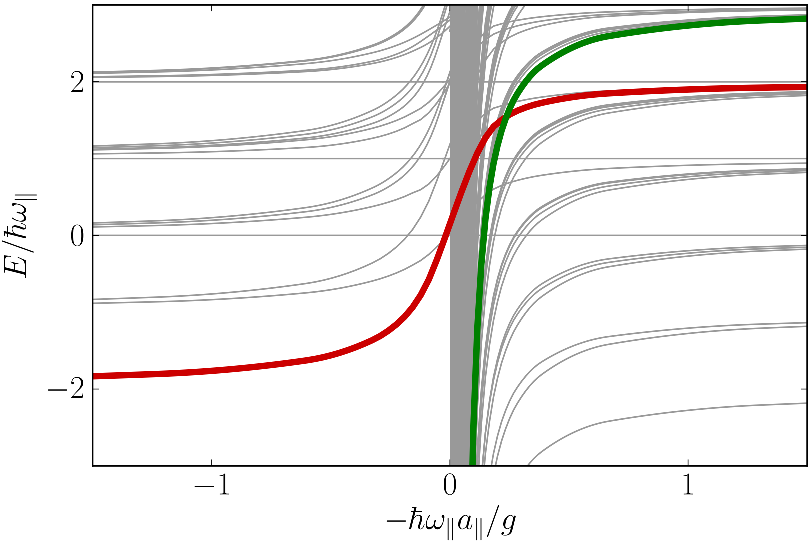
Band diagrams: $N_\uparrow = N_\downarrow = 1$



Band diagrams: $N_\uparrow = 2, N_\downarrow = 1$



Band diagrams: $N_\uparrow = 2, N_\downarrow = 1$



Band diagrams: $N_\uparrow = 3, N_\downarrow = 2$