Classical and Quantum Liquids Induced by Quantum Fluctuations

Miguel M. Oliveira†   Pedro Ribeiro†   Stefan Kirchner‡

†CeFEMA, Instituto Superior Técnico, Universidade de Lisboa Av. Rovisco Pais, 1049-001 Lisboa, Portugal
‡Zhejiang Institute of Modern Physics, Zhejiang University, Hangzhou, Zhejiang 310027, China

Ordered vs Liquid Phases

At low temperatures, materials typically transition into an ordered phase that spontaneously breaks some symmetry of the underlying microscopic system. Examples are ferromagnetic, superfluid and superconducting phases.

Frustrated interactions can lead to systems that evade this paradigm, the so-called **liquid phases**. They fail to order even at very low temperatures and are characterized by non-trivial low energy excitations that can be quite exotic.
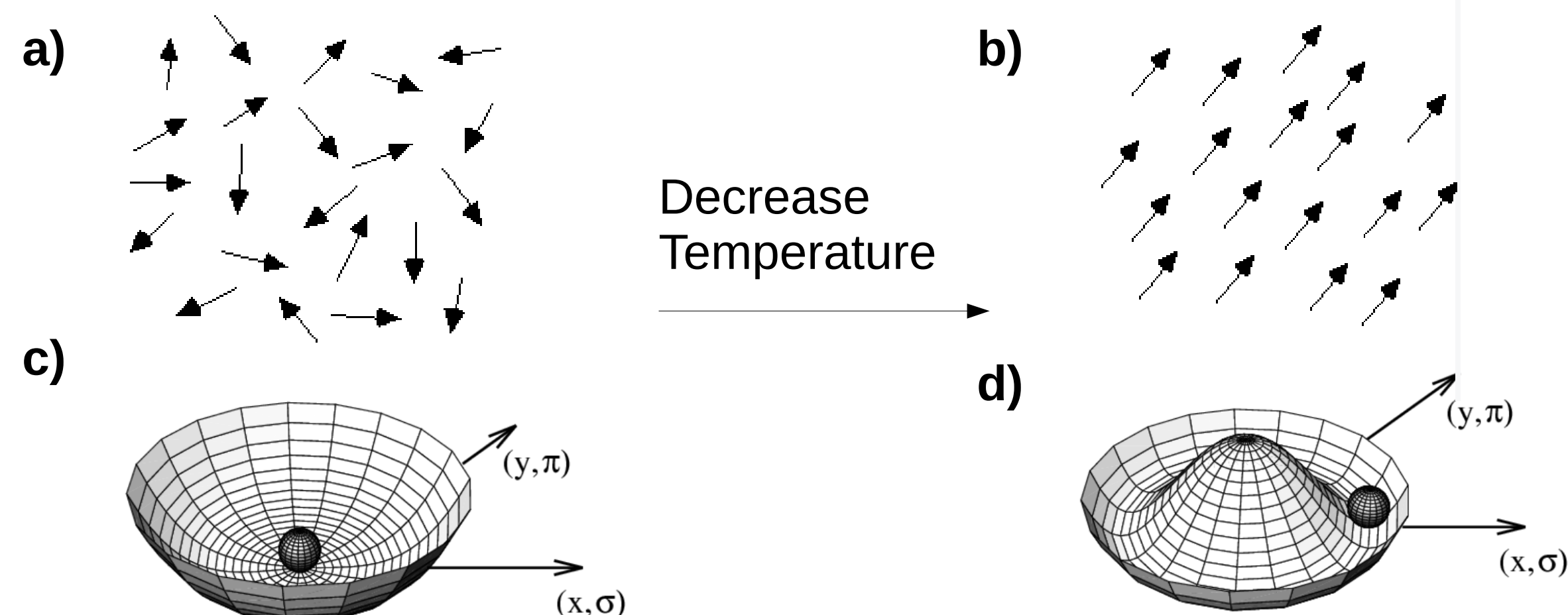
Figure 1: **a)** disordered, **b)** ordered spin configuration. Free energy for **c)** symmetric phase and d) symmetry-broken phase **[1]**.

Classical Liquids

Frustration occurs when there are competing interactions that cannot be mutually satisfied. This leads to a massive degeneracy of the ground state.

Examples of classical liquids:

- Anti-ferromagnetic Ising model on the triangular lattice, which possesses an extensive entropy at zero temperature;

- Spin Ice, whose ground state is also highly degenerate and obeys the local constraint of the ice rule. It contains "magnetic" monopole excitations.
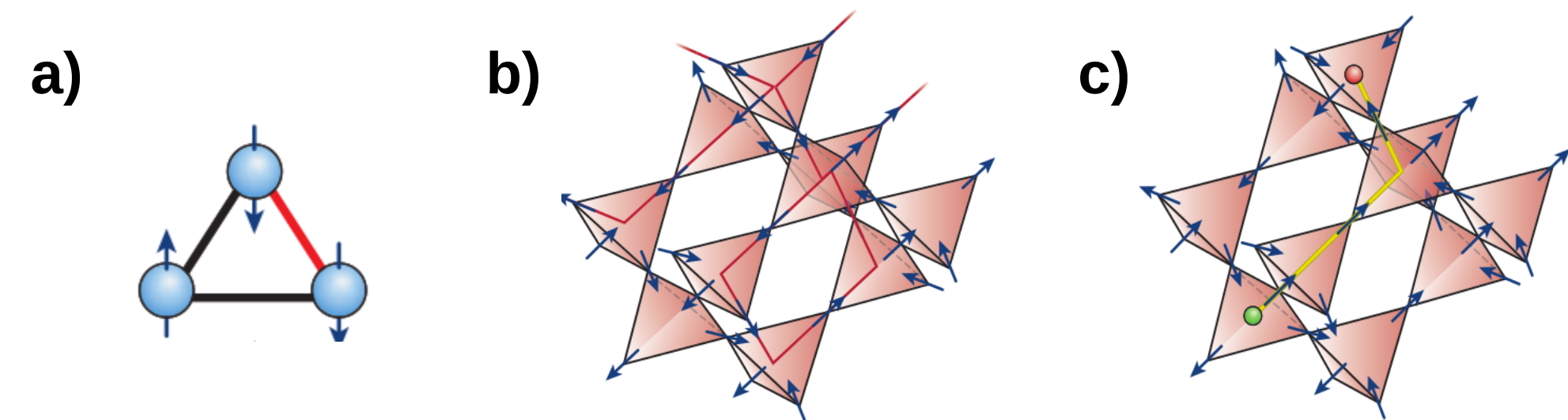
Figure 2: **a)** example of anti-ferromagnetic interaction on triangle. Spin ice **b)** displaying ice rule and **c)** with magnetic monopoles **[2]**.

Falicov-Kimball model

We studied the Falicov-Kimball model on the triangular lattice

$$H = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + U \sum_i n_{f,i} c_i^\dagger c_i - \mu_f N_f - \mu_c N_c$$

It's a hybrid model of both classical and quantum degrees of freedom. On the triangular lattice it can lead to frustrated interactions and liquid-like regimes at low temperature.
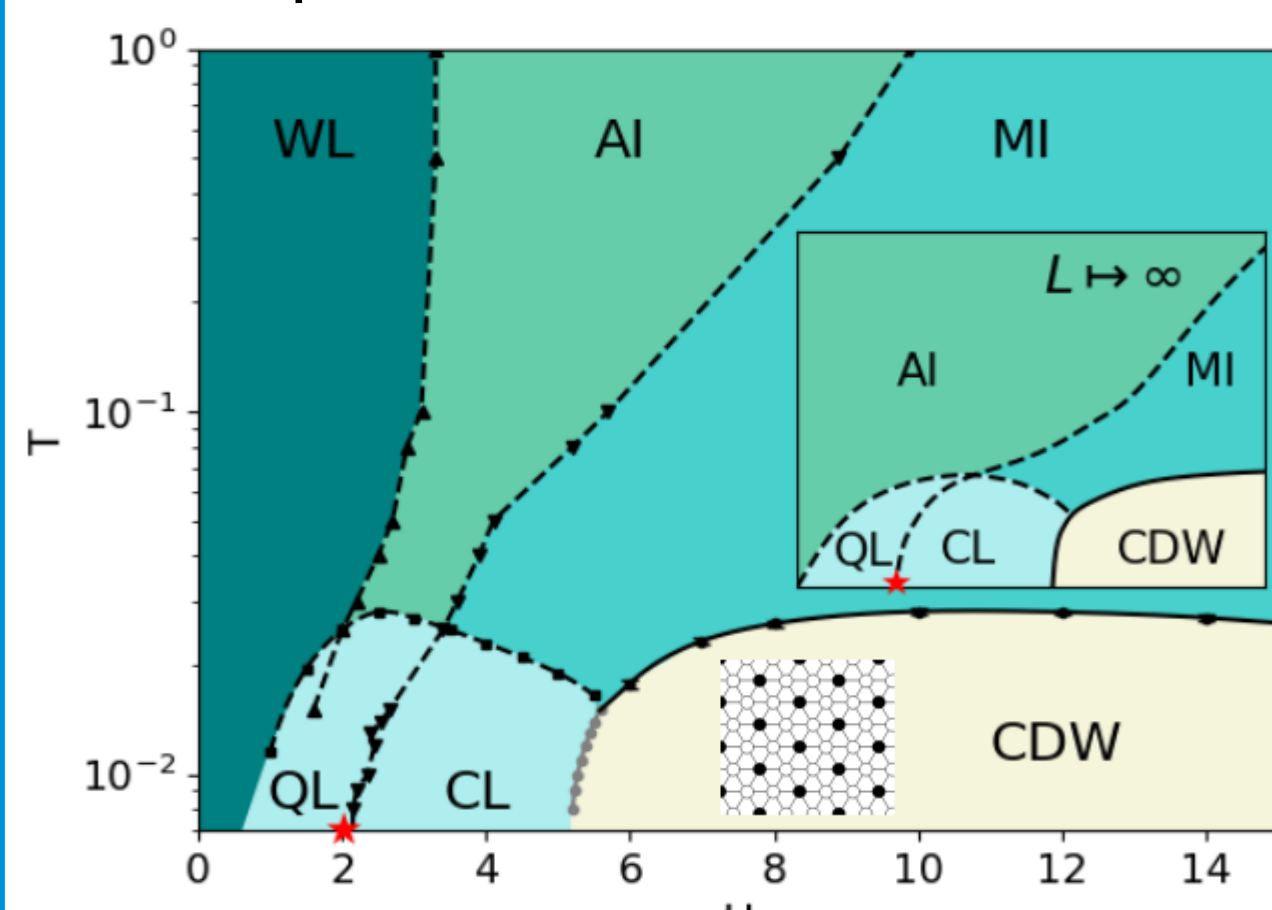
Figure 3: T-U phase diagram of the FK model on the triangular lattice for 1/3 filling **[3]**.

Frustration in the FK model

In the large U limit the FK model can be expanded into an effective classical model **[4]**. The competition of the different interactions is responsible for the frustration present in this model for some particle fillings.

$$H_{eff} = J_1 \sum_{|i-j|=1} s_i s_j + J_2 \sum_\Delta s_\Delta + J_3 \sum_P s_P + J_4 \sum_{|i-j|=\sqrt{3}} s_i s_j + J_5 \sum_{|i-j|=2} s_i s_j$$
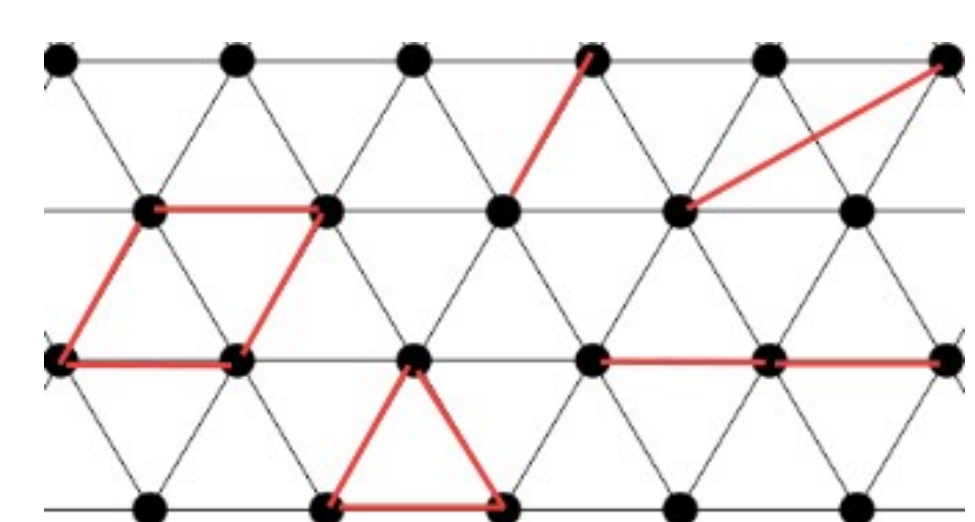
Figure 5: Schematic of the different interactions from the effective model.

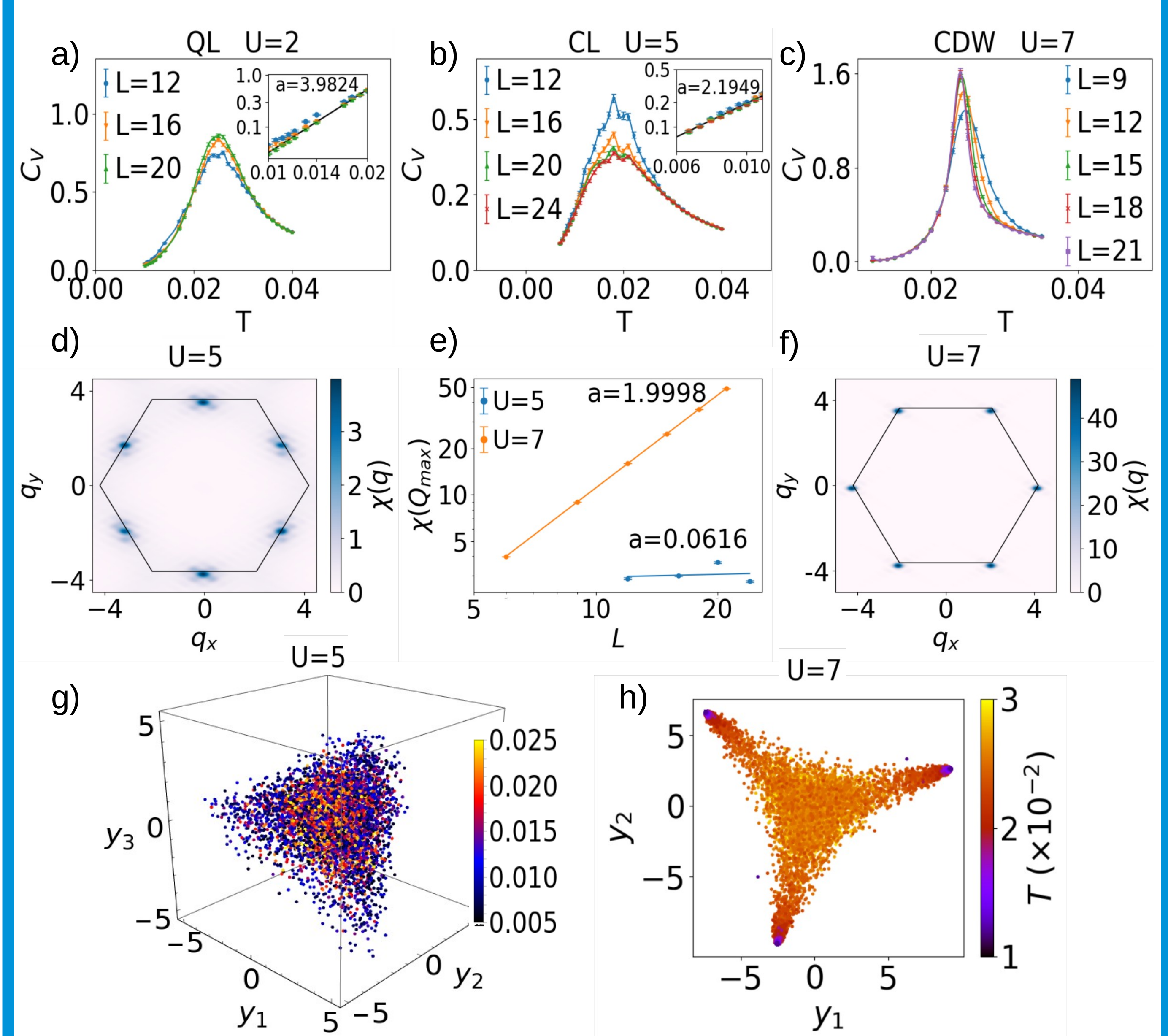## Analysis of the low temperature phases

Figure 4: Specific heat as a function of T for U = 2 **a)**, U = 5 **b)** and U = 7 **c)**. Momentum resolved susceptibility of the f-charges χ(q) for U = 5 **d)** and U=7 **f)**. Finite size scaling of χ(Q Max) with L **e)**. PCA yielding 3 most important components for U = 5 **g)** and 2 for U = 7 **h)**, plotted for a range of T **[3]**.

References

[1] V. Koch, International Journal of Modern Physics E, 06(02):203–249 (1997)
[2] L. Balents, Nature, 464:199 EP (2010)
[3] M. M. Oliveira, P. Ribeiro, S. Kirchner, arXiv:1810.10582 (2018) (accepted for publication in PRL)
[4] C. Gruber et al, Journal of Statistical Physics, 86(1):57–108 (1997)
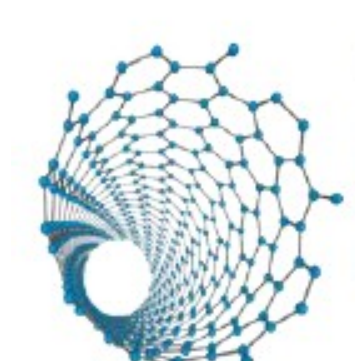
Future Work Directions

There are two main anticipated work directions:

- Verify if the liquid regions in the FK model are robust towards turning on the f-electron hopping;

- Obtain the phase diagram of the FK model on the triangular lattice at half-filling and compare it with the present results

TÉCNICO LISBOA

CeFEMA Center of Physics and Engineering of Advanced Materials

FCT Fundação para a Ciência e a Tecnologia

miguel.m.oliveira@tecnico.ulisboa.pt