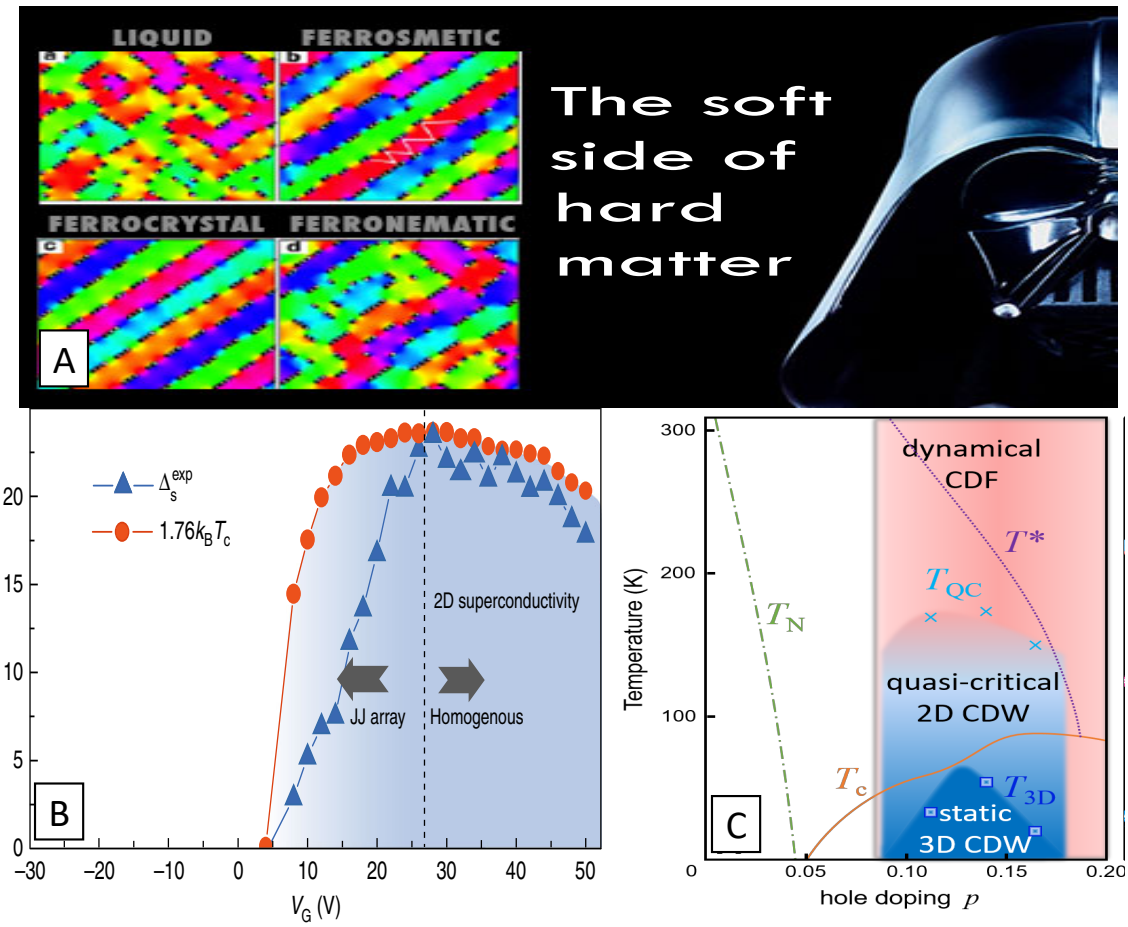
'THE SOFT SIDE OF HARD CONDENSED MATTER': THE SAGA GOES ON



(A) Various electronic phases that are expected to form by hole-doping an insulating $La_{2-x}Sr_xCuO_4$ cuprate [4]. The doped holes form `polymers' of charge and give rise to various soft-matter-like phases. (B) Gap and critical temperature of a $LaAlO_3/SrTiO_3$ superconducting interface as a function of gate potential (i.e. electron density)[2] (C) Phase diagram of $NdBa_2Cu_3O_{6+x}$ superconducting cuprates, where dynamical charge density fluctuations (CDF) have been recently discovered [7]

Electrons in solid metals customarily belong to the so-called `hard condensed matter.' They are usually highly mobile, minimize their energy by forming Bloch states, and are uniformly distributed in the whole system, as they essentially behave as a free electron gas (although correlations and the lattice may `dress' them, giving rise to fermionic quasiparticles with more or less increased effective mass). This standard `textbook' situation may drastically change when the metallic state is characterized by low electron density, `lives' in a reduced dimensionality, or competes with other phases of matter. Over the last two or three decades, hard condensed matter has faced an increasing interest in low-dimensional electrons systems and competing electronic phases. On the one hand, low-dimensional systems are of interest for nanoscopic devices because they are obviously smaller than bulky systems, because layers can be somewhat `adjusted' with external parameters, like strain, and the electron density can be more easily tuned with doping and gate fields. On the other hand, specific phenomena occur in low-dimensional systems, where ordered states are more hardly realized, opening the way to competitions between different phases (insulating, superconducting, magnetic, charge-ordered, …).

The key point is that all these effects are often accompanied by some form of softening of the electronic matter. In other words, when the electron density is the relevant parameter ruling the competition between phases, large fluctuations in the electron density occur leading to a generic softness (i.e., large compressibility) of the electronic matter. The consequences may be various,

ranging from high-temperature superconductivity, to glassy or nanoscopically inhomogeneous coexisting states. These issues, that are of obvious fundamental and applicative interest, have been theoretically addressed along the years by some people in Rome in collaboration with important italian and foreign experimental groups. The results of this work have been published in important scientific journals (among which Nature Materials and Science, see reference list), and show that electronic softness is at work, e.g., in some oxide interfaces (like $LaAlO_3/SrTiO_3$), where a low-density two-dimensional electron gas is sandwiched between insulating oxide layers. This two-dimensional gas may be driven superconducting, but clearly displays an inhomogeneous character, which is due to an intrinsic softness of the electron gas [1,2]. The inhomogeneous character is very sensitive to the filling of various electron sub-bands that are formed at the interface [1], so that there are interfaces for which the filling of a new sub-band results in a multi-condensate superconducting state that arguably appears less inhomogeneous [3].

In a previous episode of `the electron softness saga' a competition with magnetic states was instead at the origin of an electronic softness inducing an electronic nematic state in two classes (cuprates [4] and iron arsenide [5]) of high-temperature superconductors. Despite the quantum nature of electrons in metals, these nematic states shared several similarities with the nematic states occurring, e.g., in liquid crystals and in other classical soft-matter system. More recently it has been assessed that electron softness is widely at work in high-temperature superconducting cuprates, in the form of fluctuating electronic charge density waves. In this metallic state, the electron gas constantly feels `frissons' of density fluctuations, that greatly alter the metallic properties, giving rise to the highly anomalous behavior observed in these systems. What has recently and remarkably been found [6,7] is that these `shivers' of the electron gas are not a minor accessory phenomenon, rather they uniformly pervade the phase diagram of cuprates. This form of electron softness is therefore a constitutive characteristic of these systems.

In conclusion, the quite common occurrence, although in various forms, of electron softness in different systems and materials strongly suggests that it might be a rather universal feature of low-density and/or low-dimensional electronic states.

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