The mLPDA approach: the case of study of the Josephson effect

Verdiana Piselli[1], **Leonardo Pisani**[2], **Giancarlo Calvanese Strinati**[1,3]

1. *School of Science and Technology, Physics Division, CQM group, University of Camerino, 62032 Camerino (MC), Italy*
2. *Dipartimento di Fisica e Astronomia, Università di Bologna, Via Irnerio 46, 40126 Bologna, Italy*
3. *CNR-INO, Istituto Nazionale di Ottica, Sede di Firenze, 50125 (FI), Italy*

Abstract: The mLPDA approach offers an efficient way to investigate inhomogeneous superconducting systems, treating pairing fluctuations and inhomogeneity on equal footing, with no need for external parameters, providing a simpler alternative to previously developed approaches.

The investigation of the Josephson effect plays a pivotal role in the design of superconducting devices for the implementation of quantum technology, ranging from the standard Al-based [1] to the more exotic twisted high-Tc junctions [2]. To properly investigate these inhomogeneous superconducting systems, a theoretical approach that treats inhomogeneity and pairing fluctuations on equal footing needs to be developed. In this regard, efforts have been made to provide a suitable generalization of the Bogoliubov-de Gennes (BdG) equations through an extension of density-functional theory to superconductors [3,4]. However, these approaches retain the numerical complexity of the BdG equations, and their reliance on external parameters limits their application to T=0 along the BCS side of the crossover up to unitarity.

For these reasons, we have developed a new approach, called mLPDA (modified Local Phase Density Approximation) [5], which include pairing fluctuations at the level of the non-self-consistent *t*-matrix approximation, on top of the LPDA equation (based on a coarse-graining of the BdG equations) [6]. We have applied this approach to investigate the experimental systems realized in Refs. [7, 8] with superfluid atoms, and obtained a good quantitative agreement for the Josephson critical current both as a function of coupling at low temperature and as function of temperature at unitarity [9].

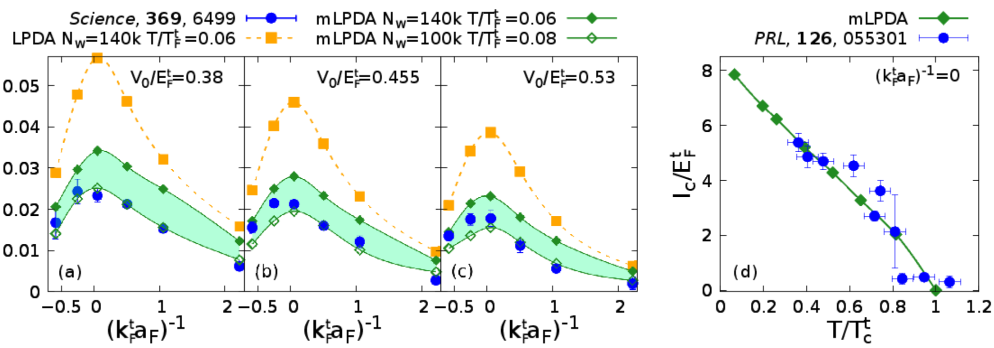

Fig. 1 (a) (b) (c) Comparison between the theoretical results (the orange squares and the green diamonds represent the LPDA and mLPDA outcomes, respectively) and the experimental data (blue dots) for the Josephson critical current vs coupling at low temperature. (d) Comparison between the theoretical results (green diamonds) and the experimental data (blue dots) for the Josephson critical curret at unitarity as a function of temperature.

The usefulness of the mLPDA approach relies on the fact that it could be further improved due to its built-in modularity, it does not need external parameters and can be applied to investigate inhomogeneous superfluid systems throughout the whole coupling-temperature phase diagram in the broken-symmetry phase, without limitation.

References

[1] A. Barone, G. Paternò, *Physics and Applications of the Josephson Effect* (New York, Wiley, 1982).

[2] V. Brosco, G. Serpico, V. Vinokur, N Poccia, U. Vool, "Superconducting Qubit Based on Twisted Cuprate Van der Waals Heterostructures", Phys. Rev. Lett. **132**, 017003 (2024).

[3] L. N. Oliveira, E. K. U. Gross, and W. Kohn, "Density-functional theory for superconductors", Phys. Rev. Lett. **60**, 2430 (1988).

[4] A. Bulgac, M. McNeil Forbes, P. Magierski, *The BCS-BEC Crossover and the Unitary Fermi Gas*, W. Zwerger, (Springer-Verlag, Berlin, Heidelberg, 2012) Chapter.

[5] L. Pisani, V. Piselli, G. C. Strinati, "Inclusion of pairing fluctuations in the differential equation for the gap parameter for superfluid fermions in the presence of nontrivial spatial constraints", Phys. Rev. B **108**, 214503 (2023).

[6] S. Simonucci, G. C. Strinati, "Equation for the superfluid gap obtained by coarse graining the Bogoliubov–de Gennes equations throughout the BCS-BEC crossover", Phys. Rev. B **89**, 054511 (2014).

[7] W. J. Kwon, G. Del Pace, R. Panza, M. Inguscio, W. Zwerger, M. Zaccanti, F. Scazza, and G. Roati, "Strongly correlated superfluid order parameters from dc Josephson supercurrents", Science **369**, 84 (2020).

[8] G. Del Pace, W. J. Kwon, M. Zaccanti, G. Roati, F. Scazza, "Tunneling transport of unitary fermions across the superfluid transition", Phys. Rev. Lett. **126**, 055301 (2021).

[9] Piselli, V.; Pisani, L.; Strinati, G.C. "Josephson current flowing through a nontrivial geometry: Role of pairing fluctuations across the BCS-BEC crossover", Phys. Rev. B **108**, 214504 (2023).