Master 2: ***International Centre for Fundamental Physics***

INTERNSHIP PROPOSAL

(One page maximum)

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Thesis possibility after internship: YES
Funding already obtained for a PhD: NO If YES, which type of funding:

Quantum geometry effects on collective modes in superconductors

The recent experimental discovery of the Higgs particle matching the theoretical prediction of the Standard Model is among the great achievements of physics. The underlying mechanism by which a bosonic condensate (the Higgs field) produces massless modes (such as photons) and gapped modes (the Higgs mode, or "particle") was first predicted by P.W. Anderson [1] in condensed matter systems, namely as the two excitations of a superconductor, which is a condensate of Cooper pairs of electrons. The Anderson-Higgs mode was observed in recent years in quantum materials too, including the NbSe2 superconductor [2]. This superconductor has multiple Cooper condensates (due to multiple electronic bands), allowing for another collective mode of oscillation between condensates, predicted by Leggett, and experimentally detected recently [3]. The NbSe2 material received a lot of interest due to its spin-orbit coupling, that leads to quantum geometric effects. The theoretical question is hence: How does quantum geometry interplay with collective modes in multiband superconductors?

Theoretically, the Anderson-Higgs modes have been studied systematically [4] for single-band superconductors in quench experiments, while the more elusive Leggett mode was studied [5] for spectroscopic experiments. In our group at LPS Orsay we have studied the interplay of quantum geometry and multiband spin-orbit-coupled superconductors such as NbSe2 [6], in the context of spectroscopy and thermodynamics.

In this internship, the student will study analytically and numerically the dynamics of multiple superconducting condensates in toy models of two-dimensional superconductors with multiple bands and spin-orbit coupling. The models are inspired by NbSe2, with the idea to tune the parameters and observe the effects, if any, of the quantum geometry. The analytical part requires a Bogoliubov-de Gennes self-consistent mean-field description of the superconductor. A simple static problem can be considered first, extracting the effects of quantum geometry on the transition temperatures in presence of magnetic field. Studying the collective modes next, numerics will be required to solve the time-dependent equations of motion. The study will be complemented with time-dependent versions of Ginzburg-Landau equations for the superconducting condensates.

[1] P.W. Anderson, Phys. Rev. **110**, 827 (1958); P. W. Higgs, Phys. Rev. Lett. 13, 508 (1964).
[2] M.-A. Méasson *et al.,* Phys. Rev. B **89**, 060503(R) (2014).
[3] A.J. Leggett, *Prog of Theor Phys*, 36, 901 (1966); J.J. Cuozzo, Nat. Phys. 20, 1118 (2024).
[4] L. Schwarz *et al., Nature Communications* 11, 287 (2020).
[5] M.V. Klein, Phys. Rev. B **82**, 014507 (2010).
[6] L. Engström *et al.*, arXiv :2412.13042 ; M. Uldemolins et al., PRB 110, 224519 (2024).

Please, indicate which speciality(ies) seem(s) to be more adapted to the subject:

Condensed Matter Physics:	YES	Soft Matter and Biological Physics:	NO
Quantum Physics:	YES	Theoretical Physics:	YES