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### **Who is the Lord of the Rings in the Zeeman-spin-orbit Saga: Majorana, Dirac or Lifshitz?<sup>1</sup>**

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I discuss the simultaneous effects of Zeeman and spin-orbit fields during the evolution from BCS to BEC superfluidity for ultra-cold fermions. It has been recently demonstrated experimentally that Zeeman or spin-orbit fields and interactions can be tuned in the context of ultra-cold atoms and allow for the visitation of several different phases. For systems with zero Zeeman field, the evolution from BCS to BEC superfluidity in the presence of spin-orbit effects is only a crossover [1] as the system remains fully gapped, even though a triplet component of the order parameter emerges. In contrast, for finite Zeeman fields, spin-orbit coupling induces a triplet component in the order parameter that produces nodes in the quasiparticle excitation spectrum leading to bulk topological phase transitions of the Lifshitz type [2]. Additionally, a fully gapped phase exists, where a crossover from indirect to direct gap occurs. For spin-orbit couplings with equal Rashba and Dresselhaus strengths the nodal quasi-particles are Dirac fermions that live at and in the vicinity of rings of nodes. Transitions from and to nodal phases can occur via the emergence of zero-mode Majorana fermions at phase boundaries, where rings of nodes of Dirac fermions annihilate [3,4]. Lastly, I characterize different phases via spectroscopic and thermodynamic properties and conclude that Lifshitz is the “Lord of the Rings.”

[1] Li Han, C. A. R. Sá de Melo, “Evolution from BCS to BEC superfluidity in the presence of spin-orbit coupling,” Phys. Rev. A 85, 011606(R) (2012), see also arXiv:1106.3613v1.

[2] Kangjun Seo, Li Han and C. A. R. Sá de Melo, “Topological phase transitions in ultra-cold Fermi superfluids: the evolution from BCS to BEC under artificial spin-orbit fields,” Phys. Rev. A 85, 033601 (2012), see also arXiv:1108.4068v2.

[3] Kangjun Seo, Li Han and C. A. R. Sá de Melo, “Artificial spin-orbit coupling in ultra-cold Fermi superfluids,” arXiv:1110.6364v1.

[4] Kangjun Seo, Li Han, and C. A. R. Sá de Melo, “Emergence of Majorana and Dirac Particles in Ultracold Fermions via Tunable Interactions, Spin-Orbit Effects, and Zeeman Fields,” Phys. Rev. Lett. 109, 105303 (2012), see also arXiv:1201.0177v1.

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