

Critical phenomena in compressible polar active fluids: Dynamical and functional renormalization group studies

Patrick Jentsch[✉] and Chiu Fan Lee[✉]

Department of Bioengineering, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom

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Active matter is not only relevant to living matter and diverse nonequilibrium systems, but also constitutes a fertile ground for novel physics. Indeed, dynamic renormalization group (DRG) analyses have uncovered many new universality classes (UCs) in polar active fluids (PAFs)—an archetype of active matter systems. However, due to the inherent technical difficulties in the DRG methodology, almost all previous studies have been restricted to polar active fluids in the incompressible or infinitely compressible (i.e., Malthusian) limits, and, when the ϵ -expansion was used in conjunction, to the one-loop level. Here, we use functional renormalization group (FRG) methods to overcome some of these difficulties and unveil critical behavior in compressible polar active fluids, and calculate the corresponding critical exponents beyond the one-loop level. Specifically, we investigate the multicritical point of compressible PAFs, where the critical order-disorder transition coincides with critical phase separation. We first study the critical phenomenon using a DRG analysis and find that it is insufficient since two-loop effects are important to obtain a nontrivial correction to the scaling exponents. We then remedy this defect by using a FRG analysis. We find three universality classes and obtain their critical exponents, which we then use to show that at least two of these universality classes are out of equilibrium because they violate the fluctuation-dissipation relation.

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I. INTRODUCTION

Active matter refers to many-body systems in which the microscopic constituents can exert forces or stresses on their surroundings and, as such, detailed balance is broken at the microscopic level [1,2]. However, even if the microscopic dynamics are fundamentally different from more traditional systems considered in physics, it remains unclear whether novel behavior will emerge in the hydrodynamic limits (i.e., the long-time and large-distance limits [3]). One unambiguous way to settle this question is to identify whether the system's dynamical and temporal statistics are governed by a new universality class (UC), typically characterized by a set of scaling exponents [4–6]. These exponents can in principle be determined using either simulation or renormalization group (RG) methods. However, simulation studies can be severely plagued by finite-size effects (e.g., two recent controversies concern the scaling behavior of active polymer networks [7,8] and critical motility-induced phase separation [9–11]). Therefore, RG analyses remain as of today the gold standard in the categorization of dynamical systems into distinct UCs. This perspective has been particularly fruitful in bio-

logical physics, where many new nonequilibrium universality classes have been discovered in biology inspired systems [12–15]. Specifically for polar active fluids (PAFs) [16–18], an archetype of active matter systems, the use of dynamic renormalization group (DRG) [19] analyses have led to, on one hand, surprising realizations that certain types of PAFs are no different from thermal systems in the hydrodynamic limit [20,21], and on the other hand discoveries of diverse novel phases [17,18,22–30], critical phenomena [31–33] and discontinuous phase transitions [34]. However, due to the inherent technical difficulties in DRG methods, all of these studies have been restricted to PAFs in the incompressible or infinitely compressible (i.e., Malthusian) limits except for rare exceptions [23,24]. Further, when a DRG analysis was used in conjunction with the ϵ -expansion method, which was typically the case, it has always been restricted to the one-loop level.

In this paper, we apply functional RG (FRG) methods [35–42] on compressible PAFs and overcome some of these technical challenges. Specifically, we investigate a multicritical region of “dry” (i.e., momentum nonconserving) compressible PAFs. Although experimentally less accessible than simple critical points, multicritical points (MCPs) can offer surprising new physics, even in models that are thought to be well understood. For instance, nonperturbative fixed points have been discovered in the extensively studied $O(N)$ model [43], and in systems where two order parameters compete, whose individual critical points belong to equilibrium universality classes, the multicritical region where both critical points coincide can be manifestly out of equilibrium and demonstrate intriguing, spiral phase diagrams [44].

[✉]p.jentsch20@imperial.ac.uk

[✉]c.lee@imperial.ac.uk

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Dynamical Aspects Of Critical Phenomena

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