



Packed Swarms on Dirt: Two-Dimensional Incompressible Flocks with Quenched and Annealed Disorder

Leiming Chen, Chiu Fan Lee, Ananyo Maitra, John Toner

► To cite this version:

Leiming Chen, Chiu Fan Lee, Ananyo Maitra, John Toner. Packed Swarms on Dirt: Two-Dimensional Incompressible Flocks with Quenched and Annealed Disorder. *Physical Review Letters*, 2022, 129, 10.1103/physrevlett.129.188004 . hal-03889088

HAL Id: hal-03889088

<https://hal.science/hal-03889088>

Submitted on 7 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Packed Swarms on Dirt: Two-Dimensional Incompressible Flocks with Quenched and Annealed Disorder

Leiming Chen^{1,*}, Chiu Fan Lee^{2,†}, Ananyo Maitra^{3,‡}, and John Toner^{4,5,§}

¹*School of Material Science and Physics, China University of Mining and Technology, Xuzhou Jiangsu, 221116, People's Republic of China*

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

³*Laboratoire de Physique Théorique et Modélisation, CNRS UMR 8089, CY Cergy Paris Université, F-95032 Cergy-Pontoise Cedex, France*

⁴*Department of Physics and Institute of Theoretical Science, University of Oregon, Eugene, Oregon 97403, USA*

⁵*Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Strasse 38, 01187 Dresden, Germany*



(Received 28 May 2022; accepted 14 September 2022; published 27 October 2022)

We show that incompressible polar active fluids can exhibit an ordered, coherently moving phase even in the presence of quenched disorder in two dimensions. Unlike such active fluids with *annealed* disorder (i.e., time-dependent random white noise) *only*, which behave like equilibrium ferromagnets with long-range interactions, this robustness against quenched disorder is a fundamentally nonequilibrium phenomenon. The ordered state belongs to a new universality class, whose scaling laws we calculate using three different renormalization group schemes, which all give scaling exponents within 0.02 of each other, indicating that our results are quite accurate. Our predictions can be quantitatively tested in readily available artificial active systems and imply that biological systems such as cell layers can move coherently *in vivo*, where disorder is inevitable.

DOI: [10.1103/PhysRevLett.129.188004](https://doi.org/10.1103/PhysRevLett.129.188004)

One of the most significant discoveries in statistical mechanics in the 20th century was the “Mermin-Wagner-Hohenberg” theorem [1], which says that continuous symmetries cannot be spontaneously broken in equilibrium two-dimensional systems at finite temperature. This implies, in particular, that magnetic systems with continuous rotational symmetry like the XY or Heisenberg models cannot exhibit long-range polar order characterized by a nonzero magnetization in two dimensions (2D).

It is precisely for this reason that it was so surprising to learn that 2D *active* systems *can* spontaneously develop long-range polar order even in the presence of noise [2–6]. In particular, polar self-propelled particles moving over a frictional substrate (a system often described as a “dry polar active fluid”) can “flock,” that is, form a state with a nonzero average velocity $\langle \mathbf{v} \rangle$, even when perturbed by noise.

In equilibrium systems, it is known that *quenched* disorder [7–10]—that is, disorder that is time *independent*—is even more destructive of long-range order than thermal noise, which is, of course, time *dependent*. Indeed, even arbitrarily small quenched disorder destroys long-ranged ferromagnetic and crystalline order in all spatial dimensions $d \leq 4$ [7–10].

The above discussion raises the obvious question: Can active systems retain long-range order even in the presence of quenched disorder [11–20]? It has been shown [11,12] that, for three-dimensional dry polar active systems with quenched disorder, long-range polar order (i.e., a nonzero

average velocity $\langle \mathbf{v} \rangle$) can survive such quenched disorder. But in 2D, only quasi-long-range polar order (i.e., $\langle \mathbf{v} \rangle$ vanishes as a power of system size L as $L \rightarrow \infty$) was found [11,12,21].

In this Letter, we report that it is possible to achieve true *long-range* polar order in 2D in dry polar active systems with quenched disorder, if those systems are *incompressible*.

There are many ways to experimentally realize incompressibility in active systems. One is to make them very dense so that the effective compressibility of the flocks vanishes [22,23]. An even more realizable incompressible system is a suspension of swimmers in a fluid confined in a narrow channel with “no slip” or “partial slip” boundary conditions at the channel wall. Such boundary conditions destroy momentum conservation in the fluid. Here, the active agents “inherit” the incompressibility of the background fluid [23–25]. Strictly speaking, swimmer suspensions differ from the systems we consider here, due to the presence of an extra hydrodynamic variable in the former: the density of the swimmers. However, if the swimmers in the channel are constantly being born and dying [26] or can switch between an active, motile state and a passive, immotile one, so that the number of active swimmers is not globally conserved, the dynamics of the system is described by the theory presented here.

Finally, spin systems interacting via dipolar interactions have the same long-time, large-distance properties as magnets with a divergence-free constraint on the

magnetization [22,27]. It has further been shown [28–30] that the hydrodynamics of spin systems with non-equilibrium and nonreciprocal asymmetric interactions are described by the equations originally constructed for (Malthusian) flocks [26]. Therefore, the hydrodynamics of dipolar magnets with asymmetric exchange interactions [30] is equivalent to incompressible flocks [22,31]. If such a magnetic system were subject to quenched disorder, it would again be described by the theory we develop here.

Any real flock with short-ranged interactions will, of course, be compressible, even if only slightly so. Our results should still apply to such systems, provided (i) that the “Mach number” $M \equiv (v_0/c)$, defined as the ratio of the typical speed v_0 of the motile active agents to the typical sound speed c , is very small (i.e., $M \ll 1$), and (ii) that the length scales L under consideration are so small that the longest-wavelength sound mode has a period much shorter than the shortest-wavelength diffusive mode under consideration. This requirement leads to the condition

$$\frac{L}{c} \ll \frac{a^2}{\mu}, \quad (1)$$

where μ is a typical diffusion constant and a is a microscopic length. This condition can be rewritten as

$$L \ll L_c \equiv \frac{a^2 c}{\mu}, \quad (2)$$

which makes it clear that systems with a large sound speed c will be well described by our theory out to extremely large length scales L_c . For example, estimating μ as the kinematic viscosity of water (10^{-2} cm²/sec), c as the sound speed in water (1.5×10^5 cm/sec), and $a \sim 5$ μ m (a typical bacteria size) gives $L_c \sim 3.75$ cm, which is enormous on the scale of a bacteria swarm.

Motivated by all of the examples above, we consider here incompressible flocks in 2D [22] on a substrate with quenched disorder. We also include the effects of “annealed” disorder (by which we mean simply the usual time-dependent “Langevin white noise”), which proves to be subdominant for the equal-time correlations but gives time dependence to the fluctuations, which would otherwise be static. Considering the full nonlinear theory, we demonstrate that the moving phase of such a flock can sustain long-range polar order. A similar result was found, based on a purely *linearized* theory, for number-conserving active suspensions with quenched disorder [32] (which, as noted above, differ somewhat from our system).

Using a dynamic renormalization group (DRG) analysis, we calculate the long-time, large-distance scaling of the fluctuations $\mathbf{u}(\mathbf{r}, t)$ of the local active fluid velocity $\mathbf{v}(\mathbf{r}, t)$ about its mean value $\langle \mathbf{v} \rangle \equiv v_0 \hat{\mathbf{x}}$, where we have defined our coordinate system so that $\hat{\mathbf{x}}$ is along the mean velocity spontaneously chosen by the system. This analysis leads to

scaling laws for the correlations of $\mathbf{u}(\mathbf{r}, t) \equiv \mathbf{v}(\mathbf{r}, t) - v_0 \hat{\mathbf{x}}$, which we obtain using three different DRG schemes: two different $d = (d_c - \epsilon)$ expansions, which we term “hard continuation” and “soft continuation,” and an uncontrolled expansion in exactly 2D.

Specifically, we show that the $u-u$ correlations are given by

$$\langle \mathbf{u}(\mathbf{r}, t) \cdot \mathbf{u}(\mathbf{0}, 0) \rangle = |y|^{2\chi} \mathcal{G}_Q \left(\frac{|x|}{|y|^\zeta} \right) + |y|^{2\chi'} \mathcal{G}_A \left(\frac{|x|}{|y|^\zeta}, \frac{|t|}{|y|^z} \right), \quad (3)$$

where $\mathcal{G}_{A,Q}$ are scaling functions that are universal up to an overall multiplicative factor, corresponding to the annealed (i.e., time-dependent) and quenched parts of the correlations, respectively. The exponents in Eq. (3) are

$$z = 0.49 \pm 0.01, \quad \zeta = 0.77 \pm 0.01, \quad (4a)$$

$$\chi = -0.23 \pm 0.01, \quad \chi' = -0.37 \pm 0.02, \quad (4b)$$

in the physical case $d = 2$, where the error bars correspond to the differences between the three aforementioned DRG schemes. The fact that both χ and χ' are negative implies that the fluctuations of the velocity field about a *nonzero* mean velocity are finite and, hence, that the system has long-range polar order [33].

The existence of a common anisotropy exponent ζ for the quenched and the annealed parts of the correlation function (3) and a simple scaling form for the latter is a highly nontrivial result, which is a direct consequence of the anomalous hydrodynamics of our system. Indeed, a *linearized* treatment of our hydrodynamic model predicts a much more complicated “double-scaling” form, with different anisotropy exponents for the quenched and annealed correlations, and a more complicated form for the annealed part of the correlation function (what we mean by this will become clear below). The latter is reminiscent of, e.g., simple fluids, whose spatiotemporal correlation functions have a structure that reflects both the dispersionless propagation of sound [which is characterized by a dynamic exponent ($z = 1$) and the diffusive nature of viscous damping ($z = 2$)].

Model.—The hydrodynamic equation of motion (EOM) of incompressible polar active fluids moving on a disordered substrate can be constructed based on symmetry considerations alone [3,4,22,31,34] and is, therefore, a description of the long-time, large-distance behavior of incompressible flocks formed by *all* kinds of active polar particles regardless of the details of their interactions, as long as those interactions (i) are short-ranged and (ii) do not break any symmetries such as rotation and translation invariance. We defer its derivation to the companion paper [35]. The EOM in the moving phase is identical to that studied in Ref. [22], except for the presence of the

quenched noise. Specifically, keeping only “relevant” terms, by which we mean terms that can change the long-distance, long-time behavior of the system, the EOM governing $\mathbf{u}$ is, in Einstein component notation,

$$\begin{aligned} \partial_t u_i = & -\partial_i \Pi - \gamma \partial_x u_i - b \delta_{ix} \partial_x u_x + \mu_\perp \partial_y^2 u_i + f_Q^i + f_A^i \\ & + \mu_x \partial_x^2 u_i - \alpha \left(u_x + \frac{u_y^2}{2v_0} \right) \left(\delta_{ix} + \frac{u_y}{v_0} \delta_{iy} \right), \end{aligned} \quad (5)$$

where the indices i and j label the spatial coordinates. In Eq. (5), the “pressure” Π acts as a Lagrange multiplier to enforce the incompressibility condition: $\nabla \cdot \mathbf{u} = 0$, while γ and b are (positive or negative) constants, and α and $\mu_{x,\perp}$ are positive constants [35]. The quenched and annealed noises $\mathbf{f}_Q(\mathbf{r})$ and $\mathbf{f}_A(\mathbf{r}, t)$, respectively, are zero mean Gaussian white noises with variances:

$$\langle f_Q^i(\mathbf{r}) f_Q^j(\mathbf{r}') \rangle = 2D_Q \delta_{ij} \delta^2(\mathbf{r} - \mathbf{r}'), \quad (6a)$$

$$\langle f_A^i(\mathbf{r}, t) f_A^j(\mathbf{r}', t') \rangle = 2D_A \delta_{ij} \delta^2(\mathbf{r} - \mathbf{r}') \delta(t - t'). \quad (6b)$$

Note the time independence of the noise $\mathbf{f}_Q(\mathbf{r})$; this is what we mean by “quenched.” As mentioned earlier, Eq. (5) differs from the EOM in Ref. [22] only through the presence of the quenched noise $\mathbf{f}_Q(\mathbf{r})$. Note also that the annealed noise $\mathbf{f}_A(\mathbf{r}, t)$ is simply the usual delta-correlated white noise used to model the stochastic dynamics of active agents.

Linear regime.—The linearized version of EOM (5) is solved in Fourier space by projecting Eq. (5) transverse to the wave vector using the projection operator $P_{li}(\mathbf{q}) = \delta_{li} - (q_l q_i / q^2)$. Autocorrelating these solutions and using the correlations (6a) and (6b) for the noises, we obtain the correlation functions

$$\langle u_i(\tilde{\mathbf{q}}) u_i(\tilde{\mathbf{q}}') \rangle = C_A^i(\tilde{\mathbf{q}}, \tilde{\mathbf{q}}') + C_Q^i(\tilde{\mathbf{q}}, \tilde{\mathbf{q}}'), \quad (7)$$

where $\tilde{\mathbf{q}} \equiv (\mathbf{q}, \omega)$, with ω being the frequency and $\mathbf{q}$ the wave vector of the perturbation,

$$C_A^{x,y}(\tilde{\mathbf{q}}, \tilde{\mathbf{q}}') = \frac{q_{y,x}^2}{q^2} \frac{2D_A \delta(\omega + \omega') \delta(\mathbf{q} + \mathbf{q}')}{[\omega - (\frac{bq_x^2}{q^2} + \gamma)q_x]^2 + [\frac{aq_y^2}{q^2} + \Gamma(\mathbf{q})]^2}, \quad (8a)$$

$$C_Q^{x,y}(\tilde{\mathbf{q}}, \tilde{\mathbf{q}}') = \frac{q_{y,x}^2}{q^2} \frac{4\pi D_Q \delta(\omega) \delta(\omega') \delta(\mathbf{q} + \mathbf{q}')}{(\frac{bq_y^2}{q^2} + \gamma)^2 q_x^2 + [\frac{aq_y^2}{q^2} + \Gamma(\mathbf{q})]^2}, \quad (8b)$$

where $\Gamma(\mathbf{q}) \equiv \mu_\perp q_y^2 + \mu_x q_x^2$ and the subscripts A and Q denote the annealed and quenched parts, respectively.

The real-time, real-space autocorrelation of $\mathbf{u}(\mathbf{r}, t)$ obtained via inverse Fourier transforming (8) is

$$\begin{aligned} \langle \mathbf{u}(\mathbf{r}, t) \cdot \mathbf{u}(\mathbf{0}, 0) \rangle = & |y|^{-1/3} \mathcal{C}_Q \left(\frac{|x|}{|y|^{2/3}} \right) \\ & + |y|^{-1/2} \mathcal{C}_A \left(\frac{|x - \gamma t|}{|y|^{1/2}}, \frac{|t|}{|y|} \right), \end{aligned} \quad (9)$$

where $\mathcal{C}_{A/Q}$ are scaling functions displayed in Ref. [35]. Thus, the linear theory predicts $\chi = -1/6$, $\chi' = -1/4$, and $z = 1$, and also predicts different anisotropy exponents for the quenched and annealed parts: $\zeta_{\text{quenched}} = 2/3$ and $\zeta_{\text{annealed}} = 1/2$. Note also that the first argument of the scaling function $\mathcal{C}_A$ in the linear theory involves a “boosted” x coordinate $x - \gamma t$, in contrast to the nonlinear result (3), in which the first argument of the annealed scaling function involves only x , with no t dependence. The negativity of the roughness exponents χ and χ' implies that the incompressible flock has long-range polar order within the linear theory [32]. We will show that these exponents are modified in the nonlinear theory, and, in particular, the two anisotropy exponents ζ_{quenched} and ζ_{annealed} become equal.

This persistence of two-dimensional long-range polar order in a disordered medium is a result of a combination of the effects of incompressibility and, crucially, active motility, as can be seen from Eq. (8). Indeed, in a 2D equilibrium divergence-free magnet [27], the equal-time correlator of the magnetization diverges as $1/\mu_x^2 q_x^4$ instead of as $1/\gamma^2 q_x^2$ for $q_y = 0$ in the presence of quenched disorder. This divergence is strong enough to destroy *even* quasi-long-range order (QLRO). This implies that, while incompressible flocks perturbed by annealed noise are equivalent to *equilibrium* divergence-free magnets [22,27], they are much more resistant to quenched disorder. Because of motility, the quenched disorder is effectively “annealed” for fluctuations propagating along the ordered direction $\hat{\mathbf{x}}$ at a speed γ : Along $q_y = 0$, $C_A^y(\mathbf{q}, \mathbf{q}')$ and $C_Q^y(\mathbf{q}, \mathbf{q}')$ both diverge as $\sim 1/q_x^2$ as $\mathbf{q} \rightarrow \mathbf{0}$.

Nonlinear regime and DRG analysis.—We now turn to the full, nonlinear EOM of $\mathbf{u}$ (5).

Considerable past experience tells us that it is important to check whether nonlinearities change the long-distance behavior of the system. Many systems exhibit QLRO in the linear approximation but only short-ranged order in reality. Some examples are three-dimensional equilibrium smectics [36], and the $O(n)$ model in $d = 2$ with $n \geq 2$ (see, for instance, Refs. [33,37] and driven 2D (isotropic) Bose liquids [38]).

Indeed, we find here that nonlinearities do *always* change the long-distance behavior for 2D incompressible flocks. To see this, we begin by Fourier transforming, both in space and time, the full, nonlinear EOM of $\mathbf{u}$ (5) and operating on both sides with the transverse projection operator P_{ly} , we obtain

$$\begin{aligned}
 -i\omega u_y &= P_{yx}(\mathbf{q})\mathcal{F}_{\tilde{\mathbf{q}}}\left[-\alpha\left(u_x + \frac{u_y^2}{2v_0}\right)\right] \\
 &+ \mathcal{F}_{\tilde{\mathbf{q}}}\left[-\gamma\partial_x u_y - \lambda u_y\partial_y u_y - \frac{\alpha}{v_0}\left(u_x + \frac{u_y^2}{2v_0}\right)u_y\right. \\
 &\left.+ f_A^y + f_Q^y\right], \quad (10)
 \end{aligned}$$

where we have neglected terms that are irrelevant in the dominant regime of wave vector $q_y \ll q_x$, as we discovered in our treatment of the linear theory. We will verify *a posteriori* that this continues to hold for the nonlinear theory. The symbol $\mathcal{F}_{\tilde{\mathbf{q}}}$ represents the $\tilde{\mathbf{q}}$ th Fourier component, i.e.,

$$\mathcal{F}_{\tilde{\mathbf{q}}}[\mathbf{u}(\mathbf{r}, t)] \equiv \mathbf{u}(\tilde{\mathbf{q}}) = \frac{1}{(2\pi)^{3/2}} \int d^2r dt e^{i(\mathbf{q}\cdot\mathbf{r} - \omega t)} \mathbf{u}(\mathbf{r}, t). \quad (11)$$

To evaluate the importance of the nonlinear terms in Eq. (10), we rescale time, lengths, and fields as

$$t \rightarrow t e^{z\ell}, \quad x \rightarrow x e^{\zeta\ell}, \quad y \rightarrow y e^{\ell}, \quad u_y \rightarrow u_y e^{\chi\ell}, \quad (12)$$

respectively, implying $u_x \rightarrow u_x e^{(\chi+\zeta-1)\ell}$, and keep the form of the resultant EOM unchanged by absorbing the rescaling factors into the coefficients. The coefficients of the linear terms $P_{yx}u_x$ and $\partial_x u_y$ and the noise strength are rescaled, respectively, as

$$\alpha \rightarrow \alpha e^{(z+2\zeta-2)\ell}, \quad \gamma \rightarrow \gamma e^{(z-\zeta)\ell}, \quad (13a)$$

$$D_A \rightarrow D_A e^{(z-2\chi-\zeta-1)\ell}, \quad D_Q \rightarrow D_Q e^{(2z-2\chi-\zeta-1)\ell}, \quad (13b)$$

and the coefficients of the nonlinear terms $P_{yx}u_y^2$, $u_y\partial_y u_y$, $u_x u_y$, and u_y^3 as

$$\frac{\alpha}{2v_0} \rightarrow \frac{\alpha}{2v_0} e^{(z+\chi+\zeta-1)\ell}, \quad \frac{\alpha}{v_0} \rightarrow \frac{\alpha}{v_0} e^{(z+\chi+\zeta-1)\ell}, \quad (14a)$$

$$\lambda \rightarrow \lambda e^{(z+\chi-1)\ell}, \quad \frac{\alpha}{2v_0^2} \rightarrow \frac{\alpha}{2v_0^2} e^{(z+2\chi)\ell}. \quad (14b)$$

We choose z , ζ , and χ to fix α , γ , and D_Q , which control the size of the dominant fluctuations (i.e., those coming from the quenched noise), which yields

$$z = \frac{2}{3}, \quad \zeta = \frac{2}{3}, \quad \chi = -\frac{1}{6}. \quad (15)$$

As expected, these values of ζ and χ are identical to those for the quenched correlations obtained from our linear theory [e.g., see Eq. (9)]. Note that, while the choice of z is formally necessary to restore the EOM to its original form, it does not appear in the correlation function (9), because

the leading-order part of that correlation function is static, since the quenched disorder that induces those leading-order fluctuations is. Its value is different from the z in (9), since the time-dependent part of the fluctuations comes from the subdominant annealed disorder.

Substituting these values into Eq. (14), we find the coefficients of the nonlinear terms $P_{yx}u_y^2$, $u_x u_y$, and u_y^3 rescale as

$$\frac{\alpha}{2v_0} \rightarrow \frac{\alpha}{2v_0} e^{\ell/6}, \quad \frac{\alpha}{v_0} \rightarrow \frac{\alpha}{v_0} e^{\ell/6}, \quad \frac{\alpha}{2v_0^2} \rightarrow \frac{\alpha}{2v_0^2} e^{\ell/3}, \quad (16)$$

which clearly all diverge as $\ell \rightarrow \infty$. This implies that these nonlinear terms are *relevant* in the hydrodynamic limit. In contrast, $\lambda \rightarrow \lambda e^{(z+\chi-1)\ell}$ vanishes, which implies $u_y\partial_y u_y$ is irrelevant and, hence, can be neglected.

To deal with the relevant nonlinearities, we will perform a one-loop DRG calculation using an ϵ -expansion method. Our approach is that of Refs. [39,40] and is explained in detail in the companion paper [35].

To employ the ϵ -expansion method, we rely on analytic continuity to generalize our calculation to dimensions $d > 2$. We have two distinct choices for doing this; we can treat the soft x direction as one dimensional and the hard y direction as $d-1$ dimensional, or we can take x to be $d-1$ dimensional while treating y as one dimensional. These lead to two *distinct* ϵ -expansion schemes which we term the *hard* and *soft* continuations, respectively [41]. Alternatively, we perform an uncontrolled one-loop calculation in exactly $d=2$. The numerical values given at the beginning of the Letter for the exponents represent an average of the results from these three schemes.

Crucially, in all three schemes, we make use of an important simplification: Because of the rotation invariance of our hydrodynamic EOM, it is convenient to choose the values of χ and ζ so that all three α 's appearing in the EOM (10) remain identical upon the rescaling, i.e.,

$$\chi = \zeta - 1. \quad (17)$$

Using the above simplification to eliminate the roughness exponent χ , the DRG recursion relations, to one-loop order, for the hard continuation are [35]

$$\frac{d \ln \alpha}{d\ell} = z + 2\zeta - 2 + \eta_\alpha, \quad (18a)$$

$$\frac{d \ln \gamma}{d\ell} = z - \zeta + \eta_\gamma, \quad (18b)$$

$$\frac{d \ln \mu_x}{d\ell} = z - 2\zeta + \eta_\mu, \quad (18c)$$

$$\frac{d \ln D_Q}{d\ell} = 2z - 3\zeta + 3 - d + \eta_Q, \quad (18d)$$

$$\frac{d \ln D_A}{d\ell} = z - 3\zeta + 3 - d + \eta_A, \quad (18e)$$

where the η 's represent graphical corrections. To lowest order in perturbation theory [35],

$$\eta_\alpha = -\frac{1}{27}g, \quad \eta_\gamma = \frac{8}{27}g, \quad \eta_Q = \frac{10}{27}g, \quad \eta_A = \frac{16}{27}g, \quad (19a)$$

$$\eta_\mu = g_\mu + \frac{2}{27}g, \quad (19b)$$

where we have defined

$$g \equiv \frac{S_{d-1}}{(2\pi)^{d-1}} |\gamma|^{-7/3} \alpha^{1/3} \Lambda^{(3d-7)/3} D_Q, \quad (20a)$$

$$g_\mu = \frac{S_{d-1}}{(2\pi)^{d-1}} \Lambda^{d-3} |\gamma|^{-1} \mu_x^{-1} D_Q, \quad (20b)$$

with S_{d-1} the area of a $(d-1)$ -dimensional unit sphere and Λ the inverse of the short-wavelength cutoff (which is the inverse of the largest length scale of the following three: the sample thickness, the interaction range, and the inter-particle distance). In writing the recursion relations (18), we have ignored some corrections arising from the annealed noise D_A which prove to be irrelevant (that is, to vanish as $\ell \rightarrow \infty$) [35].

From Eqs. (18), we can construct closed recursion relations for g and g_μ :

$$\frac{dg}{d\ell} = \frac{1}{3}(7 - 3d - g)g, \quad (21a)$$

$$\frac{dg_\mu}{d\ell} = (3 - d - g_\mu)g_\mu. \quad (21b)$$

For $d < 7/3$, the above flow equations indicate that the generic stable fixed point is at

$$g^* = 3\epsilon + \mathcal{O}(\epsilon^2), \quad g_\mu^* = \frac{2}{3} + \epsilon + \mathcal{O}(\epsilon^2), \quad (22)$$

where $\epsilon = 7/3 - d$ and the $\mathcal{O}(\epsilon^2)$ part can be obtained only through higher-order in perturbation theory calculations. For $d = 2$, $\epsilon = 1/3$, which is extremely small for ϵ expansions. Therefore, we expect our one-loop DRG results to be quantitatively *very* accurate.

The fact that both g and g_μ flow to nonzero stable fixed points also implies two *exact* relations between the η 's. The definition of g (20a), together with Eq. (18), implies

$$\frac{d \ln g}{d\ell} = \frac{1}{3}(7 - 3d) - \frac{7}{3}\eta_\gamma + \frac{1}{3}\eta_\alpha + \eta_Q, \quad (23)$$

which leads to the exact relation, valid to *all* loop orders,

$$7 - 3d - 7\eta_\gamma + \eta_\alpha + 3\eta_Q = 0, \quad (24)$$

since $d \ln g/d\ell = 0$ at the fixed point. Similarly, Eqs. (20b) and (18) lead to the second exact relation:

$$3 - d + \eta_Q - \eta_\gamma - \eta_\mu = 0. \quad (25)$$

Note that η_μ does not vanish as ϵ goes to zero, since the upper critical dimension of g_μ is 3 instead of $7/3$ [see Eq. (20b)]. Since μ_x controls the annealed part of the correlation, this implies that this part starts to depart from the linear prediction, as d is decreased, from $d = 3$, in contrast to the quenched part, which first does so at $d = 7/3$. As shown in detail in Ref. [35], while within the linear theory the anisotropy exponent for the quenched and annealed parts of the correlator are distinct, the annealed anisotropy exponent assumes the same value as the quenched one for all $d \leq 7/3$, that is, in precisely the dimension at which the quenched anisotropy exponent first departs from its linear value.

Scaling exponents.—We now use the DRG procedure to calculate the real-time, real-space correlations $C_Q(\mathbf{r})$ and $C_A(t, \mathbf{r})$, which represent the quenched and annealed parts of $\langle \mathbf{u}(\mathbf{r}, t) \cdot \mathbf{u}(\mathbf{0}, 0) \rangle$, respectively. They are related to those of the rescaled system [42] via

$$C_Q(\alpha_0, \gamma_0, D_{Q0}, \mathbf{r}) = e^{2\chi\ell} C_Q \left[\alpha(\ell), \gamma(\ell), D_Q(\ell), \frac{|\mathbf{x}|}{e^{\zeta\ell}}, \frac{|\mathbf{y}|}{e^\ell} \right], \quad (26a)$$

$$C_A(\alpha_0, \mu_{x0}, D_{A0}, t, \mathbf{r}) = e^{2\chi'\ell} C_A \left[\alpha(\ell), \mu_x(\ell), D_A(\ell), \frac{|t|}{e^{z\ell}}, \frac{|\mathbf{x}|}{e^{\zeta\ell}}, \frac{|\mathbf{y}|}{e^\ell} \right], \quad (26b)$$

where α , γ , and D_Q control the magnitude of $C_Q(\mathbf{r})$, while α , μ_x , and D_A control the magnitude of $C_A(\mathbf{r}, t)$ and the subscript “0” denotes the bare values of the parameters. We choose ζ and z such that α , γ , μ_x , and D_Q are all fixed [i.e., equate the rhs of Eqs. (18a)–(18b) to 0], which is possible, since $\eta_{\gamma, \alpha, Q, \mu}$ are constrained by the exact relations (24) and (25). Choosing $\ell = \ln(\Lambda|\mathbf{y}|)$ and taking the renormalization factor of D_A to the front, we write the rhs of Eqs. (26a) and (26b) in the form displayed by Eq. (3) with

$$\mathcal{G}_Q \left(\frac{|\mathbf{x}|}{|\mathbf{y}|^\zeta} \right) \equiv \Lambda^{2\chi} C_Q \left[\alpha_0, \gamma_0, D_{Q0}, \frac{|\mathbf{x}|}{(|\mathbf{y}|\Lambda)^\zeta}, \frac{1}{\Lambda} \right] \quad (27)$$

and

$$\mathcal{G}_A \left(\frac{|t|}{|\mathbf{y}|^z}, \frac{|\mathbf{x}|}{|\mathbf{y}|^\zeta} \right) \equiv \Lambda^{2\chi'} C_A \left[\alpha_0, \gamma_0, D_{A0}, \frac{|t|}{(|\mathbf{y}|\Lambda)^z}, \frac{|\mathbf{x}|}{(|\mathbf{y}|\Lambda)^\zeta}, \frac{1}{\Lambda} \right], \quad (28)$$

with the various exponents being

$$\zeta = \frac{2 + \eta_\gamma - \eta_\alpha}{3} = \frac{2}{3} + \frac{1}{3}\epsilon + O(\epsilon^2), \quad (29a)$$

$$z = \frac{2 - 2\eta_\gamma - \eta_\alpha}{3} = \frac{2}{3} - \frac{5}{9}\epsilon + O(\epsilon^2), \quad (29b)$$

$$\chi = \frac{-1 + \eta_\gamma - \eta_\alpha}{3} = -\frac{1}{3} + \frac{1}{3}\epsilon + O(\epsilon^2), \quad (29c)$$

$$\chi' = \frac{\eta_A - \eta_\gamma - 1}{2} = -\frac{1}{2} + \frac{4}{9}\epsilon + O(\epsilon^2), \quad (29d)$$

where in the second equalities we have used Eq. (19) and the results for g and g_μ to $O(\epsilon)$ given by Eq. (22). Note that this calculation shows explicitly that, beyond the linear theory, the anisotropy exponents for the quenched and the annealed correlations become equal, and the x dependence of the annealed part of the correlation function involves an “unboosted” x , not a boosted variable $x - \gamma t$. This confirms our earlier claim.

The analysis for the soft continuation and the uncontrolled one-loop calculation in precisely $d = 2$ are very similar and give comparable quantitative results [35]. In fact, coincidentally, the uncontrolled one-loop calculation obtains precisely the same numerical values for the exponents as the hard continuation. The exponents quoted earlier are an equally weighted average of these three results; the quoted error bars more than cover the spread between the three different calculations.

Summary and outlook.—We have demonstrated that a combination of active motility and incompressibility leads to the formation of two-dimensional long-range ordered flocks, even in the presence of random quenched disorder. In contrast, neither active motility nor incompressibility *alone* can overcome quenched disorder, although either can successfully compete with annealed (i.e., time-dependent) noise [5,27].

One experimental realization of incompressibility in a two-dimensional system is motile particles moving through a narrow channel filled with an incompressible fluid [23,24] or at high particle densities [22,23]. Since some degree of disorder will always be present in all experimental systems, especially biological ones, our work should be valuable in interpreting numerous experiments in both artificial and biological active systems. In particular, our finding demonstrates that confluent cell layers on substrates can move coherently despite the presence of static random impurities.

We also look forward to quantitative tests of our predictions in artificial active systems, for instance, Quincke rotors [20] or vibrated granular systems [43].

L. C. acknowledges support by the National Science Foundation of China (under Grant No. 11874420).

J. T. thanks the Max Planck Institute for the Physics of Complex Systems, Dresden, Germany, for their support through a Martin Gutzwiller Fellowship during this period. A. M. was supported by a TALENT fellowship from CY Cergy Paris Université. L. C. also thanks the Max Planck Institute for the Physics of Complex Systems (MPI-PKS), where the early stage of this work was performed, for their support.

*leiming@cumt.edu.cn

†c.lee@imperial.ac.uk

‡nyomaitra07@gmail.com

§jtt@uoregon.edu

- [1] N. D. Mermin and H. Wagner, Absence of Ferromagnetism or Antiferromagnetism in One- or Two-Dimensional Isotropic Heisenberg Models, *Phys. Rev. Lett.* **17**, 1133 (1966); P. C. Hohenberg, Existence of long-range order in one and two dimensions, *Phys. Rev.* **158**, 383 (1967).
- [2] T. Vicsek, A. Czirók, E. Ben-Jacob, I. Cohen, and O. Shochet, Novel Type of Phase Transition in a System of Self-Driven Particles, *Phys. Rev. Lett.* **75**, 1226 (1995).
- [3] J. Toner and Y. Tu, Long-Range Order in a Two-Dimensional Dynamical XY Model: How Birds Fly Together, *Phys. Rev. Lett.* **75**, 4326 (1995).
- [4] J. Toner and Y. Tu, Flocks, herds, and schools: A quantitative theory of flocking, *Phys. Rev. E* **58**, 4828 (1998).
- [5] J. Toner, Reanalysis of the hydrodynamic theory of fluid, polar-ordered flocks, *Phys. Rev. E* **86**, 031918 (2012).
- [6] H. Chaté, Dry aligning dilute active matter, *Annu. Rev. Condens. Matter Phys.* **11**, 189 (2020).
- [7] A. B. Harris, Effect of random defects on the critical behaviour of Ising models, *J. Phys. C* **7**, 1671 (1974).
- [8] G. Grinstein and A. H. Luther, Application of the renormalization group to phase transitions in disordered systems, *Phys. Rev. B* **13**, 1329 (1976).
- [9] A. Aharony, in *Multicritical Phenomena*, edited by R. Pynn and A. Skjeltorp (Plenum, New York, 1984), p. 309.
- [10] D. S. Fisher, Stability of Elastic Glass Phases in Random Field XY Magnets and Vortex Lattices in Type-II Superconductors, *Phys. Rev. Lett.* **78**, 1964 (1997).
- [11] J. Toner, N. Guttenberg, and Y. Tu, Swarming in the Dirt: Ordered Flocks with Quenched Disorder, *Phys. Rev. Lett.* **121**, 248002 (2018).
- [12] J. Toner, N. Guttenberg, and Y. Tu, Hydrodynamic theory of flocking in the presence of quenched disorder, *Phys. Rev. E* **98**, 062604 (2018).
- [13] Yu Duan, Benoît Mahault, Yu-qiang Ma, Xia-qing Shi, and Hugues Chaté, Breakdown of Ergodicity and Self-Averaging in Polar Flocks with Quenched Disorder, *Phys. Rev. Lett.* **126**, 178001 (2021).
- [14] Ydan Ben Dor, Sunghan Ro, Yariv Kafri, Mehran Kardar, and Julien Tailleur, Disordered boundaries destroy bulk phase separation in scalar active matter, *Phys. Rev. E* **105**, 044603 (2022).
- [15] Sunghan Ro, Yariv Kafri, Mehran Kardar, and Julien Tailleur, Disorder-Induced Long-Ranged Correlations in Scalar Active Matter, *Phys. Rev. Lett.* **126**, 048003 (2021).

- [16] Oleksandr Chepizhko, Eduardo G. Altmann, and Fernando Peruani, Optimal Noise Maximizes Collective Motion in Heterogeneous Media, *Phys. Rev. Lett.* **110**, 238101 (2013).
- [17] Fernando Peruani and Igor S. Aranson, Cold Active Motion: How Time-Independent Disorder Affects the Motion of Self-Propelled Agents, *Phys. Rev. Lett.* **120**, 238101 (2018).
- [18] Oleksandr Chepizhko and Fernando Peruani, Diffusion, Subdiffusion, and Trapping of Active Particles in Heterogeneous Media, *Phys. Rev. Lett.* **111**, 160604 (2013).
- [19] Alexandre Morin, Nicolas Desreumaux, Jean-Baptiste Caussin, and Denis Bartolo, Distortion and destruction of colloidal flocks in disordered environments, *Nat. Phys.* **13**, 63 (2017).
- [20] A. Chardac, S. Shankar, M. C. Marchetti, and D. Bartolo, Emergence of dynamic vortex glasses in disordered polar active fluids, *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2018218118 (2021).
- [21] This conclusion is somewhat controversial; see O. Chepizhko, E. G. Altmann, and F. Peruani, Optimal Noise Maximizes Collective Motion in Heterogeneous Media, *Phys. Rev. Lett.* **110**, 238101 (2013).
- [22] L. Chen, C. F. Lee, and J. Toner, Mapping two-dimensional polar active fluids to two-dimensional soap and one-dimensional sandblasting, *Nat. Commun.* **7**, 12215 (2016).
- [23] A. Maitra, P. Srivastava, M. C. Marchetti, S. Ramaswamy, and M. Lenz, Swimmer Suspensions on Substrates: Anomalous Stability and Long-Range Order, *Phys. Rev. Lett.* **124**, 028002 (2020).
- [24] T. Broto, J.-B. Caussin, E. Lauga, and D. Bartolo, Hydrodynamics of Confined Active Fluids, *Phys. Rev. Lett.* **110**, 038101 (2013).
- [25] A. Bricard, J.-B. Caussin, N. Desreumaux, O. Dauchot, and D. Bartolo, Emergence of macroscopic directed motion in populations of motile colloids, *Nature (London)* **503**, 95 (2013).
- [26] J. Toner, Birth, Death, and Flight: A Theory of Malthusian Flocks, *Phys. Rev. Lett.* **108**, 088102 (2012).
- [27] A. Kashuba, Exact Scaling of Spin-Wave Correlations in the 2D XY Ferromagnet with Dipolar Forces, *Phys. Rev. Lett.* **73**, 2264 (1994).
- [28] L. Chen, C. F. Lee, and J. Toner, Moving, Reproducing, and Dying Beyond Flatland: Malthusian Flocks in Dimensions $d > 2$, *Phys. Rev. Lett.* **125**, 098003 (2020).
- [29] L. Chen, C. F. Lee, and J. Toner, Universality class for a nonequilibrium state of matter: A $d = 4 - \epsilon$ expansion study of Malthusian flocks, *Phys. Rev. E* **102**, 022610 (2020).
- [30] L. P. Dadhichi, J. Kethapelli, R. Chajwa, S. Ramaswamy, and A. Maitra, Nonmutual torques and the unimportance of motility for long-range order in two-dimensional flocks, *Phys. Rev. E* **101**, 052601 (2020).
- [31] L. Chen, C. F. Lee, and J. Toner, Incompressible polar active fluids in the moving phase in dimensions $d > 2$, *New J. Phys.* **20**, 113035 (2018).
- [32] A. Maitra, Active uniaxially ordered suspensions on disordered substrates, *Phys. Rev. E* **101**, 012605 (2020).
- [33] P. M. Chaikin and T. C. Lubensky, *Principles of Condensed Matter Physics* (Cambridge University Press, Cambridge, England, 1995).
- [34] H. H. Wensink, J. Dunkel, S. Heidenreich, K. Drescher, R. E. Goldstein, H. Löwen, and J. M. Yeomans, Meso-scale turbulence in living fluids, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 14308 (2012).
- [35] L. Chen, C. F. Lee, A. Maitra, and J. Toner, companion paper, Hydrodynamic theory of two-dimensional incompressible polar active fluids with quenched and annealed disorder, *Phys. Rev. E* **106**, 044608 (2022).
- [36] G. Grinstein and R. A. Pelcovits, Anharmonic Effects in Bulk Smectic Liquid Crystals and Other “One-Dimensional Solids”, *Phys. Rev. Lett.* **47**, 856 (1981); Nonlinear elastic theory of smectic liquid crystals, *Phys. Rev. A* **26**, 915 (1982).
- [37] D. R. Nelson and R. A. Pelcovits, Momentum-shell recursion relations, anisotropic spins, and liquid crystals in $2 + \epsilon$ dimensions, *Phys. Rev. B* **16**, 2191 (1977).
- [38] E. Altman, L. M. Sieberer, L. Chen, S. Diehl, and J. Toner, Two-Dimensional Superfluidity of Exciton-Polaritons Requires Strong Anisotropy, *Phys. Rev. X* **5**, 011017 (2015).
- [39] D. Forster, D. R. Nelson, and M. R. Stephen, Long-Time Tails and the Large-Eddy Behavior of a Randomly Stirred Fluid, *Phys. Rev. Lett.* **36**, 867 (1976).
- [40] D. Forster, D. R. Nelson, and M. J. Stephen, Large-distance and long-time properties of a randomly stirred fluid, *Phys. Rev. A* **16**, 732 (1977).
- [41] We call y and x hard and soft directions, respectively, since the Fourier modes of the velocity with their wave vectors along y have the smallest fluctuations, while those with their wave vectors along x have the largest.
- [42] D. R. Nelson, Crossover scaling functions and renormalization-group trajectory integrals, *Phys. Rev. B* **11**, 3504 (1975).
- [43] N. Kumar, H. Soni, S. Ramaswamy, and A. K. Sood, Flocking at a distance in active granular matter, *Nat. Commun.* **5**, 4688 (2014).