A Mechanics Perspective for Dry Active Matter: From Force Balance to Odd Response

Journal:	*Acta Mechanica Sinica*
Manuscript ID	ams2026-0388.R1
Manuscript Type:	Themed Topic on Mechanics of Active Matter (invited)
Date Submitted by the Author:	17-May-2026
Complete List of Authors:	Sun, Zihao; Hangzhou Normal University, Physics; Zhejiang University, Physics Li, Longfei; Institute of Physics CAS Chen, Jiangxing; Hangzhou Normal University Ye, Fangfu; Institute of Physics CAS; University of the Chinese Academy of Sciences; Wenzhou Institute of Biomaterials and Engineering; Oujiang Laboratory Yang, Mingcheng; Institute of Physics CAS; University of the Chinese Academy of Sciences
Keywords:	Dry Active Matter, Anomalous Mechanical Behaviors, Intrinsic Pressure, Odd Response

Note: The following files were submitted by the author for peer review, but cannot be converted to PDF. You must view these files (e.g. movies) online.

ams2026-0388.R1-Editable main document.zip

Springer Acta Mechanica Sinica CrossMark click for updates

• Perspective •

Acta Mech. Sin., Vol.???, ??? (2026)
https://doi.org/??-???-?

A Mechanics Perspective for Dry Active Matter: From Force Balance to Odd Response

Zihao Sun[1,2], Longfei Li[3], Jiangxing Chen[1*], Fangfu Ye[3,4,5,6*], and Mingcheng Yang[3,4*]

[1] *Department of Physics, Hangzhou Normal University, Hangzhou 311121, China;*
[2] *Department of Physics, Zhejiang University, Hangzhou 310027, China;*
[3] *Beijing National Laboratory for Condensed Matter Physics and Laboratory of Soft Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China;*
[4] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China;*
[5] *Wenzhou Institute, University of Chinese Academy of Sciences, Wenzhou, Zhejiang 325001, China;*
[6] *Oujiang Laboratory (Zhejiang Lab for Regenerative Medicine, Vision and Brain Health), Wenzhou, Zhejiang 325000, China*

Received ???; accepted ???; published online ???

Driven by continuous energy injection, active systems inherently break time-reversal symmetry, exhibiting anomalous physical behaviors that defy equilibrium thermodynamic descriptions. Mechanical laws nonetheless retain their universal validity, providing a reliable basis for understanding these non-equilibrium systems. In this Perspective, we examine how mechanical analysis yields physical insight into dry active matter. We first introduce exotic mechanical behaviors of passive probes in active baths, and then examine the definition of pressure, demonstrating how the intrinsic pressure framework provides a consistent and convenient physical explanation for diverse active phenomena. Furthermore, we explore how introducing microscopic chirality breaks spatial parity, forcing mechanical constitutive equations to expand into the antisymmetric tensor space. Finally, we outline promising future directions for the mechanics of active matter.

Dry Active Matter, Anomalous Mechanical Behaviors, Intrinsic Pressure, Odd Response

Citation: Z. Sun, L. Li, J. Chen, F. Ye and M. Yang, A Mechanics Perspective for Dry Active Matter: From Force Balance to Odd Response, Acta Mech. Sin. **???**, ??? (2026), https://doi.org/??-???-?

1. Introduction

From bacterial colonies to synthetic active colloids, active matter units continuously convert available energy into self-propelled motion [1-4]. This persistent energy input fundamentally breaks time-reversal symmetry and, consequently, violates detailed balance. Such a departure from equilibrium not only gives rise to various anomalous collective phenomena [5-9], but also endows active matter with intriguing mechanical properties [10, 11]. In this context, returning to the fundamental laws of mechanics provides a reliable approach to deciphering these non-equilibrium systems [12, 13].

In this Perspective, we illustrate how a mechanical viewpoint illuminates diverse phenomena of dry active matter, where hydrodynamic interactions are absent. We first examine how the self-propulsion of active bath particles induces anomalous mechanical behaviors, ranging from non-Markovian tracer dynamics to constraint-dependent effective interactions. Expanding to a broader scope, we explore the mechanical equilibrium of active matter and elaborate on the intrinsic pressure framework, revealing that the aforementioned anomalies essentially originate from the fact that the spatial distribution of the polarization force density is shaped by the properties of the embedded probes. Furthermore, we demonstrate how breaking time-reversal and spatial parity symmetries via microscopic chiral activity endows response tensors with antisymmetric components, yielding a rich phenomenology of odd mechanics. Finally, we conclude by outlining the open challenges and future research directions.

2. Probe Mechanics in Active Baths

In the study of active fluids, introducing a passive tracer serves as a canonical method to probe local mechanical properties. Unlike classical thermal baths governed by the fluctuation-dissipation theorem, the persistent energy injection in active baths fundamentally breaks time-reversal symmetry, giving rise to novel mechanical phenomena.

For the single-probe dynamics, the persistent self-propulsion of active particles and the resulting local structural relaxation introduce a history-dependent memory kernel [14, 15]. A free tracer thus experiences non-Markovian colored noise with pronounced heavy tails [16,17], while the geometric asymmetry of the probe further induces a nonzero mean force or torque through differential active particle accumulation (see Fig. 1(a)) [18-20]. When the probe is externally driven, the structural relaxation of the active bath instead manifests as a pronounced microstructural asymmetry. As active units dynamically reorganize around the moving probe, the resulting local stress imbalance drastically reduces the effective microviscosity—termed "swim-thinning" [21]—and can even exert a net forward thrust yielding a negative effective friction [14, 22].

When multiple passive inclusions are introduced, the asymmetric accumulation of active particles around their boundaries generates effective depletion forces. Unlike the attractive Asakura-Oosawa depletion force in equilibrium suspensions [23], active depletion forces can shift to repulsion (Fig. 1(b)) [24] and are highly sensitive to inclusion geometry [25]. Crucially, the surface-generated active currents around asymmetric bodies further mediate long-range forces and torques between inclusions, which do not obey the action-reaction principle [26].

More intriguingly, these effective interactions cannot be uniquely determined by spatial configurations of probes; rather, they substantially depend on the external constraints imposed on the passive inclusions (Fig. 1(c)) [27]. This constraint dependence stems from a direct mechanical feedback: a rigidly fixed obstacle forces active units to pile up into a dense, high-pressure boundary layer, whereas an object allowed to yield or move relieves this local stress, dynamically reshaping the surrounding density profile. Such constraint dependence manifests across various mechanical properties, dictating the mechanical pressure on passive inclusions [28], the active noise experienced by a trapped tracer [29], and the active depletion torques between anisotropic bodies (Fig. 1(d)) [30].

These anomalous mechanical phenomena can be quantitatively characterized through calibrated optical or magnetic traps and statistical analysis of probe behaviors [18,27,31,32] and share a common physical origin: the dynamic, non-equilibrium restructuring of the active fluid around the passive inclusions. Capturing the underlying physics of these diverse anomalies motivates a unified framework based on mechanical equilibrium.

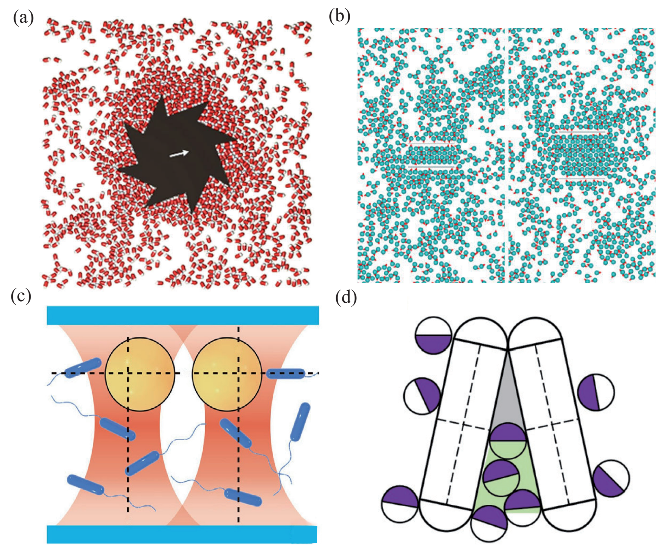


Figure 1 Anomalous mechanical phenomena governed by active structural reorganization. (a) Geometry-induced net torque driving the spontaneous rotation of an asymmetric gear immersed in a bacterial bath (reproduced by permission from Ref. [18]). (b) Long-range effective forces between passive plates mediated by self-propelled colloidal hard spheres (reproduced by permission from Ref. [24]). (c) Constraint-dependent effective forces due to the dynamic accumulation of self-propelled particles (adapted by permission from Ref. [27]). (d) Constraint-dependent effective torques on passive anisotropic objects immersed in an active bath (reproduced by permission from Ref. [30]).

3. Mechanical Equilibrium of Active Matter

Whereas the violation of detailed balance in active systems invalidates traditional equilibrium thermodynamics, the dynamical evolution of these systems remains strictly dictated by fundamental mechanical laws. Consequently, a purely mechanical analysis provides a reliable basis for bridging microscopic active units and macroscopic phenomena. A central question for such an analysis is how to formulate a local pressure for generic dry active systems. Unlike passive systems, active systems contain an additional ingredient—the self-propelling force F^{a}—which is conventionally regarded as an internal force. A natural strategy is to absorb it into the stress tensor, defining an effective active pressure [33-35]. One can start from the conservation equation for the number density n, $\partial_t n = -\nabla \cdot \boldsymbol{J}^{\mathrm{n}}$, obtained by integrating the evolution equation over particle orientations. The particle flux along x reads:

$$\gamma_t J_x^n = f_x^m + f_x^{ext} - \frac{dP^k}{dx} + I_1(x), \tag{1}$$

where $f_x^m \equiv n\langle F^a \boldsymbol{e}_x \rangle$ is the polarization force density emerging from the self-propelling forces, $f_x^{ext} \equiv n\langle F_x^{ext} \rangle$ the external force density, $P^k = n\langle M v_x^2 \rangle$ the kinetic pressure with M the particle mass, and $I_1(x)$ the contribution from interparticle interactions, whose spatial integral defines the interaction pressure $P^c(x) = \int_x^\infty I_1(x')\, dx'$ [36].

For torque-free active Brownian particles (ABPs) with spatially uniform activity, the polarization force density takes a pure-divergence form that can be fully absorbed into a swim pressure $P^s = F^a J_{xx}^m / D_r$, where J_{xx}^m denotes the polar order flux. The active pressure is then defined as $P^a \equiv P^k + P^c + P^s$, providing valuable physical insight into various active phenomena [37-39]. In generic systems, however, the polarization force cannot be reduced to a pure divergence and the mechanical equilibrium condition based on the active pressure reads [40, 41]:

$$\frac{dP^a}{dx} = f_x^{ext} - \gamma_t J_x^n + J_{xx}^m \frac{d}{dx}\left(\frac{F^a}{D_r}\right) + \frac{F^a}{D_r}\mathcal{R}_x, \tag{2}$$

where $\mathcal{R}_x$ denotes a torque-induced source of polar order. The last two terms—arising respectively from spatial variation of self-propulsion and from torques—do not vanish in generic systems, where they cannot be interpreted as recognizable mechanical forces. In such systems, the active pressure exerted on the wall depends on the specific particle–wall interaction and boundary geometry, and cannot serve as a state function determined by the bulk (Fig. 2(a)) [10, 42, 43]. This breakdown has been directly observed in experiments on active disks confined by flexible bead chains, where the measured wall pressure varies with the chain's mechanical compliance [44]. Moreover, the local definition of active pressure is not unique in generic systems, as different formulations that coincide for ABPs produce distinct values [41].

As an alternative framework, intrinsic pressure rests on a different physical picture: a dry active matter system comprises not only the active particles but also an external environment—often left implicit—that exerts the self-propelling force on the active particles. Once the mechanical analysis is restricted to the active-particle phase, the polarization force naturally enters the force balance as an external force (Fig. 2(b)), rather than as an internal contribution to be absorbed into the stress. Reorganizing the flux relation Eq. (1) gives:

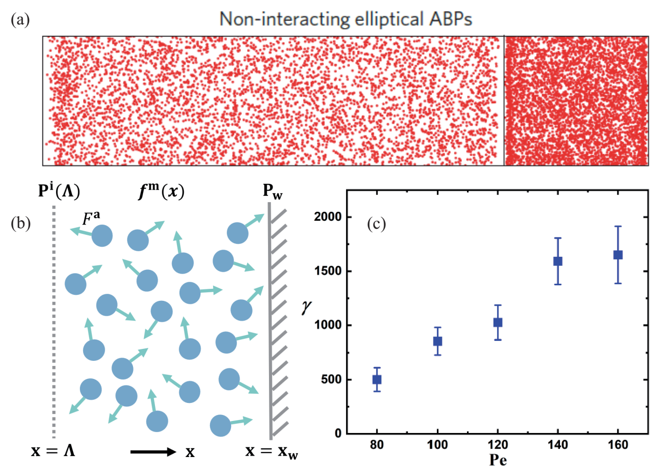


Figure 2 Mechanical equilibrium and surface tension in active matter. (a) For elliptical active particles, distinct particle-wall interactions drive spontaneous piston motion, illustrating the breakdown of the traditional equation of state (reproduced by permission from Ref. [10]). (b) The emergent polarization force density directed toward the boundary (arrows indicate self-propulsion directions) exactly compensates for the pressure gap between the boundary and the bulk (adapted by permission from Ref. [41]). (c) The mechanical surface tension of MIPS calculated via the intrinsic pressure framework is significantly positive (reproduced by permission from Ref. [45]).

$$\frac{dP^i}{dx} = f_x^m + f_x^{ext} - \gamma_t J_x^n, \tag{3}$$

where $P^i \equiv P^k + P^c$ retains the conventional form of pressure in passive systems, which is directly accessible in active-matter simulations [46]. In this formulation, every term carries a transparent mechanical meaning such that the intrinsic pressure provides a natural and convenient framework for analyzing the mechanics of dry active matter without introducing additional complexity [41]. Experimentally, this force balance has been verified on a programmable robotic platform, where the intrinsic pressure and the integrated polarization force density—extracted independently from particle trajectories—were shown to compensate exactly across the activity interface [47].

This local force balance, in turn, reveals the unified physical origin of the mechanical anomalies described in Sect. 2: these anomalies, from geometry-induced directed forces to constraint-dependent interactions, can now be understood through the specific spatial distributions of the polarization force density $\boldsymbol{f}^m$. The conceptual advantage of this framework is further manifested in analyzing the interfacial tension of motility-induced phase separation (MIPS) for minimal ABPs: in contrast to the counterintuitive negative surface tension obtained via the active pressure [48], Li et al. [45]

demonstrated that the intrinsic pressure framework naturally yields a strictly positive surface tension (Fig. 2(c)), intuitively consistent with stable MIPS. Moreover, the intrinsic pressure framework allows the calculation of interfacial tension for generic active systems, where the active pressure approach remains problematic.

4. Odd Mechanics of Chiral Active Matter

While the preceding sections focus on the mechanical consequences of translational self-propulsion, active matter exhibits a richer phenomenology when its constituent units possess intrinsic rotation or structural chirality [49-53]. Traditionally, linear response tensors connecting stress to strain or strain rate are symmetric [54]. However, chiral active matter simultaneously breaks time-reversal and spatial parity symmetries, forcing the mechanical constitutive equations to expand into an antisymmetric (odd) tensor space [11, 55-57]. The resulting stress response takes the general form:

$$\sigma_{ij} = \left(R^{\mathrm{e}}_{ijkl} + R^{\mathrm{o}}_{ijkl}\right) X_{kl}, \tag{4}$$

where $R^{\mathrm{e}}_{ijkl} = R^{\mathrm{e}}_{klij}$ is the conventional symmetric (even) component, and $R^{\mathrm{o}}_{ijkl} = -R^{\mathrm{o}}_{klij}$ is the emergent antisymmetric (odd) component. Depending on the physical context, X_{kl} represents the velocity gradient $\partial_k v_l$ in chiral active fluids (giving rise to odd viscosity), or the displacement gradient $\partial_k u_l$ in chiral active solids (giving rise to odd elasticity). Physically, the odd non-dissipative viscosity generates transverse stresses in response to the applied shear, while the non-conservative odd elasticity enables net work extraction during closed deformation cycles ($\oint \sigma_{ij} \mathrm{d}u_{ij} \neq 0$, shown in Fig. 3(a)) [11, 56]. Such antisymmetric responses have been quantitatively measured—odd viscosity in chiral colloidal fluids of spinning magnets [58], and odd elasticity in microcontroller-driven active metamaterials [59].

This antisymmetric tensor structure represents a macroscopic transverse response, generating anomalous transport and boundary phenomena. Passive tracers within chiral active baths experience odd mobility (Fig. 3(b)) and odd diffusivity [60-62], while the chiral fluid itself exhibits a Hall-like transverse flux upon flowing through obstacle matrices [63]. At geometric boundaries, the odd-viscosity-enhanced attractive depletion force pins passive cargo to the interface, enabling robust unidirectional edge transport (Fig. 3(c)) [64]. In addition, confinement introduces density inhomogeneities, driving spatially oscillating edge flow due to rotational viscosity [65].

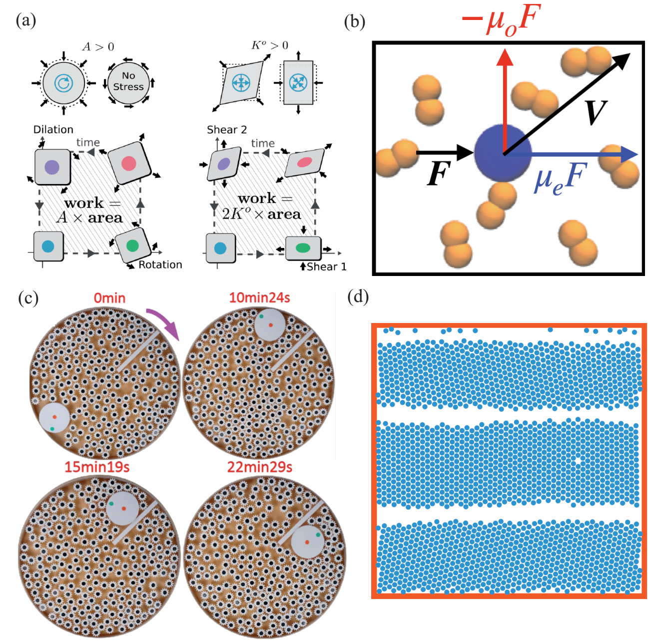


Figure 3 Odd mechanics in chiral active matter. (a) Antisymmetric odd response tensors enable non-conservative work extraction during closed deformation cycles (reproduced by permission from Ref. [11]). (b) The odd mobility characterizes the orthogonal drift of a driven passive tracer in a chiral active bath (reproduced by permission from Ref. [61]). (c) Topologically protected edge flow enables robust cargo transport aided by odd-viscosity-enhanced depletion interactions (reproduced by permission from Ref. [64]). (d) The synergy of odd viscosity and odd elasticity drives the phase separation of active spinners into stripes (adapted by permission from Ref. [66]).

Beyond fluid transport, such antisymmetric mechanical responses govern large-scale structural instabilities and phase transitions in odd media. In active solids, the odd stress field drives the spontaneous glide of dislocations, kneading crystalline lattices into macroscopic whorls [51]. Extending from structural defects to macroscopic instabilities, the interplay of odd viscosity and odd elasticity induces an effective negative compressibility, driving the phase separation of active spinners into stripes (Fig. 3(d)) [66].

Odd mechanics establishes a unified theoretical framework for chiral active matter. By translating microscopic symmetry violation directly to macroscopic antisymmetric response tensors, it provides the mechanical origin of the diverse phenomena of chiral active systems.

5. Outlook

The preceding discussion focuses on dry active matter, where hydrodynamic interactions among particles are negligible. Extending this perspective to wet active matter, in which momentum is no longer absorbed by the dissipative substrate but transferred through the fluid medium [1, 3, 67], is the next step toward broader applicability. The active particles and the fluid thereby constitute a coupled two-component system: particle self-propulsion drives flow fields that generate additional stress, while the fluid in turn mediates hydrodynamic interactions among particles. At the probe level, the recent work by Ning et al. [68] demonstrated that the bacterium-generated flow field produces a long-range attraction between parallel plates, overwhelming the repulsion from direct bacterium-plate collisions. For the mechanical framework, the fluid-mediated interactions can potentially be re-expressed as effective external forces on the active particle phase, extending the intrinsic pressure framework to suspended active particles in wet systems. Nevertheless, how such an extension modifies the interfacial mechanical balance and determines the interfacial tension in wet motility-induced phase separation remains an open question.

When the focus shifts to the interaction mechanism, active systems regulated by communication-mediated interactions represent a further direction of growing interest. In such systems, particles sense and respond to neighbors through communication protocols rather than direct collisions, as realized experimentally in light-controlled active colloids [69,70] and programmable robotic swarms [71]. This endows the collective with novel properties: interaction ranges determined by perception rather than particle size [70,72,73], nonreciprocal couplings that arise from the asymmetry among agents [74], and response rules that can be actively designed and tuned [75]. Whether these features can be exploited to organize active matter into collective mechanical modes—programmable stress transmission, topologically protected signal transport, or sustained extraction of work from the environment—represents an open frontier with implications for designing active functional materials and autonomous machines [76, 77].

Beyond these two frontiers, the mechanical viewpoint extends naturally to other settings: finite inertia or viscoelasticity introduces explicit time-dependence, requiring generalized constitutive equations that incorporate memory kernels [78-80]; for biological assemblies, traction forces, substrate adhesion, and tissue-level stress redistribution constitute the mechanical basis of morphogenesis and collective migration [81-85]. Regardless of the complexity of the system under investigation, mechanical analysis retains its validity precisely where equilibrium thermodynamic descriptions cease to apply. As the scope of active matter research expands into fluid-coupled, information-mediated, and biological environments, a rigorous mechanical perspective provides not merely physical insight but a unifying language across these domains.

This work was supported by the National Key R&D Program of China (2022YFF0503504) and the National Natural Science Foundation of China (Grants No.12274448, T2325027, 12274110).

1 Bechinger, C., Di Leonardo, R., Löwen, H., Reichhardt, C., Volpe, G., Volpe, G.: Active particles in complex and crowded environments. Reviews of Modern Physics **88**(4), 045006 (2016)

2 Elgeti, J., Winkler, R.G., Gompper, G.: Physics of microswimmers—single particle motion and collective behavior: a review. Reports on Progress in Physics **78**(5), 056601 (2015)

3 Marchetti, M.C., Joanny, J.F., Ramaswamy, S., Liverpool, T.B., Prost, J., Rao, M., Simha, R.A.: Hydrodynamics of soft active matter. Reviews of Modern Physics **85**(3), 1143–1189 (2013)

4 Gompper, G., Stone, H.A., Kurzthaler, C., Saintillan, D., Peruani, F., Fedosov, D.A., Auth, T., Cottin-Bizonne, C., Ybert, C., Clément, E., Darnige, T., Lindner, A., Goldstein, R.E., Liebchen, B., Binysh, J., Souslov, A., Isa, L., di Leonardo, R., Frangipane, G., Gu, H., Nelson, B.J., Brauns, F., Marchetti, M.C., Cichos, F., Heuthe, V.L., Bechinger, C., Korman, A., Feinerman, O., Cavagna, A., Giardina, I., Jeckel, H., Drescher, K.: The 2025 motile active matter roadmap. Journal of Physics: Condensed Matter **37**(14), 143501 (2025)

5 Tailleur, J., Cates, M.E.: Statistical mechanics of interacting run-and-tumble bacteria. Physical Review Letters **100**(21), 218103 (2008)

6 Luo, N., Li, L., Yang, M., Peng, Y.: Flocking phase separation in inertial active matter. Physical Review Letters **135**(17), 178301 (2025)

7 Granek, O., Kafri, Y., Kardar, M., Ro, S., Tailleur, J., Solon, A.: Colloquium: Inclusions, boundaries, and disorder in scalar active matter. Reviews Of Modern Physics **96**, 031003 (2024)

8 He, S.Q., Yin, X., Liang, D., Chang, Z., Xu, G.K.: Spontaneous oscillation in collective microswimmers: Insights from a chiral self-propelled rod model. Physical Review E **111**, 014411 (2025)

9 He, S.Q., Chang, Z., Liang, D., Li, C.H., Liang, Q.L., Yin, X., Xu, G.K.: A self-enhanced mobility mechanism drives the spontaneous emergence and transformation of vortex patterns. Soft Matter **21**, 6627–6640 (2025)

10 Solon, A.P., Fily, Y., Baskaran, A., Cates, M.E., Kafri, Y., Kardar, M., Tailleur, J.: Pressure is not a state function for generic active fluids. Nature Physics **11**(8), 673–678 (2015)

11 Scheibner, C., Souslov, A., Banerjee, D., Surówka, P., Irvine, W.T.M., Vitelli, V.: Odd elasticity. Nature Physics **16**(4), 475–480 (2020)

12 Ramaswamy, S.: The mechanics and statistics of active matter. Annual Review of Condensed Matter Physics **1**(1), 323–345 (2010)

13 Omar, A.K., Row, H., Mallory, S.A., Brady, J.F.: Mechanical theory of nonequilibrium coexistence and motility-induced phase separation. Proceedings of the National Academy of Sciences **120**(18), e2219900120 (2023)

14 Granek, O., Kafri, Y., Tailleur, J.: Anomalous transport of tracers in active baths. Physical Review Letters **129**(3), 038001 (2022)

15 Feng, Mengkai, Hou, Zhonghuai: Effective diffusion of a tracer in active bath: A path-integral approach. Natl Sci Open **3**(4), 20230069 (2024)

16 Maggi, C., Paoluzzi, M., Pellicciotta, N., Lepore, A., Angelani, L., Di Leonardo, R.: Generalized energy equipartition in harmonic oscillators driven by active baths. Physical Review Letters **113**(23), 238303 (2014)

17 Maggi, C., Paoluzzi, M., Angelani, L., Di Leonardo, R.: Memory-less response and violation of the fluctuation-dissipation theorem in colloids suspended in an active bath. Scientific Reports **7**(1), 17588 (2017)

18 Angelani, L., Di Leonardo, R., Ruocco, G.: Self-starting micromotors in a bacterial bath. Physical Review Letters **102**(4), 048104 (2009)
19 Sokolov, A., Apodaca, M.M., Grzybowski, B.A., Aranson, I.S.: Swimming bacteria power microscopic gears. Proceedings of the National Academy of Sciences **107**(3), 969–974 (2010)
20 Mallory, S.A., Valeriani, C., Cacciuto, A.: Curvature-induced activation of a passive tracer in an active bath. Physical Review E **90**(3), 032309 (2014)
21 Peng, Z., Brady, J.F.: Forced microrheology of active colloids. Journal of Rheology **66**(5), 955–972 (2022)
22 Knippenberg, T., Bebon, R., Speck, T., Bechinger, C.: Negative drag force on beating flagellar-shaped bodies in active fluids. Physical Review Letters **135**(11), 118301 (2025)
23 Asakura, S., Oosawa, F.: On interaction between two bodies immersed in a solution of macromolecules. The Journal of Chemical Physics **22**(7), 1255–1256 (1954)
24 Ni, R., Cohen Stuart, M.A., Bolhuis, P.G.: Tunable long range forces mediated by self-propelled colloidal hard spheres. Physical Review Letters **114**(1), 018302 (2015)
25 Harder, J., Mallory, S.A., Tung, C., Valeriani, C., Cacciuto, A.: The role of particle shape in active depletion. The Journal of Chemical Physics **141**(19), 194901 (2014)
26 Baek, Y., Solon, A.P., Xu, X., Nikola, N., Kafri, Y.: Generic long-range interactions between passive bodies in an active fluid. Physical Review Letters **120**(5), 058002 (2018)
27 Liu, P., Ye, S., Ye, F., Chen, K., Yang, M.: Constraint dependence of active depletion forces on passive particles. Physical Review Letters **124**(15), 158001 (2020)
28 Liu, P., Li, L., Ning, L., Zheng, N., Yang, M.: Constraint dependence of pressure on a passive probe in an active bath. Journal of Physics: Condensed Matter **35**(44), 445102 (2023)
29 Ye, S., Liu, P., Ye, F., Chen, K., Yang, M.: Active noise experienced by a passive particle trapped in an active bath. Soft Matter **16**(19), 4655–4660 (2020)
30 Li, L., Liu, P., Chen, K., Zheng, N., Yang, M.: Active depletion torque between two passive rods. Soft Matter **18**(22), 4265–4272 (2022)
31 Hiratsuka, Y., Miyata, M., Tada, T., Uyeda, T.Q.P.: A microrotary motor powered by bacteria. Proceedings of the National Academy of Sciences **103**(37), 13618–13623 (2006)
32 Seyforth, H., Gomez, M., Rogers, W.B., Ross, J.L., Ahmed, W.W.: Nonequilibrium fluctuations and nonlinear response of an active bath. Physical Review Research **4**(2), 023043 (2022)
33 Takatori, S.C., Yan, W., Brady, J.F.: Swim pressure: stress generation in active matter. Physical Review Letters **113**(2), 028103 (2014)
34 Takatori, S.C., Brady, J.F.: Swim stress, motion, and deformation of active matter: effect of an external field. Soft Matter **10**(47), 9433–9445 (2014)
35 Solon, A.P., Stenhammar, J., Wittkowski, R., Kardar, M., Kafri, Y., Cates, M.E., Tailleur, J.: Pressure and phase equilibria in interacting active Brownian spheres. Physical Review Letters **114**(19), 198301 (2015)
36 Irving, J.H., Kirkwood, J.G.: The statistical mechanical theory of transport processes. IV. The equations of hydrodynamics. The Journal of Chemical Physics **18**(6), 817–829 (1950)
37 Takatori, S.C., De Dier, R., Vermant, J., Brady, J.F.: Acoustic trapping of active matter. Nature Communications **7**(1), 10694 (2016)
38 Li, Y., ten Wolde, P.R.: Shape transformations of vesicles induced by swim pressure. Physical Review Letters **123**(14), 148003 (2019)
39 Xie, K., Gorin, B., Cerbus, R., Alvarez, L., Rampnoux, J.M., Kellay, H.: Activity induced rigidity of liquid droplets. Physical Review Letters **129**(13), 138001 (2022)
40 Omar, A.K., Wang, Z.G., Brady, J.F.: Microscopic origins of the swim pressure and the anomalous surface tension of active matter. Physical Review E **101**(1), 012604 (2020)
41 Sun, Z., Li, L., Wang, C., Wang, J., Chen, H., Wang, G., Liu, L., Ye, F., Yang, M.: Intrinsic pressure as a convenient mechanical framework for dry active matter. arXiv preprint arXiv:2507.14644 (2025)
42 Wysocki, A., Elgeti, J., Gompper, G.: Giant adsorption of microswimmers: Duality of shape asymmetry and wall curvature. Physical Review E **91**(5), 050302 (2015)
43 Yan, W., Brady, J.F.: The curved kinetic boundary layer of active matter. Soft Matter **14**(2), 279–290 (2018)
44 Junot, G., Briand, G., Ledesma-Alonso, R., Dauchot, O.: Active versus passive hard disks against a membrane: Mechanical pressure and instability. Physical Review Letters **119**, 028002 (2017)
45 Li, L., Sun, Z., Yang, M.: Surface tension between coexisting phases of active Brownian particles. Proceedings of the National Academy of Sciences **122**(29), e2505010122 (2025)
46 Shaebani, M.R., Wysocki, A., Winkler, R.G., Gompper, G., Rieger, H.: Computational models for active matter. Nature Reviews Physics **2**(4), 181–199 (2020)
47 Sun, Z., Li, L., Wang, C., Wang, J., Chen, H., Wang, G., Ye, F., Liu, L., Yang, M.: Experimental verification of intrinsic pressure framework in an activity landscape. Chinese Physics Letters **43**(1), 010901 (2026)
48 Bialké, J., Siebert, J.T., Löwen, H., Speck, T.: Negative interfacial tension in phase-separated active Brownian particles. Physical Review Letters **115**(9), 098301 (2015)
49 Tsai, J.C., Ye, F., Rodriguez, J., Gollub, J.P., Lubensky, T.C.: A chiral granular gas. Physical Review Letters **94**, 214301 (2005)
50 Tan, T.H., Mietke, A., Li, J., Chen, Y., Higinbotham, H., Foster, P.J., Gokhale, S., Dunkel, J., Fakhri, N.: Odd dynamics of living chiral crystals. Nature **607**(7918), 287–293 (2022)
51 Bililign, E.S., Balboa Usabiaga, F., Ganan, Y.A., Poncet, A., Soni, V., Magkiriadou, S., Shelley, M.J., Bartolo, D., Irvine, W.T.M.: Motile dislocations knead odd crystals into whorls. Nature Physics **18**(2), 212–218 (2022)
52 Kole, S.J., Alexander, G.P., Maitra, A., Ramaswamy, S.: Chirality and odd mechanics in active columnar phases. PNAS Nexus **3**(10), pgae398 (2024)
53 Maitra, A.: Activity unmasks chirality in liquid-crystalline matter. Annual Review of Condensed Matter Physics **16**, 275–295 (2025)
54 de Groot, S., Mazur, P.: Non-equilibrium Thermodynamics. Dover Books on Physics. Dover Publications (1984)
55 Banerjee, D., Vitelli, V., Jülicher, F., Surówka, P.: Active viscoelasticity of odd materials. Physical Review Letters **126**(13), 138001 (2021)
56 Fruchart, M., Scheibner, C., Vitelli, V.: Odd viscosity and odd elasticity. Annual Review of Condensed Matter Physics **14**(1), 471–510 (2023)
57 Markovich, T., Lubensky, T.C.: Nonreciprocity and odd viscosity in chiral active fluids. Proceedings of the National Academy of Sciences **121**(19), e2219385121 (2024)
58 Soni, V., Bililign, E.S., Magkiriadou, S., Sacanna, S., Bartolo, D., Shelley, M.J., Irvine, W.T.M.: The odd free surface flows of a colloidal chiral fluid. Nature Physics **15**(11), 1188–1194 (2019)
59 Chen, Y., Li, X., Scheibner, C., Vitelli, V., Huang, G.: Realization of active metamaterials with odd micropolar elasticity. Nature Communications **12**(1), 5935 (2021)
60 Hargus, C., Epstein, J.M., Mandadapu, K.K.: Odd diffusivity of chiral random motion. Physical Review Letters **127**(17), 178001 (2021)
61 Poggioli, A.R., Limmer, D.T.: Odd mobility of a passive tracer in a chiral active fluid. Physical Review Letters **130**(15), 158201 (2023)
62 Duclut, C., Bo, S., Lier, R., Armas, J., Surówka, P., Jülicher, F.: Probe particles in odd active viscoelastic fluids: How activity and dissipation determine linear stability. Physical Review E **109**, 044126 (2024)
63 Lou, X., Yang, Q., Ding, Y., Liu, P., Chen, K., Zhou, X., Ye, F., Podgornik, R., Yang, M.: Odd viscosity-induced hall-like transport of an active chiral fluid. Proceedings of the National Academy of Sciences **119**(42), e2201279119 (2022)
64 Yang, Q., Zhu, H., Liu, P., Liu, R., Shi, Q., Chen, K., Zheng, N., Ye, F., Yang, M.: Topologically protected transport of cargo in a chiral active fluid aided by odd-viscosity-enhanced depletion interactions. Physical Review Letters **126**(19), 198001 (2021)
65 Liu, P., Zhu, H., Zeng, Y., Du, G., Ning, L., Wang, D., Chen, K., Lu, Y., Zheng, N., Ye, F., Yang, M.: Oscillating collective motion of ac-

tive rotors in confinement. Proceedings of the National Academy of Sciences **117**(22), 11901–11907 (2020)

66 Ding, Y., Wang, B., Yang, Q., Zhao, Z., Komura, S., Seto, R., Yang, M., Ye, F.: Odd response-induced phase separation of active spinners. Research **7**, 0356 (2024)

67 Koch, D.L., Subramanian, G.: Collective hydrodynamics of swimming microorganisms: living fluids. Annual Review of Fluid Mechanics **43**(1), 637–659 (2011)

68 Ning, L., Lou, X., Ma, Q., Yang, Y., Luo, N., Chen, K., Meng, F., Zhou, X., Yang, M., Peng, Y.: Hydrodynamics-induced long-range attraction between plates in bacterial suspensions. Physical Review Letters **131**(15), 158301 (2023)

69 Bäuerle, T., Fischer, A., Speck, T., Bechinger, C.: Self-organization of active particles by quorum sensing rules. Nature Communications **9**(1), 3232 (2018)

70 Lavergne, F.A., Wendehenne, H., Bäuerle, T., Bechinger, C.: Group formation and cohesion of active particles with visual perception–dependent motility. Science **364**(6435), 70–74 (2019)

71 Li, S., Phan, T.V., Di Carlo, L., Wang, G., Do, V.H., Mikhail, E., Austin, R.H., Liu, L.: Informational memory shapes collective behavior in intelligent swarms. Physical Review Letters **136**, 138302 (2026)

72 Negi, R.S., Winkler, R.G., Gompper, G.: Collective behavior of self-steering active particles with velocity alignment and visual perception. Physical Review Research **6**, 013118 (2024)

73 Ziepke, A., Maryshev, I., Aranson, I.S., Frey, E.: Acoustic signaling enables collective perception and control in active matter systems. Physical Review X **15**, 031040 (2025)

74 Fruchart, M., Hanai, R., Littlewood, P.B., Vitelli, V.: Non-reciprocal phase transitions. Nature **592**(7854), 363–369 (2021)

75 Grauer, J., Schwarzendahl, F.J., Löwen, H., Liebchen, B.: Optimizing collective behavior of communicating active particles with machine learning. Machine Learning: Science and Technology **5**(1), 015014 (2024)

76 Yu, H., Fu, Y., Zhang, X., Chen, L., Qi, D., Shi, J., Wang, W.: Programmable active matter across scales. Programmable Materials **1**, e7 (2023)

77 Veenstra, J., Gamayun, O., Guo, X., Sarvi, A., Meinersen, C.V., Coulais, C.: Non-reciprocal topological solitons in active metamaterials. Nature **627**(8004), 528–533 (2024)

78 Gomez-Solano, J.R., Blokhuis, A., Bechinger, C.: Dynamics of self-propelled Janus particles in viscoelastic fluids. Physical Review Letters **116**(13), 138301 (2016)

79 Narinder, N., Bechinger, C., Gomez-Solano, J.R.: Memory-induced transition from a persistent random walk to circular motion for achiral microswimmers. Physical Review Letters **121**(7), 078003 (2018)

80 Scholz, C., Jahanshahi, S., Ldov, A., Löwen, H.: Inertial delay of self-propelled particles. Nature Communications **9**(1), 5156 (2018)

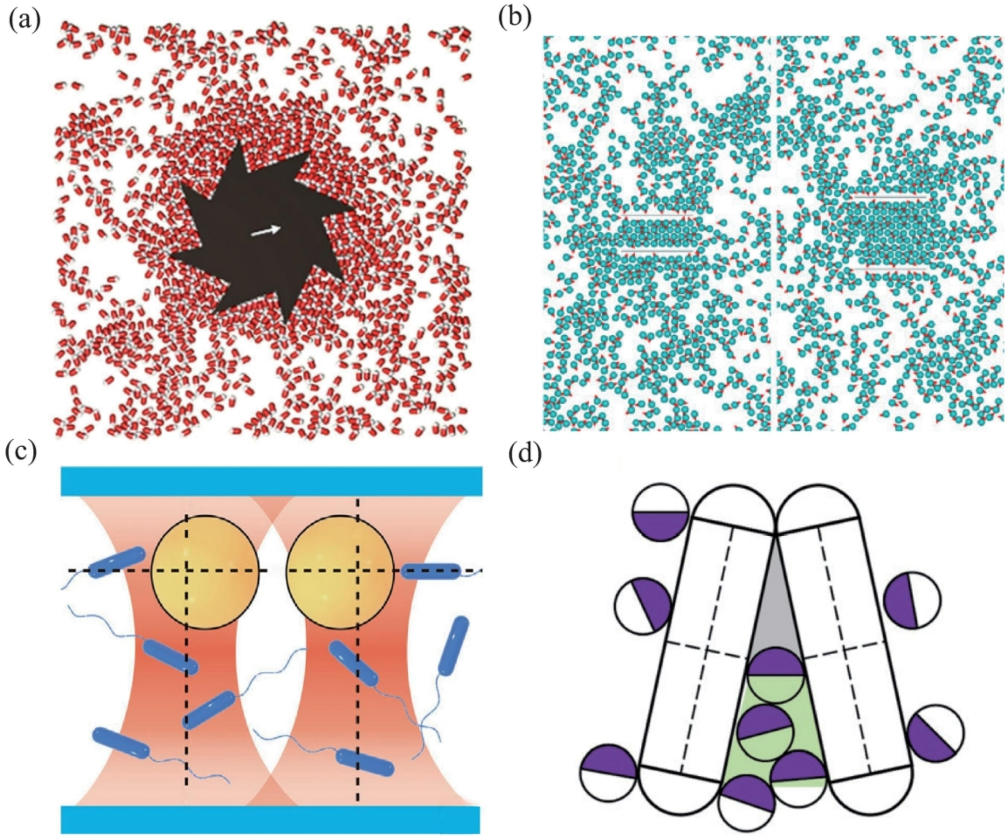
81 Friedl, P., Gilmour, D.: Collective cell migration in morphogenesis, regeneration and cancer. Nature Reviews Molecular Cell Biology **10**(7), 445–457 (2009)

82 Guillot, C., Lecuit, T.: Mechanics of epithelial tissue homeostasis and morphogenesis. Science **340**(6137), 1185–1189 (2013)

83 Hakim, V., Silberzan, P.: Collective cell migration: a physics perspective. Reports on Progress in Physics **80**(7), 076601 (2017)

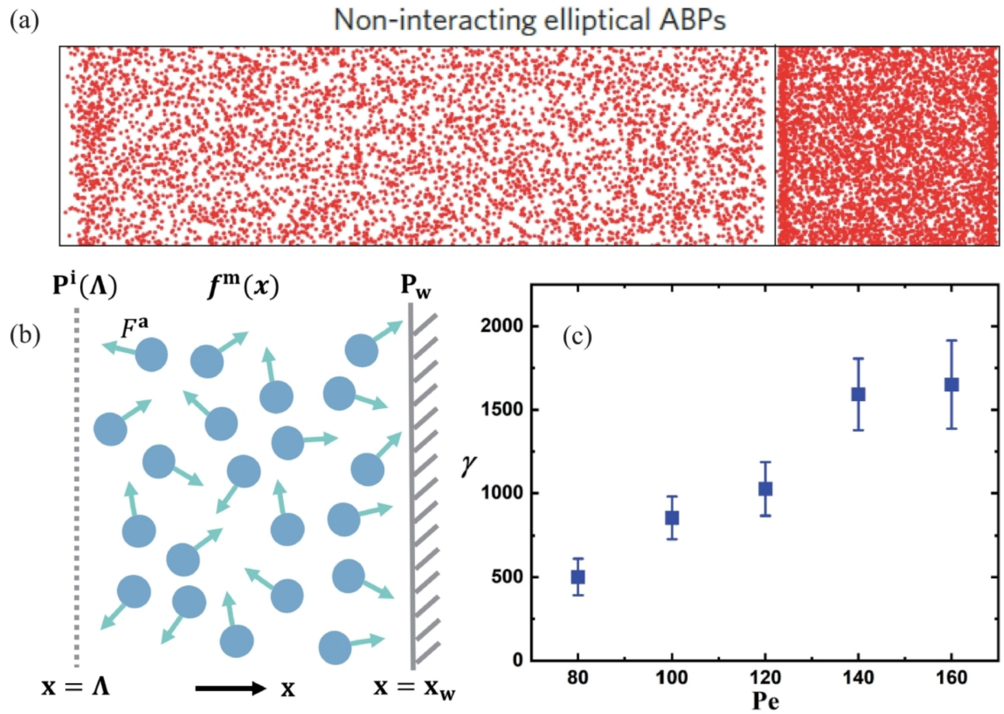
84 Feng, X.Q., Li, B., Lin, S.Z., Wang, M.Y., Chen, X.D., Zhang, H.X., Fang, W.: Mechano-chemo-biological theory of cells and tissues: review and perspectives. Acta Mechanica Sinica **41**(7), 625315 (2025)

85 Yu, P., Li, B.: Three-dimensional morphogenesis of epithelial tubes. Acta Mechanica Sinica **40**(2), 623297 (2024)



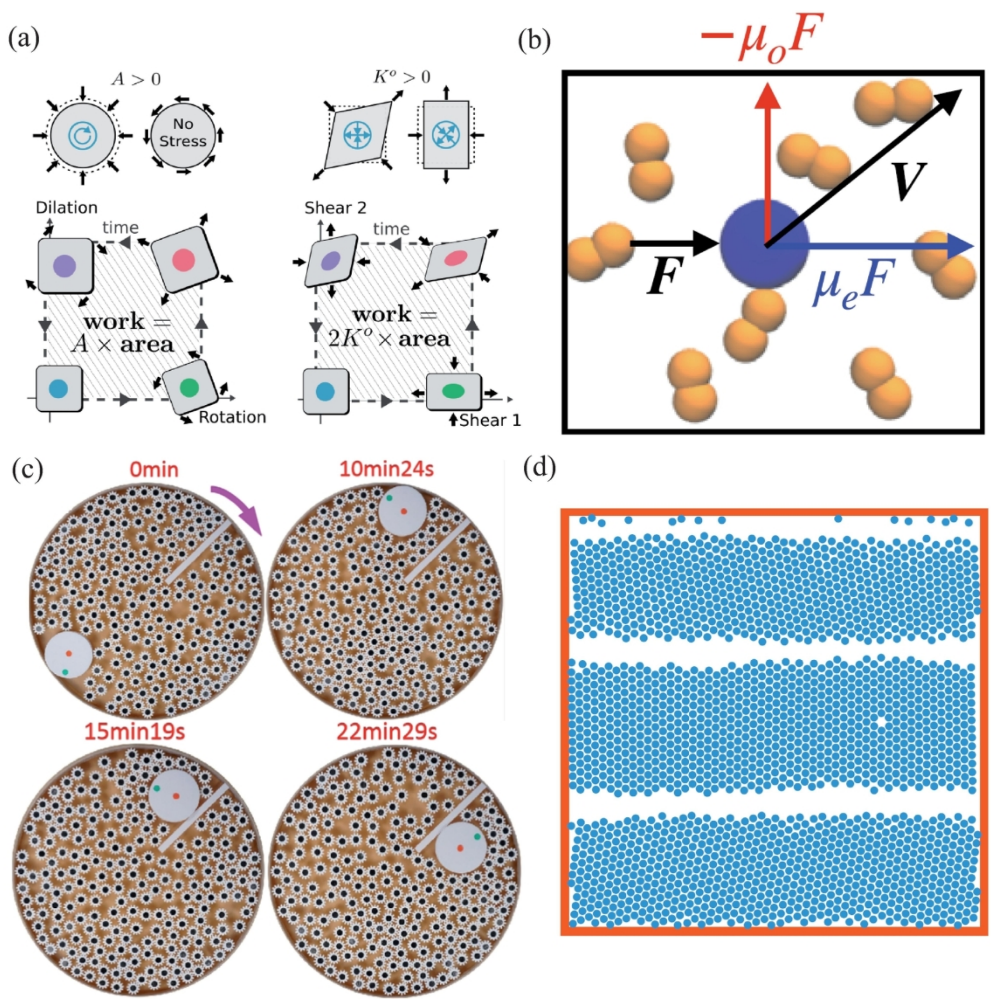
Anomalous mechanical phenomena governed by active structural reorganization. (a) Geometry-induced net torque driving the spontaneous rotation of an asymmetric gear immersed in a bacterial bath (reproduced by permission from Ref.~\cite{angelani2009self}). (b) Long-range effective forces between passive plates mediated by self-propelled colloidal hard spheres (reproduced by permission from Ref.~\cite{ni2015tunable}). (c) Constraint-dependent effective forces due to the dynamic accumulation of self-propelled particles (adapted by permission from Ref.~\cite{liu2020constraint}). (d) Constraint-dependent effective torques on passive anisotropic objects immersed in an active bath (reproduced by permission from Ref.~\cite{li2022active}).

166x139mm (300 x 300 DPI)



Mechanical equilibrium and surface tension in active matter. (a) For elliptical active particles, distinct particle-wall interactions drive spontaneous piston motion, illustrating the breakdown of the traditional equation of state (reproduced by permission from Ref.~\cite{solon2015pressure2}). (b) The emergent polarization force density directed toward the boundary (arrows indicate self-propulsion directions) exactly compensates for the pressure gap between the boundary and the bulk (adapted by permission from Ref.~\cite{sun2025intrinsic}). (c) The mechanical surface tension of MIPS calculated via the intrinsic pressure framework is significantly positive (reproduced by permission from Ref.~\cite{li2025surface}).

183x130mm (300 x 300 DPI)



Odd mechanics in chiral active matter. (a) Antisymmetric odd response tensors enable non-conservative work extraction during closed deformation cycles (reproduced by permission from Ref.~\cite{scheibner2020odd}). (b) The odd mobility characterizes the orthogonal drift of a driven passive tracer in a chiral active bath (reproduced by permission from Ref.~\cite{poggioli2023odd}). (c) Topologically protected edge flow enables robust cargo transport aided by odd-viscosity-enhanced depletion interactions (reproduced by permission from Ref.~\cite{yang2021topologically}). (d) The synergy of odd viscosity and odd elasticity drives the phase separation of active spinners into stripes (adapted by permission from Ref.~\cite{ding2024odd}).

169x167mm (300 x 300 DPI)