Chiral active motion across scales: from exact ISF theory to macroscopic robot experiments

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Chiral self-propulsion appears across vastly different length scales, from microswimmers near to centimeter-scale bristle bots. This talk brings together two complementary strands—exact theory for the intermediate scattering function (ISF) of a Brownian circle swimmer [1] and quantitative single-agent experiments on free chiral robots (hexbugs) [2]—to provide a coherent, data-driven description of chiral active motion.

On the theoretical side, I will outline an exact characterization of the ISF for an anisotropic Brownian circle swimmer derived from the Fokker–Planck equation for the conditional probabilities. The solution is expressed in terms of generalizations of the Mathieu functions and provides a complete, non-perturbative description of how chirality, anisotropic translational diffusion, and rotational noise shape the dynamics. This framework identifies distinct spatiotemporal regimes that are directly accessible in scattering experiments: (i) at large wavenumbers, the ISF reflects bare translational diffusion; (ii) at intermediate wavenumbers that probe the circular swimming radius, the ISF exhibits a plateau with characteristic oscillations, a clear dynamical signature of persistent circular motion; and (iii) at small wavenumbers, the dynamics crosses over to an enhanced effective diffusion regime. The analytical structure enables a transparent interpretation of ISF shapes and decay rates across these regimes.

On the experimental side, I will discuss measurements on a free chiral hexbug (Nano-Newton Series) tracked via video microscopy and analyzed within the overdamped Langevin framework for active Brownian circle swimmers. We compare the measured trajectories to theoretical predictions using two complementary observables: the mean-squared displacement (MSD) and, critically, the ISF. The MSD and ISF jointly capture the crossover from short-time, noise-influenced motion to intermediate-time persistence due to chirality and finally to long-time effective diffusion. We find good agreement between the hexbug dynamics and model predictions for both MSD and ISF. Notably, deviations appear in the short-time behavior of the real-space propagator, where translational noise is most evident, while the ISF remains a particularly sensitive and robust diagnostic across time and length scales.

Taken together, these results support overdamped Langevin models as a reliable coarse-grained description of macroscopic single-agent chiral motion and demonstrate the power of ISF- and propagator-based analyses for characterizing active dynamics. The combined theoretical and experimental insights offer a principled route to refine coarse-grained models and to interpret measurements of chiral trajectories using directly measurable quantities.

References:

[1] C. Kurzthaler, T. Franosch, Intermediate scattering function of an anisotropic Brownian circle swimmer, Soft Matter 13 (37), 6396–6406 (2017).

[2] T. Kiechl, A. Altshuler, A. Lüders, Y. Roichman, T. Franosch, Free chiral self-propelled robots compared to active Brownian circle swimmers, Phys. Rev. E 113, 045409 (2026).