Title: Emergent Collective Dynamics in Complex Networks: From Instabilities to Cooperation and Synchronization

Abstract: Emergent collective behavior is a hallmark of complex systems, where interactions among individual units give rise to large-scale organization, synchronization, and spatial patterns. Understanding the emergence, stability, and transitions of such collective states remains a central challenge in nonlinear dynamics and network science. In this talk, I will explore two complementary mechanisms through which dynamical instabilities, network structure, and evolutionary feedback shape collective behavior. First, I will discuss how diffusion-induced instabilities promote cooperation in eco-evolutionary networks. In a networked public goods game, faster diffusion of defectors destabilizes a homogeneous, defector-dominated state, leading to cooperative spatial patterns. Linear stability analysis identifies the critical mobility ratio, while a degree-based mean-field approach reveals how network heterogeneity favors cooperation on highly connected nodes. Next, I will turn to the coevolution of synchronization and cooperation in networks with higher-order interactions. Using an evolutionary Kuramoto framework, I will show how group interactions sustain cooperation, enhance synchronization, and generate bistability through dynamical–evolutionary feedback. Together, these studies reveal distinct yet interconnected routes to collective organization, highlighting how interaction mechanisms and network structure govern the emergence of collective states.