Impurities as Quantum Detectors of Phase Transitions: from BKT Criticality to Scale-Invariant Mott-Instulator-to-Superfluid Physics

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Detecting quantum phase transitions in strongly correlated many-body systems remains a central challenge, as conventional order parameters are often inaccessible or ill-defined, especially in low dimensions. In this talk, I will show how mobile impurities provide a powerful and conceptually simple alternative: they act as local, dynamical detectors of collective many-body physics.I will cite examples beginning with a focus on the case of two-dimensional Fermi gases and discuss how an impurity couples to excitations near a Berezinskii–Kosterlitz–Thouless transition, where the absence of a local order parameter obscures the critical behavior. I will then turn to lattice bosons and focus on the Mott-insulator–to–superfluid transition, where we demonstrate that the impurity polaron energy exhibits sharp and universal signatures of criticality. Remarkably, numerical results reveal that this energy becomes scale invariant across the transition, reflecting the emergent critical degrees of freedom rather than microscopic details. Building on this framework, I will present ongoing work where polarons in Fermi gases are used as probes of more exotic ordered states, in particular FFLO physics, where spatially modulated pairing leaves distinct fingerprints in impurity observables. Finally, I will argue that this detector paradigm is far more general: collective excitations such as phonons can play an analogous role in solid-state and semiconductor systems, offering a new route to sensing phase transitions in platforms where direct probes are limited.