Towards painting finite-range interactions in many-body cQED with a mesoscopic tweezer

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Ultracold atoms coupled to high-finesse optical cavities have proven to be a powerful and versatile platform to study quantum many-body physics [1]. In these systems, strong photon-mediated inter-atomic interactions can give rise to self-ordered superradiant phases [2], supersolid formation [3], or dynamical phases [4]. However, since interactions are mediated by photons of a global cavity mode, they naturally are of an all-to-all connectivity, effectively describing zero dimensional systems. Breaking this low dimensionality and reintroducing locality to engineer tunable, finite-range interactions remains a remarkable challenge in the field of analogue quantum simulation.

In this talk, I will present our recent experimental progress in addressing this challenge by implementing a dynamical mesoscopic pump beam. Replacing the traditional global pump with a localized optical tweezer, we are now able to spatially address sub-ensembles of the ultracold atomic cloud. I will describe the technical implementation and first results on this new physical system, as well as our strategy for "painting" finite-range interactions with tunable shape and range when scanning the beam over the cloud. This approach not only provides a route toward simulating finite-range interacting systems but also opens the doors into the unexplored regime of mesoscopic superradiance, where local perturbations and finite system effects can compete with global order.

[1] F. Mivehvar et al, *Advances in Physics* **70(1)** (2021)
[2] K. Baumann et al, *Nature* **464** (2010)
[3] J. Léonard et al, *Nature* **543** (2017)
[4] D. Dreon et al, *Nature* **608** (2022)

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