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Seeing with the nano-eye: accessing structure, function, and dynamics of matter on its natural length and time scales

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To understand and ultimately control the properties of most functional materials, from molecular soft-matter to quantum materials, requires access to the structure, coupling, and dynamics on the elementary time and length scales that define the microscopic interactions in these materials. To gain the desired nanometer spatial resolution with simultaneous spectroscopic specificity we combine scanning probe microscopy with different optical, including coherent, nonlinear, and ultrafast spectroscopies. The underlying near-field interaction mediated by the atomic-force or scanning tunneling microscope tip provides the desired deep-sub wavelength nano-focusing enabling few-nm spatial resolution. I will introduce our generalization of the approach in terms of the near-field impedance matching to a quantum system based on special optical antenna-tip designs. The resulting enhanced and qualitatively new forms of light-matter interaction enable measurements of quantum dynamics in an interacting environment or to image the electromagnetic local density of states of thermal radiation. Other applications include the inter-molecular coupling and dynamics in soft-matter hetero-structures, surface plasmon interferometry as a probe of electronic structure and dynamics in graphene, and quantum phase transitions in correlated electron materials. These examples highlight the general applicability of the new near-field microscopy approach, complementing emergent X-ray and electron imaging tools, aiming towards the ultimate goal of probing matter on its most elementary spatio-temporal level.