



PhD THESIS DEFENSE: Near-field photocurrent in correlated 2D moire materials

SERGI BATLLE PORRO

May 30, 2025

12:00

ICFO Auditorium

Since the discovery of graphene, two-dimensional (2D) materials have garnered significant attention from the condensed matter physics community owing to their potential to engineer new physical, optical, and mechanical properties. The 2D material class now includes insulators (hexagonal boron nitride, hBN), semiconductors (transition metal dichalcogenides, TMDs), superconductors (NbSe₂), topological insulators (Bi₂Te₃), and ferromagnets (CrI₃). Beyond their inherent properties, layered materials allow for new characteristics through vertical stacking. Recent developments have led to the discovery of moire materials, in which electronic properties are significantly altered by twisting adjacent 2D layers.

The discovery of superconductivity in magic-angle twisted bilayer graphene (MATBG) marked a milestone in moire physics, initiating a rapidly growing field. The resulting phase diagrams

of other high- T_c superconductors, MATBG, serve as a platform for exploring highly tunable strongly correlated states. At a twist angle of approximately 1.1° , the "magic angle" MATBG shows significant band flattening near the Dirac points, reducing the Fermi velocity and making the kinetic energy smaller than the repulsive Coulomb interactions. This results in superconductivity and various emergent phases dominated by many-body physics, including correlated insulators, orbital magnetism, nematic orders, and topological states. Moiré materials with large superlattice unit cells facilitate the exploration of strongly correlated phenomena at low charge carrier densities. Local back-gate electrodes enable capacitive tuning between strongly correlated states in-situ, a unique feature not available in other high- T_c superconductors. Advances in scanning probe techniques have allowed researchers to determine local properties at the sub-nanometer scale. Scattering-type scanning near-field optical microscopy (s-SNOM) is particularly suited for exploring MATBG because it can measure scattering and photovoltage signals at the nanometer scale while simultaneously probing mesoscopic electron transport.

Utilizing a groundbreaking cryo-near-field nanoscopy method, we will conduct s-SNOM measurements at cryogenic temperatures (as low as 8 K) to assess the optical and photovoltage near-field responses. This approach employs energies in the mid-infrared (IR) and terahertz (THz) ranges, which align with the anticipated optical transition energies in the band structures of these materials.

The primary objectives of this thesis are to ascertain the pertinent optical and thermoelectric coefficients in twisted moiré materials, evaluate the impact of inhomogeneities through gate-tuned near-field photovoltage and optical measurements, visualize correlated phenomena and broken symmetry states, and comprehend the nature of dephased signals in various measurements. This dissertation seeks to highlight crucial advancements in quantum phases, quantum nano-optoelectronics, and thermoelectricity, while supporting interest in unresolved questions, such as the characteristics of low-temperature correlated states. Additionally, it outlines future objectives for near- and far-field photovoltage experiments.

Friday May 30, 12:00 h. ICFO Auditorium

Thesis Directors: Prof. Dr. Frank Koppens and Dr. Petr Stepanov

Hosted by: Academic Affairs