Unraveling exciton dynamics in 2D quantum materials on ultrashort time- and lengthscales using time-resolved momentum microscopy

Stefan Mathias

I. Physical Institute, University of Göttingen, Germany

Two-dimensional semiconducting quantum materials and organic semiconductors have emerged as promising materials for next-generation optoelectronics and energy harvesting. At their heart lies the process of exciton formation: when light is absorbed, Coulomb-bound electron-hole pairs, termed excitons, carry and convert energy on nanometer spatial and femtosecond temporal scales. Understanding the very first moments of light–matter interaction, along with subsequent exciton relaxation and energy conversion, is vital for designing devices with new functionality and high efficiency.

To study light-matter interaction and exciton dynamics in such 2D quantum material heterostructures, we have developed a state-of-the-art, photoemission-based experiment [1] that enables us to observe exciton dynamics in space and time, spanning nanometers and femtoseconds. This approach uncovers the characteristic fingerprints of exciton generation, tracks their dynamics of energy transfer and thermalization, and lets us map the elusive dark exciton landscape in 2D semiconductors.

In my talk, I will show how we probe ultrafast light-matter interactions [2] and resolve the formation dynamics of dark interlayer excitons across a variety of 2D quantum materials [3-7]. I will discuss the identification of distinctive photoemission signatures linked to these processes, show how the dark exciton landscape can be mapped, and introduce "photoemission exciton tomography" [6], a new technique that enables tracing ultrafast charge transfer from transition metal dichalcogenides (TMDs) to organic layers in real time [7].

[1] Reutzel et al., Adv. in Physics X 9, 2378722 (2024).
[2] Merboldt et al., Nature Physics 21, 1093-1099 (2025).
[3] Schmitt et al., Nature 608, 499 (2022).
[4] Bange et al., Science Adv. 10, eadi1323 (2024).
[5] Schmitt et al., Nature Photonics 19, 187-194 (2025).
[6] Bennecke et al., Nature Communications 15, 1804 (2024).
[7] Bennecke et al, Nature Physics 21, 1973–1980 (2025).