The world around us is characterized by one temporal dimension and three spatial dimensions. Physicists studying condensed matter have long been exploring systems with lower dimensionality, including two-dimensional (2D) quantum wells, one-dimensional (1D) quantum wires, and zero-dimensional (0D) quantum dots. Among these, 2D systems have found widespread technological applications. The reduced dimensions of these systems enable the operation of efficient LEDs, laser diodes, fast transistors in integrated circuits, and WiFi radio amplifiers. Trapped electrons in two dimensions can exhibit behaviors that are fundamentally different from those of free electrons. For instance, in graphene, a two-dimensional carbon structure with a honeycomb symmetry, electrons behave as if they were massless, similar to light particles known as photons.

In this project, photons will be manipulated to behave like chargeless electrons. This will be achieved through the creation of periodic photonic structures using self-organization by spontaneous pattern formation, resulting in photonic quasiparticles that emulate the behavior of electrons in solid-state systems. To accomplish this, I will employ a microcavity filled with a birefringent medium, specifically, a liquid crystal. The microcavity consists of two perfect mirrors, forming a standing electromagnetic wave inside. By applying an electric voltage across the microcavity, the liquid crystal molecules inside can be rotated in a manner that alters the internal energy and state of the linearly polarized plane wave light passing through the cavity. This process may even enable the generation of right- and left-handed circularly polarized components, as my group demonstrated in a Science paper in 2019. The mathematical description of this phenomenon is related to what is known as spin-orbit interaction, where the polarization of light plays the role of a spin.

With these photonic devices featuring various 1D and 2D periodic structures, I will be able to create ultra-heavy or ultra-light photonic quasiparticles, similar to those for electrons found in solid-state crystals. I will investigate how the spin-orbit interaction modifies the so-called band structure and influences the lasing of emitters integrated within cavities. Through the careful design of crystal structures and leveraging the tunability of liquid crystal optical properties, along with the incorporation of laser dyes, I aim to modify the energy and polarization of light emission.

The controlled splitting of electromagnetic modes of the cavity can be understand in terms of artificial magnetic field ad synthetic Hamiltonians. I will develop analytical and numerical methods for modeling of light behavior in low-dimensional periodic photonic structures.

Finally I would like to use tunable optical cavities in quantum optics. In this project single photon experiments performed on so-called inseparable optical states discovered by my group in 2021 and 2022 would be performed and Bell’s inequalities would be checked. The bosonic nature of photons, which allows them to occupy the same quantum state, should result in destructive interference when they encounter a photonic state in a microcavity. This destructive interference, in turn, leads to the creation of a specific quantum state called a "two-photon NOON state" at the output of the cavity. This state represents a highly entangled configuration of two photons, which can have applications in quantum optics and quantum information processing.

In summary, this project not only promises technological advancements in photonics but also extends the boundaries of our knowledge in condensed matter physics and quantum optics. It holds the potential to reshape the way we harness and understand light, with far-reaching implications across various scientific and technological domains.