# DISCO: Dicke-enhanced Single-emitter Strong Coupling at Ambient Conditions as a Quantum Resource

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## Introduction

Quantum electrodynamic strong coupling is a fundamental resource for emergent quantum technologies that interface light and matter [1]. Recent experiments have demonstrated the strong coupling of a colloidal quantum dot (cQD) and a broadband plasmonic nanoresonator at room temperature [2], and to explain the results, the existence of a broadband multilevel coupling leading to a Dicke-like enhancement of the single-emitter coupling strength was postulated [2,3]. In the DISCO project, this conjecture will be put under scrutiny and carried forward towards a quantum resource

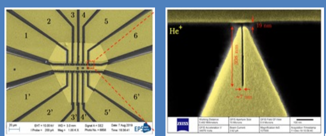
To experimentally achieve a Dicke-like enhancement of the coupling strength, we will employ Cd- and Pb-based cQDs that offer up to 64 near-degenerate levels close to the conduction band edge, which is expected to increase the coupling strength by nearly one order of magnitude and thereby confer improved robustness and accessibility of strong coupling quantum technologies. To achieve this significant advance, progress will be made in terms of nanotechnology, materials synthesis and quantum nano-optical theory. To highlight the potential of the developed platform, we will demonstrate a prototype device architecture – a scalable, quantum nanophotonic transistor that will be able to modulate an optical signal at the single photon level under ambient conditions.

## Advances in Quantum Theory and Technology

### ➢ Quantum theory & simulation:

We will develop a state-of-the-art, quantum-dynamical approach for simulating the near-field interaction of cQDs with plasmonic nanoresonators, combining a *Green's function quantisation scheme for the quasinormal modes* with a *multilevel description of the emitter.* Our methodology will establish the Dicke-like enhancement of single-emitter light-matter interaction via broadband multilevel coupling as a potential facilitator of the strong and perhaps even ultrastrong coupling regimes, and thus as a novel quantum resource.

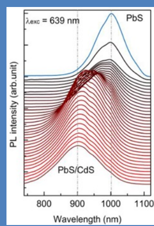
### ➢ Quantum device fabrication & characterisation:

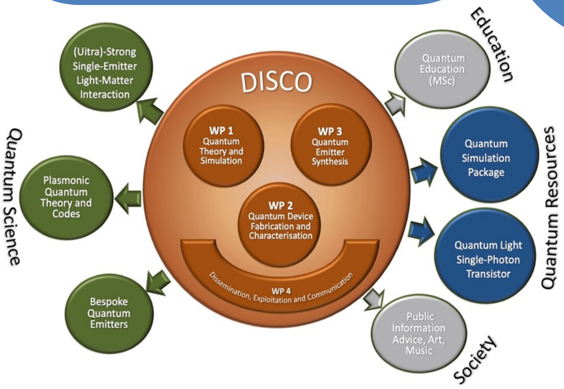


We will experimentally develop a *robust platform for nanoscale, integrated quantum optics* comprising strongly coupled cQDs and plasmonic resonator systems on a substrate. *Dielectrophoresis* will be used to accurately position cQDs at desired locations, such as plasmonic hotspots, leveraging *electrically-driven plasmonic nanostructures* (a technological advance that was pioneered in Würzburg [4]). An additional advantage of such nanostructures is the possibility to apply very large DC electric fields to quantum emitters, which will be used to introduce *tunability via the quantum-confined Stark effect*.

### ➢ Nanomaterials synthesis:

We will synthesize and optimize *core-shell CdSe(Te)/ZnS(Se) and PbS(Se)/CdS(Se) cQDs* using wet-chemical techniques, whose structural and optical quality will enable precise single-emitter experiments and quantum photonic transistor realization. We will leverage cation exchange mechanisms for *core-shell architecture formation and surface engineering* to avoid oxidation and formation of defects, as well as to improve the cQD quantum yield. Throughout we will perform *optical stability tests* (e.g., in terms of quantum yield), as well as *characterization of both the QD emission properties* (e.g., via PL and FTIR spectroscopy) *and structural features* (e.g., via HRTEM).

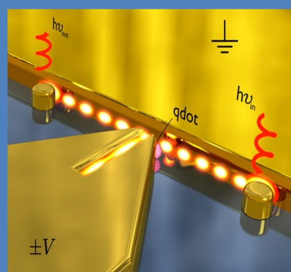



## Single-photon Quantum Transistor

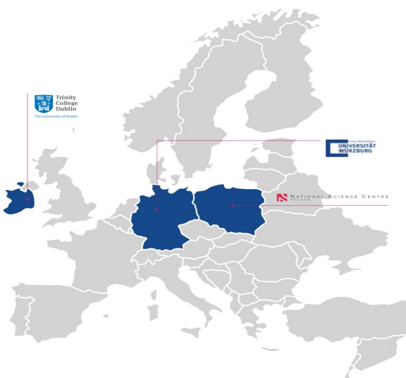
The feasibility of electrically manipulable and thus on-demand, room-temperature strong coupling combined with the preserved nonlinearity of the Jaynes-Cummings ladder (via the Dicke mechanism itself) will enable pioneering explorations of a prototype quantum-optical transistor architecture, capable of modulating optical signals at the single-photon level.

Its architecture indicates a completely new way of realizing quantum devices under ambient conditions, which are compatible with large scale integration and therefore promise a new route to real-world, integrated quantum-optical chips.




## The DISCO Consortium

- **The Trinity team** contributes to DISCO their long-standing expertise in the theory and computational simulation of active quantum nanophotonic, nanoplasmonic and quantum metamaterial systems. They maintain an internationally unique and continuously advancing foundation of numerical codes that has been developed over the last 25 years, which in particular, allows research into the vital link between quantum materials physics and quantum nanophotonics.
- **The Würzburg team** offers extensive experience in the fabrication of hybrid plasmonic nanostructures and electrically-driven nanocircuitry at the highest level of precision. Furthermore, the Würzburg lab is among the few worldwide that have experimentally achieved strong coupling of a single quantum emitter at room temperature – a condition that they can now access routinely.
- **The Wrocław team** is highly interdisciplinary and offers expertise in nanomaterials synthesis, surface chemistry, optical spectroscopy and prototyping of cQD-based devices. The team also has experience in commercialization. The provision of bespoke cQD quantum emitters is a key contribution to the DISCO project.



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**References**
[1] X. Xiong *et al.*, *Appl. Phys. Lett.* 118, 130501 (2021).
[2] H. Groß *et al.*, *Sci. Adv.* 4, eaar4906 (2018).
[3] T. Tufarelli *et al.*, *Phys. Rev. Research* 3, 033103 (2021).
[4] R. Kullock *et al.*, *Nat. Commun.* 11, 115 (2020).