

# Felicidades al nuevo graduado de doctorado del ICFO

## El Dr. Daniel Goncalves Romeu se ha doctorado con una tesis titulada i¿½Novel approaches for quantum technologies wi h atoms and photons in free spacei¿½

November 15, 2024

Felicitamos al Dr. Daniel Goncalves Romeu que ha defendido su tesis esta manana en la sala Elements del ICFO.
El Dr. Goncalves Romeu obtuvo su Master en Fotonica por la Universitat Politecnica de Catalunya antes de unirse al grupo de investigacion de Theoretical Quantum-Nano Photonics dirigido por el profesor ICREA en ICFO el Dr. Darrick Chang. Su tesis titulada i¿½Nov l approaches for quantum technologies with atoms and photons in free spacei¿½fue supervisada por el Prof. Darrick Chang.

**RESUMEN:**
The rapid advancement of quantum technologies is currently pushing the boundaries of scientific and technological innovation. Among the various platforms for translating quantum

theory into practical applications, photons have emerged as particularly strong contenders. Their inherent advantages, such as low decoherence and swift propagation, make them ideal carriers of quantum information for communication, computation and sensing purposes. However, the efficient manipulation and control of photonic quantum states presents significant challenges, often requiring the use of interfaces. In this Thesis, we investigate several novel approaches to engineer and control the properties of light using a very traditional system: trapped neutral atoms in free space.

In Chapter 2, we introduce a novel method to observe and manipulate strong quantum interference effects between a few photons and a single free-space atom. The approach uses a Maltese-cross configuration, where two perpendicular pump and probe coherent fields drive the atom. Even for a weak atom-light coupling, we demonstrate that adjusting the relative pump-probe strength ratio and phase can simulate an artificially enhanced coupling efficiency for specific observables. In particular, we are able to engineer photon correlations from fully anti-bunched to extremely bunched states, and control the linear transmission properties in specific directions.

In Chapter 3, we propose the combination of ordered atomic arrays and Rydberg Electromagnetically Induced Transparency (EIT) as a promising platform for quantum nonlinear optics. The spatial periodicity of the array enables precise control over photon scattering, reducing the inherent dissipation associated with traditional Rydberg EIT protocols. Using a two dimensional array, we design and characterize a single photon switch, where the storage of a single photon as a Rydberg excitation results in a strong change in the system's optical response. This switch can be used to implement a photon-photon gate with an error scaling with the Rydberg blockade radius as Rb^{-4}, potentially reaching gate efficiencies of up to 99% for realistic experimental parameters. Additionally, we model the optical properties of the array in the strong driving regime, where the system is multiply excited.

In Chapter 4, we discuss a recent experiment that observed features of the Driven-dissipative Dicke phase transition in a driven elongated cloud in free space. This is unexpected, as the Dicke model typically involves an ensemble coupling identically to a single, lossy photonic mode, akin to an ensemble coupled to a cavity. Instead, a free-space ensemble interacts with a continuum of modes, encoding propagation effects. Solving a simple model to explain this behavior, based on the one-dimensional Maxwell-Bloch equations, we observe nonanalytic behavior in certain observables. However, a closer analysis reveals a significant spatial inhomogeneity in atomic properties. We thus argue that the free-space system does not undergo a phase transition but rather a i¿½phase separation,i¿½ roughly speaking, bet een saturated and unsaturated regions. Beyond understanding the phase transition, we lso elucidate under which conditions some properties of atoms in cavities can be mappe to atoms in free space.

Together, the results in this Thesis represent a meaningful contribution towards better

understanding phenomena associated to atom-light interactions in free space, and towards translating that knowledge into practical useful implementations.

**Tribunal de Tesis:**

Prof. Dr. Carlos Gonzalez-Ballesteros, TU WIEN

Prof. Dr. Hugues de Riedmatten, ICFO

Prof. Dr. Alejandro Gonzalez-Tudela, IFF-CSIC